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University of Glasgow

Department of Civil Engineering

Sustainability of Water Resources Development for Malawi with Particular Emphasis on North and Central Malawi

by

Patsani G. Kumambala

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in Fulfilment of the
Degree of Doctor of Philosophy

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If we do not respond to the fact that nearly a third of humanity is without safe clean water, that half of our family is living on less than US$2 per day, that thousands of children die each day from preventable diseases and starvation, and that the failure to protect the environment hits these innocent victims the hardest we are contributing to a gross injustice of enormous proportions. From such injustice only the whirlwind of chaos will be reaped

Desmond Tutu (2009)

To my son, Emmanuel

ACKNOWLEDGEMENTS

I am very grateful to God, the almighty, maker of heaven and earth and that is in it for the strength and well being that enabled me to complete this research.

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Lastly but not least, I would like to register my grateful thanks to my mother, whose love, care and desire was to see me educated up to University level.

ABSTRACT

The world population regardless of location and development stage needs energy and water. According to the United Nations, the present world population stands at about 6.7 billion with an average annual growth rate of 1.3%. Population increase calls for increased allocation of water for domestic use, agriculture and industrial use. The increased water allocation among different sectors has always resulted in conflicts among users, and stress on freshwater environment. Therefore it is essential that water resources be developed in a sustainable manner to accommodate future generations to meet their water needs. In recent years studies regarding stress on water resources due to population increase have always been done without considering the effect of climate change while studies on the effect of climate change on river flows have always ignored the effect of population increase.

An assessment of the sustainability of the water resources primarily of the Central and Northern highland river basins of Malawi is presented in this thesis based on basin hydrology, human health, environment and climate change. A complete hydrological data set is not readily available in developing countries like Malawi. That being the case, a method of estimating missing data in hydrological data records has been presented. Climate change predictions have been done based on United Kingdom (UK) Meteorological Office Hadley Centre HadCM3 experiments. All the river basins in the Central and Northern part of Malawi drain into Lake Malawi. Lake Malawi plays a major role in the provision of energy for the country and water supply to the southern part of Malawi through its outlet Shire river. Planning of alternative water resources schemes on river basins in the northern part of Malawi needs an assessment of the hydrological behaviour of the lake. In view of this, the report further explores the sustainability of water levels of Lake Malawi based on generated climate scenarios.

A method of extending river flow records based on climate scenario is presented. In the proposed method a simple rainfall runoff model of Linear Perturbation Model has been used to extend flow records with inputs from

HadCM3 experiments. The results showed a good correlation between predicted and observed series. Climate change prediction downscaled from HadCM3 general circulation models using statistical techniques were used to create 25 year river flow scenarios from 2001 to 2100.

The thesis further reports a method of extending evaporation data based on climate change prediction since evaporation plays a major role in the development of irrigation. The future evaporation scenarios have been incorporated in the water balance model of Lake Malawi for the assessment of sustainability and future water levels of the lake.

A method of formulating water resources sustainability index through the integration of knowledge from hydrology, human health and environment is presented. The Water Sustainability Index has been developed as a tool for assessment of multipurpose water resources development comparing one river basin with another in a sustainable manner.

In conclusion the method proposed in this thesis can be used as a tool for assessing the strategic sustainability of water resources development as planned under the Malawi National Water Development Programme (MNWDP) phase II. The goal of MNWDP II is to develop a water resources investment strategy for Malawi by looking at the current available water resources and the impact of developing these water resources. Although it is hoped that the methods can be of benefit under MNWDP II, investigations into other techniques would be beneficial

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 GENERAL

According to the United Nations, the present world population stands at about 6.7 billion and with an average annual growth rate of 1.3%, this population is estimated to reach 8 billion in 2025 (UN, 2006). Population increase calls for increased allocation of water for the domestic, agriculture and industrial sectors leading to tensions, conflicts among users, and excessive pressure on the environment. The increasing stress on scarce freshwater resources brought about by ever rising demand and extravagant use, as well as by growing pollution worldwide, is of serious concern (Gleick, 2004; Zeman *et al*., 2006). The major concern comes in because of the limited availability of freshwater accessible by human beings (Gleick, 1996). The world population, regardless of location and development stage, needs food, energy and water. Water is essential not only for human needs but also for food production. Freshwater and energy are two resources that are intricately connected. Energy is used to clean and transport water and water is used to help produce energy and food.

Energy and water are related to the multidimensional aspects of sustainable development: social, economic and environment as shown in the energy-water-food triangle in Figure 1.1. Access to modern energy and water services is an indispensable element of sustainable human development (IEA, 2004) and a pre-requisite for meeting the Millennium Development Goals (UN, 2000). People in rural areas require energy options that provide a wide range of energy services such as income generation, lighting, potable water, health services, education and improved agricultural activities. Multipurpose schemes for energy production, irrigation and water supply are known to provide all of these ranges of services (Bakis, 2007). It is therefore necessary to develop water resources in a sustainable manner in order to satisfy the above elements while considering future generations as well. According to the World Commission on Environmental Development (WCED, 1987) sustainable development has been defined as;

> "development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

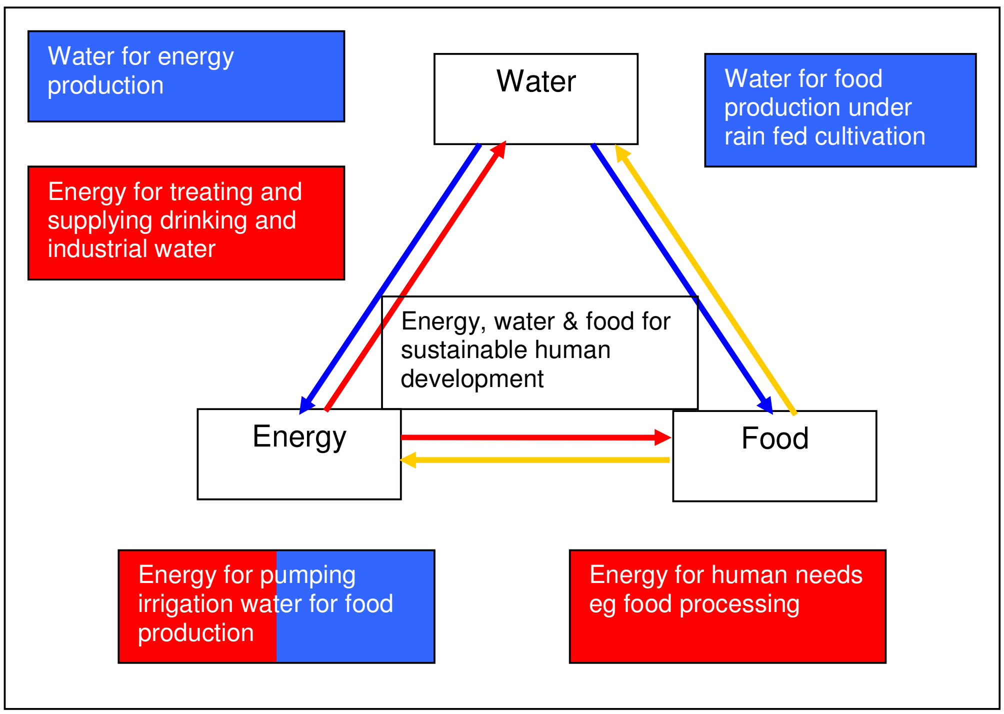


Figure 1.1 Water-food-energy triangle showing linkage between the three elements in sustainable human development

Sustainable development of a region depends on the health of renewable energy sources (Oliver, 2002) and hydropower is the leading source of renewable energy as it is derived from water which is a renewable resource. Hydropower provides more than 97% of all electricity generated by renewable sources in Malawi (GoM, 2003b) and currently provides about 20% of the world's electricity supply, and more than 40% of the electricity used in developing countries (Bakis, 2007). Hydropower's future development is assured given both the growing need for hydropower and advances in sustainable dam design (Kumambala and Ervine, 2008).

While development of all the world's remaining hydroelectric potential could meet only a proportion of future world demand for electricity, it is clear that it is the resource with the greatest capability to provide clean renewable energy to the parts of the world which at present have the greatest need, and when implemented as part of a multipurpose water resources development scheme, a hydro station can offer a number of side benefits, which no other source of energy can compete with (Bakis, 2007; WCD, 2000). Today, approximately 30% of large dams, using the International Commission on Large Dams (ICOLD) definition, are for multipurpose usage. Mainly, the functions of these dams are: irrigation (48%), electricity generation (36%), water supply (36%), flood control (39%), recreation (24%), inland navigation (5%), and fish breeding (5%) (WCD, 2000).

The choice of site for multipurpose water resources project is based on the close interaction between the various demands within the catchment. It is therefore necessary to establish the demand for available water within a basin. Various factors considered while assessing multipurpose sites for water resources development are: topography, land use pattern and water resource availability (hydrological pattern), water and energy demand within the basin. Therefore realistic long-term river flow data are required if sustainability of multipurpose water resource projects is to be investigated using computer models. Water resources projects cause wide alteration of stream flows (Anderson *et al*., 2006b; Rosenberg *et al*., 1995). Recently, large dam projects have often attracted attention from the international conservation community, on the basis of their widespread environmental and social impacts (Rosenberg *et al*., 1995); examples of these impacts include flooding of tropical forests, greenhouse gas emissions from reservoirs, altered flow and sediment regimes, imperilment of aquatic biota, resettlement of human populations, and road construction in wilderness areas (Fearnside, 1995; Goodland *et al*., 1993; Rosenberg *et al*., 1995; WCD, 2000).

Multipurpose water resources projects relies much on rainfall which is a natural resource currently being threatened by climate change (IPCC, 2007). It is increasingly necessary to consider the effects of climate change on water resources, especially when dealing with long term investigations. Long term changes in flow regimes will affect hydropower generation, water supply and irrigation in river basins (Holmgren and Öberg, 2006; Kundzewicz *et al*., 2008). It is therefore important that sustainable development of multipurpose water resources projects incorporate the effects of climate change on water resources. Historically, climate change has been modelled in a very detailed way using either statistical or dynamical downscaling methods (Fujihara *et al*., 2008; Matondo *et al*., 2004a; Wilby *et al*., 2006). These results are then used in broad scale catchment models to model runoff reaching the river. To make this process faster it would be beneficial to incorporate climate change predictions when extending the historical flows for water resources development. This can quickly create a modified flow series that can be used to investigate the effect of climate change on multipurpose water resources development.

In summary, a method of predicting the impact of climate change on long-term river flows would aid sustainability assessment of water resource projects. The method would allow historical flow series to be extended simply, but realistically, and would have the capability to incorporate climate predictions into the solution. This method could then provide a powerful tool for long term water resources sustainability investigations completed using Hydrological Models and would provide a useful tool for assessing the effects of climate change on water resources development.

1.2 STUDY AREA

This thesis will focus exclusively on Malawi in Africa investigating the water resources potential primarily in Central and Northern Malawi. Further more the thesis will look at sustainability aspects of Central and Northern highland river basins of Malawi, water balance of Lake Malawi and the outlet Shire river based on climate change threats in the region and the role of the proposed National Water Development Plan II. Figure 1.2 is Map of Malawi showing the rivers of Central and Northern region of Malawi together with rivers from Tanzania and

Mozambique which forms the catchment area of Lake Malawi.

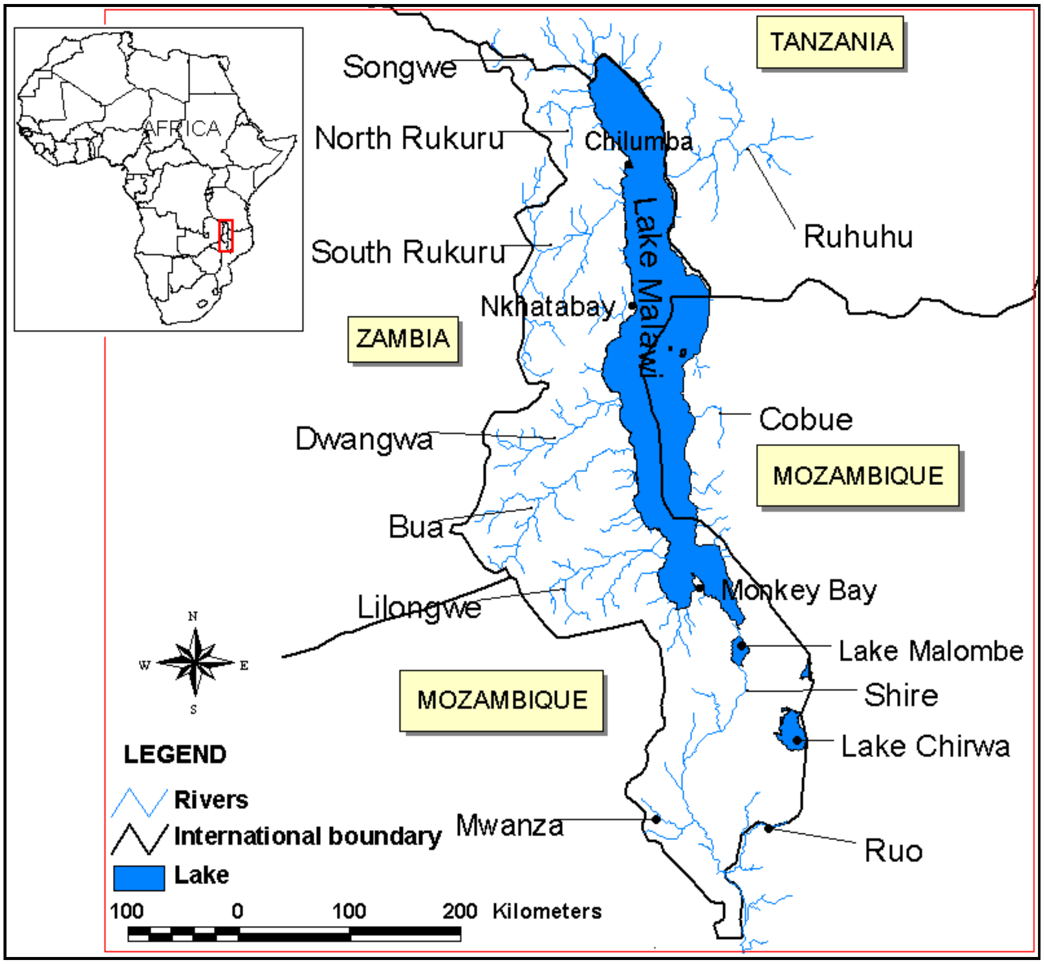
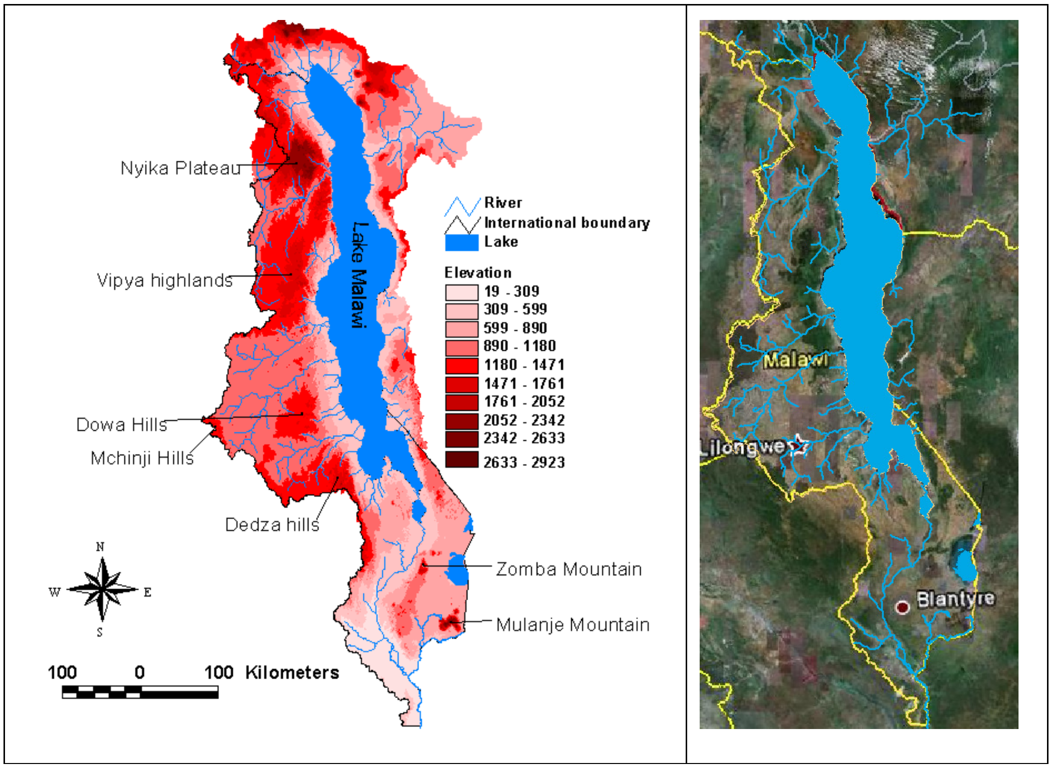


Figure 1.2 Study area showing Malawi's main rivers

Malawi is a landlocked country, lying in Southern Africa (Figure 1.2) between latitudes 9°22'S and 17°03'S and longitudes 32°40'E and 35°55'E. The country has a total area of 118 480 km^2 with a total length of about 900 km and a maximum width of about 250 km (Msiska, 2001). The country's topography shown in Figure 1.3 can be divided into four zones: Highland, plateau, rift valley escarpment and rift valley plains (Fry *et al.*, 2003). About 21 percent of its total area is covered by the surface water bodies including Lake Malawi. All the rivers in the northern part of Malawi shown in Figure 1.2 originate from the western highland areas. The drainage pattern of these rivers is oriented towards the rift valley passing through the rift valley escarpment zone before draining into Lake Malawi on the eastern side. The river Shire is the only outlet from

Lake Malawi which supports all Malawi's hydropower and irrigation in the Lower Shire Valley (LSV) and water supply to the city of Blantyre. The setup of the available water resources and water resources development has been presented by a schematic diagram in Figure 1.4.



Digital Elevation Model | Areal view

Figure 1.3 Topographic map of the study area

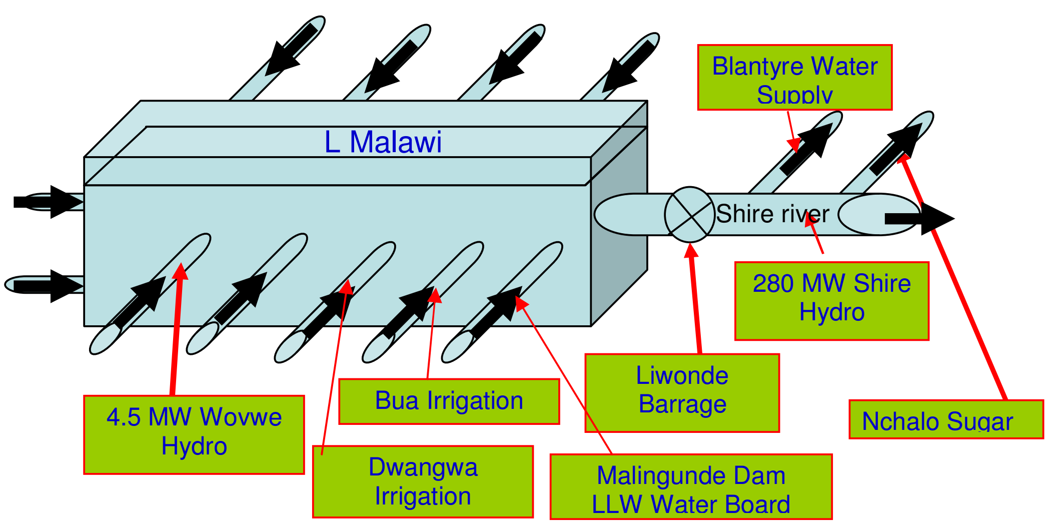


Figure 1.4 Conceptual diagram of Malawi's water resources setup and development

1.3 OVERVIEW OF HYDROPOWER, WATER SUPPLY AND IRRIGATION DEVELOPMENT IN MALAWI

1.3.1 Hydropower

Dam functions and their magnitude have changed at an accelerating pace since the first hydroelectric dam entered service at Appleton, Wisconsin in the United States in 1882 (Sternberg, 2006). In recent years expanding urban populations and subsequent increases in demands for electricity, water supply and irrigation have resulted in the construction of hundreds of dams on tropical rivers over the last two decades (WCD, 2000).

In Africa hydroelectric development began on a large scale in the 1950s at the end of the colonial era when projects such as Kariba (Zimbabwe/Zambia) and Owen falls dam (Uganda) were undertaken (WCD, 2000). In the 1960s Ghanaian Akosombo and Nigerian Kainja were built in west Africa and Aswan High Dam (Egypt) and Roseires (Sudan) were built in North Africa, while Cabora Bass (Mozambique) and Inga (Zaire) followed in the 1970s (Figure 1.5 and Plate 1.1). Following the 1970 oil crisis more comprehensive investigation into hydro resources across the continent was undertaken and a wide range of projects were prepared for implementation (Grant and Cibin, 1996). However the economic status of most African countries has resulted in delays in implementation of many major projects.

Malawi is generally rich in water resources which are stocked in its lakes, rivers and aquifers as shown in Figure 1.2. Despite the availability of water resources in Malawi, only 286 MW hydropower plants have been installed in Malawi producing only 2.6 percent of the country’s energy needs (GoM, 2003b). At present, it is estimated that 27.5 percent of urban and 1.1 percent of the rural population has access to electricity (NSOM, 2006). The majority of the population still depends on biomass for their energy needs and rainfall for agricultural production. Biomass in the form of fuel wood and charcoal provides 93 percent of all the energy consumed (GoM, 2003b). The massive use of traditional energy sources is an indication of acute poverty and a rural based economy, which has resulted in stress on woodland resource leading to deforestation in many parts of the country. In this regard, sustainable and renewable energy issues have been included in the country's Poverty Alleviation Policy Framework to a certain extent (GoM, 1994).

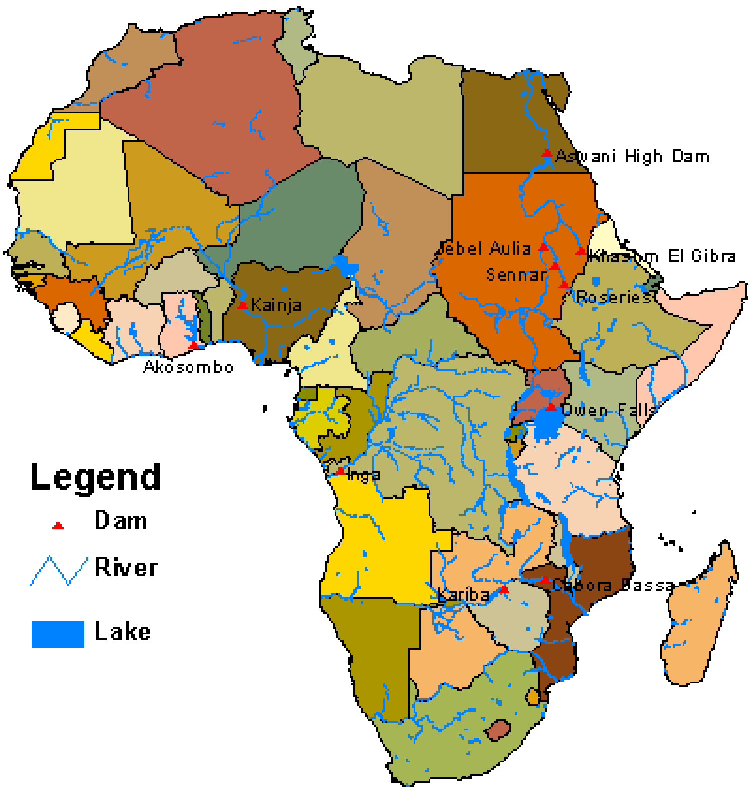


Figure 1.5 Map of Africa showing some of the major dams built in the 19th Century

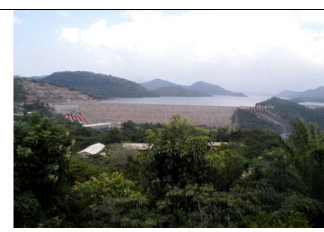
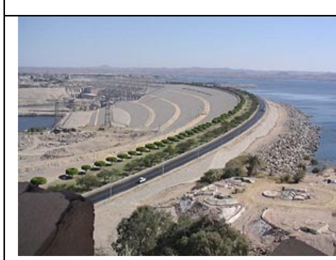
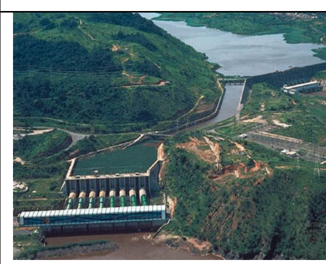
		
Kariba dam, Zimbabwe	Owen falls dam, Uganda	Akosombo dam, Ghana
		
Aswan Dam, Egypt	Cabora Bassa, Mozambique	Inga Dam, Zaire

Plate 1.1 Africa's major hydropower development in the last century (1900) (Google Earth, 16 July 2009)

Table 1.1 Malawi Hydropower Installation Capacity (ESCOM, 2009)

Plant	River	MW	Cumulative MW	Year	Population
Nkula A	Shire	24	24	1966	4,039,583
Tedzani I	Shire	20	44	1973	4,943,112
Tadzani II	Shire	20	64	1977	5,547,460
Nkula B Phase I	Shire	60	124	1980	6,188,788
Nkula B Phase III	Shire	20	144	1982	6,657,021
Nkula B Phase II	Shire	20	164	1986	7,702,443
Wovwe	Wovwe	4.5	168.5	1995	9,360,607
Tadzani III	Shire	50	218.5	1996	9,547,920
Kapichira	Shire	64.8	283.3	2000	10,816,294

In Malawi, hydroelectric development began on a large scale in the 1960s when Nkula A on the Shire river was officially installed in 1966 (Table 1.1) (GoM, 1986). Malawi's hydro generation is concentrated along the Shire river except for Wovwe mini hydro plant as shown in the conceptual diagram in Figure 1.4. This makes Malawi's power generation system very vulnerable to the considerable variation in water levels of Lake Malawi and, hence flow rates on the Shire river which is the only outlet from Lake Malawi. Malawi's power sector is dominated by a publicly owned utility; Electricity Supply Corporation of Malawi (ESCOM), which was established by an Act of parliament in 1957 (revised 1963 and 1998) (GoM, 2004). Currently, the ESCOM Act has been revised and an Electricity Act (1998) has been produced to remove ESCOM's monopoly and regulate the power sector (GoM, 2004). The main features of the Electricity Act, 1998 are that it liberalised the electricity supply industry by introducing separate licensing for generation, transmission, and distribution permitting private sector participation in all parts of the industry. Under the Electricity Act 1998, an independent electricity regulator, Electricity Council of Malawi was established and ESCOM changed its status from a para-statal agency into a limited liability company with 99 percent of its shares being held by the Malawi Government and 1 percent by Malawi development corporation (MDC). Under the same legislation, ESCOM was permitted to operate business units in generation, transmission and distribution. This has resulted in the same monopoly which

ESCOM had in the past. In view of this there is need for further reforms to attract private sector participation in electricity industry.

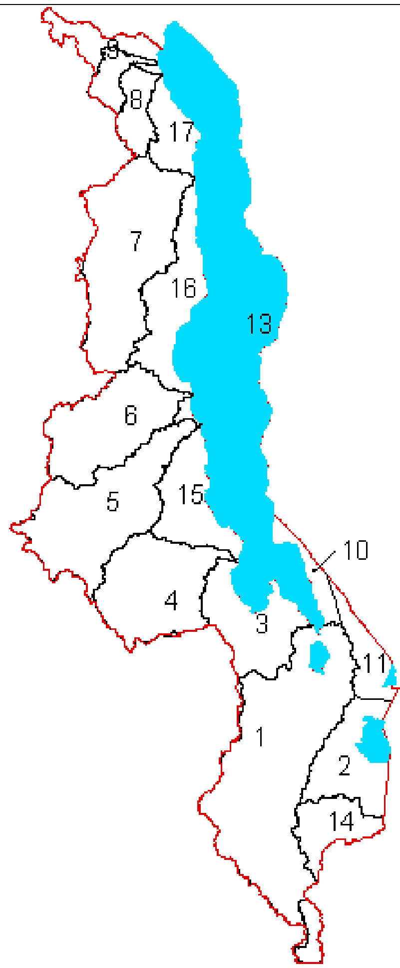
Recently the overdependence of power production on the Shire river has proved to be unreliable because of silting problems and declining flows in the Shire river (GoM, 2003a). Persistent droughts and sedimentation resulting from erosion in the catchment areas have resulted in low lake levels in Lake Malawi and reduced flow of the Shire river to well below the required flow rate of 170m^3 per second (GoM, 2003a). This has affected generation downstream such that demand is sometimes not adequately met as there are no reliable alternatives to hydropower. Furthermore, clearing of land for agricultural purposes and poor agricultural practices have resulted in environmental degradation of the catchment areas of not only the Shire river, but also other rivers, which have potential sites for hydro plants (GoM, 2003b). The siltation problem has resulted in rapid wear and tear of generation equipment and the service providers incur considerable expenses in silt-removal.

Currently Malawi has embarked on rural electrification programme as a means of improving the quality of life of the majority of the population and promoting their socio-economic development (GoM, 2003a). It has become apparent that the fulfilment of this goal cannot be achieved solely through the extension of the national grid due to economic reasons (Girdis and Hoskote, 2005). Grid expansion is very costly in view of the comparably small amount of electricity that the rural population requires and can afford. It is unlikely that the population living a few kilometres away from the grid will be connected to it in the near future, even where ESCOM identifies a major economic activity warranting grid extension. In view of this, it is important to develop hydro in highland areas which can easily serve the rural communities as well.

1.3.2 Water resources development

1.3.2.1 Water resources availability

Malawi's water resources are used in various social and economic activities including water supply and sanitation, hydropower, irrigation, navigation, commerce, fisheries, and wildlife. The country's surface water resources are divided into 17 Water Resources Area (WRA) as shown in Figure 1.6. Small areas outside the major Water Resources Area along Lake Malawi forms part of Karonga Lakeshore River Basins in the North and Nkhotakota Lakeshore River Basins for areas in the Central region of Malawi.



1	Shire River Basin
2	Lake Chilwa Basin
3	South West Lakeshore River Basin
4	Linthipe River Basin
5	Bua River Basin
6	Dwangwa River Basin
7	South Rukuru River Basin
8	North Rukuru River Basin
9	Songwe Lufira River Basin
10	South East Lake Shore River Basin
11	Lake Chiuta River Basin
12	Likoma Island River Basin
13	Chizumula Island
14	Ruo River Basin
15	Nkhotakota Lakeshore River Basin
16	Nkhatabay Lakeshore River Basin
17	Karonga Lakeshore River Basin

Figure 1.6 Water Resources Areas (WRA) of Malawi (GoM, 1986)

The 17 WRA are grouped into 2 major drainage systems: Lake Malawi system, which covers Lake Malawi plus it's catchment area and Shire river which is the main outlet from Lake Malawi and the Lake Chirwa system (Fry *et al*., 2003). Replenishment of surface water resources is dependent on the seasonal rainfall. Consequently, the rivers and lakes display seasonal flow and water level patterns, and often a number of these rivers dry up during the months of July to November.

Groundwater sources are widespread throughout the country. However, limited knowledge on its occurrence and distribution has placed limitations on how much can be abstracted. Its occurrence is associated with three major aquifers, basement, escarpment and alluvial aquifers. The basement aquifers are low yielding and discontinuous but widely distributed throughout the extensive pre-cambrian basement gneiss complex formations, which make up approximately 85% of Malawi's geology (GoM, 1986). These aquifers can yield up to 2 litres per second and are found in the weathered or fractured zones of the basement complex (FAO, 2006). The alluvial aquifers are relatively high yielding and occur in quaternary alluvial deposits occurring in the lakeshore plains and the Lower Shire Valley (FAO, 2006). Yields of up to 20 litres per second can be achieved. The third type, escarpment zone aquifers, occurs in escarpment areas and has water yields of up to 12 litres per second.

1.3.2.2 Water supply

The sectoral distribution of water in Malawi has been estimated to be 34 percent domestic, 17 percent industry and 49 percent agriculture and natural resources (GoM, 1998). The existing urban and rural water supply schemes and systems provide access to potable water facilities for up to 54 % of the country's population, which reduces to 32 % with access to potable water at any one time due to breakdowns, drying up of sources and other operational and maintenance problems (GoM, 1998). Urban water supply schemes, except those for Blantyre and Lilongwe were run by Government but are now decentralised and are under the management of commercial Water Boards, established under Waterworks Act (1995), to improve efficiency. The rural water supply schemes and systems, however, still remain the responsibility of Ministry of Water Development but are being developed and managed without adequate administrative policies and legislation. The gravity piped water supply schemes are implemented with no formal agreed policy and strategies among the stakeholders. The Government is a proponent of transferring ownership to the beneficiary communities, empowering them to operate, maintain, and manage their own rural water systems (boreholes and gravity piped water supply) under Community Based Management (CBM) scheme.

The existing development, utilisation and management of groundwater lack sustainable strategies, despite its extensive use for rural water supply. The monitoring and assessment of groundwater is almost non-existent. Donors, NGOs and government departments, construct boreholes without agreed and consistent control, co-ordination and regulation policies and legislation for the implementation of boreholes development and construction programmes. The boreholes construction industries are equally uncontrolled and unregulated to check compliance with standards and protect the water resources from degradation and the public from malpractice. In fact very little groundwater research and development programmes are being done to improve development and management technologies. Most areas in Malawi cannot have boreholes that can pump adequate water supply for irrigation or urban water supply due to limitations in the understanding of groundwater hydraulics and appropriate technologies.

1.3.2.3 Irrigation

Agriculture and natural resources uses one-half of the countries water resources, mainly in the form of rainfall. Malawi's economy largely depends on agricultural production, which in turn relies on natural precipitation and it so happens that rainfall variation determines the annual economic performance of the nation. One-third of Malawi's gross domestic product is generated from agricultural produce (GoM, 1994). The country has experienced severe droughts in the past notable among these occurred in 1948/49, 1991/92 1996/97 and 2001/02 seasons (Chavula, 1999; FAO, 2006). Malawi economic performance follows a volatile pattern that mimics the rainfall variation and this is not suitable for long term plans on poverty reduction. Without aggressive water harvesting and management, Malawi is likely to remain poor due to uncertainty of the rainfall regime.

The seasonality in crop production and increase in population growth in Malawi has forced farmers to expand the areas under cultivation in order to increase crop production. If this is to be avoided deforestation due to agricultural expansion and biomass energy demand must be slowed down and eventually reversed (Girdis and Hoskote, 2005). This can only be achieved by an improved energy production and higher agricultural productivity in the form of multipurpose water resources development to support hydropower, irrigation and water supply. Though Irrigation is an obvious solution for high crop production, only 21,000 hectares of arable land is under irrigation, with Dwangwa and Nchalo sugar estates accounting for 15,000 hectares (Figure 1.4) (GoM, 1994). Dwangwa and Nchalo sugar schemes are run-of-river projects drawing water from Dwangwa river and Shire river respectively. Tea, coffee, tobacco and wheat cover an area of 3,000 hectares. Currently there are 16 major irrigation schemes run by the government covering 3500 hectares under small holder irrigation program. Most of the schemes are very old having been established between 1968 and 1980 (GoM, 1998). In view of this modern and sustainable irrigation techniques that are less wasteful will be more useful in poverty alleviation programs. In order to tackle the water supply problem the Malawi government has embarked on the National Water Development Programme Phase II with support from the World Bank and other bilateral donors.

1.3.2.4 Malawi National Water Development Programme

The Malawi government with the support of the United Development Programme conducted a thorough study of the country's water resources between 1984 and 1986 under National Water Resources Master Plan Project (GoM, 1986). The activities under NWRMP were:

- water resources data collection and processing evaluation,
- water resources studies and appraisal,
- water resources Master Plan with proposal on urban and semi urban water supply, rural water supply, hydropower and irrigation development,
- water resources development planning, phasing and strategy
- water sector legislation

Overall NWRMP was for the appraisal of water resources, allied studies and preparation of an overall Water Resources Master Plan with the objective of ensuring economic development. Recommendation of the NWRMP led to the foundation of the National Water Development Programme (NWDP) in which some of the recommendations in MWRMP were implemented under NWDP phase I. NWDP I was officially completed in December 2003 although some activities are still on going until now. Due to increase in population and change in water resources data and availability, Malawi has now embarked on second phase of NWDP running from 2007 – 2012 funded partly through the World Bank and other international donors. The development objective of the Second National Water Development Project of Malawi is to increase access to sustainable water supply and sanitation services for people living in cities, towns, market centers, and villages and improve water resources management at the national level. NWDP and NWRMP projects have recognised that water resources management is key for the sustainable development of water resources and meeting United Nations Millennium Development Goals.

1.3.2.5 Water Resources Management

The legal and regulatory structures for water resources management and water services in Malawi have been (and continue to be) framed from the Water Resources Act (1969) and Water Works Act (1995). The Water Resources Act and subsequent amendments is the legal instrument currently available for the regulation of water resources management in Malawi. It makes provision for the control, conservation, apportionment and use of water resources of Malawi. The Water Works Act (1995) repealed all previous Water Works Acts in Malawi, including the Blantyre Water Works Act, 1971 and the Lilongwe Water Works Act, 1987 which gave legal status to Blantyre and Lilongwe Water Boards, respectively. All Water Boards now are established and operate under the Water Works Act (1995). This Act essentially provide the legal framework for implementing the 1994 Water Resources Management Policy and Strategy (WRMPS) in the provision of water supply and water borne sanitation services to urban and semi-urban centres in Malawi. The focus of WRMPS is to improve water supply and sanitation services that had deteriorated and were facing major challenges of sustainability and addressing the needs of the stakeholders. The emphasis was on decentralisation and commercialisation, which have been successfully done with the establishment of three regional water boards from the now defunct District Water Supply Fund of the then Ministry of Water Development under the Water Works Act (1995).

The Water Works Act (1995) has changed water management institutional set up giving the Ministry of Water Development responsibility for water policy and legal framework development, spearheading and coordinating the development of water resources planning. Implementation of water resources projects and delivery of services is now left in the hands of Water Boards.

1.4 PROBLEM STATEMENT

Rapid population increase and lack of infrastructure to much the population growth is one of the major challenges the Malawi Government is facing in water resources development. Malawi's population is estimated at 13,630,164 in 2008. This population has an uneven access to safe drinking water. Access to safe drinking water is estimated at 42.6 percent for the rural population and 88.6 percent for the urban population (MNSO, 2006). The countries average water use is 29.7 litres/person/day which is below the minimum human basic water requirement of 50 litres/person/day (Gleick, 1996; Shiklomanov, 1997; MNSO, 2006). The average consumption in litres/person/day is higher in urban areas: Blantyre 42.28, Lilongwe 87.98 and Mzuzu 56.

Table 1.2 List of existing Dam development for water supply in Malawi. Source of data (Hydrology Section of the Ministry of Irrigation and Water Development, Malawi)

Name	Location	Dam Capacity (Mm^3)	Catchment area (Km2)	Dam Height (m)	Type of Dam	Use
1.Lunyangwa	Mzuzu City	4.36	25.0	19.5	Earth fill	WS
2. Chitete Dam	Kasungu Boma	4.5	44.0	12.2	Earth fill	WS
3.Mulunguzi	Zomba Plateau	3.375	18.9	45.0	Rock fill	WS
4.Mpira-Balaka	Ntcheu	3.72	42.0	29.0	Earth fill	WS
5.Kamuzu Dam I	Lilongwe	5.2		18.4	Earth fill	WS
6.Kamuzu Dam II	Lilongwe	19.0	1,800	24.0	Earth fill	WS
7. Mudi Dam	Blantyre City	1.4	8.903	17.0	Earth fill	WS
8.Lake Chingali	Nkhota-kota	14.35			Earth fill	Irr
WS = Water supply; Irr=Irrigation						

Malawi water resources utilization heavily depends on run-of-river schemes whether the use is for hydropower, irrigation and water supply. Run-of-river projects have no reservoir and depend only on the natural, unregulated river flow. Run-of-river projects are more vulnerable to climate change as has been the case with Malawi in recent years. The current Dam impoundments are for single purpose use only, either water supply or hydropower (Table 1.2). The history of dam development in Malawi dates back as far as the colonial times under Nyasaland government from 1908 to 1964. During this time a number of small and medium earth dams were built across the country for water supply, irrigation, livestock watering and conservation. According to the National Water Resources Master Plan study in 1986, there is total of 749 impoundments ranging from large to very small. Very few of these dams are in good condition (GoM, 1986).

Despite the potential and economic viability of multipurpose water resources projects, where a dam can be developed for water storage and raw water can be sold in bulk and used in irrigation, water supply, fisheries and electricity generation, Malawi has not exploited the opportunities. Currently Malawi has embarked on a US$260 million National Water Development Project (NWDP II) noted in section 1.3.2.4 which is aimed at increasing access to sustainable water supply and sanitation services from 67% to 79% by 2012 with a universal coverage projected to be achieved by 2025 (World Bank, 2008). The project is being funded by the World Bank and other bilateral donors. Exploring the opportunities for multipurpose project under NWDP II would make water relatively more available and less costly to the investor and the local population.

1.5 RESEARCH AIMS AND OUTLINE OF THE THESIS

The research was aimed at assessing the sustainability of water resources development in Malawi and in particular the Central and Northern river basins together with Lake Malawi. The Central and Northern river basins form the major part of the catchment area of Lake Malawi, which acts as the main water storage unit for Malawi as shown in Figure 1.4. Currently the Malawi Government is planning for multipurpose water resources development in the Central and Northern river basins. Therefore work completed for this thesis aimed to investigate techniques for long-term sustainability of water resources projects with regard to the environment. The focus of the project was data collection and Hydrological modelling coupled with climate change models to assess the sustainability of water resources development and developing water resources sustainability index for Central and North Malawi.

The thesis is organised into 8 Chapters beginning with Chapter 1 which is a brief introduction regarding the study area in terms of water resources development. Chapter 2 is a comprehensive literature review of global water resources distribution, uses and tools used in water resources planning together with factors affecting the sustainability of water resources ranging from climate change to human influence. Chapter 3 draws together all known water related data for Malawi with particular focus on Central and North Malawi together with Lake Malawi and the Shire river system. Chapter 4 is the modelling of climate change impact on the water resources of Malawi in particular North and Central river basins as well as Lake Malawi. Chapter 5 has a focus on developing a water balance model for Lake Malawi as a tool for sustainable planning and management of water use of Lake Malawi especially along its outlet, the Shire river. Chapter 6 is an interaction of the water balance model of Lake Malawi and the water budget of its outlet, the Shire river system. Chapter 7 focuses on how water resources data can be used to produce new sustainability index for water resources development in Central and North Malawi river basins. The final chapter is a summary and conclusion as well as a statement towards the Malawi National Water Development Programme II.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

Recent events of flood, drought, urban water shortages as well as water pollution and energy demand in Malawi and various parts of the world have underlined the need for the rational planning of water resources. It is not often realised except in times of shortages and drought that water is a unique resource that has no substitute and it is a valuable raw material whose limited reserves demand a thoughtful and sensible approach to its utilisation. It is time to stop regarding water as an unlimited natural resource that could be used by anyone at his own discretion because it is freely available through rainfall. The importance of water to man cannot be over emphasized as man cannot survive longer without water than without food. Water is a must for meeting the water supply demands of the people, for domestic use, irrigation and agricultural use, hydropower generation, navigation, recreation and many other purposes. Water has to be transformed from its natural raw state and then transported to our homes and factories to satisfy man's needs. It is therefore necessary to develop multipurpose water resource projects in a sustainable manner to meet all the basic human needs (energy, food and water). Multipurpose water resources projects are constructed to serve two or more functions within or outside the river basins such as water supplying domestic, irrigation, industrial water, flood control and electricity generation. The research work presented in this thesis is covering sustainable multipurpose water resource development for hydropower, irrigation and water supply in Malawi. To that end the chapter will commence with a section on global water resources, followed by sections on sustainability index, hydrology of catchments, water for energy, irrigation and water supply. All these aspects feed into the water resources strategy and sustainability for Malawi and are core aspects of later chapters of the thesis.

2.2 GLOBAL WATER SCARCITY – A LOOMING CRISIS

Water is an essential element for any living creature on earth. However the world is facing a freshwater crisis (Abu-Zeid, 1998; Falkenmark, 1991; Gleick, 2004; Shiklomanov, 1997) which is considered by many to be a major environmental challenge of the 21st Century as described by UNESCO at the 1998 Paris international conference on “World Water Resources at the Beginning of the Twenty-first Century” (UNESCO, 1998). Climate change, increased population and water degradation due to industrial and agricultural pollution have contributed heavily to water scarcity (Shiklomanov, 1999; UN, 2009). Although 70 percent of the earth’s surface is covered with water, only 3 percent of the earth’s water is available as freshwater for human use (Shiklomanov, 1999). Only 0.3 percent of the earth’s freshwater is accessible by human beings as surface water in rivers, swamps and lakes as shown in Figure 2.1. Figure 2.1 is the distribution of the earth’s water in terms of saline and freshwater. Competition for water between food production and domestic usage is also a major challenge world wide.

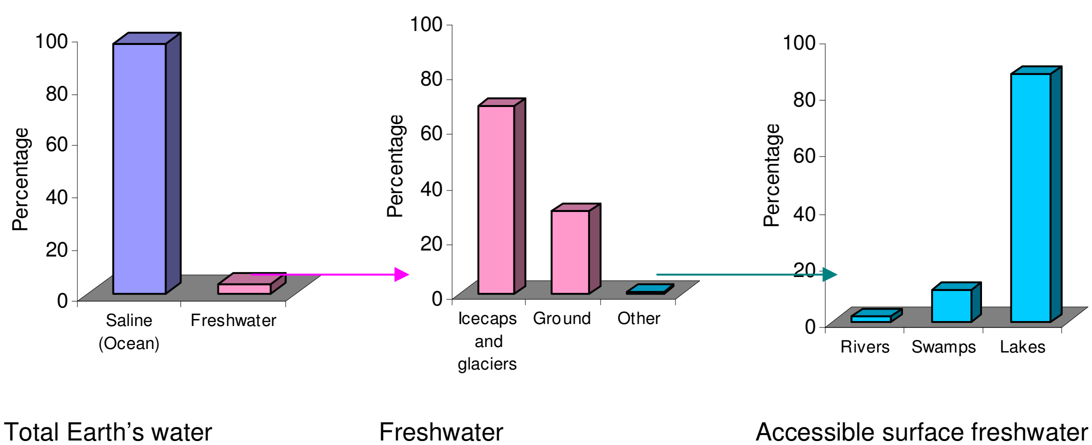


Figure 2.1 Earth’s water distribution (WRI, 2009)

2.2.1 Growing population and development pressure

Efforts to characterize the volume of water available to a given nation have been ongoing for several decades(Falkenmark, 1991; Gleick, 1996). The amount of renewable freshwater per capita per year is referred to as Total Renewable Water Resource (TRWR). TRWR is an index that reflects the water resources theoretically available for development from all sources within a region and according to Falkenmark (1991), water stress occurs when water availability falls below 1,700 m^3/person/year. This is also referred to as the Basic Water Requirement (BWR) for human activities (Gleick, 1996). Recent estimates of water resources and flows through the world's hydrologic cycle and their spatial-temporal variability indicates that 41 percent of the world population live in water stressed river basin (WRI, 2009) as shown in Figure 2.2(a) and (b). 3.3 billion people world wide lack access to clean water and 2.6 billion have no access to water and sanitation services (Watkins, 2006). Based on the current trend it is estimated that population living in water stressed river basins will increase to 48 percent by 2025 with TRWR dropping to less than 1000 m^3/person/year in the current stressed areas as shown in Figure 2.2 (Shiklomanov, 1999; WRI, 2009). The majority to be affected by water shortage are people from developing countries mainly in rural areas and urban slums (Watkins, 2006). Poor sanitation has resulted in the increase of number of deaths per year with an estimated 1.8 million deaths per year due to diarrheal diseases of which 90 percent are children under the age of 5 years living in developing countries (UNICEF&WHO, 2004; WWF, 2003). United Nations human development report of 2006 reported that water borne diseases such as diarrhoea kills more people than Malaria or Tuberculosis and five times as many children than those who die of HIV/AIDS (Watkins, 2006).

In developing countries an estimated 443 million school days per year are lost to water related illness as well as children being required to carry water for hours everyday (Watkins, 2006). This has shown to reduce the potential of children gaining education and being productive members of the society. The end result is reduction in earning potential and poverty in adulthood in most developing countries.

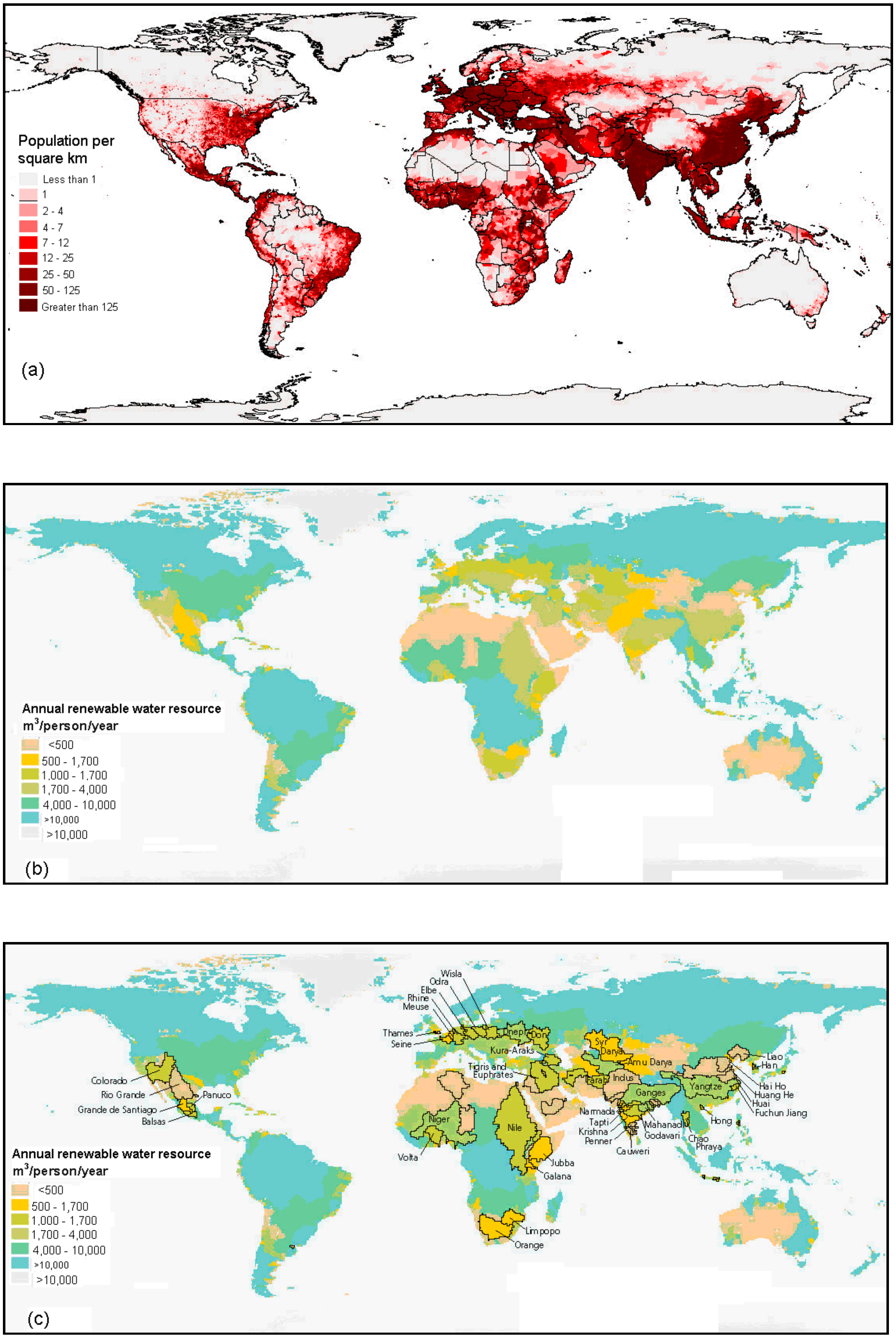


Figure 2.2 (a) Global population density, (b) annual renewable water supply per capita as of 1995 (c) projected annual renewable water supply per Person by River Basin, 2025. Source:(WRI, 2009)

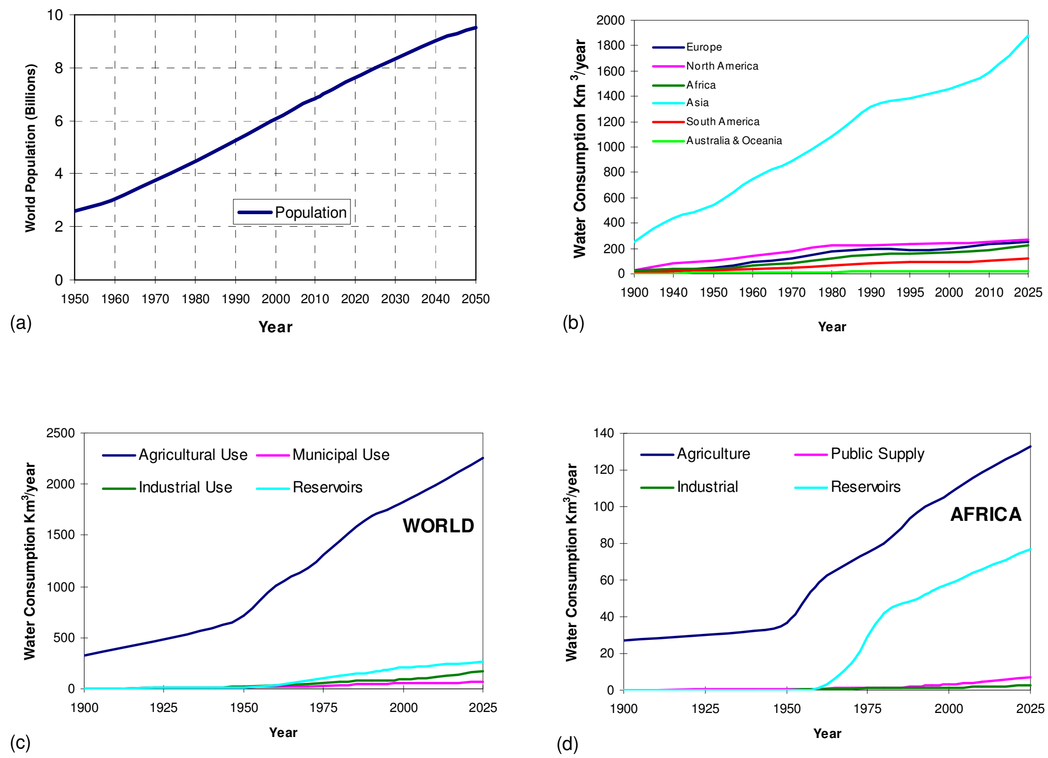


Figure 2.3 (a) World population growth trend, (b) water use in the world by continents, (c) water use in the world (total) over the kinds of economic activities (Km^3/year), (d) water use over the kinds of economic activities in Africa, (Km^3/year) (Shiklomanov, 1997)

The global population which is increasing at a rapid rate is expected to grow from 6.7 billion today to 8.9 billion by 2050 as shown in Figure 2.3(a) (UN, 2006). This will result in an increase in water withdrawal for domestic, agriculture and industrial use to support the growing population as projected in Figure 2.3 (b), (c), and (d). For the last 60 years there has been a rapid increase in water withdraw for agriculture worldwide as well as in Africa following rapid population increases shown in Figure 2.3 (WRI, 2009). Today food production through agriculture uses 70 percent of the water withdrawals worldwide as shown in Figure 2.3 (c) (Shiklomanov, 1999). Today several rivers are being over abstracted to meet growing population water requirement. This has resulted in rapid decline of groundwater levels in excess of natural recharge rates. Examples in literature include the Rio Grande and Colorado river basins in the United States of America, Yellow and Hiahe river basins in China and several river basin in North Africa (Rosegrant *et al.*, 2002).

2.2.2 Increasing contaminant loading to freshwater

Water resources degradation is another major factor exerting pressure on water scarcity resulting from land and water resources being degraded by industrial and agricultural waste (UNICEF&WHO, 2004). Water pollution reduces the amount of freshwater available for human use. Population growth, industrialisation, urbanisation, growth of mega cities and intensive agriculture have led to increased pollution of freshwater resources (Revenga and Mock, 2000; Shiklomanov, 1997). Pollution of freshwater results from discharge of sewage from industrial and domestic source, chemical from agriculture and urban runoff and heavy metals from mining areas. The problem is severe in developing countries where there is rapid population growth and development demand is great (Zeman *et al.*, 2006). In developing countries, on average, 90 to 95 percent of all domestic sewage and 75 percent of all industrial waste are discharged into surface waters without any treatment whatsoever resulting in pollution of the existing freshwater resources (Carty, 1991). An analysis of the water quality of streams within the city of Blantyre in Malawi revealed that the impairment of water quality in a stream depended on the type of industry in its vicinity and state of sewer lines which conduit the wastewater from the source to the designated Blantyre City Assembly wastewater treatment plants (Kuyeli *et al.*, 2009). Kuyeli *et al.* (2009) further noted that concentrations of phosphorus, nitrates and Biological Oxygen Demand (BOD) concentrations were above the maximum allowable limits set by the regulatory bodies suggesting that effluents from industries in the city had high potential of polluting water bodies. This was attributed to lack of monitoring and enforcement of environmental laws and regulations by the City of Blantyre. Similar studies on the catchment area of Kamuzu I and II dams in Lilongwe, Malawi revealed that there was no pollution with respect to BOD on the upstream catchment area of the two dams (Hranova *et al.*, 2006). Kamuzu dam I and II on Lilongwe river are the main source of water supply for the city of Lilongwe in Malawi. Further studies by Mtethiwa *et al.* (2008) on the effluent from Lilongwe City sewage ponds revealed that the following concentration: Faecal Coliform Bacteria 4.59×10^3 CFU, Total Phosphorus (TP) 1.94×10^3µg/L, Total Nitrogen (TN) 1.78×10^3µg/L, Chlorophyll-a 4.68×10^3µg/ and Biological

Oxygen Demand (BOD) 10.6mg/L. The above figures are above the WHO guidelines for drinking, swimming and bathing waters: Faecal Coliform Bacteria 0.00 CFU, Total Phosphorus (TP) 25 µg/L, Total Nitrogen (TN) 750 µg/L, Chlorophyll-a 3.00×10^3µg/ and Biological Oxygen Demand (BOD) 4 mg/L (WHO, 1997). Hranova *et al.* (2006) and Mtethiwa *et al.* (2008) results revealed that sewage disposal from the City of Lilongwe are the major polluters of the Lilongwe river. Most of the urban rivers in Malawi are polluted due to careless disposal of wastes (Mtethiwa *et al*., 2008; Phiri *et al*., 2005).

Agriculture is the dominant component of human water use, accounting for almost 70% of all water withdrawals (Zeman *et al*., 2006). Use of agricultural chemical results in water pollution of near by streams as well as groundwater due to chemicals from agricultural runoff and leaking of agricultural chemicals into the soil (Revenga and Mock, 2000; Shiklomanov, 1997). In Malawi, a comprehensive study on water quality from rivers within the catchment area of Lake Malawi has revealed that nitrogen and phosphorus concentration levels are on the increase due to the excessive use of fertilizer by farmers in the catchment area of Lake Malawi (Kingdon *et al*., 1999).

2.2.3 Global climate change impact

Freshwater resources are highly sensitive to variations in weather and climate. The changes in global climate that are occurring as a result of the accumulation of greenhouse gases in the atmosphere will affect patterns of freshwater availability and will alter the frequencies of floods and droughts (IPCC, 2007; UN, 2009). Climate model simulations and other analyses suggest that total flows, probabilities of extreme high or low flow conditions, seasonal runoff regimes, groundwater-surface water interactions and water quality characteristics could all be significantly affected by climate change over the course of the coming decades (IPCC, 2007; Kundzewicz *et al*., 2008).

It is not only human beings who are under threat by the world water shortage and pollution. The most vulnerable are a world species in freshwater ecosystems (WWF, 2003). According to WWF (2003), half of the world wetlands have been destroyed in the last century due to conversion of wetlands to other uses such as agriculture, industry, dams and canals. It is therefore necessary to address the global water crisis in a sustainable manner. Addressing the water crisis will help reduce poverty, hunger and water related illness and help children obtain education and make it possible that the scarce resource is also available for future generations. Therefore addressing global water crisis require commitment, targeted investment and good governance in recognising water as a human right. This calls for sustainable water resources development and management and the following section looks at the background of water resources sustainable development.

2.3 WATER RESOURCES SUSTAINABILITY ISSUE

The provision of efficient, affordable, reliable and clean energy, drinking water and food to rural people is one of the key challenges facing Malawi as it tries to achieve the Millennium Development Goals, future sustainability and self reliance. Sustainability is an important target and the stated objective of multipurpose water resource developments. Water resources sustainability requires meeting our water needs (i.e drinking, irrigation, industrial, recreation and energy) upon which economic development depends, while protecting the environment and improving social conditions (Ioris *et al*., 2008; Sullivan and Meigh, 2003; Sullivan and Meigh, 2005). This section presents a discussion of the general aspects of sustainability as related to water resources development.

2.3.1 Background of Sustainability Index

Sustainability is a concept that is used to describe dynamic condition of complex systems particularly the biosphere of the earth and the human social economic system within it (Gremmen and Jacobs, 1997). Sustainability reflects people's desire for a good life with a hope that it will endure for future generations (Sullivan and Meigh, 2003). The concept of sustainability has always been used in various sciences such as biology and ecology and economics. In Biology, sustainability has always been recognised as a result of underlying organization of life in earth's biosphere for over 3 billion years. Ecology has provided a concept of sustainability as the concept of carrying capacity of the ecosystem. Whenever the carrying capacity of the ecosystem is exceeded by the population the end result is decline in food, water and shelter to sustain the population. Therefore the carrying capacity concept makes us mindful that every species experiences limits in its relationship with its environment.

In Economics, the concept of sustainability requires that income or goods should be spent without causing the liquidation or decline of the capital. This is popularly known as "don't spend principal" (Hicks, 1946). The principal is there to sustain economic activity that generates income. The concept of sustainability or sustainable development was popularized by the 1987 Brundtland Commission report "Our Common Future" by the World Commission on Environment and Development (WCED, 1987). WCED briefly defined sustainable development as "development that meets the present needs and goals of the population without compromising the ability of future generations to meet theirs". The 1987 WCED report stressed the importance of striking a balance between economic development and environmental preservation in local, regional, and global spheres and of also taking social, cultural and political aspects into consideration for development strategies as illustrated in Figure 2.4.

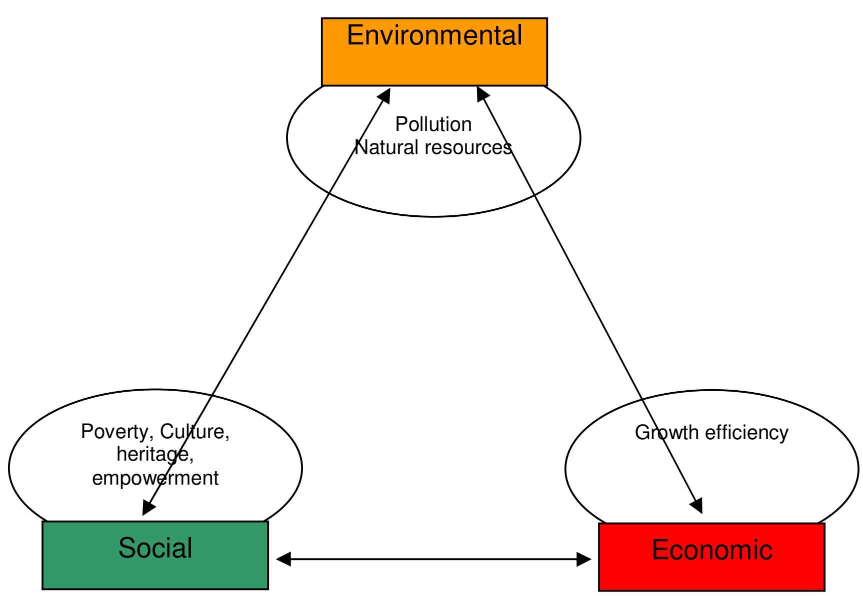


Figure 2.4 Linkage of the elements of sustainable development (WCED, 1987)

Since the Brundtland Commission report of 1987 much effort has been devoted to indentify and promote actions that are consistent with the principles of sustainable development (Bell and Morse, 2003; Lundin and Morrison, 2002). A number of development indices have been developed since 1987. For example the United Nations Development Program has been using the Human Development Index (HDI) (UNDP, 1998) which integrates educational, life expectancy, and income information for municipalities, states and countries to assess development worldwide. Sullivan and Meigh (2003) developed a Water Poverty Index (WPI) which is an integrated assessment of water stress and scarcity, linking physical estimates of water availability with socioeconomic variables that reflect poverty. The WPI aims at assessing the water scarcity and accessibility to water of poor populations on a spatial basis. The index was partly developed in response to the United Nations Millennium Development Goals addressing poverty and water access (UN, 2000) as a means for monitoring progress and prioritizing water needs. Lawrence *et al.* (2003) applied the WPI to different countries of the world and found that the WPI somewhat correlated with the countries HDI (r=0.81). The Canadian Policy Research Initiative developed a Canadian Water Sustainability Index (CWSI) to examine water related issues relevant to Canada with emphasis on rural and remote communities (CWSI, 2007). The CWSI, which is a modified version of the WPI, is a composite index that evaluates the well-being of Canadian communities with respect to freshwater. The CWSI integrates a range of water-related data and information into a series of indicators that together provide a holistic profile of a community's key water issues. The key water issues addressed by the indicators fall into the following broad policy categories: Freshwater Resources, Ecosystem Health, Water Infrastructure, Human Health and Well-being; and Community Capacity. Sullivan and Meigh (2005) developed a Climate Variability Index CVI which integrates social, biophysical, and economic information, providing for a holistic assessment of human vulnerability to changes in water resources, at different scales. Since the WCED report of 1987 a number of organisations and researchers have directed their efforts in measuring sustainability using indices (Lundin and Morrison, 2002). A sustainability index is a combination of different indicators which are the core aspects of the item being measured. The following section outlines the major requirement for indictors for water resources sustainability.

2.3.2 Sustainability Indicators and Index

Assessing the sustainability of water resources requires appropriate frameworks of indicators, which can, provide essential information on the viability of a system and its rate of change, and on how these contribute to the sustainable development of the overall system. An indicator is a piece of information which has a wider significance than its immediate meaning (Bakkes *et al*., 1994). If an indicator relates to a criterion, an objective or a target, it may be referred to as a performance indicator. If various indicators are combined into one it is referred to as an index, while a set of indicators is a number of indicators which together represent a larger issue (Bakkes *et al*., 1994).

According to Gallopín (1997) the major functions of indicators are:

- to assess conditions and trends;
- to compare across places and situations;
- to assess conditions and trends in relation to goals and targets;
- to provide early warning information;
- to anticipate future conditions and trends

During the last decade there has been an increasingly intensive desire to measure and describe different aspects of sustainability (Lundin and Morrison, 2002). The use of the tools currently being applied to assess 'sustainability' within the water sector varies widely due to differences in the purpose of assessment, the nature of the activity being assessed, and the decision-making context in which the tools are used (Ashley *et al*., 2003). Tools can advance the assessment of development of multipurpose water projects by utilising a multidisciplinary and integrated process. Integrated process of sustainability indicators can influence project development by helping to identify viable design alternatives that are environmentally and socially acceptable, and provide opportunities to meet varying demands within the basin. Several authors have formulated criteria or characteristics for desirable sustainability indicators (Bell and Morse, 2003; Braat, 1991; HTCF, 2003; Liverman *et al*., 1998). Watershed indicators shall be:

- ***Available*:** the indicator data shall be available and easily accessible. They shall be collected throughout the watershed, published in a routine basis, and made available to the public.
- ***Understandable***: indicators shall be easily understood by a diverse range of nontechnical audiences.
- ***Credible***: indicators shall be supported by valid, reliable information, and interpreted in a scientifically defensible manner.
- ***Relevant***: indicators shall reflect changes in management and in activities in the watershed. They shall be able to measure changes over time.
- ***Integrative***: indicators shall demonstrate connections among the environmental, social and economical aspects of sustainability.

An index formed by indicators meeting the above criteria could be universally applied to watersheds, and would significantly increase usefulness in establishing the sustainability of water resources in river basins. One of the major challenges facing the sustainability of water resources is climate change. Climate change has emerged to be a threat to the sustainability of the water resources because it is a long term process which has resulted in extreme weather condition in many different parts of the world (IPCC, 2007). It is therefore necessary to combine studies of sustainability index with studies of climate change effects on the water resources if sustainability of water resources is to be maintained. The following section looks at the effects of climate change on water resources based on present literature.

2.4 CLIMATE CHANGE AND DEVELOPING COUNTRIES

The review of ‘‘Climate Change 2001: The Scientific Basis’’ prepared by the Intergovernmental Panel on Climate Change (IPCC, 2001) has concluded that globally averaged mean evaporation, precipitation, and rainfall intensity will very likely increase in response to increased concentrations of greenhouse gases in the atmosphere. There is now growing empirical evidence that climate change can cause significant impacts on water resources such as flooding, severe drought and diminished ice cover. Developing countries, such as Malawi, will be more vulnerable to climate change mainly because of the larger dependency of their economy on agriculture. Hence, assessing vulnerability of water resources to climate change at a watershed level is very crucial for water resources sustainability. Many have investigated the possible effects of climate change on water resources, for example (Fujihara *et al.*, 2008; Matondo *et al.*, 2004b; Wilby *et al.*, 2006). The section gives an overview of climate change modelling stretching from downscaling methods and possible impacts on the water resources using the present literature.

2.4.1 Global observed changes in climate

The climate system, is an interactive system composed of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere with the atmosphere as the most unstable and rapidly changing part of the system (LeTreut *et al.*, 2007), The climate system is influenced by various external forcing mechanisms, the most important of which is the sun and human activities. The hydrological cycle is one of the most important connections of the climate sub-systems, where the energy and water fluxes between the atmosphere, biosphere and the land are of highest importance (LeTreut *et al.*, 2007) as shown in Figure 2.5.

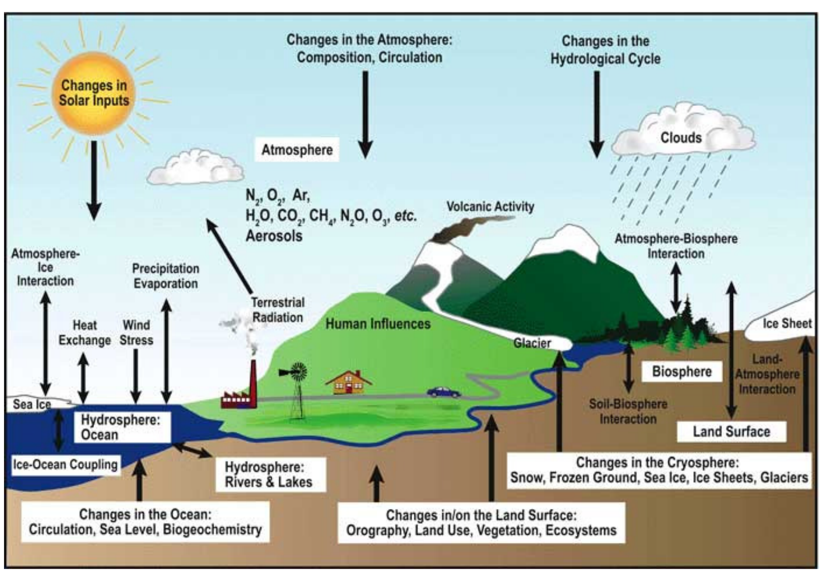


Figure 2.5 Climate system, subsystem and linkages. (LeTreut *et al.*, 2007).

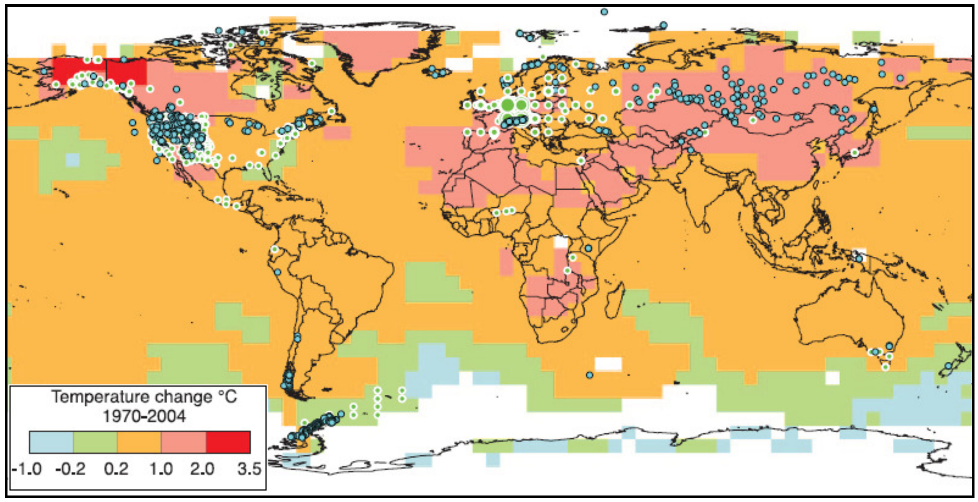


Figure 2.6 Global surface temperature change from 1970 to 2004. Source: (IPCC, 2007)

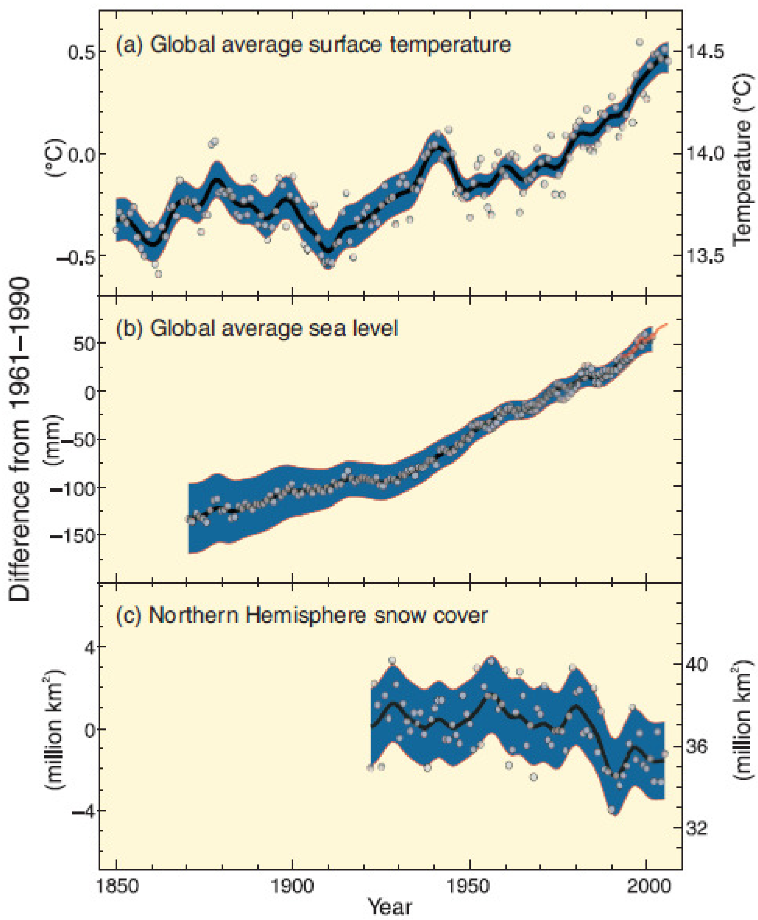


Figure 2.7 Observed changes in (a) global average surface temperature; (b) global average sea level (c) Northern Hemisphere snow cover for March-April. All differences are relative to corresponding averages for the period 1961-1990. The shaded areas are the uncertainty intervals estimates by different climate models. Source: (IPCC, 2007).

It is accepted throughout in literature that the climate of the world is changing (LeTreut *et al.*, 2007). Warming of the climate system is clear evidence of climate change, as is now evident from observation of increase in global average air temperature (Trenberth *et al.*, 2007), widespread melting of snow and ice in the polar region (Lemke *et al.*, 2007) as well as rising global average sea level (Bindoff *et al.*, 2007). Temperature increase is widespread over the globe and is greater at higher northern latitudes as shown in Figure 2.6 and Figure 2.7(a) where temperatures have increased at almost twice the global average rate in the past 100 years. Temperature observations from 1970 to 2004 have shown that the land regions of the planet have warmed faster than the oceans (Figure 2.6). Rise in global average sea level is another evidence of climate change (Figure 2.7(b)). Global average sea level has been rising at an average rate of 1.8 mm per year ranging from 1.3 to 2.3 mm per year over the period 1961 to 2003 (IPCC, 2007). The average sea level rise over the period 1993 to 2003 was 3.1 mm per year ranging from 2.4 to 3.8 mm (IPCC, 2007). Mountain glaciers and snow cover in both hemispheres have declined due to rise in temperature by up to 3^{o}C (Figure 2.6 and Figure 2.7(c)). Snow melting has resulted in the decrease of seasonally frozen ground by about 7 percent, with decrease in spring of up to 15 percent.

At continental and regional level numerous aspects of climate change have been observed such as changes in precipitation amounts and patterns. Over the period 1900 to 2005 precipitation increased significantly in eastern parts of North and South America, northern Europe and northern and central Asia whereas decrease in precipitation has been observed in the Mediterranean, southern Africa and parts of southern Asia (IPCC, 2007). Since 1970 the areas affected by drought have increased at global level.

Malawi is already experiencing the effect of climate change. In Malawi the observed climate changes are evidenced by the changes in the rainfall season, pattern and temperature, and changes in the frequency of droughts and floods (Mkanda, 1999) as well as significant variations in Lake Malawi and river levels (Calder *et al.*, 1995; Jury and Gwazantini, 2002). Analysis of climatic records from southern Africa have shown that both temperature and the amount of rainfall have varied over the past millennium and rainfall pattern in these regions varied inversely over long periods of time (Holmgren and Oberg, 2005). Droughts which started abruptly were of multi-decadal to multi-centennial length and the changes in the hydrological budget were of large amplitude. The changes in rainfall and temperature could have far reaching consequences on the water resources of Malawi as well as the country's economy since Malawi's economy is based on agriculture.

2.4.2 Drivers of climate change

Changes in the atmospheric concentrations of greenhouse gas (GHGs) and aerosols, land cover and solar radiation alter the energy balance of the climate system and are drivers of climate change (LeTreut *et al*., 2007). Climate change may result from both natural and human causes (IPCC, 2001). Naturally climate will vary due to variations in the earth's orbital characteristics, variations in the energy emitted by the sun, interaction between the ocean and atmosphere and volcanic eruptions. Human activities have also contributed to climate change. Human activities, principally from the burning of fossil fuels (like coal, oils and gas), forest destruction and agriculture (rice field cultivation and the keeping of livestock), result in emissions of four long-lived greenhouse gases (GHGs): carbon dioxide CO2, methane (CH4), nitrous oxide (N2O) and halocarbons a group of gases containing fluorine, chlorine or bromine) (IPCC, 2007). The major component of greenhouse gas is carbon dioxide. Carbon emission has increased by 80 percent between 1970 and 2004 from 21 gigatonnes (Gt) to 38 (Figure 2.8(a)) representing 77 percent of total GHG emission of 2004 as shown in Figure 2.8 (b). A review of the last three decades has shown that the rate of increase of CO_2 emission was higher during the period of 1995 to 2004 than in the previous period of 1970 to 1994 (Rogner *et al*., 2007). Rogner *et al.* (2007) further noted that the largest increase in GHG emissions between 1970 and 2004 has come from energy supply, transport and industry, while waste and waste water treatment, residential and commercial buildings, forestry (including deforestation) and agriculture sectors have been growing at a lower rate. The major sources of GHG as of 2004 are as shown in Figure 2.8 (c).

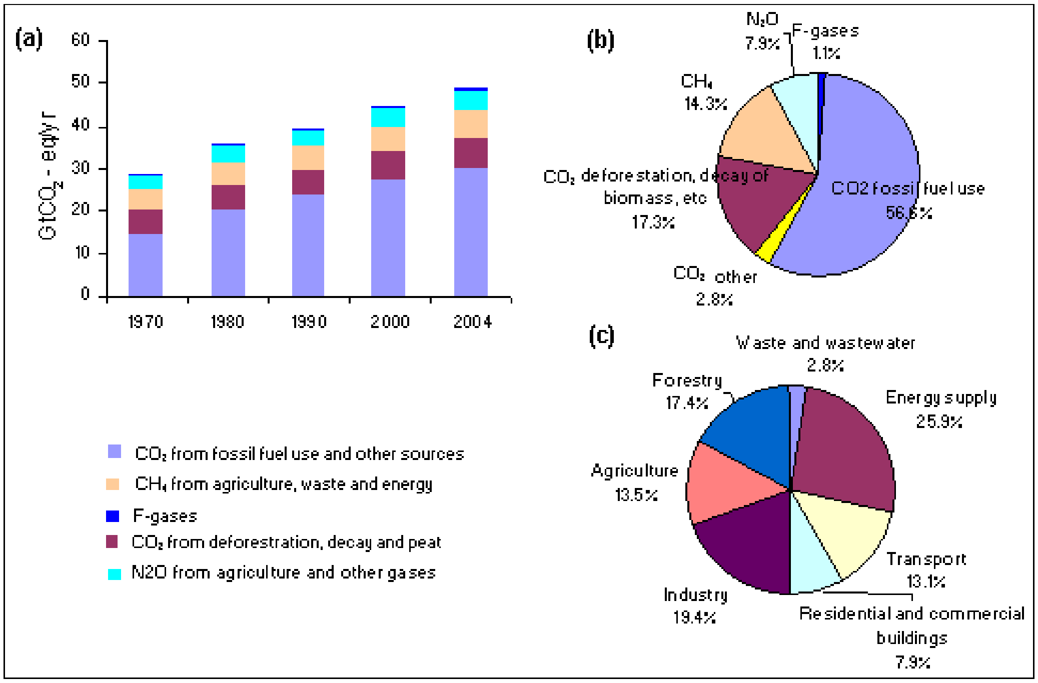


Figure 2.8 (a) Global annual emission of greenhouse gas from 1970 to 2004 (b) Major components of greenhouse gas (c) Major sources of greenhouse gas as of 2004 (Rogner *et al.*, 2007)

The greenhouse gases absorb the outgoing terrestrial energy, trapping it near the Earth's surface, and causing even more warming. There is a general consensus in literature that all aspects of the climate will be affected by the implications of climate change. The consensus view in literature is that there will be an increase in annual average global temperature of 0.15 – 0.3°C per decade as predicated by general circulation models (GCMs), if the concentrations of greenhouse gas continue to increase at the present rate (IPCC, 2007; Matondo *et al.*, 2004a). This will lead to an increase in precipitation in some regions while other regions will experience reduced precipitation (±20%). Not only will the temperature and precipitation be affected but, in addition, there will be implications that could lead to extinction of some species on the planet (IPCC, 2007; Mkanda, 1999). In view of this, temperature and rainfall are the most important aspects for investigating the effect of climate change on the water resources.

2.4.3 Climate change impact on water resources

According to IPCC 2001, the African continent is vulnerable to the impacts of climate change because of widespread poverty, recurrent droughts and overdependence on rain fed agriculture. Efforts to provide adequate water in Africa are continuously being confronted by several challenges such as population pressure, land use and changes in the available water. Variation in the available water which is evidenced through droughts and floods is associated with climate change making the problem more complex than expected.

Many studies have been completed to investigate the effect of climate change on water resources in different regions and countries (for example Dibike and Coulibaly, 2005; Fujihara *et al*., 2008; Matondo *et al*., 2004b; Tate *et al*., 2004). These investigations are based on the application of the most recent methods of predicting climate parameters like rainfall and temperature. The generally accepted method in literature has been to estimate climate parameters and use them in rainfall-runoff model to predict the future river flows. The simulated runoff is associated with a prescribed indicator to assess the impact. There are several indicators of water resources stress in literature including the amount of water available per person per day, frequency of floods and droughts.

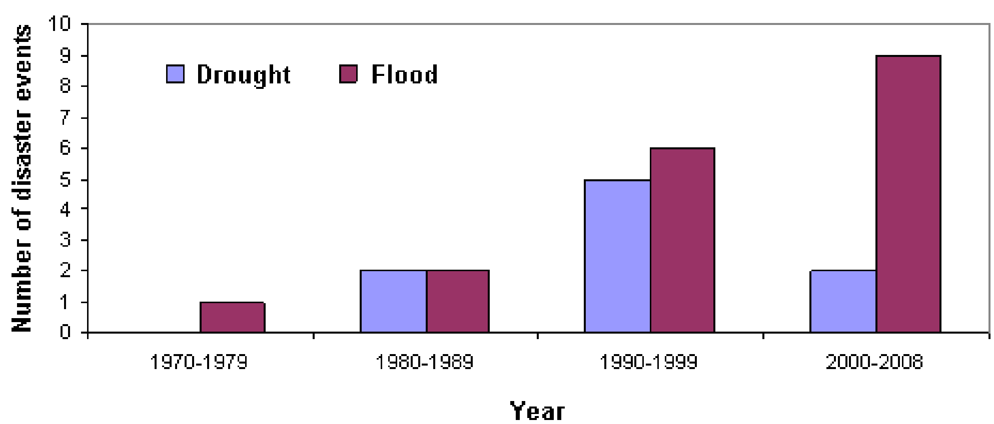


Figure 2.9 Evidence on the increasing frequency of floods and droughts in Malawi. Source of data (NSOM, 2006)

In Malawi, droughts and floods have increased in frequency (Figure 2.9), intensity and magnitude over the recent decades and have adversely impacted on food and water security, water quality, energy and the sustainable livelihoods of rural communities (Clay *et al.*, 2003). Recently the energy sector of Malawi has been affected by floods due to siltation and droughts due to low levels in Lake Malawi which is the main source of water for the hydro power stations along the Shire river (Calder *et al.*, 1995; GoM, 2003a). Droughts of 1978/79, 1981/82, 1991/92, 1993/1994, 2001/02 and 2004/05, resulted in frequent and increasingly long dry spells, and erratic onset and cessation of rainfall (Clay *et al.*, 2003). This has rendered the growth in agricultural production negative and the impact has been severe on smallholder farmers who accounts for the greater part of maize production, Malawi's main staple food (Clay *et al.*, 2003).

Mkanda (1999) investigated the impact of climate change on Malawi's wildlife habitats specifically the Lengwe National Park in the lower Shire valley using three general circulation models (GCMs): Canadian Climate Centre (CCC) model (McFarlane *et al.*, 1992); GFD3 model from the Geophysical Fluid Dynamic Laboratory (Manabe and Wetherald, 1987); and United Kingdom Meteorological Office UK89 model (Mitchell *et al.*, 1989). The conclusions of these studies show that temperature in Lengwe National Park will increase by 3^0C at the end of the year 2050. However, there was no consistancy in precipitation predictions as shown in Table 2.1. Mkanda (1999) further concluded that the high temperatures will result in high evaporation rates reducing the available water in the park. The consequences will be low vegetation productivity that would likely lead to habitat degradation. Consequently, the habitat would be unable to sustain a high population of large mammals currently in the park.

Table 2.1 Changes in precipitation and temperature under 3 GCM, Lengwe National Park, Malawi by 2050 (Mkanda, 1999)

Scenario	Change in Temperature ^{0}C	Change in precipitation %
UK89	3.8	2.11
GFD3	3.1	17.23
CCC	3.2	-8.26

Jury and Gwanzantini (2002) investigated the impact of climate change on the water levels of Lake Malawi using historical records. The results of the study indicated that there is a close relationship between lake inflows, river stream flows and catchment rainfall. The hydrological resources (rainfall and temperatures) were found to be sensitive to inter-annual variations of climate change. A study on Lake Malawi levels by Calder *et al*. 1995 indicates that variations in rainfall alone, without changes in either evaporative demand or in the hydraulic regime of the lake, are sufficient to explain lake level changes.

However Jury and Gwanzantini (2002) and Calder *et al*. (1995) did not look into the possibility of climate change impact using GCM models as their studies were based on historical records. Lake Malawi is Malawi's major reservoir which is used for navigation and sustains flows into the Shire river. The Shire river is the major source of water for the city of Blantyre as well as Malawi's hydropower stations. Therefore it is very important that the effects of climate change as downscaled by GCMs be incorporated into the investigation of the water resources of Malawi at watershed scale to assess the impact of climate change on the river basin in the catchment area of Lake Malawi as well as the Lake.

2.4.4 Modelling the impact of climate change on water resources

Detailed estimations on climate parameters such as temperature, precipitation, cloud cover and relative humidity due to climate change for different emission scenarios exist. These estimations are made from General Circulation Models.

General Circulation Models (GCMs) are numerical models representing physical processes in the atmosphere, ocean, cryosphere and land surface to simulate the response of the global climate system to increasing greenhouse gas concentrations (IPCC, 2007). Results of global and regional climate models (GCM/RCM) are widely available and allow the quantification of future climate change. However the outputs from GCMs are inadequate for assessing land surface impacts. The reason being that GCMs outputs are too coarse in space (typically of the order 50,000 Km^2) to be useful in predicting the effect of climate change on river basins (Fujihara *et al*., 2008; Wilby and Dawson, 2007; Wilby and Wigley, 2000). GCMs divide the atmosphere and ocean into a horizontal grid with a horizontal resolution of 2^0 to 48^0 latitude and longitude, with 10 to 20 layers in the vertical (Figure 2.10 and Figure 2.11). The second reason is that of doubt about the reliability of some GCM output variables (IPCC, 2007; Wilby *et al.*, 2009). In recent years, the advent of high-speed computers has led to an increase in model complexity by including more climate components and high spatial resolution GCM data in model simulation of future climate. Models used to evaluate future climate change have evolved in spatial resolution ranging from 500 km grid size during IPCC First Assessment Report in 1990 (FAR) to 110 Km in the IPCC Fourth Assessment Report in 2007 (AR4) (LeTreut *et al.*, 2007) as shown in Figure 2.11.

Due to coarse resolution of GCM outputs, downscaling methods are employed to relate GCM results to a particular catchment (Wilby and Wigley, 2000). A number of researchers have investigated the downscaling methods for establishing a connection between GCM results and river basin hydrological models for example (Fujihara *et al.*, 2008; Matondo *et al.*, 2004b; Wilby *et al.*, 2006). The most widely used methods are classified into Statistical and Dynamical downscaling methods.

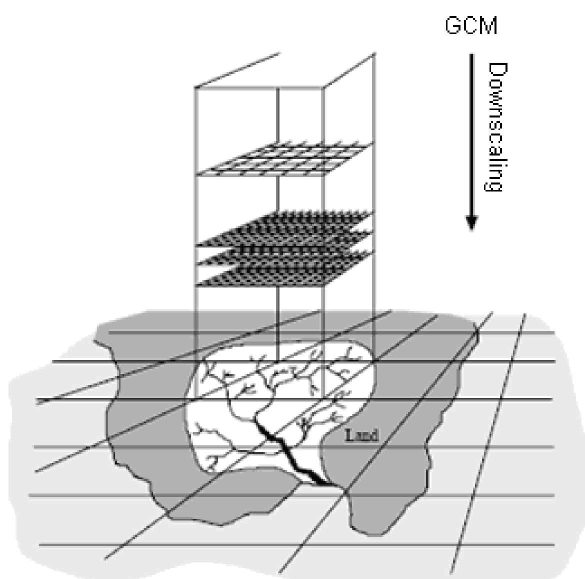
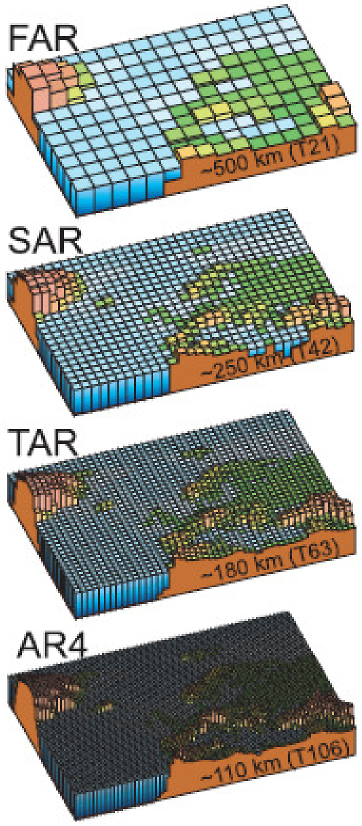


Figure 2.10 A schematic illustration of the general approach to downscaling. Source: (Wilby and Dawson, 2007)



FAR IPCC First Assessment Report (1990). 500 km grid resolution

SAR – IPCC Second Assessment Report (1995). 250 km grid resolution

TAR – IPCC Third Assessment Report (2001). 180 km grid resolution

AR4 – IPCC Fourth Assessment Report (2007). 110 km grid resolution

Figure 2.11 Grid resolution of the climate models used in the IPCC Assessment Reports: FAR (1990), SAR (1995), TAR(2001) and AR4(2007) (LeTreut *et al.*, 2007)

2.4.4.1 Statistical downscaling methods

Statistical downscaling methods employ statistical or empirical transfer functions to relate the local climate data to GCM outputs. According to Wilby and Wigley (2000) statistical downscaling is based on the assumptions that:

- suitable relationships can be developed between grid- and larger-scale versus grid- and smaller-scale predictor variables;
- observed empirical relationships are valid under future climate conditions;
- predictor variables and their changes are well characterised by GCMs.

Statistical downscaling methodologies have several practical advantages over dynamical downscaling approaches. Statistical downscaling represents the more promising option in situations where low–cost, rapid assessments of localised climate change impacts are required (Wilby *et al*., 2002). However statistical downscaling methods have been criticized for employing the assumption that empirical relationships are stationary, which imposes a limitation on statistical methods (Fowler *et al*., 2007; Hay *et al*., 2002)

2.4.4.2 Dynamic downscaling methods

In dynamical downscaling methods, a regional climate model (RCM) uses GCM outputs as its initial and boundary conditions to relate the local climate to GCM outputs. Dynamical downscaling methods respond to different external forcing in a physically consistent manner but suffer from high computation requirements and a lack of information and data. According to Wilby *et al.* (2000), Hay *et al.* (2002) Hay and Clark (2003) dynamical downscaling methods can resolve important atmospheric processes such as orographic precipitation in a manner better than that of coarse-resolution GCMs. However, it has been well reported that dynamical downscaling methods cause significant errors because of the accumulation of GCM and RCM biases, for example (Hay *et al*., 2002; Wang *et al*., 2004; Wood *et al*., 2004). Therefore, no study has succeeded in directly using dynamically downscaled data as inputs for hydrologic simulations. In fact, serious efforts are directed in tuning the GCM parameters and to correct the biases of downscaled data so that these data can be used as inputs to hydrologic models. Dynamical downscaling methods for hydrologic use have limitations with regard to the application region (Christensen *et al*., 2004; Fowler and Kilsby, 2007; Hay and Clark, 2003; Hay *et al*., 2002; Wood *et al*., 2004).

Predicting the effects of climate change on hydrological and ecological processes is crucial to avoid future conflicts over water and to conserve biodiversity. This requires tools for connecting GCM outputs and water resources availability in a river basin. A number of researches have investigated the use of hydrological models in assessing the impact of climate change on river flows. In recent years hydrological models have been found to have a wider application in water resources development, planning and management. The following section presents a discussion of general aspects of hydrological modelling as applied to water resources development and management.

2.5 OVERVIEW OF HYDROLOGICAL MODELLING OF WATER RESOURCES

This section presents a discussion of the general aspects of hydrological modelling and their application. It further discusses the challenges in modelling stretching from input data problems to the new science of climate change. Finally, the experience of the use of hydrological models in Southern Africa and Malawi in particular is reviewed.

2.5.1 General aspect of hydrological models

Hydrological modelling is an attempt to determine the operation of the hydrological system in the transformation of rainfall into runoff. A hydrological system can be defined as a structure or volume in space, surrounded by a boundary that accepts water and other inputs operates on them internally and produces an output (Killingtveit and Saelthun, 1995). A hydrological system model is an approximation of the actual system. Its input and outputs are measurable hydrological variables and the model's structure is a set of equations linking input to output. However hydrologic phenomena are extremely complex, and difficult both to measure and understand in full detail (Kachroo and Liang, 1992; Killingtveit and Saelthun, 1995). Because of these complications, it is not possible to describe all the physical processes within the catchment with exact laws. Using the system concept, the effort is instead directed to the construction of a model representing the most important processes, and their interaction within the whole system (Kachroo, 1992b). According to Kachroo and Liang (1992) a practical hydrological model should represent to an acceptable degree of accuracy, the hydrological regimes of wide variety of catchments.

2.5.2 Historical perspective of hydrological models

The science and art of modelling is said to have developed in response to the research community's perceived opportunities for advancing the state of knowledge in the subject, and the engineering community's need for predictive hydrological tools (O'Connell, 1991). Hydrological modelling dates back to 150 years when an Irish Engineer Thomas James Mulveney (1822 to 1892) developed the rational method for estimating peak flows (Beven, 2001). In 1920 Ross made the first attempt to split a catchment into zones on the basis of travel time to the catchment outlet using Mulveney's hydrograph concept (Beven, 2004). Ross argued that the production of runoff could be calculated for each area combined with flow routing of the runoff to the catchment outlet to obtain the prediction of the hydrograph. The major set back of the Ross time-area concept was lack of information on velocities of flows for all the possible surface and subsurface flow pathways. In 1932 Sherman introduced the unit hydrograph concept to avoid the problem. Sherman's idea was that the various time delays for runoff produced on the catchment to reach the outlet could be presented as a time distribution as shown in Figure 2.12 (Beven, 2004).

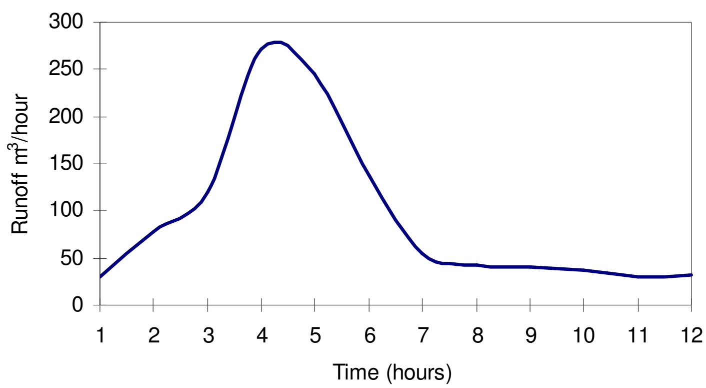


Figure 2.12 Sherman unit hydrograph concept showing runoff as a time distribution

Today Sherman's unit hydrograph concept remains a linear routing technique such that the principle of superposition can be applied (Beven, 2004). In more recent times hydrological models have played an important role in solving a large span of problems in hydrology and water resources. Recently hydrological models have been used in simulation of water quality, water quantity and sediment transport process (Heppner *et al*., 2006; Hesse *et al*., 2008). Along with development and advances in technology, models are gradually becoming more and more complex and are often used to integrate scientific findings from different disciplines. The increasing requirement of environmental awareness and the need for impact assessment of human activities on the natural hydrological regime have introduced a new concept in the development of hydrological models (Beven, 2004). The main emphasis of hydrological modelling has shifted over the last decade from river forecasting to more general topics such as sustainable protection of water resources, environmental protection and management and climate change (Hesse *et al*., 2008; Lorup *et al*., 1998; Refsgaard, 1987). The necessary interdisciplinary cooperation in model development has created a situation where no one really has the overview of all components of the model and where the user of the results has to rely upon judgments from the modellers regarding confidence in the results (Lorup *et al*., 1998). In view of the above inappropriate model structures or combinations of substructures, incomplete model calibration and control and poor modelling ethics can easily ruin the confidence in models as productive tools.

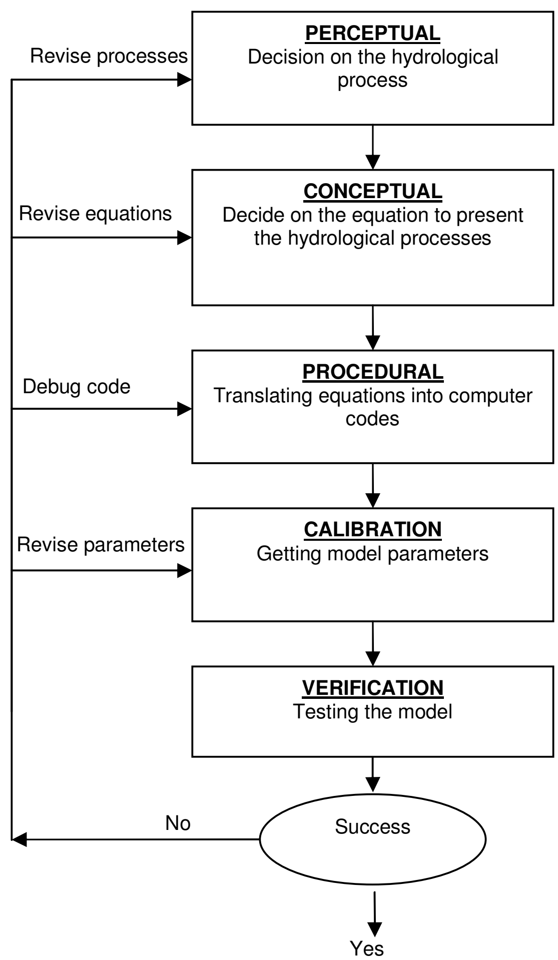


Figure 2.13 Schematic diagram of the steps involved in hydrological model formulation

The process of constructing a hydrological model involves the steps outlined in Figure 2.13:

- Understanding the behaviour of the catchment in terms of its response to input variables such as precipitation, evaporation and other hydro meteorological variables;
- Drawing a schematic diagram of the hydrological processes and devising a mathematical model representing the major perceived catchment response characteristics;
- Utilising state-of-the-art tools and techniques to translate the mathematical model into computer codes with parameter values and constraints.

2.5.3 General classification of hydrological models

Generally hydrological models can be classified on the basis of their function and objectives, their structure and their level of spatial dis-aggregation. Hydrological models may be broadly classified into systems analysis, conceptual models and physically based models.

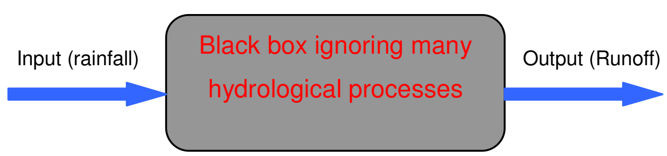


Figure 2.14 Conceptual representation of systems model

2.5.3.1 Systems Model

The 'systems analysis' or 'black box approach' depends on the prior assumption of a very general, flexible relationship (e.g. linear time-invariant input output model, (Kothyari and Singh, 1999)), the expression of which can be obtained by the application of systems analysis methods to the records. Systems models ignore the spatial distribution of the input variables and parameters, which characterize the physical processes. Examples in the hydrological context include the 1932 Sherman's unit hydrograph method

(Beven, 2004) the linear perturbation model (Nash and Barsi, 1983), simple linear model (Nash and Foley, 1981), linearly varying gain factor model (Ahsan and O'Connor, 1994) and many similar models found in literature.

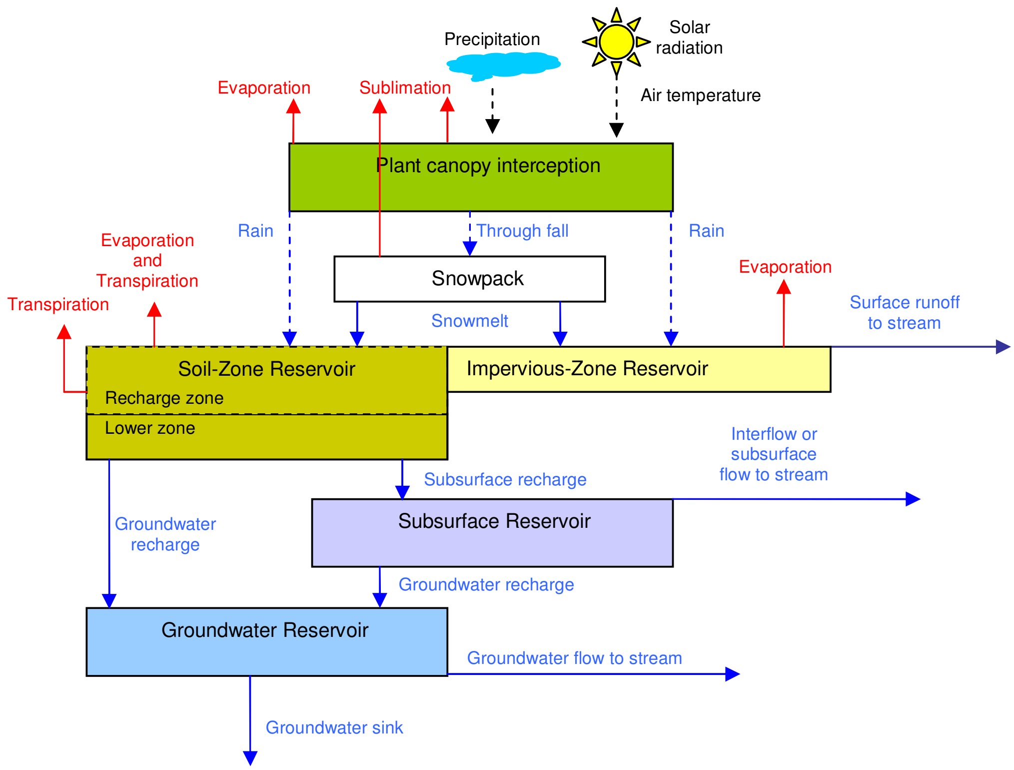


Figure 2.15 Schematic diagram showing various storage units and processes considered in conceptual hydrological models (Healy *et al.*, 2007)

2.5.3.2 Conceptual Models

The 'Conceptual Model' is an alternative approach, in which it is attempted to represent the transformation of input into output by a model, which consists of a series of steps representing more or less faithfully, but in a simplified manner, the known physical processes (Kachroo, 1992c). The input data are simplified by replacing spatially variable functions by their areal means. In conceptual models attempts are made to identify various physical processes and their inter-relationships as shown in Figure 2.15. Conceptual Models are designed on modular basis, each module simulating a major physical process component of the hydrological system (Madsen, 2000; O'Connell *et al.*, 1970). Empirical relationships or simplified assumptions are made in order to avoid excessive mathematical complexity in describing the various sub processes involved in the transformation. These models are also dependent on recorded data for the determination, not perhaps of the model structure, but of the parameter values, although ‘diagnostic checks’ subsequently carried out on the model output errors may lead to redesign and improvement of the model structure (Madsen, 2003). Conceptual models must be ‘calibrated’ for a particular catchment, by selecting that set of parameter values which, in some chosen sense, best enables the model to transform the inputs into outputs (Madsen, 2000). Usually this is done by empirical searching in the space of reasonable parameter values, to minimize the value of an objective function based on the extent of divergence between the observed outputs and the corresponding computed outputs of the model. Depending on the degree to which the model represents the relevant physical processes, some identification of parameter values with catchment characteristics or measurements made on the catchments may be achieved. Examples in the hydrological context include the “Nedbor – Afrstromnings – Model” (NAM) developed at the Technical University of Denmark (DHI, 2008), the Soil Moisture Accounting and Routing Model (SMAR), also known as layers model (O’Connell *et al.*, 1970) and many similar models found in literature.

2.5.3.3 Physically Based Models

Physically based models are based on the understanding of the physics of the hydrological processes which control the catchment response and use physically based equations to describe these processes (Beven, 1989). Also, these models are spatially distributed since the equations from which they are formed generally involve one or more space coordinates. The parameters of these models have direct physical interpretation and their values might be established by field or laboratory investigations. Human activities on the catchment, for example deforestation or irrigation, could be represented directly by changes in parameter values and the models could be used to predict the hydrological effects of such changes. Examples in this class include Système Hydrologique Européen, SHE (Abbott *et al.*, 1986), and GeoSFM (Asante *et al.*,2007), and TOPMODEL (Beven, 1989; Beven *et al.*, 1984). The use of physically based models is not popular in developing countries because of the lack of availability of input data. Physically-based distributed models usually work at a small size and require a large amount of data and lengthy computation times. This limits their application especially in developing countries where data is not readily available (Beven, 1989; Liu and Todini, 2002).

2.5.4 Spatial variability in hydrological models

Systems model and conceptual models utilise areal-weighted or average rainfall data as input data to the models rather than allowing the spatial variability of precipitation and evaporation over the catchment. This approximation may be considered adequate for smaller catchments rather than large catchments where there is a large variation in the input parameters from the upstream to the downstream. To overcome the inadequacy of areal-weighed or averaged input data, a distributed modelling approach is employed in hydrological modelling.

2.5.4.1 Lumped modelling

Lumped models are expressed by ordinary differential equations that describe simple hydraulic laws. Lumped conceptual models consider the catchment as a single unit with state variables that represent averages over the catchment area, such as precipitation over the catchment area. Lumped models have a conceptual structure based on the interaction between storage elements representing the different processes with mathematical functions to describe the fluxes between the storage (e.g. ‘Système Hydrologique Européen, ‘SHE’’, (Abbott *et al.*, 1986); Soil Moisture Accounting Routing ‘SMAR’, (O’Connell *et al.*, 1970).

2.5.4.2 Distributed modelling

Distributed models accounts for the spatial variability of process, inputs, boundary conditions and system characteristics (Healy *et al.*, 2007; Madsen, 2003). They make predictions that are distributed in space and time by discretizing the catchment into a larger number of elements or grid squares and solving the equations for the state variables associated with every element grid square (Beven, 2004; Madsen, 2003). Examples are SHE (Abbott *et al*., 1986), WetSPA (Liu and Smedt, 2004) and GeoSFM (Asante *et al*., 2007). Distributed models normally run on Arc View or Arc GIS platform to process large volume of data in transforming rainfall into runoff.

2.5.5 Stochastic and deterministic nature in hydrological models

Hydrological models can further be classified as deterministic or stochastic models depending on the nature of the equation used and the resulting output. Deterministic models allow only one single output from a simulation with one set of input and model parameters (Beven, 2001). Stochastic models allows for some randomness or uncertainty in the possible outcomes due to uncertainty in input variables, boundary conditions or model parameters (Beven, 2001). Stochastic models use mathematical and statistical concepts to link a certain input (for instance rainfall) to the model output (for instance runoff). The commonly used techniques in stochastic modelling are regression, transfer functions, neural networks and system identification.

2.5.6 Model Calibration and evaluation measures

2.5.6.1 Model calibration

The first step in model formulation is identification of the model. Once a model has been identified, the next step is to estimate the parameters of the model. The process of parameter estimation is known as model calibration. There have been many contributions to the hydrological literature on the subject of model fitting, calibration processes, objective functions and parameter estimation (Kachroo, 1992b; Madsen, 2000). The main purpose of the model calibration is to obtain a parameter set for a catchment which gives the best possible fit between the simulated and observed flows in terms of peak/low flows with respect to timing, rate and volume for the calibration period (B´ardossy, 2007; Kachroo, 1992b; Madsen, 2000; Madsen *et al*., 2002). In model calibration and verification the available record is split into two periods, in one of which the model is calibrated and in the other, the ‘verification’ period, it is tested and proved. The different methods of parameter estimation are: trial and error parameter optimization (Gupta *et al.*, 1998); automatic parameter optimization and a combination of trial and error and automatic parameter optimization with a constraint applied to refine the parameters (Anderton *et al.*, 2002; Madsen, 2000; Madsen *et al.*, 2002).

Trial and error parameter optimization is based on the selection of model parameters by trial and checking the goodness of fit of the estimated output. In automatic parameter estimation different search techniques exists in literature such as ordinary least squares, simplex method, golden search method and Rosenbrock method are used (Madsen, 2000). In this technique the model parameters are estimated automatically with the goal seeking algorithms (Killingtveit and Saelthun, 1995; Madsen, 2000; Madsen *et al.*, 2002).

2.5.6.2 Model requirements and objective functions

It is desirable that a model should represent as closely as possible the physical process occurring within the catchment. It is also essential that a model should represent accurately the transformation of the input into output. In hydrological context there are three main model requirements and these are model accuracy, model consistency, and model versatility (Kachroo, 1992b). The performance of a model is judged on the extent to which it satisfies its practical objectives (Kachroo, 1992b). This is referred to as model accuracy. According to Killingtveit and Saelthun (1995) a commonly used objective function is the sum of squares of differences between the observed and estimated discharges, with the summation taken over the whole calibration period, as shown in the equation below.

$$F = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \qquad i = 1,2,3,............,n \qquad 2.1$$

$\hat{y}$ being the model output estimate of the measured output y. The quantity F is an index of residual error, which reflects the extent to which a model is successful in reproducing the observed discharges. The second requirement is that of ‘model consistency’, where by the level of accuracy and estimates of parameter values persist through different samples of the data (Kachroo, 1992b). Model consistency is achieved by splitting the available record into two periods, in which one the model is calibrated and in the other the ’verification’ period, it is tested and proved. The tendency has been to use most of the available data in calibration and to confine the verification period to a couple of years (Kachroo, 1992b; Madsen, 2000). The third requirement of a good hydrological model is model versatility. A versatile model may be defined as one, which is accurate and persistent when subjected to diverse applications involving model evaluation criteria not directly based on the objective function used to calibrate the model (Kachroo, 1992b). The criterion for expressing model accuracy given in equation 2.1 is not a dimension-less quantity and it is not suitable for comparing the performance of a model on different catchments or with different lengths of records. Nash and Sutcliffe (1970) met this objection by defining the model ‘efficiency’ R^2 as in equation 2.2.

$$R^2 = \frac{F_0 - F}{F_0} \qquad 2.2$$

where F_0 is the initial variance given by the following equation

$$F_0 = \sum_{i=1}^{n} \left(y_i - \bar{y}\right)^2 \qquad i = 1,2,3,............,n \qquad 2.3$$

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{n} y_i \qquad 2.4$$

$\bar{y}$ is the mean in the calibration period and N is the number of data points.

For comparing the relative accuracies of different models (say model 1 and 2) using the same data, the R^2 criterion provides a convenient index of comparison of the corresponding sums of squares of model residual errors (Kachroo, 1992b)Such criteria my be expressed in the form;

$$r^2 = \frac{R_2^2 - R_1^2}{1 - R_1^2} \tag{2.5}$$

2.5.7 Application of hydrological models

Survival of communities living in river basins depends on the efficient management of their river network systems, sensible estimates of water yield and stream flow for water supply, irrigation and design of hydraulic structures and flood alleviation works. A wide range of Hydrological Models (H-M) are used by researchers, however the application of these models is highly dependent on the purpose for which the modelling is made.

Hydrological models are used in flood forecasting, where stream flow forecasts for a particular location are required in order to issue warning and to permit evacuation of population (Kachroo, 1992b). They are used also in providing for the efficient operation of storage reservoirs for hydroelectric power, water supply and other purposes (Killingtveit and Saelthun, 1995). At the design stage of many hydrological works, simulations of possible discharge series may be required. The simulated discharge series may be obtained by using hydrological models and later on used in the design of the hydrological works. Design of hydrological models also facilitates:

- The development of mathematical models for investigating the effects of climate change and environmental impacts on the phase of the hydrological cycle;
- The preparation of Disaster Management Plans (DMP) and Environmental Impact Assessment (EIA) Reports;
- The decision-making process, by equipping engineers and technocrats with a tool to objectively justify certain decisions in water resources planning providing scientific validation.

Flow simulation on unagauged catchment is also a typical application case for hydrological models (Refsgaard, 1997), however there are relatively few studies regarding this issue in the literature. The small number (or even the lack) of observations of key variables that influence hydrological processes limits the application of hydrological models. For example in most river basins discharge is only measured at a few locations and precipitation measurements are taken at some selected points. The problem is more prevalent in developing countries whereby the entire river basin has neither gauging station nor precipitation recording station. This poses more difficult problems as the model parameters for hydrological models are estimated using calibration based on observed data. The current tendency by many hydrologists is to transfer calibrated parameters from gauged catchment to ungauged catchment by using regression based regionalisation methods (Abdulla and Lettenmaier, 1997; Bastola *et al.*, 2008; Kokkonen *et al.*, 2003). However it is difficult to associate the parameters estimated through calibration with the characteristics of the catchment and to transfer them to ungauged locations because: optimal model parameter sets depend on the models and the objective functions used to measure their performance (Gupta *et al.*, 1998; Madsen, 2003), model parameters are themselves uncertain (Bastola *et al.*, 2008; Kuczera and Mroczkowski, 1998), parameters are not unique - a diverse set of possible parameter values can lead to similar model performances (equifinality) (Beven and Freer, 2001). B´ardossy (2007) indicated that parameter sets can be considered transferable if the corresponding model performance (defined as the Nash-Sutcliffe efficiency) on the donor catchment is good and the regional statistics: means and variances of annual discharges estimated from catchment properties and annual climate statistics for the recipient catchment are well reproduced by the model.

In recent years potential impact of climate change on water resources and hydrology has gained consideration among researchers. Flow forecasting in many hydrological models depends on the historical data input into the model. The input data in hydrological models is climate data which is affected by climate change. Currently General Circulation Models (GCMs) have been developed to simulate the present climate and predict future climate change. In view of this hydrological models can be used to forecast future river flows and levels based on the simulated future climate by GCM.

2.5.8 Review of hydrological models used in this study

2.5.8.1 The Linear Perturbation Model (LPM)

The LPM was originally proposed by Nash and Barsi (1983). Perturbation models are used to account for the seasonality of the observed rainfall and the runoff. The model is based on the following assumptions:

- If, in a particular year, each input function, is equal, for each day of the year to its expected value for that date, then the output will also equal to its expectation for that date (Kachroo and Liang, 1992),
- Perturbations or departures from the date expected input values are linearly related to the corresponding perturbations or departures from the date expected output values.

The transformation is introduced in the observed data of rainfall x_i and the runoff y_i. The transformation has the form of;

$$Q_i = y_i - y_s \quad \text{and} \quad R_i = x_i - x_s$$
$$\text{for} \quad i = 1,2,3,......,n \quad \text{and} \quad s = 1,2,3,.....,365 \qquad 2.6$$

where x_s and y_s are the seasonal mean rainfall and discharge respectively. The relationship between the perturbations of the discharge Q_i and rainfall R_i is given by convolution summation form shown in equation 2.7.

$$Q_i = \sum_{j=1}^{m} R_{i-j+1} h_j + e_i \qquad i = 1,2,3,..........,n \qquad 2.7$$

where h_j is the jth ordinate of the pulse response ordinate, m is the memory length which implies that the effect of any input x_i lasts only through m intervals of duration time, and e_i is the model error term or residual. Model-estimated departure values are added to the seasonal expectations to give the estimated discharge series. Research has shown that LPM performs well in tropical regions due to the seasonal variation in the rainfall pattern (Matondo *et* *al*., 2004a; Yawson *et al*., 2005). According to Yawson *et al.* 2003 LPM performs well in catchments where seasonal variation of river flow is significant.

2.5.8.2 Nedbor – Afstromings – Model (NAM)

In this section a conceptual model NAM, which was applied to North Malawi river basins in simulating lumped inflows into Lake Malawi, is described. NAM model was developed by the Danish Hydraulic Institute (DHI) in conjunction with the Department of Hydrodynamics and Water Resources at the Technical University of Denmark. NAM is an abbreviation of the Danish "Nedbor – Afstromings – Model", meaning precipitation runoff model (DHI, 2008). NAM is a deterministic, lumped conceptual rainfall-runoff model, which represents various components of the rainfall-runoff process by continuously accounting for the water content in five different and mutually interrelated storages, where by each storage represents different physical elements of the catchment (Figure 2.15 and Figure 2.16).

Data requirements

The basic input data for NAM model consist of: meteorological data, hydrological data, initial conditions and model parameters. The basic meteorological data required to run NAM model are rainfall, potential evapotranspiration, and temperature and radiation data. Temperature and radiation data are required when snow modelling is included in the simulations. Hydrological data required by NAM model covers observed discharge data at the catchment outlet for comparison with simulated runoff for model calibration and verification. NAM model also allows the modelling of human activities such as irrigation and groundwater abstraction which affects the hydrological cycle. That being the case a time series of irrigation and groundwater abstraction will be required in NAM simulations.

Structure and Concept of NAM model

NAM model is an imitation of the hydrological cycle simulating rainfall-runoff in five different storage zones as shown in Figure 2.16. These storage zones are:

snow storage, surface storage, lower zone storage, upper groundwater storage and lower groundwater storage (Madsen, 2000). The following section is an outline of the NAM model after DHI (2008).

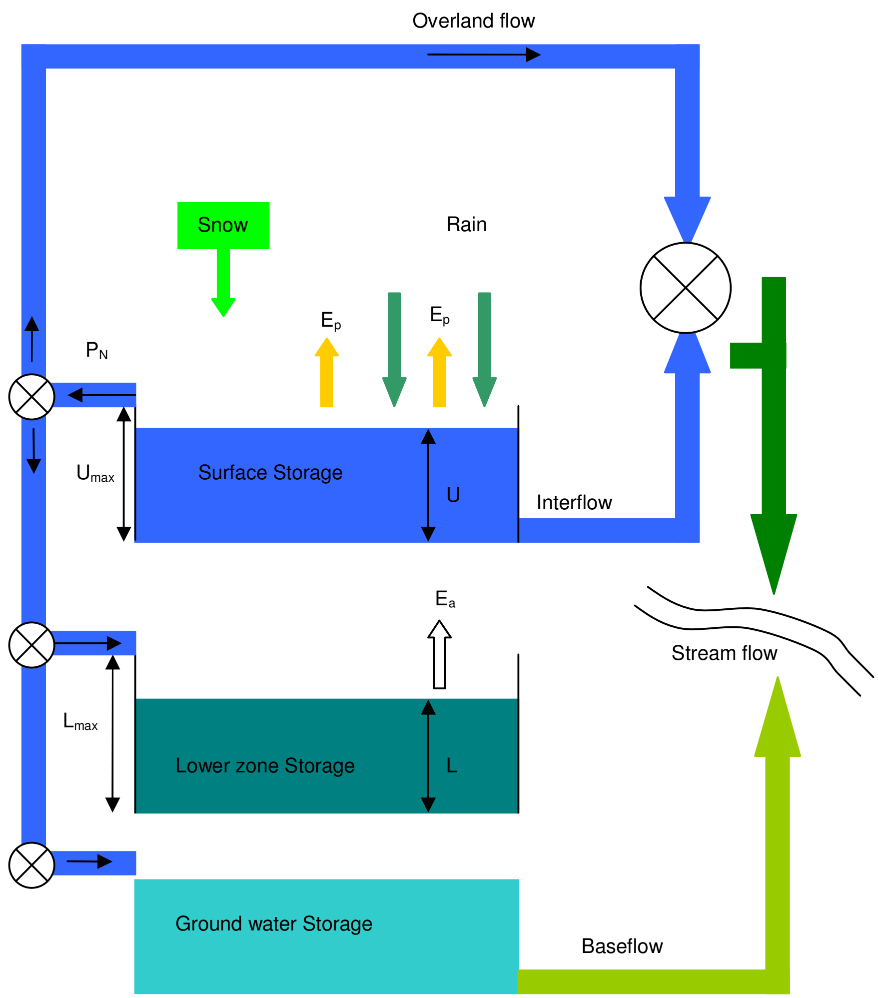


Figure 2.16 Schematic diagram of NAM model (DHI, 2008).

Surface storage zone represents moisture intercepted on the vegetation as well as water trapped in depressions. The amount of water in this zone is denoted by *U,* with U_{max} denoting the upper limit of the amount of water in the surface storage zone. The amount of water in this zone is lost by evaporation as well as horizontal leakage. When maximum surface storage is reached U_{max}, some of the excess water enters the stream as overland flow and the remainder infiltrates to the lower zone and groundwater.

Lower zone or root zone storage is the soil layer below the surface from which vegetation can draw water for transpiration. Moisture content in this zone is denoted by L, with L_{max} denoting the upper limit of moisture content in this zone.

Evapotranspiration is at potential rate E_p in the surface zone when surface zone storage is larger than potential evapotransipiration. Once surface zone storage is less than E_p then evapotransipiration draws water from the lower zone at an actual evaporation rate E_a. E_a is assumed to vary linearly with soil moisture content of the lower zone storage.

$$E_a = (E_p - U)\frac{L}{L_{max}} \qquad 2.8$$

Overland flow denoted by QOF results from excess water P_N from the surface zone. In addition to overland flow excess water P_N from surface zone reaches gives rise to infiltration. QOF is assumed to be proportional to P_N and to vary linearly with relative soil moisture of the lower zone storage.

$$QOF = \frac{CQOF\, L/L_{max} - TOF}{1 - TOF} P_N \text{ for } L/L_{max} > TOF \qquad 2.9$$

$$QOF = 0 \qquad \text{for } L/L_{max} \le TOF$$

Where $CQOF$ is the overland flow runoff coefficient ($0 \le CQOF \le 1$) and TOF is the threshold value for overland flow $0 \le TOF \le 1$.

Interflow QIF, is assumed to be proportional to U and vary linearly with the relative moisture content of the lower zone storage.

$$QIF = (CKIF)^{-1} \frac{L/L_{max} - TIF}{1 - TIF} U \text{ for } L/L_{max} > TIF \qquad 2.10$$

$$QIF = 0 \qquad \text{for } L/L_{max} \le TIF$$

where $CKIF$ is the time constant for interflow, and TIF is the root zone threshold value for interflow $0 \le TIF \le 1$.

Flow routing of interflow and overland flow (OF) is based on linear reservoir concept. Interflow storage is routed through two linear reservoirs in series with a time constant CK_{12}.

$$CK = CK_{12} \qquad \text{for } OF < OF_{min} \qquad 2.11$$

$$CK = CK_{12}\left(\frac{OF}{OF_{min}}\right)^{-\beta} \qquad \text{for } L/L_{max} \le TIF$$

where OF_{min} is the upper limit for linear routing (0.4mm/hour) and $\beta = 0.4$ corresponds to the using the Manning formula for modelling overland flow. This ensures that the routing of the real surface flow is kinematic.

Groundwater recharge. The amount of water (G) infiltrating into the groundwater storage zone depends on the soil moisture content in the root zone.

$$G = (P_N - QOF)\frac{L/L_{max} - TG}{1 - TG}U \quad \text{for } L/L_{max} > TG \qquad 2.12$$

$$G = 0 \qquad \text{for } L/L_{max} \le TG$$

Where TG is the root zone threshold value for groundwater recharge ($0 \le TG \le 1$).

Soil moisture content. The net rainfall between overland and infiltration to the ground root zone increases the moisture content L within the lower zone storage by ΔL amount

$$\Delta L = P_N - QOF - G \qquad 2.13$$

The base flow BF from the groundwater storage is calculated as the output from a linear reservoir with time constant CK_{BF}

Numerous criteria can be adopted for choosing the "right" hydrological model for the project requirements and needs. Data requirements, model parameters and model structure in representing hydrological processes can be considered as selecting factors. Two rainfall runoff models described in this section were selected based on previous studies (Lørup *et al.*, 1998; Mkhandi and Kumambala, 2006) within the region as well as data requirement. Scarcity of data is a major set back with the application of many hydrological models. However the two models described in section 2.5.8 can handle catchment areas with scarce data based on lumped assumption of the input data (Yawson *et al.*, 2005; Yew Gan *et al.*, 1997). Seasonality of the climate data is one of the major characteristics of the climate of Malawi which could easily be modelled by LPM as it takes into account the departures of daily data from their seasonal mean values. The following section is a brief overview of hydrological modelling in Southern Africa as well as Malawi.

2.5.9 Water resources modelling in southern Africa

The Southern Africa region, of which Malawi is member state, is a vast region covering 6.8 million square kilometres with a population of almost 150 million (Meigh and Matt, 2004). This region is also referred to as Southern Africa FRIEND in water resources research area. FRIEND was launched as a contribution to UNESCO's Third International Hydrological Programme (IHP-III) from 1984-1988 with an initial focus on data-rich basins of northwest Europe (Northern European FRIEND) (Gustard and Cole, 2002). Between 1989 and 1993 FRIEND expanded geographically covering the Mediterranean region, Central Africa, West Africa and later on southern Africa in collaboration with the Southern Africa Development Community (SADC). Today the Southern Africa FRIEND project remains a contribution to the International FRIEND programme which is part of the UNESCO IHP (International Hydrological Programme), in which the central objective is hydrology and water resources for sustainable development (Gustard and Cole, 2002; Meigh and Matt, 2004).

Southern Africa FRIEND region is characterised by water scarcity exacerbated by the uneven distribution of resources, recurrent drought and devastating floods (Hughes *et al.*, 2003). The growing population and ever increasing demand placed on the water resources in the Southern African region, has brought a realisation among water resource experts that it is essential to develop the water resources of Southern Africa in a sustainable manner, through the application of a range of technical, economic and institutional measures (SADC, 2001). Development of water resources requires hydrological models for the assessment of the available water resources. However it has been recognised by Hughes *et al.* (2003) that there is a lack of experience within the SADC region in the use of such tools, as well as inadequate access to software required to apply models. In 1999 the Southern Africa Development Community (SADC) realised the need for water resources assessment of the region. In view of this, Project Concept Note (PCN) 14 was conceived as a project proposal that would enhance the surface water resources assessment capabilities in the region (SADC, 2001). It has been recognized by Hughes *et al.* (2003) that the ideas of Southern Africa in the area of hydrological modelling and of PCN 14 have much in common.

Today Southern Africa FRIEND has carried out a number of research projects in the field of water resources in SADC countries (Fry *et al.*, 2003; Hughes *et al.*, 2003). One of the Southern Africa FRIEND's projects is the development of GIS software for the region based on tools used in the United Kingdom (Fry *et al.*, 2003). The GIS tool was calibrated based on data from Malawi. The findings of the study recommended that for the prototype tool to be implemented as function tool new hydrological models would need to be investigated and incorporated into the system. The study further recommended the use of improved and validated rainfall, flow and water use data sets and further research into the climate variability of the region. Frequent flooding is another problem the SADC region is facing due to current climate variability. In view of this the Southern Africa FRIEND has developed a flood estimation procedure for homogeneous regions in Southern Africa by deriving regional frequency curves for the delineated homogeneous regions (Mkhandi *et al.*, 2000). A relationship between mean annual flood and catchment characteristics for the gauged catchments was established under the same study.

Research efforts by Southern Africa FRIEND in the water resources sector in the SADC region are aimed at sustaining the water resources of the region. Water is an essential element for sustainable human development as it links food, energy and domestic water supply requirements for human beings as well as any living creature on the planet. Globally water resources are used for various activities for the benefit of mankind. The following section looks at the major water uses ranging from domestic water supply to hydropower generation as well as the current efforts by the international community in addressing global water crisis.

2.6 WATER WITHDRAWALS FOR DOMESTIC AND INDUSTRIAL USE

Water is an essential element for any living creature on earth. However the growing scarcity of fresh and clean water is among the most important issues facing mankind (Abu-Zeid, 1998; Falkenmark, 1991; Gleick, 2004; Shiklomanov, 1997). The world population, regardless of location and development stage, needs water. Access to modern water services is an indispensable element of sustainable human development and a pre-requisite for meeting the Millennium Development Goals (UN, 2002). Water is indispensable for human health and well-being and for sustaining the ecosystem on which man and his future generations depends (Abu-Zeid, 1998). According to the WHO, 1.1 billion people around the world lacked access to "improved water supply" and more than 2.4 billion, or roughly 40 percent of the world's population lacked access to "improved sanitation" in 2000. This prompted a number of nations and aid agencies to put in more effort to improve global access to freshwater and sanitation services. For example, World Water Forum (2000) in Hague called for efforts to guarantee that:

> "every person has access to enough safe water at an affordable cost to lead a healthy and productive life and that the vulnerable are protected from the risks of water-related hazards…"

In 2000 the United Nations General Assembly adopted the Millennium Development Goals with goal number 7 on water whose objective is (UN, 2000):

> "Halve by 2015 the proportion of people without sustainable access to safe drinking water"

This was followed by the Johannesburg World Summit on Sustainable Development (WSSD) in 2002 where the international community revised MDG 7 by adding (UN, 2002)

> "halving by the year 2015 the proportion of people without access to basic sanitation"

According to WSSD (2002) water is an integral to sustainable development as it is related to WSSD themes covering water and sanitation, energy, health, agriculture and biodiversity. That being the case, countries that are well endowed in freshwater resources have an economic advantage over those less fortunate (Abu-Zeid, 1998). It is now been recognised that water related diseases are amongst the main causes of illness and deaths in the developing world (Gleick, 2004). In 2004 best estimates indicate that 2 million died from waterborne, water-washed, and water- based diseases such as typhus, ameobiasis, and shistosomiasis (UNICEF&WHO, 2004). According to UNICEF & WHO (2004) globally, 1.1 billion people rely on unsafe drinking water sources from lakes, rivers and open wells with the majority of these in Asia (20%) and sub-Saharan Africa (42%). Furthermore, 2.4 billion people lack adequate sanitation worldwide. Sub Saharan Africa of which Malawi is a member state is the least developed in terms of water supply as well as sanitation as shown in Figure 2.17. In Malawi, out of the total population of 11.8 million people, only 62 percent (95 percent urban and 58 percent rural) have access to safe drinking water and 64 percent (90 percent urban and 60 percent rural) have adequate improved sanitation (NSOM, 2006). According to Gleick (2004) increasing access to safe drinking water and sanitation services by achieving the millennium development goals will halve the number deaths per year due to water related diseases. These improvements in sub-Saharan Africa alone would result in 434,000 child deaths due to diarrhoea being averted annually. In light of this the Malawi government has embarked on a programme known as National Water Development Programme which is aimed at improving the water supply for people in rural and urban areas in order to meet the target of the United Nations MGD goals.

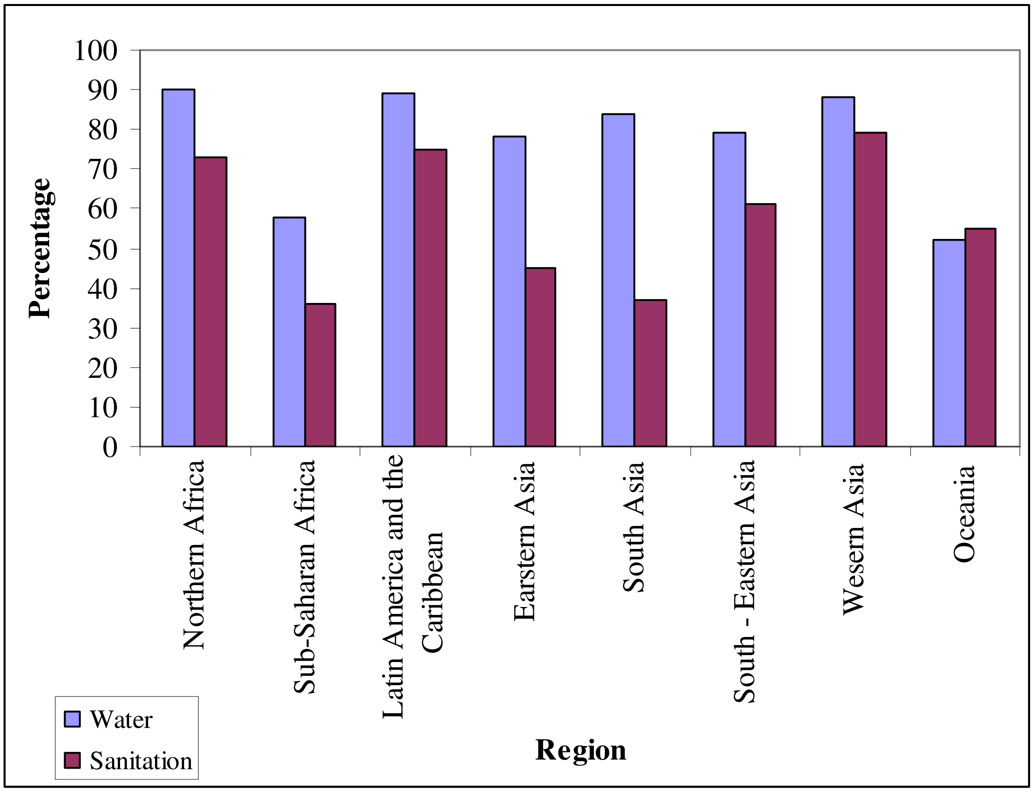


Figure 2.17 Regional drinking water and sanitation coverage for developing countries as of 2004 (UNICEF&WHO, 2004)

2.7 WATER USE FOR RENEWABLE ENERGY GENERATION

Energy is one of the most important commodities for the satisfaction of physical needs providing economic development for modern society. In accordance with (GoM, 2003a), the need for renewable, alternative and non polluting sources of energy assumes top priority for self reliance in Malawi. This demands an estimation of available energy resources. Hydropower, large and small, remains by far the most important of the 'renewables' for electrical power production worldwide (Frey and Linke, 2002; IEA, 2000; Oliver, 2002). The hydropower resources of Malawi have not been precisely evaluated, but the potential of a number of major rivers and sites have been identified (GoM, 2003a). Hydropower owes its position as a renewable resource as it ultimately depends on the runoff segment of the natural hydrological cycle. Hydropower plants use the kinetic energy of flowing water to generate electricity. The kinetic energy of flowing water offers something unique to a nation's economic development – sustainability, which has been defined as 'economic activity that meets the needs of the present generation without jeopardizing the ability of future generations to meet their needs' (WCED, 1987). The hydropower turbines and generators are installed either in or adjacent to the dams or uses pipelines to carry water to the powerhouse (Figure 2.18). The power capacity of a hydropower plant is a primary function of the flow rate Q expressed in m^3/s and the potential head H in metres, which is the elevation difference water falls in passing through the plant. Project design of hydropower plants may concentrate on either of these variables or both. Major hydropower plants components include dams, penstocks, turbines, generators, transformers and transmission lines as shown in Figure 2.18.

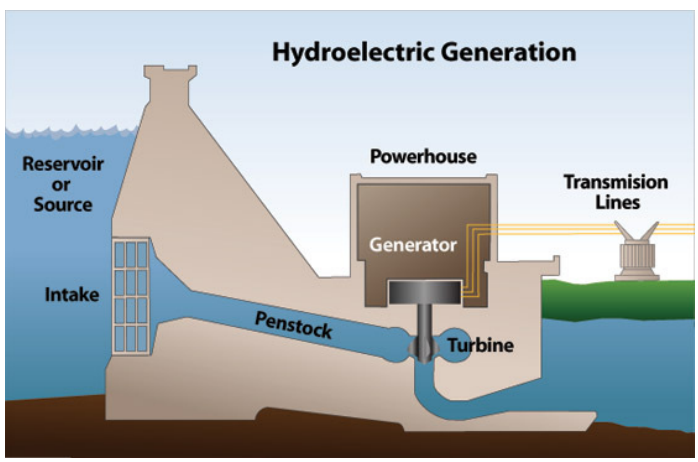


Figure 2.18 Schematic Layout of hydropower plant (Source: ww.sce.com/ Feature/ Archive/hydropowerfeature.htm)

2.7.1 Types of hydropower projects

Hydropower plants can be classified in a number of ways which are not mutually exclusive: by head (high or low), by storage capacity, by purpose (single or multipurpose) or by size (large or small) (Egre and Milewski, 2002; IEA, 2000). The classification of hydropower by size is set in accordance with the difference in scale of relatively small hydropower generation in comparison with regular hydropower generation. According to Egre and Milewski (2002) the definitions are relative and vary depending on the circumstances of each nation, hence no definitions exist which are generally acceptable all over the world. For the purpose of this research hydropower projects can be classified into two main categories: run-of-river projects with little or no storage capacity and reservoir type project with significant storage.

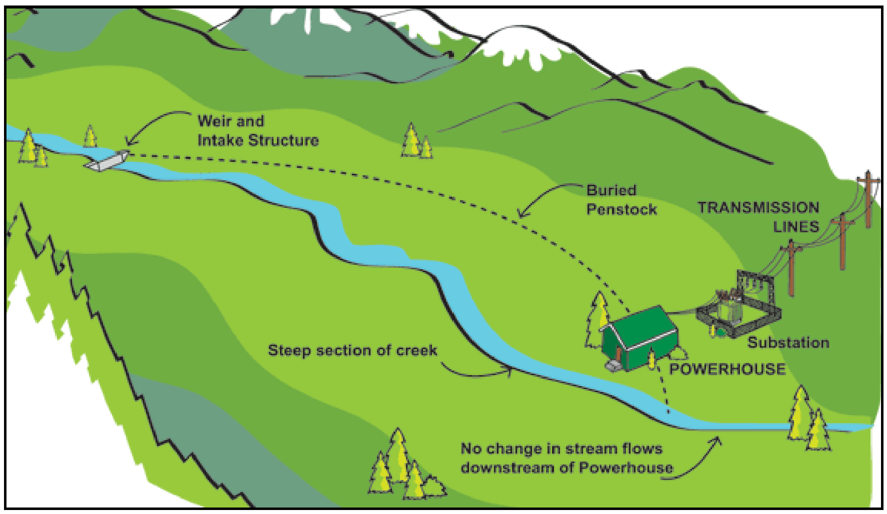


Figure 2.19 Typical set up of a run-of-river hydro project (Source: www.hydromaxenergy.com)

2.7.1.1 Run-of-river project

Run-of-river projects have no reservoir and generate only on the natural, unregulated river flow. Since the natural discharge varies with the season for most parts of the world it is only feasible to use a fraction (usually less than the annual average flow) to run the turbines (WCD, 2000). In this respect, run-of-river hydroelectricity has similarities with wind power, with the important distinction that the former kind of power plant is usually accessible for power generation at all times and can satisfy both peaking power as well as base load demands(Egre and Milewski, 2002; WCD, 2000). Run-of-river projects have relatively minor environmental impact, other than the depletion of river flows between the intake and powerhouse on tunnel schemes as shown in Figure 2.19 (Anderson *et al.*, 2006a). However due to the lack of storage they produce relatively low value base load energy, and offer few of the ancillary benefits inherent in a storage project (e.g. load following, spinning reserve, energy standby) (WCD, 2000).

2.7.1.2 Storage Projects

The seasonal runoff pattern and the differential need for electricity make facilities that have the capacity to store water feasible structures in hydroelectric systems. Reservoir power plants make a more efficient use of the annual runoff compared to run-of-river plants and their level of service makes them outstanding in their capacity to supply power during times of peak electricity demand (WCD, 2000). The reservoir provides energy storage in the form of a large body of water that accumulates in periods of high flows and can supply more than average natural amounts of water (Figure 2.20) to the turbines when the electricity demand is high. This capacity results in greater electricity production flexibility in systems with a large share of hydro. In summary storage projects produce higher quality electricity, but at the cost of generally raising more environmental concerns over such issues as loss of land, population displacement and changed flow patterns (Gyau-Boakye, 2001; Lerer and Scudder, 1999; Pringle *et al.*, 2000; Rosenberg *et al.*, 1997; Rosenberg *et al.*, 1995). Africa has a great potential for such hydropower projects because of high intense rainfall for a short period followed by long dry season. Storage reservoirs to store excess rainfall and then released during the dry season for both hydropower and irrigation would be more beneficial for most of SADC countries.

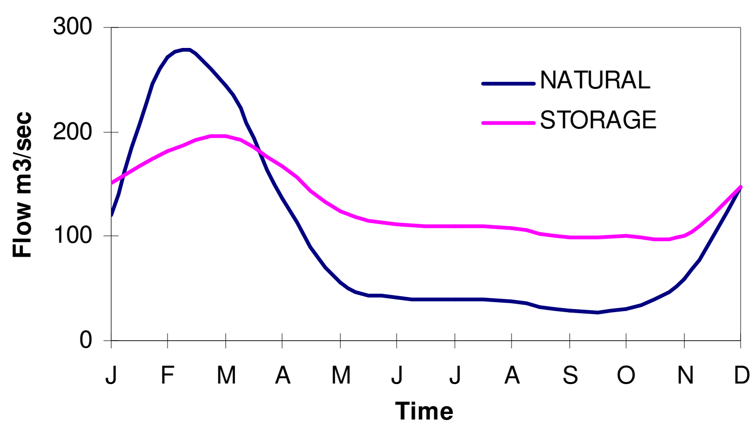


Figure 2.20 Typical change in the flow regime after construction of hydropower dams

2.7.2 Benefits of hydropower

Although hydropower provides 20 percent of the global electrical energy demand, the benefits of their outputs is proportionally greater than that from other sources. These benefits can be attributed to the electricity itself, or side benefits, often associated with reservoir development. The net environmental benefits of hydropower are far superior to fossil-based generation. For example, in 1997 it was calculated that hydropower saved greenhouse gas emissions equivalent to all the cars on the planet in terms of avoidable fossil fuel generation (IEA, 2004). Hydro schemes are generally integrated within multipurpose development to subsidize other vital functions of a project such as water supply, irrigation for food production, flood control and societal benefits such as increased recreational opportunities, improved navigations development of fisheries, etc. Hydropower is often an economic stimulus in developing countries and forms part of complex power systems in more industrialized countries (WCD, 2000). The main beneficial characteristics specific to hydropower can be summarized as follows (Bartle, 2002; IHA/IEA/CHA, 2000).

- Hydropower is a continuously renewable resource powered by the hydrological cycle. Hydroelectric is non polluting since greenhouse gases are not released in its production;
- Hydroelectric plants have the lowest operating costs and longest plant life compared with other large scale generating options;
- Hydroelectric plant efficiencies can be close to 90%, whereas fossil-fired thermal plants attain efficiencies of only 30 – 40%;
- Hydropower plants are capable of responding, within seconds, to changes in electrical demands;
- As part of a multipurpose scheme, hydro can help to subsidise other important functions such as irrigation water supply, navigation improvements and recreation facilities.

2.7.3 Social and environmental constraints of hydropower projects

Land and water are ecologically linked in a natural system called a watershed.

Water works to shape the land, taking with it sediment and dissolved materials that drain to watercourses and, in most cases, eventually to the sea. It is now recognised that when the ties between the land and the river are broken by the execution of a water project such as a dam the consequences are felt throughout the watershed, because of the huge changes which are induced on hydrology of the river (WCD, 2000). The planning and execution of many water projects in the developing world in the past seemed to have been dominated by the consideration of economic and technical feasibility (Anderson *et al.*, 2006a; Dynesius and Nilsson, 1994; Gyau-Boakye, 2001) while the adverse social and environmental impacts of the projects received less than adequate attention (Magadza, 2006). For example, in the case of the Volta river project at Akosombo, even though some adverse health impacts were anticipated, no formal coherent environmental impact assessment (EIA) of the project was undertaken (Gyau-Boakye, 2001). This may be explained by the fact that water development projects have traditionally been considered to be in the domain of the engineer, the economist and the politician (Magadza, 2006). For many of the projects, once their technical and economic feasibility were established, the main driving force behind implementation became political (Gyau-Boakye, 2001). Concerns of ecologists, anthropologists, and other specialists were often ignored. EIA probably gained wider acceptance after the United Nations Conference on Human Environment in Stockholm in 1972 and since then some attention has been paid to the unfavourable impacts of water projects. Consequently, the situation has now changed in most developing countries to the extent that EIA of all water projects has to been undertaken to assess and mitigate some of the impacts. Figure 1.5 in Chapter 1 is map of Africa showing some of the main dam projects of the 19th century in Africa.

2.7.3.1 Social constraints

Any infrastructure development inevitably involves a certain degree of change. The creation of large reservoirs to store water for power generation has a significant impact both on the population in a locality and on the environment. Creation of large dams to store water for hydropower, irrigation and water supply is associated with transformation of land use and displacement of people in the project area (Lerer and Scudder, 1999; Pringle *et al.*, 2000; Rosenberg *et* *al.*, 1997; Rosenberg *et al.*, 1995). Relocating people from the reservoir area is the most challenging social aspect of hydropower development, leading to significant concerns regarding local culture, religious beliefs and effects associated with inundating burial sites (IHA/IEA/CHA, 2000). For example, the construction of Akosombo dam in Ghana flooded 35000 km^2 (5 percent of the country's land and required the settlement of some 78000 people from 700 villages (Gyau-Boakye, 2001). The construction of Kariba Dam across the Zambezi river displaced 57,000 people most whom were resettled within the lake basin (Magadza, 2006; WCD, 2000)

The incidence of water-borne disease is a particular problem in the tropical climate of Africa, and has been found to increase dramatically in the case of certain dam projects (Lerer and Scudder, 1999). Dams create excellent habitat for water-borne disease parasites responsible for these diseases such as snails that spread schistosomiasis, and the mosquitos that spread malaria (Lerer and Scudder, 1999). For example the creation of Aswan High Dam (AHD) across the Nile river with changes in the downstream irrigation to a perennial system has caused an increase in the incidence of schistosomiasis (El-Hinnawi, 1980). In 1942, Anopheles gambiae introduced malaria from Sudan in the area of the actual AHD resulting in about 100,000 deaths of which 10,000 occurred in Upper Egypt (George, 1972). Progressive inundation of the cultivated river valley with rich soils triggered a massive development of chironomid swarms (lake flies) in Lake Nasser within the first 10 years of its existence (Entz, 1980). While the relatively calm water of the reservoir favours the spread of some diseases, the rapid water flow through dam sluices encouraged the breeding of a black fly (Simulium) carrying a human disease known as river blindness – onchocerciasis (George, 1972). Culex pipiens, the vector for filariasis was reported to be present along with the latter reported Phlebotomus spp., vector of the disease kalazar – leishmaniasis (George, 1972). The Akosombo Dam in Ghana shown in Figure 1.5 is linked to increases in the incidences of water borne diseases such as shistosomiasis, malaria and onchocerciasis (Gyau-Boakye, 2001).

Creation of a dam across a river results in changes in downstream morphology of riverbed and banks, delta, estuary and coastline due to altered sediment load

(Frihy *et al.*, 1998; Gyau-Boakye, 2001). Much of the impact of dams on downstream habitats is through changes in the sediment load of the river. All rivers carry some sediment as they erode their watershed. When the river is held behind a dam in the reservoir for a period of time, most of the sediment will be trapped in the reservoir, and settle to the bottom, so that water released from the dam will be much clearer, with less sediment than it had once had. For example the Aswan dam in Egypt has caused a big change to the lives of farmers downstream from the dam. Before the construction of Aswan High Dam, the Nile river carried about 124 million tons of sediment to the sea each year, depositing nearly 10 million tons on the flood plain and delta (Shalash, 1982). This washed up soil was extremely fertile, and renewed itself every year at in flood season. But now, since the dam was built the annual flood has been stopped and 98 percent of the sediment remains behind the dam. This has caused all the farmers downstream to have to use fertilizers to grow their crops. The reduction in the sediment deposit from Nile river on the shores of the Mediterranean Sea has also led to serious coastal erosion. This is explained and confirmed by recent hydrological changes in the Nile river regime and missing supply of suspended solids (El-raey *et al.*, 1995; Stanley and Wingerath, 1996). Akosombo dam in Ghana has cut off the supply of sediment to the Volta Estuary leading to coastal erosion across Ghana, Togo and Benin and channel bed scouring downstream of the Akosombo Dam (Gyau-Boakye, 2001). Locating dams in highland areas, where the temperature is cool would help in reducing the breeding of mosquitoes responsible for the transmission of malaria.

2.7.3.2 Environmental constraints

Environmental consequences of hydropower development stem primarily from river fragmentation, stream flow de-watering and downstream hydrological alterations (Anderson *et al.*, 2006b; Pringle *et al.*, 2000). When river water is held in a reservoir for a period, the quality of the water is affected in several ways: the temperature changes, nutrients are removed, forests are flooded and decompose, and there may be colonization of the water by aquatic plants, for example. Each of these effects may have an impact on the life that depends on that water. These effects are generally related to how long the water has remained in the reservoir. Particularly severe effects can occur when a reservoir is first formed, and submerged vegetation and soil decomposes.

Aquatic weeds such as water hyacinth degrades water bodies such as reservoirs, lakes and rivers by covering the surface of the water body as shown in Plate 2.1. This limits the effective utilization of water bodies. Aquatic weeds often choke intake structures for hydropower plants, water supply and irrigation.

Plate 2.1 Water hyacinth continues to frustrate fishing activities at Kusa beach along Lake Victoria (Source: http://www.iec.ac.uk/wifip_samaki_news.html)

Research has shown that the most significant environmental consequence of dams is that they tend to fragment river ecosystems, isolating species populations living up and downstream of the dam and cutting off migrations and other movements (Greathouse *et al*., 2006; Jager and Smith, 2008; Pringle *et al*., 2000). Of special importance, is the blocking of migrating fish travelling up rivers, and then of smolt travelling back down rivers after they have hatched. In either case, the dam or reservoir can be an enormous obstacle, often with great impact on fish populations (Schilt, 2007). In recent years fish passes which are included in dam design have always been a solution to prevent the blocking migrating fish travelling up or downstream of the dam (Lagutov and Lagutov, 2008).

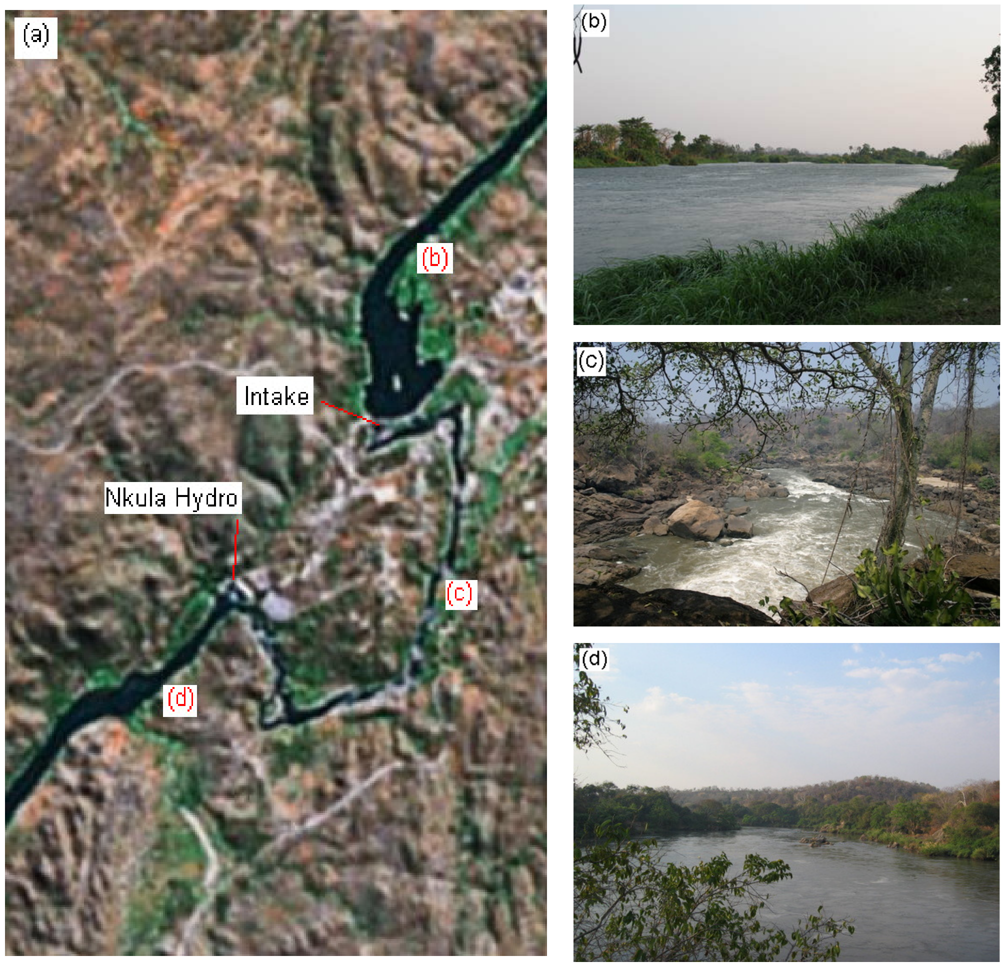


Plate 2.2 (a) Areal view of Nkula hydro intake and power plant on the Shire river in Malawi (b) Upstream view of Nkula intake, (c) dewatered section of the Shire river at Nkula hydro, (d) downstream section of Nkula hydro power plants (Google Earth)

Almost all dams also reduce normal flooding, effectively isolating the river from its floodplain, and eliminating the ecological benefits provided by this flooding. The impacts of these changes are magnified by changes in the flow pattern of rivers downstream that is caused by normal operation of dams (Jager and Smith, 2008; Poff *et al*., 1997; Richter *et al*., 2002). These changes, whether in total stream flow, in seasonal timing, or in short-term, even hourly fluctuations in flows, generate a range of impacts on rivers. This is because the life of rivers is usually tightly linked to the existing flow patterns of rivers. Any disruption of those flows, therefore, is likely to have substantial impacts.

One of the more serious ecological consequences of hydropower development is stream dewatering which is associated with the operation of run-of-river dams. In Malawi all the hydropower plants on the Shire river are run-of-river projects, diverting water from the main river course into the power house. This results in substantial flow reduction between the diversion site and the power house. The best example is the Nkula hydro power plant shown in Plate 2.2. Nkula hydro power plant requires a mean daily flow rate of 170 m^3/sec (GoM, 2003a) which is diverted from the main river course through underground tunnels into the power house. The segment of stream between the diversion site and the power house is often referred to as the de-watered reach and the physical environment of a de-watered reach is dissimilar to that of upstream and downstream areas and characterized by slower water velocities and shallower depths in riffles and pools (Anderson *et al*., 2006a) (Plate 2.2(c)). These physical changes decrease the quality and quantity of habitat for native aquatic biota in the de-watered reach, creating conditions similar to those of a prolonged drought.

Although the effects of dams and their operations extend to all aspects of river ecosystems, dams are increasingly important factors in freshwater systems around the world (Dynesius and Nilsson, 1994; Nilsson *et al*., 2005). Dams provide a major environmental benefit, by reducing the need for other sources of electricity, such as coal- or oil-fired plants that generate greenhouse gases, and therefore contribute positively to the global climate change problem.

2.7.4 Hydropower Simulation

River flow and hydraulic head are the two main factors that dictate the hydropower electricity generation potential. In order to simulate hydropower production from a river or any other water body hydrotechnics are employed. Operation simulation is a process often employed in hydrotechnical development for hydropower in simulating power production from a particular river or any other water body under investigation by considering the varying hydrological conditions (Killingtveit and Saelthun, 1995). The reason for carrying out simulation is that inflows vary through the year and from year to year.

Since hydropower 'raw energy', i.e inflow is not constant and future inflow is not known for certain, the following basic precondition are made in hydropower simulation: the inflow in the future is assumed to have the same statistical properties; mean value and pattern of variation as in an earlier historical observation (Killingtveit and Saelthun, 1995). The use of historical flows in hydropower simulation is currently being challenged by climate change. River flow depends on climate parameter such as precipitation and temperature which are currently being affected by climate change. In view of this there is need to consider climate change in hydropower simulation.

In hydropower assessment the production output in dry seasons is of special interest. Minimum operating flows known as cut-off discharge, usually 30 – 40% of maximum discharge should be considered. Hydropower time series is simulated by the following equation (Killingtveit and Saelthun, 1995):

$$N_i = \frac{g * \rho * \eta * Q_i * (H_G - h_l)}{1000} \qquad 2.14$$

$$E_i = N_i * \Delta t \qquad 2.15$$

where Δt is time step in hours, N_i is electric power (kW), E_i is the electric energy in kWh, g is acceleration due to gravity, ρ is density of water, η is efficiency factor of the machinery (turbines, generators and transformer), Q_i is plant discharge (m^3/s), H_G is gross head (m) and h_l is head loss in tunnels and penstock.

2.7.4.1 Flow Duration Curves

A Flow duration curve provides the proportion of the time (duration) a specific flow is equalled or exceeded. Flow duration curves are used to characterize the flow variability of the catchment. The shape of the flow duration curve has shown to have a strong dependence on catchment characteristics, particularly hydrology (Gustard *et al.*, 1992; Vogel and Fennessey, 1994). For the reliable assessment of hydropower production, flow duration curves are derived. A flow duration curve gives a good indication of the maximum reliable discharge for the plant to be in place with a certain percentage reliability of the time. A typical example of the flow duration curve is shown in Figure 2.21. For example if it is required to generate electricity throughout the year with small variation in the output then flow rate with a high percentage of time exceeded ($T \geq 95\%$) will be selected from the flow duration curve.

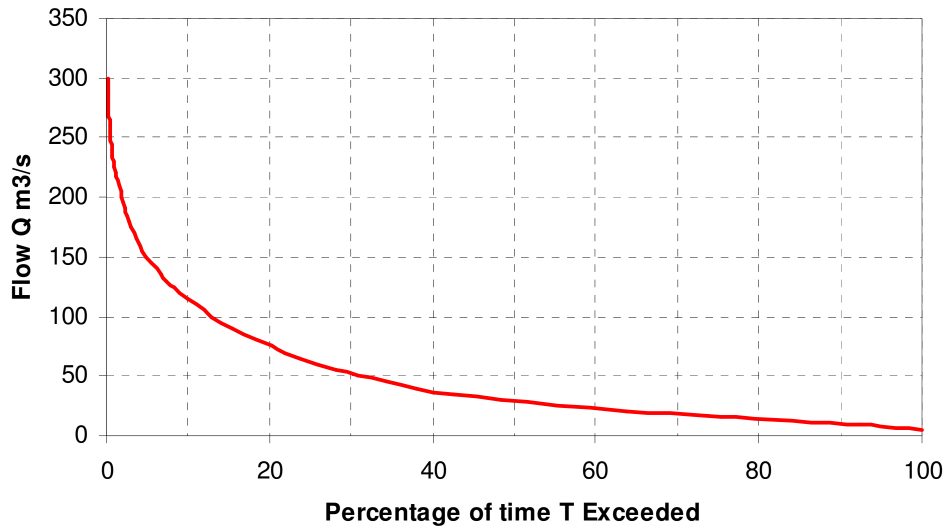


Figure 2.21 Typical South Rukuru river flow duration curve in Malawi indicating flow as a percentage of time exceeded

2.8 WATER USE FOR IRRIGATION

Irrigation is the application of water to soil to supplement deficient rainfall to provide moisture for plant growth. It is the single largest consumptive user of freshwater in the world today. To satisfy the needs of growing populations, irrigated areas have increased rapidly over the last five decades reaching the peak during 1970s and 1980s (Bhattarai *et al.*, 2007; Hussain, 2007). It is estimated that about 20% (Table 2.2) of the world's agricultural land is irrigated at present accounting for 40% of global agricultural production (FAO, 2006). Out of total global irrigated cropland, nearly 100 million hectares is in China and India, which constitutes more than one third of the total irrigated land globally.

During the past 6 decades, irrigated area has expanded by well over 160 percent (Sanmuganathan, 2000). The period 1950 to 1970 was the era of dam construction and development of new irrigation systems. Between 1970 and 1990 the focus was on rehabilitation of the systems and the 1990s the emphasis was on institutional reform (Sanmuganathan, 2000). Thus along with the thrust towards creation of higher irrigation potential, efforts are now directed towards rehabilitation and management of existing projects (Ambast *et al*., 2002). Irrigation activities require major volume of available freshwater in almost all the countries. The irrigated agriculture sector is facing increasing challenges in the face of rapid population growth, decreasing availability of land, and competition for freshwater demand from domestic, industrial, navigational and recreational uses (Ambast *et al*., 2002; Hussain, 2007). Thus the world share of water in the irrigation sector is bound to reduce significantly. This calls for sustainable policies in the development and running of water projects to satisfy all the competing areas.

Table 2.2 Areas equipped for irrigation (Source: FAO. 2006. AQUASTAT database. http://www.fao.org/ag/aquastat)

Region	Area (million hectares)			Irrigated area as percentage of agricultural land		
Year	1980	1990	2003	1980	1990	2003
World	193.022	224.188	277.098	15.8	17.3	17.9
Africa	9.491	11.235	13.37	5.1	5.7	5.9
Asia	132.377	155.009	193.89	28.9	30.5	34
Latin America	12.737	15.525	17.312	9.4	10.9	11.1
Caribbean	1.074	1.269	1.304	16.4	17.9	18.2
North America	21.178	21.618	23.17	8.6	8.8	9.9
Oceania	1.686	2.118	2.844	3.4	4	5.4
Europe	14.479	17.414	25.208	10.3	12.6	8.4

The principal purpose of irrigation development is to enhance agricultural production. In industrialised countries irrigation is seen as contributing to the food production industry while in developing countries like Sub Saharan Africa is seen principally as a tool for social development, poverty alleviation and enhancing food security (Sanmuganathan, 2000). Irrigation is not practised extensively in Sub-Saharan Africa including Malawi although at present Sub-

Saharan African has serious food security problems and this is expected to worsen in the future. High variability in rainfall and limited irrigation infrastructure in Africa calls for development of irrigation to control food shortages the continent is experiencing especially Sub-Saharan Africa.

2.8.1 Benefits of Irrigation

According to Sanmuganathan (2000) irrigation provides the basis for a better and more diversified cropping pattern and growing of high-value crops, and thus facilitates overall improvement in socio-economic conditions of the farming community. Irrigation generates benefits through several process, mechanisms and pathways. Total benefits of irrigation include both direct benefits (accrued to the farming community), and indirect benefits (accrued to wider sectors of the economy) (Bhattarai *et al.*, 2007; Hussain, 2007).

The direct benefits of irrigation are derived from increases in crop yield, increase in cropping pattern and reduction to vulnerability to the seasonality of agricultural production and external shocks (Hussain and Hanjra, 2004). The production of crops under irrigation is substantially higher than that of the same crops under rain fed conditions increasing returns to farmers. High crop production under irrigation makes food available and affordable for the poor. Access to good irrigation enables crop-switching: selecting high yielding and more profitable crops over drought –tolerant crop varieties. This implies a change from subsistence production to market oriented production. Under irrigation crops can be grown throughout the year leading to crop diversification which enables poor and smallholder farmers to spread risk more evenly over the course of the year (Hussain and Hanjra, 2004). Crop diversification is both an income maximization and risk minimization strategy (Hussain, 2007).

Irrigation development increases employment opportunities for the local communities due to the labour intensive nature of irrigation construction and subsequent maintenance, and intensive cultivation brought by irrigation development. Employment related to construction can be considered a one-time impact for labourers for the construction and supply of construction materials while employment related to subsequent maintenance and cultivation continue for the life of the system. Irrigation raises employment by increasing the number of days work per hectare, per crop season and per crop year (Brabben *et al.*, 2004; Hussain *et al.*, 2002). This helps to improve and smooth seasonal troughs in agricultural employment and improve and stabilise wage rates. Employment opportunities may also spill to landless workers who may migrate to irrigated areas to take advantage of the employment opportunities created by irrigation development

The indirect benefits of irrigation are derived from other uses of the irrigation infrastructure, other infrastructure brought in the area to support the irrigation system and other institutions which respond to incentives brought by the irrigation by opening their branches in the area (Magadza, 2006). Further, development of irrigation infrastructure results in supply and provision of other infrastructures. For example, an irrigation infrastructure funding decision influences both government and private sector decision making. Bhattarai *et al*, (2007) confirms that governments tend to allocate more resources and infrastructure facilities to high-potential favoured areas to enhance their political interests. Financial institutions, such as banks, respond to similar incentives and tend to open their branches to these high-potential areas, which in turn may become centre of growth. This sets into motion a process of market integration and technological transformation, which makes modern infrastructure and financial services accessible to the poor. In the case of Malawi, the best examples are Illovo Sugar Plantation along the Shire river in Nchalo and Dwangwa Sugar Plantation in Dwangwa where small towns with modern education, banking, market and health facilities have developed. Irrigation water is also used by the rural communities for a variety of purpose ranging from domestic water supply, fish farming and rural enterprise and industries.

2.8.2 Disadvantages of Irrigation

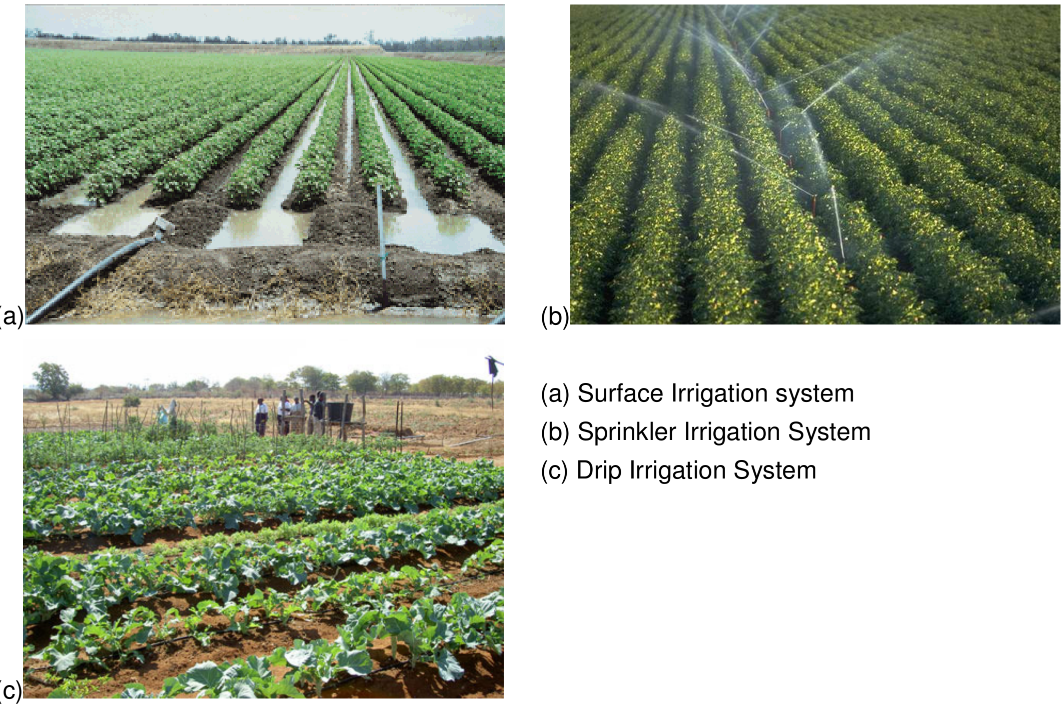
Despite the significant contribution of irrigated agriculture to increasing food production and overall socio-economic development, irrigation has come under increasing criticism over the past decade—for concerns such as social disruptions and environmental changes that are attributed to irrigation development and reservoir construction (FAO, 1997)

Large scale irrigation development coupled with dam development often involves displacement of people from the reservoir area. The scale of impact varies in accordance with size of the development and population density in the area. A survey by the WCD in 2000 reported physical displacement in 68 dams out of the 123 dams surveyed world wide. The most critical issue with displacement is the lack of involvement in decision making process of the people actually displaced when running irrigation schemes. Proponents of large scale irrigation development have often called for compensation and resettlement of the displaced communities (Magadza, 1994; Magadza, 2006). However inadequate compensation and lack of resettlement plans is a major challenge as was the case with Kariba project in Africa (Magadza, 1994). A review of the environmental impact of the Kariba dam by Magadza in 1994 revealed that people displaced by the project were not fully compensated.

Aggravating the health risk is a particular problem associated with irrigation development (Ijumba and Lindsay, 2001). Applying water to drier areas creates favourable environment for vectors and pathogens responsible for the transmission of water borne, water washed and water related diseases such as malaria, cholera, schistosomiasis and diarrhoeas. A number of studies have shown that poor canal and water management system in irrigation areas can increase the risk of water related diseases despite the fact that most irrigation schemes are designed to manage or even eliminate negative health risks and impacts (Hunter *et al*., 1993). Further studies on the health risk associated with irrigation development have revealed a more complex picture in Africa. Increased irrigation development has lead to increased malaria in areas of unstable transmission such as African highlands, but for most areas like Sub Saharan Africa where malaria is stable, irrigation has little impact on the transmission of malaria (Ijumba and Lindsay, 2001).

Increasing environmental problems associated with irrigation development and management has led to a controversial debate on the impacts of irrigation (FAO, 1997). Proponents argue that irrigation has contributed substantially to increased food production and that further expansion in irrigation would be essential to meet increasing food needs of rapidly growing populations (Bhattarai *et al*., 2007; Brabben *et al*., 2004; Hussain, 2007) while opponents argue for contraction in irrigation to reduce its negative effects on the environment, and also for reallocating more water for environmental needs. According to FAO (1997) the environmental impact associated with irrigation is: land degradation in the form of water logging and soil salinisation, degradation of water quality. Salinity is the rise in saline groundwater and the build up of salt in the soil surface in irrigated areas leading to falling crop yields and loss of land from production in a range of environments (Kitamura *et al*., 2006; Thomas and Middleton, 1993). Kitamura *et al.* (2006) showed that salinity is caused by poor irrigation practice by over-irrigation of farm land, inefficient water use, poor drainage, irrigating on unsuitable or 'leaky' soils, allowing water to pond for long periods and allowing seepage from irrigation channels, drains and water storages. This causes the water table to rise, mobilizing salts which have accumulated in the soil layers. This results in reduced crop production. For example in India 42 irrigation systems are reported to be affected by salinity problems reducing crop yields by 30 – 50 percent (Hussan *et al*, 2007). The reduction in crop yields has a wider impact by reducing agricultural contribution to national income as well as labour demand cut back leading to unemployment.

According to Allen (1998) poor irrigation practice also lead to degradation of surface and groundwater quality due to excessive use of agricultural chemicals and fertilizer for crop production. This could threaten the sustainable use of the water resources. Increased use of fertilizer in irrigation fields results in propagation of aquatic weeds. Aquatic weeds find conditions downstream of the irrigated areas and in the irrigation channels favourable for growth and proliferation due to the nutrients available in the return flows. Malawi is currently experiencing the problem of aquatic weeds down stream of the Shire river. Irrigation can adversely impact the quantity and quality of downstream water due to the excessive use of water and pollution upstream from fertilizer and agricultural chemicals (FAO, 1997). This leads to loss of biodiversity and altering the natural environment downstream resulting in adverse impact on the livelihoods of communities that derive a range of benefits from the river system downstream.



(a) (b) (c)

(a) Surface Irrigation system
(b) Sprinkler Irrigation System
(c) Drip Irrigation System

Plate 2.3 Layout of surface, sprinkler and drip irrigation (Google Earth)

2.8.3 Irrigation systems

The major objective of irrigation system management is to maximise crop production per volume of water consumed by the system. Currently there are four basic types of irrigation systems in use in Malawi – surface irrigation, sprinkler irrigation, subsurface and drip irrigation. In Malawi all the four types of irrigation systems are currently in use. The sugar plantations of Nchalo and Dwangwa usually employ surface and sprinkler irrigation system while coffee estates are the major users of drip irrigation system. Surface irrigation system is the method which is very common among smallholder famers in Malawi. Malawi has an estimated 160,900 hectares potential for irrigation development (Frenken and Faurès, 1997). Currently only 28,000 hectares has been developed for irrigation consuming an estimated 13,000 m^3 of water per hectare per year (Frenken and Faurès, 1997).

2.8.3.1 Surface irrigation

This is the oldest irrigation system in which water moves over and across the land by simple gravity flow in order to wet it and to infiltrate into the soil as shown in Plate 2.3(a). Sometimes surface irrigation is called flood irrigation because it involves flooding or near flooding of the cultivated land. According to Frenken (1997), 95 percent of the irrigated area in the world is under surface irrigation system. Surface irrigation systems have advantages over other methods as water application is not affected by windy condition as is the case with sprinkler systems. The other reason is that they are easy to operate and maintain with both skilled and unskilled labour. Low energy cost for pumping water is another advantage associated with surface irrigation systems. Surface irrigation systems allow the leaching of salts from the root zone down to the deeper layers of the soil (Savva and Frenken, 2002). Surface irrigation systems are associated with low irrigation efficiency, normally an average of 60 percent irrigation efficiency indicating that 40 percent of the water applied is lost. Efficient application and management of water is difficult due to spatial and temporal variability of soil characteristic such as infiltration rates and texture.

2.8.3.2 Sprinkler irrigation system

Sprinkler irrigation system is another method of irrigation which simulates rainfall by distributing water over the field by high pressure sprinkler guns. This method will wet the entire ground surface including the crops as shown in Plate 2.3 (b). Water distribution is always affected by wind patterns and velocity in the area. Sprinkler irrigation systems are suitable for most crops except those crops whose leaves are sensitive to prolonged contact with water. The method is not suitable for crops which require ponding such as rice. Sprinkler irrigation systems have higher irrigation efficiency than surface irrigation systems. Normally the average irrigation efficiency is 75 percent (Savva and Frenken, 2002). The major draw back of the system is high energy demand for pumping and pressurising water. In Malawi sprinkler irrigation system was the most popular method at Nchalo sugar estate in the Lower Shire Valley until 2004. However due to high energy cost the method has lost popularity and has since been replaced by surface irrigation system.

2.8.3.3 Drip irrigation

Also known as trickle irrigation, is another type of irrigation system in which water is delivered at or near the root zone of plants, drop by drop without wetting the entire soil surface or volume (Plate 2.3 (c)). This method is considered as the most water-efficient method of irrigation, normally with an average of 90 percent irrigation efficiency, if managed properly, since evaporation and runoff are minimized (Savva and Frenken, 2002). The major set back of the system is high capital cost which is not affordable by local farmers in developing countries. In Malawi the method is normally practised on large coffee estates.

2.8.4 Irrigation water assessment

Water supplied to crop field through different types of irrigation systems is required for the following purposes:

- To meet the crop water requirement defined by FAO irrigation and drainage paper number 56 (Allen *et al*., 1998b) as

  "the depth of water needed to meet the water loss through evaporation or a disease free crop growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment"

- to satisfy losses caused by evaporation from weeds, evaporation from the wet surface of vegetation and saturated soil, evaporation from moist soil, drainage of soil water, seepage, leaks and evaporation from associated reservoirs and water distribution canals.

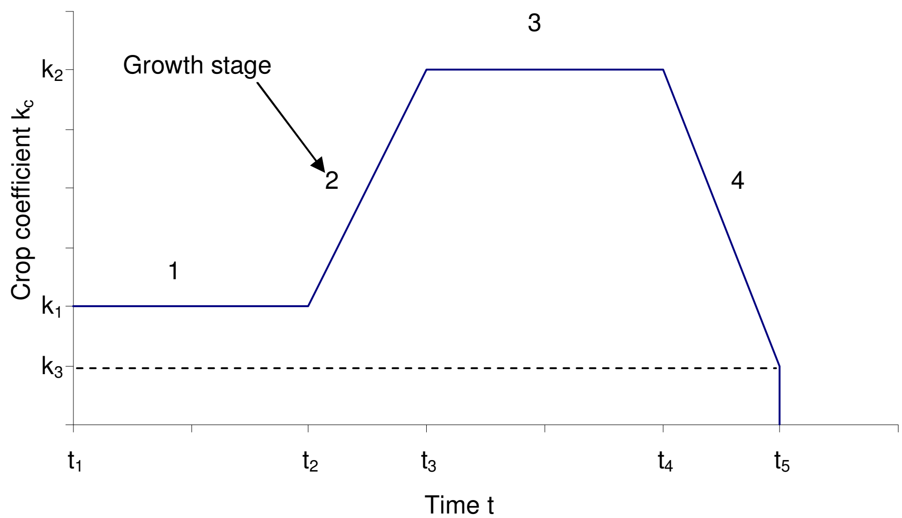
In view of the above irrigation water assessment requires accurate estimation of potential evapotranspiration of the region.

2.8.5 Methods of estimating evapotranspiration

Evapotranspiration (ET), which constitutes an important component of the hydrological cycle, is a process of the result of complex interaction between water and energy fluxes subjected to changing atmospheric, soil and vegetation conditions. In simple terms ET is the combination of evaporation from the soil surface and transpiration from vegetation. Accurate prediction and understanding ET is crucial and essential for many studies such as hydrological water balance, irrigation system design, water resources planning and management. Irrigation management requires accurate assessment of the quantity of water to be supplied to satisfy crop irrigation requirement. The crop irrigation requirement is that portion of the consumptive use, which must be supplied by irrigation (Allen *et al.*, 1998b). The needs vary for different crops and during the periods of growth. Hence irrigation water use is calculated based on reference crop evapotranspiration (ET_o) and crop coefficient to estimate different crop water requirement (ET_c). ET_o is the rate of evapotranspiration from an extensive uniformly covered surface of green grass of uniform height, which is actively growing, completely shading the ground and with adequate water (Allen *et al.*, 1998b). This is essentially the potential evaporation. The potential evaporation of another crop growing under the same conditions as the reference crop is calculated by multiplying the reference crop evaporation ET_o by crop coefficient k_c (Equation 2.16). The values of crop coefficient k_c vary over a range of about $0.2 \leq k_c \leq 1.3$, as shown in Figure 2.22 and vary with the stage of the growth of the crop (Allen *et al.*, 1998b).

$$ET_c = k_c * ET_o \qquad 2.16$$

ET can either be measured with a lysimeter or a water balance approach or estimated from climatological data. It is not always possible to measure ET with a lysimeter because it is a time consuming method and needs carefully planned designed experiment. However lysimeter measurements remain important for the evaluation of ET estimates obtained by more indirect methods (Allen *et al.*, 1998b). This has prompted the wide use of indirect methods for predicting ET based on climatological data. Currently there are several methods in literature available for the estimation of ET based on climate data: empirical methods (Thornthwaite (1948), Blaney and Criddle (1950) and Makkink (1957)) in which derived equations are based on observations; aerodynamic methods (Thornthwaite and Holzman (1942)) in which the physics of the atmospheric processes responsible for ET are evaluated; the energy budget approach (Bowen 1926, Budyko 1956, Penman 1963) which estimates the amount of energy available to cause moisture transfer back to the air; and a combination of the energy budget and aerodynamic methods such as Penman (1948).



Stage	Crop condition
1	Initial stage – less than 10% ground cover.
2	Development stage – from initial stage to attainment of effective full ground cover (70 – 80%).
3	Mid – season stage – from full ground cover to maturation.
4	Late season stage – full maturity and harvest.

Figure 2.22 The relationship between the crop coefficient k_c and the stage of crop growth Source: (Allen *et al.*, 1998b)

The combination method links evaporation dynamics with the flux of net radiation and aerodynamic transport characteristics of a natural surface. Due to wide application of ET data research efforts are still continuing in this area with several studies now concentrating on developing accurate ET estimation methods and increasing the performance of the existing methods. In 1965 Monteith modified the combined method by introducing a surface conductance term that accounted for the response of leaf stomata to its hydrological environment leading to the development of the widely known Penman-Monteith evapotranspiration model (PM) (Monteith, 1973). Jensen *et al.* (1990) tested the performance of 20 different methods against lysimeter measured ET for 11 stations located in different climate zone around the world. The conclusion from his findings was that the Penman-Monteith method was the best method for estimating ET for all climatic conditions (Jensen *et al*., 1990). Further studies (Howell *et al*., 2000; Ventura *et al*., 1999; Wright *et al*., 2000) have shown that PM yields ET estimates which are close to the observed ET values. FAO has adopted and recommended the use of PM as the standard method for estimating ET (Allen *et al*., 1998b). Although many researchers have recommended the use of PM as a standard method for estimating ET its use is limited due to the availability of the input variables (Pereira and Pruitt, 2004). PM equation requires full weather data on solar radiation, wind speed, air temperature, vapour pressure, and humidity. However, all these input variables may not be easily available at a given location. In developing countries such as Malawi in particular, difficulties are often faced in collecting accurate data on all the necessary climatic variables, and this can be a serious handicap in applying the PM equation. Among the inputs needed, temperature data are routinely measured and solar radiation can be estimated with sufficient accuracy. But the other variables are generally measured at only a few locations. In developing countries such as Malawi there are only a few weather stations over an area of hundreds of kilometres. This prompts the use of data from a near by stations which may not be in the same hydro meteorological zone. In view of the above it is necessary to estimate ET accurately where values of some of the potential influencing variables are not available. This involves calibrating different empirical ET equations against the PM ET values to obtain a preferred method and equation parameters for a particular region (Fooladmand and Haghighat, 2007; Pereira and Pruitt, 2004).

2.8.5.1 FAO Penman-Monteith Equation for potential evaporation

The FAO Penman-Monteith is based on the combination of the energy budget and aerodynamic approach. The general formula for the Penman-Monteith equation for calculating of reference evapotranspiration is as follows (Allen *et al.*, 1998):

$$ET_0 = \frac{0.408 * \Delta * (R_n - G) + \gamma * \left(\frac{900}{T + 273}\right) * U_2(e_a - e_d)}{\Delta + \gamma * (1 + 0.34U_2)} \qquad 2.17$$

where ET_o is the reference crop evapotranspiration mm per day, R_n is the net radiation at crop surface (MJm^{-2} per day), G is the soil heat flux (MJm^{-2} per day), T is the average air temperature (^0C), U_2 is the wind speed measured at 2 m height (ms^{-1}), (e_a-e_d) is the vapour pressure deficit (kPa), Δ is the slope of the vapour pressure deficit (kPa $^oC^{-1}$), γ is the psychometric constant ($kPa^{-0}C^{-1}$) which is the ratio of specific heat of moist air at constant pressure to latent heat of vaporization , and 900 is the conversion factor. The equation uses standard monthly mean values of climatological records of solar radiation (sunshine), air temperature, and humidity and wind speed. The actual vapour pressure, e_a, is estimated from the minimum daily temperature, T, using the following equation:

$$e_a = 0.611 * exp\left(\frac{17.27T}{T + 273}\right) \qquad 2.18$$

Solar radiation, R_s is estimated for inland stations from incoming extraterrestrial radiation, R_a, and temperature deficit using the relationship:

$$R_s = \left(0.25 + 0.5\frac{n}{N}\right)R_a \qquad 2.19$$

where $\frac{n}{N}$ is the relative sunshine hours.

2.8.5.2 Hargreaves method for potential evaporation

One of the most popular methods of estimating potential evaporation when climate data are limited is the Hargreaves method. This is a temperature-based method extensively used in cases where availability of weather data is limited and only maximum and minimum temperatures are available (Hargreaves and Samani, 1982). In 1990 Jansen *et al.* evaluated 20 reference ET methods and compared the results against lysimeter measurements at 11 locations around the world. The Hargreaves method ranked highest of all methods that required only air temperature data. In 1998 Allan *et al.* recommended the use of Hargreaves methods in estimating ET values where climate data is limited. The Hargreaves equation tends to overestimate ET in humid regions and underestimate ET in very dry windy regions (Allen *et al*., 1998b; Droogers and Allen, 2002; Samani, 2000). In view of this the method requires calibration before applying it for ET estimation in a particular region (Jensen *et al*., 1997 ; Temesgen *et al*., 1999). The Hargreaves equation (Hargreaves and Samani, 1982) is as follows:

$$ET_0 = 0.0023 * (T_{mean} + 17.8) * (T_{max} - T_{min})^{0.5} * Ra \qquad 2.20$$

where ET_o is in mm per day, 0.0023 is the original coefficient of the Hargreaves equation, T_{mean}, T_{max} and T_{min} are the mean, maximum and minimum temperature in ^{0}C respectively and R_a is extraterrestrial solar radiation $MJm^{-2}d^{-1}$.

2.9 SUMMARY OF KEY ASPECTS

The aim of this Chapter was to review current literature which is relevant to water resources development. Firstly an overview of the current global water resources was presented including the major threats to the world water resources. To ensure sustainable global water resources it is necessary to develop water resources in a sustainable manner taking into account the major threats to the scarce resource. A review was then presented of the general aspects of sustainability as related to water resources development as well as background of sustainable development including general aspects in index formulation.

The Chapter further looked at the impact of climate change on water resources based on current literature. Current methods utilised to relate general circulation model outputs to a particular catchment when assessing the impact of climate on water resources have been reviewed. Then a review of hydrological models which have evolved as tools for translating outputs from climate models into river flows was presented. The merits and demerits of different types of hydrological models have been reviewed. Finally the major uses of water ranging from domestic water supply, energy production and irrigation at global and regional level have been reviewed. This was followed by an overview of the efforts by the international community in addressing global water crisis.

The review in this Chapter was aimed at highlighting the most important and relevant research relating to the subject of sustainable water resources development. Most investigation and modelling of water resources development tends to be based on historical flows with the exclusion of integrated processes within the river basin. Any water infrastructure development within a particular river basin will have an impact on the water resources availability within the basin. The flow pattern will be instantly changed while water quality and the ecosystem will take many years due to other infrastructure development triggered by water resources development. Complication arises when climate change impact is considered in water resources development, as this may have significant effect on river flows and the available water resources. It is therefore necessary to investigate integrated processes of sustainability indicators to help identify viable design alternative that are environmentally and socially acceptable while providing opportunities to meet varying demands within the basin.

The purpose of this thesis is to carry out water resources sustainable development of Malawi with the aim of assessing the impact of climate change on the available water resources in the catchment area of Lake Malawi, the water levels of Lake Malawi as well as the interaction of the Lake Malawi with its main outlet, the Shire river. To that end the following chapters outlines the available water resources data, the impact of climate change on Malawi's water resources and the water balance of Lake Malawi. Finally a water resources index for Central and North Malawi rivers which forms part of the catchment area of Lake Malawi is presented.

CHAPTER 3

HYDROLOGICAL DATA COLLECTION AND ANALYSIS FOR NORTH MALAWI AND LAKE MALAWI-SHIRE RIVER SYSTEM

3.1 INTRODUCTION

The chapter aims to describe the catchment areas of North Malawi and Lake Malawi-Shire river system in terms of hydrology, geology and land use. It also gives a history of the water resources data monitoring in each basin. The chapter outlines the existing hydrological data available within the catchment ranging from rainfall to river flows and also the effect of runoff from highland areas on the water levels of Lake Malawi. The available data is organised in the following categories:

- Daily rainfall, discharge and temperature records which were collected from the Malawi Meteorological Department (MetD) database. MetD has the sole authority for the collection and compilation of climate data in Malawi.
- Population data obtained from National Statistical Office in Malawi. Rainfall and population data were implemented in Geographical Information System (GIS) to obtain a spatial distribution of rainfall and population respectively.
- Discharge data obtained from Ministry of Irrigation and Water-Malawi, Department of Hydrology in Lilongwe.
- Digital Elevation Model (DEM) data set for Malawi and land use for Malawi which were obtained from National Spatial Data Centre in

Malawi. The DEM was implemented in GIS to delineate the catchment areas through the application of HEC GeoHMS, a geospatial stream flow model.

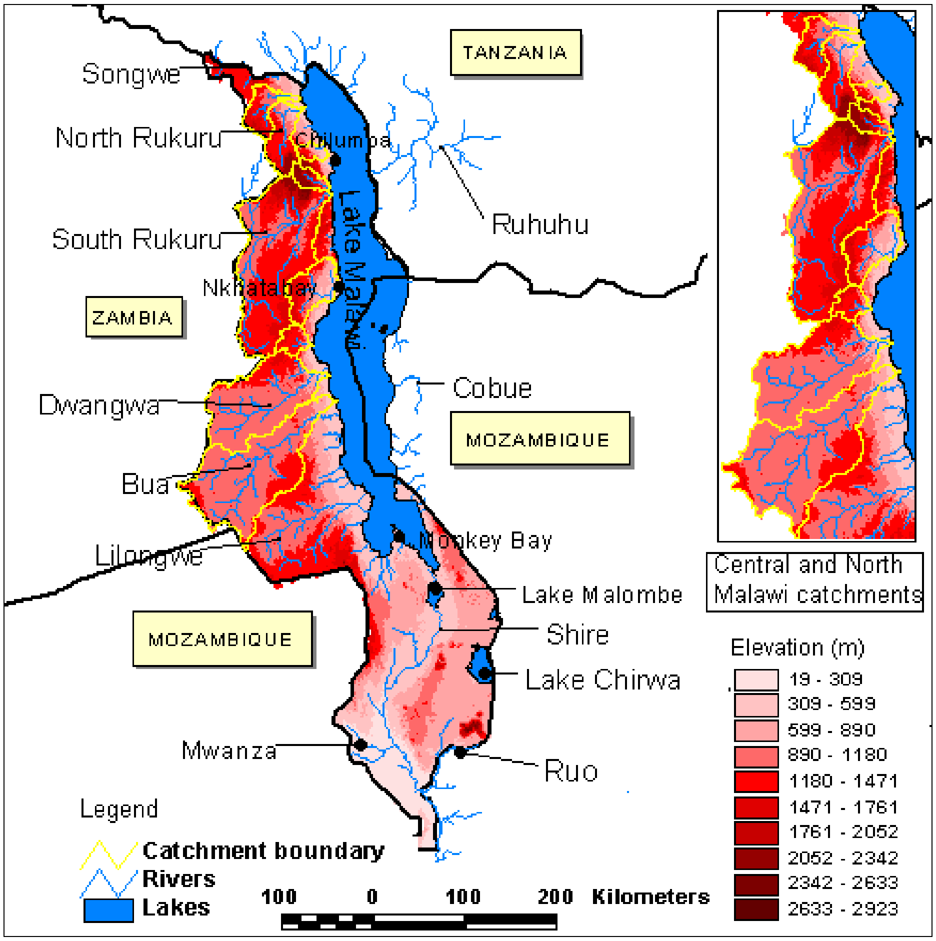


Figure 3.1 Topography of the study area, Malawi (Source of data:- (GoM, 2005))

3.2 CATCHMENT AREAS UNDER THE STUDY

The water resources study at the University of Glasgow focused on main river catchments in the northern part of Malawi namely: Bua, Dwangwa, Dwambazi and South Rukuru, Lake Malawi as the receiving basin of flows from these rivers and the Shire river which is the only outlet from Lake Malawi (Figure 3.1). Malawi's topography can be divided into four zones: Highland, plateau, rift valley escarpment and rift valley plains (Fry *et al.*, 2003). All the rivers in the central and northern region of Malawi originate from the western highland areas. The drainage pattern of these rivers is oriented towards the rift valley passing through the escarpment zone before draining into Lake Malawi on the western side, giving the rift valley a high potential for irrigated cropping and integrated farming. Lake Malawi and the Shire river system lay in the popular rift valley of Malawi. Currently there are no hydro developments on river basins in Central and North Malawi and no thorough feasibility studies have been done to explore the potential of developing these rivers for multipurpose development. The Malawi government has embarked on water resources development under the National Water Development Plan II. Under NWDP II, Malawi aims at exploring potential development of some of the major rivers in the Central and North Malawi for multipurpose dam development as well as optional measures to stabilise the water levels of Lake Malawi (WorldBank, 2007). The current earmarked rivers are Bua and South Rukuru. Therefore a thorough study of the main rivers outlined in this chapter as well as Lake Malawi-Shire river system will be a major input in NWDP II. It is hoped the results will provide a clear direction towards water resources investment strategy for Malawi.

3.2.1 Central and North Malawi river catchments

The main catchment areas in the Central and Northern part of Malawi which have been looked at in this thesis are shown in Figure 3.1. This section gives an outline of each river in terms of water resources data as well as vegetation and land use.

3.2.1.1 Bua river catchment: - Catchment relief, geology, soil and vegetation, climate and water utilisation

Catchment relief, geology, soil and vegetation

The Bua river catchment lies in the central region of Malawi and is referred to as Water Resources Unit (WRU) 5 according to the National Water Resources Master Plan (NWRMP) of Malawi (GoM, 1986). Figure 3.1 and Figure 3.2 shows the location of the basin. Bua basin covers a catchment area of 10,654 km^2 and drains into Lake Malawi.

Over 85 % of the total area of the Bua river basin comprises of plateau, which ranges in elevation between 1000 – 1100 metres above mean sea level (amsl) as shown in Figure 3.2a, Figure 3.3 and Table 3.1. The Mchinji Mountains lying in the southwest of the basin near Zambia border are the only major highlands rising to over 1750 m amsl. The main rivers have well- graded profiles and numerous meanders typical of a very old erosion surface. The Bua escarpment falls steeply towards Lake Malawi in a series of fault controlled steps down into Lake Malawi as shown in the longitudinal profile in Figure 3.3. On entering the lakeshore plain the gradient becomes very gentle and as a result much of the river load is deposited in this area (GoM, 1986).

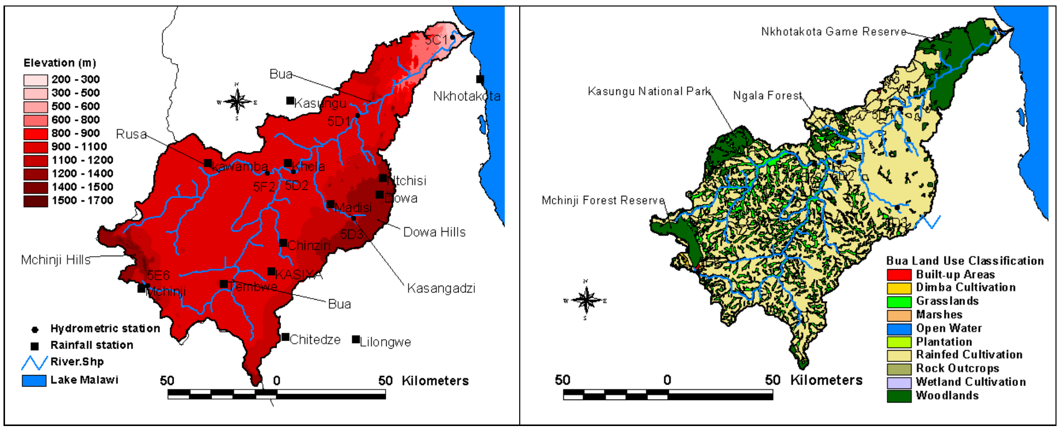


Figure 3.2a Bua topography Figure 3.2b Bua land use

Figure 3.2 Bua river basin showing hydrometric, rainfall stations, topography and land use (Source of data:- (GoM, 2005))

Table 3.1 Bua river elevation area details (Source of data:- (GoM, 2005))

Elevation m	Area km2	Percentage
474 -500	48	0.45
500 -1000	504	4.75
1000 – 1300	9940	93.30
1300 – 1500	140	1.31
Greater than 1500	20	0.91
Total	10654	100.00

The lake shore area has a high potential for irrigation. Currently there is a rice irrigation scheme in this region established by the Chinese Agriculture mission in 1976 (GoM, 1986). The scheme irrigates an area of 300 hectares and managed by Department of Irrigation in the Ministry of Irrigation and Water. The scheme takes water from the Bua river by direct run-of-river abstraction. The main tributaries of Bua river are Namitete, Kasangadzi and Rusa. There is annual flooding in the rainy season and alluvium is spread over the plain in the lower reach.

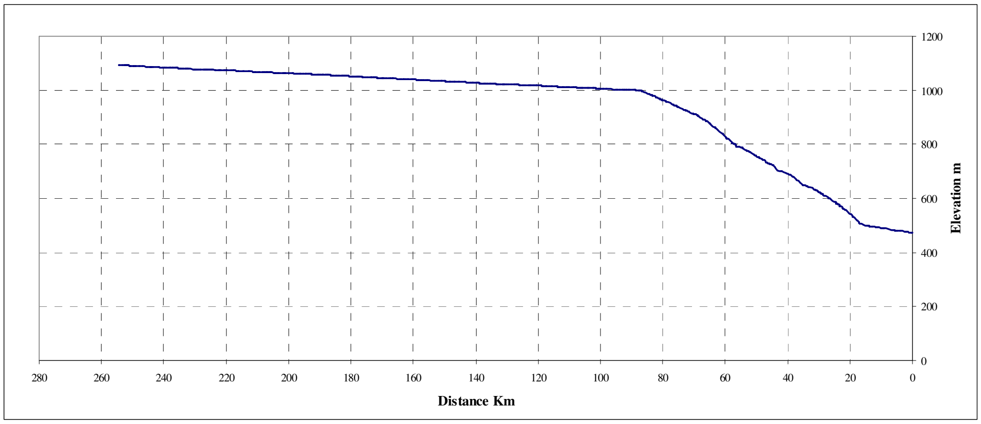


Figure 3.3 Bua river longitudinal profile (Source of data:- (GoM, 2005))

The geological nature of the catchment is of a plateau largely covered by a thick mantle of saprolite obtained by prolonged weathering of igneous rocks. The soils in the plateau area are mostly ferrallitic or ferrallitic with laterites (GoM, 2005). The ferrallitic rocks are yellowish to red with moderately sandy topsoil overlying compact, heavier textured subsoil. In the Lakeshore area, grayish brown low altitude alluvial soils are found.

The original vegetation in the catchment consisted of open woodland of Brachystegia and Julbernadia types. In recent years large-scale developments of tobacco and maize estates and farming by smallholder farmers have brought large areas under rain fed agriculture resulting in deforestation of the natural vegetation as shown in Figure 3.2b. The only woodlands remaining in the basin are protected areas: - Nkhotakota game reserve on the eastern side, Kasungu National Park and Mchinji Forest on the western side and Ngala Forest in the middle reach of the basin.

Climate data monitoring in Bua river basin

The climate is markedly seasonal and rainfall is largely associated with the migration of the Inter-Tropical convergence zone. The rainy season extends from November to March, initially intermittent and becoming more continuous in January. Rainfall data monitoring in Bua river basin started in 1921 by the then

Nyasaland Government when the first rainfall station was opened at Mchinji (GoM, 1986). By 1978, 24 rainfall stations were in operation in the basin. Most of the rainfall stations were installed on Malawi Young Pioneers (MYP) agricultural training base. The closure of MYP led to the closure of most of the rainfall stations within the basin leaving only a few stations at present.

According to the MetD (2009) there is no climate station in the Bua basin which has a complete data set in terms of humidity, temperature, and sunshine hours for use in estimating evaporation by Penman Equation. This makes estimation of evaporation for irrigation water requirement a more difficult task within the basin. The near-by stations which have climate data are Nkhotakota on the Lake Shore, Lilongwe and Chitedze lying south of the basin on the plateau area. Climate records from these stations have been used to estimate potential evaporation (PET) and calibration of temperature based method of PET for use within the basin.

Hydrometric network within Bua basin

Hydrological observations in Bua river started in 1953 with the opening of three hydrometric stations and later additional stations were set up (GoM, 1986). Locations of the hydrometric stations are marked in Figure 3.2(a). The main station in the basin is 5C1 at S53 Road Bridge. The station was opened in October 1956. This is an important station as it provides a significant portion of Lake Malawi inflow and its drainage area is 10654 km^2.

Existing utilization of surface water within Bua basin

The main uses of water in Bua river basin are irrigation and water supply. According to the National Water Resource Data base the total committed abstractions of surface water in the Bua basin are 93,991.45 m^3/day. Irrigation is the major consumptive use of surface water within Bua river basin withdrawing over 91,492 m^3/day. The main abstraction for irrigation is the Bua irrigation scheme which is in the delta area south of the Bua river near Lake Malawi. The scheme currently draws 61,344 m^3/day. All other irrigation users of water are estates growing tobacco and maize. Most of these require water during the dry season or during the early part of the rainfall season. No proper records are available for the water use from Tobacco and Maize estates and most of them have no water license although they use water on the Estates. The main users of domestic water supply within the basin are the urban water supply schemes under Central Region Water Board (CRWB). CRWB is responsible for water supply to rural town centres with a licensed abstraction value of 5600 m^3/day (NSOM, 2006).

3.2.1.2 Dwangwa river catchment: - Catchment relief, geology, soil and vegetation, climate and water utilisation

The Dwangwa river is designated as Water Resources Unit (WRU) 6 according to the National Water Resources Master Plan (NWRMP) of Malawi and is situated in the central part of Malawi as shown in Figure 3.1 and Figure 3.4. The basin covers a catchment area of 7768 km^2 and drains into Lake Malawi (GoM, 1986).

Dwangwa river catchment relief, geology, soil and vegetation

A major part of Dwangwa river basin lies between 500 and 1500 metres above mean sea level as shown in Figure 3.4 and Figure 3.5. The east and central part of the basin comprises the Kasungu plain which is gently undulating with altitudes between 975 and 1300 m above sea level. The Dwangwa river passes through the Nkhotakota lakeshore lowland before flowing into Lake Malawi. Natural vegetation in most of the basin is the Braschystegia – Jilbernadia woodland while grassland is available in depression (dambo) areas (GoM, 2005). In high altitude areas the vegetation is characterized by open grassland interspersed with relatively small patches of evergreen forest. Soils within the basin are mainly ferrallic and lithosols (GoM, 2005). Dwangwa land use can be categorized into two main parts: Rain fed cultivation and protected reserves (Figure 3.4). Kasungu National Park lies almost wholly in the basin on the western side and Nkhotakota Game Reserve on the eastern side. The middle reach of Dwangwa river basin has recently come under extensive tobacco farming both in the estate and smallholders sector. This has led to deforestation in the middle reach of the basin. The Dwangwa delta area, a large swamp, has a sugar plantation which depends on Dwangwa river for irrigation water.

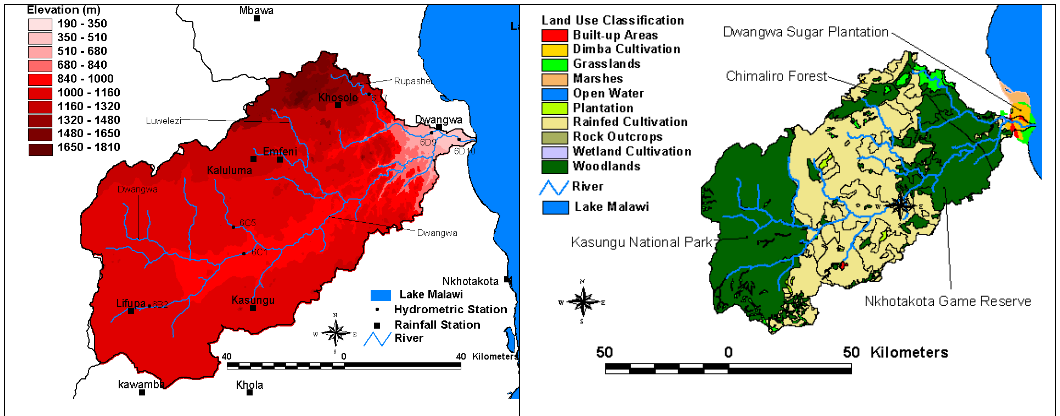


Figure 3.4(a)	Figure 3.4(b)

Figure 3.4 Dwangwa river basin showing hydrometric and rainfall stations, topography and land use (Source of data:- (GoM, 2005))

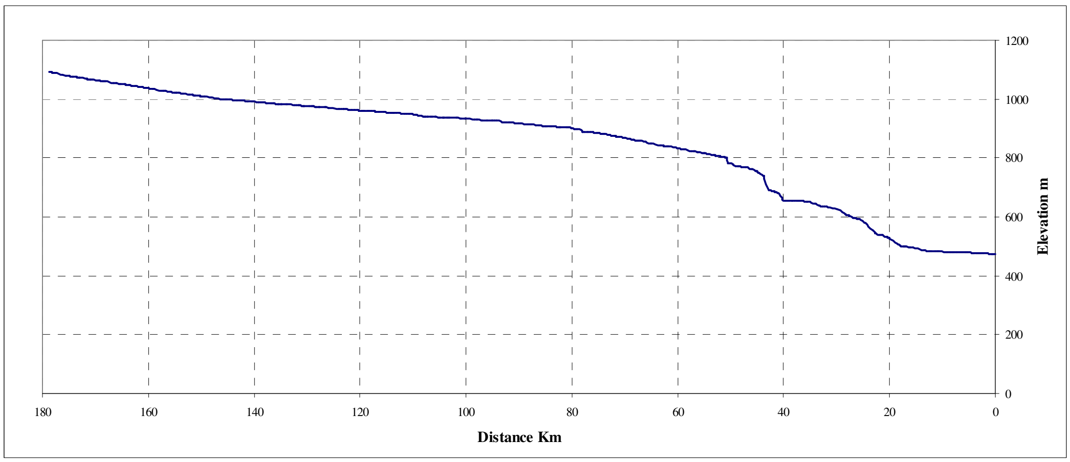


Figure 3.5 Dwangwa river longitudinal profile (Source of data:- (GoM, 2005))

Rainfall data monitoring in Dwangwa River basin

Rainfall data monitoring in Dwangwa river basin started in 1925 when the first rain gauge was installed at Kasungu district headquarters. By 1979 Dwangwa river basin had 18 rainfall stations. In recent years the number of stations has dropped from 18 to only 3 rainfall stations in 1990 (Kasungu, Lifupa and Dwangwa) and currently only Kasungu station has up-to-date records (MetD, 2009). From the analysis of rainfall records it was noted that Dwangwa river basin, except for the escarpment zone and lakeshore area, receives low rainfall. The rainfall pattern in the basin increases from west to east. Similar to Bua river, the basin does not have any climate station with complete records on sunshine hours, humidity and wind speed.

Hydrometric network within Dwangwa basin

Hydrometric data collection in Dwangwa river basin started in 1953 when a river gauging station at Kwengwele 6C1 on the Dwangwa river was set up. By 1971 the network was enlarged and altogether 11 stations were installed (GoM, 1986). However due to lack of funds and manpower from the Ministry of Water Development to provide maintenance of the network only a few stations have up-to-date data. Most of the stations have been abandoned and the main remaining station with up-to-date available data is S53 Road Bridge (6D10) at Dwangwa shown in Figure 3.4(a) (GoM, 1986). The station was opened in 1968 in the name of 6D4 and has been run mainly by the Dwangwa Sugar Corporation now known as Illovo Sugar Group. This is an important station as it provides lake inflows as well as the amount of water for irrigation on Dwangwa Sugar Plantation. The station has gone through a number of changes. In 1970 a water level recorder was installed. The recorder was replaced with a new one in March 1971 due to bed shifts which used to occur every year (GoM, 1986). In 1977 the construction of new head works led to the change in the rating curves of the station. In June 1980 the station 6D4 was replaced by station 6D10 on the downstream side of the S53 road bridge (GoM, 1986).

Existing utilization of surface water within Dwangwa river basin

The total licensed abstraction of surface water in the Dwangwa basin are 0.68 million m^3 per day. The main uses of water in Dwangwa river basin are irrigation and water supply. The main user of surface water in the basin is the Illovo Sugar Group which has a licensed use of 408,000 m^3 per day from the Dwangwa river and 184,000 m^3 per day from Lake Malawi for 6,000 hectares of sugar cane irrigation in the Dwangwa delta. Industrial use at Illovo Sugar Refinery and Ethanol Plant at Dwangwa comes next with 25,500 m^3 per day. Water supply for domestic use accounts for the remaining 6,000 m^3 per day (GoM, 1998). The main users of water supply are the urban water schemes of Kasungu and Dwangwa.

3.2.1.3 South Rukuru and North Rumphi river catchment:- Catchment relief, geology, soil and vegetation, climate and water utilisation

The South Rukuru river is part of Water Resources Unit (WRU) 7 according to the National Water Resources Master Plan (NWRMP) of Malawi (GoM, 1986). WRU 7 is the largest water resources area in Malawi draining directly into Lake Malawi covering an area of 12705 km^2 of which the South Rukuru river alone drains 11993 km^3 (GoM, 1986). The South Rukuru originates from the Viphya Mountains and drains into Lake Malawi as shown in Figure 3.1 and Figure 3.6. The main tributaries are Kasitu river, Runyina river, Rumphi river and Mzimba river. The North Rumphi river which forms part of the WRU 7 is a separate river basin with a catchment area of 712 km^2. The North Rumphi river originates from the eastern side of the Nyika Plateau and drains into Lake Malawi. The North Rumphi river catchment is almost uninhabited.

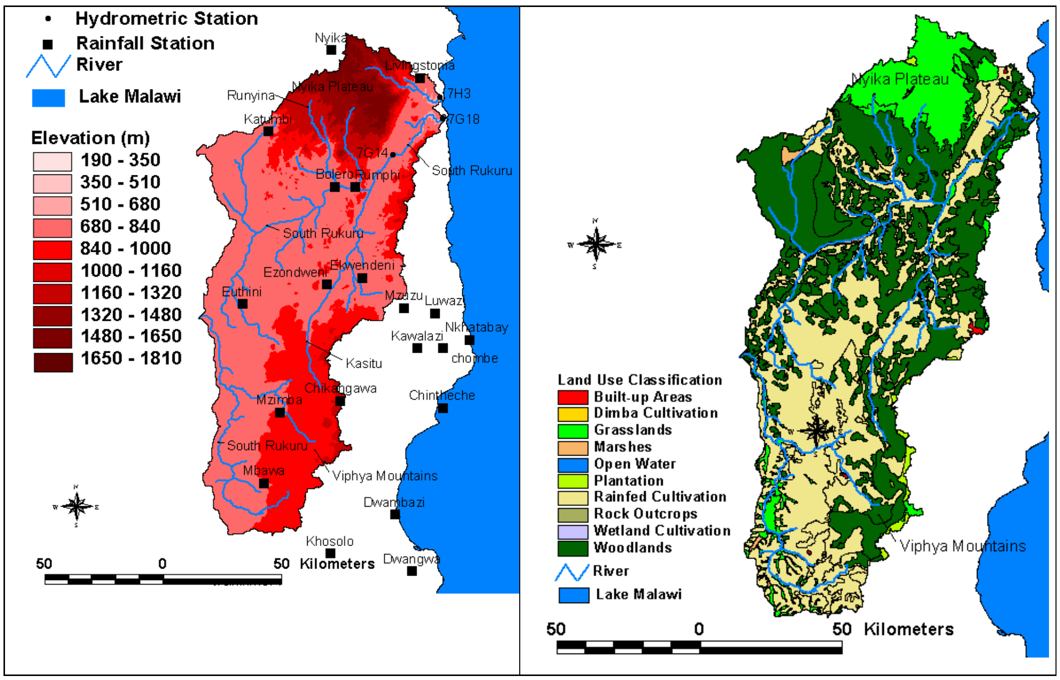


Figure 3.6a Figure 3.6b

Figure 3.6 South Rukuru and North Rumphi river basin showing hydrometric and rainfall stations, topography and land use (Source of data:- (GoM, 2005))

South Rukuru river catchment relief, geology, soil and vegetation

The South Rukuru has a varied relief which can be divided into a number of natural regions. The southern part of the basin lies between 1070 and 1830 m above sea level has flat plains and with broad dambo and swamps Figure 3.6. On the eastern side of the basin lies the Viphya Mountains which is the source of the main tributaries such as Mzimba and Kasitu. The middle reach of the basin which lies between 1000 and 1100 m above sea level contains Vwaza marsh and Nkhamanga plain with scattered hills. Lying in the northern part of the basin is the Nyika Plateau (2000 – 2600 m amsl) where Runyina and Rumphi rivers originate. The Nyika plateau is a protected reserve which has maintained its natural fauna and flora. From the confluence with Rumphi river the South Rukuru river passes through the Rukuru-Kasitu valley. Beyond Kasitu valley the river passes through a meandering gorge over a series of rapids before discharging into Lake Malawi.

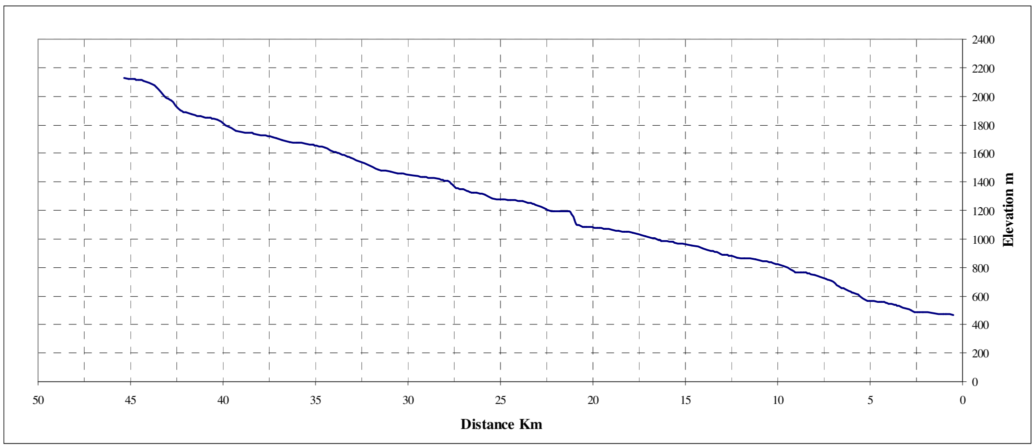


Figure 3.7 North Rumphi river longitudinal profile (Source of data:- (GoM, 2005))

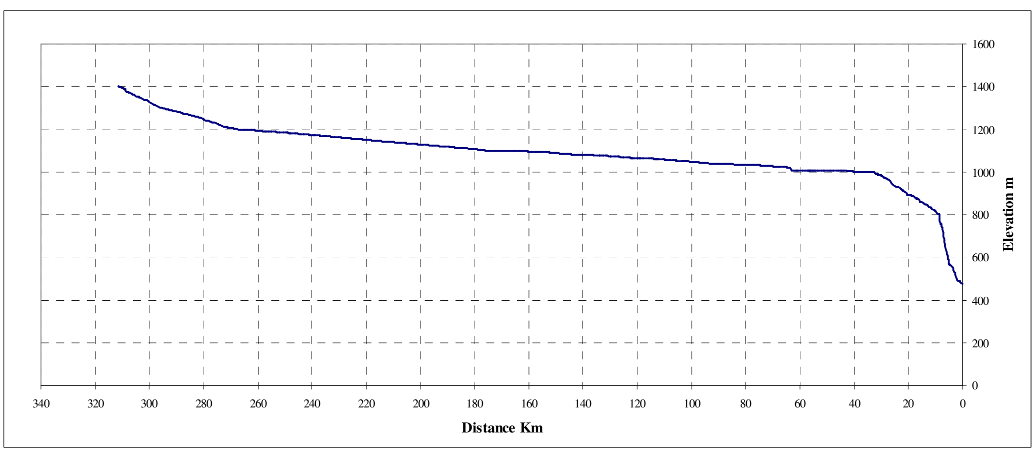


Figure 3.8 South Rukuru river longitudinal profile (Source of data:- (GoM, 2005))

The geological nature of the WRU 7 is made up of igneous and metamorphic rocks (GoM, 2005). The Nyika Plateau and parts of Viphya mountains have granite, while the rest of the low plateau area consists of schists, quartzites, gneisses and granulites. The soils in the upper and south Rukuru valley are generally ferrallitic with ferrisols and lithosols on the low hill and slopes. Humic ferralitic soils are mostly found on high altitude areas of Viphya Mountains and Nyika plateau. The Vwaza marshes have hydromorphic and ferralitic soils (GoM, 2005).

Vegetation in major parts of the catchment consists of open woodland of Brachystegia and Julbernadia types. The highland areas of Nyika and Viphya mountains have rolling grassland and scrub-lands covering most of the area. WRU 7 is one of the basin which has much of its catchment area covered with woodlands as shown in Figure 3.6b. However in recent years large-scale developments of tobacco and maize estates and farming by smallholders have brought large areas in the south west part of the basin under rain fed agriculture resulting in deforestation of the natural vegetation as shown in Figure 3.6b.

Rainfall data monitoring in WRU 7

According to the MetD (2009), the South Rukuru and North Rumphi river basin had as many as 90 rainfall stations. Rainfall data monitoring in the basin started in 1921 when the first rain gauge was installed at Mzimba district head quarters. 10 stations were set up prior to 1950 and 29 stations were set up between 1951 to 1960, while the remaining stations were established after 1960. Most of these stations do not have a continuous record of data and some of the stations have been abandoned. Currently there are only a few stations with continuous climate data as shown in Figure 3.6a. WRU 7 receives low rainfall except for the highland areas of Viphya and Nyika Plateau. The upper and middle part of the basin receives 800 - 900 mm of rainfall annually. The Vwaza marsh receives lower rainfall in the range of 650 – 700 mm, while the highland areas receive annual rainfall of 1200 to 1600 mm. The only climate station available in the basin with full complete record of climate data is Mzuzu station on the eastern side of the basin shown in Figure 3.6(a).

Hydrometric network within WRU 7 basin

Hydrometric network in WRU 7 started in 1953 when three gauging stations, one at Zombwe on Lunyangwa river, Edundu on the Kasitu river and Phoka court on the North Rumphi were set up. In later years the network expanded progressively up to 27 stations. However some of the stations have been closed and only few stations have up-to-date records. Of the current stations 7G18 and

7G14 on South Rukuru river, 7H3 on North Rumphi, 7F1 on Runyina, and 7F2 on Rumphi river have up-to-date flow records (Figure 3.6). Station 7G14 at Phwezi is the oldest important station on South Rukuru river and it drains a catchment area of 11800 km^2. In 1977 the station was upgraded by installing an autographic recorder. In 1985 another station was set up at Mlowe bridge (7G18). Station 7G18 provides lake inflows from South Rukuru river.

Existing utilization of surface water within South Rukuru river basin

The total licensed abstraction of surface water in the basin are 0.42 million m^3 per day. The main uses of water in South Rukuru river basin are irrigation and water supply. Irrigation accounts for 17000 m^3 per day, domestic water supply, industrial and other uses accounts for 16000 m^3 per day. Irrigation water is mainly used by estate owners or private farmers for irrigating tobacco nurseries before the onset of rains. A major share of the licensed abstractions for domestic water supply goes to serve the three urban centres in the basin namely Mzuzu, Mzimba and Rumphi accounting for a total of 7000 m^3 per day. The remainder is licensed to several rural piped water supply schemes within the basin.

3.2.1.4 North Rukuru river basin: - Catchment relief, geology, soil and vegetation, climate and water utilisation

The North Rukuru river is called Water Resources Unit (WRU) 8 according to the National Water Resources Master Plan (NWRMP) of Malawi (GoM, 1986). North Rukuru river drains directly into Lake Malawi covering an area of 2091 km^2.

North Rukuru river catchment relief, geology, soil and vegetation

North Rukuru river originates from Nyika Plateau (2400 m high) and flows through thinly populated forest areas till it opens out into broad valleys with a general elevation ranging 1000 – 1400 m amsl. The river then passes through forested and mostly uninhabited areas and drops down in elevation from 1000 m amsl to 500 m amsl before flowing through the lakeshore area lying between 450 – 500 amsl as shown in the longitudinal profile in Figure 3.10 and Figure 3.9(b).

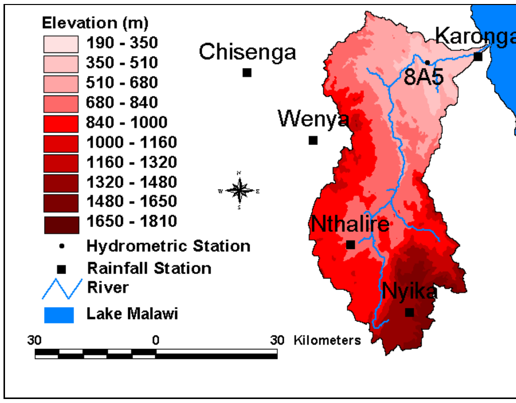


Figure 3.9a

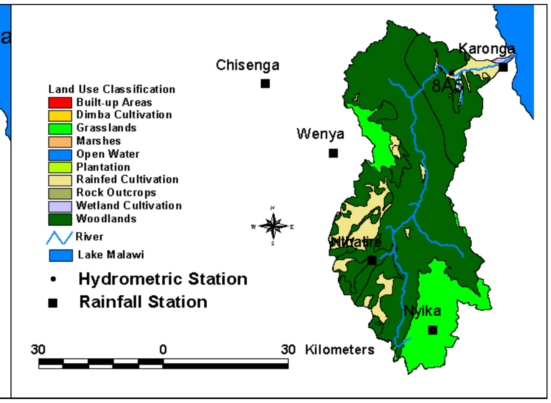


Figure 3.9b

Figure 3.9 North Rukuru river basin showing hydrometric and rainfall stations, topography and land use (Source of data:- (GoM, 2005)).

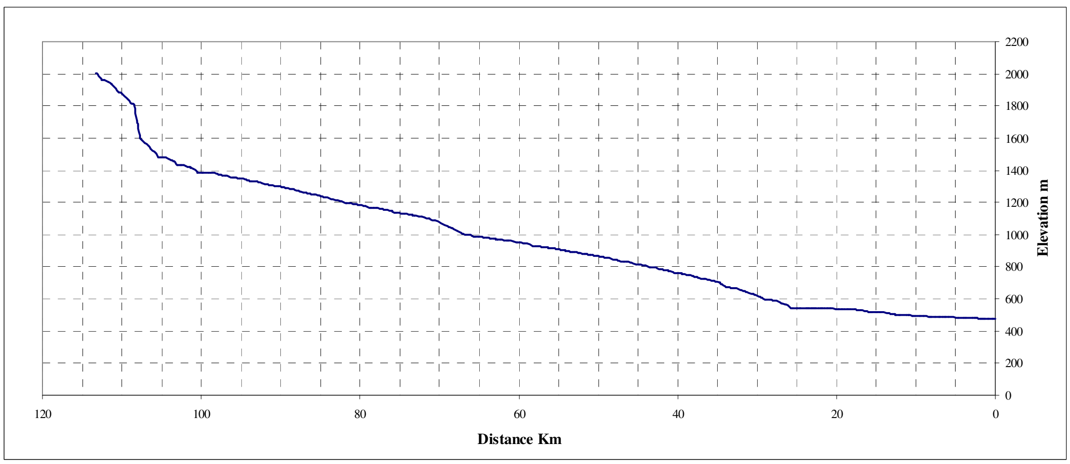


Figure 3.10 North Rukuru river longitudinal profile (Source of data:- (GoM, 2005)).

The geological nature of the basin is made up of igneous rocks. The Nyika Plateau is made up of granite, while the rest of the low plateau area consists of schists, quartzites, gneisses and granulites. The lakeshore area is composed of alluvium. The soils in the basin are generally ferallitic with ferrisols and lithosols except for the lakeshore area which has alluvial soils (GoM, 2005). WRU 8 is one of the basin which has much of its catchment area covered with open woodlands of Brachystegia as shown in Figure 3.9b. The Nyika plateau and Wenya has rolling grassland and scrub-lands (Figure 3.9b). A small portion of the catchment is under rainfed agriculture on the entry into Lake Malawi and on the western side of the basin leaving the rest of the basin with its natural vegetation.

Rainfall data monitoring in WRU 8

According to the MetD (2009) the North Rukuru river basin had a network of 6 rainfall stations. Rainfall data monitoring in the basin started in 1953 when the first rain gauge was installed at Nyika Plateau. Currently the only stations with continuous climate data is Karonga rain station (MetD, 2009). The annual rainfall record of the basin is less than 900 mm.

Hydrometric network within North Rukuru basin

Hydrometric network in WRU 8 started in 1952 when Mwakenja station on North Rukuru were set up. By 1979 the network had expanded to 6 stations. However all the stations except Mwakimeme (8A5) station shown in Figure 3.9(a) have been closed due to difficult in accessibility to the sites. North Rukuru Mwakimeme 8A5 station was opened in 1968 and it covers a catchment area of 1860 km^2.

Existing utilization of surface water within North Rukuru basin

The total licensed abstractions of surface water in the basin are 900 m^3 per day. The main users of water in North Rukuru river basin are Karonga water supply and Nthalire rural water supply shown in Figure 3.9.

3.2.1.5 Lufira river basin: - Catchment relief, geology, soil and vegetation, climate and water utilisation

Lufira is part of Water Resources Unit (WRU) 9 according to the National Water Resources Master Plan (NWRMP). WRU 9 is composed of Lufira and Songwe rivers. Lufira river has a catchment area of 1890 km^2.

Lufira river catchment relief, geology, soil and vegetation

Lufira river passes through forested uninhabited areas and drops down in elevation from 1400 masl to 500 m amsl before flowing through the lakeshore area lying between 450 – 500 m amsl. The geological nature of the basin is made up of sedimentary rocks of quartzite while the lake shore area has alluvial soils (GoM, 2005). The major part of Lufira catchment area is covered with open woodlands of Brachystegia as shown in Figure 3.11b. Open grassland and scrub-lands exist in the south west plateau area of the basin while the North

West part of the basin is under rain fed agriculture. A small portion of the catchment is under rain fed agriculture on the entry into Lake Malawi and on the western side of the basin leaving the rest of the basin with its natural vegetation.

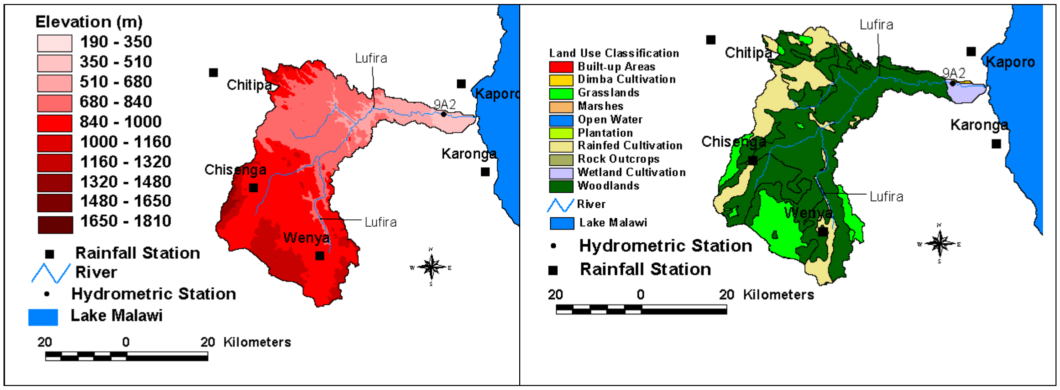


Figure 3.11a Figure 3.11b

Figure 3.11 Lufira river basin showing hydrometric and rainfall stations, topography and land use (Source of data:- (GoM, 2005)).

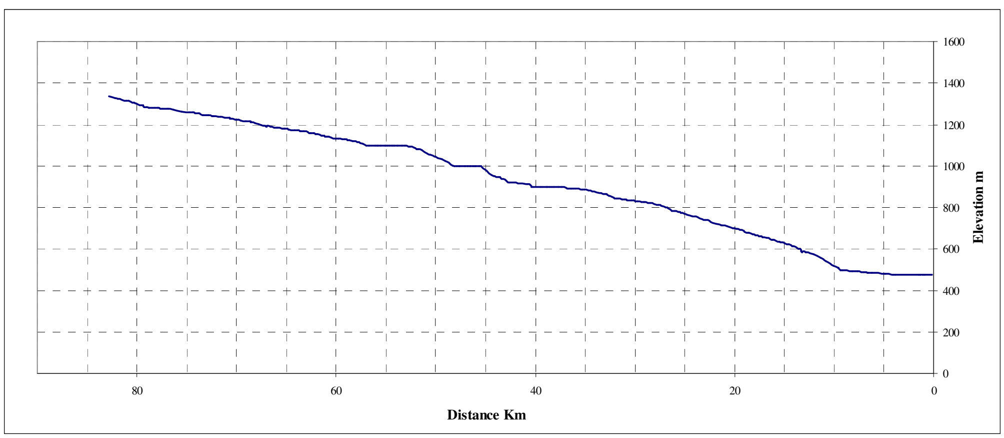


Figure 3.12 Lufira river longitudinal profile (Source of data:- (GoM, 2005)).

Rainfall data monitoring in Lufira river basin

According to the MetD the Lufira river basin had a network of 8 rainfall stations. Rainfall data monitoring in the basin started in 1948 when the first rain gauge was installed at Chisenga. As of now only two stations have sparse data, Chisenga and Wenya shown in Figure 3.11(a). The only near by climate station with continuous climate data is Karonga rain station as shown in Figure 3.11. . The annual rainfall record of the basin ranges between 850 mm to 1000 mm.

Hydrometric network within Lufira basin

Hydrometric network in Lufira started in 1953 when Ngerenge 9A2 station on Lufira river was set up. By 1979 the network had expanded to 8 stations. However all the stations except 9A2 have been closed due to lack of funds for maintenance of equipment. The Ngerenge 9A2 station shown in Figure 3.11 drains a catchment area of 1410 km^2. In 1958 gauges were removed to a new site about 200 m upstream of the original site because the channel control was unstable. The station was washed away by the1961 floods. The station was reopened in 1962 another 500 metres upstream of the original position where it remained until 1975 when the Lufira Irrigation Scheme was constructed. The present site was reopened in November 1976, 1500 m upstream of the original site and it is equipped with an autographic recorder (GoM, 1986).

Existing utilization of surface water within Lufira basin

The total licensed abstractions of surface water in the basin are 102000 m^3 per day. The main users of water in Lufira river basin are the Lufira Rice Scheme which has a licensed use of 98000 m^3 per day. The remaining 4000 m^3 per day is for rural domestic water supply within the basin

3.2.1.6 Luweya and Dwambazi river basins:- Catchment relief, geology, soil and vegetation, climate and water utilisation

Luweya and Dwambazi are the major rivers in water resources unit 14 known as the Nkhatabay lakeshore basin (GoM, 1986). WRU 14 drains a catchment area of 5458 km^2 of which Dwambazi covers 1770 km^2 and Luweya covers 2346 km^2. The area has a number of tea estates and one small holder rice scheme (GoM, 1986).

Luweya and Dwambazi catchment relief, geology, soil and vegetation

The Dwambazi river originates from Viphya Mountains and passes through forested areas through a series of dissected gorges draining into Lake Malawi. The upper reach of the river drops in elevation from 1400 to 1200 m and the middle reach elevation ranges from 1200 to 600 m then the lakeshore 600 to 474 as shown in Figure 3.13 and the longitudinal profile in Figure 3.14. The basin normally experience high flows during the rain season which results in flooding of the lake shore area rendering the S58 bridge on Dwambazi river impassable during rain season. Luweya river with its main tributary Limphasa passes through forested area and drains into Lake Malawi. Luweya river profile varies between 474 to 1000 m amsl with a gentle slope as shown in Figure 3.15 and Figure 3.16.

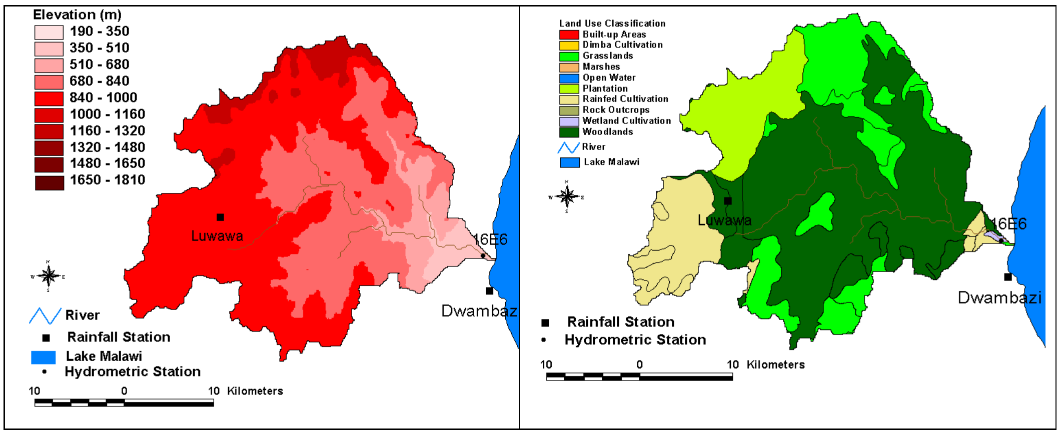


Figure 3.13a Figure 3.13b

Figure 3.13 Dwambazi river basin showing hydrometric and rainfall stations, topography and land use (Source of data:- (GoM, 2005)).

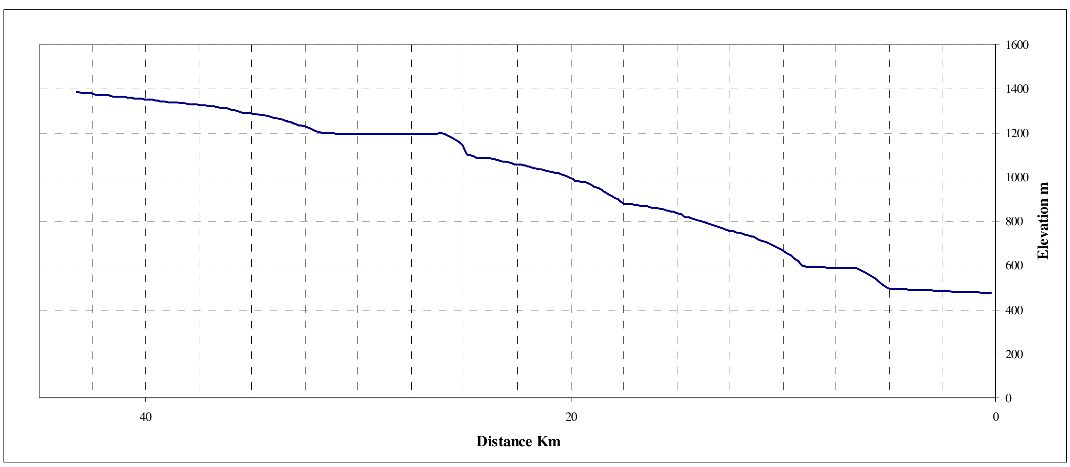


Figure 3.14 Dwambazi river longitudinal profile (Source of data:- (GoM, 2005)).

The highland areas of the two river basins have soils grouped under Ferrisols and lithosols (GoM, 2005). Ferrisol soils are red soils of uniform profile with pH value between 4.0 and 5.0 and develop in areas with annual rainfall exceeding 1200 mm. Lithosols are stony and often shallow soils on steep slopes. These soils are generally poor but are cultivated extensively for groundnuts and maize especially in the western part of Dwambazi river basin (GoM, 2005). The lake shore area of the two river basin have hydrophomic soils which are seasonally water logged forming the dambo soils.

Natural woodland forms the major part of Dwambazi and Luweya river basin natural vegetation supplemented by forest plantation. A small portion of the catchment is under rain fed agriculture on the entry into Lake Malawi in case of Luweya and on the western highland areas in the case of Dwambazi.

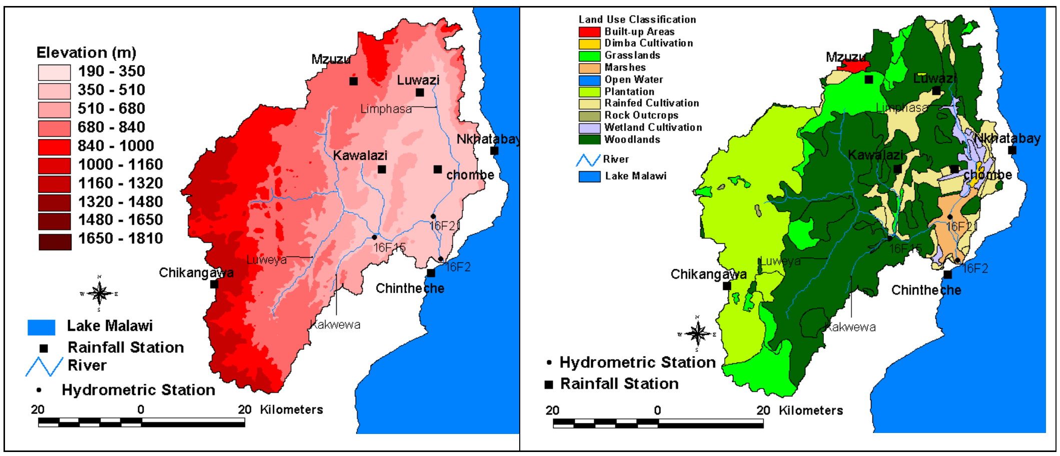


Figure 3.15a Figure 3.15b

Figure 3.15 Luweya river basin showing hydrometric and rainfall stations, topography and land use (Source of data:- (GoM, 2005)).

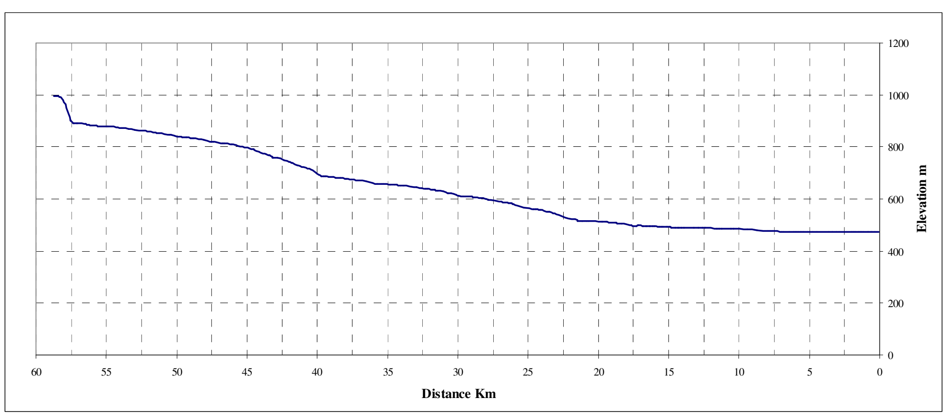


Figure 3.16 Luweya river longitudinal profile (Source of data:- (GoM, 2005)).

Rainfall data monitoring in WRU 16

According to the MetD (2009) WRU 16 had a network of 36 rainfall stations. Rainfall data monitoring in the basin started in 1905 when the first rain gauge was installed at Chintheche by missionary settlers. Location of the different climate stations within the basin area shown in Figure 3.15. As of now only two stations have sparse data, Nkhatabay and Chintheche. The only near by climate station with continuous climate data is Nkhatabay rain station. The annual rainfall record of the basin exceeds 1200 mm.

Hydrometric network within Dwambazi and Luweya

Hydrometric network in WRU 16 started in 1951 when Zayuka station on Luweya river was set up. By 1981 the network had expanded to 10 stations. However all the stations except 16E2 on Dwambazi and 16F2 on Luweya have been closed due to lack of funds for maintenance of equipment. Dwambazi 16E2 station drains a catchment area of 810 km^2 while Luweya station drains a catchment area of 2346 km^2. The two stations are major important stations within the basin as they provide lake inflows.

Existing utilization of surface water

The total licensed abstractions of surface water in the basin are 95000 m^3 per day and irrigation accounts for 90000 m^3 per day. The main user of water in WRU 16 river basin is the Limphasa Rice Scheme which has a licensed use of 73000 m^3 per day. The other users grow tea, rubber and other crops for which supplementary irrigation is required.

Section 3.2.1 has reviewed the catchment relief and vegetation of the Central and North Malawi river basins which forms 39 percent of Lake Malawi catchment area. The review has shown that hydrological data monitoring is a major problem in these rivers since only a few climate stations as well as hydrometric stations are available within the area. Some of the river basins do not have even a single climate station (for example Dwambazi and Lufira). Rainfall and evaporation estimates from such basins have always been based on near-by stations.

The review also looked at existing water utilisation as well as land use of the catchment areas. It has been noted that large scale development of tobacco and maize estates and farming by small holder farmers have brought large areas in the basin under rain fed agriculture resulting in deforestation of the natural vegetation. The worst hit are Bua river, South Rukuru and Dwangwa river basin. In view of this sustainable water resources development should also take into consideration land use pattern of river basin in addressing water related problems. All the catchment areas reviewed in section 3.2.1 drains into Lake Malawi. The following section is a review of the water levels of Lake Malawi as well as efforts by the Malawi government in maintaining high water levels in the lake.

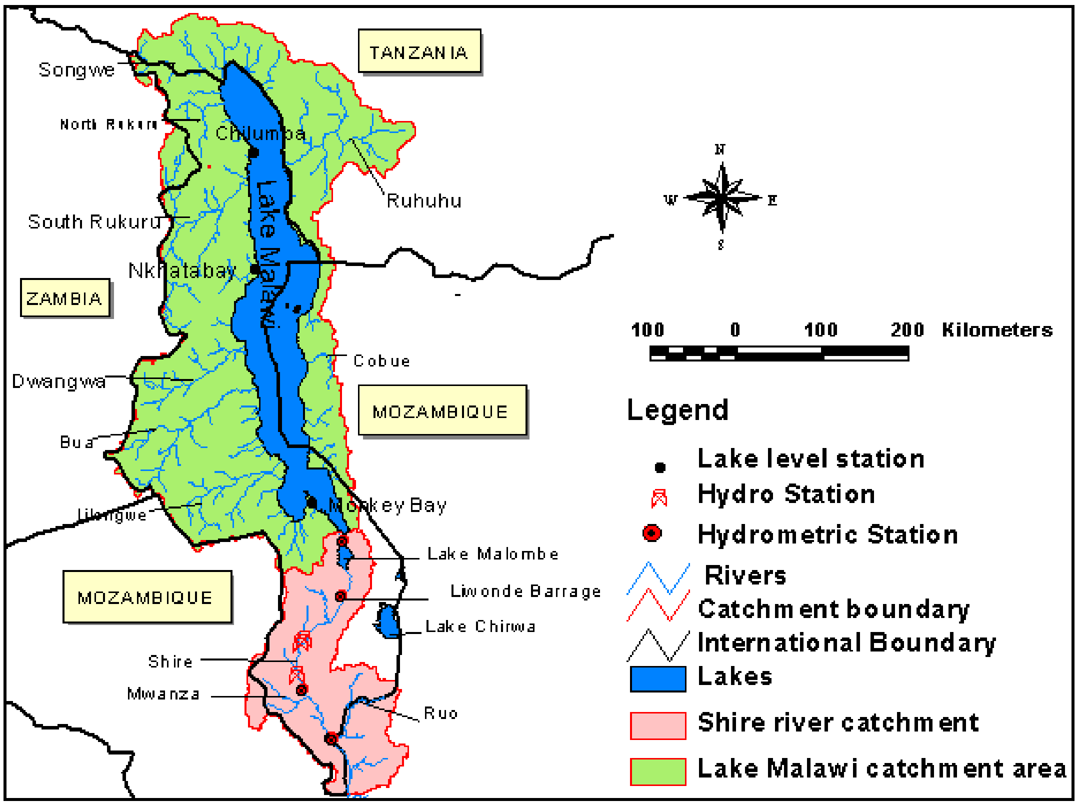


Figure 3.17 Map of Malawi showing Lake Malawi-Shire river system, catchment areas and hydro power stations along the Shire river (Source of data:- (GoM, 2005)).

3.2.2 Water levels of Lake Malawi and its catchment area

All the river basins investigated in the earlier part of this Chapter drains into Lake Malawi. In recent years rising water levels in the rainy season have caused floods along the lake while low levels in the dry season have disrupted hydropower generation and water supply along the Shire river to the south of Lake Malawi. Therefore planning alternative water resources schemes on northern highland river basins of Malawi needs an assessment of the hydrological behaviour of the lake. This should provide an insight in the future behaviour of the lake and necessary future water resources strategy.

3.2.2.1 Description of Lake Malawi

Lake Malawi is the third largest Lake in Africa after Lake Victoria and Tanganyika (Shahin, 2002). Lake Malawi drains a catchment area of 126,500 km^2 including the lake as shown in Figure 3.17. The lake surface area is 28,800 km^2 and the lake is 579 km long, 25 – 80 km wide with a maximum depth of 700 – 785 m and mean depth of 292 m (Neuland, 1984; Shahin, 2002). The land catchment area of Lake Malawi is 97,740 km^2 and it covers parts of Malawi, Mozambique and Tanzania as shown in Figure 3.17. Malawi contributes the lion share of the land catchment of 66,810 km^2 (68.35%), seconded by Tanzania with 25,470 km^2 (26%) and Mozambique 5.460 km^2 (5.58%) (Neuland, 1984). The rivers which have been outlined in section 3.1 (Bua, Dwangwa, Dwambazi, South and North Rukuru, Lufira etc) cover a total catchment area of 38,341 km^2 and forms part of the catchment area of the lake representing 39 .2 percent of the catchment of the lake. That being the case the inflows from these rivers have a significant impact on the water level in Lake Malawi. In view of this sustainable water resources strategy of the northern highland rivers will also have an effect on the sustainability of the lake. Figure 3.17 is the catchment area of Lake Malawi showing the streams supplying it with water. The other river flowing into Lake Malawi apart from those outlined in section 3.1 are Lilongwe and Songwe river from Malawi, and Ruhuhu river from Tanzania. The only river flowing out of Lake Malawi is the Shire river. The Shire river plays an important role in hydro electricity generation, water supply for domestic use and irrigation in the lower Shire. Shire river flows depends on the water level of the lake (Calder *et al*., 1995). According to Calder *et al.* (1995) knowledge of the hydrological regime of the lake as well as the inflowing rivers supplying water to the lake is vital for the planning of future water resources development.

3.2.2.2 Water level monitoring for Lake Malawi

The water levels of Lake Malawi depends on rainfall over the lake, inflows from rivers draining into the lake, evaporation losses from the lake surface and outflow from the lake through the Shire river. Studies (Calder *et al.*, 1995; Drayton, 1984; Neuland, 1984) have shown that the level of Lake Malawi has varied widely throughout 19th century, and has risen dramatically in the period 1976-1980 (Figure 3.18).

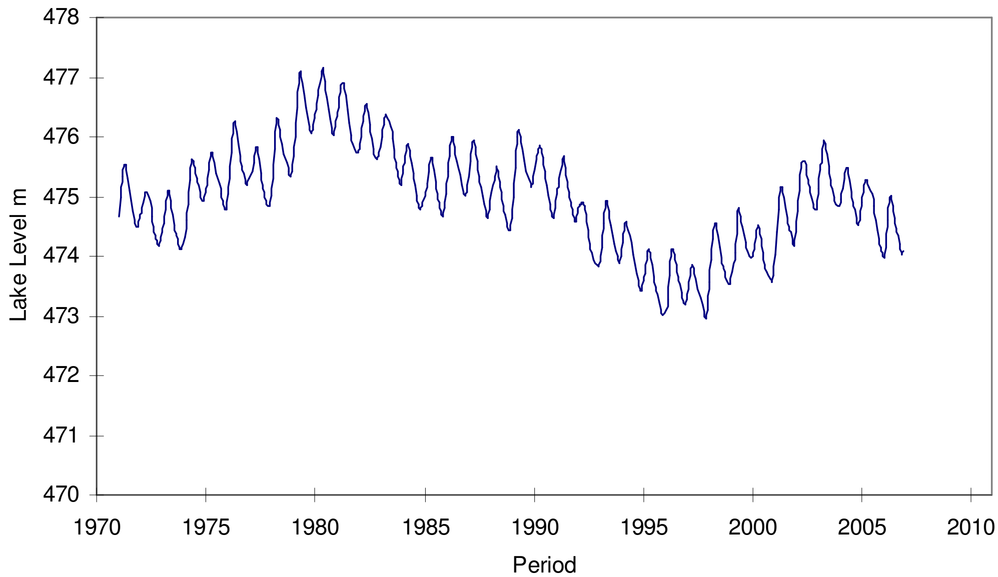


Figure 3.18 Mean water levels of Lake Malawi from 3 level stations shown in Figure 3.17. Source of data (Hydrology Section of the Ministry of Irrigation and Water Development, Malawi)

Monitoring of lake levels is done by the Ministry of Water and Irrigation on three main level stations shown in Figure 3.17:- Chilumba, Nkhatabay and Monkeybay). The lake level is an average of the daily readings from the three stations. According to Calder *et al.* (1995) lake level monitoring dates back to 1896 and between 1915 and 1937 the lake levels had fallen below the bed of the lake outlet to the Shire river. This allowed the formation of sand bars at the channel inlet and growth of vegetation within the former channel. As a result there was no outflow from the lake until rising lake levels breached the sand bars in 1937 (Calder *et al.*, 1995). Despite this scenario the lake level has remained several metres higher than those observed at the beginning of the 1915 to 1937 scenario (Calder *et al.*, 1995; Jury and Gwazantini, 2002; Neuland, 1984). However a repetition of the 1915 – 1937 scenario will have catastrophic economic consequences on Malawi since the Shire river is currently the driving force of Malawi in terms of water supply for irrigation, hydropower and water supply for domestic use.

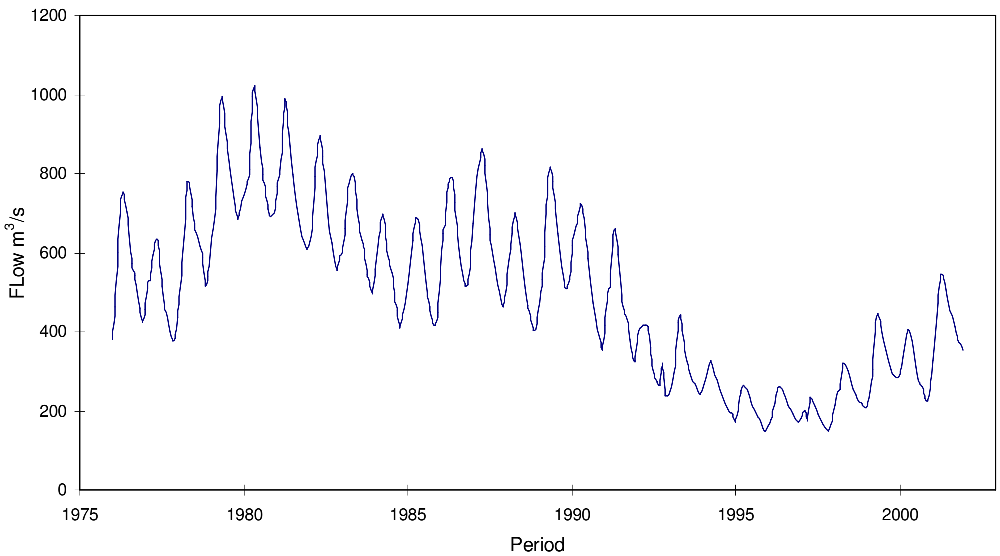


Figure 3.19 Shire river flow variations at the outlet from Lake Malawi. Source of data (Hydrology Section of the Ministry of Irrigation and Water Development, Malawi).

Lake Malawi catchment runoff

Lake Malawi catchments shown in Figure 3.17 covers parts of Tanzania, Mozambique and Malawi. Despite Malawi contributing the lion share of the land catchment, Tanzania contributes the majority of the runoff inflow into Lake Malawi as shown in Figure 3.20. Flows from Tanzania originates from Rukuhu and Northern Lakeshore catchment amounting to 60 percent of the inflow into the lake. Runoff inflow from Malawi originates from 13 catchments shown in Figure 1.8 of Chapter 1. Appended to the thesis is a CD of all the available inflow data as well as rainfall data for Lake Malawi.

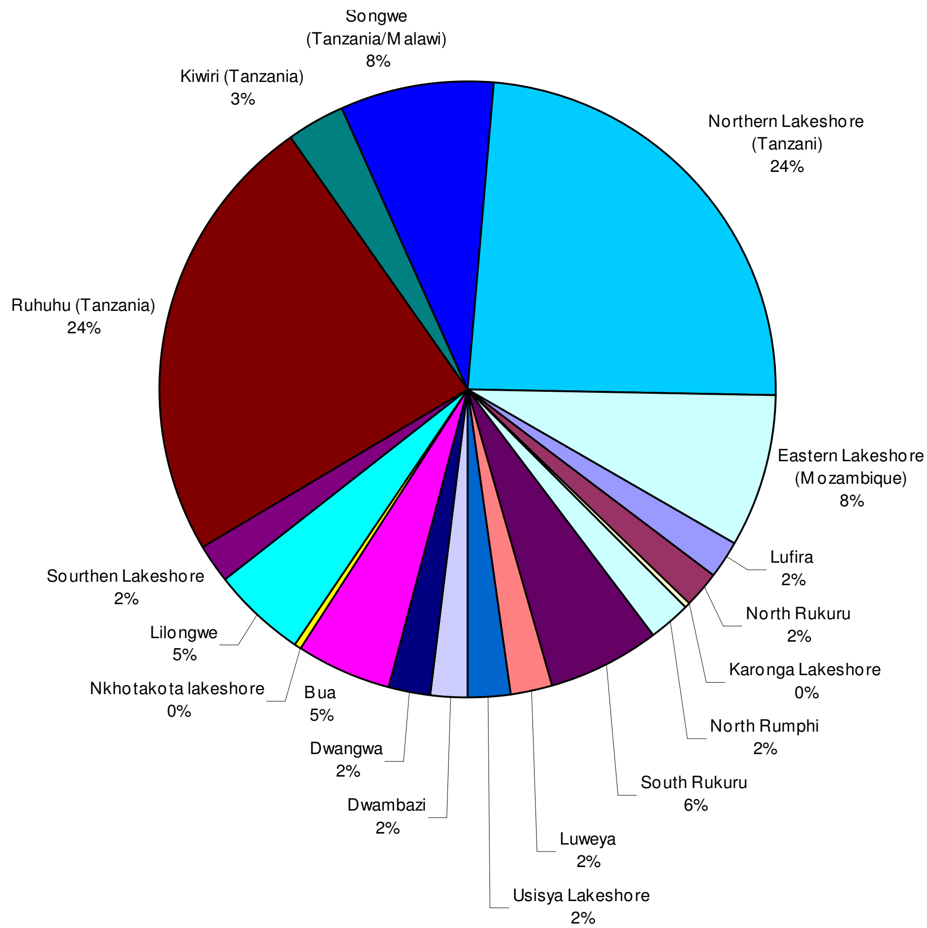


Figure 3.20 Lake Malawi inflow contribution from different catchments (Hydrology Section of the Ministry of Irrigation and Water Development, Malawi).

Outflow from Lake Malawi at Mangochi station.

Outflows from Lake Malawi have always been monitored from Liwonde barrage since 1948. The barrage is 80 km south of the lake outlet. The records at Liwonde barrage are always influenced by inflow within this reach as well as Lake Malombe which is within this reach and the operation of the Liwonde barrage which is meant to regulate flows from the lake. The Liwonde barrage shown in Figure 3.21 was built to provide a controlled outflow from the lake. In 1976 a station was installed at Mangochi, which is the actual outlet point of the Shire river from Lake Malawi. Variation of the outflows from this station is shown in Figure 3.19. The outflow from the lake corresponds with the level of the lake as shown in Figure 3.18 and Figure 3.19

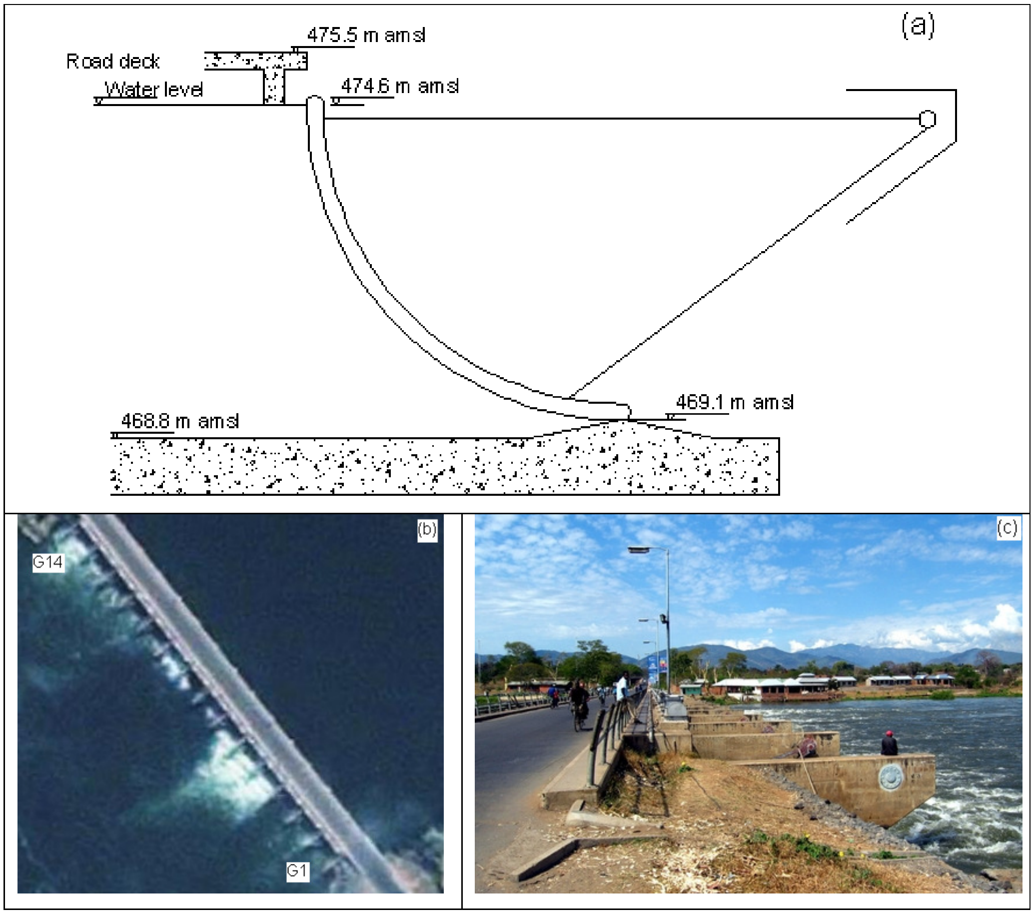


Figure 3.21 (a) Detailed cross section of the Liwonde barrage (b) Areal view of Liwonde barrage showing radial gates (G1 up to G14) (c) Pictorial view of Liwonde barrage (Google Earth).

Control of Lake Malawi outflows at Liwonde barrage

Outflows from Lake Malawi are controlled at Liwonde barrage shown in Figure 3.21. The Liwonde barrage consists of 14 radial gates as shown in the areal view in Figure 3.21(b). Construction of the barrage was completed in 1965. The justification of constructing a control gate at Liwonde was to mitigate the possibilities of failure to maintain the design flow of 170 m^3/sec for hydropower in the middle reach of the Shire river. The original rules of barrage operation adopted in 1965 were based on recommendations by Kanthack (1942) cited by Kidd (1983). The original rules were simple and straight forward, proposing a constant release of 170 m^3/sec for all water levels between 471.85 m and 473.35 amsl. However Harrison *et al.* (1976) cited by Kidd (1983) criticised these control rules on the grounds that the maintenance of constant flow for a long period was against the needs of some downstream users. Maintenance of constant flow resulted in absence of natural seasonal fluctuations. This was felt to be more damaging to the ecology of the Lower Shire Valley. As an alternative a set of control rules were proposed to maintain the natural flow regime of the Shire river. The scheme proposed by Harrison *et al.* (1976) is presented in Figure 3.22 and Table 3.2. It consists of a straight line from a point on the natural flow curve at 473.95 m amsl to a point at 472.45 m amsl. Below 472.45 m amsl, the flow is maintained at 170m^3/sec until again the natural curve is reached at a level of 471.85 m amsl. Below 471.85 m amsl, the system is assumed to have failed, as maintenance of a guaranteed flow of 170m^3/sec is no longer possible. These amended control rules were adopted by the Water Resources Board and are present policy for barrage operation. Physical operation of the barrage is done by Electricity Supply Commission of Malawi on advice by the Hydrology section of the Ministry of Irrigation and Water on water levels in Lake Malawi and outflow records from the lake.

The natural flow curve at Liwonde barrage in Figure 3.22 after Kanthack (1942) cited by Kidd (1983) is given by equation 3.1

$$Q = 20.4(L - 469.00)^{2.03} \qquad 3.1$$

where L is the water level (m) in Lake Malawi and Q is the flow rate (m^3/sec) at Liwonde barrage.

Table 3.2 Control rules for Liwonde barrage on the Shire river. (Kidd, 1983)

Shire river flow Q m^3/sec	Operation of radial gates to regulate flows
Q<170 m^3/sec	Set gates (Y) 1 to 3 and close 4 to 14
170<Q<340 m^3/sec	Set gates (Y) 1 to 3 and 4 to 14
Q>340 m^3/sec	Set all gates equally

The outflow from Lake Malawi through the Shire river makes Lake Malawi of particular importance to Malawi in number of areas such as hydropower generation along the Shire river, irrigation in the lower reach, ecosystem generation in the lower Shire valley. Sustainable management and utilisation of the Lake as well as its catchment area will have a significant impact on the water resources of the Shire river.

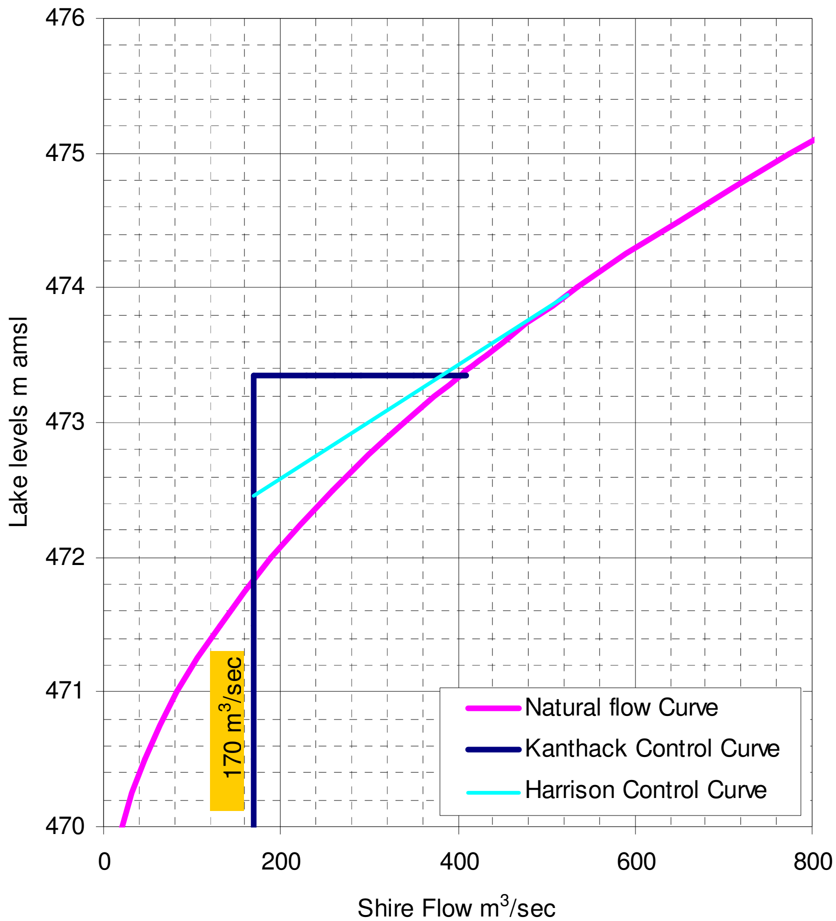


Figure 3.22 Control rules for Liwonde barrage on the Shire river (Kidd, 1983)

3.2.3 The Shire river basin

The Shire river is the largest river in Malawi and is the only outlet from Lake Malawi. The Shire river flows from Lake Malawi for a distance of 700 km to its confluence with the Zambezi river in Mozambique and 95 percent of the Shire river is in Malawi and the remaining 5 percent is in Mozambique (Chimatiro, 2004). The Shire river has a catchment area of 19,248 km^2 in Malawi including 303 km^2 of Lake Malombe (GoM, 1986). According to National Water Resources Master Plan of Malawi (GoM, 1986), the Shire river is referred to as Water Resources Unit 1 and is generally dived into three sections, namely:- the upper reach, the middle reach and the lower reach.

The upper reach of Shire river is the stretch from the southern tip of the south east arm of the lake up to the outlet of Lake Malombe (Plate 3.1 (a) and Figure 3.23). The upper section of the Shire river is characterised by low-lying sand banks.

The middle reach of the Shire river stretches from Lake Malombe outlet up to Kapichira Falls (Kapichira Dam). The middle reach of the Shire river is characterised by gorges, cataracts and falls as shown Plate 3.1(b) and Figure 3.23. The Shire river falls by approximately 384 m in altitude from Lake Malombe outlet to Kapichira Falls (Kidd, 1983). The major hydraulic infrastructures are located within the Middle reach, namely:- Liwonde barrage, Nkula, Tedzani and Kapichira Hydropower plants.

The lower reach of the Shire river stretches from Kapichira Falls up to Malawi border with Mozambique passing through the Elephant marsh. The lower reach falls in elevation from 107 m amsl at Chikwawa to 50 m amsl at Chilomo (GoM, 1986). The major tributary of the Shire river is the Ruo river which originates from Mulanje Massif and joins the Shire river at Chilomo in the lower reach section. The lower reach is characterised by meanders oxbow lakes, lagoons and islands as shown in Plate 3.1 (c) and Figure 3.23. The lower reach has a floodplain known as the Elephant marsh (Shire floodplain). The Shire flood plain is among the major seventeen flood plains in Africa and it benefits an estimated 1 million people in riparian community in Malawi and Mozambique (Chimatiro, 2004). The floodplain covers an estimated area of 1100 km^2 and is the source of 11 percent of Malawi's fish catch, irrigation water for the country's sugar plantation and grazing land for about 80 percent of Malawi's livestock production (Chimatiro, 2004). The behaviour of the Elephant marsh is controlled by both the Shire and Ruo rivers. Floods in the Ruo river, which can be several times the base flow in the Shire river, back up into the elephant marsh (GoM, 1986).

Plate 3.1 Aerial view and ground pictures of different sections of the Shire river. (a) Aerial view of the upper reach at the south-east arm of Lake Malawi, (b) the Kapichira falls in the middle reach (c) Elephant marsh in the lower Shire river (Google Earth).

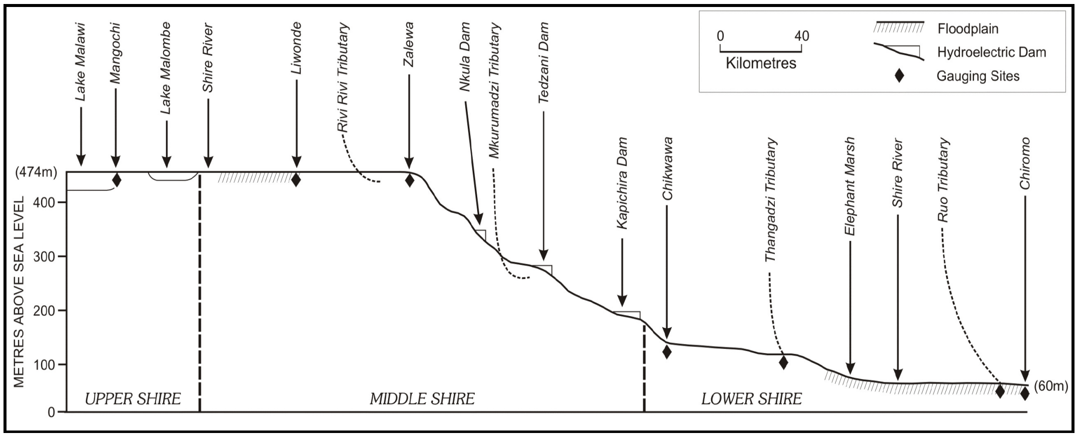
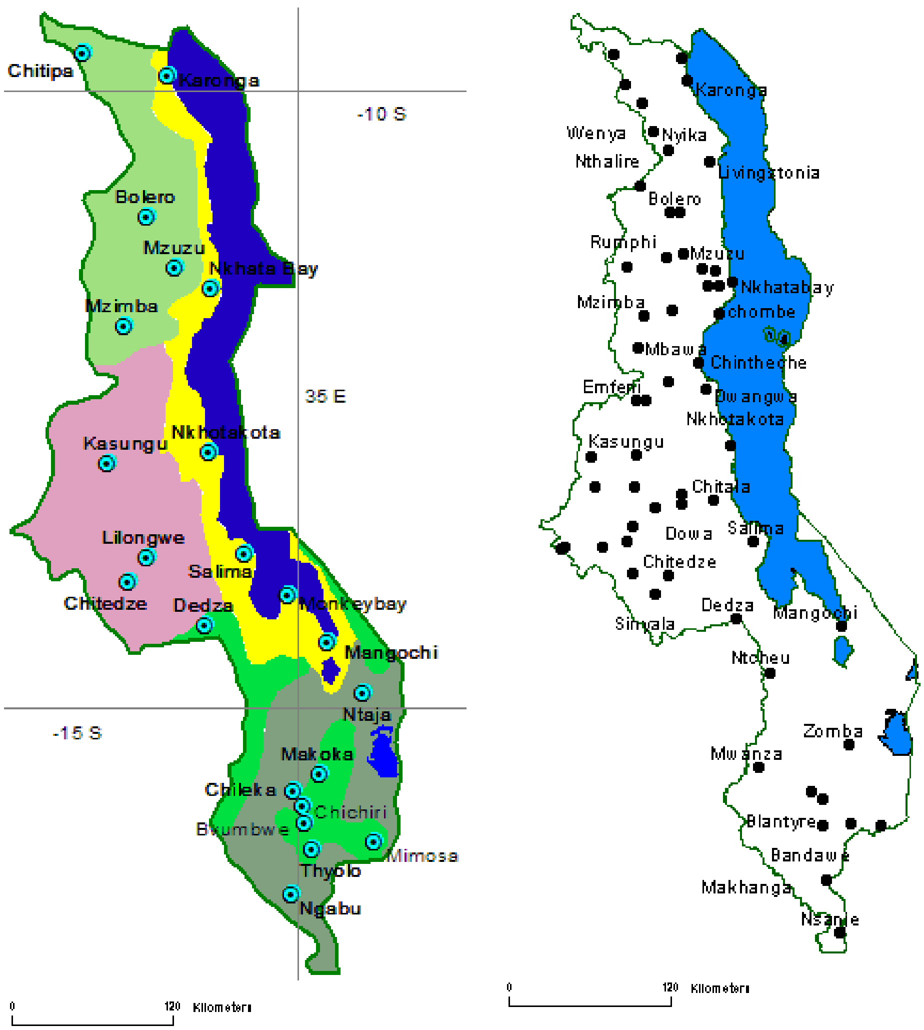


Figure 3.23 Shire river profile from Lake Malawi outlet up to the flood plains of the Lower Shire valley showing the upper, middle and lower reach sections, hydroelectric dams and flood plain (Elephant marsh). (Source:- National Water Resources Master Plan of Malawi)

Despite sparse and scanty data on water resources in the Central and North Malawi river catchments, Lake Malawi and the Shire river, it is still necessary to analyse the available data for use in sustainable decision making and planning for water resources development. Section 3.3 is an analysis of the available climate data for North and Central Malawi catchments, Lake Malawi water levels and the Shire river system.

3.3 CLIMATE DATA ANALYSIS

Climate data collection in Malawi dates back to 1890 when climate data were recorded by British Missionary settlers and farmers. This resulted in a concentration of climate stations in Tea estates areas of Thyolo and Mulanje in the southern region. In 1940 the Nyasaland government established the Meteorological department which was mandated to establish and maintain meteorological stations in the country. Between 1961 and 1970 the MetD had established a total of 270 raingauges across the country (MetD, 2009). At present a few rainfall stations are still up to date in terms of the rainfall records and the present network of meteorological stations has been reduced to 22 full meteorological stations as shown in Figure 3.24 (MetD, 2009). Most of the climate stations do not have a complete record of climate data as most of them only keep rainfall records. Figure 3.24 as well as Table 3.1 gives a summary of the major rainfall stations in Malawi. According to MetD the period of record varies between stations, and there is insufficient overlap to allow a common period of record. However, the major rainfall stations had at least 97% of data available over the period 1971 to 1995, which was deemed adequate to provide a reasonable dataset. These data were used to create a rainfall grid for the country. Rainfall stations from neighbouring countries were also taken into consideration as control boundaries when creating a rainfall map for Malawi. Table 3.3 and Table 3.4 summarises the available rainfall data within the study area. Table 3.5 is a summary of the available climate data.



(a) Climate stations as of 2009 (b) Climate stations as of 1990

Figure 3.24 Main climate stations in Malawi (Source of data:- (MetD, 2009)).

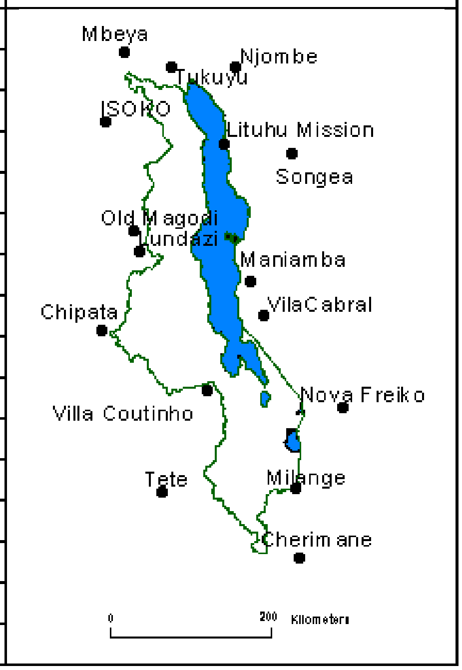
Table 3.3 Rainfall stations with available data in the study area (Source of data:- (MetD, 2009)).

No	Station	Data period	MAR mm/year	% Missing
1	Bolero	1/1/1990 - 31/12/1990	597	0.00
2	Bvumbwe	1/1/1971 - 31/12/2000	1146	0.00
3	Chikangwa	1/1/1971 - 31/12/1990	1182	0.00
4	Chileka	1/1/1971 - 31/12/2000	871	0.00
5	Chintheche	1/1/1971 - 31/12/1990	1991	1.14
6	Chinziri	1/1/1989 – 31/12/1990	859	0.30
7	Chitala	1/1/1961 - 31/12/1990	897	0.00
8	Chitedze	1/1/1961 - 31/12/2006	887	0.00
9	Chitipa	1/1/1961 - 31/12/1990	963	0.00
10	Dedza	1/1/1971 - 31/12/1990	953	0.00
11	Dowa	1/1/1979 - 31/12/1990	895	0.00
12	Karonga	1/1/1961 - 31/12/2006	1114	0.00
13	Kasiya	1/1/1961 - 31/12/1990	916	0.00
14	Kasungu	1/1/1979 - 31/12/2006	791	0.00
15	kawamba	1/1/1989 – 31/12/1990	892	0.90
16	Khola	1/1/1989 – 31/12/1990	867	0.22
17	Lilongwe	1/1/1979 - 31/12/2006	847	0.00
18	Livingstonia	1/1/1971 - 31/12/2000	1607	0.00
19	Madisi	1/1/1961 - 31/12/1990	847	0.00
20	Makhanga	1/1/1971 - 31/12/2000	761	0.00
21	Mangochi	1/1/1971 - 31/12/2000	765	0.00
22	Masamba	1/1/1971 - 31/12/1990	1435	0.00
23	Mbawa	1/1/1971 - 31/12/1990	843	0.00
24	Mchinji	1/1/1961 - 31/12/2000	1028	0.22
25	Mimosa	1/1/1971 - 31/12/2000	1713	0.00
26	Mkanda	1/1/1979 - 31/12/2006	1033	0.00
27	Mponela	1/1/1979 - 31/12/1990	859	0.00
28	Mulanje	1/1/1971 - 31/12/2000	2094	0.00
29	Mwanza	1/1/1971 - 31/12/2000	1086	0.00
30	Mwanza	1/1/1971 - 31/12/2000	1074	0.00
31	Mzimba	1/1/1961 - 31/12/2006	888	0.00
32	Mzuzu	1/1/1961 - 31/12/2006	1226	0.00
33	Namwera	1/1/1971 - 31/12/2000	1039	0.00
34	Nkhata bay	1/1/1961 - 31/12/2006	1623	2.17
35	Nkhota kota	1/1/1961 - 31/12/2006	1496	0.71
36	Nsanje	1/1/1971 - 31/12/2000	859	0.00
37	Ntcheu	1/1/1971 - 31/12/2000	998	0.00

No	Station	Data period	MAR mm/year	% Missing
38	Ntchisi	1/1/1979 - 31/12/2006	869	0.05
39	Salima	1/1/1961 - 31/12/1995	1227	0.00
40	Sinyala	1/1/1971 - 31/12/2000	905	0.00
41	Tembwe	1/1/1989 – 31/12/1999	987	0.32
42	Thondwe	1/1/1971 - 31/12/2000	1887	0.17
43	Zomba	1/1/1971 - 31/12/2000	1323	0.00
MAR = Mean Annual Rainfall				

Table 3.3 Continued

Table 3.4 Rainfall stations outside Malawi but close to Malawi (Source of data:- (MetD, 2009)).

Station	Country	MAR mm/year	Rainfall stations outside Malawi
Cherimane	Mozambique	693	
Maniamba	Mozambique	1434	
Milange	Mozambique	1824	
Nova Freiko	Mozambique	936	
Tete	Mozambique	599	
VilaCabral	Mozambique	1146	
Villa Coutinho	Mozambique	944	
Lituhu Mission	Tanzania	922	
Mbeya	Tanzania	1390	
Tukuyu	Tanzania	2469	
Njombe	Tanzania	1112	
Songea	Tanzania	1129	
Old Magodi	Zambia	950	
Chipata	Zambia	1016	
ISOKO	Zambia	1094	
Lundazi	Zambia	870	

3.3.1 Estimation of missing climatological data

A complete record of climate data is required for efficient modelling of hydrological system and water resources engineering design and management. Scarcity of these variables is a major set back in application of hydrological models (Garcia *et al*., 2006; Peck, 1997). The problem is more prevalent in developing countries like Malawi. This often restricts research efforts of many engineers. Often engineers face the problem of missing climate records due to a number of reasons. In general, the reasons for missing data occurrence are related to: records for discrete periods, not covering the entire time period of interest; short intermittent period where data have not been recorded and difficulty in the techniques and methods used in collecting data from the field. In Malawi climate records are not available in some station due to lack of resources and personnel to keep on recording climate data.

Table 3.5 Summary of climate data within Central and North Malawi catchment area (Source of data:- (MetD, 2009)).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Station	Sunshine hours (hours/day), wind speed (m/s), Relative humidity (%) and Temperature (^oC)											
Chitedze												
Sunshine Hours	5.3	5.7	6.4	7.8	8.5	8.2	7.9	8.8	9.6	9.3	7.5	5.6
Wind Speed	1.4	1.3	1.4	1.5	1.6	1.8	2.0	2.1	2.5	2.6	2.4	1.9
Relative Humidity	83.5	84.7	83.2	79.5	72.3	67.4	64.8	58.3	52.0	53.0	62.0	79.2
Max Temp	26.5	26.6	26.8	26.6	25.6	24.1	25.6	27.4	28.3	30.1	29.7	27.4
Min Temp	17.4	17.2	16.4	14.6	11.4	8.8	9.5	10.6	11.8	14.7	16.9	17.6
Karonga												
Sunshine Hours	5.8	6.1	6.7	7.4	8.2	8.8	9.2	9.9	10.2	10.3	9.1	6.9
Wind Speed	1.7	1.6	1.7	2.1	2.4	2.4	2.6	2.5	2.5	2.8	2.6	2.0
Relative Humidity	78.3	79.4	81.1	79.3	72.9	65.9	64.2	63.4	59.4	54.7	60.2	72.4
Max Temp	29.5	29.6	29.1	28.9	28.4	27.4	27.1	28.1	30.2	32.1	32.1	30.2
Min Temp	21.7	21.6	21.4	21.4	19.5	17.6	16.8	17.2	19.1	21.4	22.7	22.2
Mzuzu												
Sunshine Hours	4.7	4.9	5.3	5.7	7.0	7.3	7.7	8.9	9.6	9.7	8.4	5.8
Wind Speed	1.7	1.7	1.8	2.2	2.0	2.0	2.1	2.0	2.3	2.5	2.3	1.8
Relative Humidity	85.8	85.3	89.2	89.9	89.4	88.1	86.8	80.4	70.1	65.6	72.5	83.2
Max Temp	16.3	16.2	16.0	15.3	11.8	7.9	6.7	7.0	8.6	11.8	14.3	16.0
Min Temp	25.5	25.6	24.8	23.6	22.1	20.5	20.9	22.7	25.1	27.4	27.4	26.1
Nkhatabay												
Sunshine Hours	5.6	5.7	6.2	6.6	7.7	8.0	8.1	9.3	10.1	10.2	8.8	6.4

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Station	Sunshine hours (hours/day), wind speed (m/s), Relative humidity (%) and Temperature (^oC)											
Wind Speed	1.1	1.1	1.2	1.2	1.4	1.7	1.7	1.8	1.7	1.7	1.6	1.4
Relative Humidity	83.7	83.8	84.9	84.1	81.1	77.9	74.8	71.8	68.6	66.9	71.5	80.0
Max Temp	28.7	29.0	28.8	28.6	27.1	25.9	25.5	26.6	28.6	30.2	30.3	29.2
Min Temp	21.4	21.2	20.8	20.1	17.9	15.7	15.0	15.6	17.4	19.8	21.6	21.2
Nkhotakota												
Sunshine Hours	5.4	5.7	6.9	8.0	8.7	8.9	8.7	9.5	9.9	9.5	9.0	6.3
Wind Speed	1.6	1.7	1.9	2.2	2.4	2.7	2.8	2.6	2.7	2.8	2.6	2.0
Relative Humidity	82.9	80.7	80.5	77.3	71.7	66.8	65.4	62.1	59.2	57.7	63.2	77.3
Max Temp	28.5	28.6	28.6	28.1	26.9	25.6	25.4	26.9	29.6	31.6	31.5	29.4
Min Temp	21.2	21.3	21.0	20.2	18.0	15.8	15.4	16.0	18.0	20.9	22.1	21.6
Salima												
Sunshine Hours	6.0	6.2	7.5	8.8	9.5	9.3	9.1	9.8	10.0	9.7	9.2	6.8
Wind Speed	1.7	1.7	2.1	2.4	2.4	2.6	2.7	2.4	2.3	2.6	2.4	2.0
Relative Humidity	79.9	81.4	76.8	73.1	67.9	62.8	61.0	57.2	54.9	54.6	61.0	75.7
Max Temp	29.3	29.3	29.2	29.1	27.9	26.4	26.2	27.9	30.6	32.6	32.8	30.5
Min Temp	21.4	21.4	21.4	20.8	18.1	15.8	16.0	16.9	18.7	21.2	22.6	22.1

Table 3.5 Continued

In such circumstances estimation of missing climate data is an important task for water engineers, hydrologist and environmental protection workers. This is particularly important in developing countries like Malawi where data for longer periods and sparse data is not readily available. Several techniques have been proposed for estimating missing climate records and can be grouped under empirical methods, statistical methods, and functional fitting methods (Garcia *et al*., 2006; Peck, 1997; Thiebaux and Pedder, 1987). The empirical approaches include methods like simple arithmetic averaging, inverse distance interpolation (Hubbarda, 1994; Willmott and Robeson, 1995; Willmott *et al*., 1994) and ratio and difference technique (Wallis *et al*., 1991). Statistical approachs include multiple regression analysis (Eischeid *et al*., 1995; Wigley *et al*., 1990), multiple discriminant analysis (Young, 1992), principal component analysis and cluster analysis (Garcia *et al*., 2006; Huth and Nemesova, 1995); kriging technique (Martinez-Cob, 1996); and optional interpolation (Xia *et al*., 1999). Recently the use of remotely sensed data has also been an option to filling in missing climate data (Jeffrey *et al*., 2001).

3.3.1.1 Empirical approaches for estimating missing climate data

Simple arithmetic averaging.

This is the simplest method used in filling missing climate data. The simple average is obtained by taking an average of the closest climate station. The other option in simple averaging is the use of seasonal mean values to fill missing climate records of a particular station. Seasonal mean values are obtained from the daily series, by calculating the average for a particular day in a particular month in all the years available. The missing data on a particular day is replaced by its seasonal mean values.

$$\bar{v} = \sum_{i=1}^{ny} v_{i,d} \quad d = 1,2................,365 \text{ and } i = 1,2,...........ny \qquad 3.2$$

where ny is the number of years of the available data v is the observed climate record and $\bar{v}$ is the seasonal mean value on day d of the year. The seasonal mean value technique has an advantage in that it maintains the statistical properties of the measured climate records.

Inverse distance weighted (IDW) method.

The Inverse Distance Weighted given in equation 3.3 is simplest and most popular interpolation technique which weights every data point according to its distance from the sample point. It is a simple technique that does not require prior information to be applied to spatial prediction.

$$v_0 = \frac{\sum_{i=1}^{n} \left(v_i / d_i^m \right)}{\sum_{i=1}^{n} 1 / d_i^m} \qquad 3.3$$

where v_0 is the estimated value of the missing data, v_i is the value of the nearest weather station and d_i the distance between the station of the missing data and the nearest ith station and m is the inverse distance weighting power. Research has shown that inverse distance estimators are quite sensitive to the type of database or data characteristics, to the number of neighbours used in the estimate, and to the inverse distance weighting power (Weber and Englund, 1994).

Ratio and difference technique

The ratio and difference interpolation technique was first proposed by Paulhus and Kohler in 1952 and later on modified by Young in 1992 (Young, 1992). Missing climate data v_0 are considered as a combination of variables with different weights

$$v_0 = \frac{\sum_{i=1}^{n} w_i v_i}{\sum_{i=1}^{n} w_i} \qquad 3.4$$

where w_i is the weight of the ith nearest station and v_i is the observed data of the ith climate station. Weights are calculated according

$$w_i = \left[r_i^2 \left(\frac{n_i - 2}{1 - r_i^2} \right) \right] \qquad 3.5$$

where r_i is the correlation coefficient between the target station and the ith surrounding station, n_i is the number of stations used to derive the correlation coefficient.

3.3.1.2 Statistical approaches for filling missing climate data

Multiple regression analysis.

This is a traditional method for interpolating missing data based on observed data of surrounding stations using regression model analysis (Eischeid *et al.*, 1995; Young, 1992). Missing climate data are estimated as v_0

$$v_0 = a_0 + \sum_{i=1}^{n} (a_i v_i) \qquad 3.6$$

where $a_0, a_1, ...a_n$ are regression coefficient and v_i is the value of the ith weather station.

Cluster analysis.

This is a statistical method for estimating missing climate data used to identify homogeneous climate groups (Gerstengarbe *et al.*, 1999). The aim behind is to separate several elements into homogeneous group in such a period of time which can be considered similar. In cluster analysis measurement of dissimilarity to characterize the relationship between stations is required. The problem with cluster analysis requires climate data from a closest station which is always a problem in developing countries where climate station are spread long distances apart (DeGaetano, 2001).

Kriging technique.

This method is similar to Inverse Distance Weighted (IDW) method as it uses a weighting, which assigns more influence to the nearest data points in the interpolation of values for unknown locations. The method extends the proximity weighting approach of IDW to include random components where exact point location is not known by the function. Kriging depends on spatial and statistical relationships to calculate the surface. The two-step process of Kriging begins with semi variance estimations and then performs the interpolation. Some advantages of this method are the incorporation of variable interdependence and the available error surface output. A disadvantage is that it requires substantially more computing and modelling time, and Kriging requires more dense climate stations.

3.3.1.3 Function fitting approaches for filling missing climate data

In function fitting data are fitted as a function like thin-plate which is used to interpolate the climatological data (Hancock and Hutchinson, 2006; Hasenauer *et al*., 2003; Xia *et al*., 1999). Spline estimates values using a mathematical function that minimizes overall surface curvature, resulting in a smooth surface that passes exactly through the input points. Conceptually, it is like bending a sheet of rubber to pass through the points while minimizing the total curvature of the surface. The best will depend on the density of climate stations.

The major underlying factor in the accuracy of the three different techniques for estimating missing climate records is the density of the climate stations. For example, Willmott *et al.* (1994) noted that simple average method overestimates climate data such as temperature and rainfall in low climate station density areas. Results of the method are very poor in areas with strong precipitation/temperature gradient and station density gradient. Therefore estimating missing climate data using simple average method should also take into account the spatial and temporal variability of precipitation/temperature within the area. According to Garcia (2006) and Willmott (1995), climate data (rainfall and temperature) can be reliably estimated using inverse distance for shorter time steps (eg daily mean values) than the other methods. However the other methods outlined in this section performs well for longer time steps, from 7 to 30 days or annual values (Garcia *et al*., 2006).

3.3.1.4 Approach adopted for filling missing climate data

A number of studies of different methods for estimating missing climate data are available in literature; for example studies made by Tabony (1983) for UK temperature and sunshine, Young *et al*. (1992) for Arizona and New Mexican rainfall, and Xia *et al*. (1999) for temperature, vapour pressure, wind speed and precipitation at German forest sites. Xia *et al.* (1999) compared six different methods including the IDW to estimating missing values of climate data. The six methods gave similar estimates for precipitation. Lu and Wong (2008) showed that IDW performs better than ordinary kriging in estimating missing parameters. The general consensus in literature is that the IDW yields better results when used to interpolate rainfall and temperature data (Lu and Wong, 2008; Perry and Hollis, 2006; Tronci *et al*., 1986). IDW has an advantage over other methods in that it is relatively fast and easy to compute, and straight forward to interpret and can reliably estimate daily climate data in circumstances where there is only a few gaps in the available data (Garcia *et al*., 2006). In this research the IDW method was used to estimate missing climate data (rainfall and temperature) because most of the climate stations had at least 97% of data available (Table 3.3).

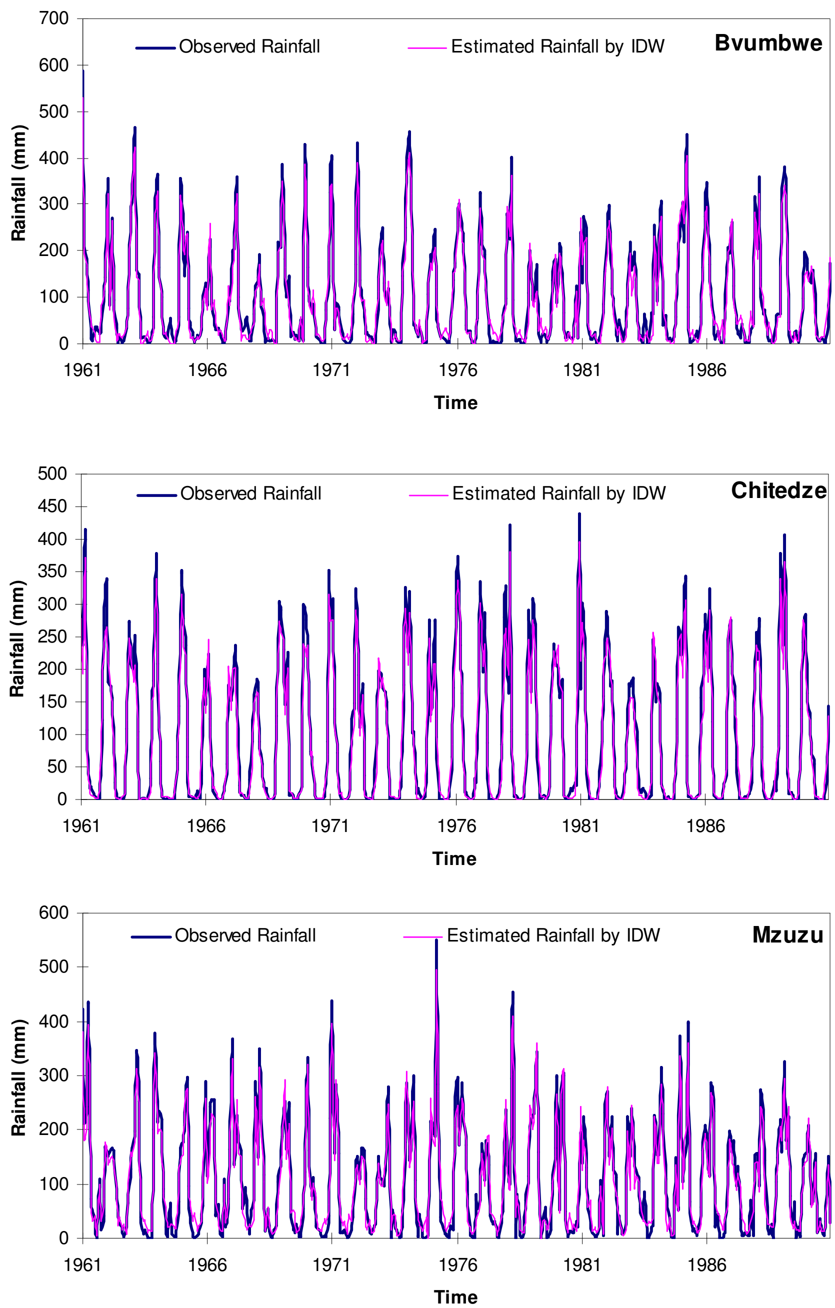


Figure 3.25 Estimated rainfall by IDW method for Bvumbwe, Chitedze and Mzuzu. Source of data, MetD (2009).

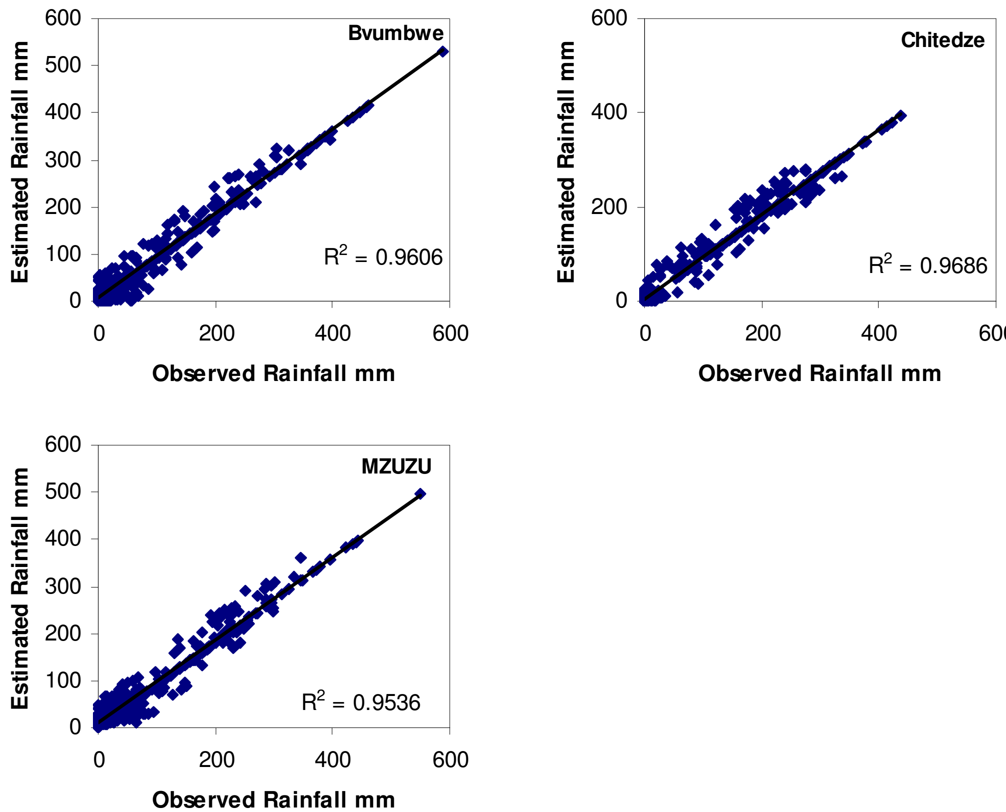


Figure 3.26 Nash-Sutcliffe model efficiency for estimated rainfall by IDW for Bvumbwe, Chitedze and Mzuzu stations.

Suitability of the IDW method for Malawi climate stations was checked by comparing IDW estimates against observed rainfall for three climate stations which were selected at random, one from each region (South, Central and North). The respective three climate stations are Bvumbwe, Chitedze and Mzuzu shown in Figure 3.24 and listed in Table 3.3. The results of rainfall estimates by IDW against observed rainfall are presented in Figure 3.25 and Figure 3.26. Generally, the IDW method performed well on the three stations, as there was a good agreement between the observed and estimated rainfall. All the three stations had Nash-Sutcliffe model efficiency greater than 0.95 despite failing to estimate peak rainfall depth for other years.

IDW was further used in creating a rainfall map for Malawi based on the data set in Table 3.3 and Table 3.4 as shown in Figure 3.27. Rainfall stations from neighbouring countries were also taken into consideration as control boundaries when creating a rainfall map for Malawi.

The rainfall map for Malawi in Figure 3.27 shows that the amounts and patterns of rainfall closely correlate with relief, such that highlands and escarpment areas experience greater precipitation than the low lying and rain shadow areas. Mulanje and Zomba mountains in the south and Nyika and Vipya plateau in the North are the prominent highland areas in Malawi with high rainfalls in the excess of 1800 mm annual rainfall while the low lying areas such as the Shire valley and the plateau regions to the west receive low rainfall.

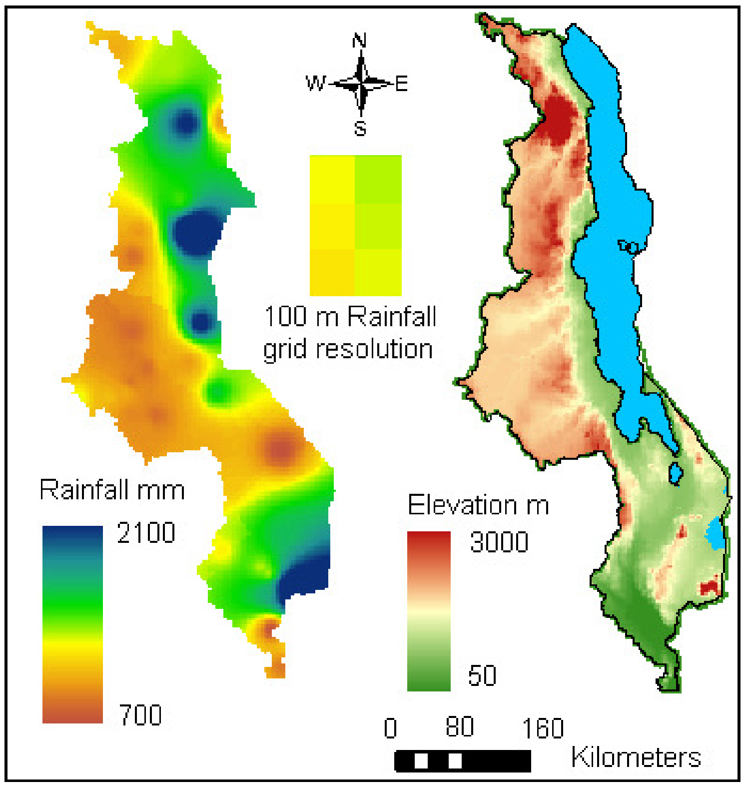


Figure 3.27 Malawi rainfall grid map showing correlation of rainfall with relief

3.4 RIVER FLOW DATA ANALYSIS

3.4.1 Estimating missing river flow data

Water resources planning and management requires a complete data set for variables such as stream flow, rainfall and temperature. River flow is critical to many activities such as designing flood protection works for urban areas and agricultural land and assessing how much water may be extracted from a river for water supply or irrigation. Scarcity of river flow data is posing a more difficult problem in hydrological modelling and water resources engineering design. This problem is more prevalent in Malawi. The reasons for missing river flow data occurrence in Malawi are related to: difficulty in the techniques and methods used in collecting data from the field, interruption of measurements because of equipment failure, mishandling of observed records by field personnel and lack of personnel to monitor flow records in remote areas. This has resulted in large gaps in the river flow data base of Malawi as well as closure of some of the river flow gauging stations.

The problem of missing river flow data has prompted hydrologists to develop tools to estimate missing data and flows for ungauged catchments. These methods can be grouped into regression analysis, time series analysis, and interpolation techniques (Kachroo et al., 1992a). Regression models and analysis requires a reliable (long term continuous) data set and involve choosing the mathematical form of the regression model, estimation of model parameters and model errors. The use of hydrological models has also been an option to filling in missing river flow data in recent years (Kachroo et al., 1992a; Yawson et al., 2005). Hydrological modelling involves model calibration based on available data, estimation of model parameters then estimating missing data based on the calibrated model. Most hydrological models require minimum input of rainfall records. If a complete rainfall record is available then estimation of missing river flow data using hydrological models becomes easy and more reliable (Kachroo et al., 1992a). In Malawi there are usually plenty of rainfall records but stream flow measurements are often limited and rarely available for a specific river under investigation. Estimation of missing river flows in Malawi dates back to 1980 when Drayton *et al.* (1980) developed methods for flow estimation using relationships between flow duration curve and rainfall. Drayton *et al.* (1980) method was considered time-consuming and technically challenging in nature since it had to be applied manually (Fry *et al*., 2003). Similar problems were noted in the methods developed by Pem Consult in 1998 which was a follow up to Drayton *et al.* (1980) studies. In view of this reason Fry *et al.* (2003) under Southern Africa FRIEND programme developed techniques for estimating low flows at ungauged sites based on relationships between spatial catchment characteristics and flow regimes.

Table 3.6 Discharge stations with available data in the North and Central Malawi area and the Shire river basin. (Hydrology Section of the Ministry of Irrigation and Water Development, Malawi).

Code	River	Data period	Area (km^2)	% missing
5C1	Bua	1/1/58 - 31/12/00	10654	12.39
7G18	South Rukuru	1/1/58 - 31/12/00	12088	1.22
7G14	South Rukuru	1/1/58 - 31/12/00	11800	1.83
7F3	Runyina	1/1/80 - 31/12/91	483	9.08
16E6	Dwambazi	1/1/73 – 31/12/94	778	1.92
16F2	Luweya	1/1/65 – 31/12/00	2381	0.75
6D10	Dwangwa	1/1/86 – 31/12/02	7610	8.21
7H3	North Rumphi	1/1/73 – 31/12/99	683	4.00
9A2	Lufira	1/1/82 – 31/12/97	1,410	2.70
8A5	North Rukuru	1/1/69 – 31/12/94	1,860	4.30
14D1	Ruo	1/1/81– 31/12/90	4,350	8.7
IT1	Shire at Mangochi	1/1/76 – 31/12/98	126,500	0.5
IB1	Shire at Liwonde	1/1/53 – 31/12/95	130,200	3.2
IL12	Shire at Chikwawa	1/1/78 – 31/12/90	138,600	2.5
IG1	Shire at Chilomo	1/1/53 – 31/12/98	149,500	3.7

In this study the Linear Perturbation Model (LPM) described in section 2.5.8.1 was used to estimate missing river flow data. The FORTRAN code for Linear Perturbation Model is in Appendix D. The LPM was originally proposed by Nash and Barsi (1983). The Perturbation models are used to take into account the seasonality of the observed rainfall and the observed river flow when simulating discharge data. Research has shown that LPM performs well in tropical regions due to the seasonal variation in the rainfall and river flow pattern (Matondo *et al*., 2004a; Yawson *et al*., 2005).

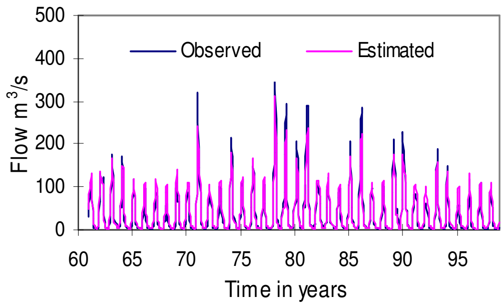
The following section outlines estimation of missing climate for Central and North Malawi catchments. Discharge data collected from the Ministry of Irrigation and Water Development was checked physically for the invalid data and missing data. The observed rainfall and discharge data series were used to calibrate systems model of LPM parameters to obtain a good estimate. Graphs for the simulated data series and observed data series were plotted on the same axes to visualize the best fit as shown in Figure 3.28. Model efficiency was based on Nash-Sutcliffe as described in section 2.5.6.2. The LPM performed quite well with Nash-Sutcliffe model efficiency greater than 0.90 in reproducing the flows of Bua, Dwangwa, Dwambazi, South Rukuru, Luweya and North Rumphi rivers. The model efficiency was lower than 0.90 for Lufira and North Rukuru rivers. Errors in the observed rainfall as well as river flow data could be a contributing factor to low model performance for these two rivers.

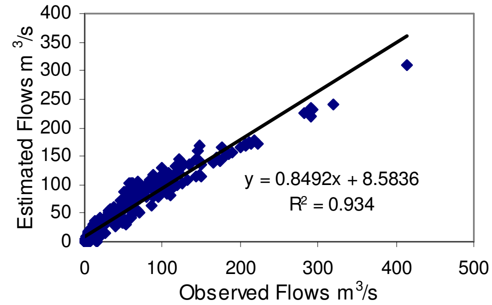
Reliable and complete streamflow and rainfall records were required for the following reasons:-

- Estimation of renewable water resources per capita for each river basin in the Central and Northern region of Malawi,
- Estimating seasonal variation of each river basin in the Central and Northern region of Malawi,
- Estimating total runoff from the upland catchment areas into Lake Malawi

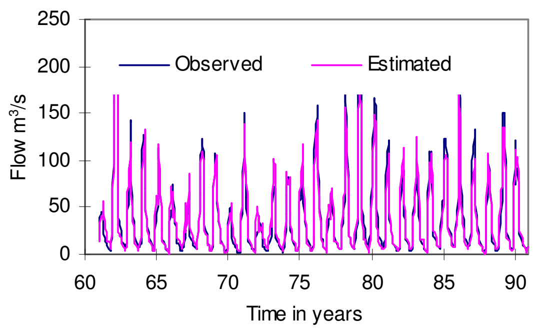
The following section is an analysis of the total renewable water resource as well as stream flow variation for selected river basin in Central and North Malawi.

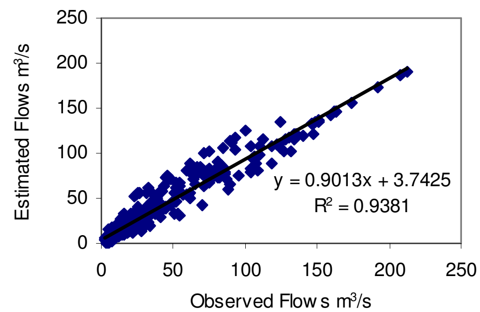
Bua



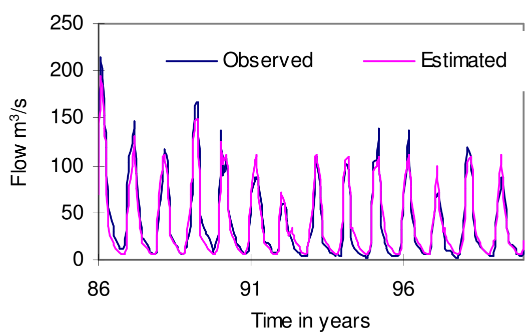


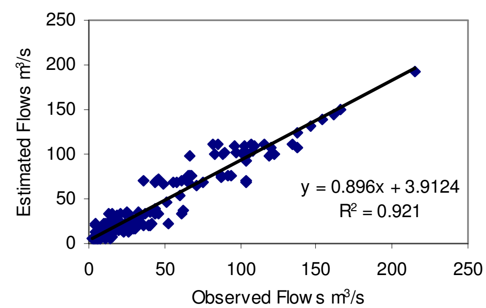
South Rukuru (7G14)



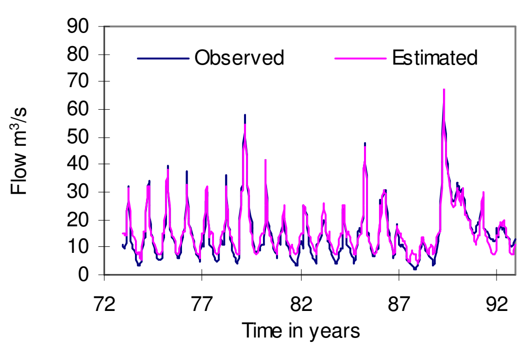


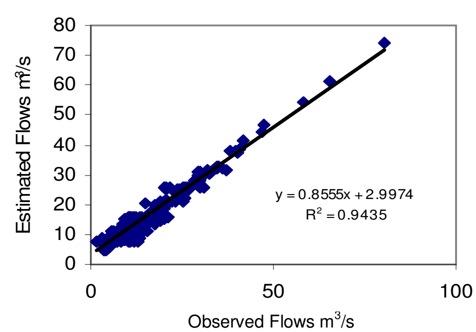
South Rukuru 7G18





Dwambazi

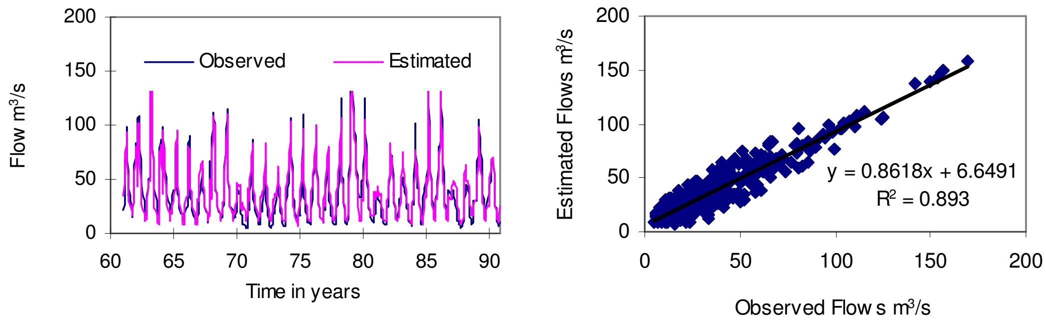




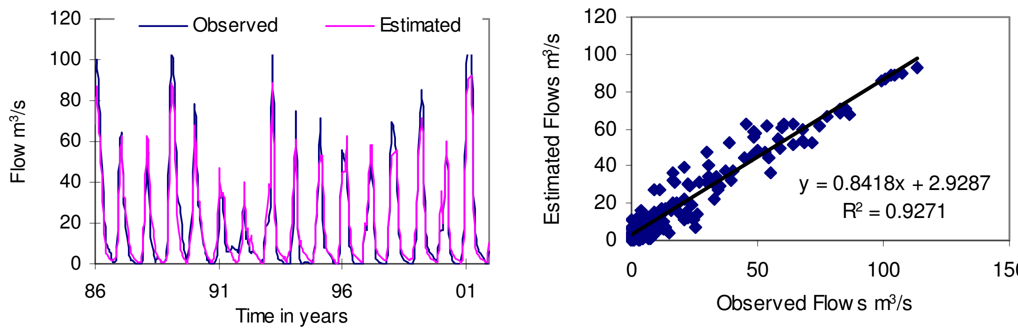
Observed and estimated flow	Correlation of estimated and observed

Figure 3.28 Estimated flows and Observed flows for filling missing data

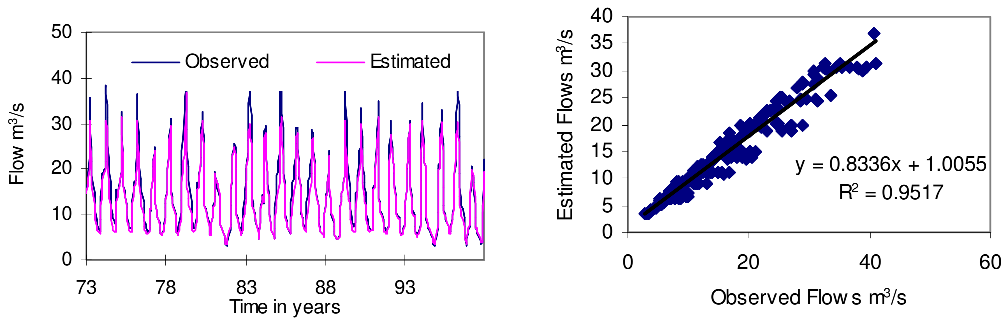
Luweya



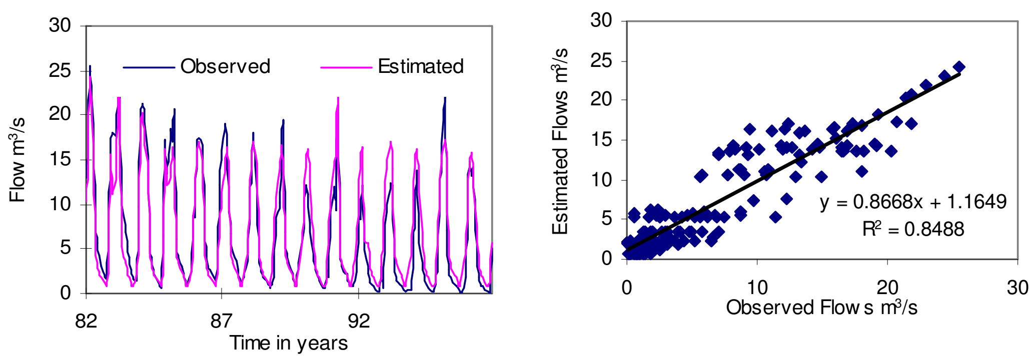
Dwangwa 6D10



North Rumphi 7H3



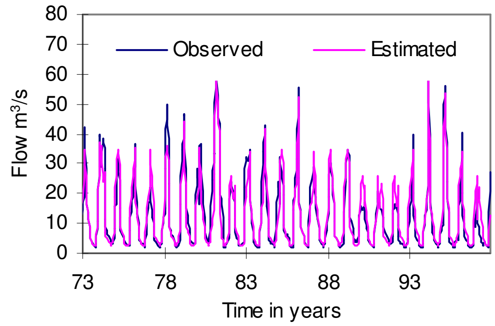
Lufira 9A2

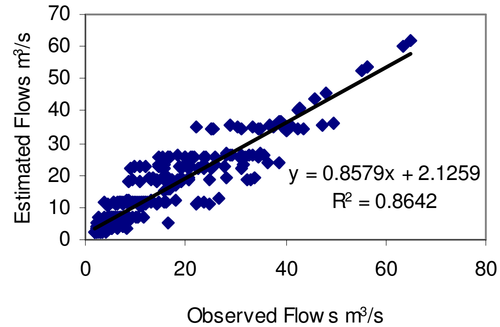


Observed and estimated flow	Correlation of estimated and observed

Figure 3.28 Estimated flows and Observed flows for filling missing data Continued

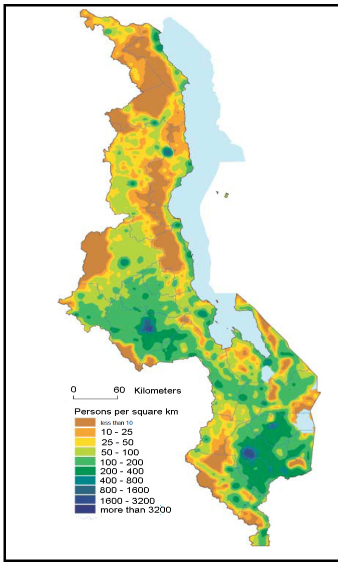
North Rukuru





Observed and estimated flow	Correlation of estimated and observed

Figure 3.28 Estimated flows and Observed flows for filling missing data Continued



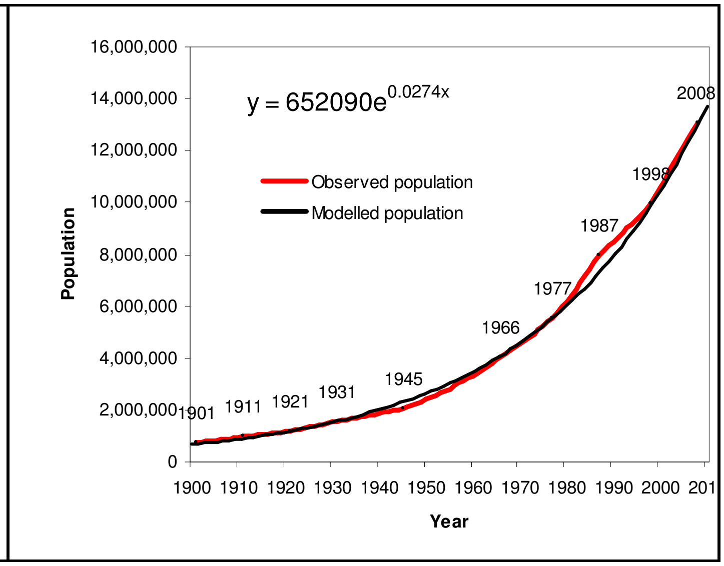


Figure 3.29 Malawi population distribution as of 2008 and population at successive census (NSOM, 2008).

3.4.2 Total renewable water resource per capita

The reliability and sustainability of multipurpose projects depends on the variation of the stream flow as well as the rainfall. River flow and rainfall variation of the catchment areas under study as well as stress on the available water resources was analysed for Central and North Malawi basins. This required information on population distribution and licensed water use within each basin. Data on licensed water use within each basin was collected from the Ministry of Irrigation and Water, Water Resources Board. Total renewable water resource per capita and the stress due to water allocation were calculated based on spatial distribution of the population in each basin. Data on population distribution was collected from the National Statistical Office Malawi NSOM in Zomba. NSOM is the main government department responsible for the collection and dissemination of official government statistics. NSOM is responsible for conducting housing and population census with most recent one being concluded in 2008. The history of census in Malawi dates back to1891 when the country was a British Colony and by 1901 the population in Malawi was only 737,000 (NSOM, 2006; NSOM, 2008). Currently the population is at 13,066,440. The population grew from 9,933,868 in 1998 representing a population growth rate of 32 percent in 10 years(NSOM, 2008). According to NSOM report on 2008 population census, Southern Region has the highest population of 5,876,784 (45 percent) followed by the Central Region, 5,491,034 (42 percent) and Northern Region, 1,698,502 (13 percent).

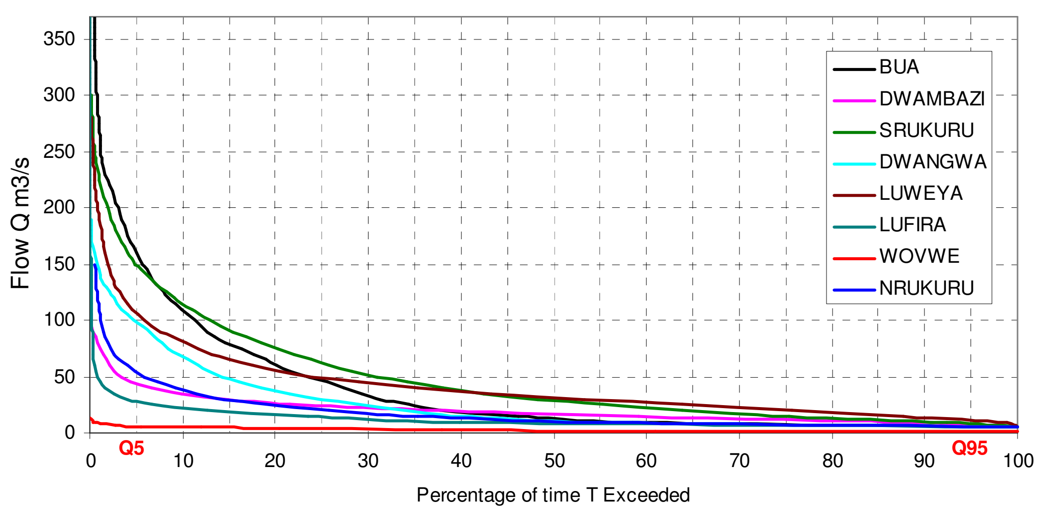


Figure 3.30 Flow duration curves indicating river flow variation in terms of high and low flows

Total Renewable Water Resource (TRWR) per capita was calculated as annual volume of water for a particular basin divided by the population within the basin TRWR per capita and annual rain days were taken into consideration in the assumption of Q5/Q95 (Gleick, 1996) from the flow duration curve in assessing the extent to which surface flows varies. The convention was to refer to the flow corresponding to an exceedence probability x as Qx. The exceedence probability is expressed as the percentage of time that a flow is exceeded; hence Q5 is the streamflow exceeded 5 percent of the time and similarly Q95 is the streamflow exceeded 95 percent of the time as shown in Figure 3.30. Thus a Flow Duration Curve provides the proportion of the time (duration) a specific flow is equalled or exceeded. It is sometimes referred to as the signature of the catchment, as it describes its behaviour and response. Flow duration curves for the various catchments were plotted and the relationship to characterise the flow variation of the northern highland river basins of Malawi as shown in Figure 3.30. Table 3.7 is a summary of the analysed hydrological parameters of the study area. According to Falkenmark (1991) 1,700 m^3/capita/year is enough to meet the water requirements for a community whereas a TRWR of less than 500 m^3/capita/year is a main constraint to life, economic development, human life and well being. All the rivers have enough water to meet the water requirement for the community except Bua river. Bua river has the lowest TRWR of 1,170 m^3/capita/year. This is due to the high population and large scale agricultural activities within the basin. In terms of flow variability, Bua has a high flow variability of (Q5/Q95 =30) seconded by South Rukuru (18.13) then Dwangwa river (15.18). High variation in these river basins could be attributed to catchment degradation due large scale agricultural activities. During the rainfall season a greater proportion of the rainfall flows straight into the river channel as stream runoff instead of being retained as groundwater due deforested catchment. Q5/Q95 ratio does not give a clear indication on how the flow varies throughout the year. It was therefore felt necessary to plot seasonal hydrological diagrams to characterise the flow and rainfall variation throughout the year.

3.4.3 Seasonal variation of runoff and rainfall

The hydrological climate variation of the catchment was expressed by hydrological graphs showing the expected variation throughout the year of rainfall and discharge. Seasonal mean $\bar{y}_d$ values were obtained from the daily series, by calculating the average for a particular day in a particular month in all the years available as shown in equation 3.1. According to Kachroo and Liang (1998), as the number of years become large, the estimate of the seasonal mean value is expected to approach a smoothly varying function of date. To remove small sample fluctuations, the values obtained by equation 3.1 were smoothed by Fourier series.

Table 3.7 Summary of the analysed hydrological parameters of Central and North Malawi

River	Lufira	Rumphi	Nrukuru	Wovwe	Mlowe	Bua	Srukuru	Dwambazi	Luweya	Dwangwa
Area (km^2)	1410	683	2128	489	120	10654	12088	778	2381	7610
Daily flow m^3/s	6.908	15.6	15.6	1.834	2.051	34.266	42.739	15.297	36.485	19.88
MAR mm	1249	1513	1285	1378	1280	960	1163	1125	1374	954
Q5/Q95	4.36	5.71	10	26	6	30	18.13	5.67	8.33	15.67
AAF m^3/yr million	217.85	511.93	492.51	57.9	64.73	1080.63	1347.83	482.68	1,152.14	627.67
Population	46,671	25,672	64,723	15,090	287	922,828	693,449	5,566	72,159	428,267
TRWR m^3/capi/yr	4,668	19,941	7,610	3,837	225,534	1,171	1,944	86,727	15,967	1,466
WS m^3/day	6,212	8,614		2,008		130,174	83,706	755	9,058	58,117
IRR m^3/day	97,773	1		67,886		92,811	32,313	23	92,309	622,006
LU m^3/yr Million	37.9544	1.1311	3.1445	25.511	0.0139	81.389	42.3469	0.284	36.999	248.245
LU/AAF	17.42	0.22	0.64	44.06	0.02	7.53	3.14	0.06	3.21	39.55
LU = Licensed Use, AAF = Annual Average Flow, MAR = Mean Annual Rainfall										

$$y_d = a_0 + \sum_{j=1}^{p} A_j \cos\left(\frac{2\pi jd}{n}\right) + B_j \sin\left(\frac{2\pi jd}{n}\right) \qquad 3.7$$

where a_o is the mean of y_d, A_j and B_j are the Fourier coefficients, *j* is the order of harmonic, p is the maximum number of harmonics and *n* is equal to 365 for a daily series. The values of A_j and B_j were estimated from the following equations:

$$A_j = \frac{2}{n} \sum_{d=1}^{n} y_d \cos\left(\frac{2\pi jd}{n}\right) \quad j = 1,2,\dots\dots\dots p \qquad 3.8$$

$$B_j = \frac{2}{n} \sum_{d=1}^{n} y_d \sin\left(\frac{2\pi jd}{n}\right) \quad j = 1,2,\dots\dots\dots p \qquad 3.9$$

Smoothing was achieved by the first four harmonics. Smoothing of daily streamflow or rainfall series is achieved by using only the first few harmonics, usually four or five harmonics (Kachroo *et al.*, 1992b). The results of seasonal hydrological graphs (Figure 3.31) of the highland catchments show that there is one high flow season in all the catchments, which occurs between January and May and low flow season, which occurs from June to November. The hydrological graphs of Dwambazi and Luweya show that these catchments have a base flow contribution in the dry season. This was depicted by the river flow graphs passing over the smoothed rainfall diagram. These two catchments have a capability of maintaining a reasonable flow in the dry season.

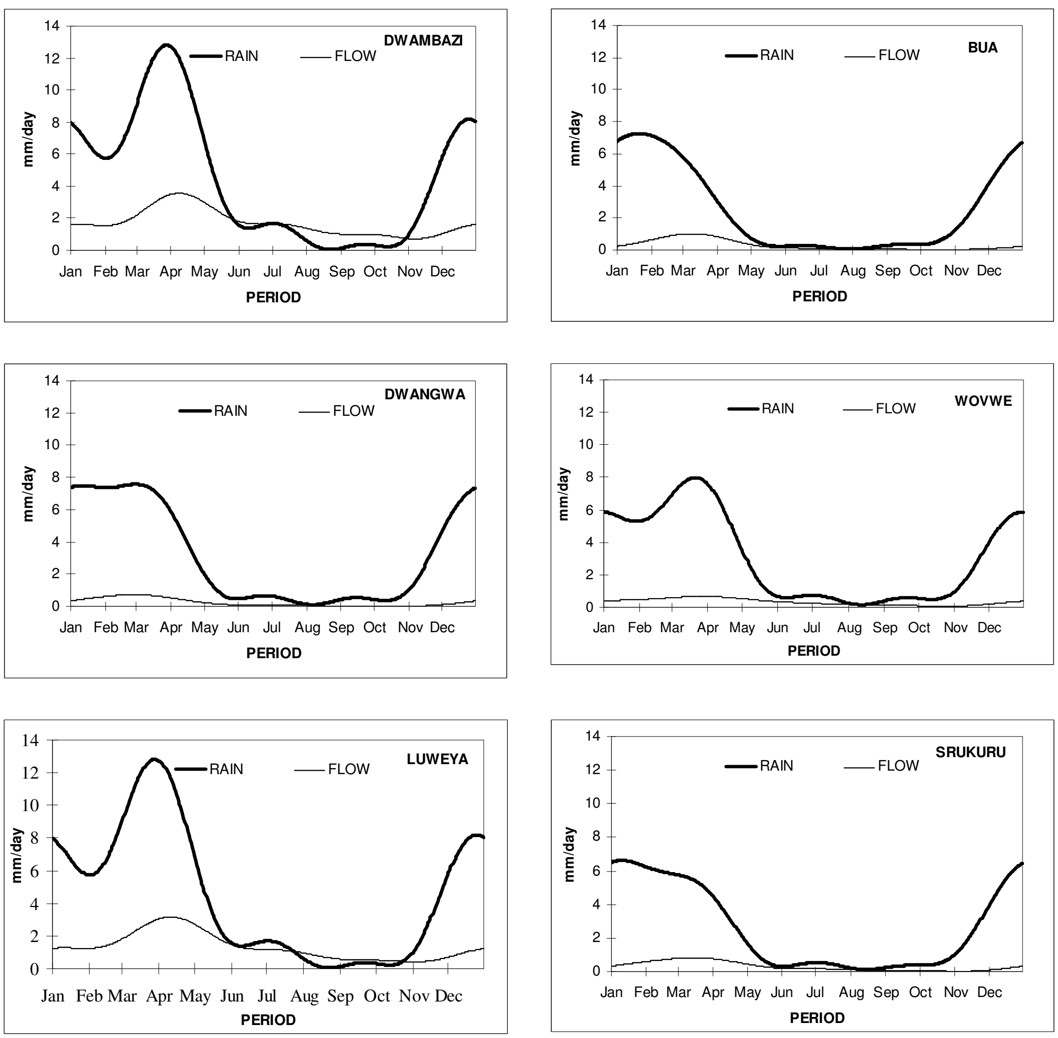


Figure 3.31 Seasonal hydrological graphs of Central and North Malawi river basins (Kumambala and Ervine, 2008)

3.5 SUMMARY OF AVAILABLE DATA

In this chapter the catchment areas of Central and North Malawi highlands have been described in terms of hydrology and land use. In addition variation in water levels of Lake Malawi as well as outflow regulation from Lake Malawi at Liwonde barrage has been investigated. The hydrological data covered in this chapter includes, river flow data, rainfall and times series of the water levels of Lake Malawi. Available climate data in terms of temperature, humidity and wind speed within the area has also been investigated. Complete data set for the study area is appended in the CD in the appendix.

The major challenge observed on the available data in the study area is scarcity of hydrological data, gaps in the few available data and closure of some of the hydrological stations. This required filling the missing gaps within the data to create a complete data set for the study area, which allows the project to be set in context. A complete data set will form the basis for hydrological modelling of the catchment areas under the study. Hydrological models coupled with General Circulation Models will be used to assess the impact of climate change on the water resources within the catchment areas as well as the water levels of Lake Malawi based on developed future climate scenarios. A complete climate data set can now be used to develop an evaporation decision support tool for catchment areas under the study and Lake Malawi. The tool will be incorporated in the Lake Malawi water balance model in assessing the future water levels of Lake Malawi.

Based on the complete data set water resources sustainability index (WRSI) can now be developed for Malawi. WRSI is the main tool being used to assess the long term sustainability development of water resources in the study area and forming the basis for a water resources investment strategy for Malawi.

CHAPTER 4

MODELLING CLIMATE CHANGE IMPACT ON WATER RESOURCES IN CENTRAL AND NORTH MALAWI

4.1 INTRODUCTION

To assess the overall sustainability of the water resources of the northern highland river basins of Malawi and the water levels of Lake Malawi, it is necessary to model or estimate how the renewable water resource will behave in the future. It is now generally accepted in literature that the future water availability will be affected not only by population increase but also by climate change. Such changes will have far reaching consequences on every aspect of human well being, ranging from agricultural and energy production to flood control and ecology of freshwater environments. Modelling the impact of climate change on water resources will require long term data including past and estimated future data set as input in hydrological models to estimate the future flow pattern as well as future fluctuation of water levels of Lake Malawi.

This Chapter presents climate change consequences for water resources of Central and North Malawi and Lake Malawi based on climate projections of general circulation models. The Chapter also explores the downscaling of temperature data from general circulation models to be used in Chapter 5 to simulate future evaporation for the water balance model of Lake Malawi. Future climate predictions requires general circulation models for simulating future climate pattern in terms of temperature and rainfall

4.2 CLIMATE CHANGE DATA – TEMPERATURE AND PRECIPITATION

General circulation models (GCMs) for simulating future climate data for temperature and rainfall were obtained from the United Kingdom (UK) Meteorological Office Hadley Centre (IPCC-DDC, 2008). The Hadley Centre is responsible for climate change prediction work and they distribute data through IPCC Data Distribution Centre (IPCC-DDC). IPCC-DDC is designed primarily for climate change researchers and provides climate, socio-economic and environmental data, both from the past and also in scenarios projected into the future (IPCC, 2000).

Research at the Hadley Centre involves validation of GCMs based on baseline data from 1961 – 1990. GCM data from Hadley Centre are derived from UK Meteorological Office coupled ocean-atmosphere GCM (HadCM3) experiments and normalized over the period 1961 – 1990 (IPCC, 2000). The period 1961 – 1990 is the standard baseline period set by IPCC based on World Meteorological Organization (WMO) normal period. GCMs are derived based on emission scenarios which were developed by IPCC in 2000. Emission scenarios are alternative images regarding how the future will be in terms of greenhouse gas emission.

4.3 EMISSION SCENARIOS

Studies on climate change impact rely much on projection of future human activities. IPCC has recognised the need for future emission scenarios to be used in driving GCM to develop climate change scenarios. In 2000, IPCC published the Special Report on Emission Scenarios (SRES) for its Third Assessment Report (TAR) in 2001. SRES 2000 have replaced IS92 scenarios which were used in Second Assessment Report (SAR) of 1995. According to IPCC (2007), scenarios are viewed as an alternative image of the future based on projected future socio-economic, demographic and technological change. IPCC scenarios were developed to represent the range of deriving forces and emission based on extensive assessment of the driving forces and emissions in the scientific literature (IPCC, 2000). IPCC emission scenarios are organized into four main families (A1, B1, A2, and B2) and three subsets of the A1 family (A1T, A1B and A1FI) as shown in Figure 4.1 and Figure 4.2.

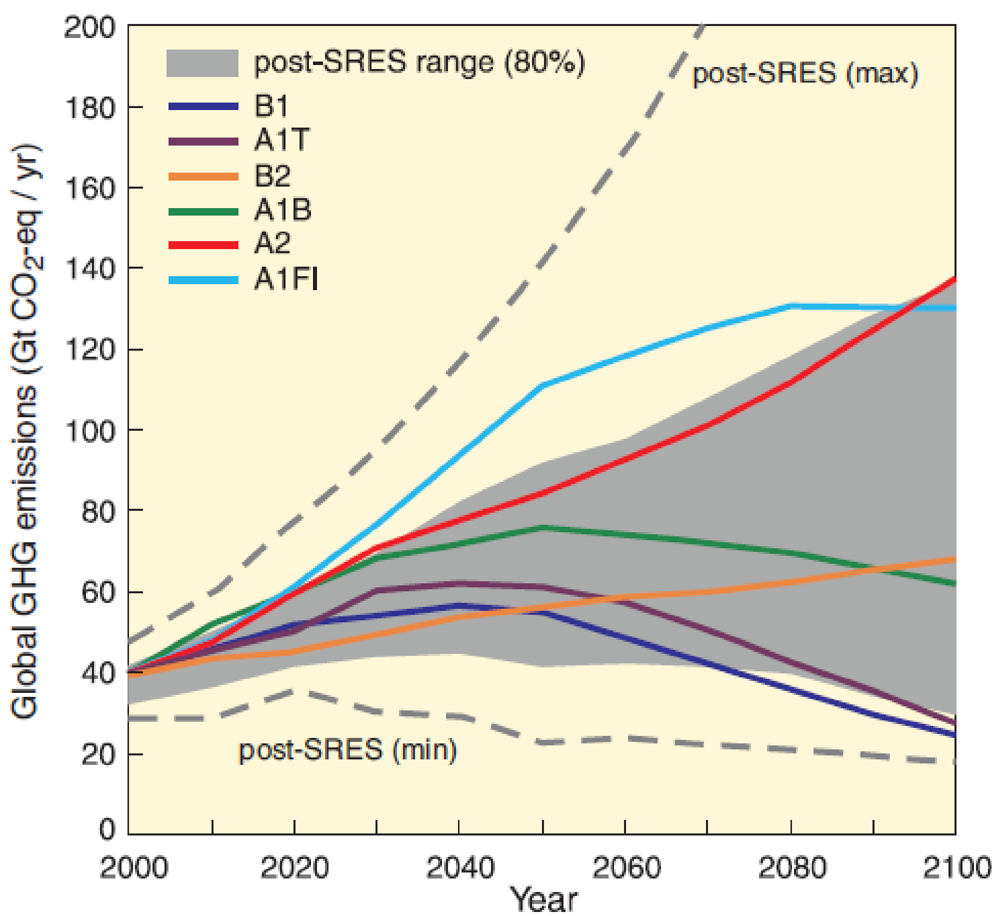


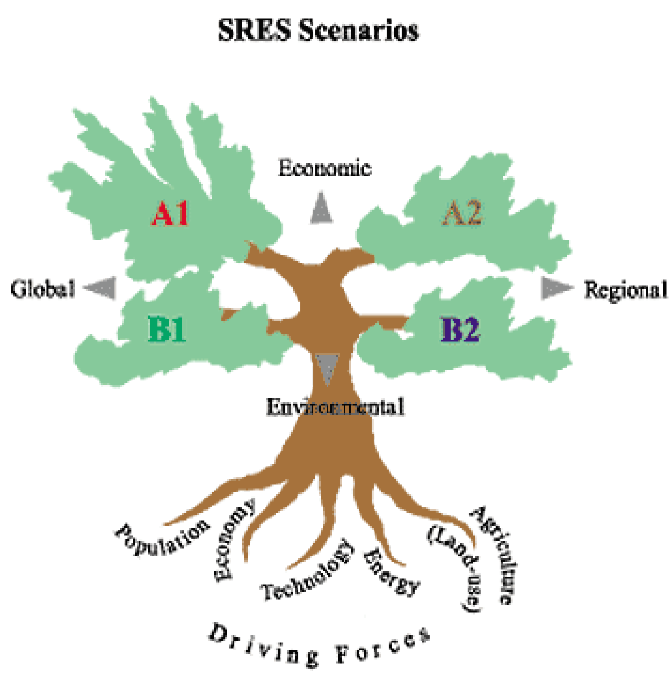
Figure 4.1 Global GHG emissions (in GtCO2-eq per year) in the absence of additional climate policies (IPCC, 2007)

<u>A1 Family</u>

- more integrated world of rapid economic growth with a global population that reaches 9 billion in 2050
- world with new and more efficient technologies
- extensive social and cultural interaction world wide and a convergence in terms of income and way of life between nations

<u>A2 Family</u>

- a more divided world with high population growth, slow economic growth and technological development.
- independently operating nations with regionally oriented economic development



<u>B1 Family</u>

- integrated world with population growth as A1 family, but with more rapid changes in economic structure towards a service and information economy
- future reduction in material intensity and introduction of clean resource and efficient technologies with emphasis on global solutions to economic, social and environmental stability

<u>B2 Family</u>

- a world more divided but more ecologically friendly like B1 family with slower population growth than the A2 family
- emphasis on local solution to economic, social and environmental stability with less rapid and more fragmented technological change than the A1 and B1 families

Figure 4.2 Summary of characteristics of different families (A1, A2, B1 and B2) of IPCC emission scenarios. (IPCC, 2000)

The A1 family has subsets which describe alternative direction of technologies:

- A1F1 which assumes an emphasis on fossil fuels,
- A1B which assumes a balance on energy sources and
- A1T which assumes emphasis on non-fossil energy source.

GCM outputs from the UK HadCM3 experiments derived based on different emission scenarios have a resolution of 2.5^{O} latitude x 3.5^{O} longitude. The course resolution of the GCM makes it difficult to take into account features on the landscape such as hills and lakes which can influence the local climate (Wilby and Dawson, 2007). In view of this climate researchers have developed tools for downscaling GCM outputs to the required area utilizing either dynamical or statistical methods. Details of the two methods have been outlined in section 2.4 of Chapter 2. This study has utilized the downscaled results obtained by using the Statistical Downscaling Model (SDSM) developed by (Wilby *et al.*, 2002) which was downloaded from the SDSM UK web site (www.sdsm.org.uk). A systematic diagram of the SDSM downscaling process is presented in Figure 4.3 with a detailed explanation of the method in section 4.4.

4.4 STATISTICAL DOWNSCALING METHOD (SDSM)

As described earlier on in section 2.4, statistical methods have several advantages over dynamical methods ranging from low cost to rapid and simplicity of use. In this research, the SDSM developed by Wilby and Dawson (2007) at Kings College London has been used in constructing climate change scenarios for catchment areas of Malawi using grid resolution GCM outputs from the HadCM3 experiments. SDSM combines a stochastic weather generator and transfer function method to relate large scale GCM outputs (the “predictors”) to local variables such as precipitation (the “predictands”) (Wilby and Dawson, 2007; Wilby *et al.*, 1999). This is based on the fundamental assumption that regional climate is conditioned by local physio-graphic characteristics as well as the larger atmospheric state. According to Wilby and

Dawson (2007), SDSM reduces the task of downscaling GCM outputs into five steps as detailed in Figure 4.3 by yellow boxes: selection of predictor variables from GCM outputs; model calibration against measured data; synthesis of observed data; generation of climate change scenarios; and finally statistical and graphical comparison of the results.

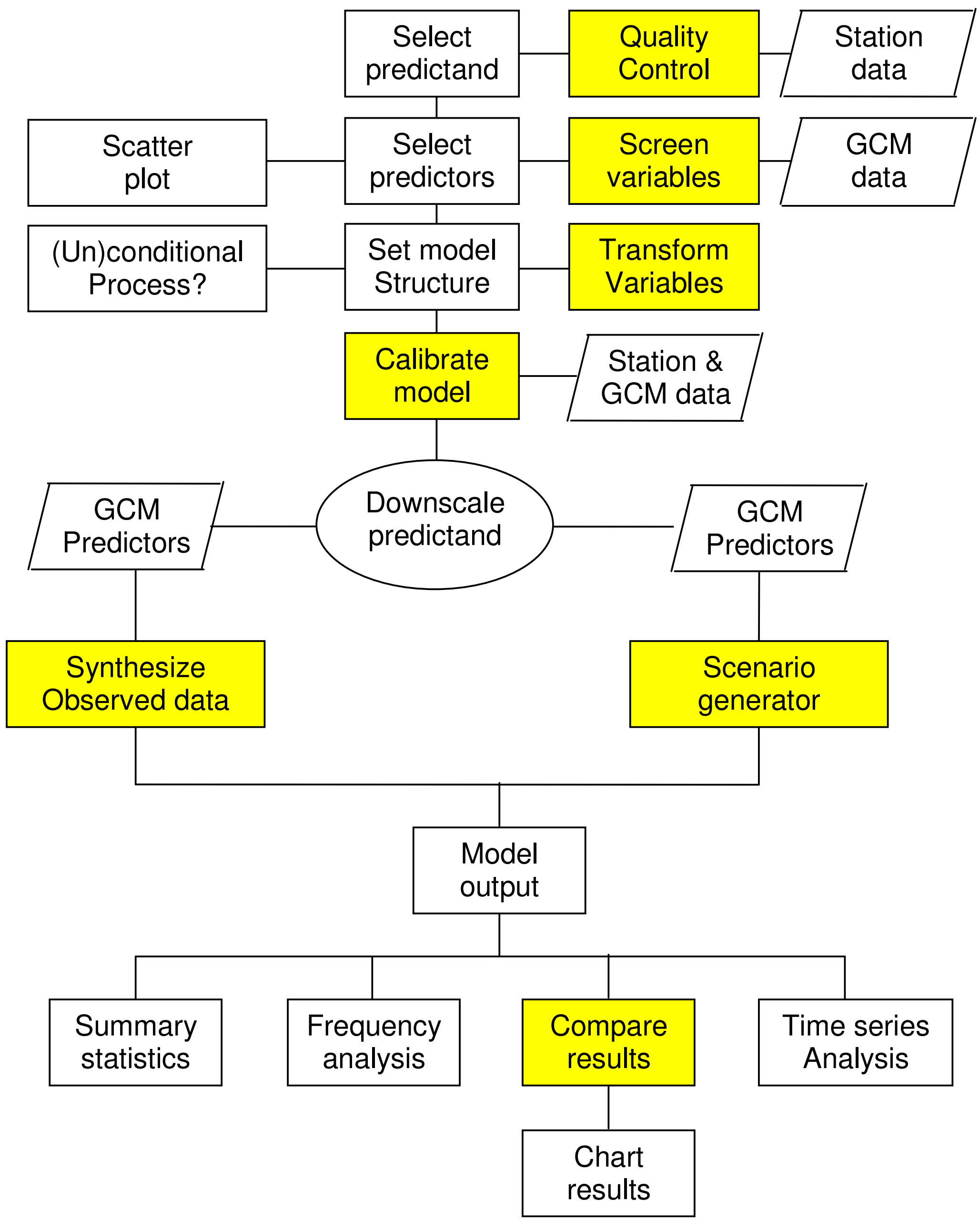


Figure 4.3 SDSM generation process adopted from (Wilby and Dawson, 2007)

There are several techniques available for downscaling GCM outputs into daily meteorological variables for use in hydrological studies. However, it is not yet clear which method provides the most reliable estimates for future climatic conditions since different climate models give different results (Dibike and Coulibaly, 2005). However downscaled results by any method can provide a better range of uncertainty for climatic and statistical indices (IPCC, 2007). Downscaling methods depends on the purpose of the study and the available data. The SDSM employed in this research requires daily observed data which was readily available in the study area. The SDSM facilitates the generation of ensembles of future climatic realisations that is a prerequisite to confidence estimation due to the stochastic nature of the model. SDSM may easily be tuned to reproduce the unique meteorological characteristics of individual station that is a valuable asset in heterogeneous landscapes or mountain terrain. The technique is far less data intensive and computationally demanding than other downscaling techniques (Wilby *et al*., 1999).

4.4.1 Preliminary assessment of the changes in North and Central Malawi rainfall and temperature (1961 to 1990)

Before applying the SDSM model to the available rainfall and temperature data, a preliminary analysis of the changes in the average rainfall and temperature data for Central and North Malawi catchments shown in Figure 3.1 was done. Available rainfall and temperature data from 1961 to 1990 was plotted and simple linear regression was used to assess whether the trend in rainfall/temperature was increasing or decreasing in the region. Figure 4.4(a) shows that rainfall is decreasing in Central and North Malawi river basins as the gradient of the trend line is negative. Figure 4.4 (b) and (c) shows that both maximum and minimum temperatures are increasing in Central and North Malawi river basins as the gradient of the trend lines for both maximum and minimum temperature are positive. The observed changes in the available rainfall and temperature data as shown in Figure 4.4 can be summarized as follows :-

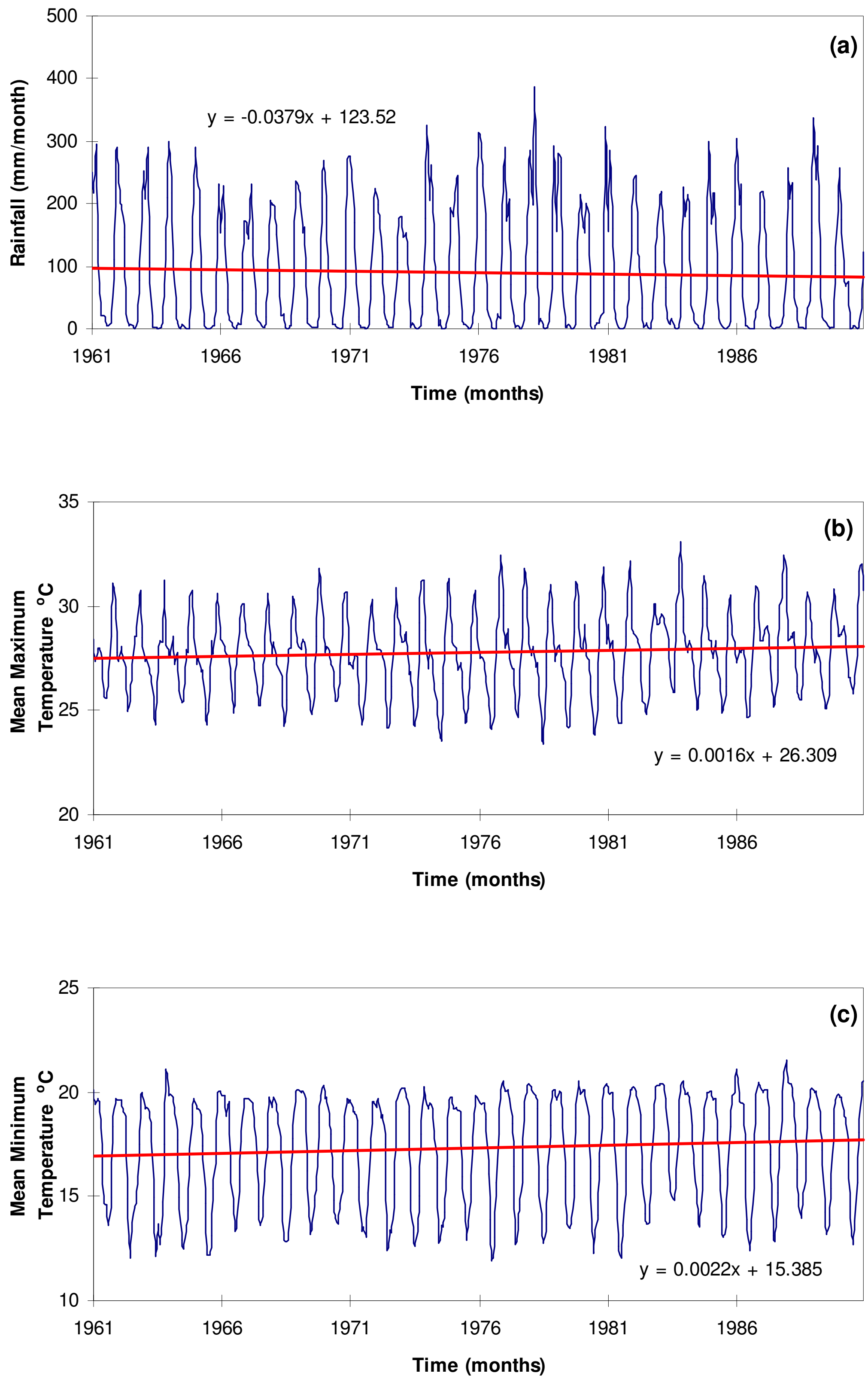


Figure 4.4 Observed changes in average rainfall and temperature for Central and North Malawi. Source of data:- (MetD, 2009).

- There is no consistency in the changes in rainfall although the gradient line in Figure 4.4(a) is indicating a decrease in rainfall. The rainfall pattern shows high rainfalls in others years followed by low rainfall in others years;
- mean annual maximum temperature has increased by 0.74 ^{0}C between 1961 and 1990 (27.84 ^{0}C in 1961 and 28.59 ^{0}C in 1990) (Figure 4.4(b));
- mean annual minimum temperature has increased by 0.48 ^{0}C between 1961 and 1990 (17.022 ^{0}C in 1961 and 17.50 ^{0}C in 1990) (Figure 4.4(c))

4.4.2 HadCM3 GCM downscaling using SDSM

Wilby and Dawson (2007) have described the SDSM model as a hybrid of stochastic weather generators and regression based techniques used to linearly correlate large scale GCM parameters to local scale weather generator parameters such as rainfall occurrence and intensity. As described in Figure 4.3 downscaling using SDSM starts with the assembly of predictand and predictors. Selection of predictand requires quality control and data transformation since few meteorological stations have 100 percent complete and fully accurate data sets. Through the quality control scheme, the SDSM has the capability to identify gross data errors, missing data as well as outliers before model calibration. Once the predictand (for example rainfall or temperature) has been identified the screen variable operation assist in the selection of the required downscaling predictor variables based on correlation between predictand and predictors. Researchers have now recognised that screening of downscaling predicator variables is the most challenging stage in the development of statistical downscaling model because downscaled climate scenario depends on the character of the selected predictors (Charles *et al*., 1999; Huth, 1999). Predictor variables used for downscaling are required to satisfy a number of criteria as outlined below (Charles *et al*., 1999; Wilby and Wigley, 2000):

- The predictor variables used should be both physically and conceptually sensible in terms of the known meteorological variables such as rainfall or temperature,

- The predictors should ideally be continuous variables in order to model extreme events,
- The predictor variables should be accurately modelled and readily available from GCM output based on the available historical data,
- The predictor variables should be strongly correlated with a suite of relevant hydro meteorological variables,
- The predictors should preserve observable correlations between downscaled parameters,
- Time series of the predictor variables should be responsive to greenhouse gas forcing.

Having selected the predictand such as rainfall along with a set of predictor variables based on the criteria by Charles *et al.* (1999) and Wilby and Wigley (2000), the SDSM requires model calibration. Calibration of SDSM involves computation of parameters of multiple regression model equation through an optimization algorithm of either simplex or ordinary least squares. The calibrated SDSM model is used to generate synthetic weather data based on observed GCM predictor variables. Synthetic data is finally graphically and statistically compared with the observed data. Once a good relationship has been established between the synthetic data and observed data, the calibrated model plus the model parameters are then used to generate future climate scenarios based on future GCM outputs from HadCM3 experiment.

4.4.3 Application of SDSM to river basins of Central and North Malawi

The SDSM model was applied to a number of river basins of Central and North Malawi using GCMs from UK HadCM3 experiments. In the first instance the SDSM model was calibrated using daily climate data of maximum and minimum temperature from the catchment areas under investigation as already detailed in Chapter 3. The SDSM model process can be classified either as conditional, based on the occurrence of an event (e.g. precipitation) or unconditional (e.g. temperature) (Wilby and Dawson, 2007). Daily precipitation, maximum and minimum temperature data were chosen as predictands for the downscaling experiment. In the case of maximum and minimum temperature, data from the six main climate stations within the study area were considered. Downscaled temperature was later used for estimating future evaporation patterns using Hargreaves temperature based method for evaporation in Chapter 5. In the case of rainfall for the river basin, areal rainfall for each basin was used in the downscaling exercise. Areal rainfall is the basin average rainfall. There are different techniques available in literature for estimating areal rainfall; including the Arithmetic mean method; the Thiessen polygon method; the inverse distance weighted and the Isohyetal method. In this research the inverse distance weighted method was considered as an appropriate method for calculating areal rainfall because of its capability in taking into consideration the distance between rainfall stations. This was important in view of the fact that rainfall stations are not evenly distributed within the study area.

4.4.4 Modelling daily rainfall occurrence

The modelling of daily rainfall was done in two steps: modelling daily precipitation occurrence followed by the modelling daily precipitation amounts. The random variation of daily precipitation occurrence O_i was modelled by the following equation (Hessami *et al.*, 2008):

$$O_i = \alpha_0 + \sum_{j=1}^{n} \alpha_j p_{ij} \qquad 4.1$$

where p_{ij} are predictors, n is the number of predictors, α_0 and α_j are the model parameters estimated using linear least squares regression. Once determined that precipitation had occurred, the precipitation amount R was downscaled based on the following regression model as described by Wilby *et al.* (1999):

$$R_i^{0.25} = \beta_0 + \sum_{j=1}^{n} \beta_j p_{ij} + e_i \qquad 4.2$$

where β are the model parameters estimated by linear least squares regression and e is the modelling error.

4.4.5 Modelling daily maximum and minimum temperature

Maximum and minimum daily temperatures were downscaled in one step on unconditional basis using the following regression equation described by Wilby *et al.* (2002)

$$T_i = \gamma_0 + \sum_{j=1}^{n} \gamma_j p_{ij} + e_i \qquad 4.3$$

where T_i is the maximum, minimum or mean daily temperature and γ is the model parameter. The model error term e_i was modelled under the assumption that it follows Gaussian distribution given by the following equation:

$$e_i = \left[\sqrt{VIF/12}\right] z_i S_e + b \qquad 4.4$$

where z_i is a normally distributed random number, S_e is the standard error of estimate, b is the model bias and VIF is the model variance inflation factor. The model variance inflation factor VIF and bias were calculated based on the following equation (Hessami *et al.*, 2008)):

$$b = M_{obs} - M_d \qquad 4.5$$

$$VIF = \frac{12(V_{obs} - V_d)}{S_e^2} \qquad 4.6$$

where V_{obs} is the variance of the observation during calibration and V_d is the variance of the deterministic part of model output with M_{obs} and M_d as their respective mean values

4.4.6 Selection of predictor variables for downscaling.

Predictors were selected from the HadCM3 data base through an iterative process partly based on extensive recommendations by Wilby and Dawson (2007) and Charles *et al.* (1999) as outlined in section 4.4.2 that predictor variables should correlate with the predictand such as rainfall. In addition to that, parameters selected as predictors should be based on those parameters that influence the predictand. This involves linear correlation and scatter plots between predictors and predictand variables. The method starts with all the terms in the model then removes the least significant terms until all the remaining terms are statistically significant based on correlation factors. Correlation factors are used as a measure of the strength of relationship between predictor variables and predictand such as rainfall and temperature. Correlation factors r_{xy} between predictor variables PX and predictand PY were calculated using the Pearson Product-Moment Correlation equation (Equation 4.7)(Wilby *et al*., 2002)

$$r_{xy} = \frac{\sum_{i=1}^{n}\left(PX_i - \overline{P}_X\right)\left(PY_i - \overline{P}_y\right)}{(n-1)S_x S_y} \qquad 4.7$$

n is the number of data points in the available predictand (rainfall, temperature) data, $\overline{P}_x$ and $\overline{P}_y$ are the means of PX and PY, S_x and S_y are standard deviation of PX and PY respectively.

Correlation of individual predictors with predictand varies on a month to month basis. In view of this, the final choice of predictors was made based on the analysis of twelve months. Table 4.1 is a list of daily predictor variables which are held in HadCM3 GCM data base. The selected predictor variables for rainfall and temperature are marked XXXX in rainfall and temperature column respectively in Table 4.1. Table 4.2 and Table 4.3 are correlation factors for selected predictor variables against the respective predictand such as temperature and rainfall. The typical range of correlation factors is from -1.0 to 1.0. A factor of -1.0 indicates lack of correlation between the predictor and the predictand while a correlation factor of 1.0 indicates a strong correlation between the predictor and the predictand. In the case of maximum and minimum temperature the autoregression component had the highest correlation ranging from 0.785 (Mzuzu station, maximum temperature under A2 Family) to 0.908 (Nkhatabay station, minimum temperature under A2 Family) as shown in Table 4.2. The auto regression was seconded by the mean temperature predictor. The other predictor variables listed in Table 4.1 had negative correlation factors and were not considered for the downscaling experiment.

Table 4.1 Large scale predictor variables held in HadCM3 and NECP data archive by IPCC-Data Distribution Centre.

Item	Daily variable	Code	Rainfall	Temperature
			Selected predictor	
1	Mean temperature temp	temp		xxxx
2	Mean sea level pressure	mslp		
3	500 hPa geopotential height	p500		
4	850 hPa geopotential height	p850		
5	Near surface relative humidity	rhum		
6	Relative humidity at 500 hPa height	r500		
7	Relative humidity at 850 hPa height	r850		
8	Near surface specific humidity	shum	xxxx	xxxx
9	Geostrophic airflow velocity	**_f		
10	Vorticity	**_z		
11	Zonal velocity component	**_u		
12	Meridional velocity component	**_v	xxxx	
13	Wind direction	**th		
14	Divergence	**zh		

Correlation factors for precipitation are presented in Table 4.3. Near surface specific humidity and meridional wind velocity component are the only predictor variables with positive correlation factors and were considered for the precipitation downscaling experiment. GCMs from UK HadCM3 A2 and B2 scenario families were considered for the downscaling experiment because the two families are the ones that represent a more realistic case for Malawi and the world at present as described in Figure 4.2.

Table 4.2 Correlation factors of predicator variables with maximum and minimum temperature for six main climate station of Central and North Malawi.

Station	Correlation of Maximum Temperature predictors				Correlation of Minimum Temperature predictors			
	A2 Family		B2 Family		A2 Family		B2 Family	
	Auto	Temp	Auto	Temp	Auto	Temp	Auto	Temp
Chitedze	0.785	0.437	0.735	0.436	0.841	0.561	0.842	0.555
Salima	0.828	0.604	0.828	0.605	0.821	0.581	0.821	0.581
Nkhatabay	0.793	0.551	0.793	0.556	0.908	0.491	0.908	0.487
Mzuzu	0.836	0.588	0.836	0.585	0.869	0.319	0.869	0.319
Karonga	0.814	0.583	0.814	0.585	0.842	0.473	0.842	0.472
Nkhotakota	0.833	0.621	0.833	0.621	0.887	0.606	0.887	0.604
Auto = Auto regression term of the SDSM .								

Table 4.3 Correlation factors of predictor variables with precipitation for seven main river basins of Central and North Malawi.

River basin	Correlation of precipitation predictors			
	A2 Family		B2 Family	
	Shum	velocity	Shum	velocity
Bua	0.49	0.345	0.486	0.345
Dwangwa	0.409	0.376	0.411	0.376
Dwambazi	0.484	0.332	0.484	0.332
Luweya	0.487	0.367	0.487	0.367
South Rukuru	0.38	0.329	0.38	0.329
North Rukuru	0.269	0.227	0.269	0.227
Lufira	0.347	0.301	0.347	0.301
Shum = Near surface specific humidity Velocity = Velocity component				

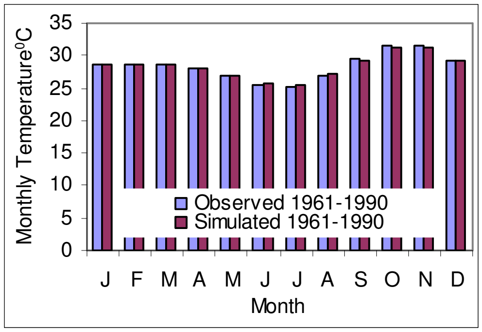
4.4.7 Downscaling temperature for Central and North Malawi

Maximum and minimum temperature data from 6 climate stations in Central and North Malawi which have a complete record of climate data was used for calibration and validation of the SDSM model. The climate stations are Chitedze, Salima, Nkhotakota, Nkhatabay, Mzuzu and Karonga. These climate stations are evenly spread over the study area as shown in Figure 3.17. The available data was split in two parts with the first 30 years (1961 – 1990) used for calibrating the SDSM regression models and the remaining 10 years (1991 – 2000) was used for validating the SDSM models. The performance of the model in both periods was presented as graphs shown in Figure 4.5 to Figure 4.8. The graphs show a good agreement between the observed and simulated temperatures using HadCM GCM scenarios. It has also been observed that the model managed to reproduce the seasonal variation of temperature for all the six climate stations. The results of future scenario in Figure 4.5 to Figure 4.8 show that the percentage change in temperature under H3B2 GCM emission scenarios is lower than the percentage change under H3A2 GCM emission scenario for both maximum and minimum temperature for all the six climate stations. This is because H3B2 family of emission scenarios emphasises on environmental sustainability as described in Figure 4.2. Hence, less emission in future projected greenhouse gas resulting in a small change in the projected temperature. Major change in maximum temperature is expected in the months of January up to June under both emission scenarios. In the case of minimum temperature, major changes are expected in the months of May, August up to September under both emission scenarios (Figure 4.5 to Figure 4.8).

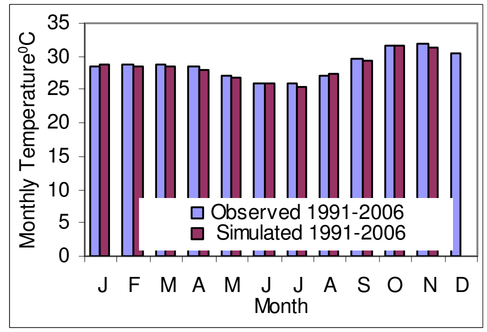
The residuals in the calibration period were analysed and presented in Figure 4.9 and Table 4.4. It has been observed that the errors in simulating minimum and maximum temperature are normally distributed with a mean negative error for all the main six climate stations. Further analysis of errors has revealed that mean error of estimate by H3A2 GCMs is similar to the mean error of estimate by H3B2 GCMs when simulating minimum temperature. A similar trend was observed when simulating maximum temperature. Large error values have been observed from the Nkhatabay climate station. This could be attributed to an error in the data records as well as model failure.

Figure 4.5 Calibration and validation and future scenario of maximum temperature pattern based on H3A2 HadCM GCM emission scenarios.

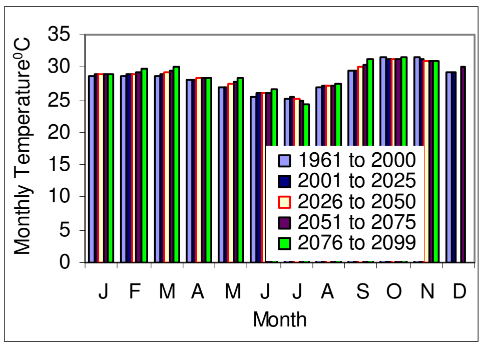
Nkhotakota



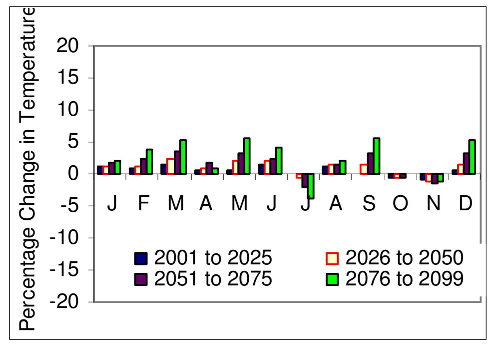
Calibration



Verification

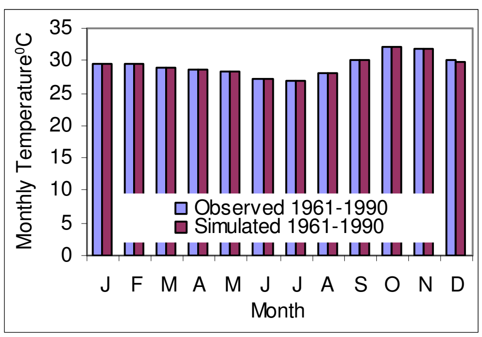


Future Scenario

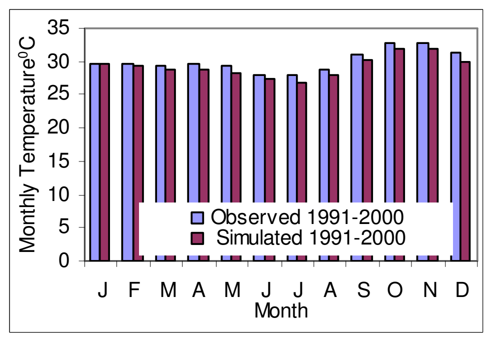


Percentage change

Karonga



Calibration



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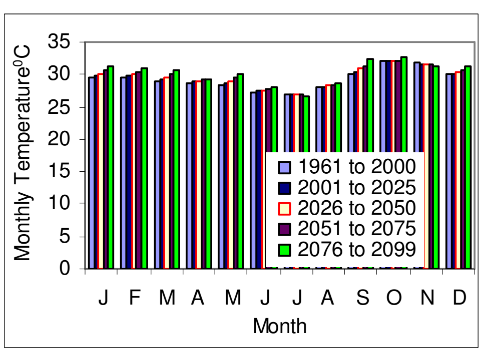
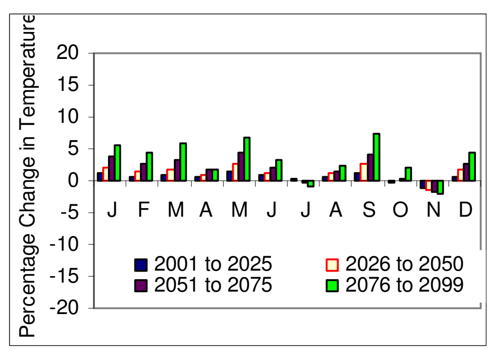


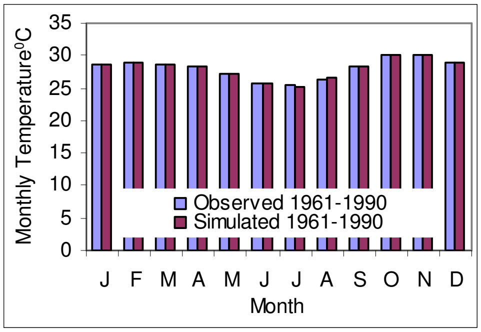
Future Scenario



Percentage change

Figure 4.5 Continued

Nkhatabay



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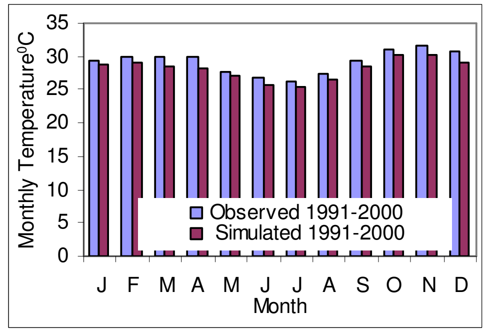

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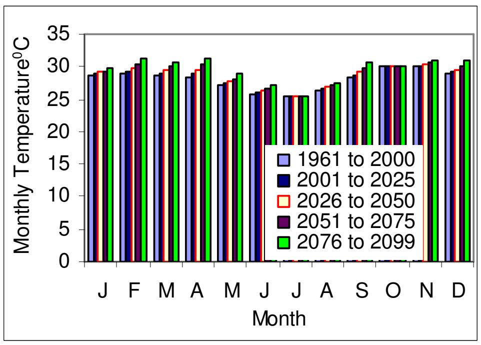
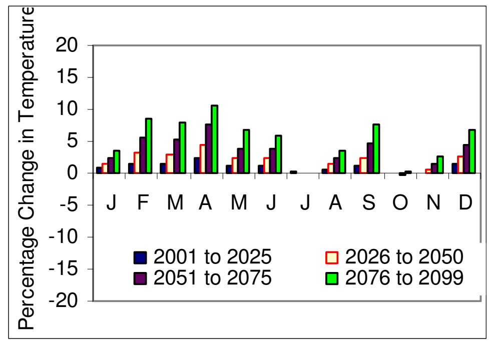
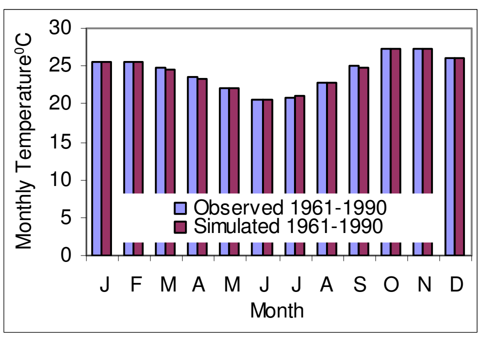


Future Scenario



Percentage change

Mzuzu



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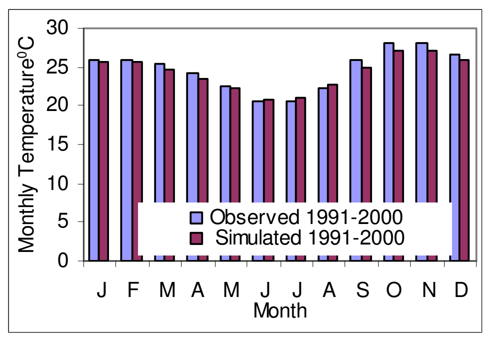

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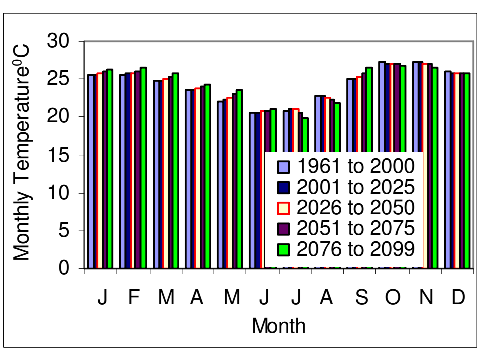
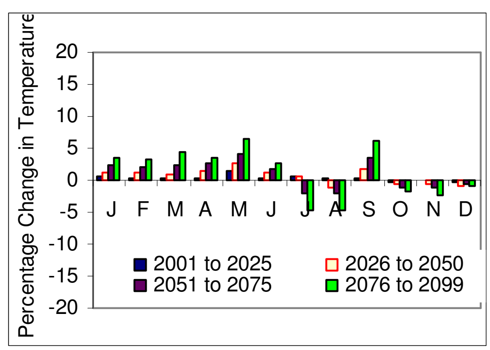


Future Scenario



Percentage change

Figure 4.5 Continued

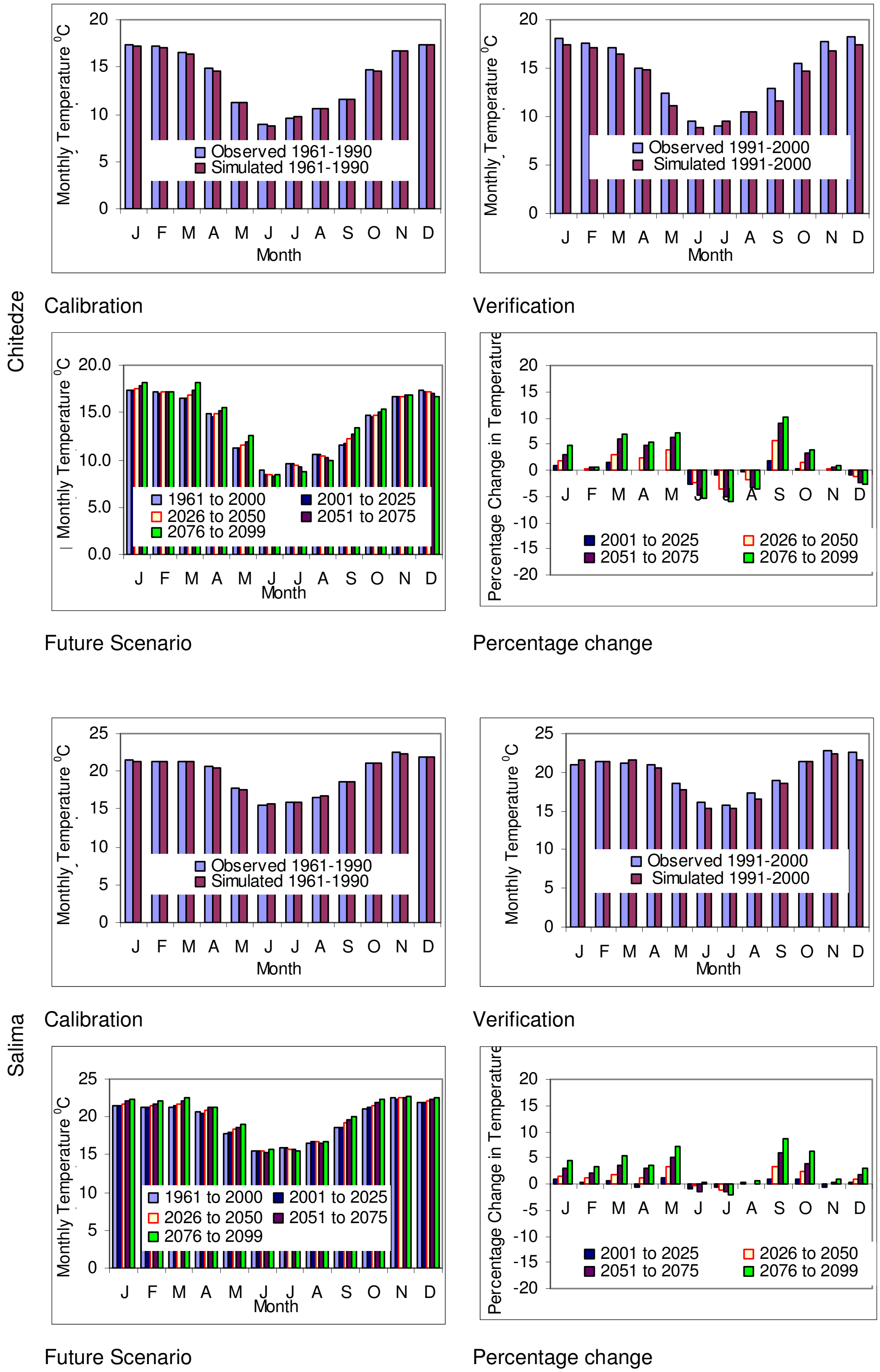


Figure 4.6 Calibration and validation and future scenario of minimum temperature pattern based on H3A2 HadCM GCM emission scenarios

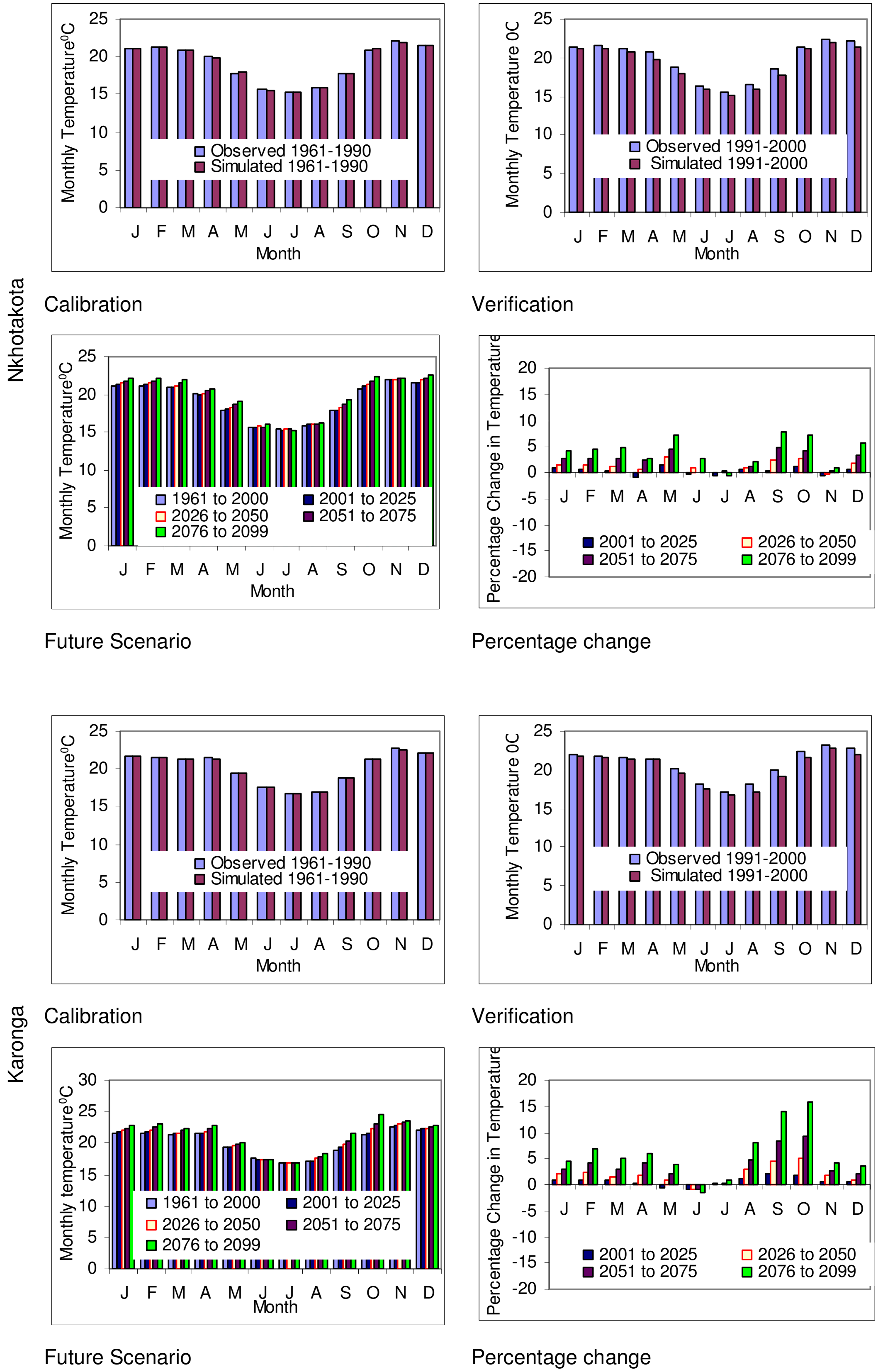
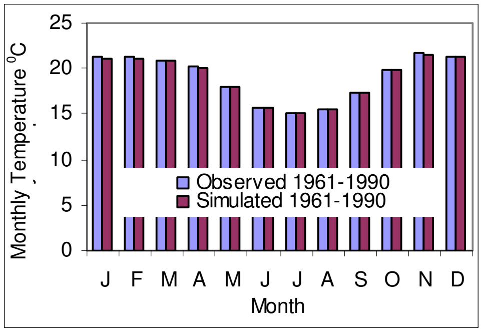


Figure 4.6 Continued

Nkhatabay



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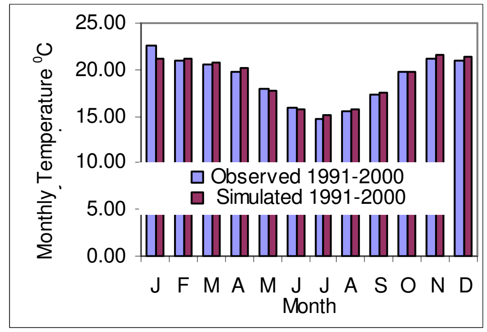
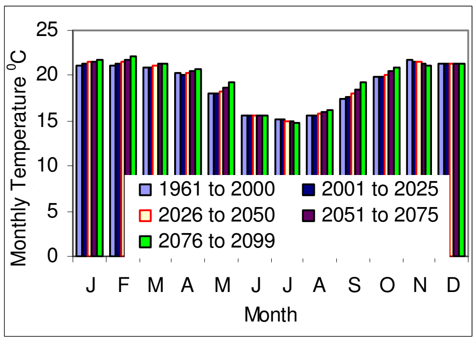
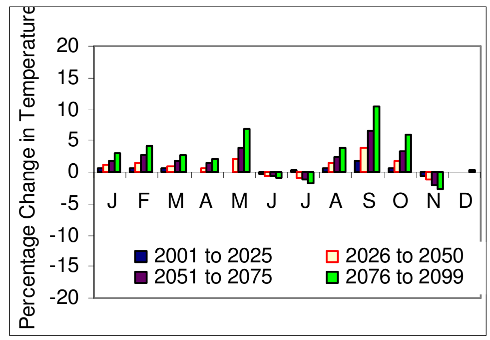


Verification

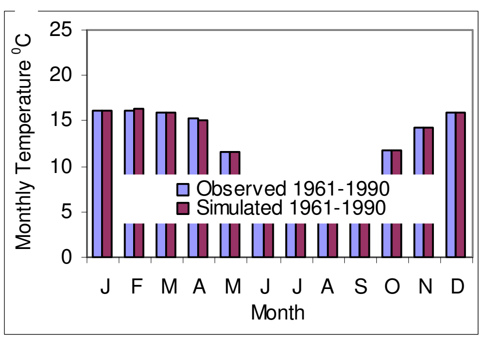


Future Scenario



Percentage change

Mzuzu



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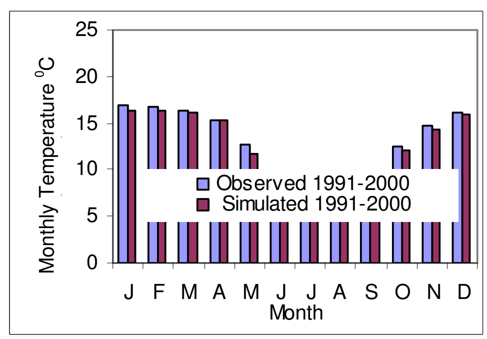

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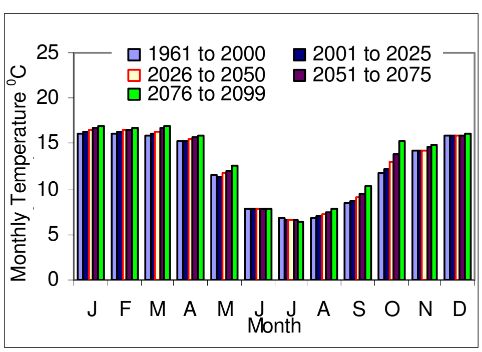
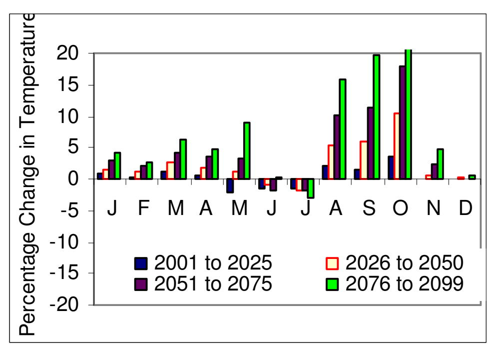


Future Scenario



Percentage change

Figure 4.6 Continued

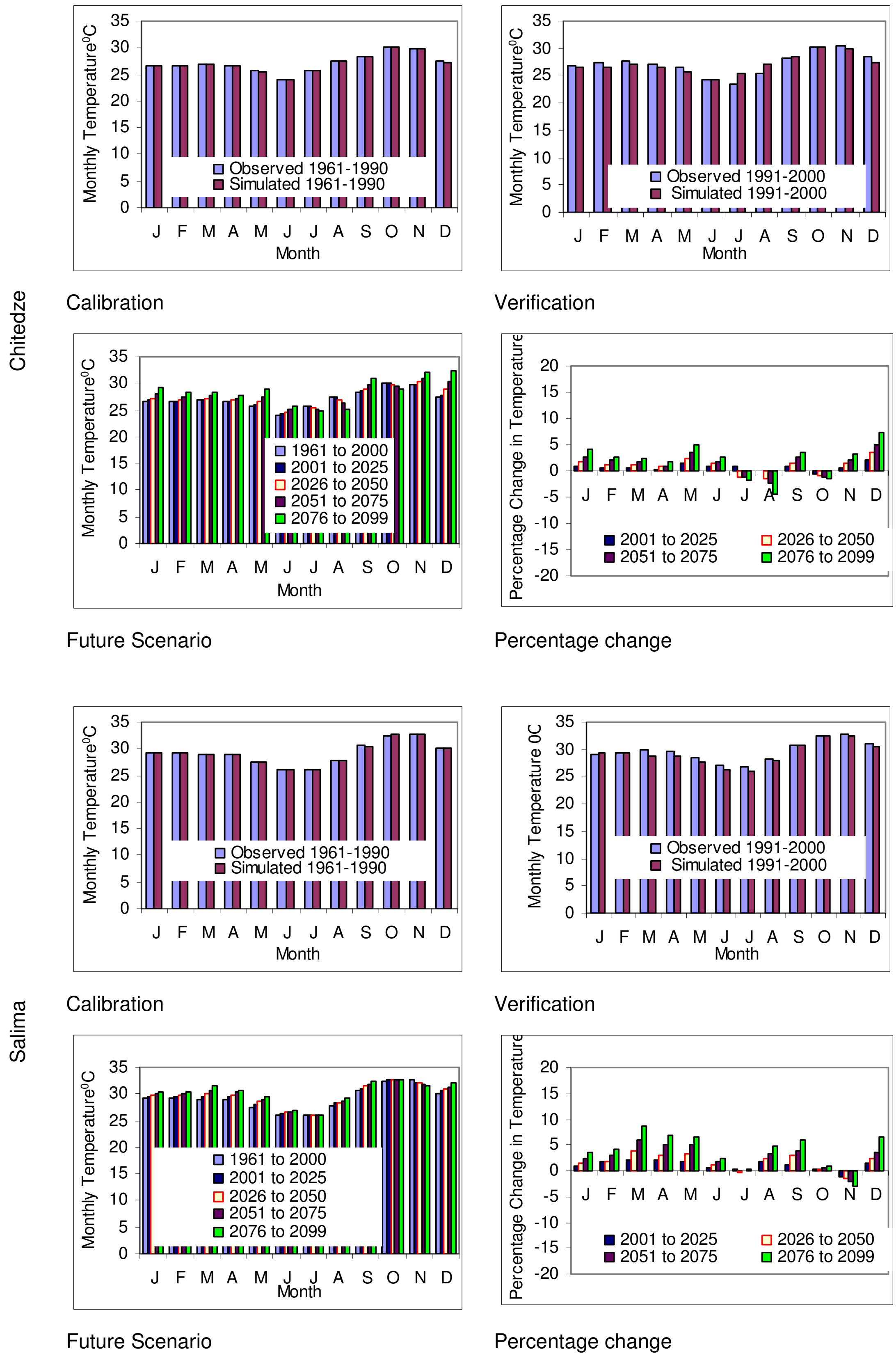
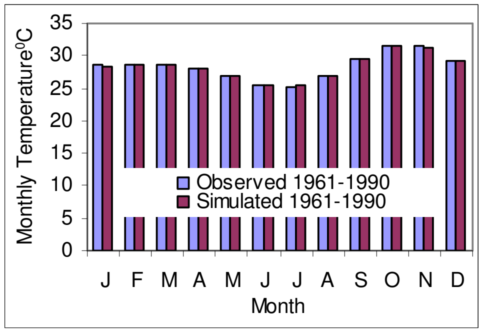


Figure 4.7 Calibration and validation and future scenario of maximum temperature pattern based on H3B2 HadCM GCM emission scenarios

Nkhotakota



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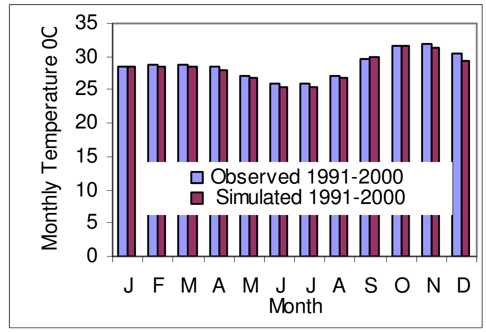
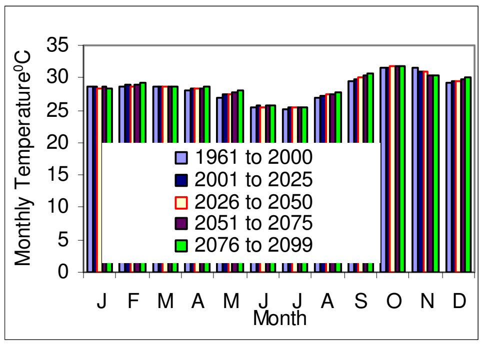
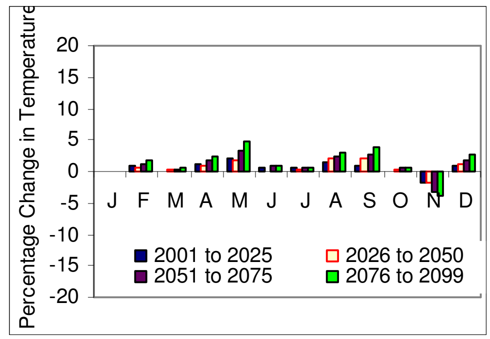


Verification

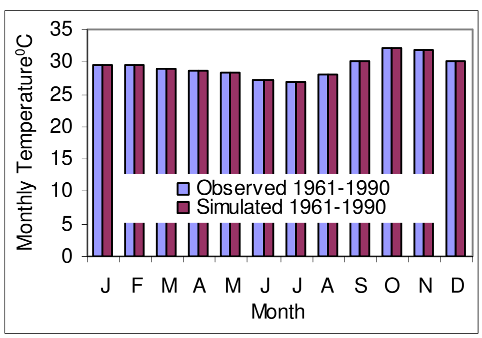


Future Scenario



Percentage change

Karonga



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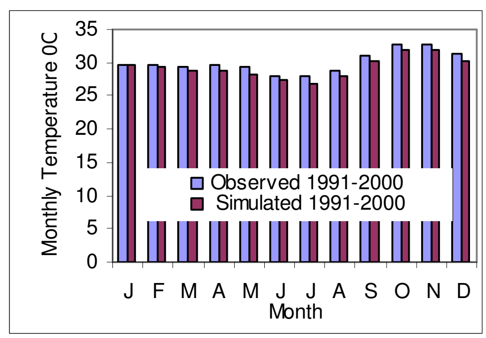

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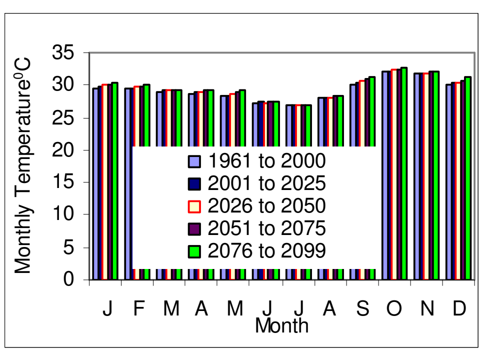
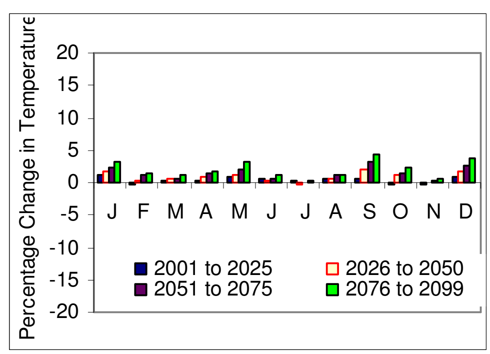


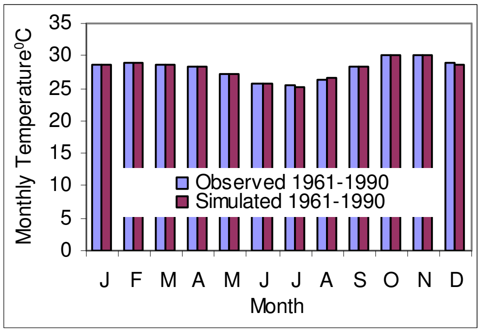
Future Scenario



Percentage change

Figure 4.7 Continued

Nkhatabay



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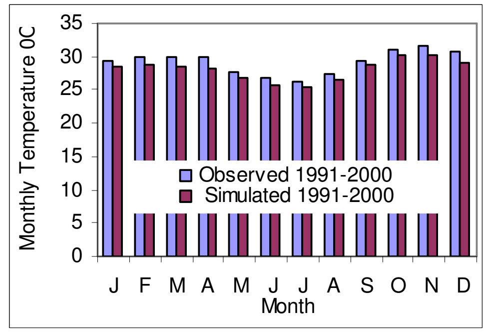

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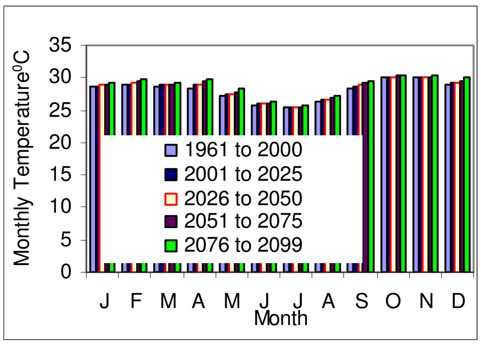
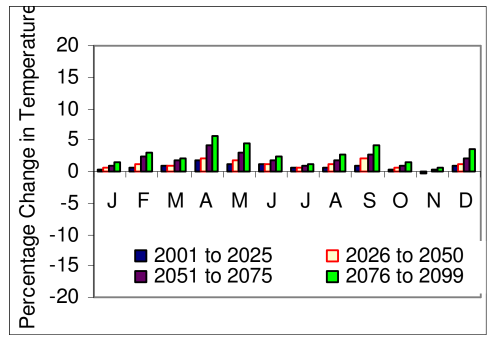
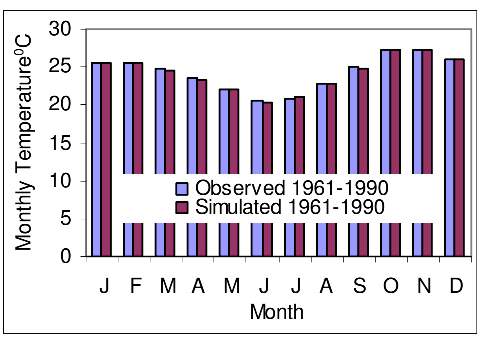


Future Scenario

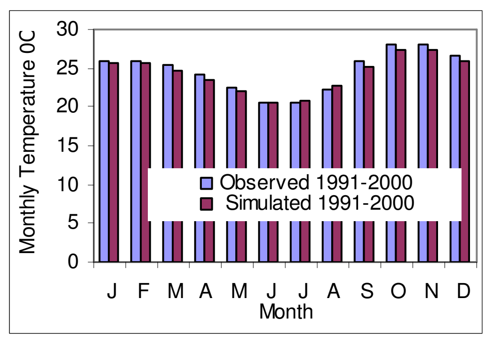


Percentage change

Mzuzu



Calibration



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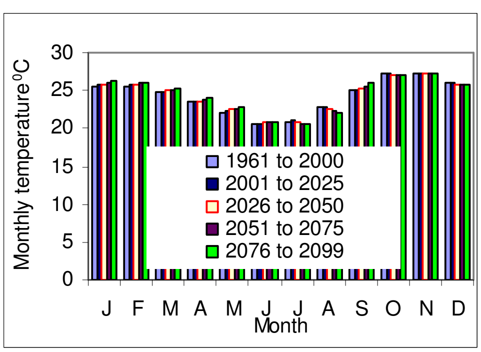
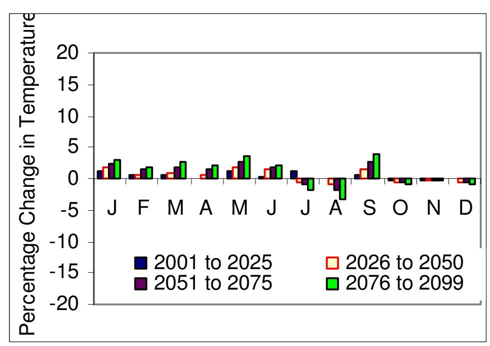


Future Scenario



Percentage change

Figure 4.7 Continued

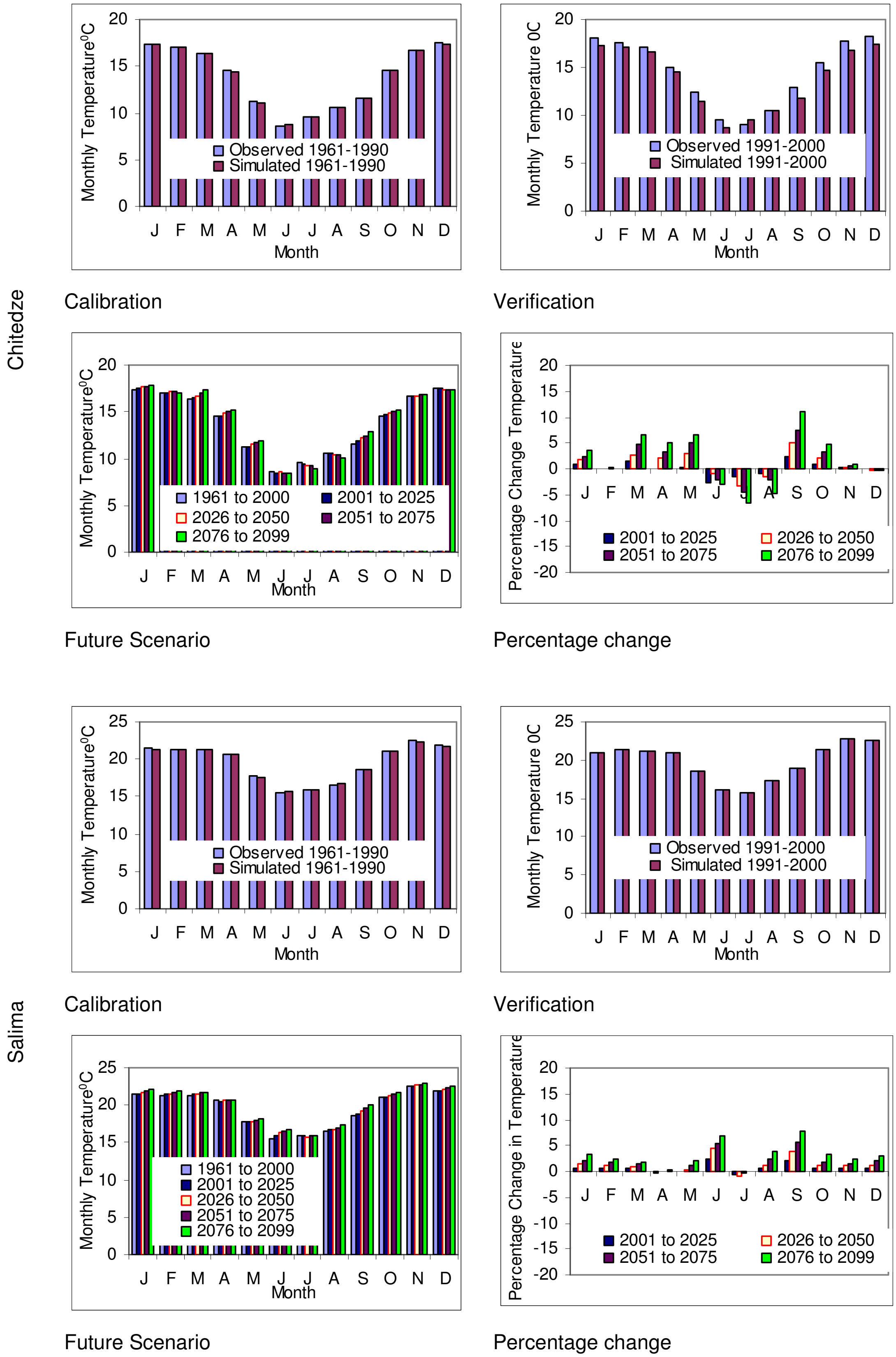
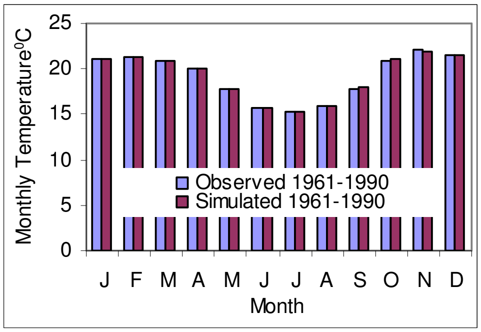


Figure 4.8 Calibration and validation and future scenario of minimum temperature pattern based on H3B2 HadCM GCM emission scenarios.

Nkhotakota



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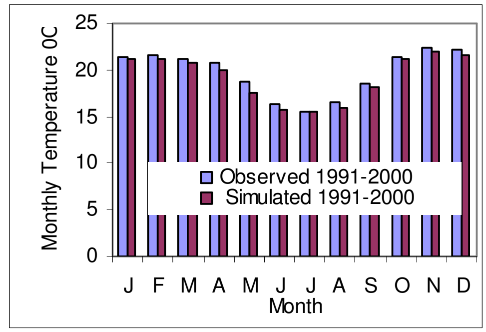

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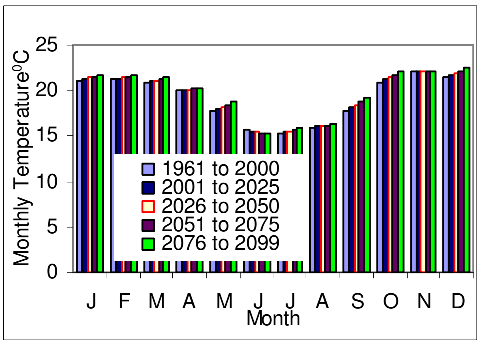
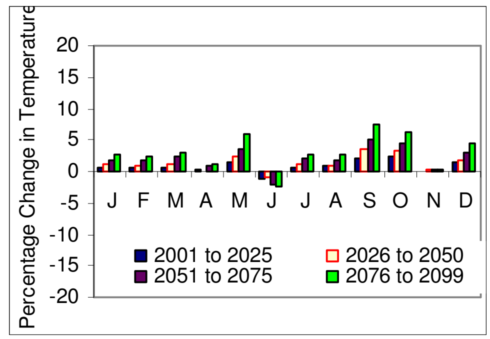
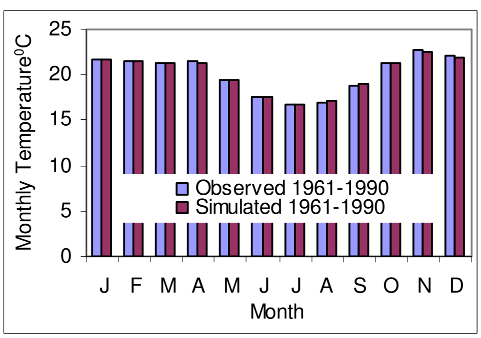


Future Scenario

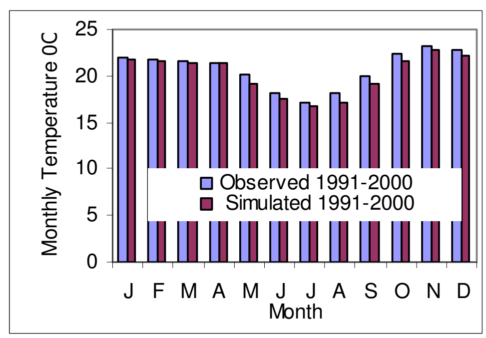


Percentage change

Karonga



Calibration



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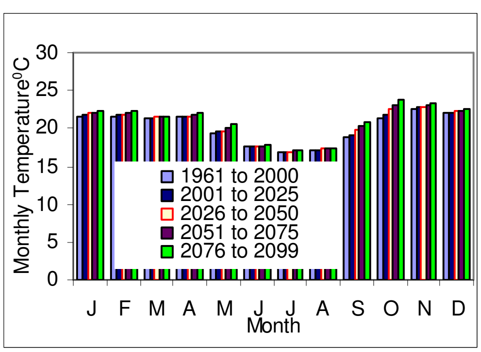
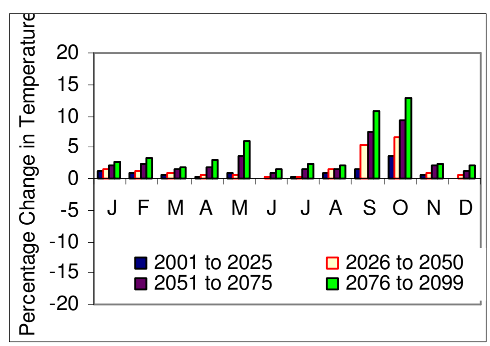


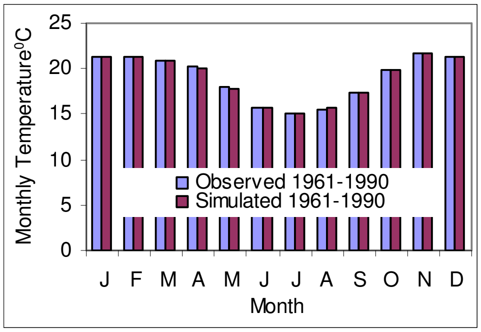
Future Scenario



Percentage change

Figure 4.8 Continued

Nkhatabay



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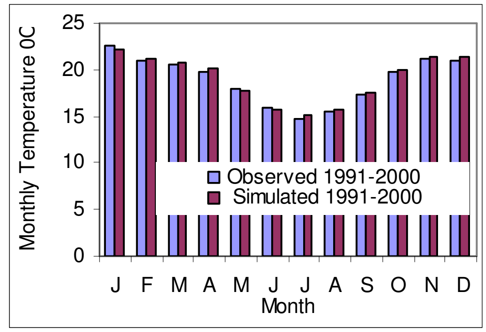

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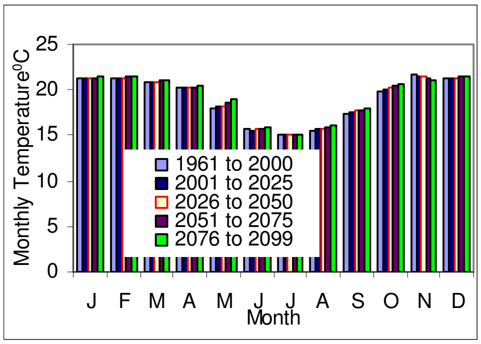
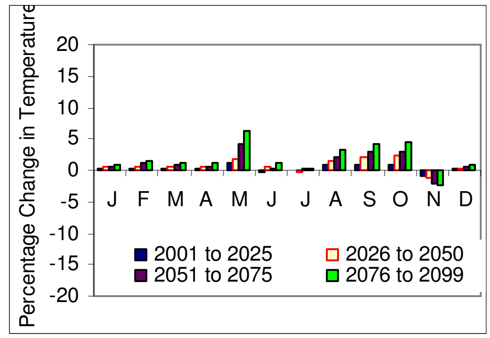
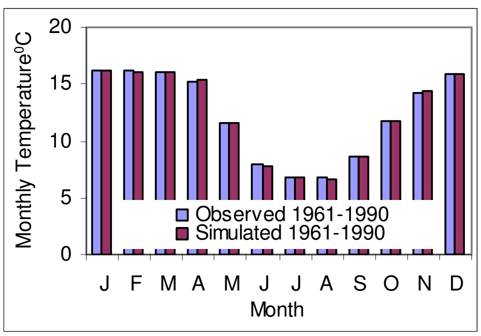


Future Scenario

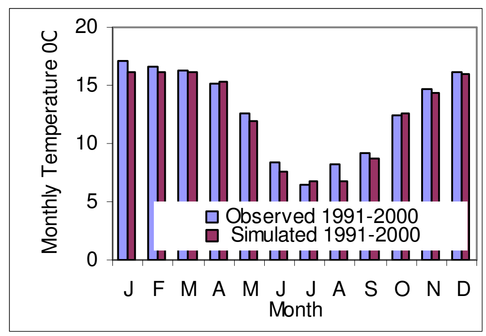


Percentage change

Mzuzu



Calibration



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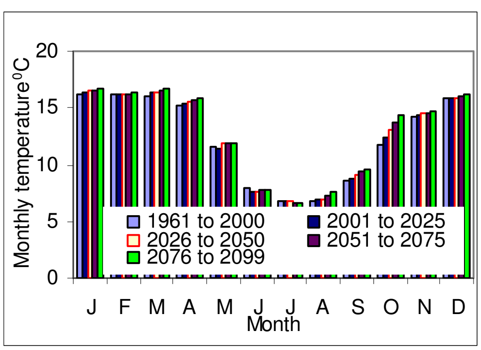
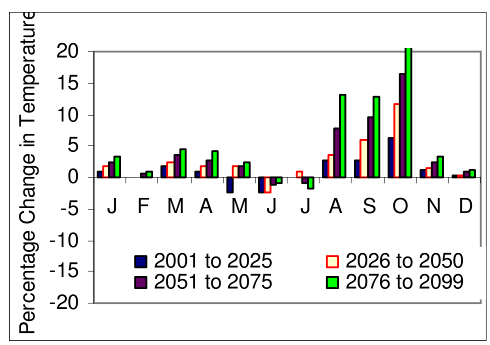


Future Scenario



Percentage change

Figure 4.8 Continued

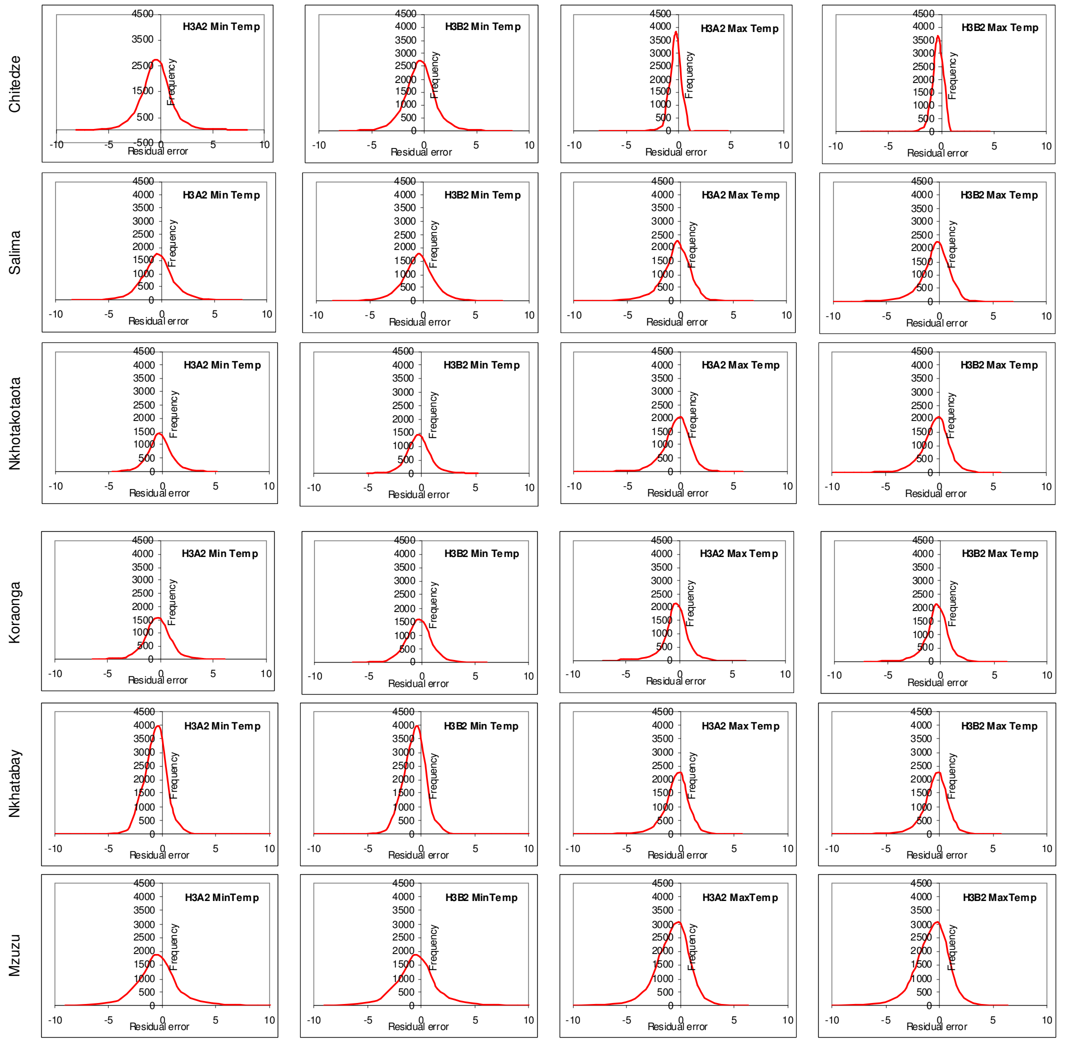


Figure 4.9 Error distribution diagrams for maximum and minimum temperature during calibration of SDSM

Table 4.4 Residuals between observed and simulated minimum and maximum temperature values for the calibration period

Station	Residual by HadCM H3A2		Residual by HadCM H3B2	
	Minimum	Maximum	Minimum	Maximum
Chitedze	-0.411	-0.346	-0.412	-0.347
Salima	-0.397	-0.453	-0.399	-0.451
Nkhotakota	-0.256	-0.411	-0.259	-0.410
Karonga	-0.313	-0.338	-0.313	-0.338
Nkhatabay	-0.681	-0.401	-0.681	-0.400
Mzuzu	-0.523	-0.777	-0.523	-0.776

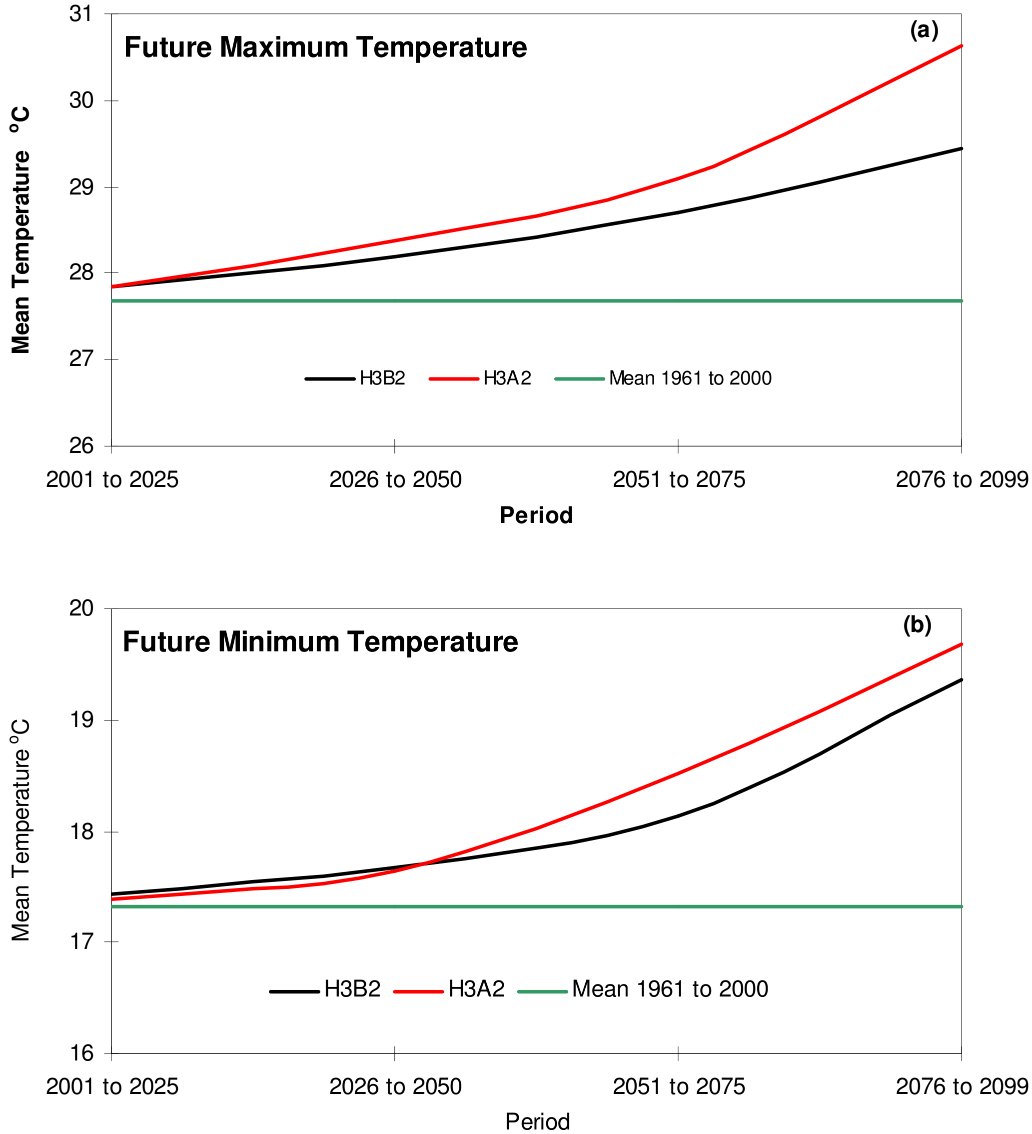


Figure 4.10 Future maximum and minimum temperature pattern for Central and North Malawi based on HadCM GCM scenarios.

The results of future scenarios indicate an increase in both maximum and minimum temperature in the region as shown in Figure 4.5 to Figure 4.8 and summarised in Figure 4.10. H3A2 scenarios shows an initial increase in minimum temperature but lower than the H3B2 scenario and midway through the century the increase exceeds the predictions by H3B2 and continue to increase higher than the H3B2 series (Figure 4.10(b)). In the case of maximum temperature, the H3A2 shows an increase in temperature that is higher than the H3B2 series throughout the century (Figure 4.10(b)). According to IPCC (2007), overall Africa has warmed by 0.7^0C over the 20^{th} century. Future projection of

Central and North Malawi temperature indicates that the maximum temperature will increase by 2.8^{0}C by the end of 21st century based on H2A2 scenario and 1.6^{0}C based on H3B2 scenario while minimum temperature will increase by 2.3^{0}C and 1.9^{0}C respectively (Figure 4.8) The increase in temperature in Africa will have negative effects on water, health and terrestrial ecosystem (Boko *et al.*, 2007).

- Temperature increase will increase favourable zones for vectors conveying infections such as dengue fever and malaria. This will simply lead to high incidence of such diseases.
- Temperature increase will lead to deforestation and degradation of grasslands resulting in increased stress to already threatened habitats, ecosystem and species in Malawi. This is likely to trigger species migration and lead to habitat reduction. According to Boko *et al.* (2007) 25 – 50 percent of Africa's biodiversity is at risk due to reduced habitat and other human induced pressure.

Downscaling minimum and maximum temperature from the main six climate stations has been deemed necessary because these stations have a complete record of climate data necessary for estimating evaporation. However most of the river basins don't have climate stations with complete record for estimating evaporation. That being the case, a temperature based method would be appropriate in such situation, hence the need to downscale temperature to be incorporated in temperature-based evaporation model for estimating evaporation.

4.5 HYDROLOGICAL IMPACT OF CLIMATE CHANGE

The hydrological impacts of climate change considered in this section are catchment areal rainfall, stream flow and flow variation throughout the year shown in Figure 4.11. Therefore having a good estimate of catchment areal rainfall the possible impact of climate change on river flow could be easily established through the use of hydrological models. In this research the systems hydrological model of Linear Perturbation Model has been employed to estimate future river flow. The steps involved calibration of the model based on downscaled rainfall from 1961 to 1990. The period 1990 to 2000 was considered as the validation period. The calibrated model was then used to estimate future scenarios of stream flow for the period 2001 to 2100. The future scenarios were divided in 25 year periods.

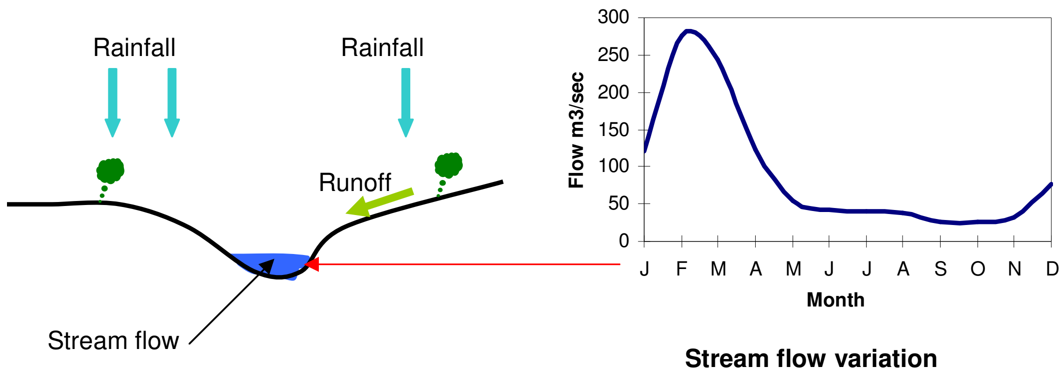


Figure 4.11 Sketch of hydrological parameters considered for climate change impact on water resources.

4.5.1 Climate change impact on North and Central Malawi rainfall

Results of downscaled rainfall for North and Central Malawi are presented in Figure 4.12 and Figure 4.13 and detailed results of downscaled catchment areal rainfall for each river basin in Central and North Malawi are presented in Figure 4.14 and Figure 4.15. The performance of the SDSM was generally considered good in all the river basins. The SDSM model overestimated areal rainfall in all the river basins with high rainfall such as Dwambazi and Luweya in the calibration period under both scenarios H3A2 and H3B2 as shown in Figure 4.14 and Figure 4.15. The following are observations in the projected rainfall under both emission scenarios:-

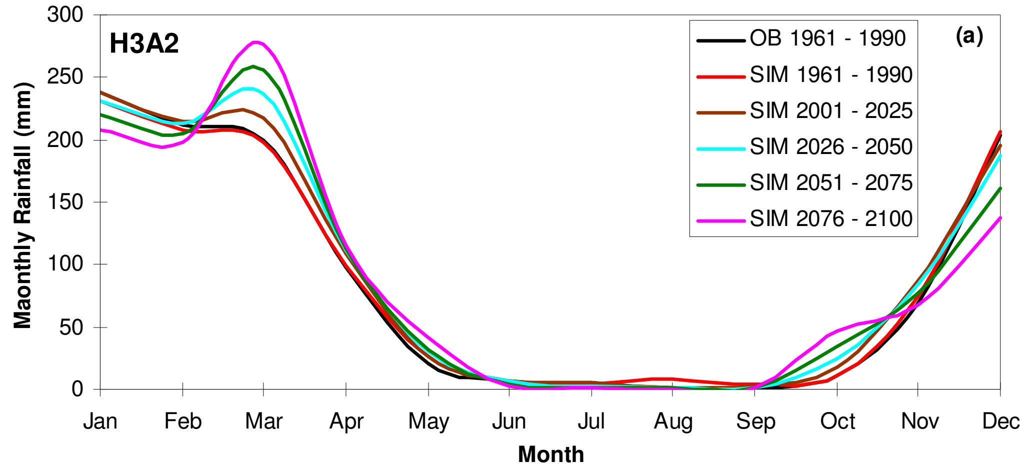
- The results of future rainfall pattern indicates an increase in rainfall in the months of March, April, May and October in all the river basins except the Dwangwa river which has an increase in the months of March, April, May and September. There is a decrease in rainfall in the months of January, February, June, July, August and September. This shows that the rainfall pattern will change to a shorter rainfall season. High intensity rainfall within a short period will render the problem of flooding a more frequent problem in the 21st century. Floods do not only destroy people's property but also increase the spread of diseases such as cholera.

- There is no marked change in the total annual rainfall under both emission scenarios. The major change is observed in the monthly rainfall totals, indicating a change in rainfall pattern as shown in Figure 4.12 and Figure 4.13.

- Significant rainfall increase is projected for the month of March. A projected rainfall amount of 276 mm under A2 emission scenarios and 250 mm under B2 scenario by the end of the century. The current observed mean rainfall for the month of March is 200 mm (Table 4.5 and Table 4.6).

- Due the to the focused shorter rainfall season, agricultural production which contributes 80 percent of Malawi's gross domestic product (GDP) will be severely compromised in many parts of the country, particularly subsistence farmers who rely much on rainfall for irrigation. Shorter rainfall season will result in shorter growing season and more uncertainty about what and when to plant, worsening food insecurity and increase in the number of people at risk from hunger. According to Boko *et al.* (2007), yields from agricultural production could be halved in sub Saharan Africa by 2020 and net revenues could fall by 90 percent by 2100.

- Shorter rainfall season will lead to calls for irrigation to supplement deficient rainfall. This will result in increase in competition for water exacerbated by the growing population.



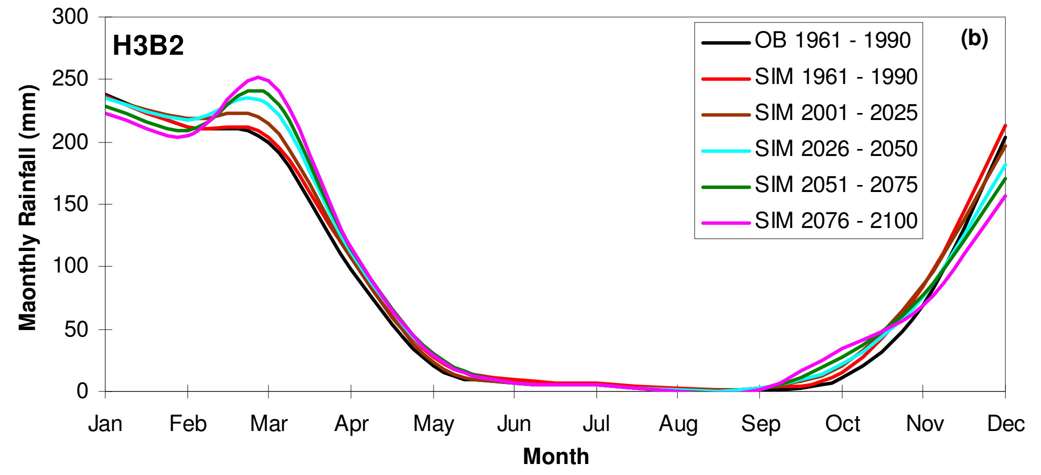
OB = Observed mean series

SIM = Simulated series from downscaled GCMs

Figure 4.12 Future rainfall pattern for Central and North Malawi based on HadCM H3A2 GCM scenarios

Table 4.5 25 years average rainfall scenarios for Central and North Malawi based on H3A2 HadCM GCM emission scenarios

	Observed	Simulated rainfall by SDSM (mm)				
Month	1961 - 1990	1961 - 1990	2001 - 2025	2026 - 2050	2051 - 2075	2076 - 2100
Jan	237	232	238	231	221	208
Feb	212	208	215	213	206	198
Mar	200	198	218	236	256	276
Apr	98	99	108	112	113	116
May	21	26	26	31	32	41
Jun	7	7	7	6	4	3
Jul	5	4	5	3	2	1
Aug	2	8	2	1	1	0
Sep	2	4	2	2	2	1
Oct	11	12	17	24	34	47
Nov	69	74	86	85	78	67
Dec	204	206	196	187	161	138
Annual	1068	1079	1122	1131	1109	1096



OB = Observed mean series

SIM = Simulated series from downscaled GCMs

Figure 4.13 Future rainfall pattern for Central and North Malawi based on H3B2 HadCM GCM scenarios.

Table 4.6 25 years average rainfall scenarios for Central and North Malawi based on H3B2 HadCM GCM emission scenarios

Month	Observed	Simulated rainfall by SDSM (mm)				
	1961 - 1990	1961 - 1990	2001 - 2025	2026 - 2050	2051 - 2075	2076 - 2100
Jan	237	236	235	235	228	223
Feb	212	211	218	217	209	205
Mar	200	204	215	229	238	250
Apr	98	108	107	112	114	115
May	21	28	24	29	30	29
Jun	7	9	7	7	7	7
Jul	5	7	6	6	5	5
Aug	2	2	1	1	1	0
Sep	2	3	2	2	2	2
Oct	11	15	20	22	27	35
Nov	69	84	85	76	77	69
Dec	204	213	197	182	171	157
Annual	1068	1120	1119	1118	1109	1097

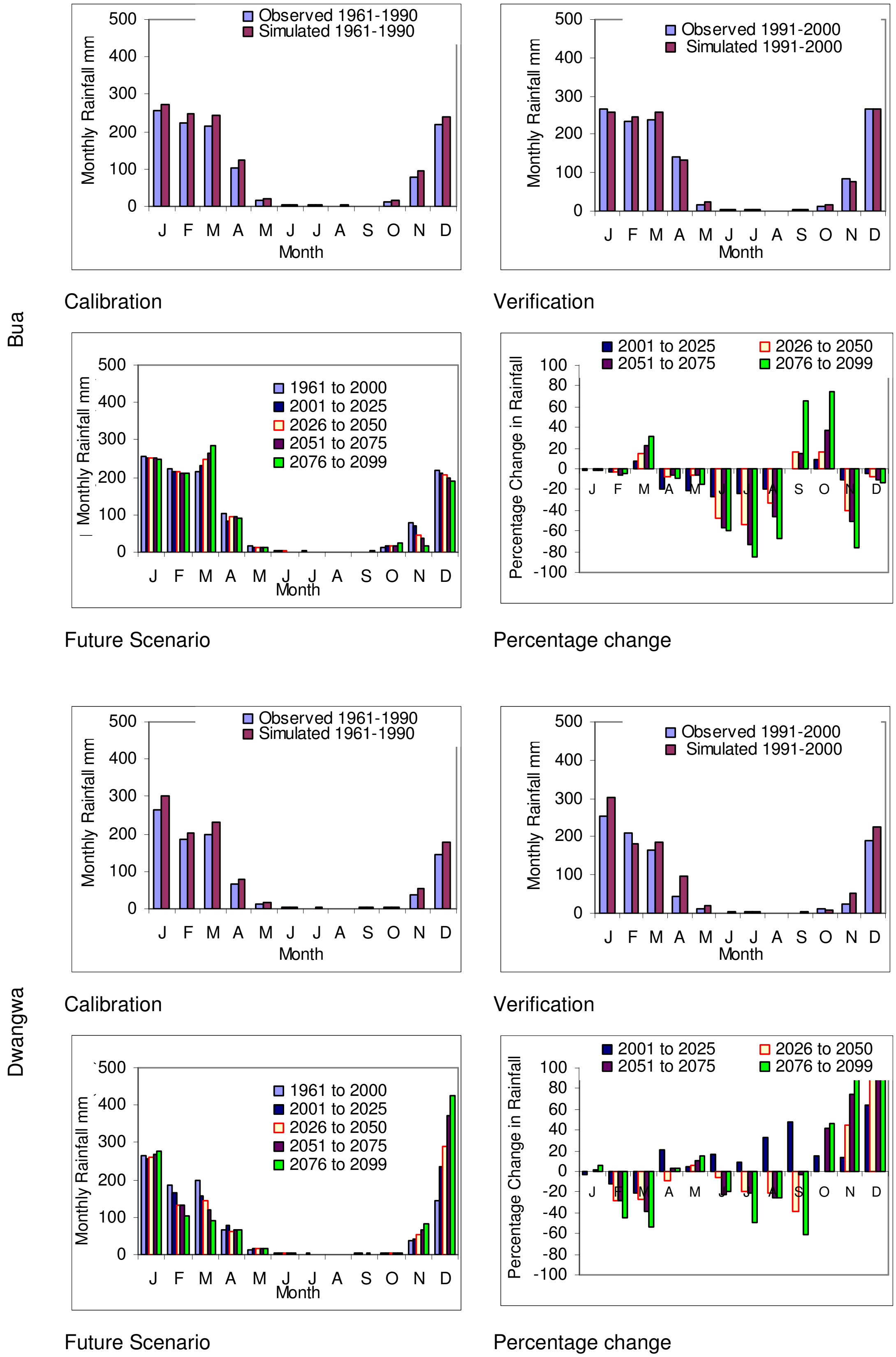


Figure 4.14 Calibration and validation and future scenario of rainfall pattern based on H3B2 HadCM GCM emission scenarios

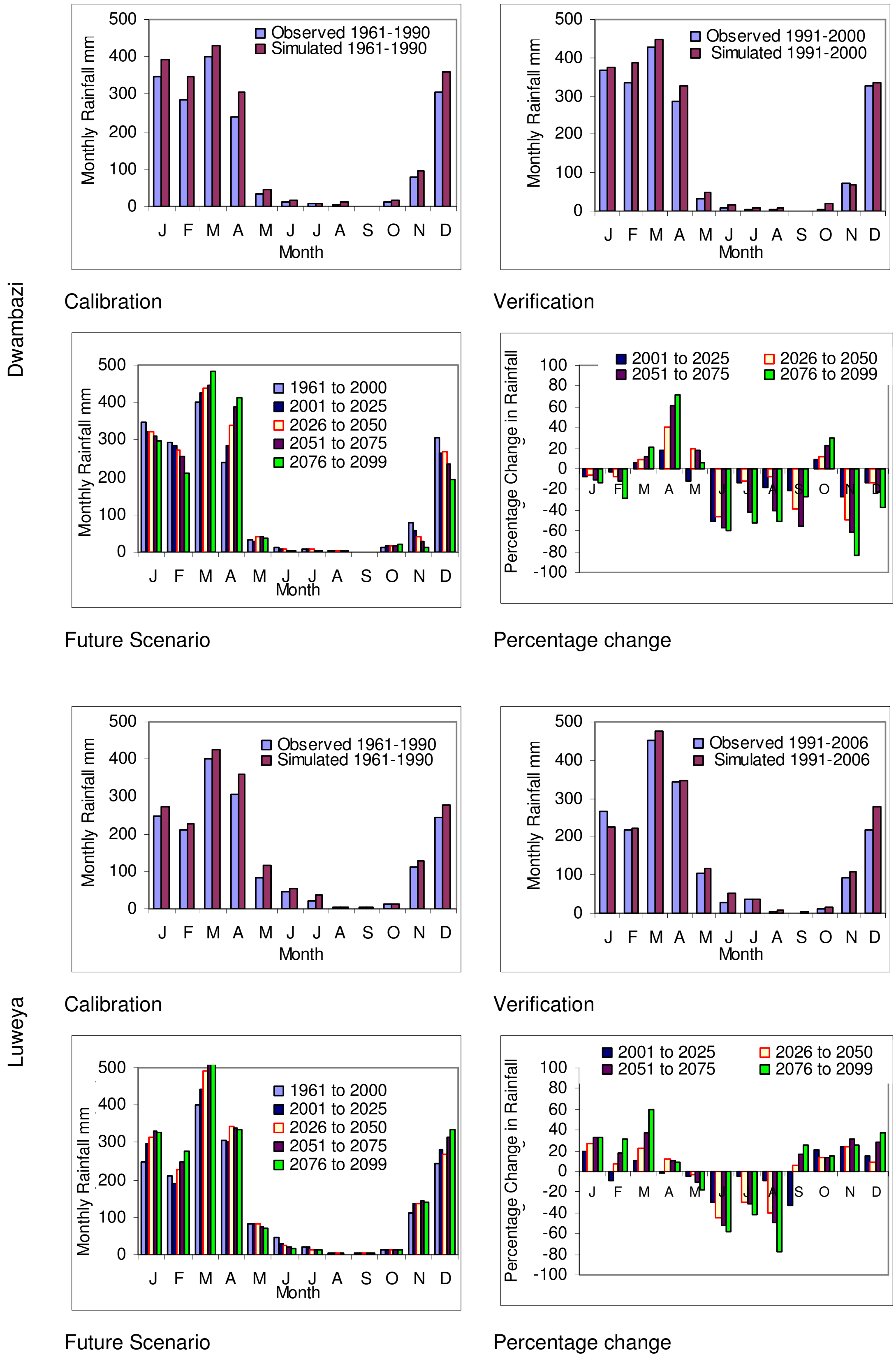
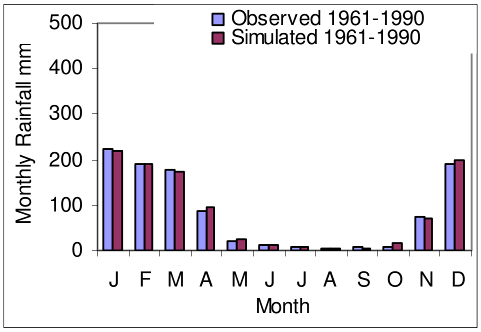
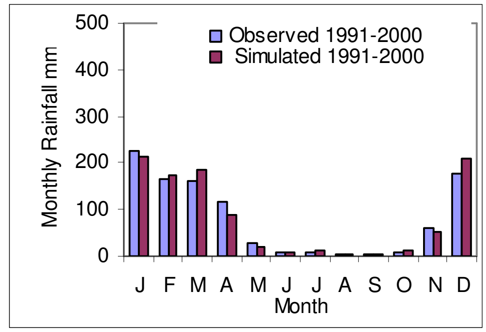


Figure 4.14 Continued

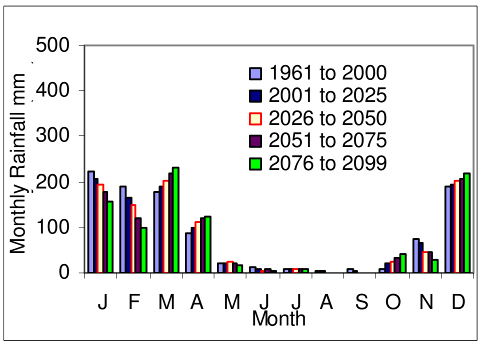
South Rukuru



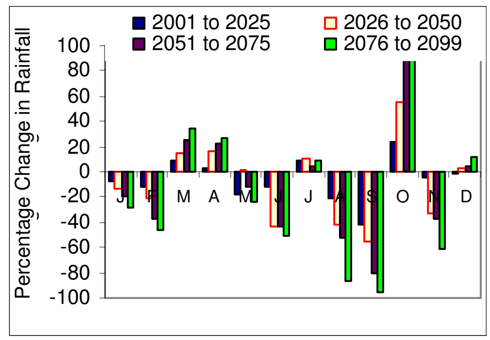
Calibration



Verification

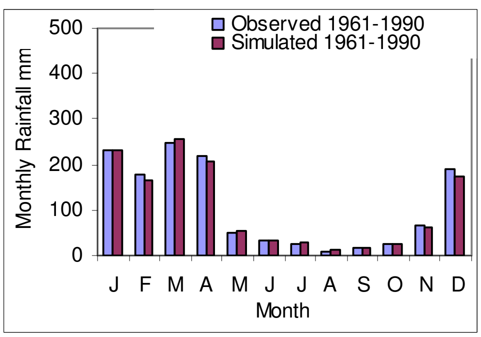


Future Scenario

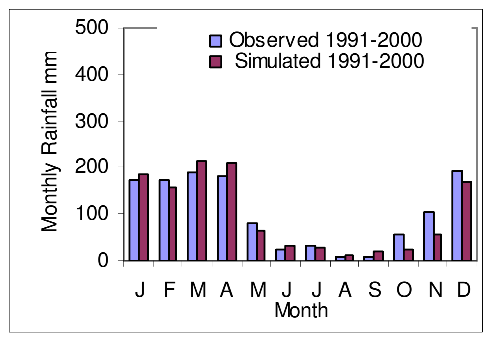


Percentage change

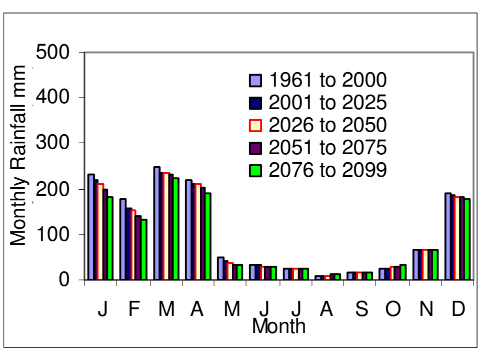
North Rukuru



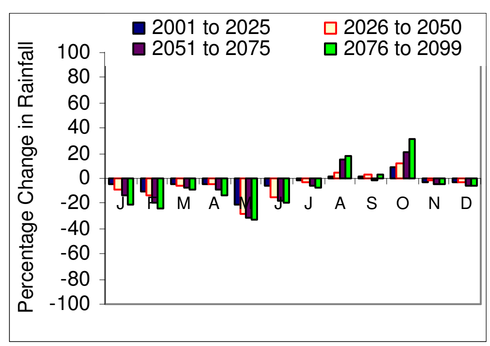
Calibration



Verification



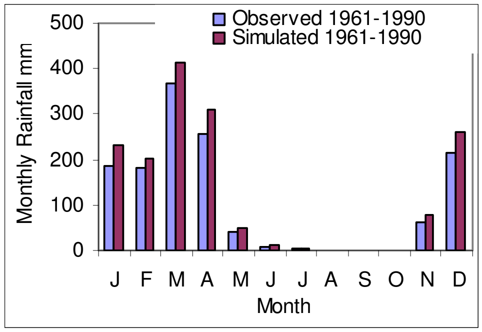
Future Scenario



Percentage change

Figure 4.14 Continued

Lufira



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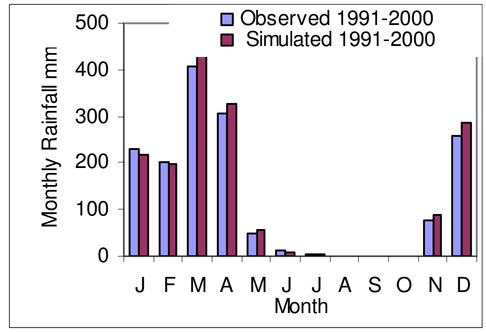

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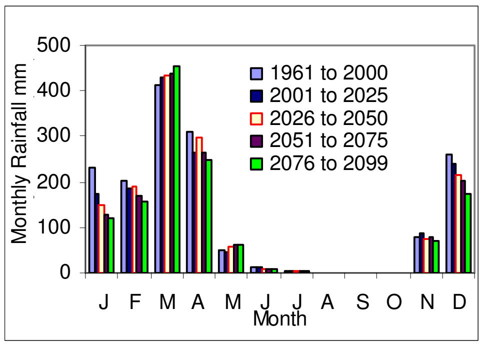
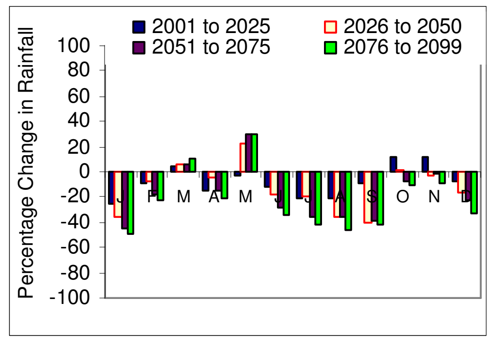


Future Scenario



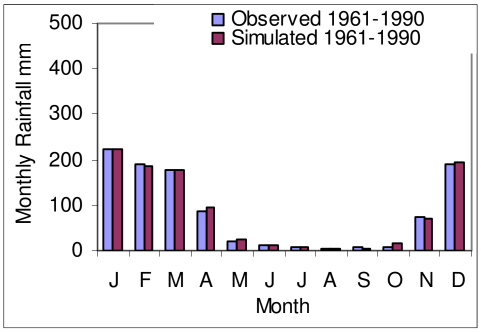
Percentage change

Figure 4.14 Continued

Figure 4.15 Calibration and validation and future scenario of rainfall pattern based on H3A2 HadCM GCM emission scenarios

Figure 4.15 continued

South Rukuru



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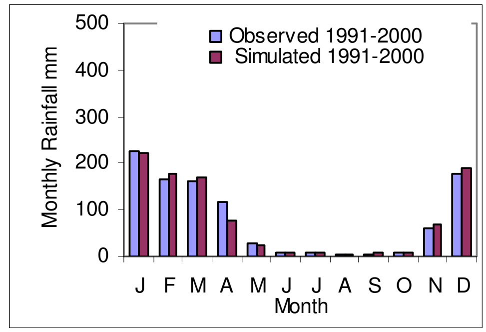

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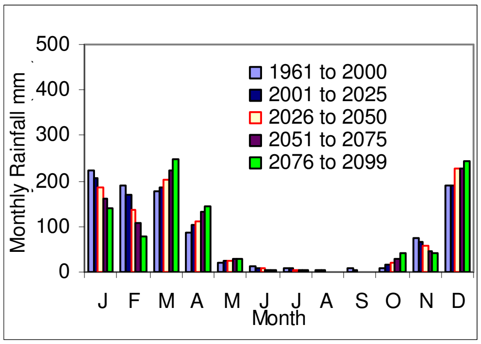
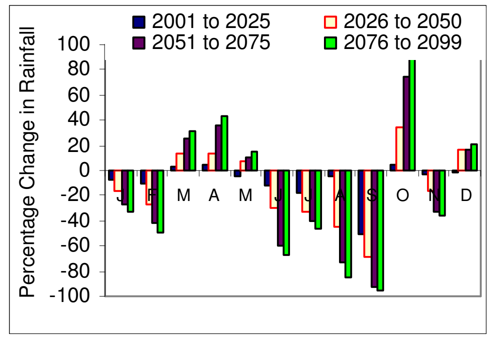
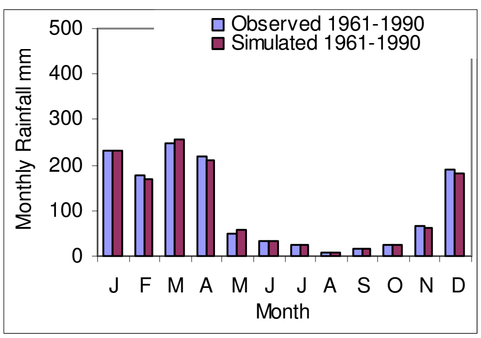


Future Scenario



Percentage change

North Rukuru



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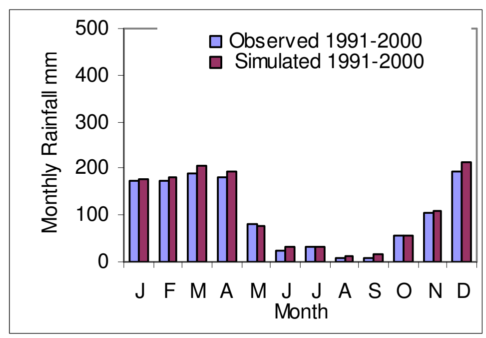

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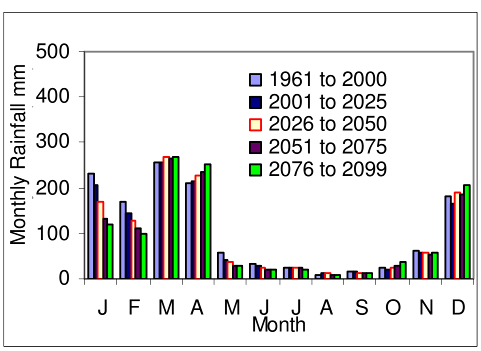
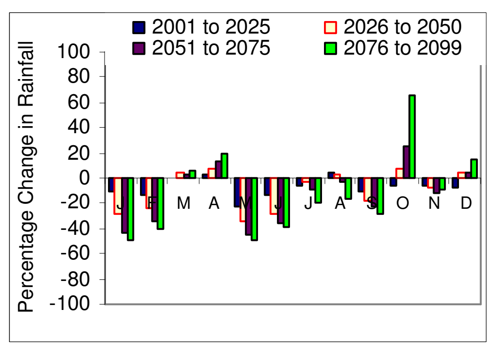


Future Scenario



Percentage change

Figure 4.15 continued

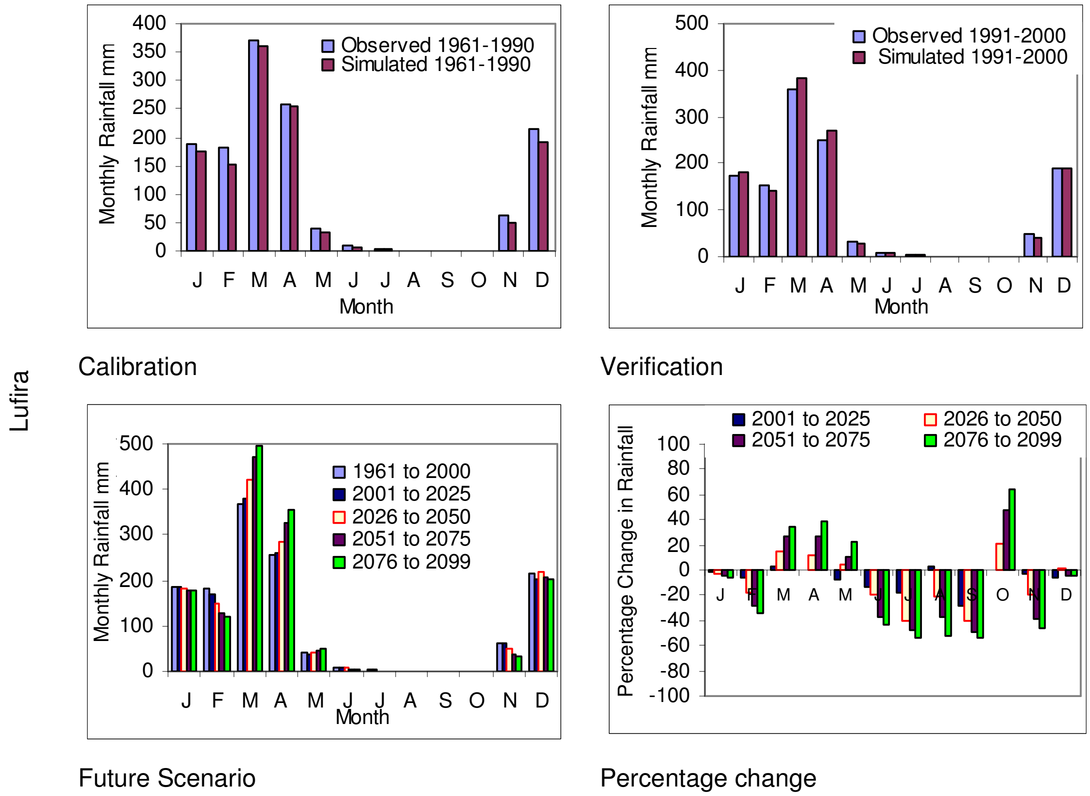


Figure 4.15 continued

Having modelled climate change impact on the rainfall pattern of Central and North Malawi, it is now necessary to model the impact of climate change on the river flows of Central and North Malawi. Any changes in the flow pattern of these rivers will have an effect on the water levels of Lake Malawi as well as water resources availability in the Shire river since Shire river is the only outlet from Lake Malawi with major economic roles in hydropower generation, irrigation and water supply as well as ecosystem generation in the Lower Shire Valley.

4.5.2 Climate change impact on river flows

4.5.2.1 Hydrological Modelling for extending flow records

Hydrological models are an approximation of the hydrological system in which input variables such as rainfall and evaporation are expected to produce an output such as surface runoff which is the same as the measured runoff from the particular catchment under investigation. The literature review in Chapter 2 provides an examination of the roles hydrological models plays in the planning and management of water resources. River flow forecasting is one of the major roles hydrological models plays in water resources management. Future climate data generated from GCMs can be used as input in hydrological models to estimate the future behaviour and variation of river flows. The hydrological model Linear Perturbation Model (LPM) described in section 2.5.8.1 has been used to extend the flow records based on GCM outputs. Two different hydrological models were looked at in literature review as possible tools for extending river flow records. LPM was selected as the preferred method since it could handle catchment areas with sparse data based on its black box approach. The Nedbor – Afstromings – Model (NAM) model described in section 2.5.8.2 requires a higher number of gauging stations within the river basin which is not possible in the case of Malawi and many other developing countries. The NAM model divides the catchment area into a number of grids.

The LPM was developed further to handle perturbations of the downscaled climate data and take into account climate change, thus creating an alternative method for extending flow records based in GCM outputs. The perturbations of the downscaled rainfall dR_i from the seasonal mean values were used in the convolution equation 4.9 of LPM to produce runoff through the following transformation:

$$Q_i = y_i - y_s \qquad and \quad dR_i = dx_i - x_s$$
$$for \qquad i = 1,2,3,......,n \quad and \quad s = 1,2,3,.....,365 \qquad 4.8$$

where x_s and y_s are the seasonal mean values for observed rainfall x_i and and observed discharge y_i respectively and dx_i is the downscaled rainfall. The relationship between the perturbations of the discharge Q_i and downscaled rainfall dR_i is given by the convolution summation form given in equation 4.9

with h_j as pulse response ordinates of the hydrograph, m as the memory length of the catchment and e_i as model errors.

$$Q_i = \sum_{j=1}^{m} dR_{i-j+1} h_j + e_i \qquad i = 1,2,3,..........,n \qquad 4.9$$

Model-estimated departure values were added to the seasonal expectations to give the estimated discharge series. For the purpose of simulating future river flows, the LPM was operated in simulation mode. Simulation mode is when any model in which the input function does not include previously observed values of the output in transforming input into output. According to Kachroo (1992) the ultimate success of a model lies in its ability to produce good forecast in simulation mode. The results of the LPM in predicting river flows using GCM data are presented in Figure 4.16 and Figure 4.17.

According to Figure 4.16 and Figure 4.17 there is generally a good agreement between the observed flow and simulated flows based on downscaled rainfall from HadCM3 A2 and B2 GCM emission scenarios. The LPM model overestimated peak flows of February, March, April and May for Lufira Dwambazi, Luweya, South Rukuru and North Rukuru using HadCM3 A2 and B2 downscaled rainfall in both the calibration and verification period. Future scenario of river flows shows that there will be an increase in river flows in the months of March, April and October in all the river basin under consideration except Dwangwa river which has an increase in January, November and December under H3A scenario.

It has also been noted that under the two scenarios all the river basins have shown that there will be a decrease in river flow during the dry season from June to September. This will result in stress on the available water resources within the river basin. Bua, Dwangwa and Lufira are the worst affected rivers in terms of decrease in flows during the dry season.

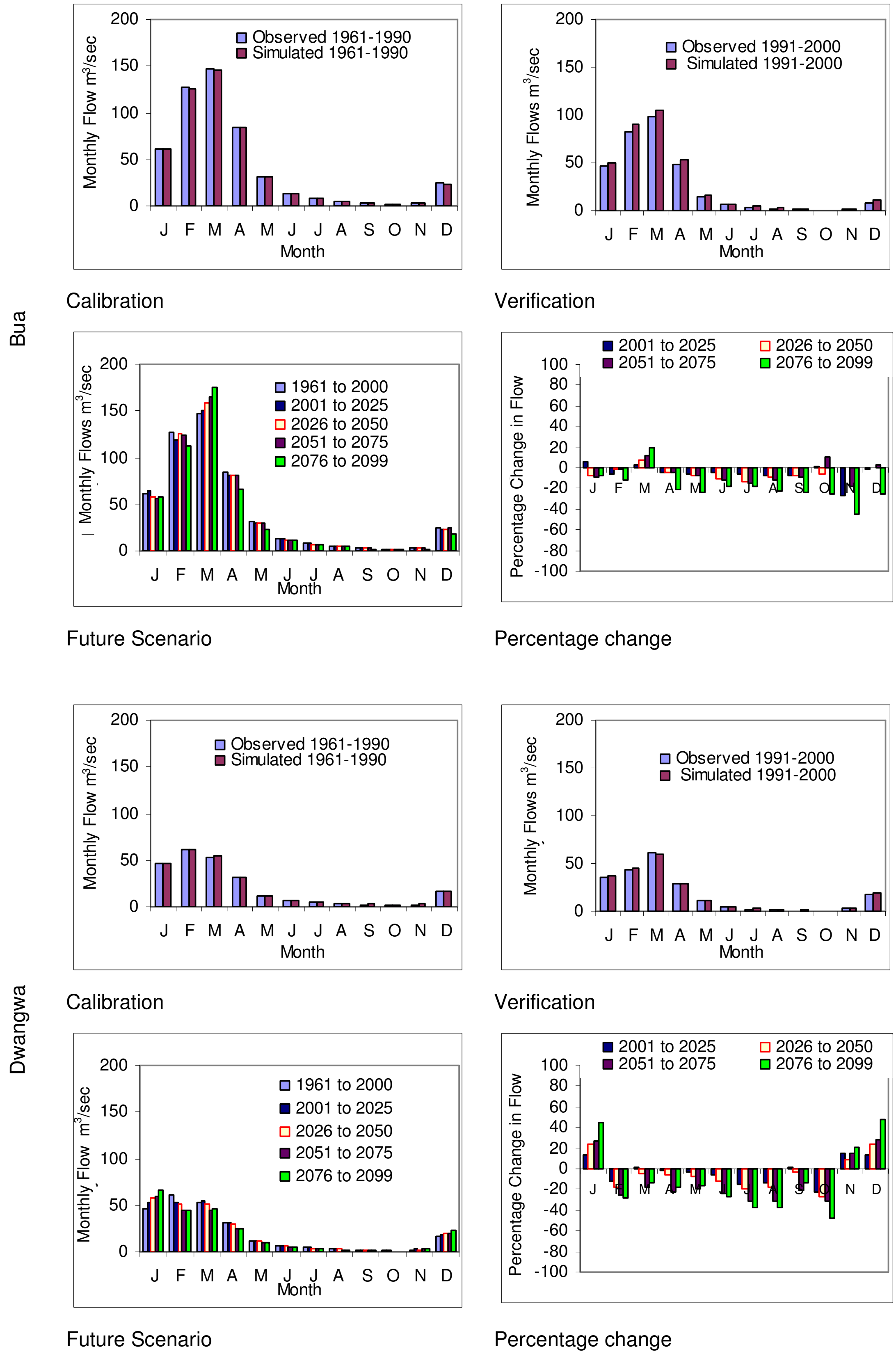
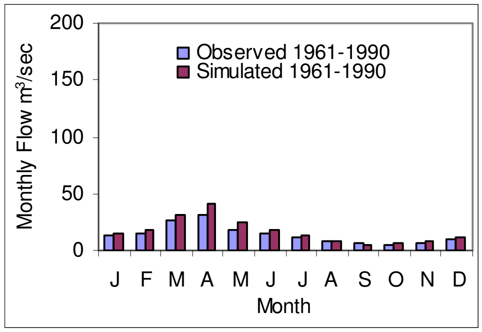
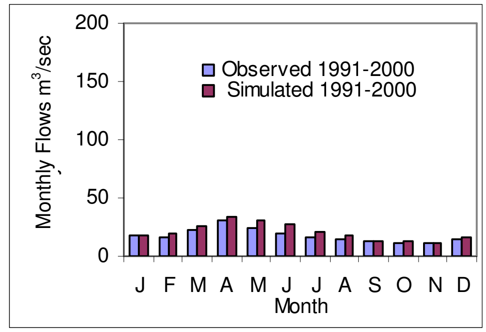


Figure 4.16 Calibration and validation and future scenario of river flow pattern based on H3A2 HadCM GCM emission scenarios

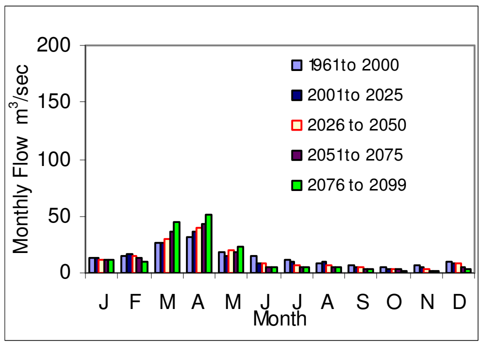
Dwambazi



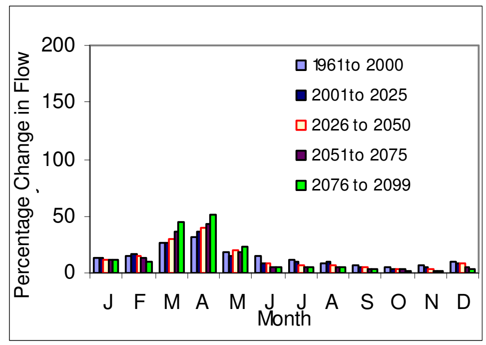
Calibration



Verification

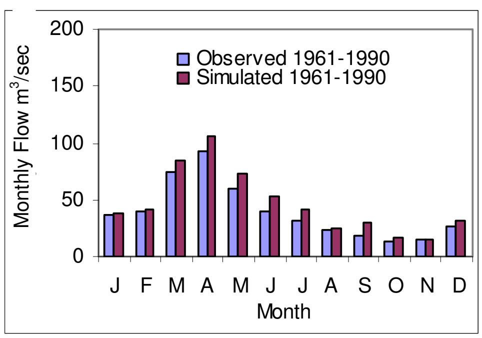


Future Scenario

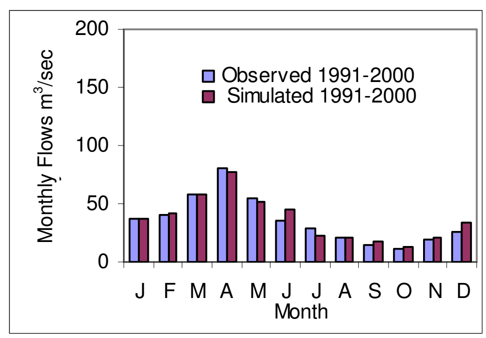


Percentage change

Luweya



Calibration



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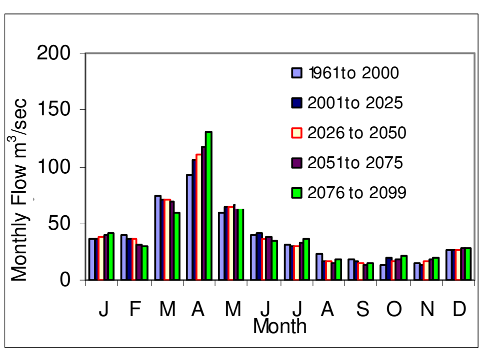
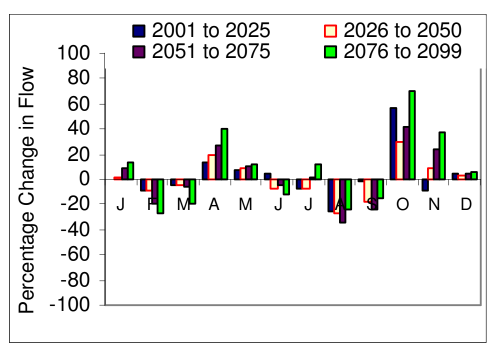


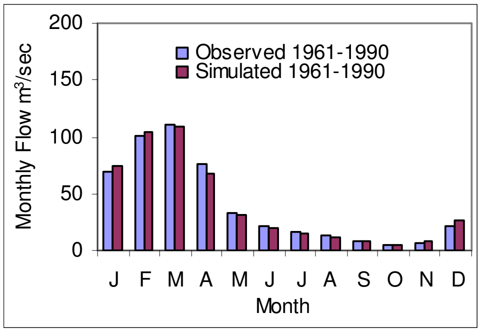
Future Scenario



Percentage change

Figure 4.16 continued

South Rukuru



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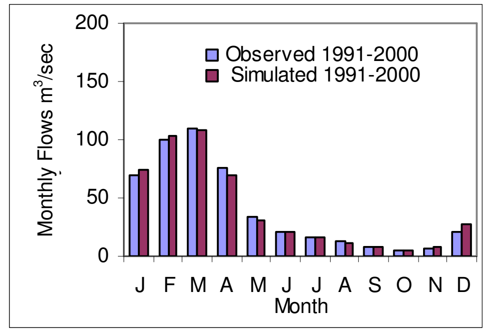

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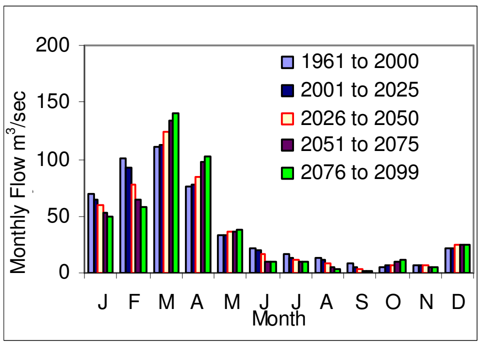
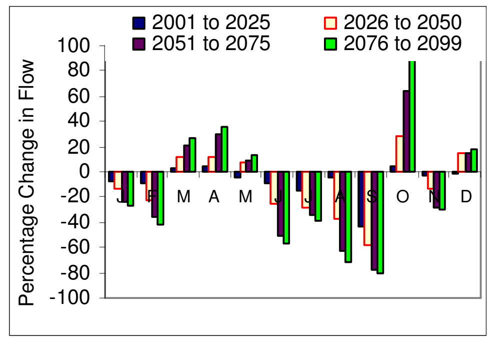
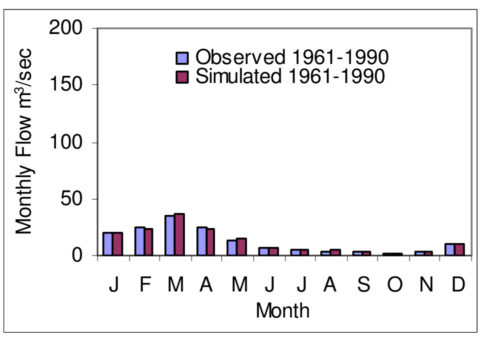


Future Scenario

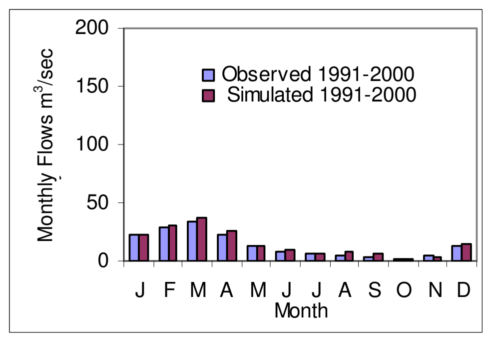


Percentage change

North Rukuru



Calibration



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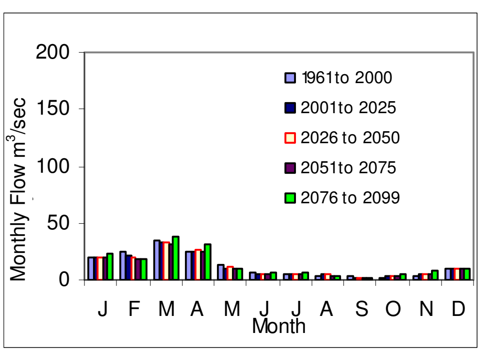
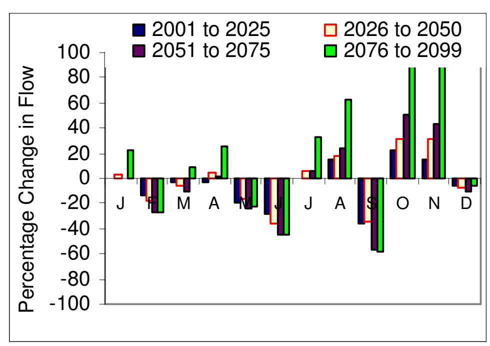


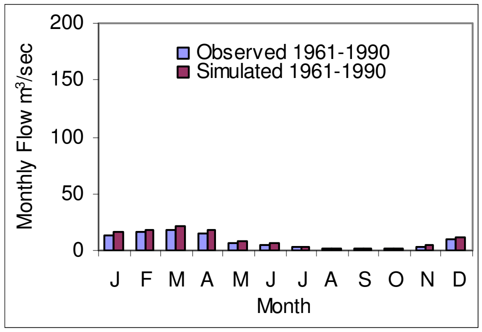
Future Scenario



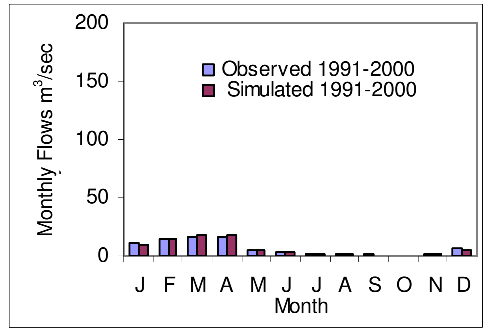
Percentage change

Figure 4.16 continued

Lufira



Calibration



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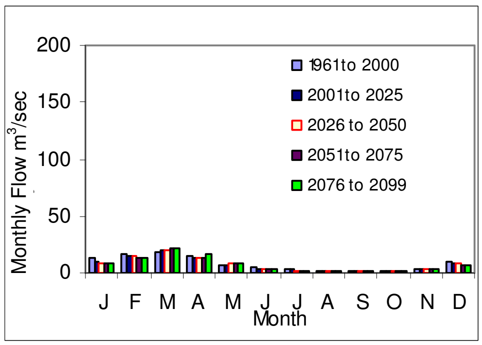
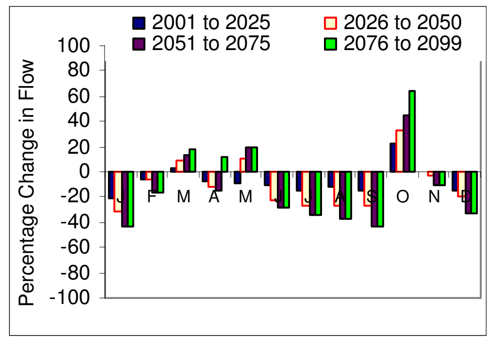


Future Scenario



Percentage change

Figure 4.16 continued

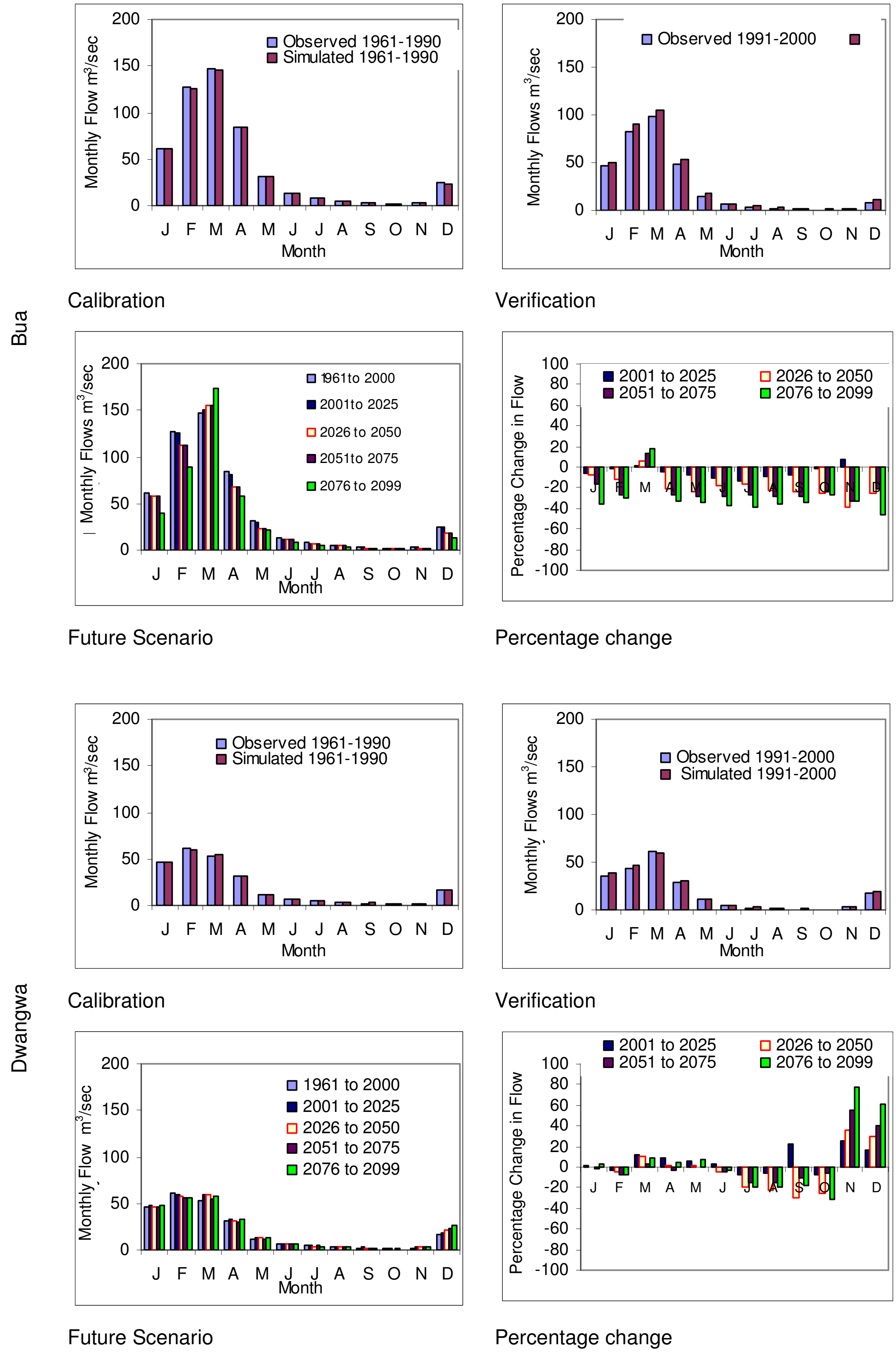
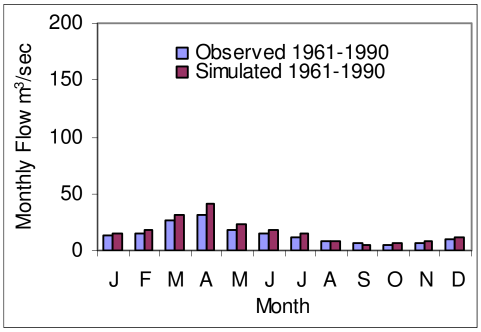
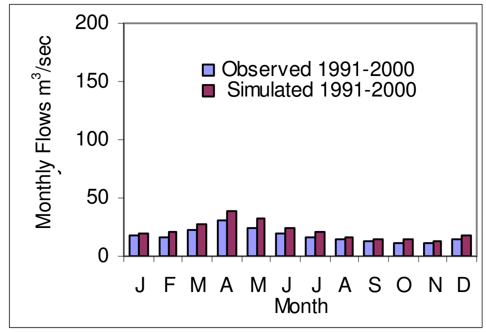


Figure 4.17 Calibration and validation and future scenario of river flow pattern based on H3B2 HadCM GCM emission scenarios

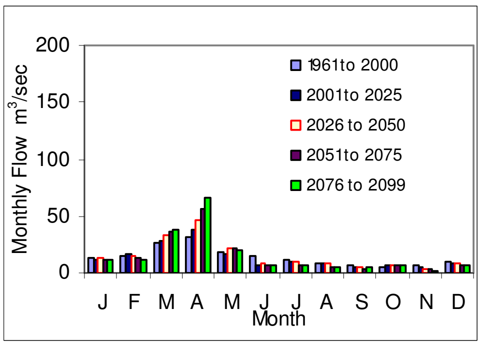
Dwambazi

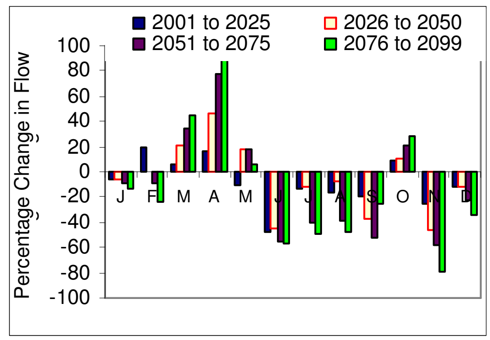




Calibration

Verification

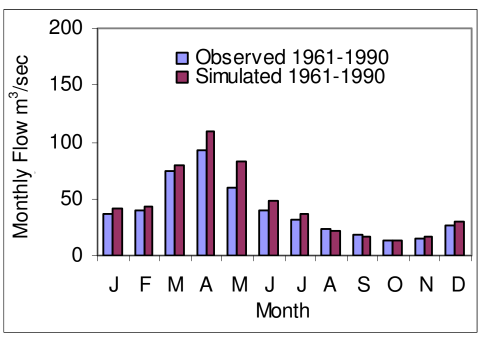


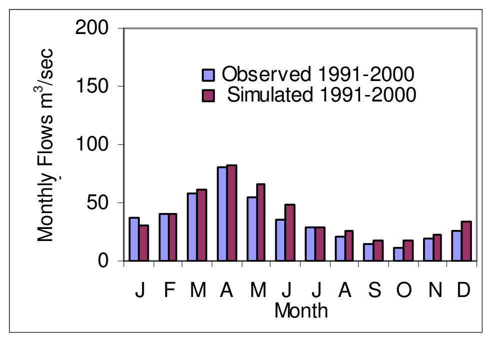


Future Scenario

Percentage change

Luweya





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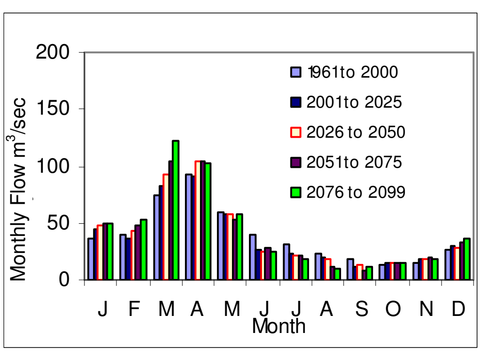
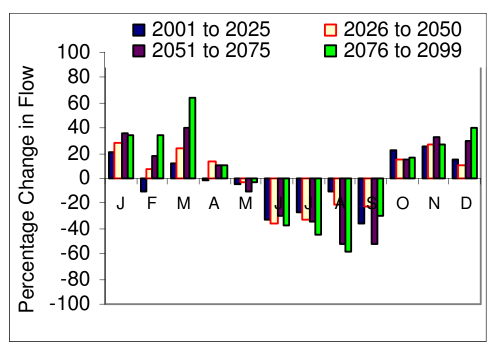


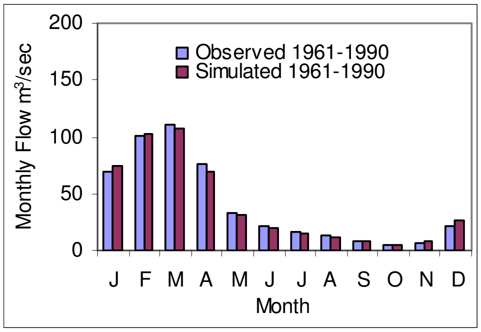


Future Scenario

Percentage change

Figure 4.17 continued

South Rukuru



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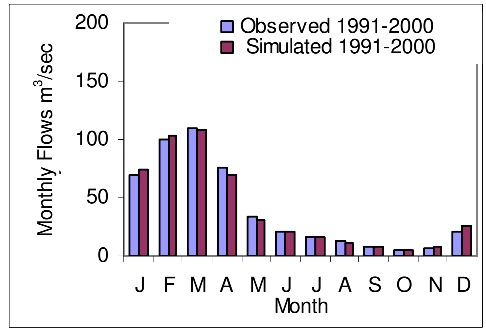

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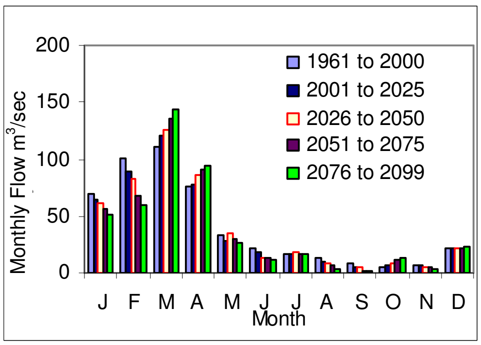

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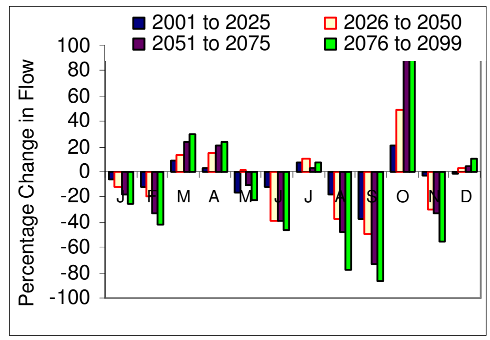
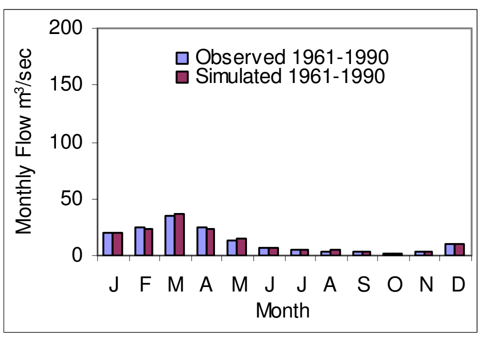


Percentage change

North Rukuru



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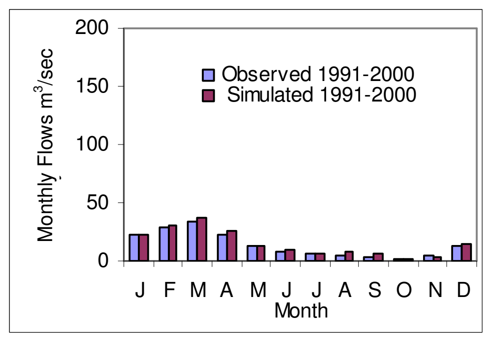

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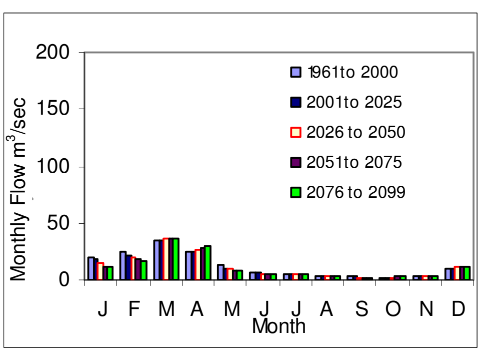
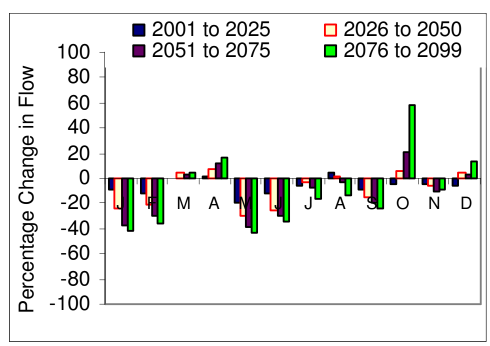


Future Scenario



Percentage change

Figure 4.17 continued

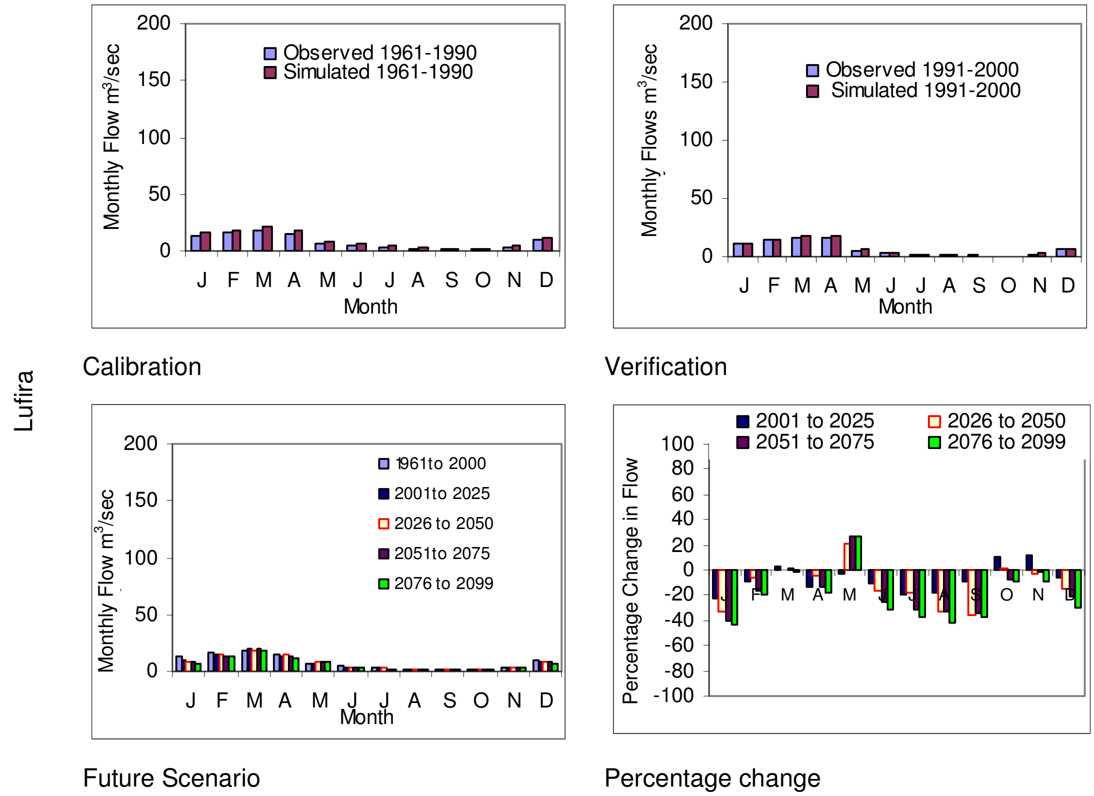


Figure 4.17 continued

A review of the land use pattern of the Central and North Malawi in Chapter 3 has shown that there is overexploitation of land resources including forest and land degradation due to agricultural activities. These activities compounded with population increase poses additional threats to water resources of Central and North Malawi. Predicted low flows and rainfall in the months of June to September indicate more droughts in the region. Low flows from rivers in the Central and North Malawi will result in reduced runoff into Lake Malawi, thereby affecting the water levels of Lake Malawi. Low water levels in Lake Malawi will have a negative effect on the irrigation abstraction in the Lower Shire Valley, hydropower generation along the Shire river as well as water supply to the city of Blantyre.

4.6 SUMMARY AND CONCLUSIONS

The aim of this Chapter was to model how the renewable water resources of

Central and North Malawi will behave in the future (21st Century). The method used Statistical Downscaling Model (SDSM) to downscale climate data for the river basins under investigation. Subsequently a hydrological model was used to create future flows based on downscaled rainfall.

The SDSM model was discussed while the hydrological model was discussed in Chapter 3. Later on required GCM data was obtained from HadCM3 data base through IPCC – data distribution centre. Selected predictor variables were used as input in the SDSM model to calibrate the model for predicting future climate data. The downscaling process involved calibration, verification and future data generation based on the calibrated statistical downscaling model.

To assess the impact of climate change on river flows, downscaled rainfall was used as input into the hydrological model to predict future runoff based on downscaled rainfall. To justify the use of the method computed flows were compared with observed flows in both calibration and verification period. It was generally observed that there was a good agreement between the observed and estimated flows in both the calibration and verification period.

Future climate scenarios of maximum and minimum temperature were also developed based on observed data from HadCM3 GCMs. Simulated temperature were also compared with observed temperature. There was generally a good agreement between the observed and estimated temperatures. Preliminary assessment of the changes in temperature of Central and North Malawi has revealed that the average maximum temperature for the region has increased by 0.74 ^{0}C and the minimum temperature has increased by 0.48 ^{0}C from 1961 to 1990. According to IPCC (2007), overall Africa has warmed by 0.7 ^{0}C over the 20th century.

The results of future rainfall, temperature and river flow scenarios have shown that Malawi is highly vulnerable to the impacts of climate change. The climate of Malawi is most variable on seasonal time scale and is predicted to become more variable, and extreme weather events are expected to be more frequent and severe. Floods and droughts will occur within months of each other, with increasing risk to food insecurity, health and life. This will lead to wide spread disruption of social-economic activities. Current estimates by Boko *et al.* (2007) indicates that one third of African population already live in drought prone areas and 220 million are exposed to drought each year.

The future temperature created in this Chapter can now be used in Chapter 5 to assess the future evaporation from the lake based on temperature based evaporation methods. The future runoff from Central and North Malawi created in this Chapter can now be used in Chapter 5 in predicting climate change impact on the water levels of Lake Malawi.

CHAPTER 5
WATER BALANCE MODEL OF LAKE MALAWI AND ITS SENSITIVITY TO CLIMATE CHANGE

5.1 INTRODUCTION

After modelling how the renewable water resource of the Central and North Malawi is likely to be affected in the future, it is now necessary to model the possible effects of climate change on the water level of Lake Malawi. Sustainable water resources development of Malawi needs a thorough assessment of the impact of climate change on the water level of Lake Malawi because Lake Malawi together with the Shire river water system is Malawi's most important water resource for hydropower generation, water supply for industrial and domestic use in the city of Blantyre and its surrounding urban areas and irrigation water in the Lower Shire Valley (LSV). Any changes in the hydrological or ecological behaviour of the lake will have far reaching consequences on the economy of Malawi. This Chapter reviews the current literature on the water balance studies of Lake Malawi and selects the preferred model. Downscaled climate data presented in Chapter 4 has been incorporated into the water balance model to assess the likely future behaviour of the lake.

5.2 IMPORTANCE OF LAKE MALAWI

Lake Malawi and the Shire river system play a major role in Malawi's economic sector. Lake Malawi is the main source of water for all the country's' hydropower stations located along the Shire river with a total installation capacity of 280 MW. At the same time the Shire is the main source of water for the country's largest sugar plantation at Nchalo and other irrigation schemes in the Lower Shire Valley (LSV) and the city of Blantyre (Figure 5.1). The lake also serves as a medium for water transportation which is conducted by government owned Malawi Lake Services (MLS). MLS operates passenger and cargo vessels on the lake. It is feared that low lake level as was the case between 1915 and 1935 when there was no outflow from the lake into the Shire river will seriously affect downstream users along the Shire as well as water transport (Kidd, 1983).

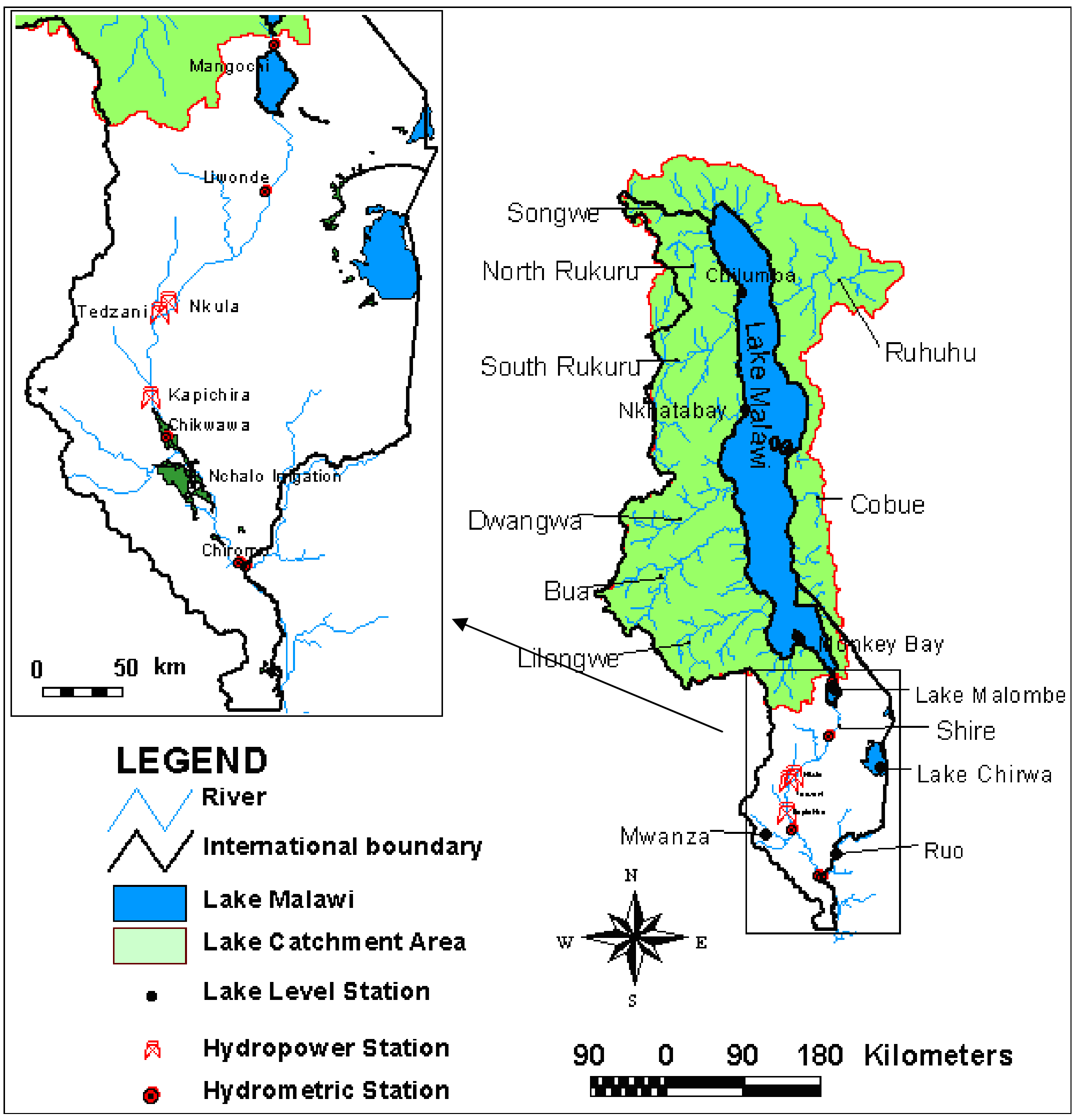


Figure 5.1 Lake Malawi and Shire river system showing the major water resources development in the Lower Shire Valley

Lake Malawi is not only recognised for its important functions in water supply, irrigation and hydropower generation but also for tourism, fishing and its richness in valuable natural resources. Lake Malawi is recognised as a world heritage site as it is home to 500 – 1000 fish species, exceeding any other lake in the world (Munthali, 1994). It is estimated that the Cichlidae species which make up 90% of the fish species found in the lake are indigenous to the lake (Konings, 1995).

The fisheries sector is recognised as an important asset for people living along the lake shore of Lake Malawi. Fisheries are an important source of proteins and contribute between 2 – 4% of Malawi's GDP employing almost 300,000 people (Banda *et al*., 1996; Munthali, 1994). Currently the fishing industry is facing increased pressure from population increases and changes in lake plankton as well as water quality. Studies have shown that the number of fish catches from the lake have declined especially in the densely populated southern part of the lake (Banda *et al*., 1996). Changes in the plankton community and water quality may lead to a decline in the fish species of the lake. According to Bootsma and Hecky (1999), the water quality and sediment load of the lake is changing due to increase in agricultural activities along the lake catchment. This calls for biodiversity and water quality control.

Despite the enormous benefits the lake sometimes causes problems especially to people living along the lake shore. The problem comes especially due to abnormally high water levels during the rainy season (Neuland, 1984). In the late 1970s the water level of the lake rose sharply and reached a maximum level of 477m in 1980. This resulted in floods along the lake shore, where fertile agricultural land was submerged and towns and villages were destroyed (Neuland, 1984). Rising levels also affects the downstream communities of the Lower Shire Valley as the high levels require maximum opening of the Liwonde barrage to release enough water from the lake. Large outflows from the lake combined with high flows from Ruo river which flows from Mulanje mountains have always been a major cause of floods in the Lower Shire Valley. Studies by Phiri (2000) regarding flood mapping of the Shire valley have revealed that high flows from Ruo river normally creates a bottle neck at Shire-Ruo confluence resulting in large flows accumulating in upper reach of the confluence along the

Shire river as shown in Figure 5.2. In recent years flooding along the Lower Shire valley (LSV) has been a perennial phenomenon and in 2008 during the rain season over 32,000 people were affected by floods in the LSV (SADC, 2009).

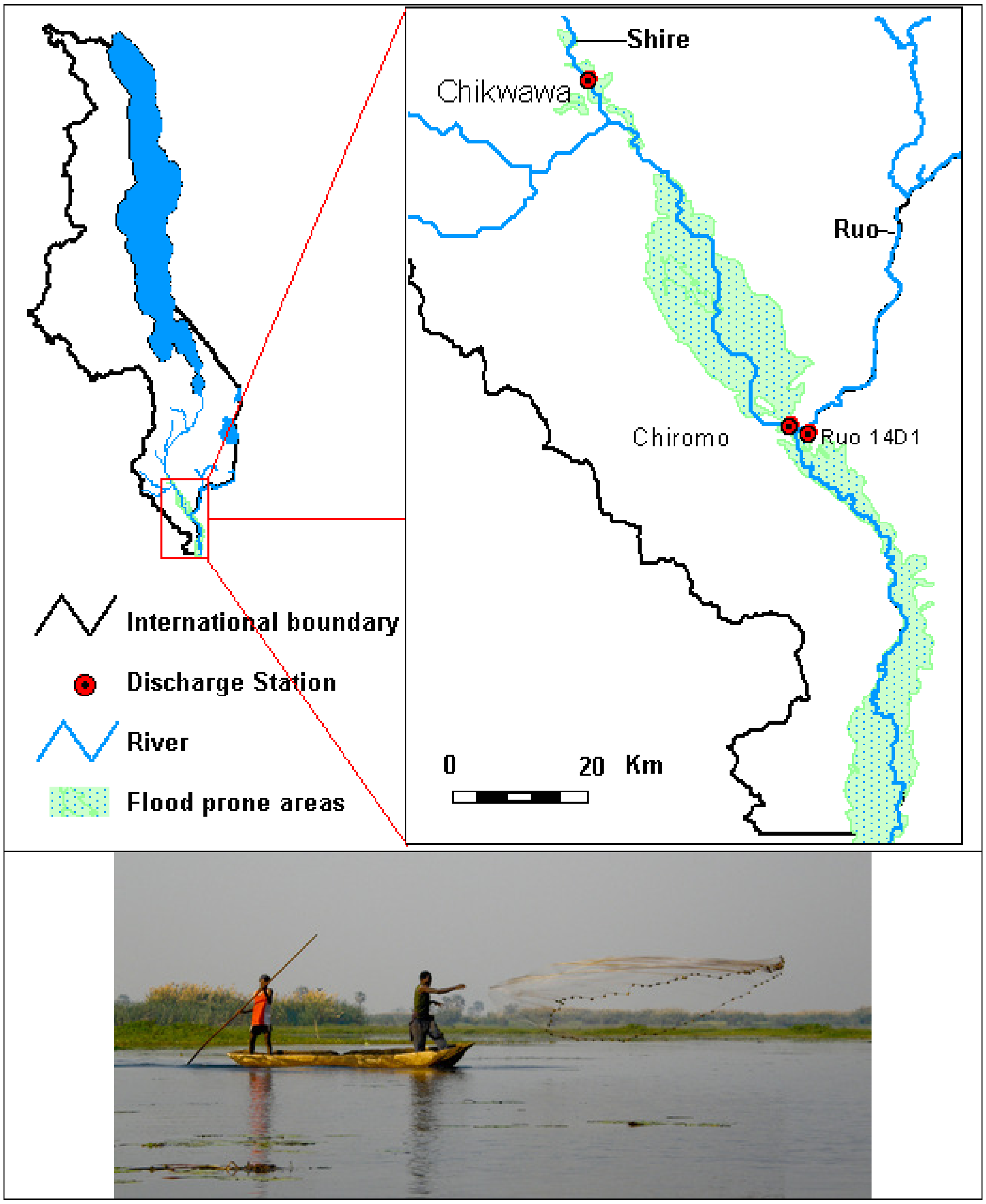


Figure 5.2 Map of the Lower Shire Valley and pictorial view showing the flood prone areas around Shire-Ruo confluence (Source of data:-(GoM, 2005)).

The outlined benefits and strategic importance of Lake Malawi calls for sustainable management of its unique eco-system. Because of that, since the colonial era, the lake has been the subject of a number of studies. The following section reviews some of the previous studies on the water balance of Lake Malawi. The aim of the review is to comment on previous models and to develop a recommendation on the optimum model to use in predicting future behaviour of the lake by introducing projected climate data based on GCM into the model.

5.3 REVIEW OF WATER BALANCE MODELS OF LAKE MALAWI

A water balance model is a mathematical expression used to describe the flow of water in and out of a hydrological system such as drainage basin or lake (Healy *et al.*, 2007). Water balance model has wider application in water resources management by predicting where there may be shortages or surplus water. In the last 3 decades a number of studies have been conducted regarding the water balance of Lake Malawi and its levels. It is therefore the interest of this section to review the current models with an aim to introduce climate change scenario testing into the existing models. This will provide insights into the future behaviour of the lake.

Lake Malawi has been a subject of a number of studies since the Halcrow study 1954 (cited by Kidd 1983). In 1983, Kidd conducted a thorough evaluation of the water resources of Lake Malawi and Shire river system. Kidd's analysis of the water balance of Lake Malawi was based on 26 years of the available data by that time. The outflow was based on flows at Liwonde barrage. At that time this was the only gauging station with a long term reliable data, starting from 1948. The main lake outlet station of Mangochi had usable data only since 1976. The model was designed to simulate historical time series of the lake level. However no firm prediction of the future behaviour of the lake was undertaken due to lack of tools to predict future rainfall behaviour.

Further studies on the water balance of the lake by Neuland (1984) revealed a gain in lake level of 0.11 m based on 26 years of data from 1954 to 1976. Neuland approach was similar to Kidd (1983). Neuland noted that rainfall over catchment and the lake plus subsequent runoff can cause abnormal high lake levels. Rainfall behaviour over the lake has shown to behave like a sine function shown in equation 5.1 (Neuland, 1984).

$$R_L(t) = 4.2 + 2.3\sin\left(\frac{360^0}{104}t + 214^0\right) + \sigma E(t) \qquad 5.1$$

R_L is rainfall over the lake, t is time in years, σ standard deviation and E is random component with (0,1) distribution. Research has shown that evaporation is the largest component in the water balance model of Lake Malawi (Calder *et al.*, 1995; Kidd, 1983; Neuland, 1984), yet it is the one which varies least (Neuland, 1984). Probability analysis of the future behaviour of the lake by Neuland (1984) has revealed that there is little risk of the lake level exceeding 477.8 m above mean sea level. Under pessimistic assumption of the hydro climate of the lake, the level remains below 477 m. Future projected levels of the lake have shown a tendency to fall approaching gradually equilibrium of 475 m amsl. Similar studies on water balance by Dryton in 1984 revealed a net positive change in storage between 1953 and 1974. Dryton's (1984) model was similar to Kidd's (1983) and Neuland's (1984) model, and was aimed at predicting annual maximum monthly water levels. Table 5.1 is a summary of the net change in storage based on previous studies:

Table 5.1. Net water storage of Lake Malawi based on previous studies

Researcher	(Kidd, 1983)	(Neuland, 1984)	(Drayton, 1984)
Data period	1954 - 1979	1954-1979	1953-1974
Rainfall over the lake (mm)	1414	1374	1350
Inflow into the lake (mm)	1000	693	693
Lake Evaporation (mm)	1872	1605	1610
Outflow from the lake (mm)	418	404	334
Change in storage (mm)	+112	+58	+59

The most recent work on the water balance of Lake Malawi is the study done by Calder *et al.* (1995). Calder *et al.* (1995) studied the impact of land use change on the water levels of the lake using a water balance model. Calder *et al.* (1995) noted that there was a good correlation between the observed and estimated levels by the model for the period 1896 to 1997 with forest coverage of 64%, except for the period 1935 to 1945 immediately following the time when there was no outflow from the lake. The model prediction for the period 1954 to 1994 was equally good and more consistent with decrease in Lake Malawi catchment forest cover of 13% over the 1967 to 1990 period. Calder *et al.* (1995) and Neuland (1984) have recognised that increase in rainfall will lead to abnormally high lake levels, accelerated by the change in runoff characteristics in the catchment due to reduced forest cover. All the previous studies on the water balance model were based on the net balance between inflow from lake catchment Q_{in}, rainfall R_L and evaporation $Evap_L$ over the lake and Shire river outflow Q_{out} in estimating the change in lake water storage ΔS as shown in Figure 5.3 and equation 5.2.

$$\Delta S = R_L + Q_{in} - Evap_L - Q_{out} \qquad 5.2$$

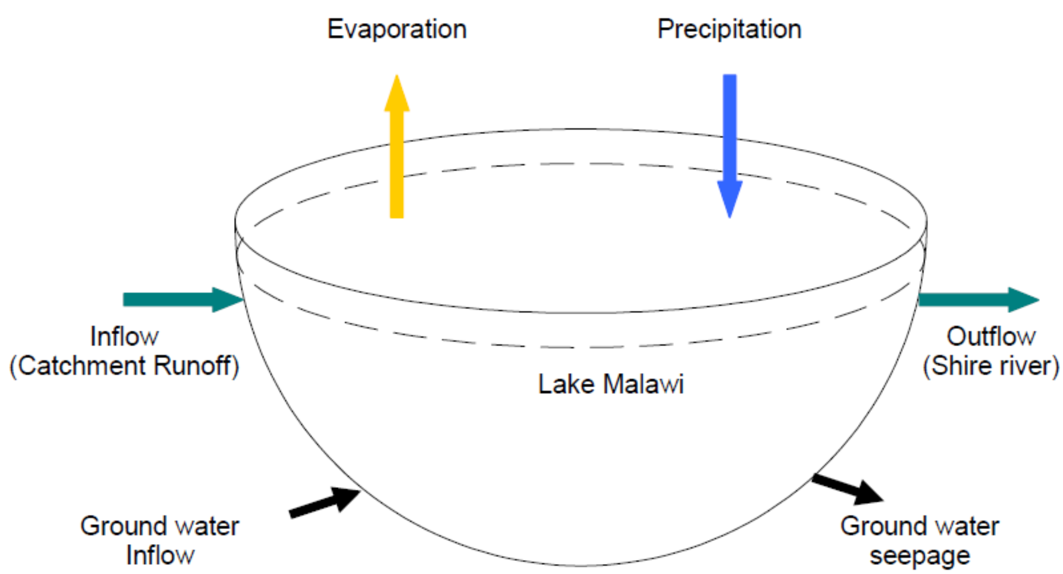


Figure 5.3 Lake Malawi Water Balance Model Components

Calder *et al.* (1995) introduced a one month time lag between inflow and outflow from the lake in estimating net storage of the lake. The modified model after Calder *et al.* (1995) is shown in equation 5.3.

$$\Delta S(t) = R_L(t) + Q_{in}(t) - Evap_L(t) - Q_{out}(t-1) \qquad 5.3$$

From the review on the water balance model, it has been noted that downscaled climate parameter has until now, not been used in predicting future behaviour of the lake. Further to that outflows from the lake have always been based on flows at Liwonde barrage (Liwonde hydrometric station shown in (Figure 5.1)) which are always affected by the operation of the barrage, direct rainfall and evaporation within the catchment area between the lake outlet and the barrage, variation in the storage of Lake Malombe. In this investigation, downscaled climate data will be used in the water balance model based on current flows at main lake outlet (Mangochi) to assess the future behaviour of the lake. This is motivated by new threats of low lake levels in recent years. In addition, a new water balance model would be beneficial due to the long time period since the previous studies were conducted. Climate data downscaled from GCM as described in Chapter 4 will be used to assess future behaviour of the lake. The following section describes the main components of the water balance model relating to Lake Malawi in particular.

5.4 WATER BALANCE MODEL OF LAKE MALAWI

5.4.1 Main components of water balance model

Studies by Calder *et al.* (1995), Dryton (1984) and Neuland (1984) on the water balance of lake Malawi have recognised that the water balance which governs the water level behaviour of Lake Malawi is a combination of runoff from rivers flowing into the lake, measured outflow from the lake, evaporation from the lake surface and rainfall on the lake (Figure 5.3). Groundwater inflow and outflow has always been ignored in previous studies because of lack of piezometric data around the lake quantifying groundwater flow around the lake. According to Kebede *et al.* (2006) equation 5.3 is a simplification of the water balance of an open lake normally given by the following differential equation

$$\frac{dL}{dt} = R_L(t) \quad Evap_L(t) + \quad \frac{Q_{in}(t) \quad Q_{out}(t) + G_{net}(t)}{A_L(h)} + \varepsilon(t) \qquad 5.4$$

where G_{net} is the net groundwater flux, A_L is the surface area of the lake and the other parameters have been described in equation 5.2 and 5.3. The final term ε, represents uncertainties in the water balance arising from errors in the data and other terms such as minor abstraction or inflow from ungauged catchments.

5.4.1.1 Inflow into the lake Q_{in}

Previous studies by Calder *et al*. (1995); Drayton (1984); Neuland (1984) have considered combination of the runoff records from all the major catchments in Malawi, Tanzania and Mozambique shown in Figure 5.1. Due to lack of data from neighbouring countries (Tanzania and Mozambique) Neuland (1984) and Calder *et al*. (1995) employed extrapolation methods to estimate the inflow contribution from Tanzania, Mozambique and ungauged catchment areas. The method involved assigning ungauged catchment to gauged areas with similar rainfall.

In this research runoff data from Lake Malawi catchments was obtained from the Ministry of Irrigation and Water, Department of Hydrology in Lilongwe. This covered all inflows from Malawi catchment as well as Tanzania catchment. However data from Mozambique is still not available. Inflow data from Mozambique was estimated by extrapolation method described by Calder *et al.* (1995).

5.4.1.2 Outflow from the lake Q_{out}

Outflow records from previous studies were based on flow records at Liwonde barrage (Calder *et al*., 1995; Kidd, 1983; Neuland, 1984). Outflows records from the lake are now available at Mangochi station from 1971 up to 2006. The relationship between water levels and lake outflows at the Mangochi station is given in Figure 5.4 and equation 5.5. There is a good correlation between the water level and the lake outflows at Mangochi ST1 station with Nash-Sutcliffe model efficiency $R^2 = 0.97$. According to Kebede *et al.* (2006) and Sene (1998) the relationship between lake outflows and water levels for naturally unregulated lakes can be expressed by the following equation;

$$Q_{out} = a(L_{eff})^b \qquad 5.5$$

where L_{eff} is the effective level of water responsible for outflow from the lake, and a and b are constants. The constant b varies between 0 and 3 in many natural lakes. The b value is always equal to 1 when there is a linear relationship between effective head and lake outflows while a lake with constant outflow will have a b value of 0.00. A plot of mean monthly outflows vs. lake levels for the period 1971 to 2001 shown in Figure 5.4 has a relationship given in equation 5.6. A datum value of 470.8 m in equation 5.6 was selected by optimising the best fit of the relationship of lake outflows vs. lake levels in Figure 5.4. The b value in equation 5.6 below indicates that a small change in lake level would have a significant effect on the lake outflow. This shows that a small change in net inflow into the lake would result in a small change in lake level as well as lake surface area but a significant change in the lake outflow.

$$Q_{out} = 30.285(L - 470.8)^{1.9145} \qquad 5.6$$

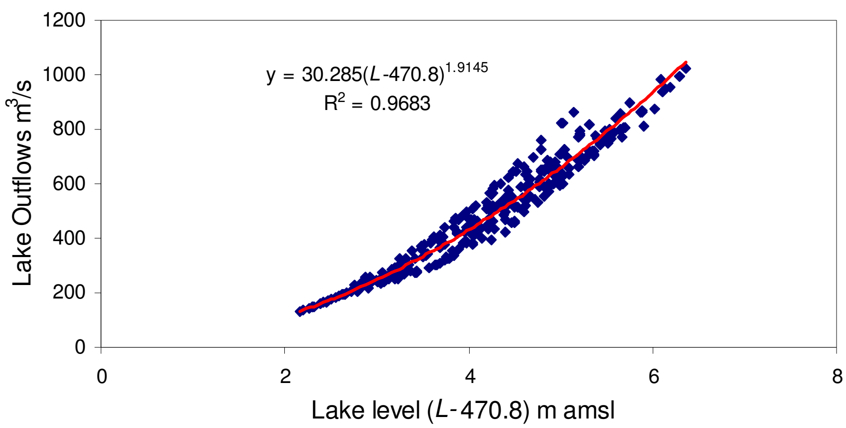


Figure 5.4 Correlation of Lake Malawi water levels and outflows at Mangochi station.

Simulated outflows from the lake based on equation 5.6 were compared with observed flows at Mangochi station as shown in Figure 5.5. The results show a good agreement between observed and estimated flows in the calibration period of 1971 to 1990 with a Nash-Sutcliffe $R^2 = 0.86$. The disagreement in the simulated and observed flows in the year 1988 and 1989 could be attributed to recording error in the lake level data or out flow data. The calibrated equation 5.6 was verified against observed lake outflows for the period 1991 to 2001. The model performed well in the verification period with a Nash-Sutcliffe $R^2 = 0.96$. There was a good agreement between the observed and estimated outflows in the verification period as shown in Figure 5.5. The 1991 to

2001 was a low level/outflow period of the lake and the model even performed well during this period. This justifies the universal use of the equation in simulating Lake Malawi outlet flows based on observed levels. Lake outflows simulated by equation 5.6 have shown to match measured flows. Some examples of the approach in literature are: simulation of Lake Tana outflows (Kebede *et al*., 2006) and Lake Ziway (Vallet-Coulomb *et al*., 2001) outflows in Ethiopia.

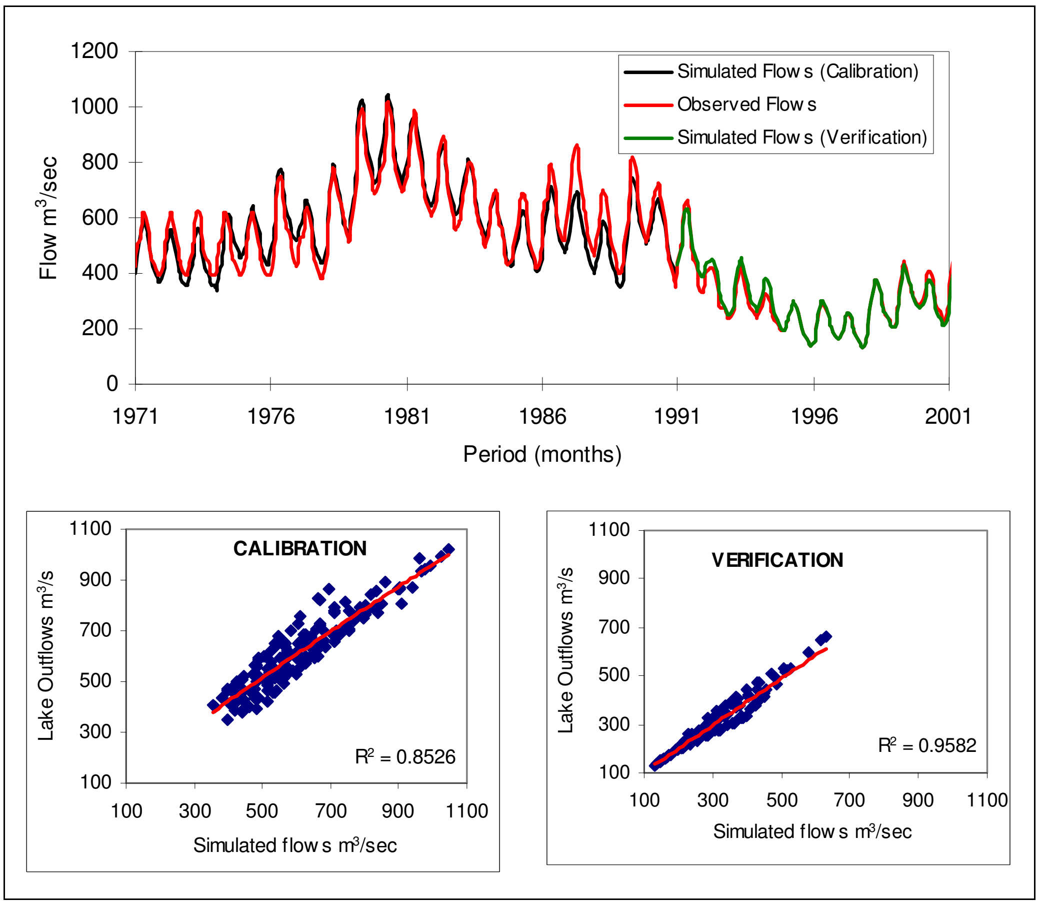


Figure 5.5 Simulated flows of Mangochi outlet station by lake level-outlet flow equation.

5.4.1.3 Direct rainfall P_L and evaporation $Evap_L$ over the lake

Precipitation over the lake has been estimated from climate stations along the lake for the period 1971 to 1990. The Inverse Distance Weighted Method described in section 3.3.1.1 has been used to estimate areal rainfall over Lake Malawi. The major challenge to the method is lack of climate records over the lake itself. This contributes to uncertainties in the water balance model. Simple linear regression model was used to assess whether the trend in rainfall over Lake Malawi was increasing or decreasing. Figure 5.6 shows that rainfall over lake Malawi is decreasing as the gradient of the trend line is negative (-0.0013).

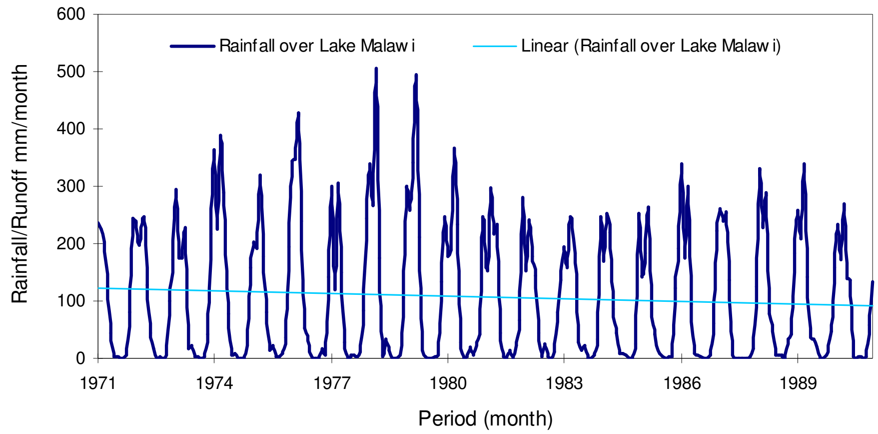


Figure 5.6 Total rainfall over Lake Malawi for the period 1971 to 1990 with a trend line showing decrease in rainfall

5.4.1.4 Evaporation $Evap_L$ over the lake

Several studies have shown that evaporation from an open water body is the largest component of the water balance but very difficult to accurately determine because of lack of climate stations within the lake area (Calder *et al*., 1995; Kebede *et al*., 2006; Neuland, 1984). There are several methods of estimating evaporation in literature as outlined in Chapter 2. Among all the methods, research has shown that the Penman method is the most reliable method for evaporation estimate under any climate condition (Allen *et al*., 1998a; Jensen *et al*., 1990). Evaporation was estimated using Penman method for open water described in Chapter 2. However future evaporation estimates by Penman method is not possible because of the data requirement. The GCMs can simulate maximum and minimum temperature but not sunshine hours as required by Penman method. That being the case it was deemed necessary to investigate temperature-based methods for predicting evaporation estimates.

5.4.2 Estimation of Penman equivalent evaporation

Scarcity of climate data for estimating evaporation is a major set back to many practicing engineers in developing countries like Malawi. It is therfore necessary to investigate other methods of estimating evaporation to supplement the available data. Estimation of evaporation from GCM outputs can also benefit from models which require few data input. This section looks at the three methods apart from Penman method as possible tools for estimating evaporation for Central and North Malawi as well as Lake Malawi. Estimates from Penman method have been compared with estimates from other methods listed in Table 5.2.

Table 5.2 Summary of evaporation models used in the study

Method	Equation	
Fao Penman Equation (Allen *et al.*, 1998a)	$ET_0 = \frac{0.408 * \Delta * (R_n - G) + \gamma * \left(\frac{900}{T+273}\right) * U_2 (e_a - e_d)}{\Delta + \gamma * (1 + 0.34 U_2)}$	5.7
Hargreaves(Hargreaves and Samani, 1982)	$ET_0 = 0.0023 * (T_{mean} + 17.8) * (T_{max} - T_{min})^{0.5} * Ra$	5.8
Priestly and Taylor	$ET_0 = \alpha \frac{\Delta}{\Delta + \gamma} (R - G); .... \alpha = 1.26$	5.9
Turc Method	$ET_0 = \beta \frac{T}{T+15} (S_n + 2.09) \left(1 + \frac{50 - RH}{70}\right) RH > 50$ $ET_0 = \beta \frac{T}{T+15} (S_n + 2.09) .... \beta = 0.31; .... RH > 50$	5.10
All the parameters are fully described in Section 2.8.5		

Using climate data outlined in Chapter 3, evaporation estimates for the 6 main climate stations within the area were made using the methods listed in Table 5.2; FAO Penman, Hargreaves, Priestly and Taylor and Turc Method. The results of the four seasonal evaporation estimates for the six climate stations have been presented in Figure 5.7 and correlation diagrams have been presented in Figure 5.8 – 5.10. The Nash-Sutcliffe R^2 criteria was used as a measure of the best fitted model (Nash and Barsi, 1983). Seasonal mean values of evaporation estimates were plotted on the same axis as the Penman estimates to compare the trend and difference with the Penman estimates (Figure 5.7). The results of evaporation estimates presented in Figure 5.7 shows that Turc overestimated evaporation for all the six climate stations.

The following two observations were noted with Turc results in Figure 5.7:-

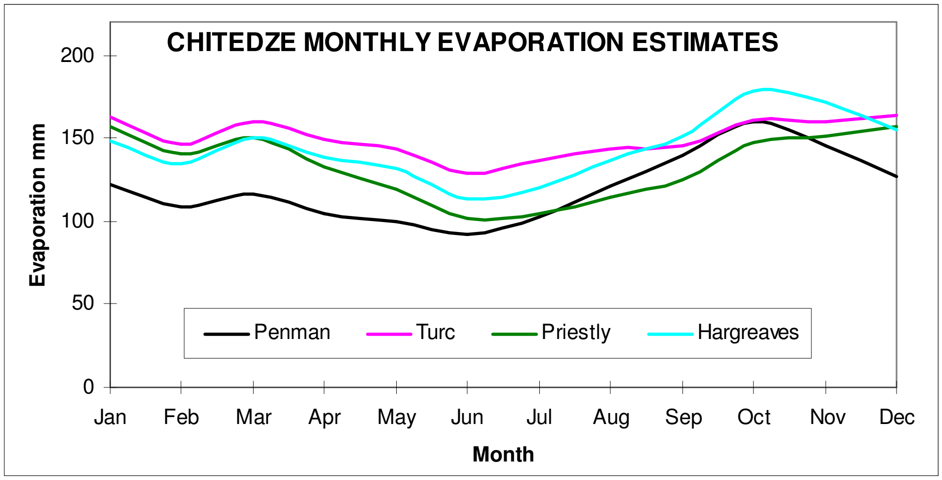
- Evaporation estimates for Chitedze, Salima, Nkhotakota and Karonga are higher for eleven months except the month of October where the results are almost equal to the Penman estimates. The four stations have the lowest humidity during the month of October; 53, 54, 57 and 55 respectively and an average annual humidity of 70, 67, 70 and 69 respectively (Figure 5.11).

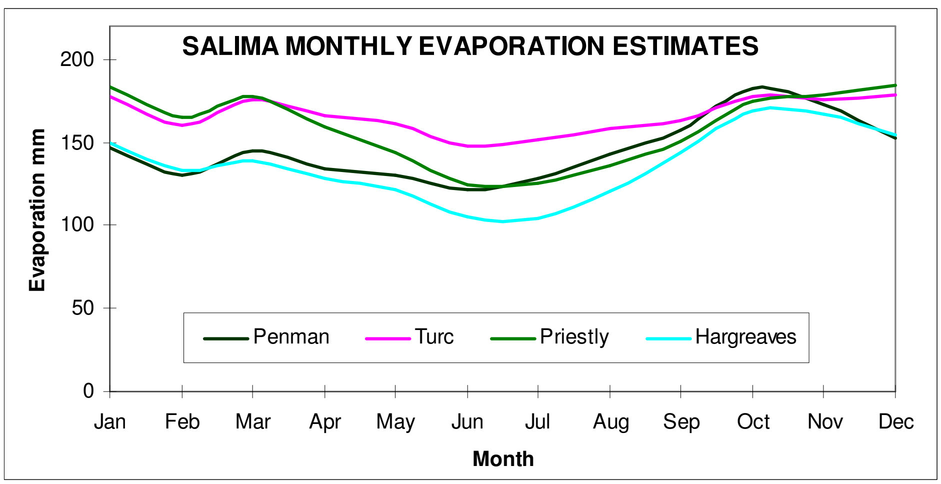
- Evaporation estimates for Mzuzu and Nkhatabay are higher than Penman estimates for all the 12 months. The seasonal graphs for Mzuzu and Nkhatabay are higher and parallel to the Penman graph. Mzuzu and Nkhatabay stations have higher humidity than the other stations through out the year with an annual average relative humidity of 82 and 77 respectively (Figure 5.11).
- In terms of model efficiency the lowest model efficiency of 0.42 was record at Chitedze. Model efficiency of lake shore stations Salima, Nkhatabay, Karonga and Nkhotakota were equally good; 0.78, 0.74, 0.74 and 0.73 respectively. Mzuzu station which has the highest humidity had the highest model efficiency of 0.86 (Figure 5.8, Figure 5.9 and Figure 5.10)

Evaporation estimates by Hargreaves method presented in Figure 5.7 shows that the model estimates were equally good for all the stations with the lowest model efficiency of 0.73 being recorded for Nkhotakota and the highest being that of Mzuzu which was 0.86. Higher model efficiency was recorded for stations with high humidity Mzuzu and Nkhatabay which had a model efficiency of 0.86 and 0.79 respectively. In terms of seasonal distribution estimate the model estimates for the 2 stations were higher than standard Penman estimates throughout the year.

Evaporation estimates by Priestly and Tylor model (Figure 5.7) were higher than Penman estimates for the months of January through July for Chitedze, Salima, Karonga and Nkhotakota stations. Priestly-Tylor model efficiency for the 4 stations was 0.31, 0.78, 0.74 and 0.73 respectively. Climate stations along the lake showed a consistently higher model performance than the inland climate station of Chitedze which had the lowest model performance of 0.31. It was also observed that model estimates for Mzuzu and Nkhatabay were higher than Penman estimates throughout the year. However the model performance for the

2 stations in terms of R^2 was 0.86 and 0.74 respectively.





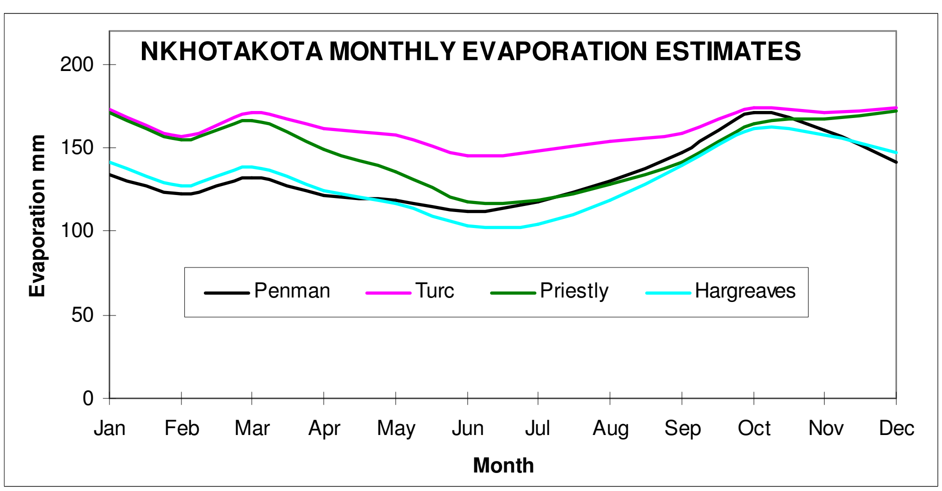


Figure 5.7 Annual distribution of evaporation estimates by Penman, Turc, Priestly-Tylor and Hargreaves method

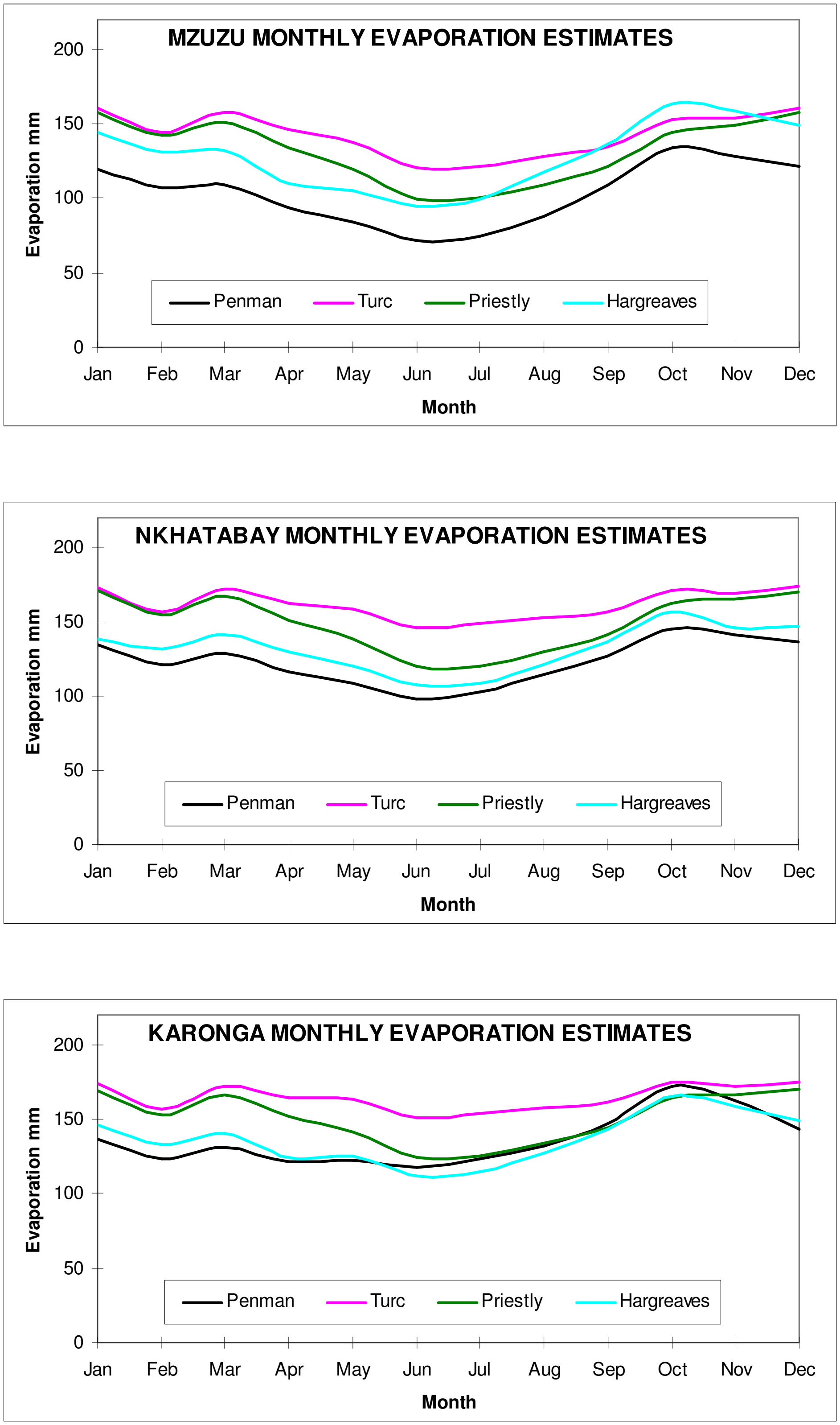


Figure 5.7 Continued

Analysis of the performance of the three models (Priestly-Tylor, Hargreaves and Turc) against the Penman model has shown that the three models have a tendency to overestimate evaporation during the months with high relative humidity. Previous research has shown that the Hargreaves method overestimates evaporation in areas with high humidity (Allen *et al*., 1998c; Droogers and Allen, 2002; Samani, 2000). Therefore the regression method has always been used to find standard parameter for converting Hargreaves and other method's estimates to the Penman equivalent estimates (Allen *et al*., 1998c; Jensen *et al*., 1997 ; Temesgen *et al*., 1999). However in this research it was observed that a single parameter would not be enough to standardize other methods to estimate evaporation in Malawi due to the fact that humidity varies considerably throughout the year. Monthly dependant conversion factors were proposed for converting model estimates to Penman equivalent as outlined in the following section.

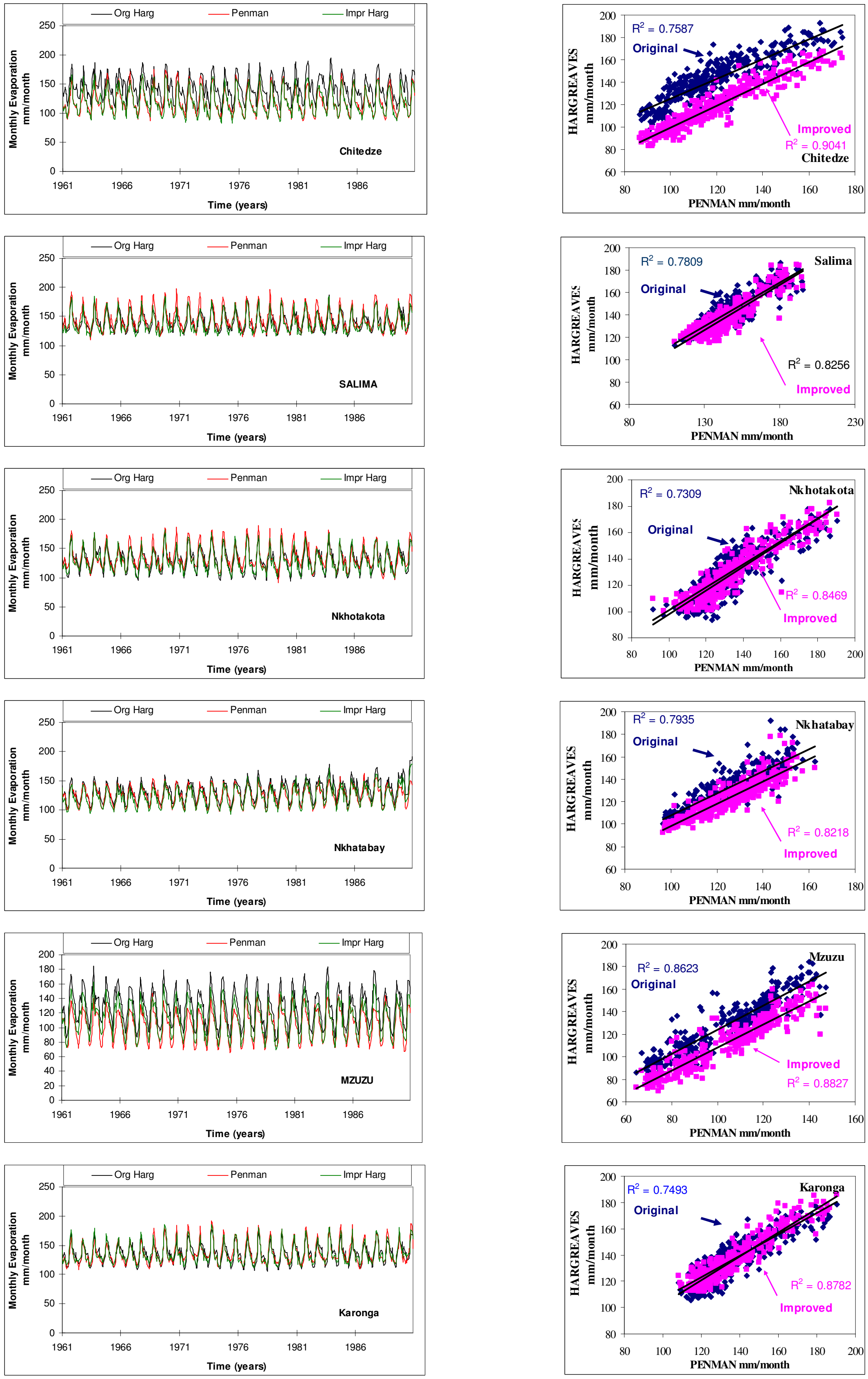


Figure 5.8 Typical improved and original evaporation estimates by Hargreaves model for 6 climate stations

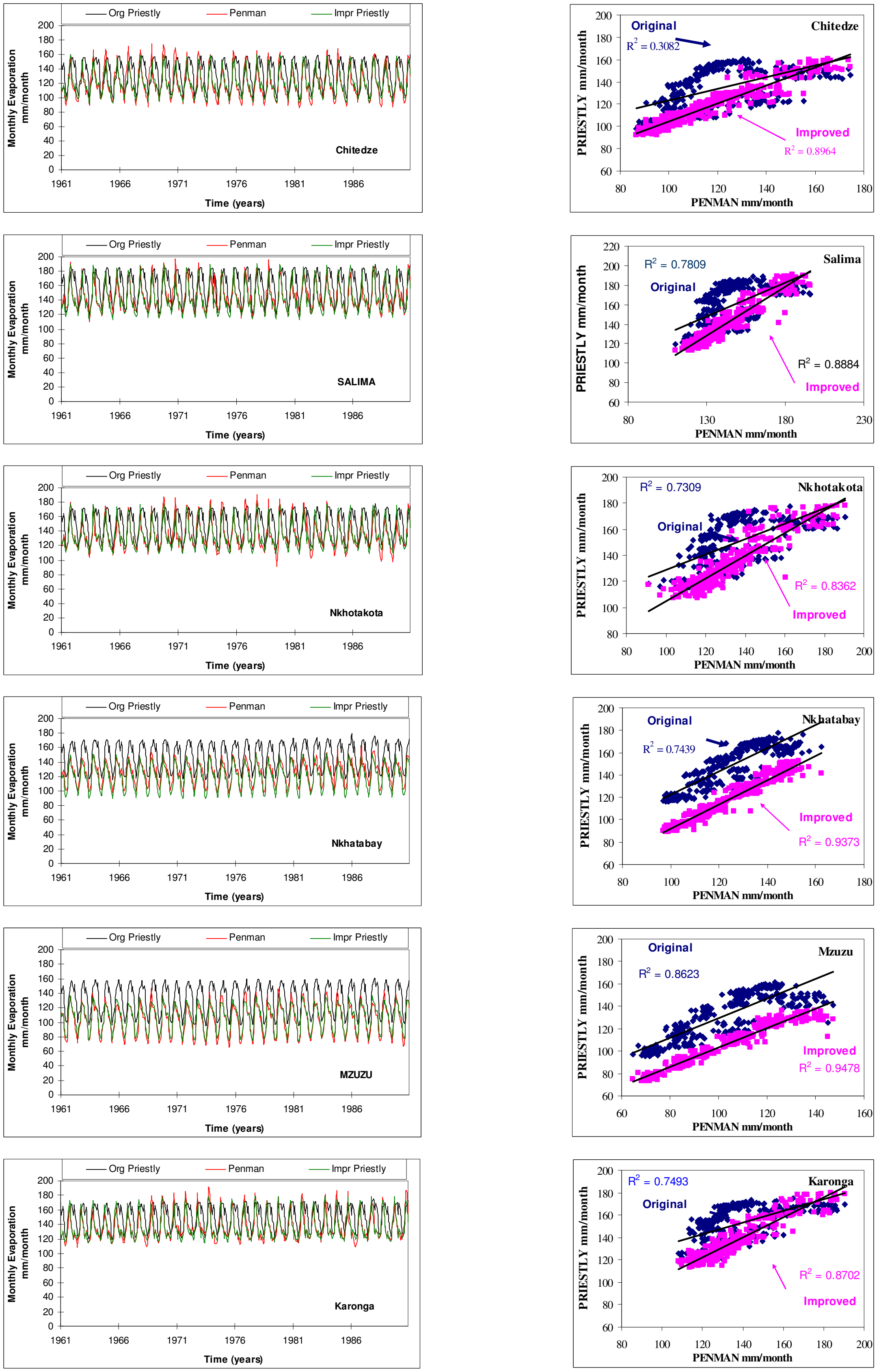


Figure 5.9 Typical improved and original evaporation estimates by Priestly model for 6 stations

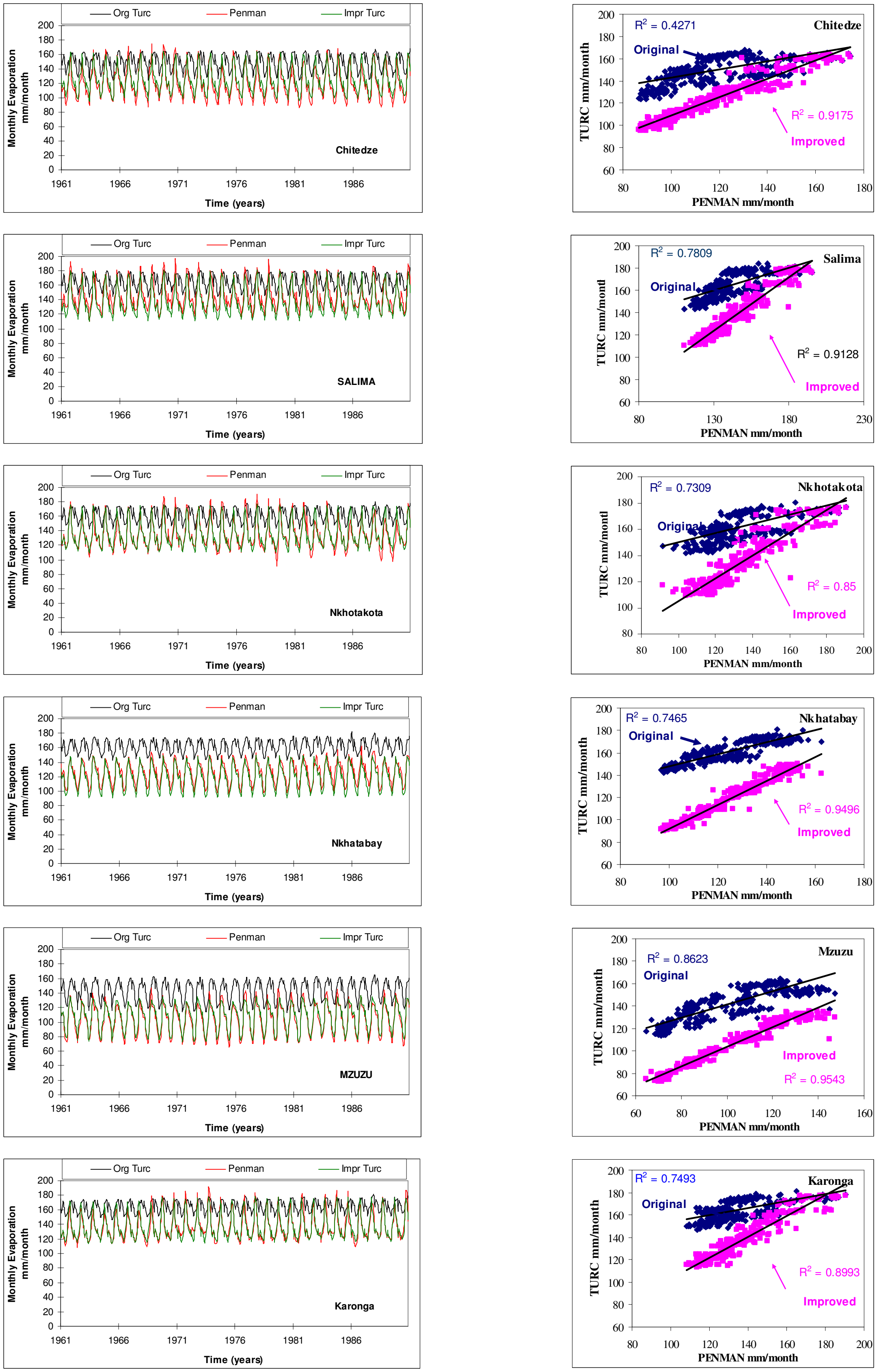


Figure 5.10 Typical improved and original evaporation estimates by Turc model for 6 climate stations

5.4.3 Derivation of station parameters for converting evaporation estimates by Hargreaves, Priestly-Tylor, and Turc method to Penman equivalent evaporation

The relative humidity for all six climate stations under consideration varies throughout the year. For instance relative humidity is low for the month of October for all the stations as shown in Figure 5.11. That being the case it was considered necessary to develop monthly conversation factors for adjusting evaporation estimates by Hargreaves, Priestly-Tylor, and Turc to Penman equivalent evaporation estimates. The 2 stations (Mzuzu and Nkhatabay) with high humidity were placed in one category and the remaining 4 stations (Salima, Chitedze, Karonga and Nkhotakota) with relatively low humidity were placed in another category. A ratio of the mean annual evaporation estimate of the month to the Penman estimate for that month was considered as a conversion factor. An average of each category was used to convert original estimates to Penman estimates. Table 5.3 is a summary of the conversion factors for the 6 climate stations. The factors presented in Table 5.3 were used to convert estimates by Hargreaves, Priestly-Tylor, and Turc estimated evaporation. This involved multiplying the monthly factor for each month with the daily evaporation estimate for that month. The results have been presented in Figure 5.8, Figure 5.9 and Figure 5.10 alongside the unimproved estimates.

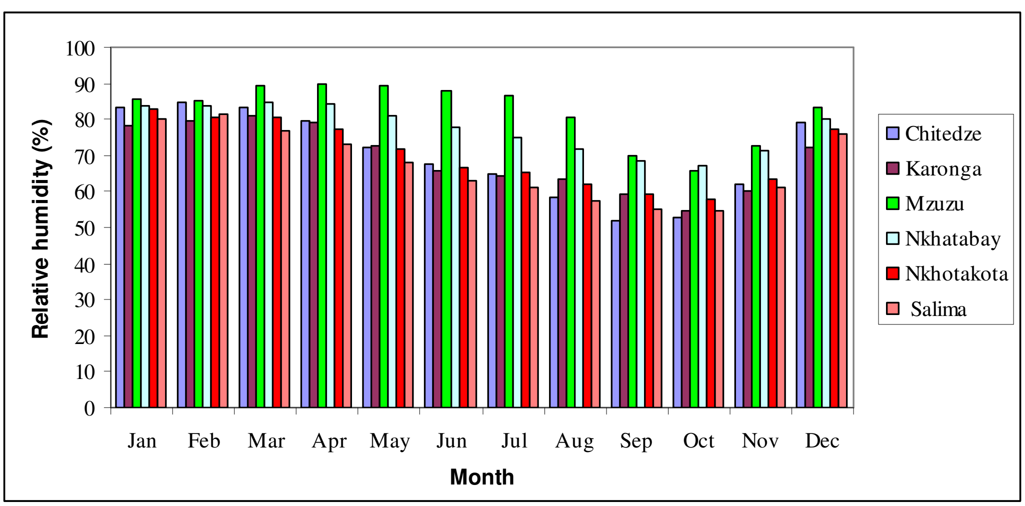


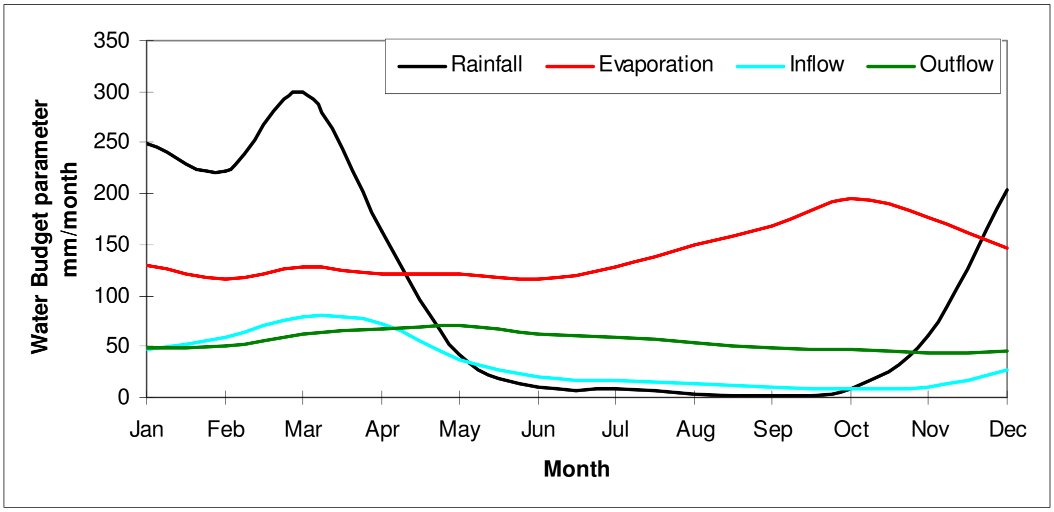
Figure 5.11 Seasonal variation of relative humidity for six climate stations Chitedze, Karonga, Mzuzu, Nkhatabay, Nkhotakota and Salima (MetD, 2009)

Table 5.3 Monthly evaporation estimates conversion factors

	Monthly conversion factors					
Month	Hargreaves		Priestly-Tylor		Turc	
	A	B	A	B	A	B
Jan	0.922	0.898	0.793	0.770	0.785	0.759
Feb	0.918	0.871	0.790	0.770	0.781	0.757
Mar	0.925	0.868	0.792	0.746	0.770	0.721
Apr	0.941	0.875	0.812	0.736	0.752	0.679
May	0.955	0.848	0.869	0.744	0.752	0.645
Jun	1.023	0.838	0.944	0.769	0.771	0.634
Jul	1.071	0.848	0.992	0.798	0.796	0.651
Aug	1.052	0.849	1.027	0.846	0.858	0.717
Sep	1.022	0.864	1.052	0.899	0.941	0.809
Oct	1.020	0.874	1.055	0.912	0.998	0.863
Nov	0.982	0.887	0.966	0.856	0.943	0.833
Dec	0.933	0.871	0.826	0.787	0.815	0.773
Category **A** is for stations with low humidity (Chitedze, Salima, Nkhotakota and Karonga Category **B** is for stations with high humidity (Mzuzu and Nkhatabay)						

5.4.4 Results of improving estimation of Penman-equivalent evaporation

After applying the monthly conversion factors to the original model estimates, the model efficiency (performance of the model based on Nash-Sutcliffe R^2) improved for all the 3 models. The results have been presented in Figure 5.8, Figure 5.9 and Figure 5.10 along side the unimproved evaporation model estimates. The lowest model efficiency after improvement was 0.85, 0.82, and 0.83 for Nkhotakota, Nkhatabay and Nkhotakota with the following models respectively Turc, Hargreaves and Priestly-Tylor model. The graph of monthly evaporation estimates for the three improved models in Figure 5.8, Figure 5.9 and Figure 5.10 shows a good correlation between model estimates and standard Penman estimates indicating that the 3 improved models are equally good. In this research the Hargreaves method has therefore been selected as a preferred method for estimating future evaporation because of lower input data requirement.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ANNUAL
Rainfall	249	222	300	163	42	11	8	3	1	9	60	204	1272
Evaporation	129	116	129	121	121	117	127	149	169	195	177	146	1695
Inflow	47	59	79	72	37	21	17	13	10	8	10	27	400
Outflow	50	50	62	68	70	63	59	54	49	47	43	45	658

Figure 5.12 Monthly and annual water budget of Lake Malawi in mm for the period 1976 – 1990

5.4.5 Mean annual water balance of Lake Malawi for the period (1976 – 2001)

After collecting all the necessary data for water balance model, a mean monthly and annual water balance for Lake Malawi (1976 – 1990) was tabulated and presented in Figure 5.12. The balance has an error of -680 mm indicating a loss in water level. The source of this huge error could be attributed to the lack of data on groundwater inflow contribution, lack of direct estimates of evaporation and precipitation over the lake. Rainfall and evaporation over the lake were based on climate stations along the lake which could not really be the true value of evaporation. This is because the lake covers a large surface area of 28,500 Km^2. The other contributing error could be in the recording of the lake level which is normally done at 3 stations a along the lake shore (Chilumba, Nkhatabay and Monkey Bay as shown in Figure 5.1) and the water level is normally the average of the three records. This normally ignores the water level gradient which is there between the north and south tip of the lake.

The annual water balance has also revealed that the peak runoff into the lake coincide with the peak rainfall over the lake in March while the outflow from the lake reaches its peak value in May two months after peak runoff indicating an average time lag of 2 months between input and runoff. Evaporation is the largest component which withdraws water from the lake and yet varies least among the Water Balance Model (WBM) components. Evaporation reaches an average peak value of 195 mm/month in October. The lowest component among the Water Balance Model components is runoff from lake catchment while the outflow from the lake is the component which has no marked variation throughout. This could be attributed to flow regulation at Liwonde barrage which is aimed at maintaining a constant flow downstream of the Shire river.

After analysing the net storage of Lake Malawi for the period 1971 to 1990, it is now necessary to simulate the behaviour of the lake based on the observed data. Simulation of lake levels require solution of the water balance equation given in equation 5.4.

5.5 LAKE WATER LEVEL SIMULATION

The water balance model given in equation 5.4 is a differential equation with two unknowns at the same time. Solution to such types of equation involves simulating the water level on monthly basis or longer time steps (Calder *et al.*, 1995; Kebede *et al.*, 2006). The differential equation 5.4 can be written as equation 5.11 with an integration period of Δt (one month and above)

$$\Delta L = R_L(t) \quad Evap_L(t) + \frac{Q_{in}(t) \quad Q_{out}(t) + G_{net}(t)}{A_L(h)} + \varepsilon(t) \qquad 5.11$$

Depending on available data, the above model can further be simplified by neglecting some of the terms on the right hand side. In our case we have assumed zero net groundwater flux because of lack of data on net ground flow around the lake. Due to lack of information on surface area – lake depth relationship, a constant surface area has been assumed in equation 5.11. This simplifies equation 5.11 into the following form

$$\Delta L = R_L(t) - Evap_L(t) + \frac{Q_{in}(t) - Q_{out}(t)}{A_L} + \varepsilon(t) \qquad 5.12$$

Any model needs to be calibrated against measured data before it can be accepted for use in issuing forecasts. That being the case the water balance model in equation 5.12 was calibrated against measured data from 1971 to 1985 and the following section describes the approach involved in calibrating the model.

5.6 CALIBRATION AND VERIFICATION OF WATER BALANCE MODEL

The water balance model presented in equation 5.12 was calibrated and verified using available data. The available data was split in two parts:- 1971 to 1985 as the calibration period and 1986 to 1990 as the verification period. Calibration and verification was based on the period 1971 to 1990 because this is the period with complete records in terms of all the WBM components. The approach in the calibration involved solving equation 5.12 to estimate the lake level based on previous time step outflow and assuming the initial starting lake level is the observed lake level of the first data point in the lake level data series. Time lag has also to be considered between the inflow and outflow, which is difficult to estimate. The approach adopted in this research was by trial and error. This involved changing the time lag between the inflow and outflow and then observing the model fit with the observed levels. Equation 5.12 was tabulated in EXCEL and iteratively adjusting the time lag between the input and out in equation 5.12. The final selection of the best estimates was based Nash R^2 criteria (Nash and Sutcliffe, 1970) and simulated levels have been compared with observed levels. For lakes and linear reservoirs equation 5.6 may be used as check for estimates by equation 5.12. Similar approach has been employed in simulating water levels of Lake Ziway and Lake Tana in Ethiopia (Kebede *et al.*, 2006; Vallet-Coulomb *et al.*, 2001). The water balance model was simulated using two different approaches. The first approach was simulation 'with updating' and the second approach was simulation 'without updating' normally known as 'simulation mode' in the scientific literature.

5.6.1 Model simulation 'with updating'

Model simulations 'with updating' involves using previously observed values of the output in the model in order to issue a forecast. Models run in updating mode normally can issue a reliable estimate at one time step ahead of the current time step (Kachroo, 1992a). Beyond that the forecast is not all that reliable and depends on the persistence of model errors. This may be particularly difficult to see unless analysis of the residual errors is done. The water balance model was run in 'updating' mode using the previously observed levels as input function in the model in order to issue a forecast as described in equation 5.13 and 5.14. The error term was ignored in the 'updating' mode.

$$\Delta L(t) = R_L(t) - Evap_L(t) + \left(\frac{Q_{in}(t) - Q_{out}(t)}{A_L} \right) \qquad 5.13$$

$$L_{Est}(t) = L_{Obs}(t-1) + \Delta L(t) \qquad 5.14$$

L_{Est} and L_{Obs} in equation 5.14 stands for estimated and observed lake level respectively, average from the three water level stations. The results of the simulation have been presented in Figure 5.13 and Figure 5.14. The results shows a good correlation between observed and estimated levels with a Nash-Sutcliffe $R^2 = 0.98$. Models run in 'updating' mode normally perform very well but lacks the capability of issuing a long term forecast as required in the case of Lake Malawi. Model run in simulation mode would be useful in the operation of Liwonde barrage in regulating flows from the lake on monthly basis.

Observing errors and error trends in model predictions helps to improve the model structure and prediction so that the improved model can be run in simulation mode. Simulation mode involves using previously estimated values as the input function in the model in order to issue a forecast. The model relies much on its previously predicted values to estimate future trend. The ultimate performance of a model depends on the model to give good estimates in simulation mode (Kachroo, 1992b).

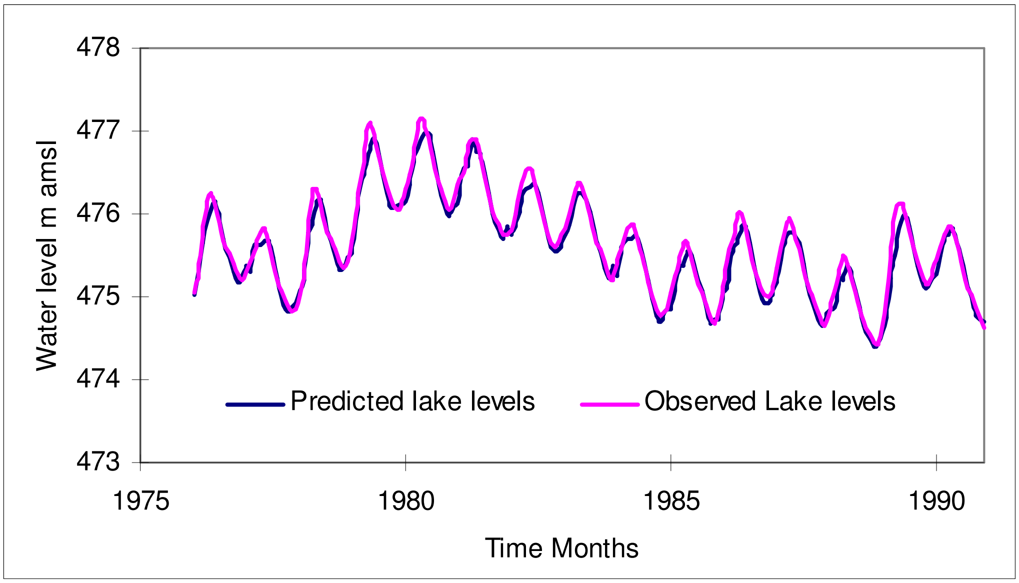


Figure 5.13 Comparison between simulated and estimated flows based on water balance model run in 'updating' mode

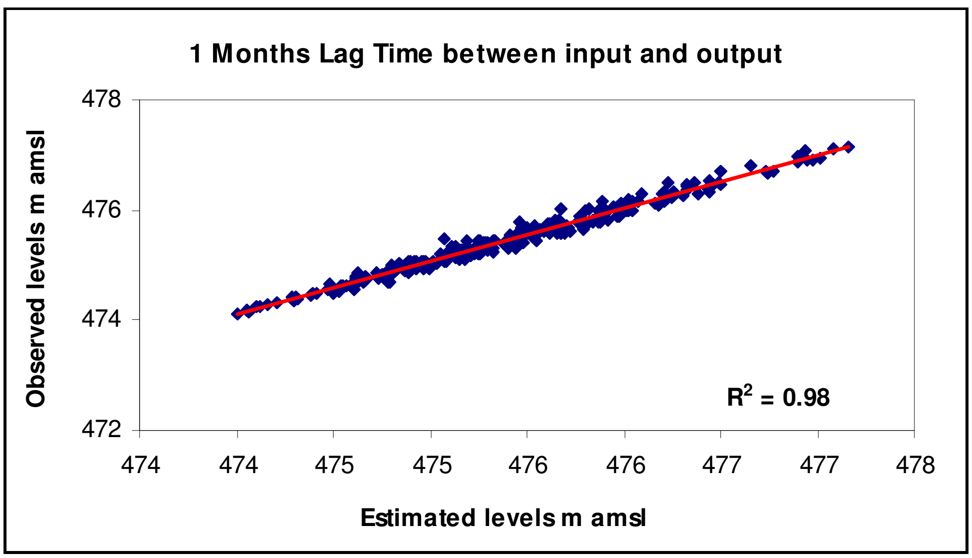


Figure 5.14 Correlation between estimated levels and simulated levels based on water balance model run in 'updating' mode

5.6.2 Model calibration and verification, simulation 'without updating'

The ultimate performance of a model lies in its ability to produce a good forecast in simulation mode. In simulation mode the model input does not include previously observed values of the output in order to issue a forecast but depends on the previously estimated value as the input function. This requires analysis of error trends so that the error term should be incorporated with better accurancy in the model. In this research the model was run in ‘simulation mode’ with the initial starting water level as the observed water level of the first data point. The rest of the levels were estimated based on previous model output. The result of the model before error correction is shown in Figure 5.15. Analysis of the errors between the observed and simulated level was done before updating the model. The error term was observed to increase linearly with time from the point when the first forecast was issued. Figure 5.16 is the relationship between the error and time. The time t starts from the point where model simulation started and in steps equivalent to model simulation time up to the last data point N. The observed increase in the error overtime as shown in Figure 5.16 shows that the same error keeps on recurring at every time step of the simulation. This results in accumulation of model error and hence the divergence between the observed and predicted values in Figure 5.15. The error could be attributed to the inclusion of groundwater flux in the model residues, errors in the input data records and the assumption behind the other water balance components.

From the results of error analysis, a linear relationship was observed between model errors and time step t with an $R^2 = 0.99$ as presented in Figure 5.16. The error term presented in equation 5.15 was deduced from the plot and incorporated in the water balance model (equation 5.13) in order to issue a forecast in simulation mode. Finally the water level was simulated based on equation 5.16. Results of running WBM in simulation mode have been presented in Figure 5.17.

$$\varepsilon_t = 0.0554t \qquad 5.15$$

$$L_{Est}(t) = L_{Est}(t-1) + \Delta L(t) \qquad 5.16$$

The WBM produced a good simulation of the levels of Lake Malawi in the calibration period. Generally there is a good agreement between the observed and estimated levels as shown in Figure 5.17 and Figure 5.18 ($R^2 = 0.88$). The disagreement in the observed and estimated levels in the year 1977 and 1978, then in the dry season of 1984 and 1985 could be attributed to errors in the model input variables such as rainfall, evaporation, measured lake level and outflow. The other contributing factor could be the incorporation of net groundwater flux in the model residuals.

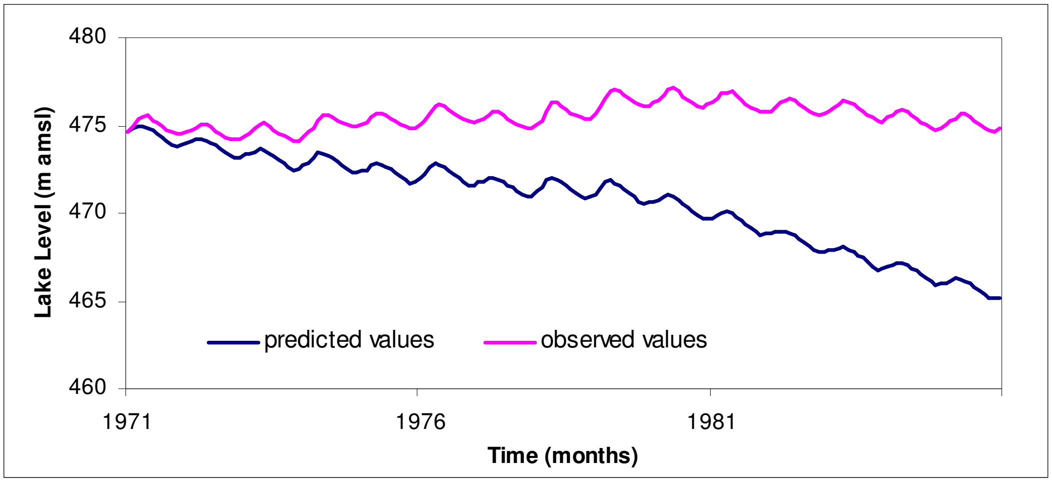


Figure 5.15 Comparison between simulated and estimated flows based on water balance model run in 'without updating' mode before error correction.

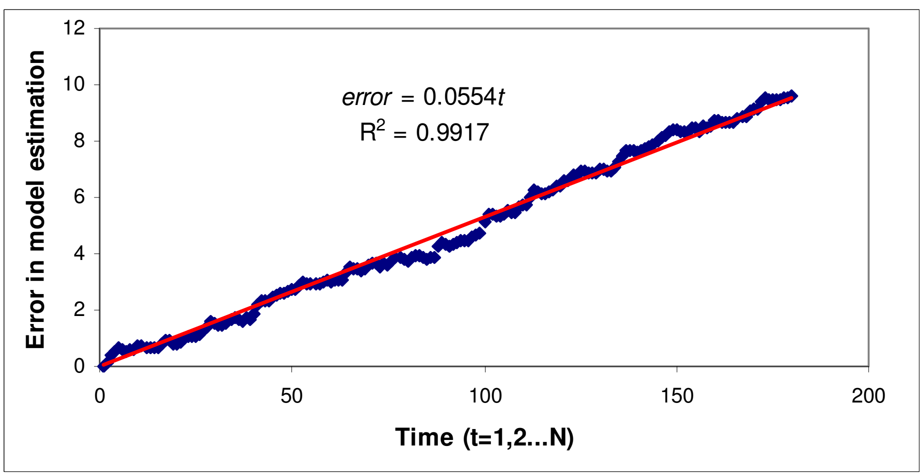


Figure 5.16 Trend of model errors in water balance model run in 'updating' mode

Model ultimate performance is judged by its capability to give accurate long term forecast. This requires verifying a calibrated model against available measured data. The calibrated model was verified against measured data by incorporating the model error term deduced from the calibration period. The model simulated the water level in the verification period with a Nash-Sutcliffe model efficiency $R^2 = 0.89$ as shown in Figure 5.17 and Figure 5.18.

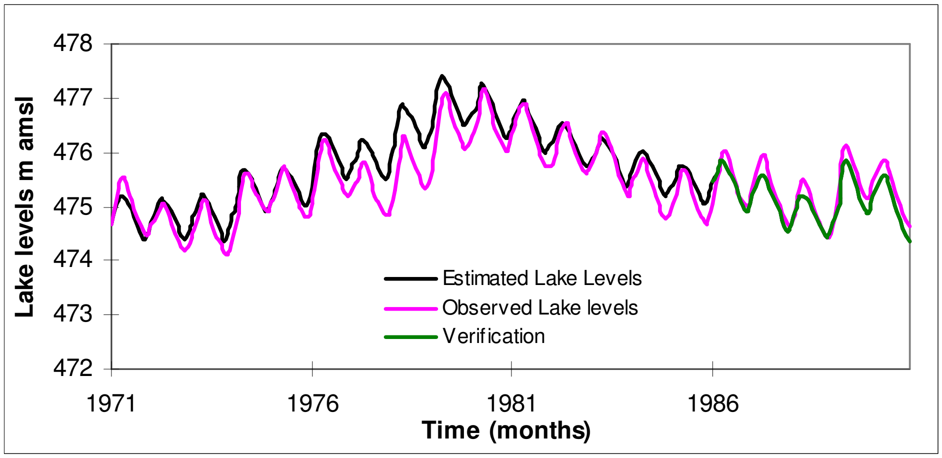


Figure 5.17 Comparison between simulated and estimated flows based on water balance model run in 'simulation' mode

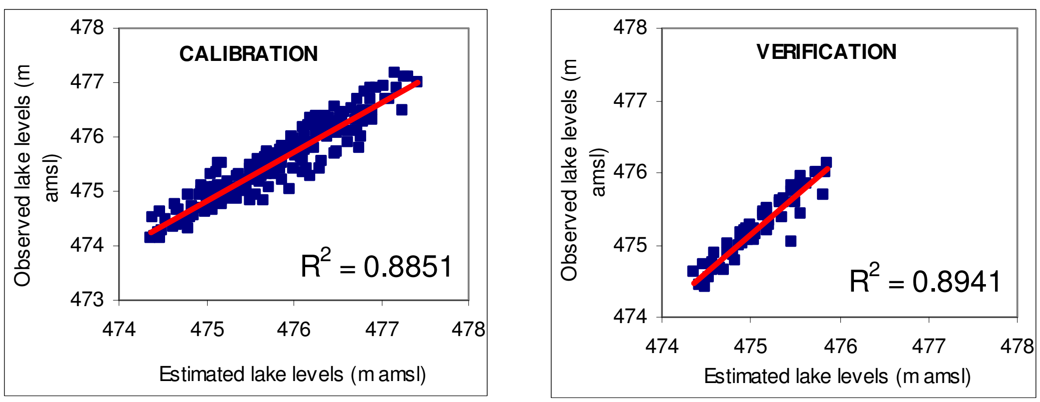


Figure 5.18 Correlation between estimated levels and simulated levels based on water balance model run in 'simulation' mode

After calibrating and verifying the water balance model of Lake Malawi it is now the intention of the following section to analyse the impact of climate change on the water level of Lake Malawi using the WBM. Assessment of climate change impact on the lake using WBM needs a thorough assessment of the sensitivity of the lake level and its outflow to changes in the major components of the WBM: rainfall and evaporation. The following section describes the lake level and outflow sensitivity to WBM components.

5.7 LAKE LEVEL AND OUTFLOW SENSITIVITY TO CLIMATE CHANGE.

Analysis of the WBM components has revealed that rainfall and evaporation are the major components of the WBM. However these two components are under threat by climate change being experienced globally. Any change in these two major components could have an adverse impact on the water level of Lake Malawi. Among the water balance components rainfall is the component which varies most while evaporation varies least. It is therefore necessary to analyse lake level and outflow sensitivity to climate change based on projected changes in the water balance model components. The most difficult component to estimate is the runoff from the land catchment as the runoff originates from river basins with different catchment characteristics. In view of this a lumped conceptual hydrological model, NAM, described in chapter 2 was used to convert catchment rainfall into runoff.

5.7.1 Rainfall runoff model of the lake catchment

A mathematical rainfall runoff model was calibrated and fitted to convert rainfall over the lake catchment (Tanzania, Malawi and Mozambique) into runoff. The model was calibrated based on observed rainfall and runoff for the period 1971 – 1990. Fitting of the NAM hydrological model involved observing the shape of the estimated graph along the observed runoff graph and Nash-Sutcliffe R^2 criteria. Rainfall over the land catchment was calculated as areal mean using IDW method. Runoff was calculated as a summation of runoff from of all the rivers draining into the lake. The results of the fitted model are presented in Figure 5.19. The results show a good agreement between estimated and observed runoff under both emission scenarios. The hydrological model overestimated some of the peak runoff and under estimated the minmum runoff for other years like 1979, 1980 and 1987, This could be attributed to errors in the input especially runoff from ungauged catchment which have been estimated by extrapolation based on rainfall coverage. Rainfall could also contribute to the residual errors due to an even distribution of rainfall station within the catchment area.

Having calibrated and fitted a rainfall runoff model for the lake catchment it is now necessary to use downscaled climate data to estimate future behaviour of the lake.

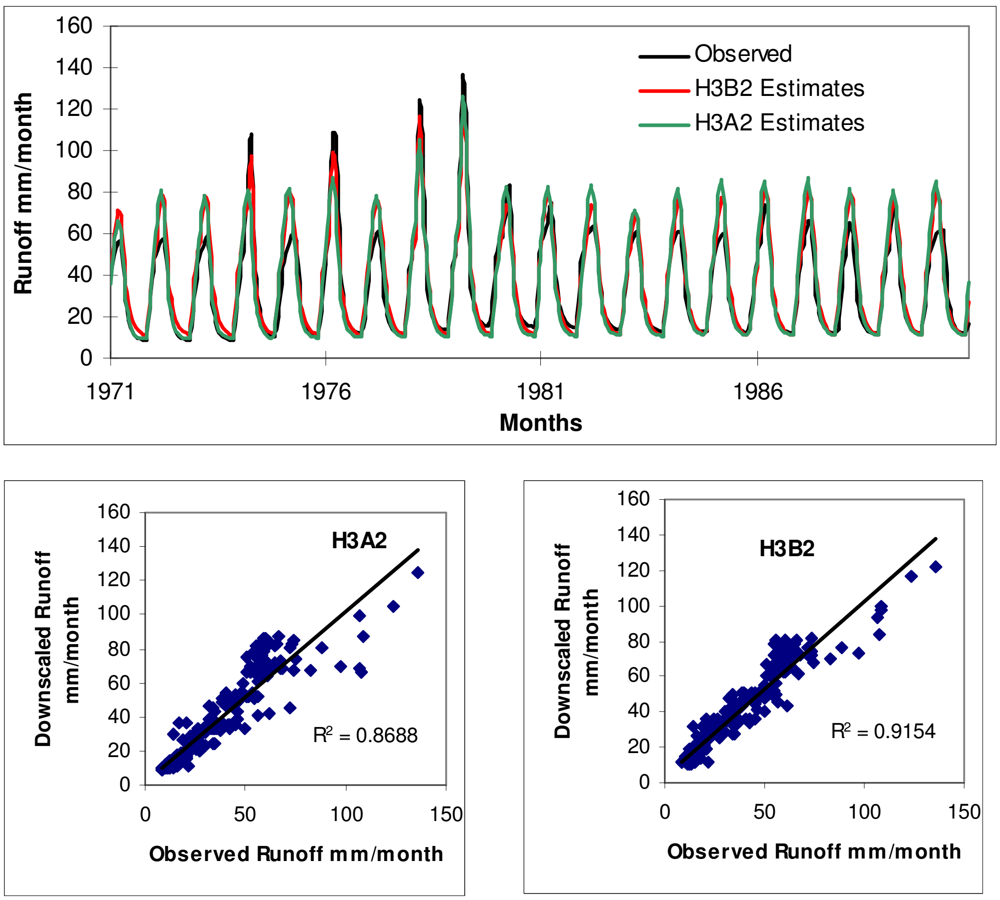


Figure 5.19 Results of fitting NAM model over Lake Malawi land catchment

5.7.2 Applying climate change to the WBM

Climate data used in the study have been obtained from the HadCM3 GCM emission scenarios of the UK Hadley Centre for climate change. The GCMs were used to define a baseline climate of the lake based on observed climate data for the period 1971 – 1990. This period is within the IPCC base period of 1961 – 1990. The projected future climate data based on IPCC emission scenarios; B2 and A2 have been used to estimate the future behaviour of the lake as discussed in section 4.4 and 4.5.

Downscaled daily temperature from HadCM3 GCMs has been used to estimate future evaporation from the lake and the land catchment area of the lake. Runoff from the lake catchment has been estimated using calibrated rainfall runoff model, NAM. Results of the downscaled rainfall, temperature and evaporation using Statistical Downscaling Method (SDSM) described in chapter 4 have been presented in Figure 5.21 to Figure 5.23. The results show that there is a marked change in the magnitude and seasonal rainfall pattern. The rainfall pattern shows an increase in rainfall during the months of March and a decrease in rainfall during the month of January and February (Short rainfall season with high rainfall within a short period and longer dry season). The observed pattern is similar in both A and B emission scenarios. High intense rainfall within a short period will lead to flooding along the lakeshore. This normally results in full opening of the Liwonde barrage which controls outflows from the lake. Full opening of the barrage ends up in transferring the problem down to the Lower Shire Valley. Release of water from the lake to avoid flooding within a short period compounded with long dry season will result in low lake levels.

In the case of temperature the results shows that predicted temperature will increase over the lake and the land catchment during the months of January – May, August, September, October and December. The months of June, July and November have no marked change in temperature. Temperature increase will result in increase in evaporation as shown in Figure 5.24. The major challenge will be on the land catchment where an increase in evaporation will lead to an increase in crop water requirement (water required for full growth of crops and natural vegetation). This will result in reduced runoff into the lake as well. Increase in evaporation over the lake, reduction in runoff and longer dry season will reduced the net basin supply component of the lake in water balance model. Estimated future temperature based on both emission scenarios was later on used as input data in the calibrated Hargreaves evaporation model described in section 5.4.2 to estimate future evaporation over the lake. The results shows a slight decrease in evaporation for the months of March, April, and May for the period 2001 – 2050 and an increase in evaporation during the months of October, November and December under both scenarios. The period 2051 – 2075 has an evaporation trend similar to the base period of 1961 – 1990 with an increase during the months of October, November and December. Marked increase in evaporation has been observed under both emission scenarios for the period 2076 – 2099. A2 emission scenarios estimates are higher than the estimates made using B2 emission scenarios.

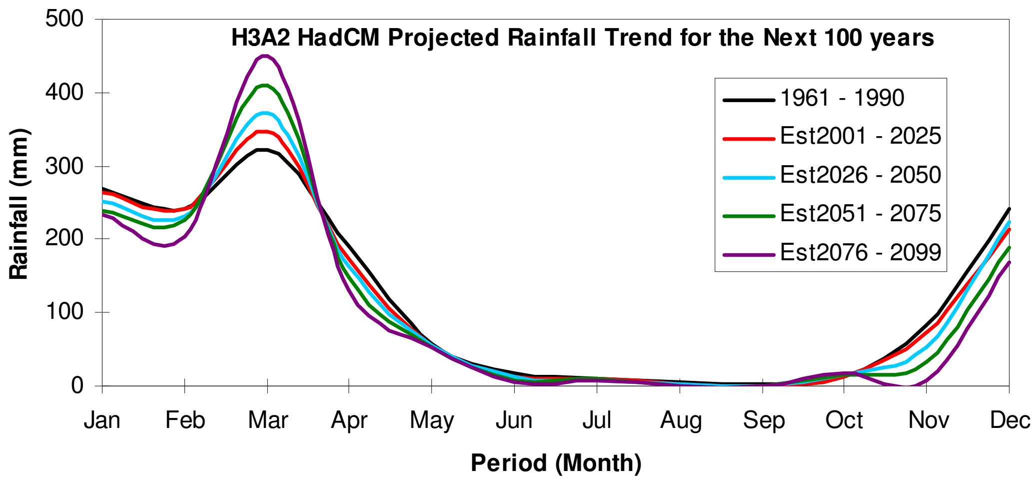


Figure 5.20 Projected rainfall pattern over Lake Malawi based on HadCM3 A2 emission scenarios

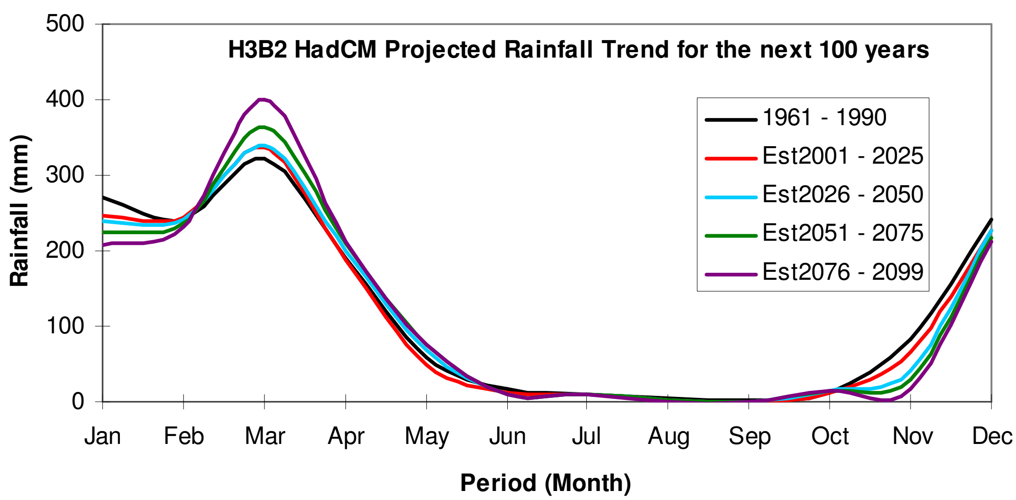
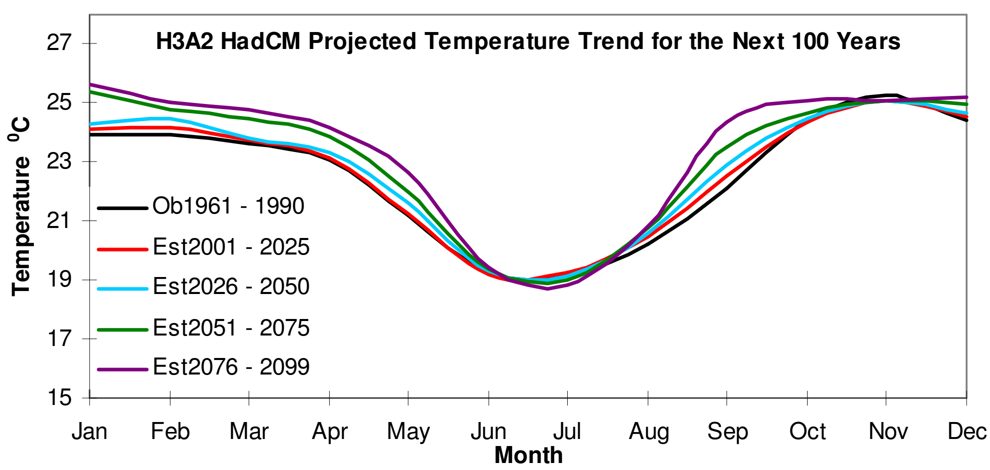


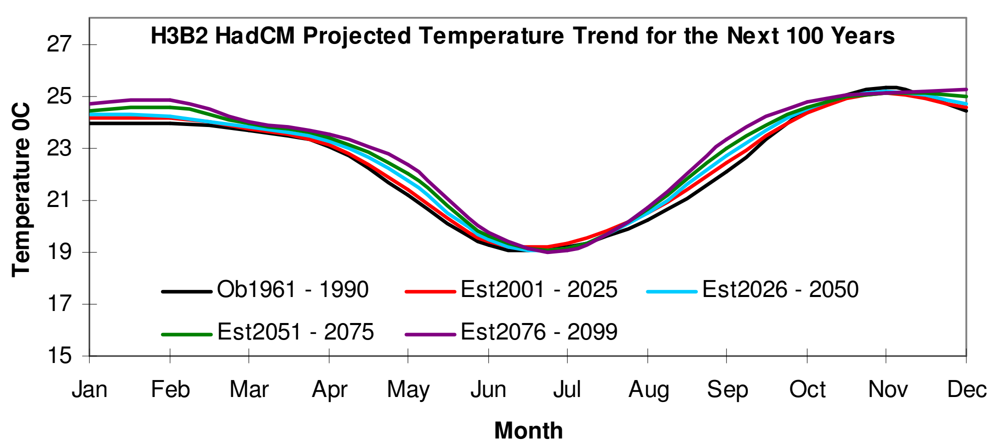
Figure 5.21 Projected rainfall pattern over Lake Malawi based on HadCM3 B2 emission scenarios



Ob = Observed

Est = Estimated

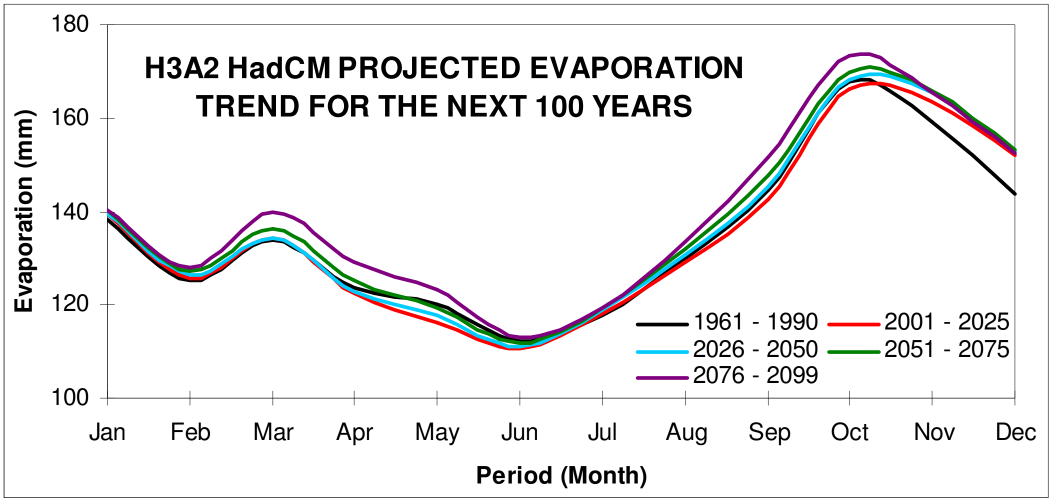
Figure 5.22 Projected temperature pattern over Lake Malawi based on HadCM3 A2 emission scenarios



Ob = Observed

Est = Estimated

Figure 5.23 Projected temperature pattern over Lake Malawi based on HadCM3 B2 emission scenarios



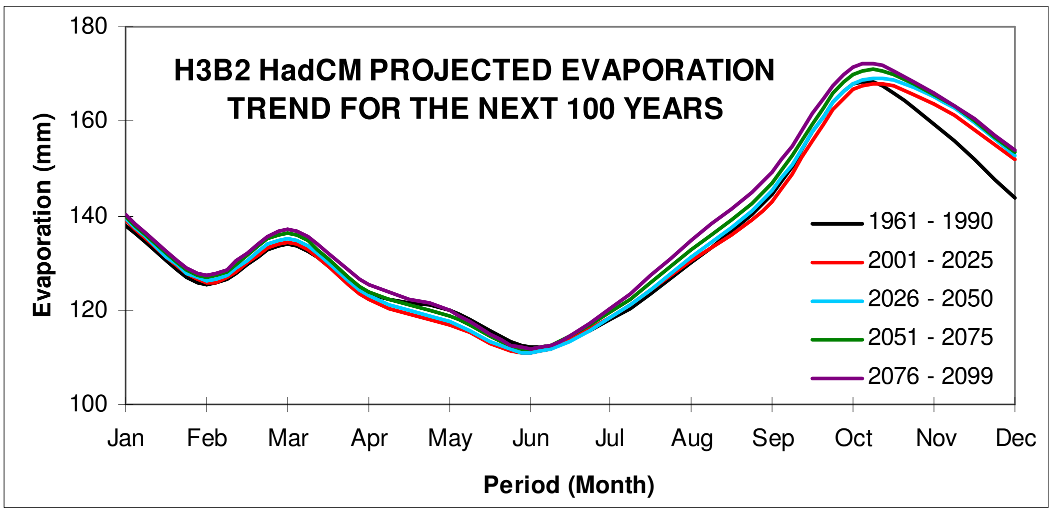


Figure 5.24 Projected evaporation pattern over Lake Malawi based on HadCM3 A2 and B2 emission scenarios

The projected increase in evaporation especially during the months of July through December as depicted by both emission scenarios for the period 2051 – 2099 coupled with the change in rainfall pattern will have an effect on the water balance of Lake Malawi. It is therefore necessary to use projected estimates in the water balance model to estimate the future behaviour of lake levels. The estimated changes in rainfall, runoff and evaporation derived from HadCM3 for the period 2001-2100 in 25 years mean scenarios were applied to the Lake Malawi WBM. Outflow from the lake was estimated using the lake level-outlet flow equation (equation 5.7) calibrated in section 5.4.1. Lake level simulation was done using the calibrated Water Balance Model in section 5.6.2

with simulation without updating. The pattern of the future behaviour of the lake is now presented in Figure 5.25. Under both emission scenarios the water level continues to drop from 2001 up to 2100. Mean monthly lake levels shown in Figure 5.25 shows that during the first quarter of the century the water level ranges from 474.5 to 475.5 m amsl with a drop at the end of the first quarter then starts to gain till the mid of the second quarter of the century. From the mid of the second quarter of the century the water level ranges from 474.25 to 475.25 and till mid of the third quarter of the century. A marked drop was observed in the last quarter of the century where the water level range ranges from 473.75 to 474.75. The lowest lake level has been predicted at mid of the last quarter of the century by both emission scenarios. A total fall in water level of 0.5 to 1.0 m is forecast for this century based on climate change.

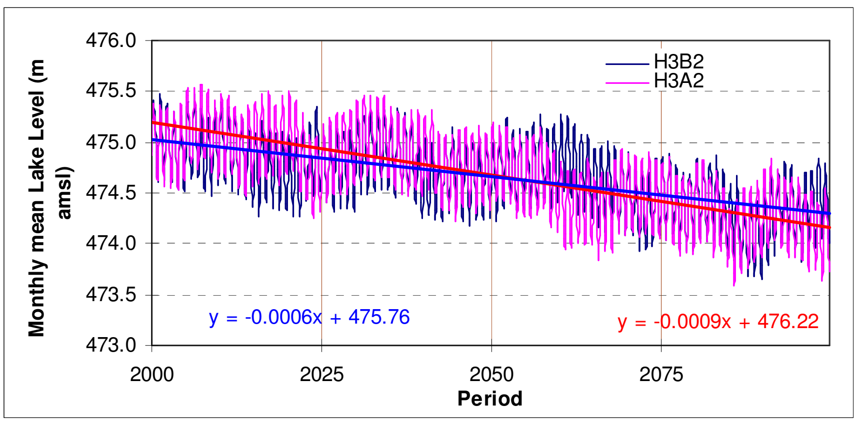


Figure 5.25 Monthly mean projected future behaviour of the lake based on HadCM3 A2 and B2 Scenarios

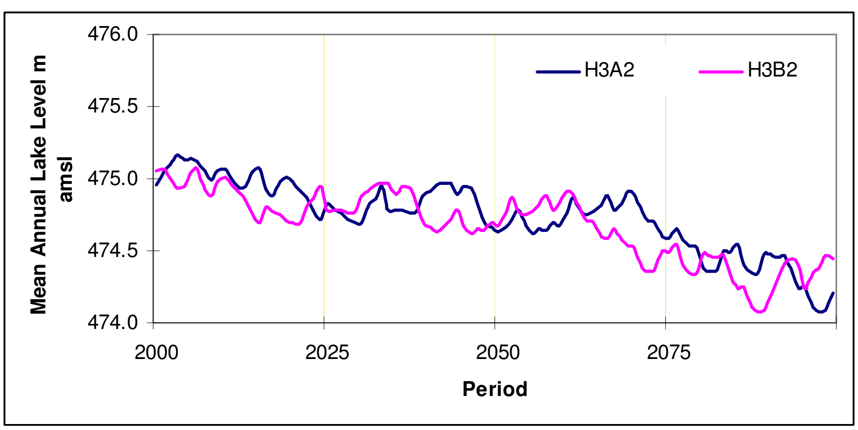


Figure 5.26 Annual mean projected future behaviour of the lake based on HadCM3 A2 and B2 Scenarios

The expected low lake levels as projected by the emissions scenarios will have far reaching consequences especially on the downstream benefits along the Shire river. According to Calder *et al*. (1995) there is no outflow from the lake with an observed water level below 470.1 m amsl as was the case from 1915 to 1935. Table 5.4 is a summary of the mean predicted water level for every 25 years. The predicted continuous decrease in lake levels as predicted by the two scenarios indicates that there is going to be a drop in the water levels of the lake even if the magnitude will not be as predicted. This calls for sustainable management of the lake catchment as well as other hydropower generation option along the Shire river and the rivers in the Lake Malawi catchment area.

Table 5.4 Summary of lake levels under HadCM3 emission scenarios

Period	2001 -2025	2026 - 2050	2051 - 2075	2076 - 2100
Emission Scenario	Projected mean level for every 25 years (m amsl)			
H3A2	474.99	474.82	474.74	474.40
H3B2	474.88	474.78	474.67	474.36

The difference in the projected annual mean lake level by the two emission scenarios indicates the limitation of climate change scenarios for climate change impacts. There are different emission scenarios from different experiments and the HadCM3 emission scenarios used in this research should serve as an example for modelling the hydrological response of large lake system to climate change. According to (IPCC, 2001) inter-model consistency in regional precipitation and temperature change are high over South East Africa, including Lake Malawi. There is no clear direction and magnitude in the change of temperature and rainfall within the South East African region with each GCM model giving its own results and direction. The results presented here should therefore not serve as the actual predicted future lake levels of Lake Malawi but more as an illustration of the sensitivity of water levels of Lake Malawi to one possible future possible climate change pattern under HadCM3 A2 and B2 emission scenarios. The other scenarios and GCM will also result in a different water level trend.

Despite climate change Lake Malawi is also under threat due to population increase in Malawi. Malawi current population is 13 million and is expected to increase to 20 to 30 million during this century. This will result in increase in demand for water for domestic use, irrigation and hydropower generation.

5.8 LAKE LEVEL AND OUTFLOW SENSITIVITY TO DAM CONSTRUCTION IN LAKE MALAWI CATCHMENT AREA

The water balance model of Lake Malawi has been developed as a tool for assessing the effects of changes in water resources development on the water levels of Lake Malawi as well as its outflows from the lake. One of the major scenarios being considered in this section is dam development for hydropower, irrigation and water supply in the catchment areas of Lake Malawi. The case study for dam development has considered South Rukuru river basin which is the largest river basin in the catchment area of Lake Malawi. South Rukuru river is Water Resources Unit 7 as shown in Figure 1.6. South Rukuru river was chosen based on the fact that it is the river which has been earmarked by the Malawi government for multipurpose water resources development mainly focusing on hydropower due to the topography of the catchment. South Rukuru river has a mean annual flow of 42 m^3/sec and contributes 6 percent to the total annual inflows of Lake Malawi.

Dam construction normally affects the flow regime downstream of the dam. The common hydrological effects of dams are reduced flood peak discharge, reduced flood frequency, and increased flows in downstream reaches during low flow period due to regulated flows from the dam (Petts, 1984). These changes have positive and negative effects on the downstream river environment as outlined in section 2.7.3.2. In this thesis particular interest was placed on the effects of change in downstream flows on the water levels of Lake Malawi.

5.8.1 Brief assessment of dam development on South Rukuru river

The South Rukuru river basin shown in Figure 1.6 and Figure 3.6 covers a catchment area of 12,000 km^2. The river flows varies on seasonal basis with very lows flows in the dry season as shown in seasonal hydrological diagrams in Figure 3.31. Flow duration curve and stream flow hydrograph were analysed to fully understand the flow variability of the South Rukuru. The South Rukuru has a mean annual flow of 42 m^3/sec which has an exceedence probability of 33 percent of the time Figure 5.27 (b). The main tributaries of the South Rukuru river are Runyina, Rumphi and Kasitu rivers. The basin has 41,000 hectares potential for irrigated agriculture as shown in Figure 5.28 which was mapped by the Ministry of Irrigation and Water Development through the Department of Irrigation. Current agricultural activities in the mapped areas for irrigation shown in Figure 5.28 depend on rainfall.

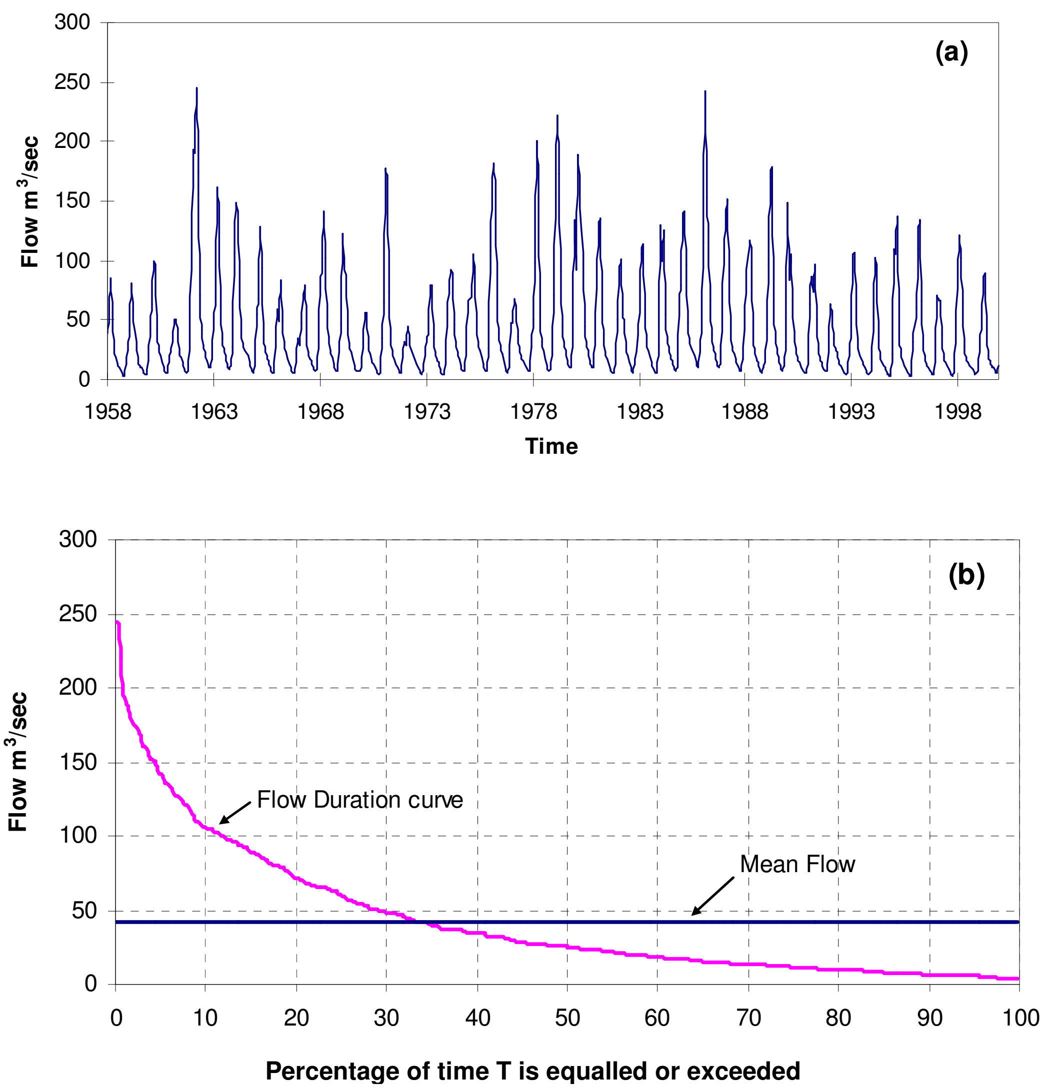


Figure 5.27 (a) South Rukuru stream flow hydrograph (b) South Rukuru Flow duration curve for station 7G18

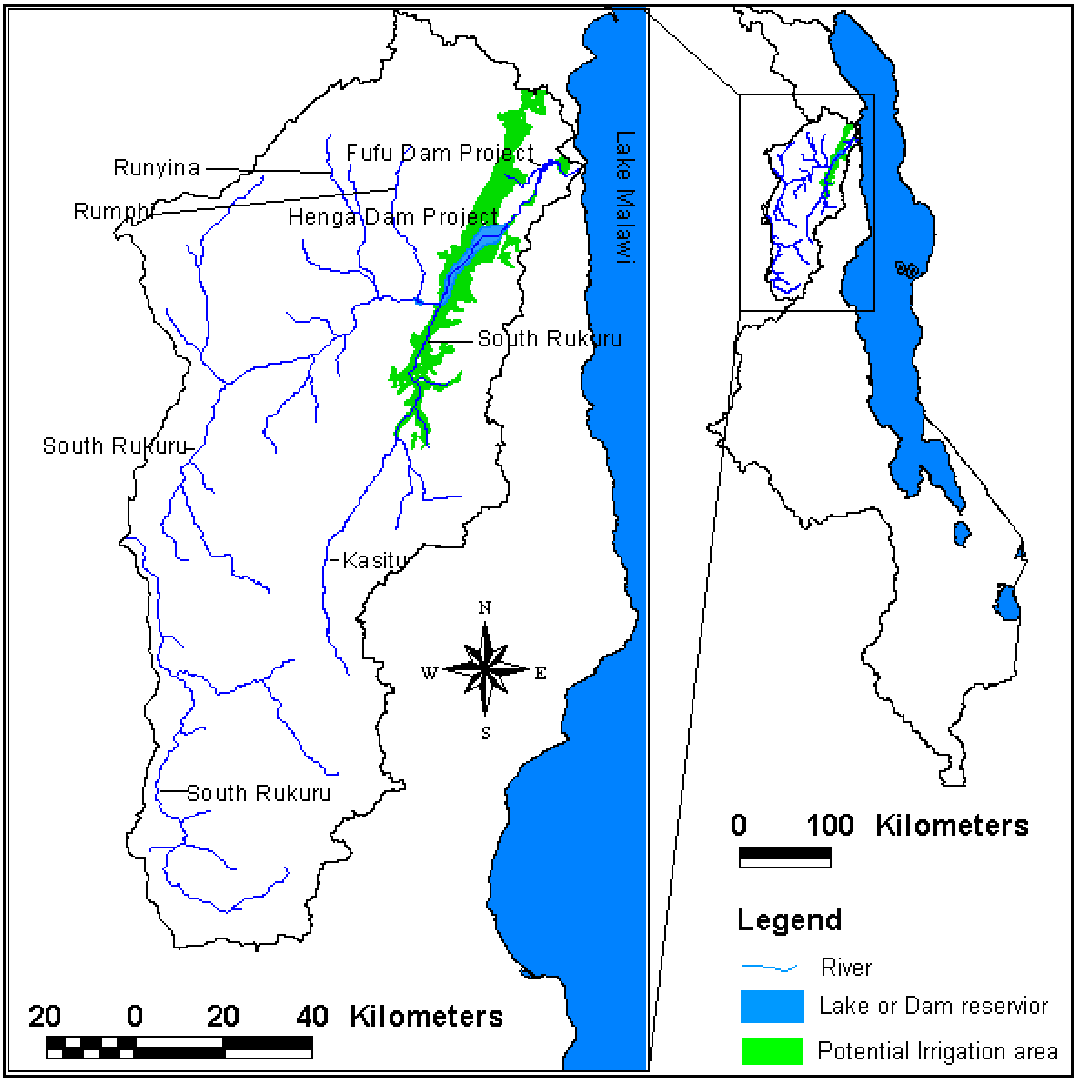
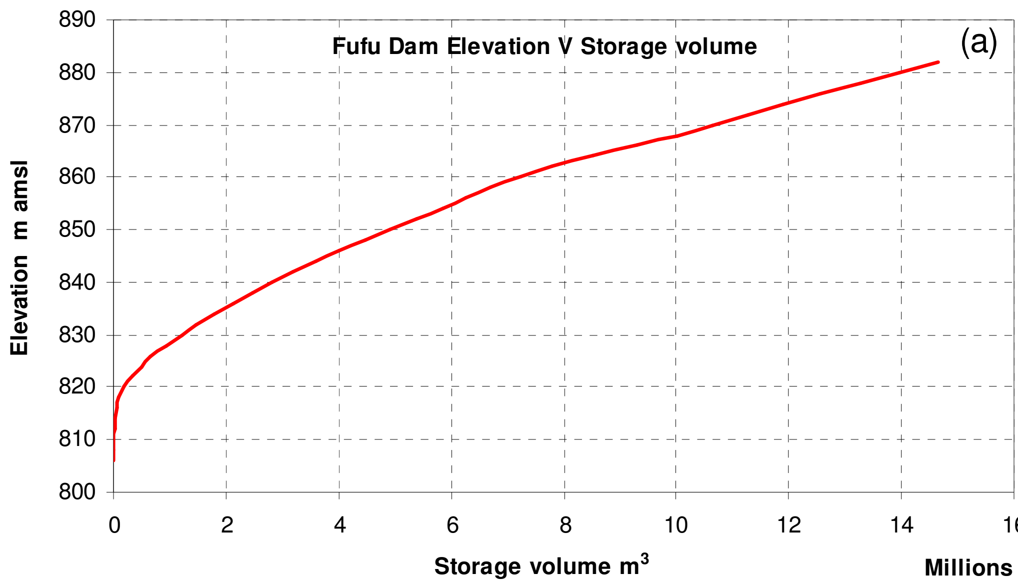


Figure 5.28 South Rukuru basin showing potential irrigation area and proposed Henga and Fufu dams for hydropower, irrigation and water supply

An analysis of South Rukuru river profile shown in Figure 3.8 shows that the lower reaches of the river downstream of Rumphi have potential for dam development for hydropower together with irrigation and water supply. The most significant power potential on the South Rukuru is in the last 20 km stretch of the river at Fufu and Henga shown in Figure 5.28. Due to proximity of these two sites to the mapped agricultural area, the two sites have a potential to serve as multipurpose water resources projects for irrigation water supply and hydropower.

According to the National Water Resources Master Plan of Malawi the assumption behind the proposed Henga and Fufu projects is that 60 percent of the mean flow of 42 m^3/sec could be regulated with a storage volume, and then a net firm flow of 24 m^3/sec could be adopted taking into account evaporation from the reservoir surface (GoM, 1986). The following volume area relationship shown in Figure 5.29 was established for the two sites using HecGeo HMS model based on the topography of the area.



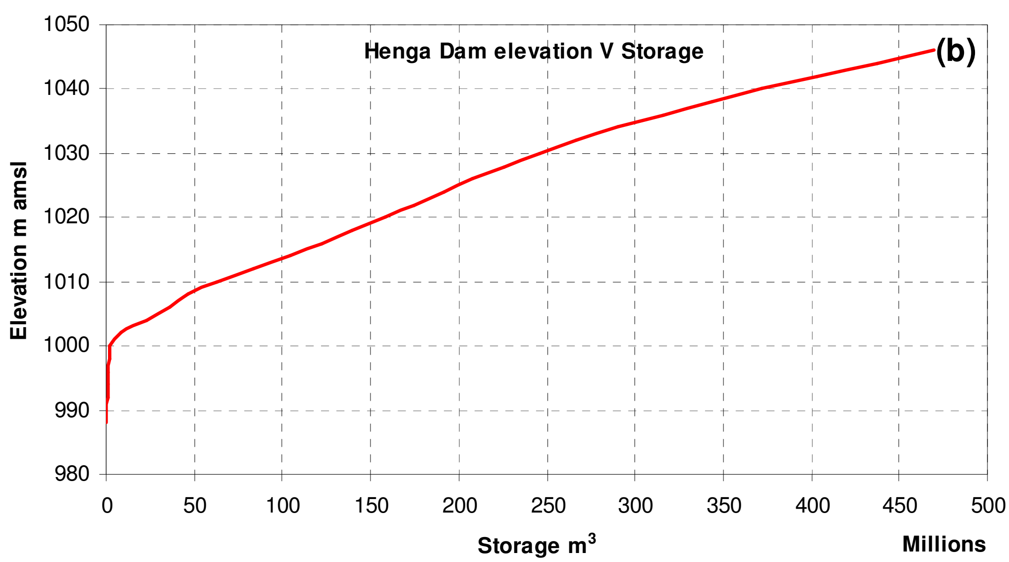
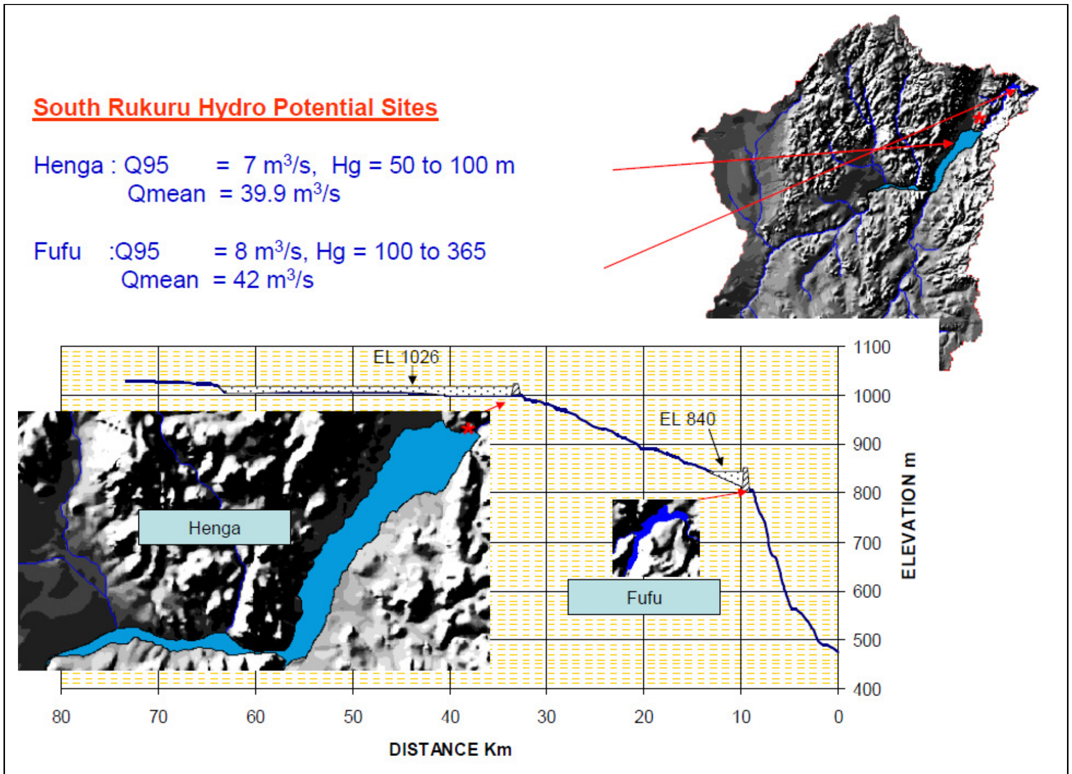


Figure 5.29 Proposed dam elevation versus storage on South Rukuru river (a) Fufu dam project (b) Fufu Dam project (GoM, 1986)



	FUFU	HENGA
Mean flow m^3/sec	42	39
Height of Dam m	70	45
Storage m^3 (million)	14	450
Net Head (m)	365	100
Firm flow (m^3/sec)	24	22
Firm Power (MW)	90	24

Figure 5.30 Characteristics of Fufu and Henga dam sites on South Rukuru river for multipurpose dam development

The river profile and volume-area relationships for the two proposed sites were estimated from a 100 m grid resolution Digital Elevation Model (DEM) of Malawi using ArcView GIS software. The DEM data set was obtained from the National Geospatial Data Centre in Malawi (GoM, 2005). Analysis of the volume-elevation relationship for the two sites shows that there is no suitable topography at Fufu to create a reservoir (70 m of dam height equates to a storage volume of 14,000,000 m^3 reservoir) as shown in Figure 5.29 (a). However Henga site has a potential for a reservoir (45 m of dam height equates to a storage volume of 450,000,000 m^3 reservoir) as shown Figure 5.29 (b). Due to the proximity of the two sites, dam development at Henga could serve the two sites with Fufu having an intake weir only. Figure 5.30 is a summary of the main characteristics of the two sites for multipurpose dam development. Combined development of the two sites would generate an approximately 115 MW. The Henga reservoir could serve as storage for irrigation water for the surrounding agricultural land and water supply for the surrounding villages.

5.8.2 Impact of regulated flows from Rukuru dam on water levels of Lake Malawi

The above section gives a brief outline of the proposed option for the South Rukuru river. The proposed regulated flows from the proposed option were used as inputs in the WBM of Lake Malawi to assess the effect of Henga reservoir development on the water levels of Lake Malawi.

Construction of dam reduces flow downstream. This reduction in the volume of water flowing into the lake could reduce the water levels of Lake Malawi. In this scenario of dam construction along South Rukuru river, the natural flow of South Rukuru river was replaced with a regulated flow of 24 m^3/sec as proposed in the National Water Resources Master Plan of Malawi (GoM, 1986). The water balance model of Lake Malawi was then simulated without control rules of barrage operation at Liwonde. The results presented in Figure 5.31(a) indicate that annual peak water levels of the lake would be reduced if there is no control at the lake outlet. On average the lake level for the period 1971 to 1990 would have reduced by 0.041 m. This can easily be explained by the fact that excess runoff which results in high lake levels is held in the dam during the rainfall season resulting in minor drop in the lake levels during this period. There is no significant effect on the water levels during the dry season (period of low lake levels) as shown in Figure 5.31(a).

In the second scenario testing of the effect of dam construction on the South Rukuru river, the water balance model of Lake Malawi was simulated with control rules of barrage operation at Liwonde and a regulated flow of 24 m^3/sec from South Rukuru river as proposed in the National Water Resources Master Plan of Malawi (GoM, 1986). The results presented in Figure 5.31(b) indicate that annual low water levels of the lake would be increased if there is a combined flow regulation from the dam in the catchment area into Lake Malawi and flow regulation from Lake Malawi outlet at Liwonde barrage. The results indicate that the average lake levels for the period 1971 to 1990 would have increased by 0.036m as shown in Figure 5.31(b). This is a very small change in lake level. However from the results of fitting a reservoir outlet equation (equation 5.6), the *b* value in the equation indicates that a small change in lake level would result in a significant change in the lake outflow. Using equation 5.6 the corresponding mean lake outflow for the 1971 to 1990 period would have been 603 m^3/sec against the observed 597 m^3/sec.

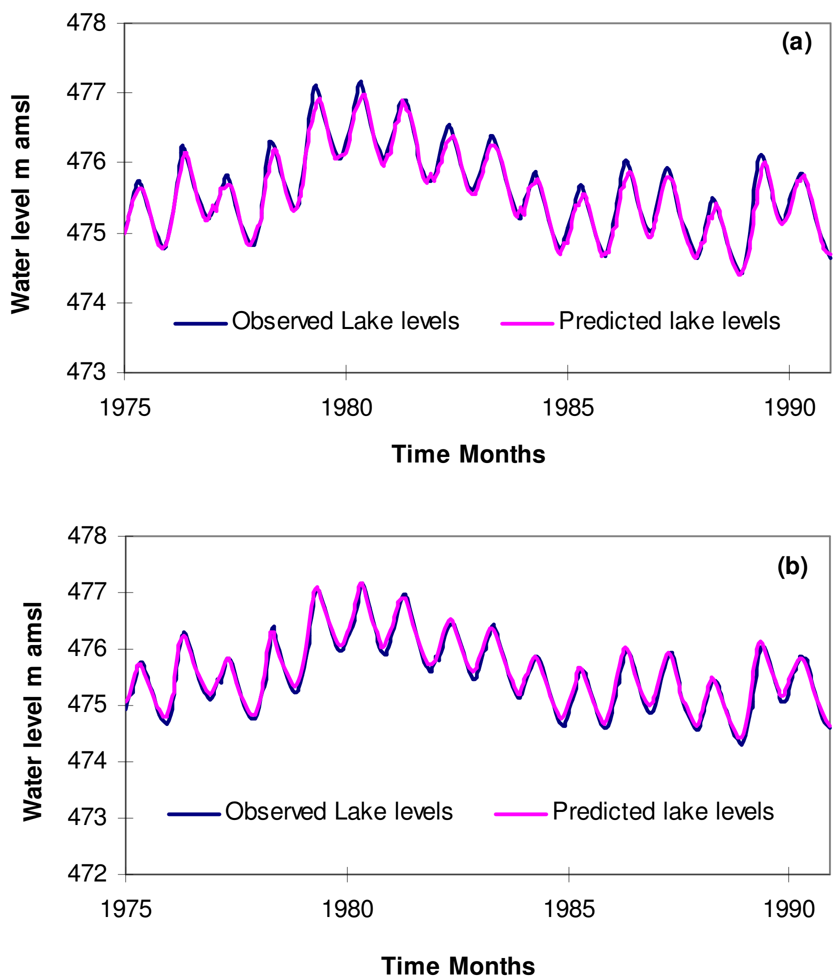


Figure 5.31 Effects of dam development in the lake catchment area on the water levels of Lake Malawi (a) water balance simulation without rules of barrage operation (b) water balance simulation with rules of barrage operation

In conclusion, multipurpose water resources development in the Central and North Malawi river basins for hydropower, irrigation and water supply would help to sustain lake levels as well as high flows from the lake outlet. This could easily be achieved by combined flow regulation from the lake outlet at Liwonde barrage and flow regulation from reservoirs in the lake catchment area. Reservoirs in the catchment area of Lake Malawi such as the one proposed at Henga on South Rukuru river would easily save to retain excess discharge during the rainfall season before it goes into the lake. This could reduce the risk of flooding along the lakeshore, which promotes full open the Liwonde barrage to release excess discharge from the lake. The excess discharge retained in the dam could be released into the lake in the dry season, which is the annual low lake level period of Lake Malawi.

5.9 SUMMARY AND CONCLUSIONS

Lake Malawi and the Shire river system play a major role in the Malawi economic sector through hydropower generation, irrigation, water supply and lake transport. Lake Malawi is not only recognised for the above functions but also for tourism, fishing and its richness in valuable natural resources. It is for the unique enormous benefits of the lake that sustainable management of its unique eco-system should be a priority for the Malawi government and all the countries which share the water boundary of the lake.

In this Chapter previous water balance studies on the WBM of Lake Malawi have been reviewed. In all the previous studies estimates of the behaviour of the lake was based on the probability analysis and outflows from the lake were based on flow rates at Liwonde barrage which is 80 km downstream of the main lake outlet station of Mangochi. The WBM has finally been reviewed and revised based on current data. Lake outflows in the WBM were based on the main lake outlet gauging station at Mangochi. Rainfall and evaporation over the lake was estimated from climate stations along the lakeshore. This could be a contributing factor to model errors since the lake area of 28750 km covers a significant portion of the whole catchment of 124500 km2. The other contributing factor could be lack of data on groundwater flux.

A preliminary estimate of the water budget of Lake Malawi has shown that evaporation is the largest component of the WBM components and outflow from the lake is the lowest component. Rainfall over the lake is the largest component which contributes water into the lake in order to sustain its levels. There is little variation in the lake outflows throughout the year. This could be attributed to flow regulation at Liwonde barrage.

The lake level has shown to be sensitive to rainfall over the entire catchment. Significant variation in the past 20 years of the available data has led to significant variation in lake level. The high *b* value in the outflow-lake level equation ($Q_{out} = a(L_{eff})^b$) shows that a small change in the lake level due to net basin supply will results in significant variation in lake outflows.

The results of fitting the WBM both in 'updating' and 'without updating' mode shows an overall good agreement between the observed and estimated lake levels. Overall good agreement in 'without updating' mode confirms the validity of the WBM of Lake Malawi. The results of fitting a lumped conceptual rainfall runoff model to analyse the catchment runoff behaviour has shown that the catchment can easily be fitted by such model despite great variation in the river basin characteristics. The NAM rainfall runoff model performed well in simulating lumped runoff into the lake with areal rainfall as input into the model.

The impact of dam development in the catchment area of Lake Malawi for multipurpose use has shown to have an effect on the water levels as well as the outflows from the lake. A small change in water levels in the lake due to regulated flows from reservoir in the catchment area of Lake Malawi would result in significant change in outflow from the lake.

The results of sensitivity analysis of the WBM of Lake Malawi to climate change have shown that water level will continue to drop following a decrease in the rainfall season and an increase in evaporation rates from the lake. The results further shows that it is very unlikely for the water level to increase to a maximum height of 477 m amsl as was in 1980. Future assessed lake levels based in HadCM3 A2 and B2 emission scenarios shows a tendency to fall approaching an average of 475 m amsl for the first half of the century and 474 m amsl for the last half of the century. Similar analysis by (Neuland, 1984) based on probability analysis showed that there is little risk of the future lake level exceeding 477.8 m and Neuland's future assessment of lake levels showed a tendency to fall approaching gradually an equilibrium of 475 m amsl. A marked drop in water level is predicted in the last quarter of the century by both scenarios. The predicted future drop in water level of the lake calls for alternative proposals for both hydropower and irrigation development as the current system relies too much on the lake.

The water level and outflows from Lake Malawi have been modelled using a WBM. The WBM run in simulation mode has shown to be a reliable hydrological tool for water resources management and decision making for Lake Malawi-Shire river system especially in application such as Liwonde barrage flow regulation, issuing flood and low lake level warning. This could help all the interested parties in the system in taking necessary steps in the operation of the water resources project within the system in a sustainable manner. For the ultimate performance of the model it is recommended that the model should be updated on regular basis based on the current observed data due to uncertainties in GCM emission scenarios in predicting future climate (IPCC, 2001). The GCM used in the study should serve as an example of one possible future climate pattern of the lake.

Ultimate sustainable management of Lake Malawi depends on the sustainable operation and management of the water resources projects along the Shire river which derives its benefits from the water storage of Lake Malawi. It is therefore necessary to analyse how the WBM interacts with the flow requirements downstream of the Shire river. Chapter 6 looks at the water resources within the Shire and Ruo river system which forms part of the Lake system.

CHAPTER 6
INTERACTION OF LAKE MALAWI AND THE SHIRE RIVER SYSTEM

The need to manage the water resources of Shire river basin in Malawi in a sustainable manner still remains the priority of the Malawi Government in the water sector. The Shire river is the largest river basin in Malawi and forms the outlet of Lake Malawi flowing south towards the Zambezi river. This Chapter looks at the water resources availability in the Shire river basin as well as the interaction between the Water Balance Model of Lake Malawi and the Water Budget Model for the Shire river system.

6.1 INTRODUCTION

The Shire River is the most important river in Malawi and derives its benefits and flow sustainability from the water storage in Lake Malawi. The benefits derived from the Shire river include hydroelectric power generation in the middle reach of the Shire river itself at Nkula, Tedzani and Kapichira falls; abstraction of water at Walker's Ferry (Nkula) by Blantyre Water Board, which is then supplied to the city of Blantyre and its peri-urban areas with a population of 913,000 ; and further South, a sugar irrigation at Nchalo, where both sprinkler and furrow systems are concurrently utilized; plus the development of the fishery industry in the Elephant Marsh; livestock production in the Lower Shire Valley. The Shire basin is also a home to wildlife found in national parks and game reserves (Clay *et al.*, 2003; GoM, 2003a; Kidd, 1983) . Figure 6.1 is a detailed map of the major water use in the Shire River Basin. It is not just the positive aspects that make the basin significant in the economic development of the country; the Shire and its tributary the Ruo have a long history of flood disasters in the Lower Shire Valley (Clay *et al*., 2003). Despite of the availability of this freshwater, Malawi faces serious famine and droughts (Chavula, 1999). In view of the above, it is imperative that appropriate management plans based on sound scientific research are developed and put in place for the sustenance and enhancement of activities on the river Shire that yield positive benefits, together with the mitigation of flood disasters. This is where the need to develop water resources in a sustainable manner becomes a necessity rather than an option. It is therefore necessary to look at the relationship between the Shire river system and Lake Malawi (water balance model) in order to support water resources development plans under National Water Development Plan II.

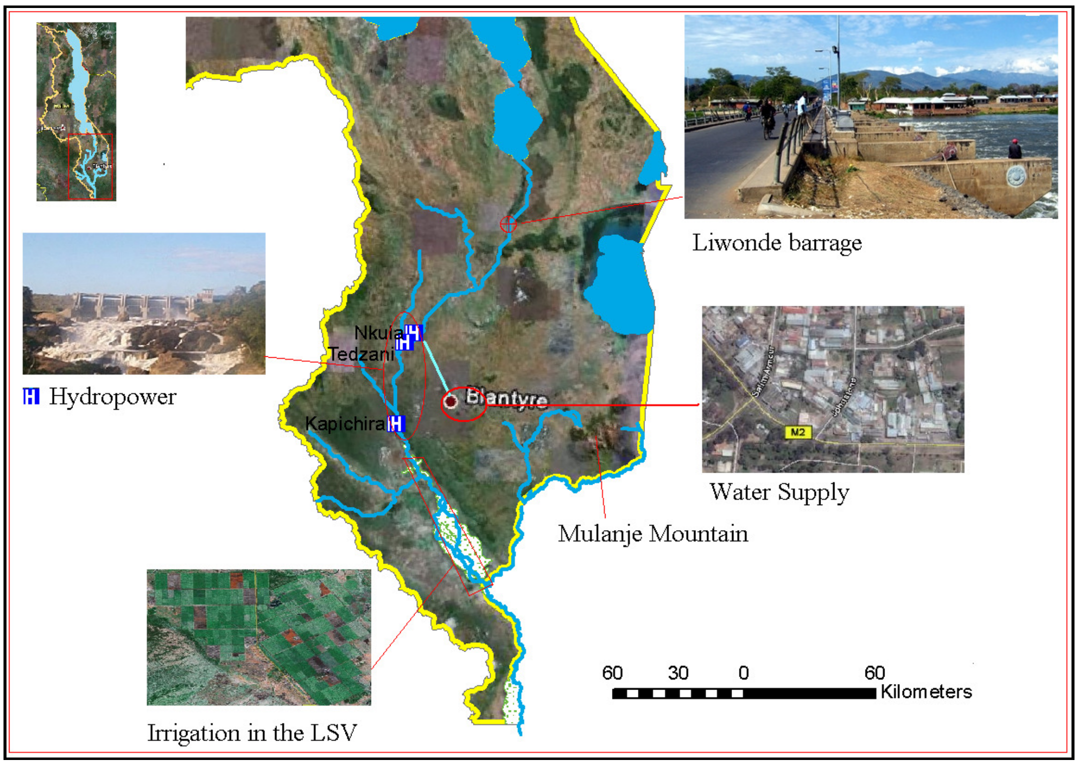


Figure 6.1 Detailed Map of the major water use in the Shire river basin (Google Earth)

The Shire river is the only outlet from Lake Malawi and the flow pattern in the river is closely dependant on the water level of Lake Malawi. Previous studies on the Lake Malawi-Shire river system have been on specific sections of the river. For example Calder *et al.* (1995), Neuland (1984), Kidd (1983) were concerned with the water levels of Lake Malawi; Kanthack (1942) and Watermeyer (1959) cited by (GoM, 1986) were concerned with hydropower development in the middle reach of the Shire river. Kanthack (1942) and Watermeyer (1959) proposed the construction of a barrage at Liwonde (Figure 6.1) to regulate flows downstream of the barrage for hydropower development. The Liwonde barrage was finally constructed in 1965 with an aim to provide a firm flow of 170 m^3/sec for hydropower plants at Nkula in the middle reach of Shire river. In recent years, new hydropower development, irrigation and water supply have similarly benefited from the 170 m^3/sec firm flow at Liwonde barrage. Due to an increase in dependant utilization of water resources availability in the Shire river, there is now a growing realization that a holistic understanding of the interaction between the water availability and water levels of Lake Malawi and the hydrology of the Shire river basin is an important step towards the sustainable management of the water resources projects in the basin

A thorough understanding of the water resources availability of the Shire river basin, in particular the link between the water availability and water levels of Lake Malawi is important as it may provide a better understanding of the sustainable development of the water resources in the basin. Until now the hydrology and water resources of the Shire river basin have not been thoroughly analysed. The latest assessment of the water resources of the Shire river is the National Water Resources Master Plan of 1986.

The climate of Shire river is characterised by two well defined seasons; a hot dry season from May to October and the warm wet season from November to April. The Shire basin receives an even distribution of rainfall with Ruo sub-basin having rainfall in excess of 1500 mm/year while the Lower Shire Valley has low annual rainfall (between 650 to 750 mm) (Figure 6.2). In recent years the water resources of the Shire river basin have been affected by frequent drought particularly the 1992 drought and subsequent low rainfall series from 1993 to 1998 (Clay *et al.*, 2003). Droughts and subsequent low rainfall has resulted in low water levels of Lake Malawi and a record low level of 473 m above mean sea level (amsl) was recorded in 1992 corresponding to a flow rate of 130 m^3/sec at Mangochi hydrometric station (Figure 6.2). The low water level of Lake Malawi in 1998 interrupted power generation along the Shire river where by some of the turbines were switched off to accommodate the flow rate of 130 m^3/sec. However since 1998 the water levels in the Shire river have remained well above 170 m^3/sec required for hydropower generation in the middle reach of the Shire river.

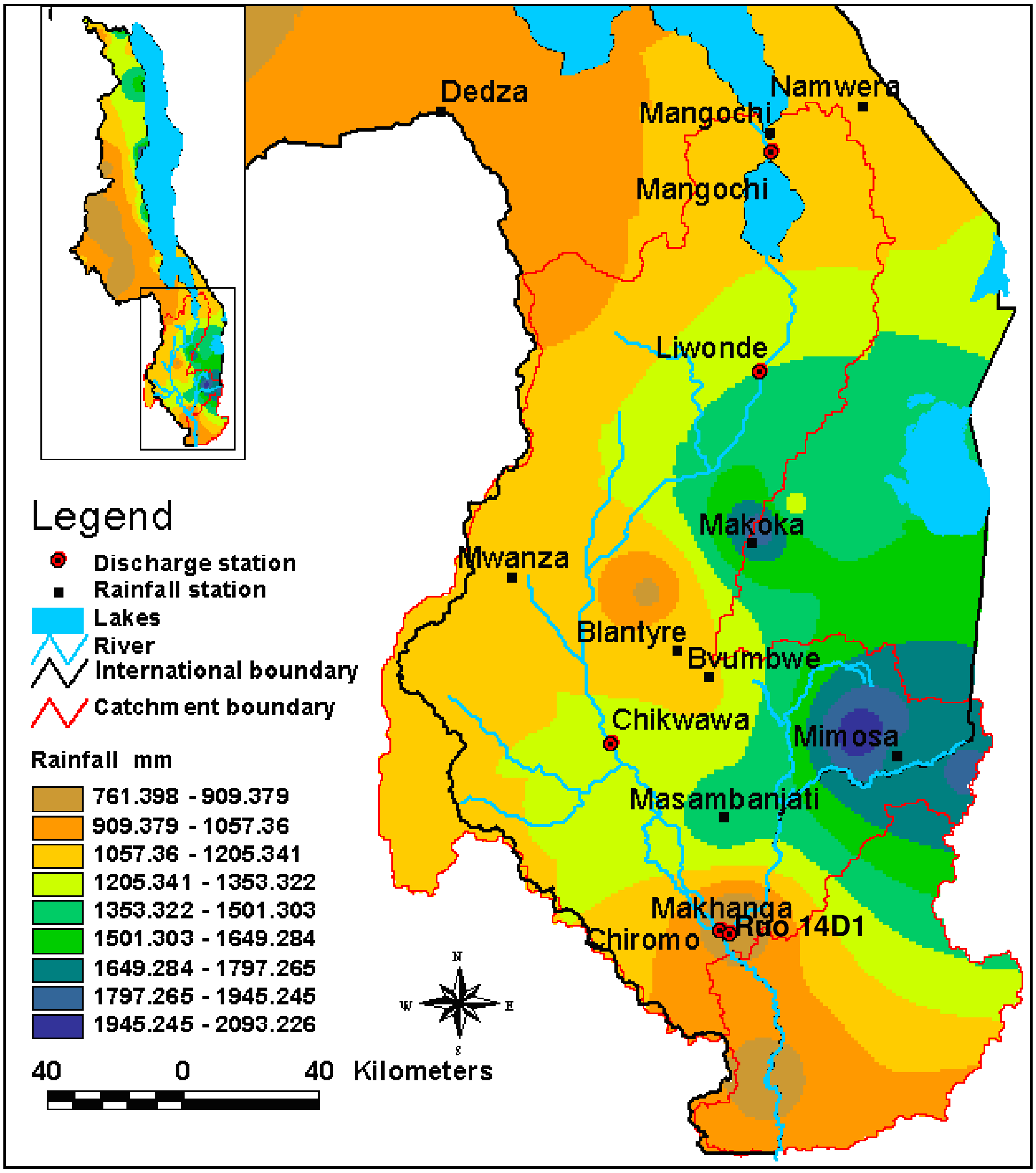


Figure 6.2 Annual average rainfall distribution over the Shire River Basin (Source of data:-(MetD, 2009))

The pattern of the hydrological events in the Shire river basin is not repetitive each year. However a predictable pattern after a certain period of time (years) must emerge. Estimation of extreme hydrological events in a particular river basin is required for economic planning, conservation and utilisation of water resources for various purposes (Mkhandi *et al.*, 2000). In view of this hydrologists have developed techniques known as frequency analysis for estimating the occurrence of hydrological extreme events. Frequency analysis is the means by which a hydrological event (such as floods) is related to probability of being equalled or exceeded in any year or to its frequency of occurrence. Previous studies on the occurrence of floods in the lower Shire have shown that flooding in the lower Shire valley is caused by Ruo river which backs up the Shire river at Shire-Ruo confluence (GoM, 1986)(Figure 5.2). The results of these studies were based on the qualitative analysis not hydrological parameters such as rainfall and river flows.

Floods and droughts are two hydrological extreme events which have an impact on Malawi's economy because of overdependence on the Shire river for hydropower, irrigation and water supply (Ibrahim and Alex, 2009). However for the sustainable management of the water resources of the Shire river basin there is need to develop simple tools capable of predicting the occurrence of extreme events as well as timing the flow events from one point of the river to another point. Knowledge of the flow pattern of the Shire river is vital in the planning and management of the water resources projects along the basin.

The objective of this part of the study is to analyse the flow pattern of the Shire river and develop a water budget tool for timing the flow events with flow inputs from the water balance model of Lake Malawi described in Chapter 5. The water budget will serve as a tool for future decision making in the planning and management of water resources in the Shire river basin. **The water budget gives a clear interaction between the Shire river flows and Lake Malawi water storage as well as effects of climate change and future abstraction on the water resources availability in the Shire river basin.** The section further looks at the separation of runoff and base flow at the most important strategic gauging stations in order to assess the effect of the water balance model of Lake Malawi on the water availability within the basin. The information served as a basis for understanding the influence of the water levels on the Shire river flows in the Lower Shire Valley.

6.2 MATERIALS AND METHODS

6.2.1 Hydrological climate and river flow analysis of Shire river basin

The hydrological climate of the Shire river basin was investigated using daily mean values from 9 main climate stations and 5 river discharge stations as shown in Figure 6.2. The hydrological data covered daily rainfall, daily river flows from 5 river main hydrometric stations, maximum and minimum temperature. Hydrometric stations used in the study are Mangochi, Liwonde barrage, Chikwawa and Chilomo on the Shire river and Ruo (14D1) on Ruo river (Figure 6.2). River flow data was obtained from the hydrology section of the Ministry of Water and Irrigation and rainfall data was obtained from the Meteorological office in Blantyre.

Due to the nature of human interference in the flow regime of the Shire river it was necessary to analyse the flow pattern of the Shire river basin both before the construction of the Liwonde barrage and after the construction of the Liwonde barrage. The period 1953 – 1955 is considered as a common period before the construction of the Liwonde barrage. The chosen post barrage construction common period for all the hydrometric stations is 1981 to 1990. Hydrographs for both periods (before and after the construction of Liwonde barrage) were plotted and compared on the same axis. The hydrographs also served as a simple comparison in analysing the effect of the Liwonde barrage on the downstream of the Shire river. Information gathered in the hydrological data was used in simulating a simple water balance of the Shire river and Ruo river.

6.2.2 Water budget of the Shire River Basin

In order to determine the factors affecting the availability of water in the Shire River Basin, a simple water budget (balance) of the Shire river was calculated. The water balance was calculated for the reach between Liwonde barrage and Chilomo station along the Shire river and for the Ruo river sub-catchment. Water availability has become an important concern in the 21st Century due to the increase in human population in Malawi and demand for water by other sectors such as irrigation and water supply. To ensure sustainable water supplies an understanding of the hydrological budget of a particular river basin is essential. In recent years a water budget has evolved as a tool that water managers use to quantify the availability and sustainability of water supply (Fikos *et al*., 2005; Johnson and Curtis, 1994). A water budget states that the difference between the rates of water flowing into and out of an accounting unit is balanced by a change in water storage (Healy *et al*., 2007). Analysis of changes in the water budget over time can be used to assess the effects of climate change and human activities over the water resources in the watershed area (Tate *et al*., 2004). The main terms considered in a water balance of a catchment are: change in storage within the catchment (dS/dt), precipitation (R), evapotranspiration (E) and outflow (Q) from the mouth of the catchment as shown in Figure 6.3.

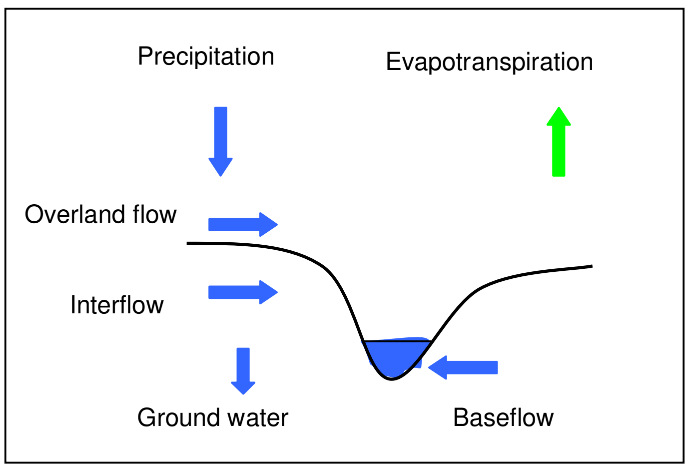


Figure 6.3 Typical parameters of the water balance of a watershed

Typical parameters of the water balance of a watershed shown in Figure 6.3 are related through equation 6.1 (Johnson and Curtis, 1994; Zhang *et al*., 2008).

$$\frac{dS}{dt} = R - Q - E \qquad 6.1$$

The storage component defines the amount of water in the catchment including groundwater, water in lakes, rivers and swamps within the catchment. The underlying assumption behind the model is that groundwater transfer across boundaries is negligible (Johnson and Curtis, 1994; Zhang *et al*., 2008). Equation 6.1 is a differential equation which can be solved based on a convenient time step depending on the available data. In the case of Shire river the model presented in equation 6.1 needs additional parameters such as an error term to account for the uncertainties in the available data such as groundwater abstraction, groundwater flow as well as errors in the available data. The density of climate stations in the river basin also accounts for the uncertainty in the accuracy of the model. The differential equation presented in equation 6.1 can be written as equation 6.2 with an integration period time step Δt .

$$\Delta S_{t+1} = R_t - E_t - Qout_t + Qin_t + \varepsilon_t \qquad 6.2$$

$Qout$ is the outflow and Qin is the inflow into the catchment and ε is the model error. A summation of the right hand terms in equation 6.2 excluding the error term is known as net basin supply (NBS) (Tate *et al*., 2004). NBS is normally used as a measure of the net contribution to the water balance of a catchment (Sene, 1998). It also gives an understanding on how the net water supply varies within the basin. However this should not be taken as an absolute measure of the changes in the basin water because actual evapotranspiration rates changes depends on ground cover and soil for the catchment under consideration.

The main problem associated with water balance studies of a river basin is to determine actual evapotranspiration, groundwater storage and all the other process associated in the hydrological cycle shown in Figure 6.4. The most difficult parameter to determine is groundwater storage because of lack of data on groundwater storage properties and flow particularly in Malawi. In recent years hydrological models (HM) have evolved as important tools in water budget studies (Vaitiekuniene, 2005). Hydrological models contributes substantially to the understanding of the hydrology of watersheds, rivers and aquifers, serving as an integral tool in the management of the water resources (Kachroo, 1992b). Hydrological models predict stream discharge based in response to input parameters such as precipitation and evaporation usually accounting for evapotranspiration as shown in Figure 6.4. Equation 6.2 can be transformed into a rainfall runoff equation (Equation 6.3) by taking into account the assumption that groundwater storage variation is negligible (Mandeville and Batchelor, 1990).

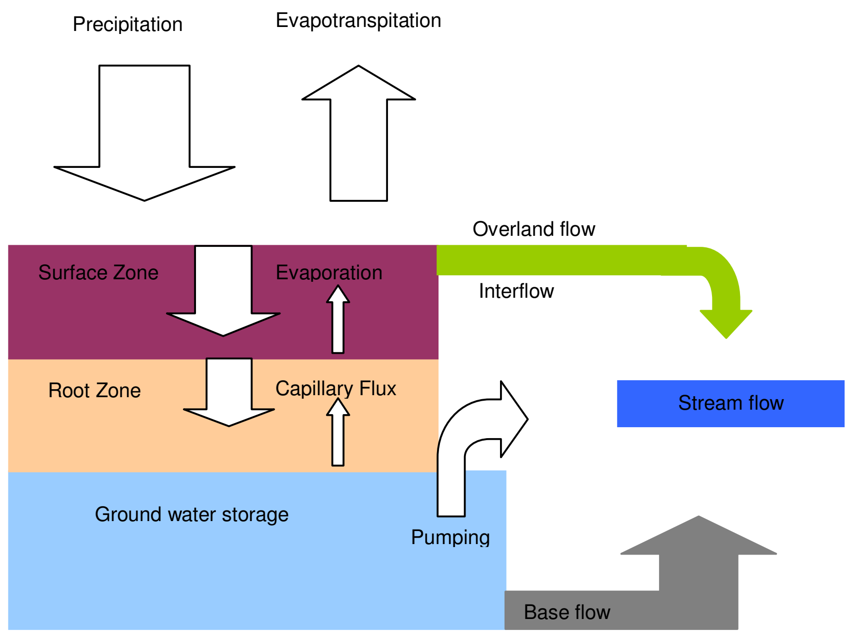
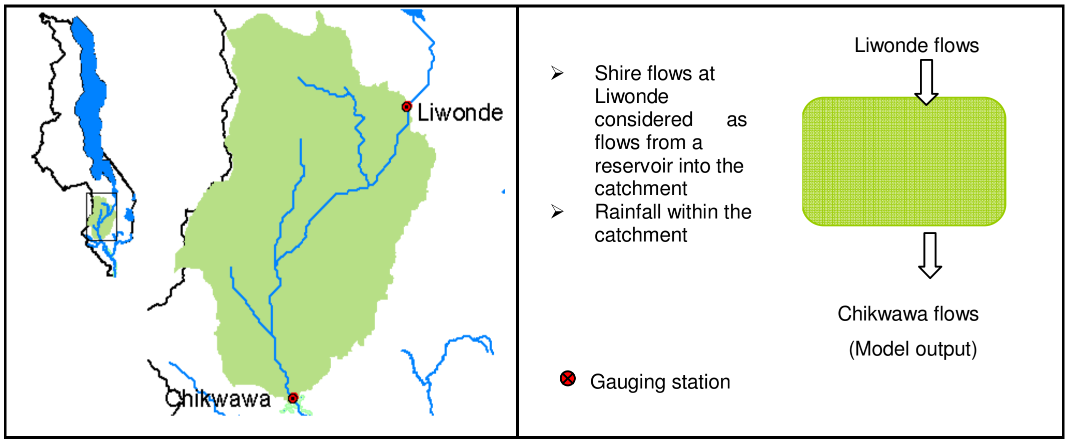


Figure 6.4 Schematic diagram showing various processes that are considered by hydrological models in transforming inputs into stream flow in water budget studies

$$Qout_t = R_t - E_t + Qin_t + \varepsilon_t \qquad 6.3$$

Equation 6.3 can easily be translated into runoff by using hydrological models. There is an abundance of literature concerning hydrological modelling (Kachroo et al., 1992a). However most of the studies assume that there are plentiful data for evaporation, precipitation and streamflow. This is not the case with developing countries like Malawi which has very few climate stations as well as hydrometric stations. Soil-water data used by many conceptual hydrological models in translating rainfall into runoff and groundwater flow is non existent in Malawi. This limits the use of hydrological models in water balance studies. An attempt to apply the Nedbor – Afstromings – Model (NAM) hydrological model failed because of lack of data on evaporation and soil water within the Shire river basin. The approach adopted in this research in developing the water balance model for Shire river basin was to employ the Linear Perturbation Model (LPM) described in Section 2.5.8 of Chapter 2. LPM is a lumped hydrological model for simulating rainfall into runoff as a function of the perturbations from the seasonal mean values.



Catchment area | Sketch for Modelling

Figure 6.5 An example of the conceptual model input diagram for catchment area between Liwonde barrage and Chikwawa hydrometric station

As already noted in Chapter 3 and 5, the Shire river flows are affected by human infrastructures along the river such as Liwonde barrage and a number of hydropower dams and water abstraction for Blantyre City water supply as well as irrigation water in the Lower Shire Valley. In order to accommodate human influence especially flow regulation at Liwonde barrage, the approach involved hydrological modelling of each gauging station in turn resulting in two steps from Liwonde to Chilomo gauging station. The flow rates recorded at the upstream station (Liwonde barrage) were considered as flows regulated from a reservoir into the downstream catchment. For example the modelling of flows at Chikwawa was considered using the conceptual diagram shown in Figure 6.5. This required revising the Linear Perturbation Model presented in Section 2.5.8 to handle multiple input data such as Liwonde flows as inflows and water withdraws for water supply and irrigation. The modified Linear Perturbation Model is presented in equation 6.4.

$$Q_i = \sum_{k}^{J} \sum_{j=1}^{m(k)} D_{i\ j+1}^{(k)} h_j + \varepsilon_i \qquad i = 1,2,3,\ldots\ldots\ldots\ldots n \qquad 6.4$$

J is the total number of model inputs ranging from rainfall to water withdraws from the catchment. $D^{(k)}$ are perturbations or departures of the kth input from their seasonal mean values.

Since the aim behind the water balance was to analyse the available water within each reach of the Shire river as well as the effect of flows from Lake Malawi on the downstream water availability, it was considered necessary to analyse the unit hydrograph for each gauging station along the Shire river. This required separating streamflow into quick runoff and baseflow. In order to achieve this, base flow separation technique was incorporated into the LPM hydrological model for this purpose.

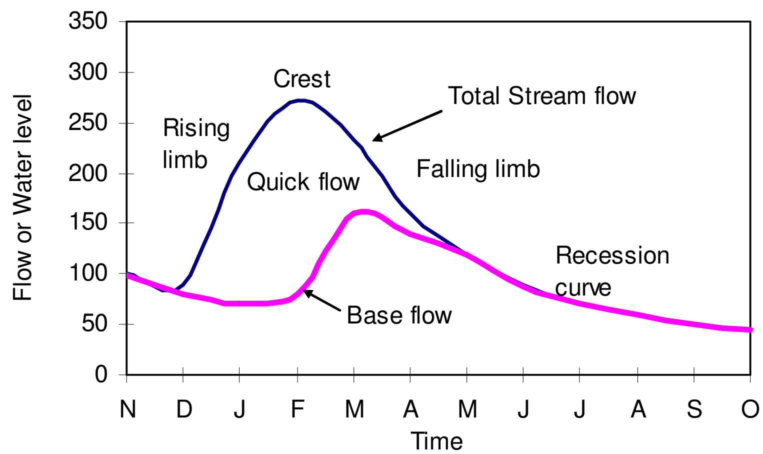


Figure 6.6 Sketch of typical components of a streamflow hydrograph

6.2.3 Baseflow separation

The stream flow hydrograph is used to describe the change in river discharge over time and consist of quick flow and base flow (Bloomfield *et al.*, 2009; Brodie and Hostetler, 2005). The quick flow component consists of interflow which is the lateral movement of water in the soil profile, surface runoff as a direct response to rainfall event, and precipitation over the channel (Brodie and Hostetler, 2005). The base flow component represents the longer term discharge derived from saturated groundwater storage (Bloomfield *et al.*, 2009). Figure 6.3 shows the water budget components and clearly indicates how the two components quick flow and base flow are inter-related. According to

Bloomfield *et al.* (2009) groundwater varies in response to relatively long seasonal changes in evaporation, and rainfall over the catchment. The difference in area under the total stream flow hydrograph and the base flow hydrograph is a long term measure of baseflow index (BFI). BFI is defined as the long term ratio of groundwater flow to total stream flow (Bloomfield *et al.*, 2009). This is used as a measure of groundwater contribution to stream flow. There are several methods of baseflow separation in literature ranging from graphical methods to manual filter methods (Nathan and McMahon, 1990).

Graphical techniques tend to define the points where base flow intersects the rising limb of the quick flow component of the total stream flow hydrograph as shown Figure 6.6 (Brodie and Hostetler, 2005). Filter methods involve the use of the entire stream hydrograph data to deduce a groundwater (baseflow hydrograph) (Brodie and Hostetler, 2005; Eckhardt, 2005). Both methods are aimed at separating the quick component of flow from the long term slow component due to groundwater recharge. Currently there is no universally accepted method for estimating baseflow component from the stream flow hydrograph due to the fact that the true values of baseflow are always unknown (Bloomfield *et al.*, 2009; Eckhardt, 2008). In this research it was deemed necessary to separate the baseflow from the stream flow for each gauging station along the Shire river (Mangochi, Liwonde, Chikwawa and Chilomo stations) and Ruo 14D1 on Ruo river. This was aimed at finding the flow contribution of Lake Malawi into the Shire river.

The digital filter method was incorporated in the Linear Perturbation model to estimate groundwater contribution at each gauging station along the Shire river. The digital filter method was selected because the method is flexible for development in computer codes that process large volumes of data compared to manual filter methods which are too time-consuming to separate even one year daily data. The digital filter method is often used in signal analysis and processing to separate high frequency signals from low frequency signals (Nathan and McMahon, 1990). This method has been adopted in unit hydrograph analysis because high frequency waves can be associated with quick response to rainfall event as direct runoff and low frequency waves can be associated with the baseflow which is a low flow but a longer term discharge derived from groundwater storage, reservoir or lake storage (Eckhardt, 2005). The general formulation of parameter digital filter for hydrograph analysis after Eckhardt (2005) is given in equation 6.5.

$$Qb_t = \frac{(1 - BFI_{max})aQb_{t-1} + (1 - a)BFI_{max}Q_t}{1 - aBFI_{max}} \qquad 6.5$$

Qb is the baseflow, t is the time step, Q is the total stream flow, a is the recession constant, and BFI_{max} is the maximum value of baseflow index that can be measured. Table 6.1 is a summary of the suggested initial BFI_{max} values for various river conditions after Eckhardt (2005). In the present study, the Shire river is considered as a perennial river because of the long lasting flow contribution from Lake Malawi hence a BFI_{max} of 0.8 was used as a starting value in the simulation.

The recession constant was analysed by a method called recession analysis proposed by Eckhardt (2008). Every stream flow Q_t was taken into consideration in the recession analysis period of at least 5 days. A stream flow has to satisfy equation 6.6 to qualify for use in recession analysis.

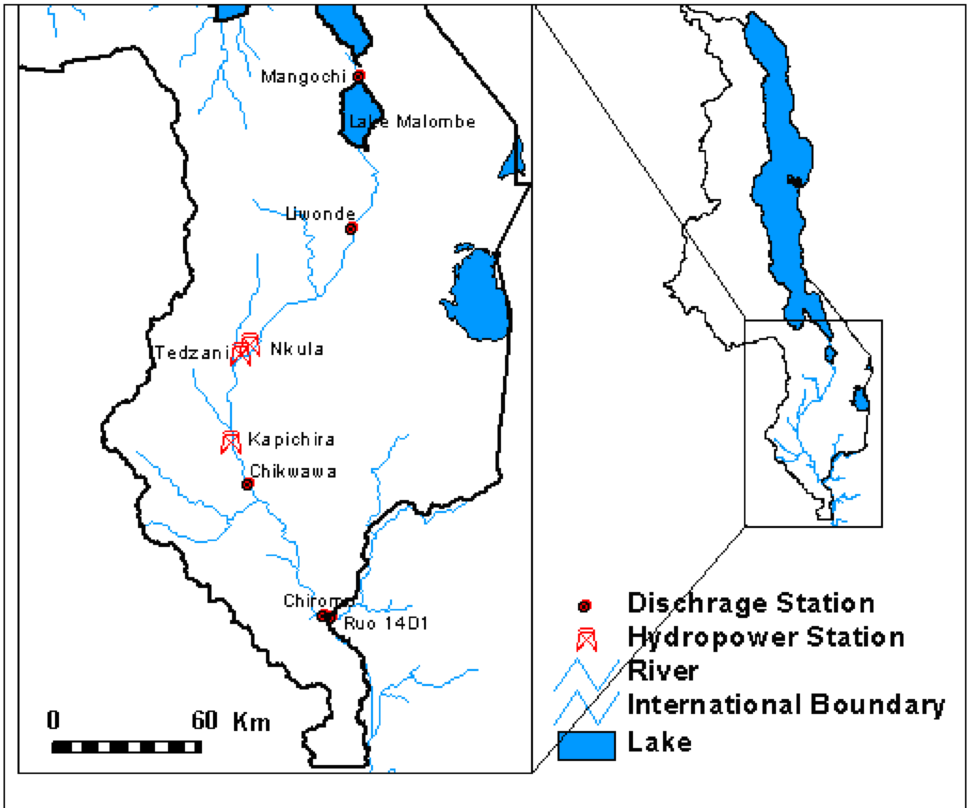
$$Q_{t-3} > Q_{t-2} > Q_{t-1} > Q_t > Q_{t+1} > Q_{t+2} \qquad 6.6$$

A series of river flows from equation 6.6 was used for a scatter plot of streamflow Q_{t+1} against Q_t and fitted with a trend line from the origin. The slope of the fitted line is the recession constant a.

Table 6.1 BFI_{max} values for various river conditions after Eckhardt (2005)

River flow condition	BFI_{max}
perennial streams with porous aquifers	0.80
ephemeral streams with porous aquifers	0.50
for perennial streams with hard rock aquifers	0.25

The following section is an analysis of the results of the river flow, water budget as well as the hydrological model and the baseflow separation based on the methods outlined in the section 6.2.



Station	Mean m^3/sec	Maximum m^3/sec	Minimum m^3/sec
Mangochi	626.61	1051	330
Liwonde	604.12	954	241
Chikwawa	648.996	1394	273
Chilomo	660.85	1355	303
Flow records for the period 1981 to 1990			

Figure 6.7 Map showing hydrometric stations along the Shire river and their mean annual flows for the period 1981 to 1990

6.3 RESULTS OF SHIRE RIVER FLOW ANALYSIS

The three sections of the Shire river, represented by the 4 gauging stations shown in Figure 6.7, have unique characteristics in the flow pattern. The mean monthly flows at Chilomo before and after the construction of the barrage are presented in Table 6.2 and the corresponding seasonal hydrographs are presented in Figure 6.8. The seasonal hydrograph at Chilomo shows an increase in flow in the lower Shire river throughout the year after the construction of the barrage. The mean flow at Chilomo has increased from a mean annual flow rate of 319.82 m^3/sec to 660 m^3/sec presenting an annual increment of 106 percent from the base period of the pre barrage construction period of 1953 – 1955 (Table 6.2). The percentage increase varied from 53.22 percent in the month of March to 175.32 percent in the month of October as shown in Table 6.2. From Table 6.2 and Figure 6.8 the percentage increase in flow is higher during the dry season months from May to December showing the effective utilisation of the barrage in regulating flows in the Shire river. However the large increase of 106 percent on average is not due the construction of the barrage. There was no outflow from the lake from 1915 to 1937 due to low water levels in Lake Malawi and accumulation of sand bars at the lake outlet (Calder *et al.*, 1985). Since 1937, progressive rise in water levels in Lake Malawi has led to a progressive increase in flows into the Shire river. Therefore a 106 percent increase in flows from 319 (1953 – 1955 mean value) to 660 (1981 – 1990 mean value) is due to progressive rise in lake levels , breaching of sand bars at the lake outlet and operation of Liwonde barrage.

Table 6.2 Summary of the changes in stream flow at Chilomo hydrometric station on Shire river due to the construction of Liwonde barrage

Period	1953 – 1955	1981 - 1990	
Month	Mean monthly flows m^3/sec		Percentage Change
Jan	381.48	695.37	82.28
Feb	499.02	902.18	80.79
Mar	556.46	852.59	53.22
Apr	437.46	811.56	85.52
May	344.99	753.88	118.52
Jun	317.17	704.42	122.10
Jul	273.71	645.19	135.72
Aug	235.49	573.56	143.55
Sep	200.16	516.59	158.09
Oct	174.39	480.12	175.32
Nov	179.36	463.21	158.27
Dec	238.17	531.61	123.20
Mean	319.82	660.86	106.63

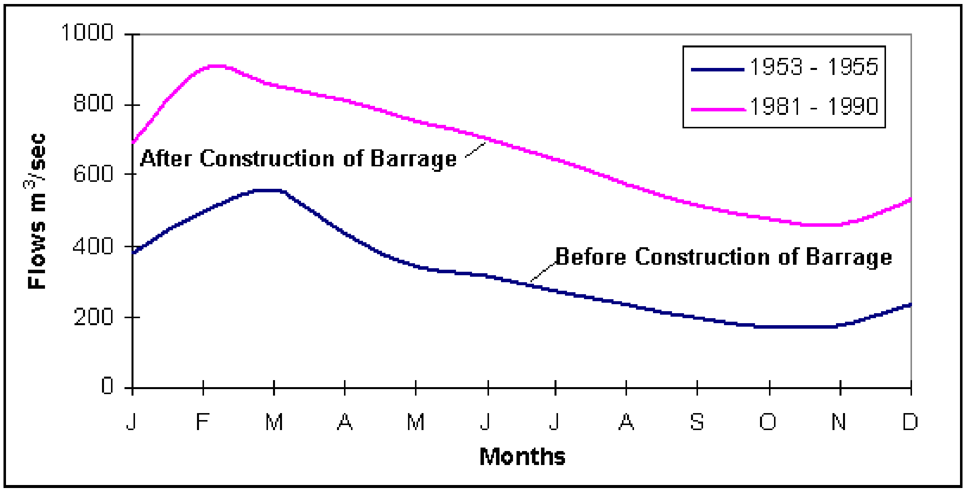


Figure 6.8 Seasonal flow hydrograph for Chilomo hydrometric station before and after construction of the Liwonde Barrage

The seasonal hydrograph of Mangochi station which is the main lake outlet station has a shape similar to the hydrograph at Liwonde as shown in Figure 6.9. The only difference is noted during the rain season when the flows at Mangochi are higher than the flows at Liwonde further. This could be due to high rainfall over the lake or lake catchment resulting in high flows from the lake. The similarity in shape between the hydrographs for the two stations is due to flow regulation at Liwonde barrage and the difference in magnitude is due to inflow contribution from the catchment area between the two stations including Lake Malombe storage function. Figure 6.7 is a detailed map showing the location of the hydrometric stations as well as Lake Malombe along the Shire river.

Seasonal hydrographs of the lower Shire at Chikwawa and Chilomo are similar during the dry season from May to November as shown in Figure 6.9. The major difference between the two stations was noted during the rain season from November to April. During the rainfall season the flows at Chilomo are quite higher than flows at Chikwawa although the two stations are so close to each other as Shown in Figure 6.1. The reason behind this is the high flows coming from Ruo river which creates a bottleneck at Shire-Ruo confluence resulting in flows backing in the upstream section of Chilomo station. This can easily be noted in the annual peak flows of Chilomo station which coincides with annual peak flows of Ruo river. The relative flatness of the region is another contributing factor to the backing of flows into the Shire river (Figure 6.10). A number of researchers have argued that high dam development to contain the Lower Shire floods would have negative effects on the flood plain. Flooding of the Lower Shire Valley is a natural phenomenon which sustains the natural ecosystem of the Lower Shire Flood plains (Chimatiro, 2004; Kidd, 1983).

The four stations (Chilomo, Chikwawa, Liwonde and Mangochi) along the Shire river shown in Figure 6.7 have hydrographs with similar shape during the dry season indicating their reliability on flow regulation from Lake Malawi during the dry season. The difference during the rainfall season indicates an effect of the rainfall contribution from the catchment between Lake Malawi outlet and the hydrometric station under consideration.

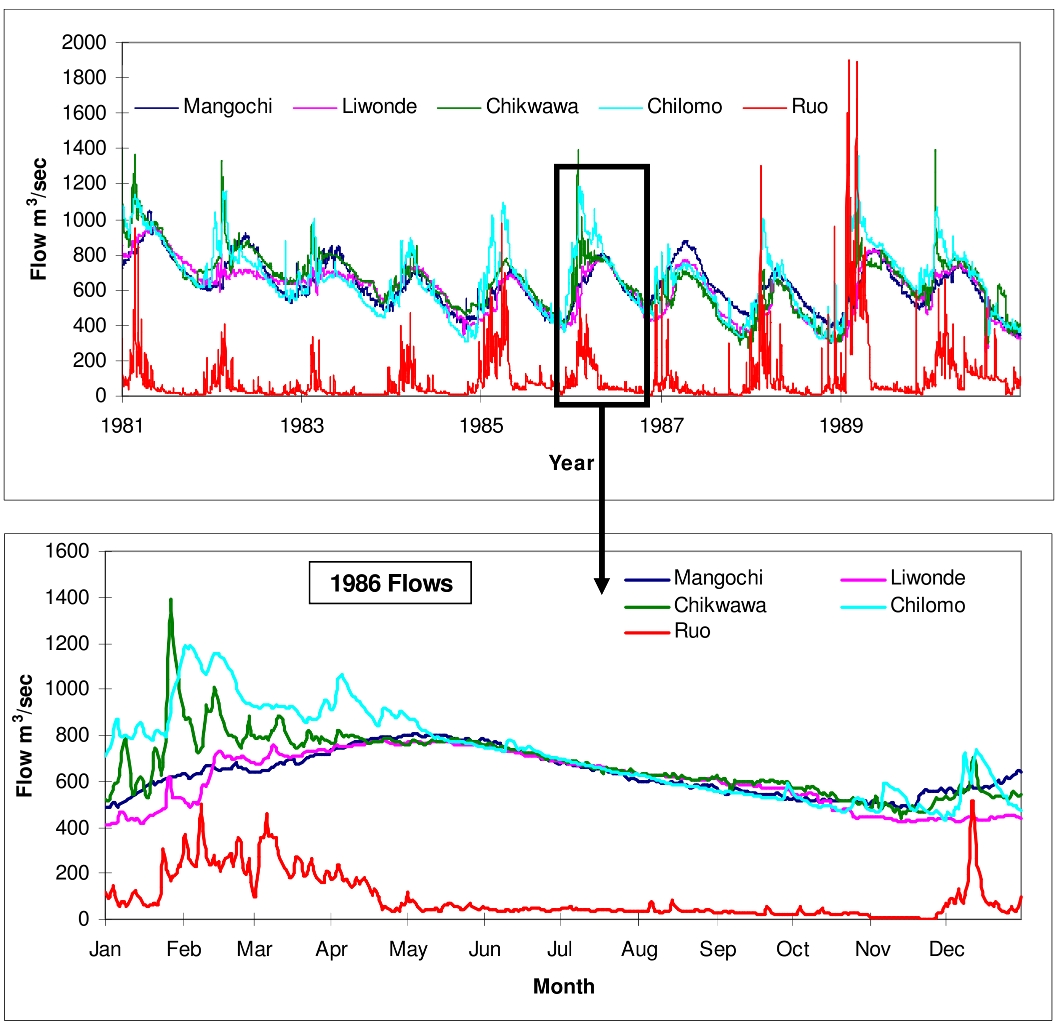


Figure 6.9 Seasonal hydrographs for the main 5 hydrometric stations within the Shire River basin

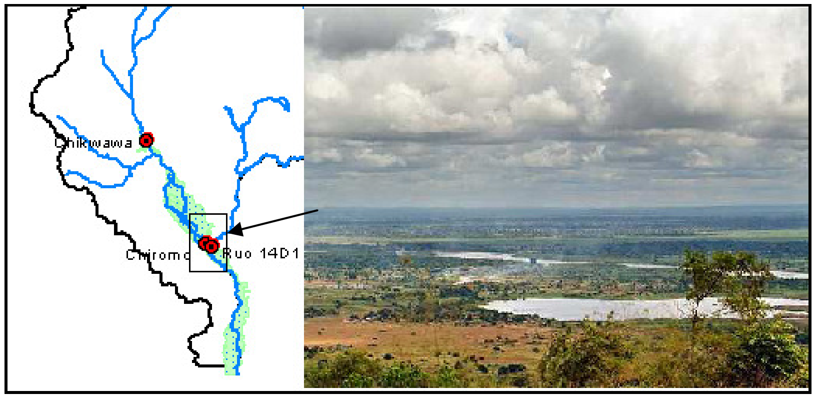


Figure 6.10 Photo of the flood plains of Lower Shire Valley

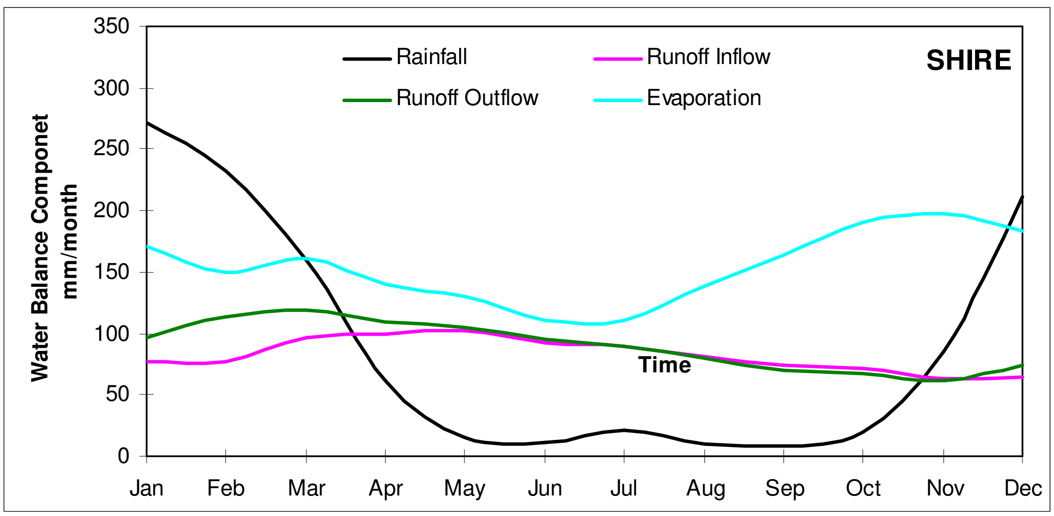
6.4 RESULTS OF WATER BALANCE OF SHIRE RIVER BASIN

6.4.1 Annual water budget for Shire and Ruo river

A simple water budget for Ruo and Shire rivers between Liwonde barrage and Chilomo station was calculated based on equation 6.2. The water balance of Shire river shows that the runoff inflow from Lake Malawi at Liwonde is almost the same as the runoff outflow at Chilomo hydrometric station as shown in Figure 6.11 and Table 6.3. The minor difference is observed during the rainy season when the runoff outflow from the reach between Liwonde and Chilomo hydrometric station is higher than the runoff inflow from Lake Malawi. The Shire river has an average annual evaporation of 1846 mm, runoff outflow of 1077 mm, runoff inflow of 987 mm and rainfall of 1106 mm. The runoff outflow is higher than the runoff inflow indicating rainfall contribution within the catchment area. There is a monthly variation in the Net Basin Supply components. For example during the rainy season from December to March, the runoff outflow is higher than the runoff inflow which peaks in March and April. There is little difference between the inflow and outflow runoff during the dry season indicating little groundwater contribution from the catchment rather than flows from Lake Malawi. This justifies the assumption made in deriving equation 6.3 that variation in catchment storage over time is negligible.

The Ruo river receives an average annual rainfall of 1290 mm. The annual runoff from the Ruo river into the Shire river is 639 mm. Ruo river has a similar pattern of Net Basin Supply as the Shire river with gain in Net Basin Supply during the rain season as shown in Figure 6.11 and Table 6.4. Despite causing floods at Shire-Ruo confluence, only 50 percent of Ruo rainfall is converted into runoff at the outlet.

From Figure 6.11 Net Basin Supply pattern has emerged regarding the water budget of Shire river basin and Ruo river. In both basins rainfall is the major parameter that derives the monthly NBS. The NBS presented in Figure 6.11, Table 6.2 and Table 6.3 is a rough estimate of the variation in the available water within the respective basin because of lack of actual evaporation data.



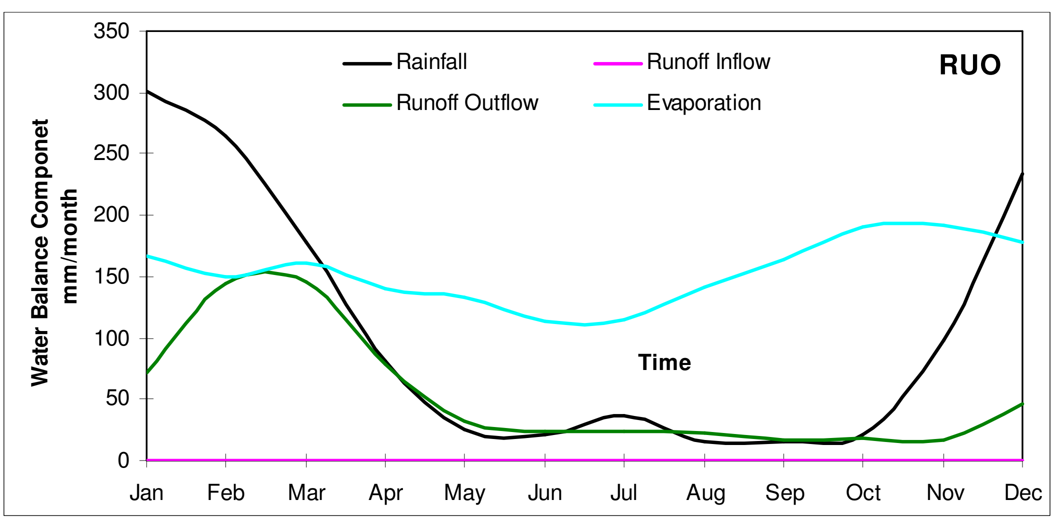


Figure 6.11 Annual variation of water budget components of Shire and Ruo river

In estimating Net Basin Supply there is a need to use actual evaporation data, however this information is not readily available. Studies by Mandeville and Batchelor (1990) have suggested that the actual evaporation from Malawi catchments can be estimated as the difference between annual total rainfall and runoff from a particular basin in consideration. The method assumes that there is no variation in groundwater storage hence any amount of water that comes into the basin is either lost as runoff or evaporation. However actual evaporation estimates require more information on land use and cover as well vegetation type within the catchment which is not readily available. In this study potential evaporation values have been used in the annual water budget just to give a picture in the variation of water balance within the basin. Scarcity of data on actual evaporation estimates prompted the use of hydrological model to translate the water budget components into runoff as described in the following section.

Table 6.3 Summary of water budget components of Shire

Month	Rainfall	Runoff Inflow	Runoff Outflow	Evaporation
Shire	mm/month			
January	271	77	97	171
February	233	77	113	150
March	160	96	118	161
April	61	100	109	139
May	15	102	105	130
June	12	93	95	111
July	20	89	90	111
August	9	81	80	139
September	9	74	69	164
October	19	71	67	191
November	86	63	62	198
December	211	64	74	183
Annual	1106	987	1077	1846

Table 6.4 Summary of water budget components of Ruo

Month	Rainfall	Runoff Inflow	Runoff Outflow	Evaporation
RUO	mm/month			
January	301	0	71	166
February	264	0	145	149
March	178	0	145	161
April	81	0	79	140
May	25	0	32	133
June	21	0	24	113
July	36	0	24	115
August	15	0	22	141
September	15	0	17	164
October	20	0	19	190
November	98	0	17	192
December	234	0	46	178
Annual	1290	0	639	1842

6.4.2 Results of hydrological modelling of Shire and Ruo river

The Net Basin Supply presented in the previous section was based on potential evaporation estimates not actual evaporation because of lack of available data. In view of this uncertainty, a hydrological model was applied to the main hydrometric station to translate Net Basin Supply input parameters into runoff at the basin outlet. The fitted model will serve as a tool in assessing water resources availability within the basin. Equation 6.4 was applied to the two main stations along the Shire river (Chilomo and Chikwawa) and the Ruo river outlet (14D1) into Shire river to translate Net Basin Supply parameters into output runoff. The model performed quite well for the three stations as shown in Figure 6.12 and Figure 6.13. In the case of Chilomo station the model managed to simulate the flows well with a Nash-Sutcliffe (1970) model efficiency of 0.89 except for the period 1983 and 1985 where the model overestimated the flows. The model underestimated the flows for 1989.

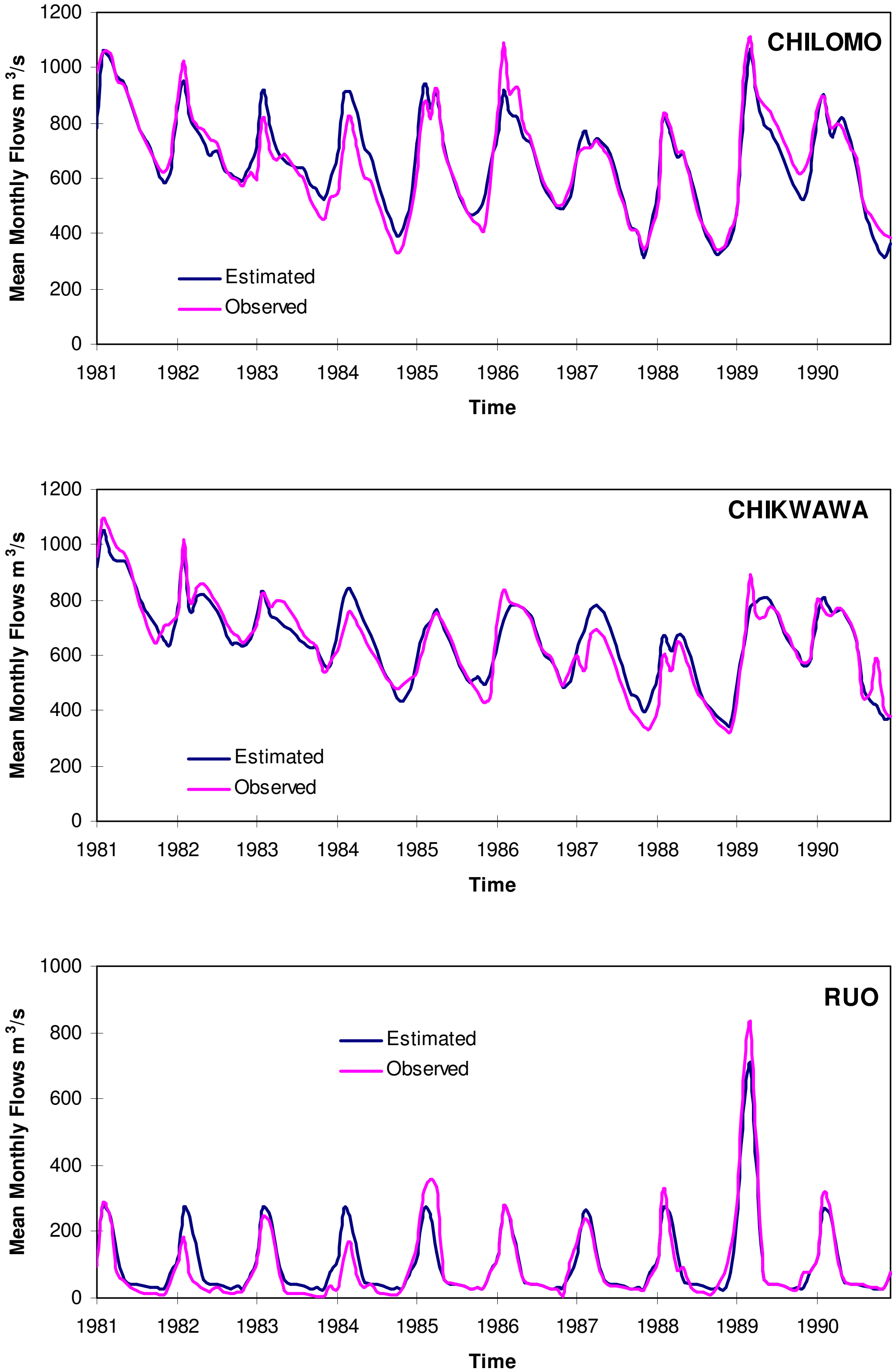


Figure 6.12 Observed and simulated flows by LP model for Chilomo, Chikwawa and Ruo hydrometric stations

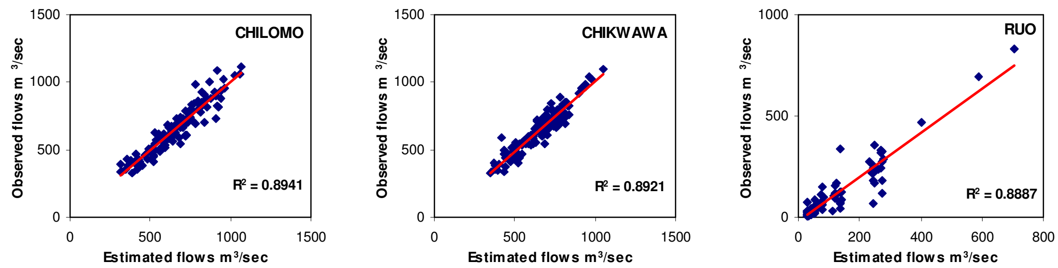


Figure 6.13 Correlation diagram for observed and estimated flows for Chilomo, Chikwawa and Ruo hydrometric stations by LPM

In the case of Chikwawa station, the model overestimated 1984, 1987 and 1988 flows. Generally, the model managed well to simulate the flows with a Nash-Sutcliffe (1970) model efficiency of 0.89. The results of Ruo river had a Nash-Sutcliffe (1970) model efficiency of 0. 89. The model overestimated flows for the year 1982 and 1984. Overall, the shapes of the hydrograph of the three main stations Ruo, Chilomo and Chikwawa area similar when comparing the observed and estimated flows by the model. The minor differences between the observed and estimated flows for all the two main stations (Chilomo and Chikwawa) along the Shire river and Ruo 14D1 on Ruo river may be due to an error in the data records. One possible reason is that in recent years the Shire river has been affected by water hyacinth due to excessive use of agricultural chemicals in the catchment area, together with siltation of the channel due deforestation in the catchment area (GoM, 2003a; Phiri *et al*., 2001). Water hyacinth is the most wide spread and damaging aquatic weed which affects many aquatic ecosystems. The dense mats of this weed degrade rivers, lakes, dams and wetlands, thereby limiting their effective utilization (Cilliers *et al*., 2003). Both water hyacinth and siltation have a significant impact on the flow regime of the Shire river as well as the rating curves of the hydrometric stations in the basin. This calls for the need to update the rating curves of the hydrometric stations on the Shire river in order to minimise errors in the river flow data.

The results of hydrological modelling have shown that the modified Linear Perturbation Model could serve as a water balance model tool in the Shire River Basin in simulating the runoff outflow from the basin based on changes in the hydrological parameters within the basin. Changes in water withdraws could easily be incorporated into the model to estimate what would be the effect on the available water within the basin. The impact of climate change and the effects of any changes in the catchment area of Lake Malawi due to human activities on the water resources availability in the Shire river could easily be assessed by simulated lake outflows using the Water Balance Model of Lake Malawi developed in Chapter 5 and GCM data as described in Chapter 5. This should take advantage of the interaction between the two tools (Water Balance Model of Lake Malawi as in Chapter 5 and Linear Perturbation Model as a Water Budget simulation tool earlier in this Chapter for the Shire river).

The assumption of using estimated outflow from Lake Malawi as inflows into the Shire river water budget model has shown to work well with the Linear Perturbation Model for the assessment of water resources availability within the basin. The water balance model for Lake Malawi developed in Chapter 5 has shown to interact well with Linear Perturbation Model in simulating the flow regime of the Shire river because the Water Balance Model for lake Malawi relates well with the flow record of Liwonde station which were used as input inflows in the Linear Perturbation Model.

The results from the simulation could not actually give an indication of the effect of the flows regulated from the lake at Liwonde barrage on the downstream water availability even though output from the water balance model for lake Malawi have shown to work well when incorporated into the LPM in simulating streamflow in the Shire river. Hence the need to incorporate a baseflow filter in the model to separate streamflow into quick runoff due to rainfall response and baseflow due storage function of the lake. The following section presents the results of base flow separation based on digital filter method

6.4.3 Results of base flow analysis

Results of base flow analysis for all the three hydrometric stations along Shire river and Ruo river have been presented in Figure 6.14 to Figure 6.18. The information presented in Figure 6.14 to Figure 6.18 includes observed and separated base flow. Table 6.5 is a summary of the BFI and recession constant for each hydrometric station. The following section gives a clear analysis of each station separately.

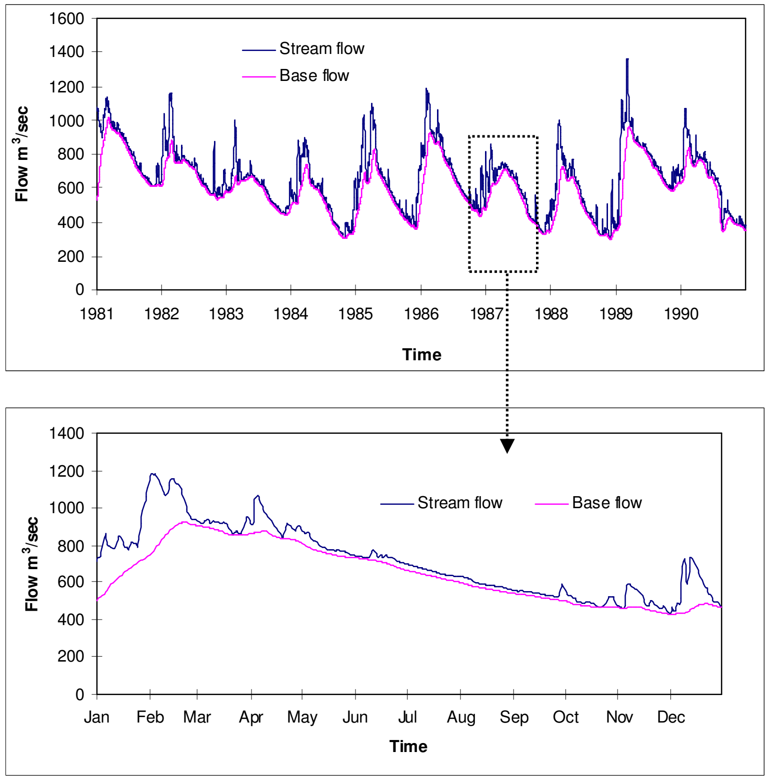


Figure 6.14 Chilomo stream flow and base flow hydrograph

6.4.3.1 Chilomo Hydrometric Station

Chilomo Hydrometric Station is the main outlet station on the Shire river in Malawi and has a high baseflow index of 0.90. The daily time series hydrograph demonstrate a very strong and quite rapidly responding rainfall season baseflow as shown in Figure 6.14. During the rainfall season there is a rapid increase in stream flow as well as base flow and the difference between the two is high during this season. There is no marked difference between baseflow and stream flow during the dry season from May to October indicating that much of the stream flow is from storage recharge either groundwater or lake storage.

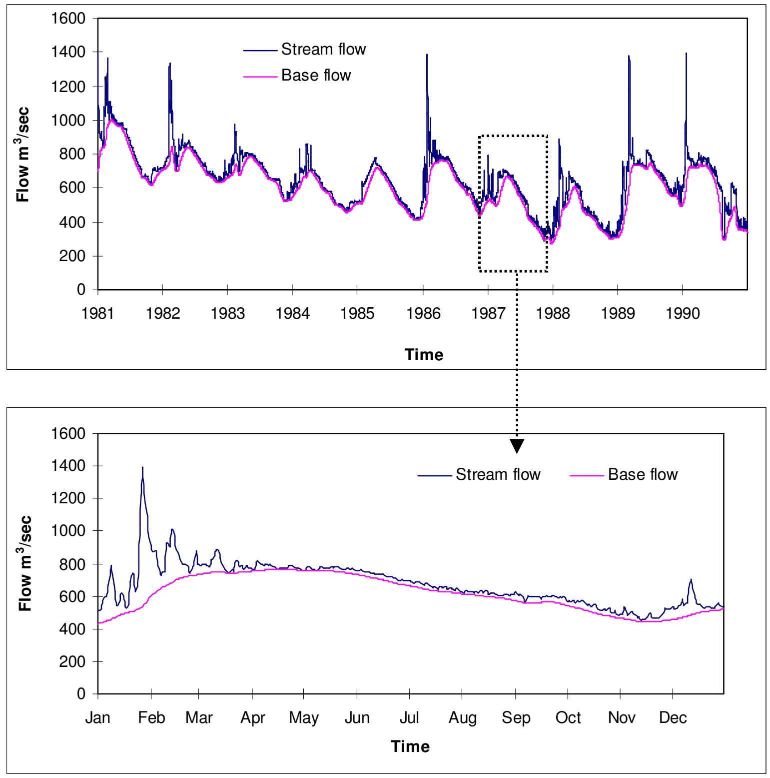


Figure 6.15 Chikwawa Stream flow and base flow hydrograph

6.4.3.2 Chikwawa Hydrometric Station

Chikwawa is the hydrometric station which is upstream of Chilomo station. The daily time series shows a similar pattern with Chilomo station as shown in Figure 6.15. The rapid increase in rainfall from November to March results in rapid increase in streamflow as well as base flow. From April to October there is no marked difference between baseflow and stream flow. The station has a baseflow index of 0.92. The high baseflow index indicates that much of the flow is from storage recharge either groundwater or lake storage.

6.4.3.3 Liwonde Hydrometric Station

Liwonde station has a baseflow index of 0.94. However there is no marked difference between baseflow and stream flow except for the month of April as shown in Figure 6.16. This is attributed to the fact that flows at Liwonde barrage are affected by the operation of the barrage in regulating flows downstream of the Shire river.

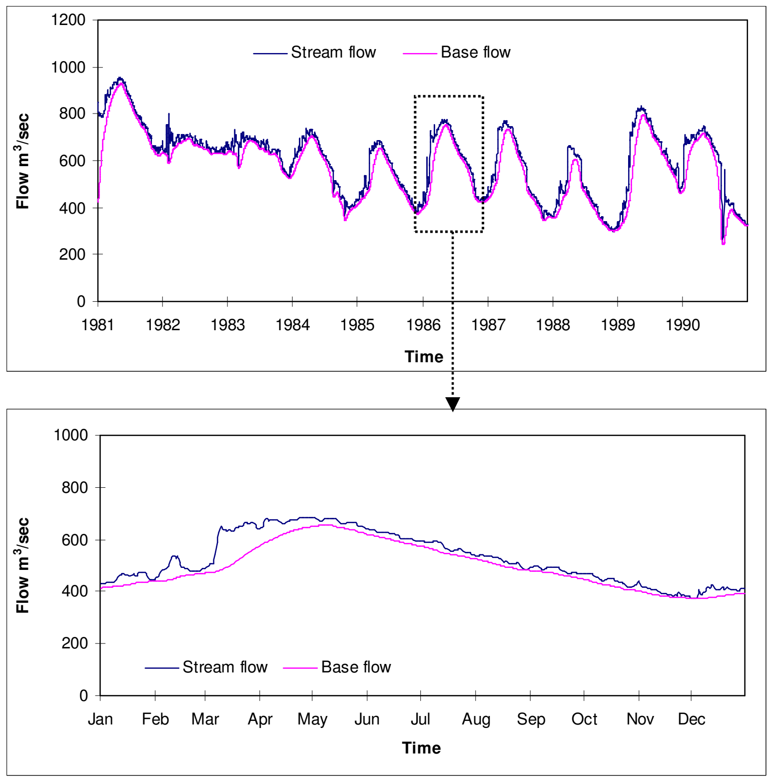


Figure 6.16 Liwonde stream flow and base flow hydrograph

6.4.3.4 Mangochi Hydrometric Station

Mangochi station has a high baseflow index of 0.94 and no marked difference between baseflow and stream flow as shown in Figure 6.17. This is attributed to the fact that flows at are coming from a storage unit, Lake Malawi. Lakes are considered as linear reservoirs (Kebede *et al.*, 2006).

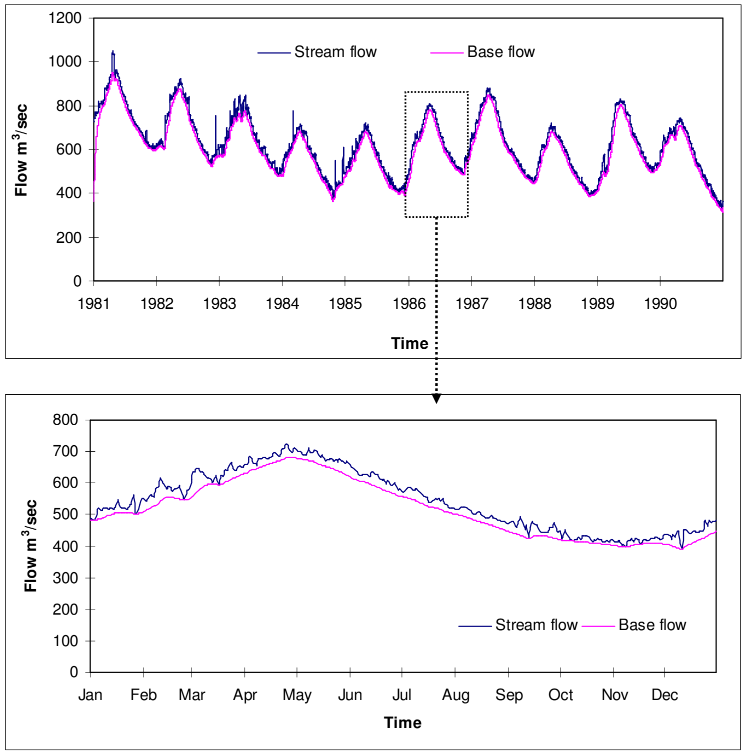
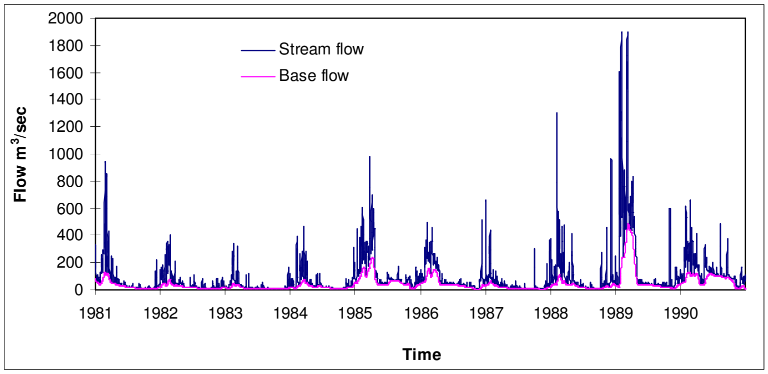


Figure 6.17 Mangochi Stream flow and base flow hydrograph

6.4.3.5 Ruo Hydrometric Station

The Ruo river has a low baseflow index of 0.46 at its outlet into the Shire river. The low baseflow index indicates lack of storage within the basin to sustain high flows in the dry season. The basin has a high and rapid response to rainfall as shown in Figure 6.18. Ruo river receives high rainfall during the months of February and April resulting in high flows up 1000 m^3/sec and a base flow of 100 m^3/sec. The is no marked difference between observed stream flow and baseflow during the dry season indicating that much of the flow during this period is from groundwater storage as there in surface storage water body within the basin.



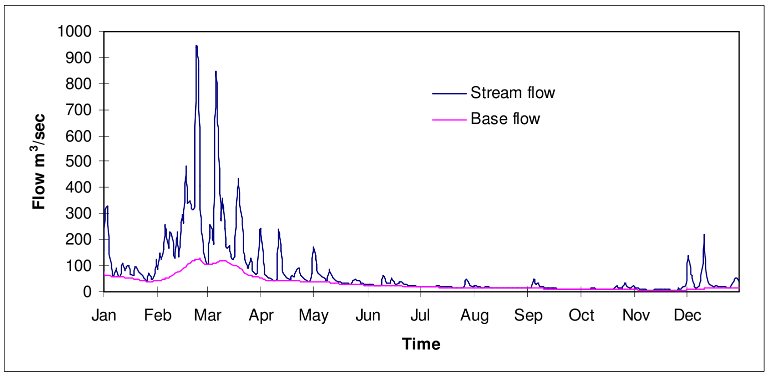


Figure 6.18 Ruo Stream flow and base flow hydrograph

Table 6.5 Baseflow index and recession values for various hydrometric stations within the Shire river basin

River	Station	Catchment area Km^2	BFI	Recession Constant
Shire	Mangochi	0	0.94	0.99
Shire	Liwonde	3,700	0.94	0.98
Shire	Chikwawa	12,100	0.92	0.98
Shire	Chilomo	23,000	0.90	0.985
Ruo	Ruo 14D1	4,350	0.46	0.92
Mangochi station is the outlet station from Lake Malawi.				

The results of baseflow have shown that all the hydrometric station along the Shire river have a high base flow contribution in the excess of 0.90 of the stream flow. Ruo river which is the main tributary into the Shire river has the lowest BFI of 0.46. Recession analysis was carried out on the baseflow series to confirm whether much of the flow in the Shire river is due to regulated flows from Lake Malawi or groundwater storage within the Shire river. Recession analysis was based on a method of a scatter plot of stream flow Q_{t+1} against Q_t (Eckhardt, 2008). The results of the recession analysis have been presented in the section 6.4.4

6.4.4 Recession analysis of Shire and Ruo flows.

The time series analysis analysed in this study consisted of daily mean values of stream flows. Plots of stream flow Q_{t+1} against Q_t derived from equation 6.6 are presented in Figure 6.19. According to Eckhardt (2008) the linear relationship in equation 6.7 would hold under the assumption listed below:-

Assumptions

- The stream flow Q_{t+1} and Q_t derived from equation 6.6 constitute entirely of baseflow;
- There is no groundwater recharged during time step t and $t+1$;
- Contribution to the flow is from a reservoir such as lake or swamp.

$$Q_{t+1} = aQ_t \qquad 6.7$$

where a is the recession constant. A recession constant of $a = 1$ indicates flows from a linear reservoir (Eckhardt, 2008).

Figure 6.19 shows that all the hydrometric station along the Shire river (Mangochi, Liwonde, Chikwawa, and Chilomo) have a high recession constant of 0.99, 0.98, 0.98 and 0.985 respectively. This justifies Eckhardt (2008) assumption that a large portion of the stream flow is from a reservoir, Lake Malawi rather than groundwater. According to Eckhardt (2008) a recession constant of $a = 1$ shows flows in a particular stream are due to flow release from a reservoir rather than groundwater. A recession constant of $a = 0.99$ at Mangochi station shows that flows at this station are a function of storage from Lake Malawi. An increase in recession constant from 0.98 at Chikwawa to 0.985 at Chilomo would be accorded to the storage function of Lower Shire Valley flood plain between the two stations shown in Figure 6.10.

Ruo river has a recession constant of 0.92 which is lower than the other stations. This shows that the flow contribution in the Ruo river during the dry season is from groundwater contribution.

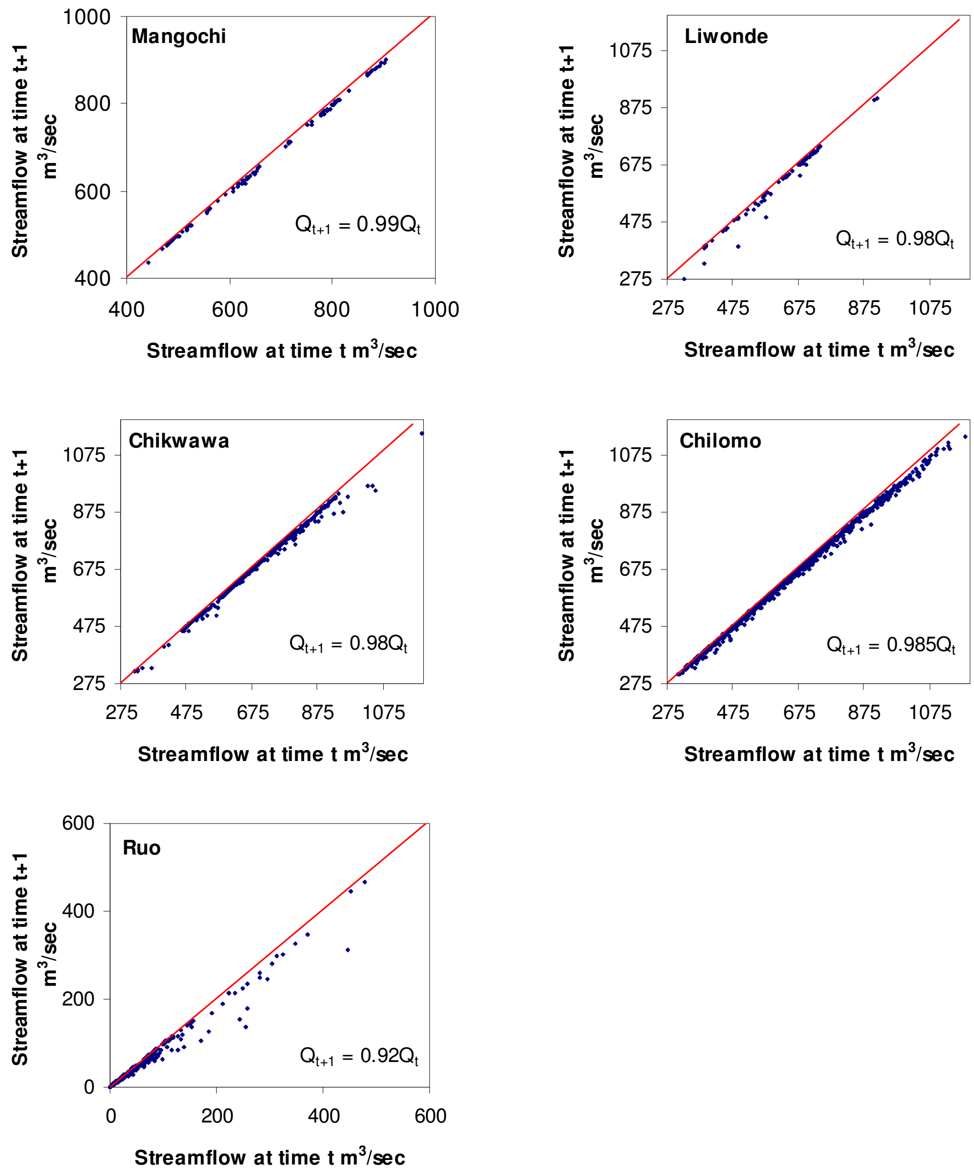


Figure 6.19 Scatter plot for streamflow Q_{t+1} against Q_t during recession period with trend line through the origin

Overall the results of baseflow and recession analysis have shown that all the hydrometric station along the Shire river have a high base flow contribution in the excess of 0.90 of the stream flow. This shows that Lake Malawi contributes over 90 percent of the available water in the Shire river basin.

6.5 IMPACT OF IRRIGATION DEVELOPMENT AND INCREASED WATER DEMAND ON SHIRE FLOWS

The Shire river water budget simulation tool presented in equation 6.4 with schematic diagram in Figure 6.4 was applied to the Chilomo hydrometric station to assess the impact of future irrigation expansion in the lower Shire and increased abstraction for Blantyre City water supply. The current major irrigation development in the basin is the Nchalo irrigation scheme with an irrigation water demand of 18 m^3/sec for 15000 hectares. The government of Malawi has now called for expansion of irrigated land in the lower Shire. An estimated 42000 hectares has been earmarked with an estimated irrigation demand of 55 m^3/sec. Malawi urban population is increasing at a rapid rate of which Blantyre City is which depends on the Shire river is not exceptional. Current Blantyre City water demand is 1.2 m^3/sec from the Shire river.

The water budget simulation tool was used to assess the impact of an increase in demand for water supply and irrigation on the water availability in the lower Shire. Assuming a 100 percent increase in demand for water supply and an irrigation demand of 55 m^3/sec, the results of the water budget simulation are presented in Figure 6.20 and Table 6.6. The results shows that irrigation development with an abstraction daily demand of 55 m^3/sec and increase in urban water supply of 2 m^3/sec has a minor effect on the flows of Shire river. On average a 7 percent reduction in flow would be induced on the Shire flows ranging from 2.9 percent in the month of March during the rainy season to 11.18 percent in the month of October during the dry season. The results in Figure 6.20 show that the impact is high during the dry season and in years of low flow period such as 1982 to 1983, and 1987. The results presented in Figure 6.20 are based on current observed data excluding climate change impact. Climate change impact as modelled from the Water Balance Model of Lake Malawi in Chapter 5 would result in a significant impact on the available water in the Lower Shire Valley. Therefore water resources management of the basin should always start with proper planning and management of the usage of Lake Malawi.

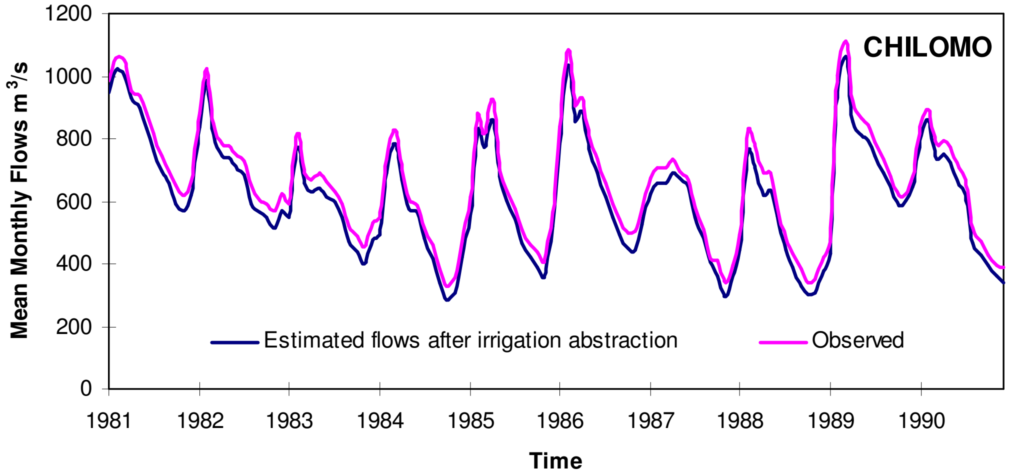


Figure 6.20 Flows at Chilomo hydrometric stations showing the impact of increased abstraction for irrigation and water supply on the upstream reaches of Shire river

Table 6.6 Impact of irrigation and water supply abstraction on Chilomo hydrometric station on Shire river

Month	Observed Flow m^3/sec	Flows after abstraction m^3/sec	Percentage impact on Flows
Jan	695.4	660.2	5.1
Feb	903.0	868.4	3.8
Mar	852.6	827.9	2.9
Apr	811.6	775.5	4.4
May	753.9	709.6	5.9
Jun	704.4	659.4	6.4
Jul	645.2	597.6	7.4
Aug	573.6	524.6	8.5
Sep	516.6	465.3	9.9
Oct	480.1	426.4	11.2
Nov	463.2	411.9	11.1
Dec	531.6	486.4	8.5
Mean	660.9	617.8	7.1

In conclusion the water budget simulation tool of the Shire river has shown to be a successful tool in assessing the impact of water resources development in the

Shire river. The tool has also demonstrated that large scale development of irrigation would have minor effect on the flows of Shire river due to high flows regulated from Lake Malawi.

6.6 SUMMARY AND CONCLUSION

The need to manage the water resources of the Shire river basin in Malawi in a sustainable manner still remains a top priority of the Malawi Government under the proposed National Water Development Programme II. Lake Malawi together with the Shire river system play a major role in the economic sector of Malawi through hydropower generation, irrigation and water supply from Shire river. Despite the many positive benefits the Shire river is well-known for causing floods in the Lower Shire Valley.

In this Chapter the flow events of the Shire river before and after the construction of the Liwonde barrage have been analysed. A simple water budget of the Shire and Ruo rivers has been analysed based on current climate data. Lake outflows into the Shire were based on the main lake outlet hydrometric station of Mangochi. Rainfall and evaporation over the catchment was estimated from climate stations within the Shire catchment. The major drawback and source of uncertainity is that there are only a few climate stations within the Shire river basin. The chapter further looked at the interaction between Lake Malawi and the Shire river through the application of the Linear Perturbation hydrological model. Further analysis involved separation of stream flow into baseflow and quick flow in order to analyse the effect of Lake Malawi on the water resources availability in the Shire river basin. A method proposed by Eckhardt (2005) was incorporated into the LPM to analyse the baseflow for each hydrometric station along the Shire river as well as the Ruo river.

A preliminary analysis of the stream flow hydrographs before and after the construction of the Liwonde barrage has shown that the construction of the barrage has led to an increase in the mean daily flows in the lower Shire by 53 percent through out the year. Analysis of Ruo and Chilomo hydrographs has shown that flow records at Chilomo are influenced by high flows from the Ruo river during the rain season. During the dry season Ruo has no effect on the flows at Chilomo hydrometric station. The four stations (Chilomo, Chikwawa, Liwonde and Mangochi) along the Shire river have hydrograph with similar shape during the dry season indicating their reliability on flow regulation from Lake Malawi during the dry season. The difference during the rainfall season indicates an effect of the rainfall contribution from the catchment between Lake Malawi outlet and the hydrometric station under consideration. A simple water budget of the Shire river has revealed that the Shire river loses more water than it gains from rainfall, hence its continuous reliance from Lake Malawi outflows.

The results of fitting LPM to translate the water balance components into runoff show an overall good agreement between the observed and simulated flows. The Nash-Sutcliffe model efficiency for all the stations is higher than 0.89 justifying reliability of the model in the catchment. Therefore the LPM could be used as a water balance simulation tool for the Shire river. The results from LPM required simulation of baseflow as well as quick runoff to assess how much water Lake Malawi contributes to the Shire river basin. Results of the base flow analysis have revealed that all the hydrometric stations along the Shire river have a BFI greater than 0.90. This shows that Lake Malawi contributes 90 percent of the available water in the Shire river basin. The remaining 10 percent comes from rainfall within Shire catchment area and its tributaries. In view of this sustainable development of water resources in the Shire should not overlook the sustainability of the water levels in Lake Malawi. It is therefore necessary that proposed water resources development under National Water Development II should also look at the Water Balance Model of Lake Malawi which has been developed in Chapter 5 if water resources availability is to be maintained in the Shire river basin to meet current and future demand.

The results of recession analysis of the stream flows confirm the major role Lake Malawi plays in the water resources availability in the Shire river. A recession constant of $a \geq 0.98$ in the equation ($Q_{t+1} = aQ_t$) for all the hydrometric stations along the Shire river indicates that 90 percent of the flows in the Shire river comes from a reservoir, Lake Malawi. Ruo river which is the main tributary has a BFI of 0.46 and recession constant $a = 0.90$. This is due to lack of storage component within the basin.

The results of water budget simulation tool in assessing the impact of increased irrigation and water supply abstraction have shown that an increase in water abstraction for irrigation and water supply would have minor effect on the flows of Shire river due to high flows regulated from Lake Malawi.

Therefore ultimate sustainable water resources development of Malawi will require reducing pressure on the water resources development along the Shire river. This calls for balanced water resources development set up to be spread throughout the country to avoid overdependence on the Shire river as it is the case now. In view of this NWDP II should also look at the possibility of water resources development in the catchment area of Lake Malawi. This will take an advantage of using the water before it flows into the lake. Chapter 7 of this thesis is looking at the development of a sustainability index as a water resources development tool for Lake Malawi catchment. The sustainability index has focused on the main rivers in the northern highlands of Malawi.

CHAPTER 7
A WATER RESOURCES SUSTAINABILITY INDEX FOR CENTRAL AND NORTH MALAWI

After modelling the interaction between the water balance model for Lake Malawi and the water budget model for Shire river, it is now necessary to develop a Water Sustainability Index for Central and North Malawi. The current water resources development of Malawi is concentrated mainly on the Shire river leaving the Central and Northern Malawi rivers undeveloped. Currently the Malawi government is planning to develop some of the rivers in the central and northern part of Malawi under the National Water Development Plan II. It is therefore necessary to develop a Water Sustainability Index as a tool for assessment of multipurpose water resources development comparing one river basin with another in a sustainable manner. This Chapter reports a procedure for the formulation and application of a framework of sustainability indicators, which reflects water resources sustainability at basin scale. The frame work of indicators was applied to eight river basins in the central and northern part of Malawi

7.1 INTRODUCTION

Malawi's water resources development is currently concentrated on the Shire river. The water resources projects along the Shire river heavily depends on run-of-the river water whether the use is for hydropower, irrigation or water supply. Despite the potential economic viability of multipurpose water resources projects, where a dam can be developed for water storage and raw water can be sold in bulk and used in irrigation, water supply, fisheries and electricity generation, Malawi has not exploited the opportunities. Currently the Malawi Government has embarked on a US$260 million National Water Development Project (NWDP II) which is aimed at increasing access to sustainable water supply and sanitation services from 67% to 79% by 2012 with a universal coverage projected to be achieved by 2025 (WorldBank, 2007). The project is being funded partially by the World Bank ($50 million) and other bilateral donors. Exploring the opportunities for multipurpose water project in a sustainable manner under NWDP II would make water relatively more available and less costly to the investor and the local population.

7.2 BACKGROUND TO WATER RESOURCES SUSTAINABILITY INDEX

Despite the potential economic viability of dams for multipurpose water resources projects, the ecological integrity of freshwater ecosystems may be a casualty of increasing water resources development, for example using dams for multipurpose water use transform previously intact rivers into fragmented systems (Anderson *et al.*, 2006b; Gyau-Boakye, 2001). Multipurpose water resources projects have a target to serve various functions within a catchment. The consequences of water resource development are: loss of aquatic species; dislocation of human population; inundation of cultural sites; increasing pollution and contamination of water resources (WCD, 2000). Several issues that impact the sustainability of a river basin have often been treated separately and not considered as an integrated, dynamic process (Dynesius and Nilsson, 1994; Gyau-Boakye, 2001).

Sustainability or sustainable development is the use of resources which aims at improving quality of life while preserving the environment so that future generations can also meet their needs (WCED, 1987). In order to achieve this sustainable development is always aimed at addressing the three major dimensions: social, economic and environment. However the best way to define and measure sustainability is still contested (Ashley *et al.*, 2003; Gibson, 2002;

Gremmen and Jacobs, 1997; Parris and Kates, 2003; WCED, 1987). In most attempts to describe the concept, a combination of development, equity, and environment is used to describe it (Parris and Kates, 2003). Economists often emphasize an accounting approach that focuses on the maintenance of capital stocks. Some in the environmental realm focus on natural resource depletion and whether the current rates of resource use can be sustained into the distant future. In all attempts emphasis differs on what is to be sustained, what is to be developed, how to link environment and development, and for how long a time it takes (Parris and Kates, 2003). As well, there is debate on whether criteria for sustainable development for the developed and developing worlds should differ.

A good example of water-related sustainability index is seen in the Canadian Policy Research Initiative who have developed a Canadian Water Sustainability Index (CWSI) to examine water related issues relevant to Canada with emphasis on rural and remote communities (CWSI, 2007). The CWSI integrates a range of water-related data and information into a series of indicators that together provide a holistic profile of a community's key water issues. The key water issues addressed by the CWSI fall into the following broad policy categories:

- Freshwater Resources,
- Ecosystem Health, Water Infrastructure,
- Human Health and Well-being, and
- Community Capacity.

Sustainability of water resources in a given basin is directly related to its hydrologic, environmental, life, and policy conditions. A few attempts have been made to integrate them in one single comparable number (Chaves and Alipaz, 2007). Water resources sustainability requires meeting our water needs (i.e drinking, irrigation, industrial, recreation and energy) upon which economic development depends, while protecting the environment and improving social conditions. This requires finding acceptable trade-offs between economic, environmental and social goals. During the last decade, there has been an increasingly intensive desire to measure and describe different aspects of sustainable development indicators for water resources (Ioris *et al.*, 2008;

Kondratyev *et al*., 2002; Sullivan and Meigh, 2005). A common limitation in most of the methods is the focus on biophysical aspects of sustainability, often to the exclusion of socio-economic factors that may, in fact, frequently be the driving force behind environmental change (Ioris *et al*., 2008; Kondratyev *et al*., 2002). There is a link between poverty and the environment and where population remains in poverty higher reproductive rates continue to exacerbate pressure on the environment (Sullivan and Meigh, 2003).

This Chapter is aimed at developing a framework of water sustainability indicators at basin scale that could assist in decision making for multipurpose water resources development in low income developing country like Malawi. The objectives are to:

(1) to develop an appropriate framework of indicators;
(2) apply the framework to the Northern and Central catchments of Malawi and
(3) evaluation of the framework based on the available data in Malawi

7.3 CENTRAL AND NORTHERN CATCHMENTS OF MALAWI

This Chapter has focused on the main rivers in the central and northern part of Malawi namely: Bua, Dwangwa, Dwambazi and South Rukuru as shown in Figure 7.1. The topography of these river basins can be divided into four zones: Highland, plateau, rift valley escarpment and rift valley plains (Fry *et al*., 2003). Each of these rivers originates from the western highland areas. The drainage pattern of these rivers is oriented towards the rift valley passing through the rift valley escarpment zone before draining into Lake Malawi on the eastern side, giving the rift valley a high potential for irrigated cropping and integrated farming. There are no major water resources developments in these river basins and no thorough studies have been done to explore the potential of developing these rivers for multipurpose development.

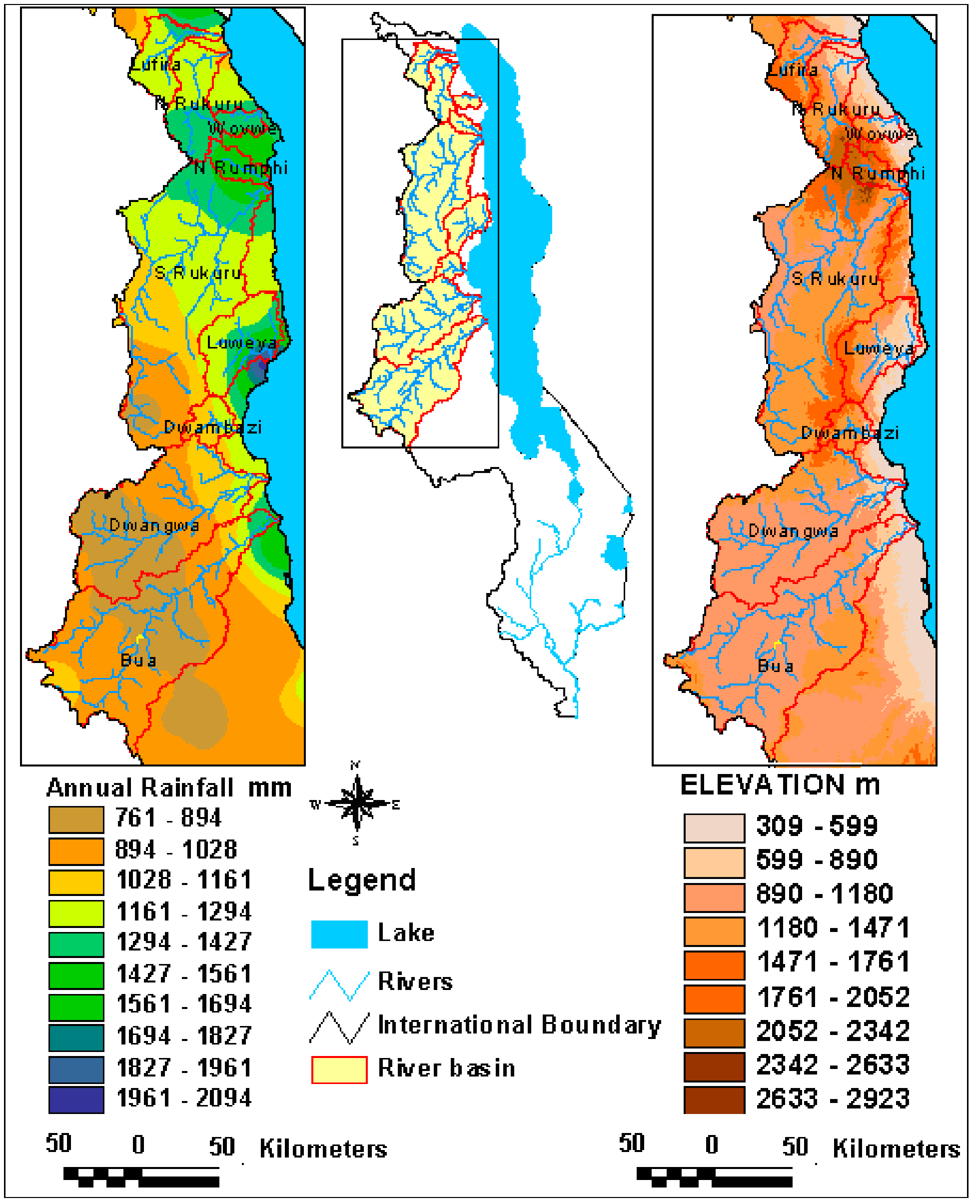


Figure 7.1 Map of Malawi showing the orientation, rainfall and topography of catchment areas used for developing Water Sustainability Index

7.4 PROCEDURE FOR DEVELOPMENT OF WATER SUSTAINABILITY INDEX (WSI)

7.4.1 Water resources available data

Developing a WSI requires a lot of water resources data which is often not readily available in developing countries like Malawi. In general, the reasons for missing data occurrence are related to: records for discrete periods, not covering the entire time period of interest; short intermittent period where data have not been recorded and difficulty in the techniques and methods used in collecting data from the field. A discussion regarding the available data on water resources in Malawi has been presented in Chapter 3. Daily rainfall records were collected from the Malawi Meteorological Department (MD) database. MD is the sole authority for the collection and compilation of climate data in Malawi. Population data was obtained from National Statistical Office in Malawi. Data on licensed water use within each basin, river flow and water quality was collected from the Ministry of Irrigation and Water, Water Resources Board. In Malawi there are very few laboratory facilities for testing water quality. Whatever little testing is done is confined to rivers flowing through the cities of Lilongwe and Blantyre. There is therefore not enough data on water quality for some of the rivers under consideration as indicated in Table 7.1. The proposed frame work of indicators was based on the water resources available data as well as the assumption that water sustainability of a basin is a function of its hydrology, human health and environment. A CD of all the available water-related data for Malawi is available and attached to this thesis.

7.4.2 Iterative procedure for developing WSI

The proposed iterative procedure for developing a meaningful water sustainability index is presented in Figure 7.2. The starting point is to specify the overall purpose. The purpose here is to assess the sustainability of water resource development at river basin scale for the purpose of multipurpose water resources development.

The next step is to define indicators. Assessing the sustainability of water resources requires appropriate frameworks of indicators, which can, provide essential information on the viability of a system and its rate of change, and on how these contribute to the sustainable development of the overall system. According to Gallopín (1997) the major functions of indicators are : to assess conditions and trends; to compare across places and situations; to assess conditions and trends in relation to goals and targets; to provide early warning information; and to anticipate future conditions and trends.

Several authors have formulated criteria or characteristics for desirable sustainability indicators (Bell and Morse, 2003; Braat, 1991; HTCF, 2003; Liverman *et al*., 1998). Variables that could be used as indicators must not only be recognized, but also known for what role they play in the system, how essential they are for the viability of the system, and whether they represent a weak link (Bossel, 1999). In this research indicators for multipurpose water resources development were selected based on water-related data availability in Malawi and published recommendations (Bell and Morse, 2003; Bossel, 1999; HTCF, 2003).

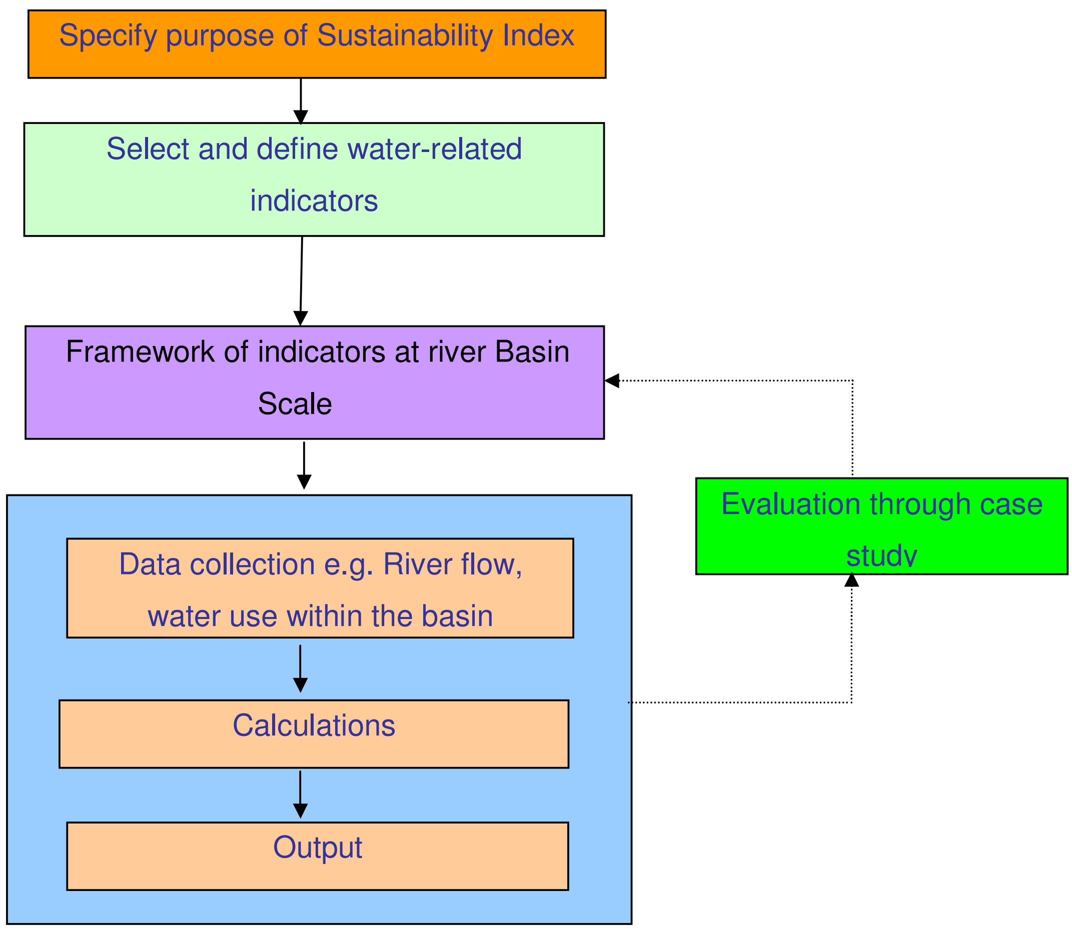


Figure 7.2 Procedure for development of Water Sustainability Index

Once indicators have been defined the next step is to define interactive activities in the multipurpose water project and develop a framework to guide the choice and identification of sustainability index. The final step is to evaluate the framework in order to improve and modify indicators through the use of case studies. In this thesis the particular cases study is the central and northern catchment areas of Malawi shown in Figure 7.1.

7.4.3 Framework of Indicators

The framework of indicators was based on the assumption that water sustainability of a basin is a function of its hydrology, human health and environment. This was aimed at addressing the needs of human beings while maintaining the ecosystem environment in order to sustain the water resources availability (hydrology). Hydrology of a river basin is highly sensitive to variations in weather and climate. The changes in global climate will affect patterns of freshwater availability and will alter the frequencies of floods and droughts (IPCC, 2007; UN, 2009).

7.4.3.1 Hydrology Indicator

In the hydrology indicator there are two sets of parameters: one relative to water quantity and the other one to variation in water supply.

Water Quantity Indicator (WQTI) - This parameter looks at the annual amount of renewable freshwater available per capita per year. Water stress occurs when water availability (WQT) falls below 1,700 m^3/person/year (Falkenmark, 1991). In this research five levels of per capita water availability were selected in multiples of minimum standard of 1,700 m^3/person years specified by Falkenmark 1991: (a)WQT<1,700 m^3/person/year (b) 1,700<WQT<3,400; (c) 3,400<WQT<5,100; (d) 5,100>WQT>6,800, and (e) WQT>6,800 m^3/person/year. Thus according to the defined water resources availability levels, water availability WQT<1,700 m^3/person/year corresponds to a score of 0.00 percent and WQT>6,800 m^3/person/year corresponds to a score of 100 percent. A basin score for water quantity indicator (WQTI) was thus calculated using the following equation:

$$WQTI = \frac{100}{6800 - 1700}(WQT - 1700) \qquad 7.1$$

Variation in supply indicator - Water runoff ratio was used to assess the extent to which surface flows varies for example seasonaly. The ratio was obtained by dividing flows that exceeded 5 percent of time by flows that exceeded 95 percent of the time on the flow duration curve (Q5/Q95) in Figure 3.30 of Chapter 3. Flow duration curves provide the proportion of the time (duration) a specific flow is equalled or exceeded. The ratio (Q5/Q95) also acts as an indication of the catchment vulnerability to drought and floods. Catchment areas in the central and northern Malawi have an exponential decay relationship between Total Renewable Water Resource (TRWR) also known as available water resources and Q5/Q95 as shown in Figure 7.3 (Kumambala and Ervine, 2008). From Figure 7.3 a minimum standard water availability (WQT=1,700 m^3/person/year) corresponds to a ratio (Q5/Q95=23.5) and maximum available water resource (WQT=6,800 m^3/person/year) as stipulated in water quantity indicator corresponds to a ratio (Q5/Q95=13.9). TRWR is strongly related to Q5/Q95, therefore a VSI score of 0.00 percent was allocated to a ratio $Q5/Q95 \geq 23.5$ and 100 percent for a ratio $Q5/Q95 \leq 13.9$. Variation in supply indicator (VSI) was finally calculated using equation 7.2.

$$VSI = \frac{100}{23.5 - 13.9}(23.5 - Q5/Q95) \qquad 7.2$$

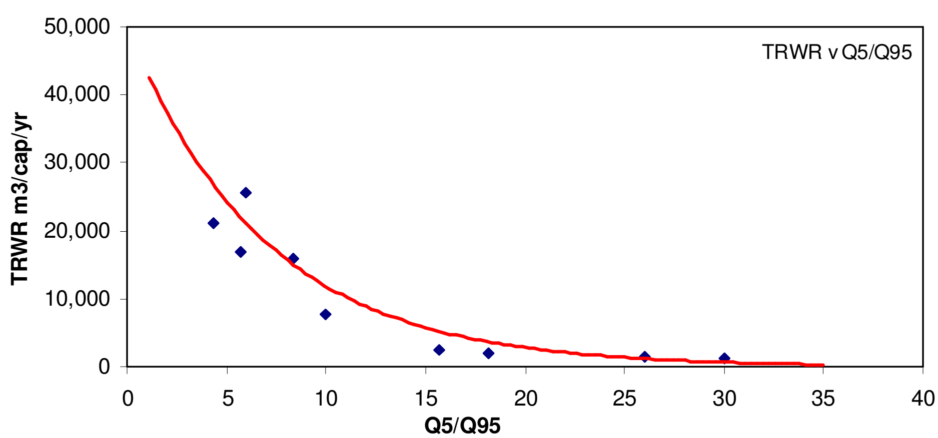


Figure 7.3 Relationship between TRWR and Q5/Q95 for Central and Northern Malawi (Kumambala and Ervine, 2008).

7.4.3.2 Human Health Indicator (HHI)

In the human health indicator there are three sets of parameters: one relative to human basic water requirement; the other one to water quality for human consumption and aquatic life; and health impact associated with insufficient water quantity or quality.

Human basic water requirement (BWR) - This looks at how much potable water is available per person. There are several assessments in the literature regarding adequate amounts of water for daily personal use. According to Shiklomanov (1997), 150 litres/person/day is the highest water requirement for human needs. Thus to evaluate the human health indicator, communities that have access to at least 150 litres/person/day receive a score of 100 and anything below 50 litres/person/day receives a score of 0.

$$BWR_A = 100 - \left(\frac{150 - AV}{150 - 50}\right) * 100 \qquad 7.3$$

where AV is water available per person in litres/person/day.

In the case of Malawi, information regarding water available per person was not available for the rural communities. Instead access to safe drinking water was used as a measure of BWR in the form of **access index** which is the percentage of population that has access to safe drinking water. Should AV data be available in the future then BWR should be assessed using equation 7.3.

Water Quality Indicator (WQ_LI) - This is an assessment of surface water quality based on the scope, frequency, and amplitude of water quality observations relative to the guidelines for protecting aquatic life and human beings. Proposed World Health Organisation (WHO) and particular country standards were considered as benchmarks. Calculation of the Water Quality Index for Malawi was based on three terms: scope (F1) – number of parameters that are not compliant with the water quality guidelines, frequency (F2) – number of times that the guidelines are not respected and amplitude (F3) – the difference between non-compliant measurements and the corresponding guidelines. The overall WQI will be given by the following equation:

$$WQ_L I = 100 - \left(\sqrt{\frac{F_1^2 + F_2^2 + F_3^2}{3}} \right) \quad 7.4$$

The higher the index value, the better the water quality.

Health Impact Indicator (HII) - The purpose of this indicator is to assess the health impact associated with insufficient water quality or quantity as well as water related diseases such as Malaria. Recently there has been an increase in the cases of cholera, bilharzia, dysentery, typhoid fever and other water-borne diseases in Malawi. In order to evaluate the HII the number of reported cases of waterborne diseases and illness was used. A score of 100 corresponds to 0 incidents and a score of 0 corresponds to 1 or more incidents occurring for every 1000 persons per year. HII was evaluated by the following equation:

$$HII = (1 - W) * 100 \quad 7.5$$

where W is the number of reported water borne disease and illness cases per 1000 people per year.

7.4.3.3 Environmental Pressure Index (EPI)

Environmental Pressure Index (EPI) is a measure of the average variation in agricultural area, population growth and ecosystem stress within the basin. Population growth is one of the crucial elements affecting long-term sustainability of water resources. The proportion of agricultural area and population within a basin is known to be correlated with the basin water quality (Hunsaker, 1995). An ecosystem can be stressed from pollution as well as excessive water use.

Natural Vegetation Area Indicator (NVAI) - The indicator looks at the percentage of basin area with natural vegetation. According to Chaves and Alipaz (2007), a 40 percent of basin area under natural vegetation indicates little pressure on the environment and catchment areas with only less than 5 percent of the natural vegetation indicates high pressure on the environment. The lower limit parameter outlined by Chaves and Alipaz (2007) is used as a benchmark for evaluating the environmental effect of basin area under natural vegetation on the catchment where a score of 0 is assigned to any value equal to or less than 5 percent basin area under natural vegetation and a score value of 100 is assigned to any value equal to or greater than 60 percent basin area under natural vegetation. Indicator score for basin area under natural vegetation, NV is thus calculated using the following equation:

$$NVAI = \left(\frac{100}{60-5}\right)(NVA-5) \tag{7.6}$$

where NVA is percentage of area under natural vegetation

Agricultural Area Indicator (AAI) - The indicator looks at the area being used for cultivation within the basin. AAI for Malawi is not strongly correlated to basin area under natural vegetation due to different land use system as described in section 3.2 such as tree plantation, protected reserves and idle land. According to (Sawyer, 1997), a 5 percentage agricultural land has no significant environmental pressure on the catchment. The parameter outlined by Sawyer (1997), was used as a benchmark for evaluating the environmental effect of agricultural land on the catchment where a score of 100 is assigned to any value equal to or less than 5 percent agricultural land and a score value of 0 is assigned to any value equal to or greater than 50 percent agricultural land. Indicator score for basin area under agriculture, AAI is thus calculated using the following:

$$AAI = 100 - \left(\frac{100}{50-5}\right)(PAA-5) \tag{7.7}$$

where PAA is percentage of area under agriculture.

Population Growth Rate Indicator (*PGRI*) - It is difficult to set a maximum acceptable level of population growth rate since ecosystem human carrying capacity is not known. Currently Malawi's population growth rate is 2.39 percent as shown in Figure 7.4 (NSOM, 2008). For the purpose of this research a score of 100 is assigned to a population growth rate of less or equal to 0 percent and a score value of 0 is assigned to any value equal to or greater than 2. A basin score for population growth rate indicator is thus calculated using the following:

$$PGRI = 100 - 50GR \qquad 7.8$$

where GR is population growth rate.

Figure 7.4 Malawi population growth rate (%) (NSOM, 2008)

Ecosystem Stress Indicator (ECS) - The Ecosystem stress indicator is intended to reflect the pressures imposed on the ecosystem as a result of excessive water use. Adopted from the CWSI, to score this indicator, the annual amount of water consumed is assessed relative to the total annual renewable surface flows. According to (OECD, 2004) 60 per cent of renewable water flows is required to maintain a healthy, functioning ecosystem and thus, in scoring this ecosystem stress indicator (ECS), a rate of consumption greater or equal to 40 percent is assigned a score 0.

$$ECS = \left(\frac{0.4 - {}^{c}/_{Tsur}}{0.4} \right) 100 \qquad 7.9$$

where c the annual amount of water consumed (m^3.year) and $Tsur$ is the total annual renewable surface flow (m^3/year).

The overall Environmental pressure index was evaluated based on percentage of basin area under natural vegetation, basin area under agriculture and population growth rate. Inorder to avoid bias EPI was considered as an average of the four parameters.

$$EPI = \frac{AAI + PGR + NVAI + ECS}{4} \qquad 7.10$$

7.5 EVALUATION OF WATER SUSTAINABILITY INDICATORS

7.5.1 Applying the framework of Indicators

To test the applicability and usefulness of the Water Sustainability Index for North and Central Malawi, the indicator framework (Equation 7.1 to 7.10) was applied to river basins of Central and northern Malawi. Catchment choice was based on the knowledge and experience of the author with remit to investigate the least developed river basins in Malawi to avoid overdependence on Shire river for most water resources development in the country. Each indicator of the WSI is presented in Table 7.1 and Figure 7.5.

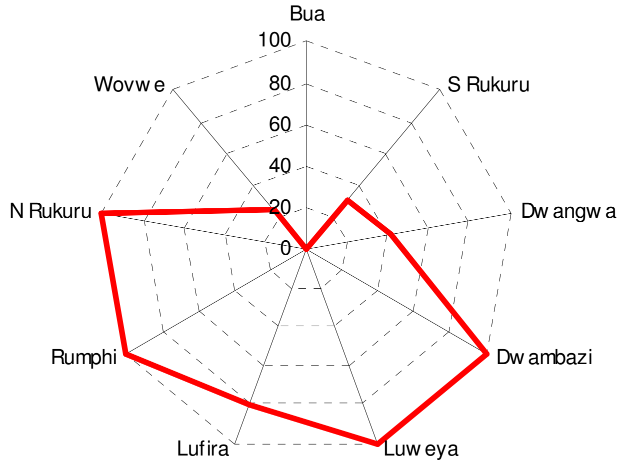
The hydrology indicator was calculated as an average score of the water quantity indicator and variation in supply indicator. Total renewable water resource per capita was simply the mean annual cumulative flow divided by the basin population. The variation in supply indicator VSI was obtained as a ratio of the flows that exceeded 5 percent of time to flows that exceeded 95 percent of the time on the flow duration curve (Q5/Q95).

Similarly to the hydrology indicator, the human health indicator was computed as the average of its human basic water requirement, water quality index and health impact. Water quality data was not available for Luweya, Lufira and Wovwe rivers. River basins which have no complete data set of water quality have high WSI value because HHI was not taken into consideration when calculating WSI in these river basins. All catchment areas for which data are

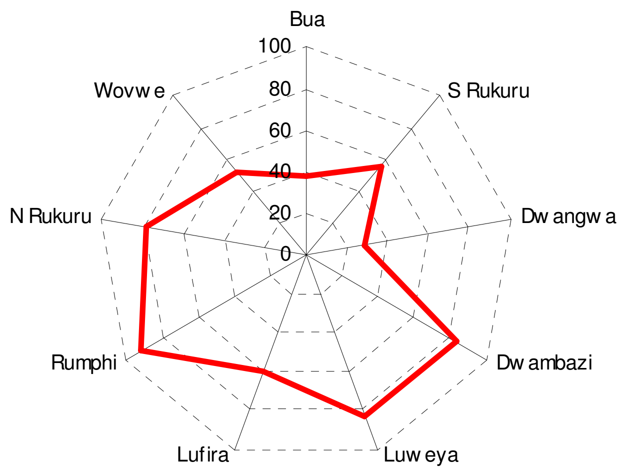
Table 7.1 Summary of indicators at basin scale

	River	Bua	S Rukuru	Dwangwa	Dwambazi	Luweya	Lufira	Rumphi	N Rukuru	Wovwe
	Area (Km^2)	10654	12088	7610	778	2381	1410	683	2128	489
Hydrology indicator **HYI** Water Quantity Indicator **WQTI** Variation in supply Indicator **VSI**	Daily flow m^3/s	34.266	42.739	19.88	15.297	36.485	6.908	15.6	15.6	1.834
	Population	922,828	693,449	428,267	5,566	72,159	46,671	25,672	64,723	15,090
	TRWR m^3/cap/yr	1,171	1,944	1,466	86,727	15,967	4,668	19,941	7,610	3,837
	WQTI	0.00	5.76	0.00	100.00	100.00	58.20	100.00	100.00	48.90
	Q5 m^3/s	150.00	145.00	94.00	42.50	100.00	24.00	40.00	50.00	6.50
	Q95 m^3/s	5.00	8.00	6.00	7.50	12.00	5.50	7.00	5.00	0.25
	Q5/Q95	30.00	18.13	15.67	5.67	8.33	4.36	5.71	10.00	26.00
	VSI	0.00	56.00	82.00	100.00	100.00	100.00	100.00	100.00	0.00
	HYI	**0.00**	**30.88**	**41.00**	**100.00**	**100.00**	**79.10**	**100.00**	**100.00**	**24.45**
Environmental Pressure Index **EPI** Agricultural Area Indicator **AAI**, Ecosystem stress **ECS**, Natural Vegetation Indicator **NVAI**, Population Growth Rate **PGRI**	Natural Veg. Km^2	3193	6315	4226	711	2073	1176	591	1908	351
	Cultivated Area Km^2	7130	5432	3477	99	284	320	94	217	95
	Population growth rate	2.75	2.38	3.27	1.76	1.66	2.91	0.47	2.63	2.13
	m^3/day WS	130,174	83,706	58,117	755	9,058	6,212	3,099	8,614	2,008
	m^3/day IRR	92,811	32,313	622,006	23	92,309	97,773	0	1	67,886
	AAI	0.00	11.24	11.59	84.06	84.57	63.74	80.55	88.41	67.94
	NVI	45.39	85.89	89.88	100.00	100.00	100.00	100.00	100.00	100.00
	PGRI	19.66	30.47	4.47	48.58	51.50	14.98	86.27	23.16	37.77
	ECS	87	95	5	100	92	58	100	99	0
	EPI	**38.01**	**55.65**	**27.74**	**83.16**	**82.02**	**59.18**	**91.71**	**77.64**	**51.43**
Human Health Indicator Water Quality Indicator **WQL**, Health Impact **HII** Basic Water Requirement **BWR$_A$**	WB icidents/1000	35	37	38	42	27	43	16	42	23
	HII	0	0	0	0	0	0	0	0	0
	Access to safe water %	28	49.25	35.6	40	37	33	64.5	NO DATA	NO DATA
	Access Index	72	50.75	64.4	60	63	67	35.5	NA	NA
	BOD mg/l	NO DATA	2.64	NO DATA	2.94	NO DATA	NO DATA	NO DATA	1.60	NO DATA
	Nitrate mg/l	1.06	0.21	1.86	3.65	NO DATA	NO DATA	1.20	0.10	NO DATA
	Suspended solids mg/l	62.50	167.00	51.25	23.00	NO DATA	NO DATA	157.50	290.00	NO DATA
	WQ	56.09	3.61	75.49	96.44	NO DATA	NO DATA	20.60	0.00	NO DATA
	HHI	**42.70**	**18.12**	**46.63**	**52.15**	**NO DATA**	**NO DATA**	**18.70**	**NO DATA**	**NO DATA**
Water Sustainability Index WSI		**26.90**	**34.88**	**38.46**	**78.44**	**91.01**	**69.14**	**70.14**	**88.82**	**37.94**

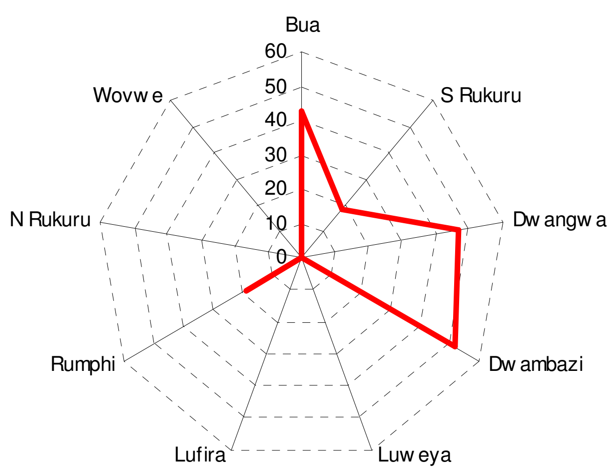
WS Water Supply
IRR Irrigation



(a) Hydrology indicator



(b) Environmental Pressure Indicator



(b) Human Health Indicator

Figure 7.5 Indicator scores for (a) Hydrology Indicator (b) Environmental Indicator and (c) Human Health Indicator (0 Score = not sustainable and 100 score = sustainable)

available the WSI is far less than the average of HYI and EPI in Table 7.1 indicating a low score contribution from the Human Health Indicator which is mainly affected by water qaulity. It is therefore necessary for the Malawi Government to implement water quality data monitoring in these basin in order to update the WSI.

Environmental pressure index was evaluated based on percentage of basin area under natural vegetation, basin area under agriculture, population growth rate and ecosystem stress. Finally the Water Sustainability Index in Table 7.1 was calculated as an average of the three main indicators: hydrology indicator (HYI), Environmental Pressure Indicator (EPI) and Human Health Indicator (HII).

$$WSI = \frac{HYI + EPI + HII}{3} \qquad 7.11$$

7.6 DISCUSSION OF INDICATOR RESULTS

This section presents an analysis of the results for each indicator. This was deemed the most useful format as any revision and improvement in the water sustainability index will be required at indicator level to accommodate changes in the data requirement and scoring benchmarks. This will also help water users and the Malawi government to address the most important issues in each basin which may improve the sustainability of the water resources.

7.6.1 Results of the Hydrology Indicator

As discussed earlier on in section 7.4.3 the hydrology indicator is made up of two main components: Water Quantity Index and Variation in Supply Index. The annual available water resource for each basin was used for scoring the water quantity index based on Falkenmark (1997) water stress index of 1,700m^3/person/year as benchmark (Section 7.4.3). Water resources availability was based on entire stream outflows and the population within the basin. The results of water quantity availability suggest that Bua and Dwangwa river basin in the central region and South Rukuru in the northern region are water stressed areas with WQTI score of 0.00, 0.00 and 5.76 respectively and their respective

TRWR are 1,117, 1,466 and 1,944, 1,700m^3/person/year (Table 7.1). This could be attributed to the large population in the basin which is involved in agricultural activities. Dwambazi, Luweya, Rumphi and North Rukuru rivers have a 100 percent score in terms of water quantity availability and there respective TRWR are 86,727, 15,967, 19,941, 7,610 m^3/person/year (Table 7.1). This could be attributed to the small population in the basin as well as low seasonal variation of the flows of these rivers. Variation in stream flow was based on stream flow from the basin outlet. Variation in supply was intended to reflect the vulnerability of water resources of a river basin to both seasonal and climate variation being experienced in Malawi. Results suggest that rivers in the central region of Malawi, Bua and Dwangwa are more vulnerable to flow variation than rivers in the north of Malawi Dwambazi, Luweya, Lufira and Rumphi(Table 7.1). Rivers with high seasonal variation in flows have a low score in terms of the hydrology indicator. An overall comparison of hydrology indicator for all the river basins is shown in Figure 7.5.

Despite the information on water resources availability and distribution being accurate the major concern with the hydrology indicator is lack of information on groundwater sustainable yields as the majority of the population in rural areas depends on boreholes for drinking water supply. It is therefore vital for the Malawi Government to introduce groundwater monitoring in the hydrology section of the Ministry Irrigation and Water Development to accommodate the information in the water sustainability index.

7.6.2 Results of Environmental Pressure Indicator

The environmental pressure index has four main components which look at the sustainability of the natural environment in order to sustain water resources availability. The results of this study have revealed that catchment areas of Bua, Dwangwa and South Rukuru are more vulnerable to agricultural activities due to the low score in the agricultural area index. The agricultural area index (AAI) score for Bua, Dwangwa and South Rukuru are 0.00, 11.21, and 11.59 respectively (Table 7.1). In terms of natural vegetation, Bua has the lowest NVI score of 45.39 while Dwangwa and South Rukuru have 85.89 and 89.88

respectively and the rest of the rivers have a 100 percent score (Table 7.1). The low AAI score in these river basins also shows that these river basins are more vulnerable to agricultural chemicals as well as suspended loads due to erosion. This will have a far-reaching consequence on the water quality of the basin due to leakage of agricultural chemicals into groundwater storage. Population growth rate in the river basins under consideration is less than the Malawi national average of 2.3 percent because the northern part of Malawi is the least populated area. Urbanisation is also a contributing factor to low population growth rate, as people tend to move from the north going to the south of Malawi. The indicator for population growth for all the river basin is very poor with Dwangwa having the least score of 4.47 and Rumphi river as the only highest scorer with a score of 86.27. Large population growth rates being experienced in the river basin will exert more pressure on the available resources in each of the river in terms of available water, agricultural land and natural vegetation. Water withdraws for water supply and agricultural activities will have to increase to meet growing population thereby increasing pressure on the ecosystem. This calls for more improved agricultural technologies to support growing population without increase in agricultural area and avoiding wasteful use of the scarce resource. This should be extended to river basins such as Dwambazi, Lufira, North Rukuru and Wovwe which have high scores in NVI and AAI in order to sustain the water resources. More effort is required by the Malawi government on civic education to maintain the population growth rate at a constant or low level.

The overall EPI scores in Figure 7.5 show that river basins with a high score in terms of NVI (Dwambazi, Luweya, Rumphi and North Rukuru) have a high EPI score. This calls for forestation programme in most of the river basins in order to sustain the water resources of Malawi

7.6.3 Results of Human Health Indicator

The human health indicator is made up of 3 main components; water quality, health impact and human basic water requirement. The major challenge in formulating this indicator was availability of water quality data. Currently there is no thorough water quality data monitoring in Malawi. All the river basins have a score of 0.00 for the occurrence of water borne incidences while access to safe drinking water is below 50% for all the river basins. The low index score in terms of human health impact as shown in Table 7.1 and Figure 7.5 is due to high dependence on unsafe drinking water such as open wells.

Finally an overall index for each basin was calculated based on the results of the three indices which have been discussed in this section. The results of the overall index have been analysed in section 7.7

7.7 NORTH AND CENTRAL MALAWI WATER SUSTAINABILITY INDEX

The overall water sustainability index is simply the average of the three indicators: Hydrology; Human Health; and Environmental Pressure. The poorest indicator combination was that of Bua river with a WSI of 26.90 (Table 7.1 and Figure 7.5). The major pressures on this basin are; agricultural activities and high variation in supply of the renewable water resource. Therefore development of water resources in such a basin should aim at reducing pressure on the resources within the basin.

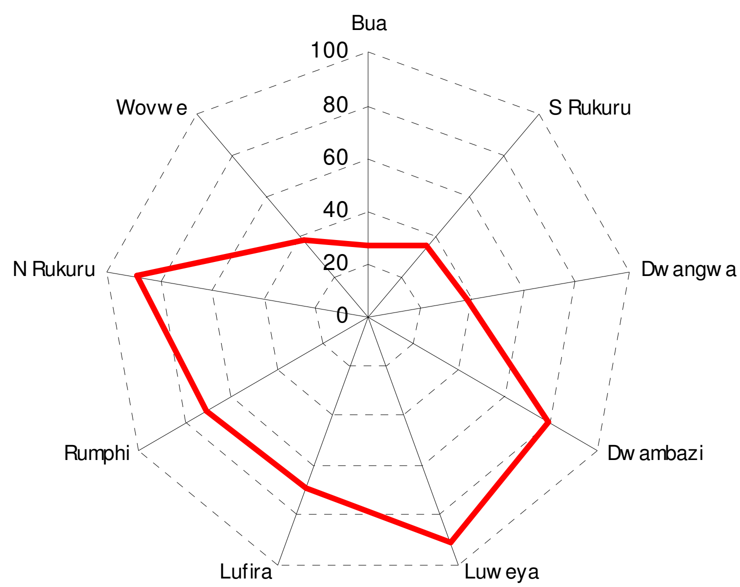


Figure 7.6 Water Sustainability Index scores for North and Central Malawi 0 Score = not sustainable and 100 score = sustainable)

There is large variation in the index score because of the missing water quality data in some of the river basins and low water quality indicator in some river such as South Rukuru. The low water quality indicator is due to high pressure on the environment as depicted by the EPI in Table 7.1. In view of this there is need to have a programme in place for data monitoring and collection which would help in future decision making in the water industry. Further to that, water resources development would require to address all the interactive activities within the basin.

7.8 TESTING OF INDICATORS BASED ON PROJECTED FUTURE CLIMATE

Projected future climate presented in Chapter 4 was used to test the sensitivity of indicators to climate change impact. Projected river flows, population and vegetation cover for the year 2025 were used as inputs in the sustainability index to assess the impact of climate change on indicators. Human health indicator was left out in the future scenario testing because of lack of information on projected water quality.

The country's deforestation rate of 0.84 percent per annum (GoM, 2005) was used to estimate the natural vegetation cover for Central and North Malawi. The results of future scenario have been presented in Figure 7.7 and Table 7.2. The results of hydrology indicator show an increase in water stress in Bua, South Rukuru and Dwangwa river basin with a WQTI score of 0.00. The corresponding TRWR for these rivers is 758, 1,315 and 841 which is below the standard minimum requirement of 1,700 m^3/person/year. Dwambazi, Luweya, Rumphi and North Rukuru rivers have maintained high scores of 100, 100, 100 and 73.85 respectively. Results from Table 7.2 show that population increase and variation in river flows has a significant effect on the hydrology indicator.

Results of projected climate change impact on the Environmental Indicator show an increase in pressure on Bua, South Rukuru, Lufira and Dwangwa river (Figure 7.7). For example, the EPI score for Bua has dropped from 38.01 to 35.56 (Table 7.2). There is no significant effect on rivers with a high EPI score (Dwambazi, Luweya, Rumphi and North Rukuru) (Figure 7.7)

Results of future scenario testing of indicators have shown that the hydrology indicator has significant impact on the sustainability of the water resources of Malawi. It is therefore necessary for the Malawi Government to look at environmental parameters, which affects the hydrological processes of the catchment such as vegetation cover and agricultural activities in order to sustain the water resources of the country. The results have also shown that Bua, Dwangwa and South Rukuru rivers needs agent attention in addressing water indicators if sustainability of these basins is to be maintained. The results have also shown that there is a need for a programme to preserve the ecosystem of river basins with high scores in WSI such as Dwambazi, Luweya and Lufira in order to avoid excessive pressure on the basins as is the case with basins with low scores such as Bua, Dwangwa and South Rukuru.

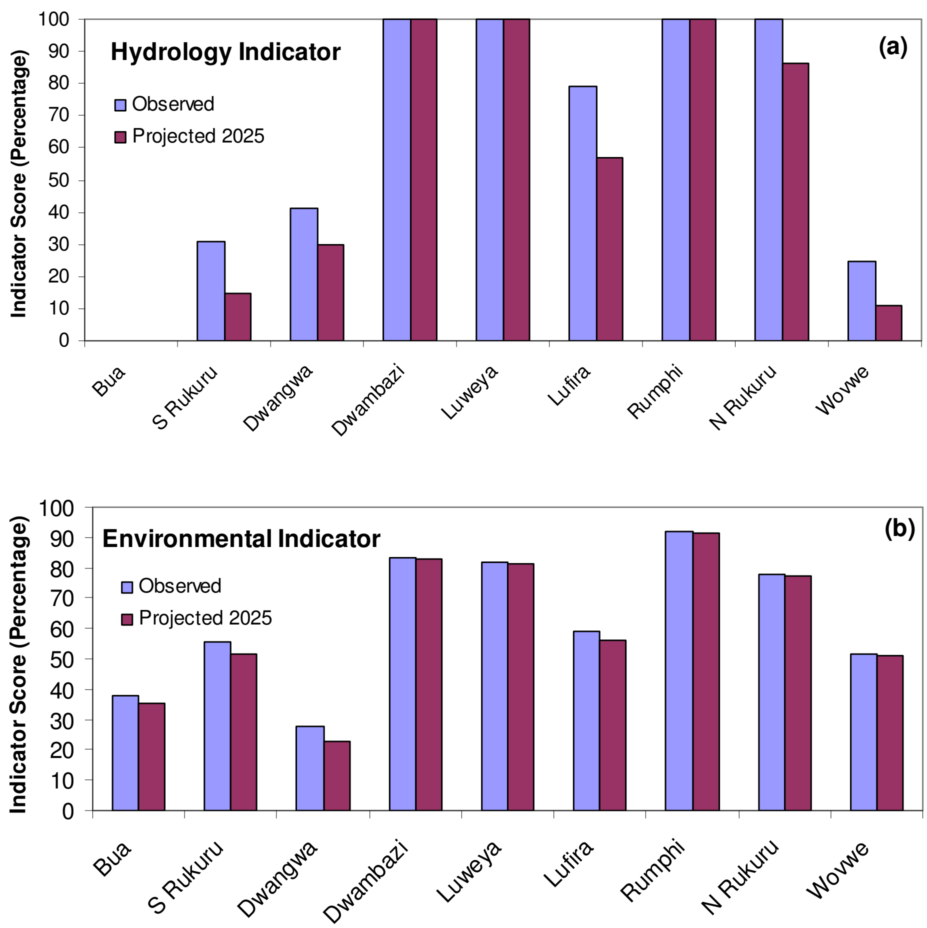


Figure 7.7 Climate change impact on hydrology and environmental indicator for the year 2025

Table 7.2 Summary of indicators at basin scale for the year 2025 based on projected climate change

	River	Bua	S Rukuru	Dwangwa	Dwambazi	Luweya	Lufira	Rumphi	Nrukuru	Wovwe
	Area (Km^2)	10654	12088	7610	778	2381	1410	683	2128	489
Hydrology indicator **HYI** Water Quantity Indicator **WQTI** Variation in supply Indicator **VSI**	Daily flow m^3/s	33.4	41.2	18.6	17.24	38.5	4.98	17	16.6	1.834
	Population	1394014	990963	699417	7248	92561	72213	27547	96026	20770
	TRWR m^3/cap/yr	758	1,315	841	75,220	13,153	2,181	19,515	5,467	2,792
	WQTI	0.00	0.00	0.00	100.00	100.00	13.76	100.00	73.85	21.42
	Q5 m^3/s	165	149	107	43	97	26	45	56	7.3
	Q95 m^3/s	4.3	7.2	4.8	6.3	9	4.7	6.4	4	0.15
	Q5/Q95	38.37	20.69	22.29	6.83	10.78	5.53	7.03	14.00	48.67
	VSI	0.00	29.22	12.59	100.00	100.00	100.00	100.00	98.96	0.00
	HYI	**0.00**	**14.61**	**6.29**	**100.00**	**100.00**	**56.88**	**100.00**	**86.41**	**10.71**
Environmental Pressure Index **EPI** Agricultural Area Indicator **AAI,** Ecosystem stress **ECS,** Natural Vegetation Indicator **NVAI,** Population Growth Rate **PGRI**	Natural Veg. Km^2	2805	5548	3713	625	1821	1033	519	1676	308
	Cultivated Area Km^2	7344	5595	3581	102	293	330	97	224	98
	Population growth rate	2.75	2.38	3.27	1.76	1.66	2.91	0.47	2.63	2.13
	m^3/day WS	130,174	83,706	58,117	755	9,058	6,212	3,099	8,614	2,008
	m^3/day IRR	92,811	32,313	622,006	23	92,309	97,773	0	1	67,886
	AAI	0.00	8.26	6.53	81.99	83.81	59.16	79.61	87.77	66.64
	NVI	38.78	74.35	79.61	100.00	100.00	100.00	100.00	100.00	100.00
	PGRI	19.66	30.47	4.47	48.58	51.5	14.98	86.27	23.16	37.77
	ECS	83	92	0	100	90	51	100	98	0
	EPI	**35.36**	**51.27**	**22.65**	**82.64**	**81.33**	**56.29**	**91.47**	**77.23**	**51.10**

7.9 WATER RESOURCES SUSTAINABILITY INDEX AS A POLICAY TOOL UNDER NWDP II

This section presents the potential application of the WSI as a policy tool for water resources development under NWDP II. Increasing the provision of freshwater to rural population is being considered in the light of the National Water Development Plan II of Malawi. NWDP is aimed at promoting a holistic approach to water resources development that attempts to be socially fair, economically feasible and environmentally sustainable. The WSI presented in this Chapter will play a major role in the development of water resources. The results of the water resources sustainability index could be used to inform planning decision and activities specifically those related to water resources development such as exploring water resources availability to meet various demand in the basin. Indicators of water quantity and variation in supply could also help inform decision making in water storage such as dams to meet water requirements during the low flow period. Such development could easily be developed for multipurpose use such as irrigation and hydropower thereby increasing the scoring of the other indices. For instance hydropower would serve the energy sector reducing the dependence on fossil fuels such as charcoal. This would end up affecting the natural vegetation indicator score of the WSI.

Indicators of environmental pressure could help identify the major elements which have an impact on the catchment ecosystem. This could inform land use planning, particularly agricultural activities on ways of reducing the pressure on the environment in order to sustain the ecosystem. The human health indicator could influence the monitoring of water quality standards to meet World Health Drinking Water standards. Where the water quality is very poor alternative development option would have to be specified based on index score. Finally the WSI could be used to compare river basins on how vulnerable they are in order to sustain water supply as well as the environment based on the growing population and water demand.

Sustainable management and development of the water resources of the Central and North Malawi will have a positive impact on the countries economy since the country's economy is an agro based economy. The country also relies much on water for hydropower development which is stored in Lake Malawi. Sustainable water resources development of the river basins in the catchment areas of Lake Malawi like the ones in the Central and Northern region will lead to sustainable levels of water in Lake Malawi. Thereby leading to a sustainable energy supply as well as irrigation in the Lower Shire Valley.

7.10 SUMMARY AND CONCLUSION

In this chapter we have demonstrated that through the integration of knowledge from hydrology, human health and environment, Water Sustainability Index (WSI) for policy and decision making can be developed. The WSI can advance the assessment of development of multipurpose water projects by utilising a multidisciplinary and integrated process. Integrated process of sustainability indicators can influence project development by helping to identify viable design alternatives that are environmentally and socially acceptable, and provide opportunities to meet varying demands within the basin.

Case study of the central and northern highland river basins in Malawi helped to reveal the information gaps and problems concerning availability and quality of information for development of WSI. Applied to the central and northern highland river basin, Bua river basin has the lowest index score. Aspects needing attention in most of the river basin are those related to Human Health, agricultural area and natural vegetation area. Increasing the forest cover and reducing agricultural area would automatically improve the environmental indicator, variation in supply index and human health indicator.

Water resources development under the proposed National Water Development Plan II (NWDP II) using a set of criteria and indicators based on the concept of water sustainability index can improve feedback information available to water resources policy makers and managers in the Ministry of Irrigation and Water Development, Malawi and the public at large. In particular it can help overcome the limitation in existing water resources development and management assessment tools that report in favour of some aspects of water resources availability in a particular river basin and less favourably on other aspects. The WSI and indicators outlined in this Chapter can also be used for evaluating policies, investment decision and management practices for the successful implementation of the NWDP.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

The purpose of this thesis was to assess the sustainability of water resources of Malawi in particular the central and northern part of Malawi as well as Lake Malawi-Shire river system. This final Chapter presents a review of the work presented in this thesis together with recommendations regarding water resources investment strategy for Malawi. The work presented in this thesis has been split into five sections:

- Hydrologic data collection and analysis,
- Modelling climate change impact on water resources of Malawi
- Water balance model of Lake Malawi
- Interaction of Lake Malawi and Shire river system
- Water resources sustainability index for Central and North Malawi

8.2 HYDROLOGIC DATA COLLECTION AND ANALYSIS

8.2.1 Summary of work

Water is the natural resource on which human life, energy, food security and the health of the ecosystem depends. The term water resource as used in this thesis refers to the portion of the hydrological cycle that provides overall support to economic, social and environmental needs. Malawi is well endowed with freshwater resources and ecosystems in the forms of Lakes, rivers and marsh.

The uses of water in Malawi as a whole are irrigation, water supply and sanitation, hydropower generation, recreation, tourism and wildlife conservation.

Proper planning and management of water resources to sustain all economic, social and environmental needs require water resources data. It has been observed that there is no information on groundwater resources in Malawi. However little information is available on surface water resources and rainfall. The major problem observed on the available data is scarcity of water resources data, gaps in the few available data and closure of some of the hydrologic stations. This requires estimating missing data to fill the gaps in the data set. A number of methods of estimating missing climate data (rainfall and temperature) were reviewed and the Inverse Distance Weighted method was selected as the preferred method for Malawi. In the case of river flow records previous method of estimating river flow data in Malawi were reviewed. In this thesis the use of rainfall runoff method was proposed as a preferred option for Malawi. That being the case the system regression rainfall runoff model of Linear Perturbation was used to estimate missing river flow data.

A complete data set on water resources of the Central and North Malawi formed the basis for modelling climate change impact on water resources in Central and North Malawi. Appended to this thesis is a CD of the available water resources data.

8.2.2 Conclusion

Water resources planning and management in Malawi is hindered by lack of adequate and reliable hydrologic, meteorological and water quality data as well as shortage of adequately trained human resources at all levels. Lack of information on social-economic characteristic and water use efficiency together with high population growth rate pose unique problem and challenge to water resources planning and management in Malawi. This is compounded by the seasonal variation in the rainfall and river flow together with global climate change. It has been noted that the renewable water resources of Central and North Malawi are highly variable with one high flow season between January and May.

8.2.3 Recommendations

Monitoring and sustainable management of water resources requires an abundance of hydrologic data. It is therefore necessary that the Malawi government should improve and spread out infrastructures and skills for recording hydrologic data. Hydrologic data would help in planning and decision making regarding the water resources infrastructure needs for the country.

In recent years the use of remotely sensed data and satellite imagery has also evolved as an option of recording water related spatial data. It is therefore necessary for the Malawi Government to work in close collaboration with organisations which can help with skills and infrastructure for recording hydrologic data using satellites. This could help in estimating rainfall, temperature and evaporation for remote areas which are not covered by gauging stations.

8.3 MODELLING CLIMATE CHANGE IMPACT ON WATER RESOURCES

8.3.1 Summary of work

The importance of water resources in Malawi justifies the need to understand how the global climate change could affect the availability and reliability of supply of the renewable water resources. Climate change impact studies are complicated by the fact that GCM outputs are too coarse in space to be useful in predicting the effect of climate change on water resources at catchment scale. This problem is resolved by employing downscaling techniques even though the downscaling procedure produces also some sort of uncertainty. The problem of downscaling was exacerbated by the lack of data in the study area. There are only six climate stations in Central and North Malawi with good quality data for a significantly long period. Despite this problem maximum effort was made to assess the impact of climate change on the water resources of Central and North Malawi. The process involved the use of Statistical Downscaling Method to relate HadCM3 GCM outputs to local climate data for the six main climate stations together with the areal rainfall for the river basins in Central and North Malawi The following conclusions and recommendations are drawn from the investigation.

8.3.2 Conclusions

The results of downscaling maximum and minimum temperature show an increase in temperature in the 21st Century for both A2 and B2 scenarios. The results show that annual average minimum temperature will increase by 2.3^0C and 1.9^0C for A2 and B2 scenarios respectively. The expected change in mean annual maximum temperature of the same period is 2.8^0C and 1.6^0C for A2 and B2 respectively. According to IPCC 2001, climate scenarios for Africa based on results from several GCMs indicate that future temperature increase across Africa in the 21st century will range from 2^0C (based on low emission scenario) to 5^0C (based on high emission scenario). Similar studies by Mkanda (1999) in the lower Shire Valley in Malawi showed a temperature increase of 2.7^0C by 2050. The increase in temperature will have negative effects on the water resources, health and Malawi's terrestrial ecosystem.

The results of downscaled rainfall reveal that rainfall does not indicate a systematic increase or decrease in the 21st Century. However during the rainy season the mean monthly rainfall indicates a decreasing trend in the beginning of rainy season in January and February and an increase towards the end of rainy season in March, April and May for both A2 and B2 emission scenarios in all the river basins. The dry months of October and November are expected to a have an increase in rainfall. The results have shown that extreme weather events due to rainfall are expected to be more frequent in the 21st Century with floods and droughts occurring within months of each other.

The results of rainfall-runoff model Linear Perturbation in simulating future runoff using downscaled data indicate that there will be high seasonal and monthly variation in streamflow. In the rainy season the river flows have shown a decreasing trend during the months of January, February and March and an increasing trend during the months of March, April and October. The months of

July up August, which is the dry season, indicates a decreasing trend in river flows.

In summary future scenarios of rainfall, river flows and temperature have shown that Malawi is highly vulnerable to the impacts of climate change. Malawi's climate is most variable on seasonal time scale and is predicated to become more variable by the end of the 21st century.

8.3.3 Recommendations

The difference in the projected mean temperature and rainfall by the two emission scenarios A2 and B2 indicates the limitation of GCM outputs for climate change impact studies on water resources. There are different GCM data from different experiments available on IPCC DDC data base and the HadCAM3 GCM emission scenarios used in this study should serve as an example for investigating the impact of climate change on water resources. According to (IPCC, 2001) inter-model consistency in regional precipitation and temperature change are high over South East Africa, including Malawi. There is no clear direction and magnitude in the change of temperature and rainfall within the South East African region with each GCM model giving its own results and direction. The results presented here should therefore not serve as the actual predicted future climate parameters but more as an illustration of the sensitivity of Malawi's water resources to one possible future climate change pattern under HadCM3 A2 and B2 emission scenarios. The other scenarios and GCM will also result in a different climate trend.

The investigation in this thesis is based on HadCM3 GCMs and two emission scenarios. It is therefore necessary that future work on climate change impact should be based on different set of emission scenarios as well as different set of GCM other than HadCM3. Possibility of using a different downscaling technique other than the statistical downscaling method would be another option. Although there are different techniques for downscaling GCM outputs into daily meteorological variables, it is not yet clear which method provides the most reliable estimates for future climatic conditions since different GCMs for climate models give different results. However the results by any method can provide a better range of uncertainty for climatic and statistical indices.

IPCC emission scenarios currently in use for climate change studies have been a subject to discussion about whether emissions growth since 2000 makes these scenarios obsolete. Efforts are underway by IPCC to review emission scenarios. The current set of GCMs will be standardized against observed data for the period 1971 - 2000, that is changing the current IPCC base period of 1961 -1990 on which this investigation has been based, to 1971 – 2000. It would therefore be necessary to review this work based on reviewed emission scenarios once they have been released by IPCC.

Future water resources investments of Malawi should always take into consideration climate change impact, since the prospect of global climate change has shown that it has serious implications for Malawi's water resources. Water stress will become acute in future as a result of a combination of climate change impacts together with increase in human population. This will result in conflicts between humans and the environment for water demand. This risk could be minimized by a more diversified economy and efficient agricultural technologies by optimising water usage through efficient irrigation and crop management. Future hydro development should aim at reducing the burden of biomass fuel use in order to sustain the country's forest reserves. Research efforts should also be intensified in crop production to explore the potential of drought resistant crops in order to adapt to climate change.

The generated future climate scenario for Central and North Malawi formed the basis for modeling climate change impact on the water balance of Lake Malawi.

8.4 WATER BALANCE MODEL OF LAKE MALAWI

8.4.1 Summary of work

Lake Malawi and the Shire river system plays a major role in the Malawi economic sector through hydropower generation, irrigation, water supply and lake transport. Lake Malawi is not only recognised for the above functions but also for tourism, fishing and its richness in valuable natural resources. It is for the unique enormous benefits of the lake that sustainable management of its unique eco-system should be a priority for the Malawi government and all the countries which share the water boundary of the lake.

Previous studies on the water balance of Lake Malawi have been reviewed. The major components of the Water balance model of Lake Malawi are: evaporation and rainfall over the lake, runoff inflow from land catchment and outflows from Lake Malawi at Mangochi station. Lack of data for estimating evaporation by standard Penman method led to the investigation on other method of estimating evaporation. Water balance modelling of Lake Malawi involved compilation of the necessary data, calibration and verification of the model based on recorded data. Future scenario of water levels in the lake were developed using downscaled hydrological data based on HadCM3 A2 and B2 greenhouse gas emission scenarios.

8.4.2 Conclusion

The results of modelling the outlet flows of Lake Malawi by a Linear Reservoir Equation show that the lake level-outlet relationship can easily be fitted by such an equation of the form $Q_{out} = a(L_{eff})^b$. The linear equation performed well in the calibration period of 1971 to 2000 with a Nash-Sutcliffe model efficiency R^2 = 0.86 and R^2 = 0.96 in the verification period of 2001 to 2006.

Simulation of the Water Balance Model in ‘up dating mode’ has shown to work well with Lake Malawi. A model efficiency of R^2 = 0.98 based on Nash-Sutcliffe criteria was recorded under updating mode. However models run in ‘up dating’ mode lacks the capability of issuing a long term focus as required in the case of Lake Malawi. An error term was incorporated in the model and the model was run in ‘simulation mode’. The model performed well with a Nash-Sutcliffe model efficiency R^2 = 0.89 both in the calibration and verification period.

The results of sensitivity analysis of the WBM of Lake Malawi to climate change have shown that water levels will continue to drop following a decrease in the rainfall and an increase in evaporation rates from the lake. The results further shows that it is very unlikely for the water level to increase to a maximum height of 477 m amsl as was the case in 1980. Similar analysis by Neuland (1984) based on probability analysis showed that there is little risk of the future lake level exceeding 477.8 m and Neuland's future assessment of lake levels showed a tendency to fall approaching gradually an equilibrium of 475 m amsl.

8.4.3 Recommendations

The water resources projects along the Shire river depends on Lake Malawi water storage. Without the barrage at Liwonde to regulate flows from the lake into the Shire river, the probability of failure to maintain design flows of 170 m^3/sec for hydropower generation would be high. This could result in serious economic and social disruption. Therefore control of Lake Malawi outflows through the use of water control structures along the Shire river is essential. The new proposed Liwonde barrage under National Water Development Programme II should therefore aim at increasing and maintaining high water levels in Lake Malawi in order to sustain the economic activities along the Shire river. Operation of water control structures requires operating rules and policies, of which the Water Balance model developed in this thesis can fit for that purpose.

The water balance model of Lake Malawi developed in this thesis has shown to be a reliable hydrological tool for water resources management and decision making for Lake Malawi-Shire river system especially in application such as Liwonde barrage flow regulation, issuing flood and low lake level warning. This could help all the interested parties in the system in taking necessary steps in the operation of the water resources project within the system in a sustainable manner.

The water balance model has also shown that Malawi's future hydropower development should be concentrated on rivers within the catchment area of the lake. Regulated flows from dams within the lake catchment area will have a significant effect on Lake Malawi outflows. Bua, South Rukuru and Dwambazi are some of the river basins with that potential within the lake catchment area.

For the ultimate performance of the Water Balance Model it is recommended that the model should be updated on regular basis based on the current observed data due to uncertainties in GCM emission scenarios in predicting future climate (IPCC, 2001).

Future scenario of Lake Malawi water levels were based on HadCM3 A2 and B2 emission scenarios. As stated in section 8.3.3 regarding the uncertainty with GCM in simulating future climate as well as the numerous GCMs and different techniques for downscaling GCMs to catchment scale, it would be necessary to investigate future trend of water levels based on other emission scenarios and downscaling techniques. The GCM used in the study should serve as an example of one possible future climate pattern of the lake.

8.5 INTERACTION OF LAKE MALAWI AND THE SHIRE RIVER SYSTEM

8.5.1 Summary of work

This part of the study was aimed at investigating the role of Lake Malawi on water resources availability and sustainability of the Shire river. This involved analyzing the flows of Shire river before and after the construction of the Liwonde barrage. This was followed by a water budget simulation tool together with baseflow separation in order to account for actual contribution of Lake Malawi on the water availability in the Shire river.

8.5.2 Conclusion

The results of flow analysis of the Shire river have shown that the construction of the Liwonde barrage to regulate flows from Lake Malawi down to the Lower Shire Valley has led to an increase in the mean flow by 53 percent. Water balance simulation of the Shire river has shown that it can easily be simulated by a modified Linear Perturbation Model with multiple inputs ranging from regulated flows at Liwonde barrage and water abstraction at different sections of the Shire river. The model can serve as a tool for water resources allocation in the basin.

Baseflow and recession analysis of Shire river flows has revealed that all the gauging stations along the Shire river have a BFI greater than 0.90 and average recession constant of 0.90. This shows that 90 percent of the flow contribution in the Shire river originates from Lake Malawi. In view of the above water balance monitoring of Lake Malawi water levels has a major role in the sustainable economic planning and management of the water resources development along the Shire river.

8.5.3 Recommendations

The section has stressed the importance of Lake Malawi on the water resources availability along the Shire river. Any future development along the Shire river or catchment area of Lake Malawi should be assessed under an integrated approach of the Water Balance Model of Lake Malawi and Water budget of Shire river. The Shire river highly depends on Lake Malawi, therefore proper management of Lake Malawi catchment together with the Shire river should be a top priority for the Malawi government in order to sustain the overall country's water resources.

The water budget simulation tool used in the study has been based on Linear Perturbation Model which is a lumped systems model due to sparse data. It would be beneficial for future studies to be based on remote sensed data and satellite imagery which has emerged in recent years as a tool for water resources monitoring and management.

8.6 WATER RESOURCES SUSTAINABILITY INDEX

8.6.1 Summary of work

The current water resources developments of Malawi are currently concentrated on the Shire river leaving Central and Northern Malawi rivers undeveloped. As noted in Chapter 6 the water resources along the Shire river heavily depends on the water levels of Lake Malawi. The current plans of the Malawi Government are to develop some of the river basin in the Central and Northern parts of Malawi which forms the catchment area of Lake Malawi. This section of the thesis was aimed at developing a Water Sustainability Index as a tool for assessment of water resources development comparing one river basin with another in a sustainable manner.

The procedure of developing water resources sustainability index started with the collection and compilation of water resources data. A set of water related indicators were defined based on the available data and published recommendations. Indicators were used to formulate a framework of indicators which was evaluated through the use of water resources data in Central and North Malawi and projected water resources data based on climate change.

8.6.2 Conclusions

Water is essential for all living things and sustaining life on earth. Its availability varies from one region to another as well as on seasonal basis. Increase in water demand due to the increase in population is resulting in pressure on the limited available water resources. In many areas water resources development to has resulted in alterations of river flows to the benefit of humans and less water for supporting the functioning of aquatic and terrestrial ecosystems. Alterations of river flows have had long-run consequences that are unintended, unanticipated, and undesirable most of the time. In view of this, development of water resources using a set of criteria and indicators based on the concept of water resources sustainability index would help to minimise such cases.

The results of water sustainability index and future scenario testing have revealed that Bua and South Rukuru rivers have low score index despite having a good topography for hydropower development. Therefore multipurpose water resources development in these river basins will require addressing the indicators which are contributing to low index score if the Malawi government is to go ahead with the project. The case study of Central and North Malawi which forms part of the catchment area of Lake Malawi has revealed that water resources sustainability index can help to integrate issues that have an impact on the availability of water resources such as social, economic, and environment. The results of the water sustainability index have shown that aspects that need attention in all the river basins of Central and North Malawi are those related to human health, agricultural area and natural forest cover.

8.6.3 Recommendations

The water resources sustainability index developed in this thesis can be used as a water resources assessment tool in comparing one basin with another and identifying water resources indicators which needs attention by the water policy makers, managers and the public. The criteria and weak indicators identified by the water resources sustainability index can be used to formulate water resources evaluation policies, investments decision together with management policies for river basins in Malawi.

The water resources sustainability index developed in this thesis was based on water resources available data in Central and North Malawi. Limited water resources data was a major setback in formulation of the index. Therefore it would be necessary if the Malawi government could improve in water resources data monitoring. The index should be reviewed regularly based on the current available data to monitor changes in the water related indicators. This will help to identify water related indicators, which needs attention to improve the quality and availability of water in the region.

8.7 STATEMENT TOWARDS THE NATIONAL WATER RESOURCES DEVELOPMENT PLAN II

The Government of Malawi through the Ministry of Irrigation and Water Development has recently embarked on the National Water Resources Development Plan II which is aimed at improving water supply and sanitation for both urban and rural sector in Malawi. The programme is being funded partially by the World Bank (US$50 million) and other bilateral donors. Under the National Water Development Programme, the Malawi government is planning to develop water resources investment strategy for Malawi. The water resources investment strategy is aimed at identifying water resources development and infrastructure needs for Malawi based on multi-sector analysis. The overall objective of the water resources investment strategy is to identify and prioritise investments in the water resources sector with a focus on national development goals of economic growth and poverty reduction. The strategy also aims at identifying the challenges in the Malawi's water resources development and management and select interventions to selected priority areas.

The work presented in this thesis could serve as possible tool in the water resources strategy for Malawi. The thesis has started with data collection and analysis which is an important step towards water resources investment strategy. The available data helped to identify the distribution and availability as well as seasonal variability of the water resources in Malawi especially in Central and Northern part. The results of water resources availability based on streamflow and population distribution within each basin in Central and North Malawi show that Bua, Dwangwa and South Rukuru river basins are water stressed areas with low water per capita of 1,171 m^3, 1,944 m^3 and 1,466 m^3 per person per year respectively. Dwambazi, Luweya Rumphi and North Rukuru have been identified as rivers with high water per capita of 86,727 m^3, 15,967 m^3, 19,941 m^3 and 7,610 m^3 respectively. Using the water sustainability index it has been identified that population growth exacerbated by agricultural activities has increased stress on the available water resources in Central and North Malawi. The worst affected basins are Dwangwa, Bua and South Rukuru river basins.

The other factor identified as a major threat to the water resources of Malawi is climate change. Climate change impact modelling of Central and North Malawi has shown that Malawi's water resources are more variable on seasonal time scale. The results further shows that the water resources will be more variable in the near future with droughts and floods occurring within months of each other. Future scenario testing of the sustainability index has revealed that Bua, Dwangwa and South Rukuru as water stresses areas by the year 2025 while Dwambazi, Luweya and Rumphi rivers have maintained there high scores. Water balance model of Lake Malawi compounded with climate change has shown a decreasing trend in water levels of Lake Malawi. The inter annual and seasonal variability of lake levels due to climate change is more likely to affect hydropower production, water supply and irrigation along the Shire river. Therefore the findings of this research could help identify future infrastructure needs for water resources development. Based on the findings of this research the following water investments options can be identified:

- Catchment management to improve groundwater storage in order to sustain flows from Central and North Malawi into Lake Malawi. This is a long term program which should be aimed at reversing the rate of deforestation due to agricultural activities and use of biomass for energy by a more coordinated forestation programme.
- Multipurpose water resources development in Central and Northern Malawi river basins with an aim to improve water supply would be a more viable option in reducing the flow variability as well as boosting energy production for rural use. The energy provided to the rural mass would result in reduction in the use of biomass which has contributed significantly in catchment degradation. Bua, Dwangwa and South Rukuru rivers have been identified as rivers which needs urgent attention in terms of intervention of catchment areas in order to sustain future flows. These rivers have been identified as potential sites for multipurpose water resources development together with Dwambazi river. Development of these rivers would have significant impact on the water resources availability in Lake Malawi together with the Shire river system. Hydro development from Bua, South Rukuru and Dwambazi rivers should be considered by the Malawi government as an option under rural electrification programme as off grid or on-grid developments.
- The water balance model developed in this thesis together with the water budget tool for Shire river system should serve as a tool for monitoring water resources availability and variability in Lake Malawi-Shire river system. This could help water resources managers and policy makers in identifying priorities in water resources interventions and related investments options in order to sustain Lake Malawi Shire river system water resources availability.
- Proposed 40,000 hectares of irrigation development along the Shire river

has no significant impact on the water resources availability in the Shire river due to high flows regulated from Lake Malawi at Liwonde barrage. Irrigation development will have a significant impact on the country's economy as well as reducing pressure on farming activities on the catchment area of Lake Malawi.

- Increased abstraction from Shire river for water supply to the City of Blantyre has no significant impact on the water flows of Shire river. However due to risk of low water levels of Lake Malawi due to the impact of Climate change, proposed option of supplying the City of Blantyre from Mulanje Massif would be a more promising option. In recent years, the Malawi Government has been investigating on alternative water supply for the City of Blantyre and Mulanje Massif has been pin pointed as a preferred option. Due to the elevation difference between Blantyre City (1,100 m above mean sea level) and Mulanje Massif (3,000 m above mean sea level), the project could be developed as a multipurpose project with hydropower development benefiting from the elevation difference. It would therefore be necessary under NWDP II to explore the potential of this project.

It is therefore the interest of this thesis to make a major contribution especially in the development and sustainability of Malawi's water resources (UN, 2009). The work presented in this thesis provides information on the major issues that affects water resources sustainability of Malawi. In addition to that, it provides tools for monitoring water resources sustainability for Central and North Malawi.

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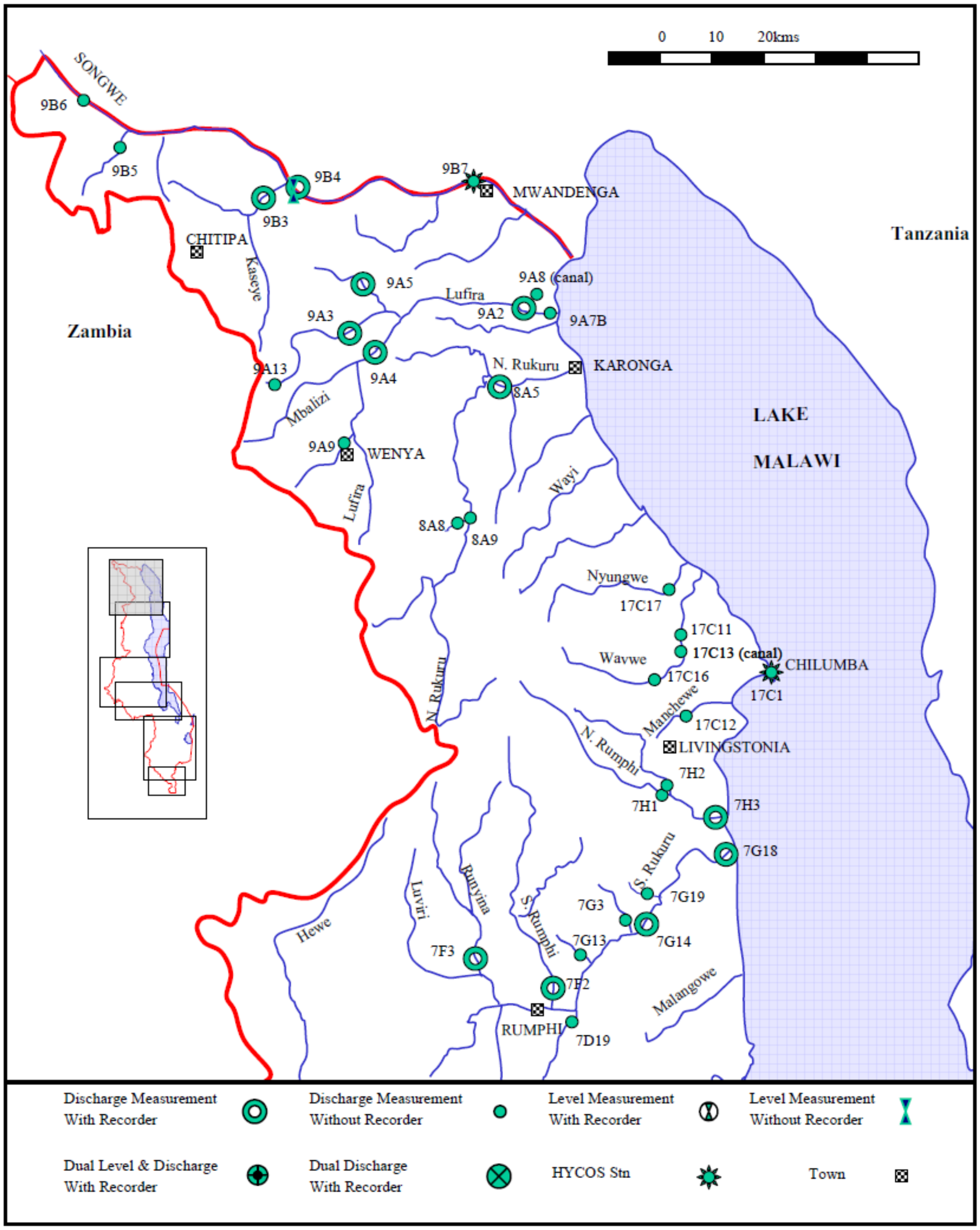
APPENDIX A

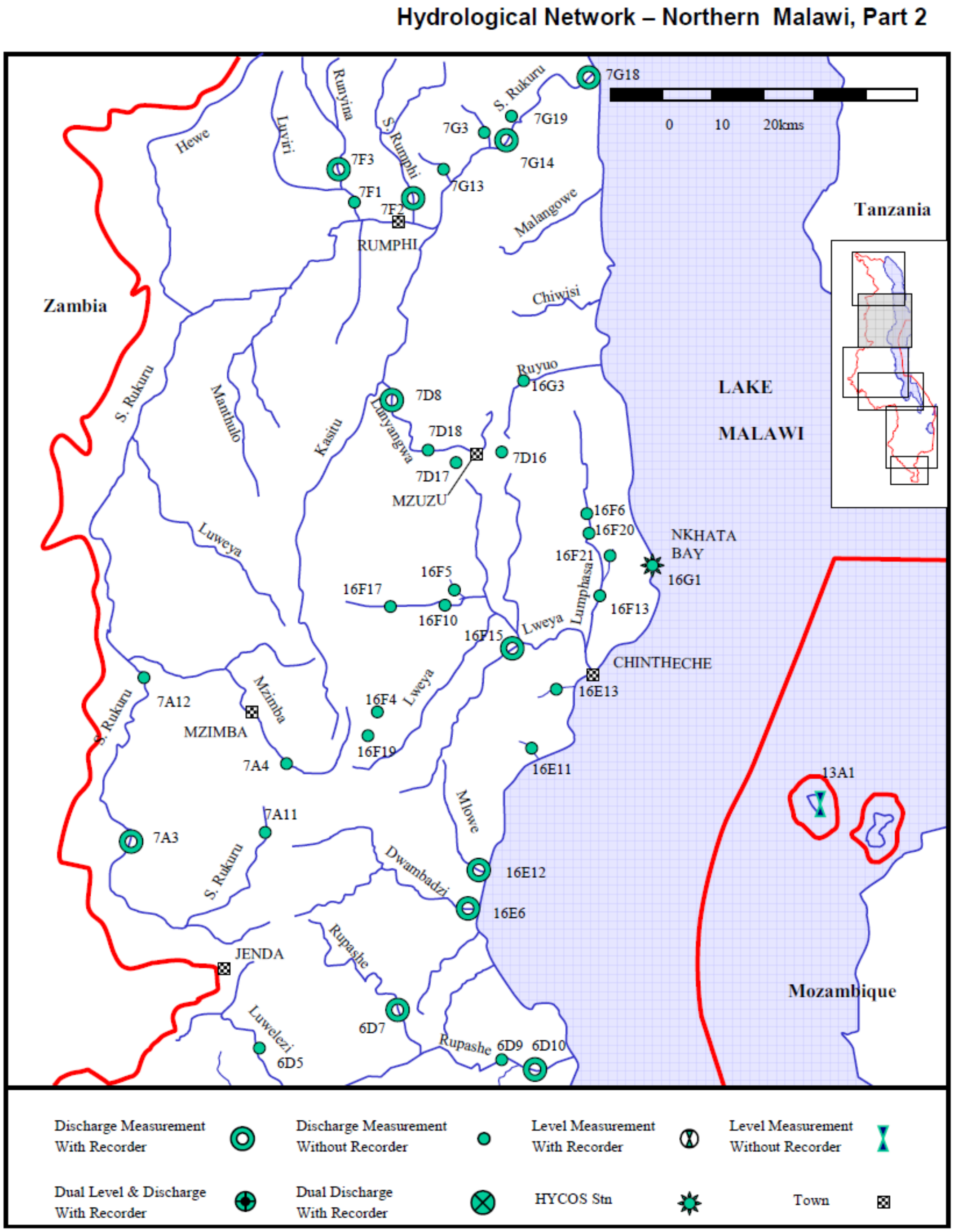
Malawi's Hydrological Network

Hydrological Network – Northern Malawi, Part 1



Source: Ministry of Irrigation and Water Development, Malawi

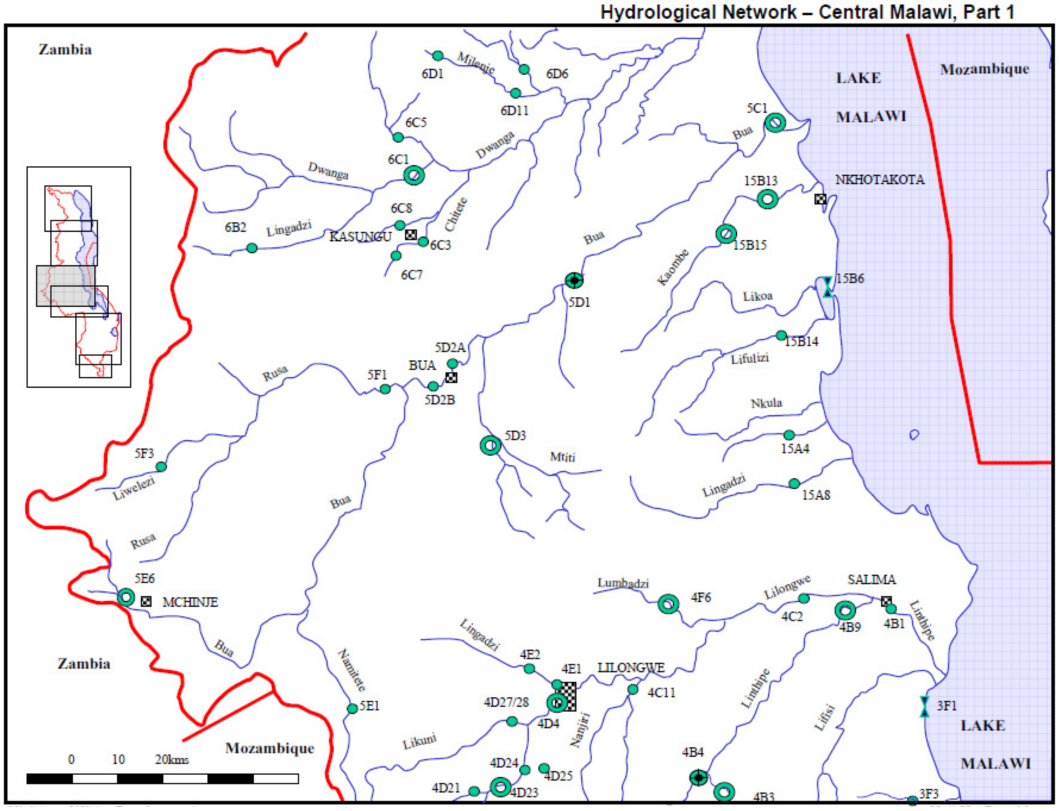
Malawi's Hydrological Network



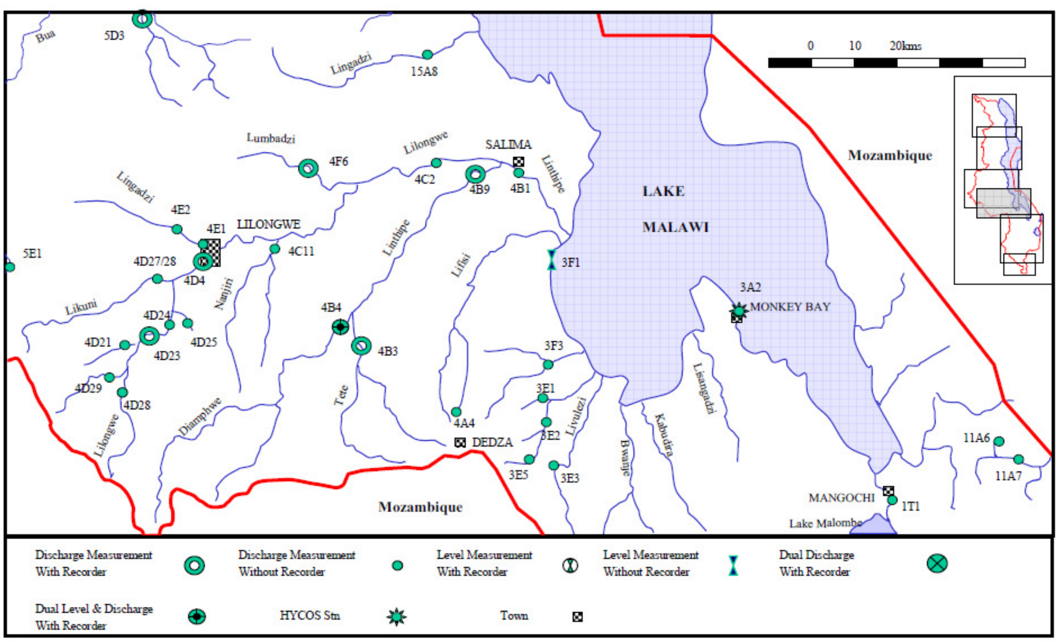
Source: Ministry of Irrigation and Water Development, Malawi

Malawi's Hydrological Network

Hydrological Network – Central Malawi, Part 1

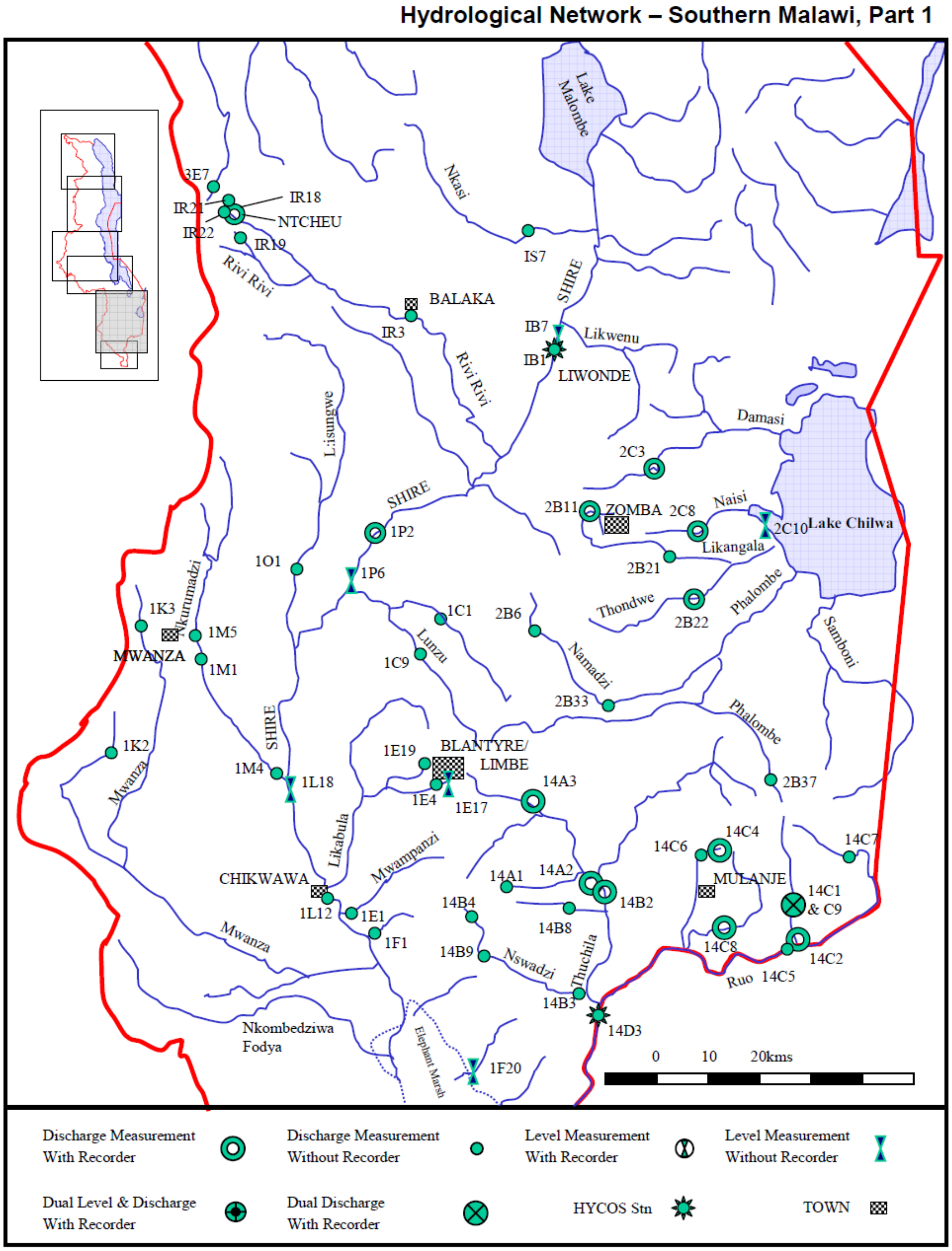


Hydrological Network – Central Malawi, Part 2



Source: Ministry of Irrigation and Water Development, Malawi

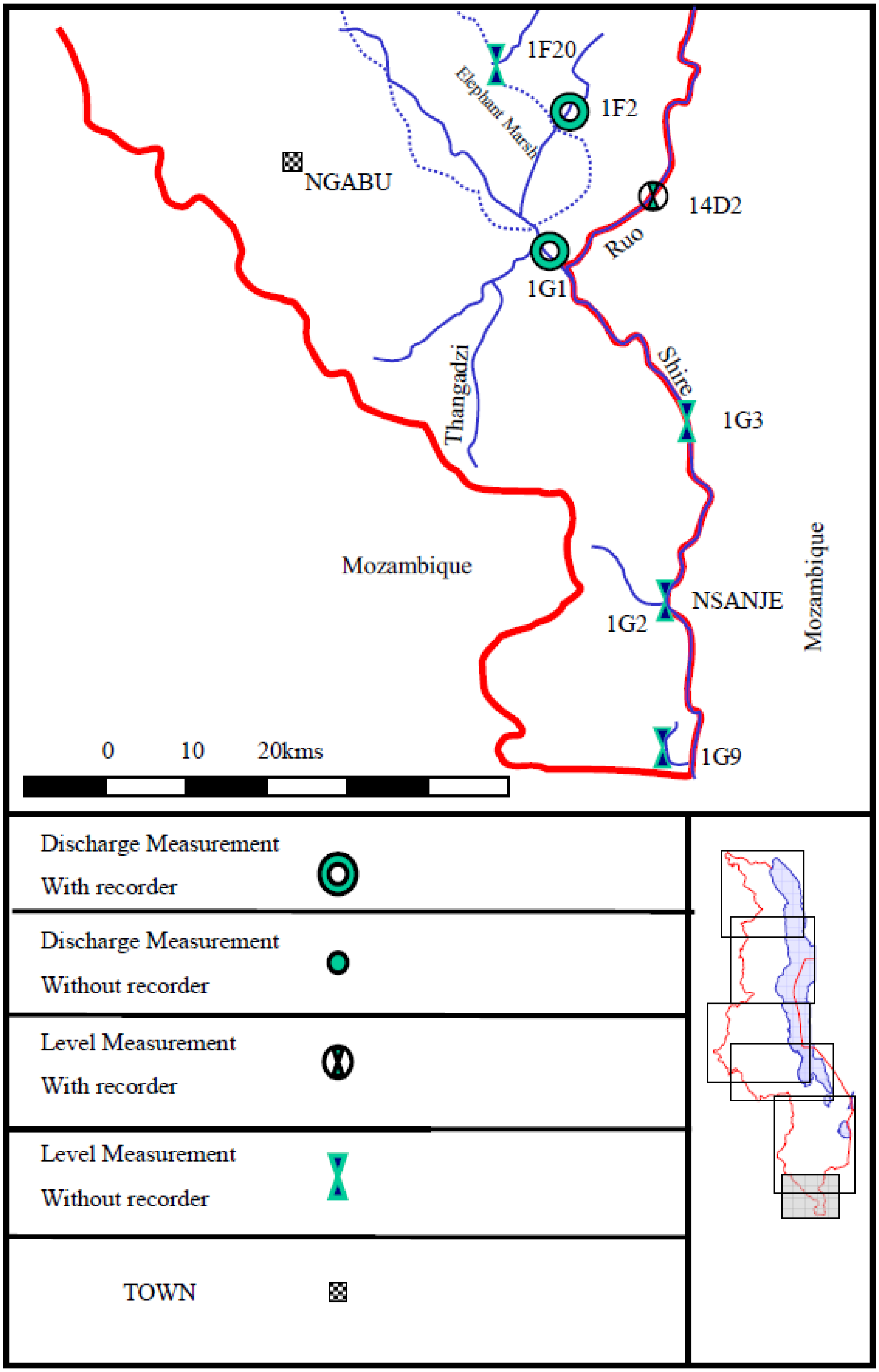
Malawi's Hydrological Network



Source: Ministry of Irrigation and Water Development, Malawi

Malawi's Hydrological Network

Hydrological Network – Southern Malawi, Part 2



Source: Ministry of Irrigation and Water Development, Malawi

APPENDIX B

Available data on the attached CD on the back cover

Hydrological data

All the hydrological network stations of Malawi are shown in Appendix and the corresponding available hydrological data used in the study as well as some other rivers is available in the attached CD. Take note that only the stations which have been used in this research are available in the CD with only a few extra stations.

Rainfall Data

Rainfall data for the stations listed in this appendix is available as well in the CD. The GIS shape files for the rainfall and weather stations is also available in the GIS directory for use in locating the actual position of the station for use by future researchers.

Weather data

Climate data on temperature, wind speed, sunshine hours, and wind speed is available as well in the attached CD for the main six climate station (Chitedze, Salima, Karonga, Mzuzu, Nkhatabay and Nkhotakota)

Demographic data

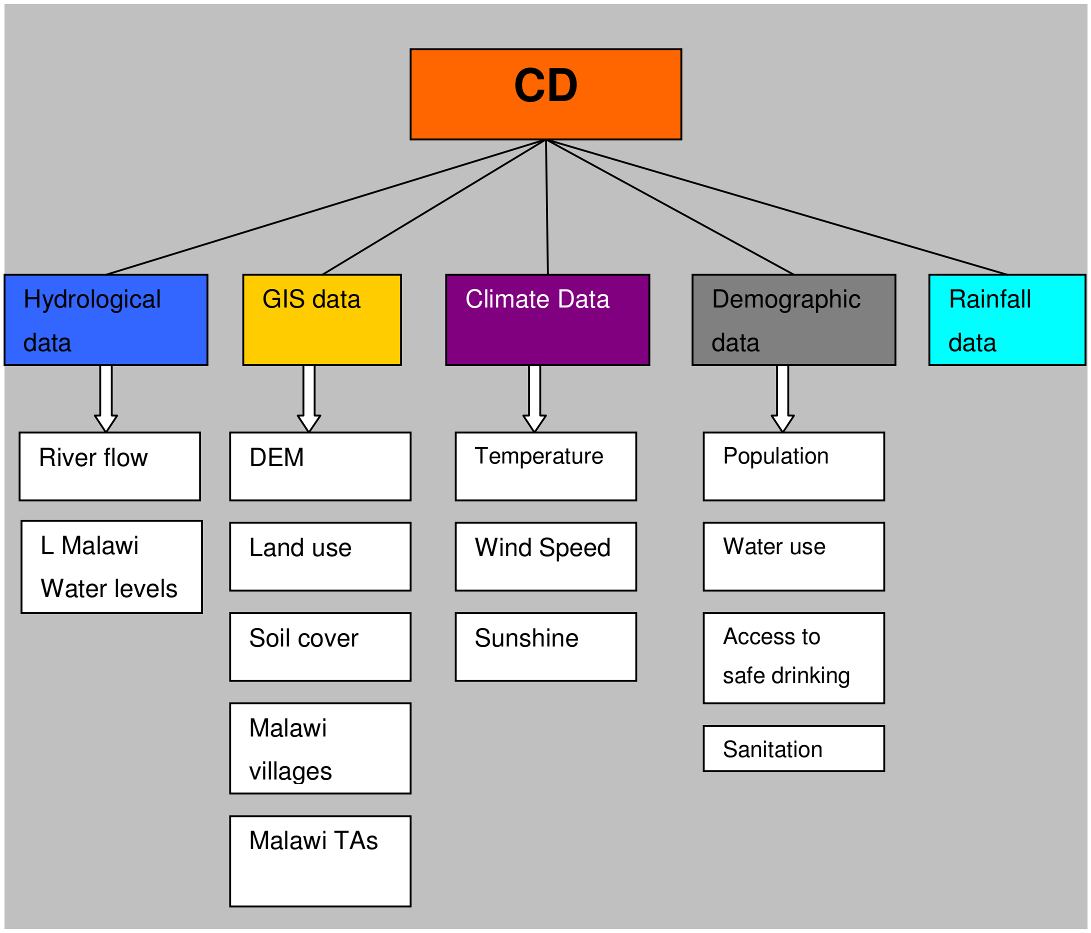
Population data set ranging from Traditional Authority, District, Regional and then Country level. The names of the traditional authority could easily be displayed on GIS interface by the user to locate the place using the GIS shape files in the GIS data directory.

GIS Data

The following GIS data for Malawi is available in the CD

- Digital elevation model (DEM)
- Land use

- Soil Cover
- Malawi villages
- Regional, District and Traditional Authority (TAs) boundaries



CD directory set of the available data

Key to Demographic Data

1 Area and Climate

Table A1.1 Land, Water Area and Land Tenure

Table A1.2 Annual Rainfall by Selected Meteorogical Stations

Table A1.3 Average Monthly Rainfall 1992-2001 by Meteorological Station

2 Population

3 Health

4 Water and Electricity supplies

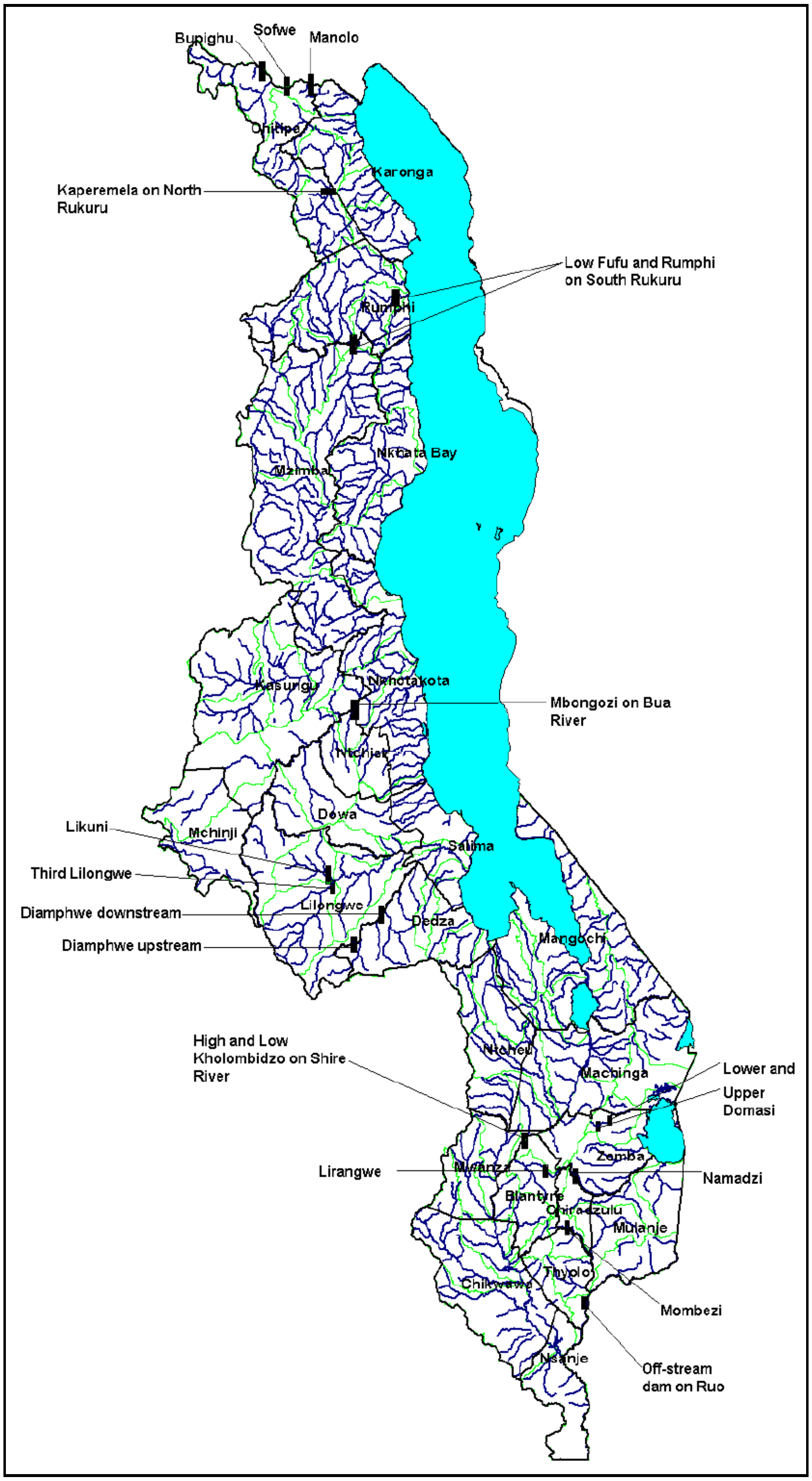
Table A4.3 Water Supplies Operated by Blantyre Water Board
Table A4.4 Water Supplies Operated by Lilongwe Water Board
Table A4.5 Water Supplies Operated by Southern Region Water Board
Table A4.6 Water Supplies Operated by Central Region Water Board
A4.7 Water Supplies Operated by Northern Region Water Board

5 Housing and Sanitation

Organised in 12 parts cover the following main areas: number of persons in dwelling units (dus) by type of structure, number of rooms, tenure, main source of drinking water during wet and dry seasons, type of toilet facility, main source of energy for cooking and lightning, radios, bicycles and ox-carts for urban and rural areas at national and regional levels

APPENDIX C

Map of potential multipurpose dam sites in Malawi



Source: Ministry of Irrigation and water Development, Malawi

APPENDIX D

FORTRAN Program – Linear Perturbation Model

```
Linear Perturbation Model
c       Method of estimation: Ordinary Least Squares

c       Subroutines called from the LPMlibrary are:
c       LPM1,LPM3,LPM7,LPM4,LPM9,LPM8,LPM5,LPM6,LPM2

c       maxx    is the maximum allowed length of the input/output data
c       maxz     is the maximum allowed sum of the memory lengths of
c                  all the inputs
c       maxi        is the maximum allowable number of inputs.
c       maxh        is the maximum allowable number of harmonics
c
        Parameter (maxx=5000,maxz=125,maxh=10,maxi=5)

        Dimension Ititle(16),ii(4),ti1(20),wq(maxx),wqc(maxx)
        Dimension d(maxx),x(maxi,maxx),xr(maxi,maxx),y(maxx),yr(maxx),
     1  a(maxh),b(maxh),c(maxh),ak(maxh),sx(365),ssx(365),sy(365),
     2  ssy(365),a1(maxz,maxz),h(maxi,maxz),c1(maxz),se(maxi,maxz),
     3
wk1(maxz),m(maxi),gf(maxi),itype(maxi),yhat(maxx),yestmt(maxx),
     4  iu(maxi),z(maxz),area(maxi)

        Write(iunito,5)
5       Format(5(/,20x,'Multiple input  LPM --  PROGRAM LPM '))
        itag = 'Program LPM'

        Write(iunito,812)
        Write(iunito,6)
6       Format(/,2x,'Name of the catchment ?',t60,'=>' )
        Read(iuniti,3)ti1
3       Format(20a1)
c
c       Store results in a Result file.
c       --------------------------------------------------------
        Write(iunito,800)
800     Format(2x,'Name of the General Result file ?',t60,'=>' )
        Read(iuniti,2)fill
```

```
2       Format(a20)
        Open(unit=40,access='sequential',file = fill,status='unknown')

                        Write(40,815)itag
815     Format(a12)
                        Write(40,5)
                        Write(40,6)
                        Write(40,3)ti1
        Write(iunito,805)
805     Format(2x,'The title of the file ?',/,t10,'=>' )
        Read(iuniti,810)(ititle(i),i=1,16)
810     Format(16a4)
                        Write(40,810)(ititle(i),i=1,16)
        Write(iunito,812)
812     Format(/,2x,70('-'),///)
                        Write(40,812)
c
c       -------------------------------------------------------------
        Write(iunito,10)
                Write(40,10)
10      Format(/////,2x,'How many inputs ?',t60,'=>')
        Read(iuniti,*)number
                Write(40,*)number
        If(number.gt.maxi)then
        Write(iunito,988)number
                Write(40,988)number
988     Format(/,20x,'DIMENSIONAL ERROR  - Increase Maxi to ',I5)
        Write(iunito,996)
                Write(40,996)
        Go to 999
        Endif

        Do 15 j = 1,number
        Area(j) = 0.0

        Write(iunito,30)j
                Write(40,30)j
30      Format(/,2x,'File name for input number ,',i1,' ?',t60,'=>')
        Read(iuniti,2)fyle
                Write(40,2)fyle
        Write(iunito,22)
                Write(40,22)
```

```
22      Format(/,2x,'Is this input rainfall (y/n)?',t60,'=>')
        Read(iuniti,1)iy
                Write(40,1)iy
1       Format(A1)
                If(iy.eq.iyes.or.iy.eq.iycs)then
                Write(iunito,16)
                        Write(40,16)
16              Format(/,2x,'The catchment area in sq. kms is
?',t60,'=>')
                Read(iuniti,*)area(j)
                        Write(40,*)area(j)
                itype(j) = 0
                Else
                itype(j) = 1
                Endif
c
c       Use subroutine LPM1 to Read the input data
c
        ier = 0
        iprint = 0
        Call
LPM1(d,n,maxx,fyle,ititle,iyear,imon,iday,ihour,imin,isec,
     1  idt,l29,icode,iunitx,iprint,ier)
        If(ier .ne. 0)then
                Write(40,998)ier
        Write(iunito,998)ier
998     Format(/,20x,'Error detected in LPM1  -  ier =', i4)
        Endif
        If(ier.gt.900)then
        Write(iunito,996)
996     Format(/,20x,'EXECUTION OF PROGRAM lpm12 IS TERMINATED')
                Write(40,996)
        Go to 999
        Endif
                If(idt.ne.86400)then
                Write(iunito,997)
997             Format(/,20x,'Program uses only daily data')
                        Write(40,997)
                Go to 999
                Endif
c
c       Check if the time series are concurrent
```

```
c
        If(j.gt.1)Go to 35
        ii(1) = iyear
        ii(2) = imon
        ii(3) = iday
        ii(4) = n
35      Continue

        If(iyear.ne.ii(1).and.
imon.ne.ii(2).and.iday.ne.ii(3).and.n.ne.
     1  ii(4))then
        Write(iunito,987)j
                Write(40,987)j
987     Format(/,20x,'Input number',i1,' is not concurrent',/,20x,
     1  'with the rest of the inputs')
        Write(iunito,996)
                Write(40,996)
        Go to 999
        Endif
        Do 45 k = 1,n
        x(j,k) = d(k)
45      Continue
15      Continue
c
c       Read the outflow discharge.
c
        Write(iunito,50)
                Write(40,50)
50      Format(/,2x,'Observed outflow data file ?',t60,'=>')
        ier = 0
        iprint = 0
        Read(iuniti,2)fyle
                Write(40,2)fyle
        Call
LPM1(y,ny,maxx,fyle,ititle,iyear,imon,iday,ihour,imin,isec,
     1  idt,l29,icode,iunity,iprint,ier)
        If(ier.ne.0)then
        Write(iunito,998)ier
                Write(40,998)ier
        If(ier.gt.900)then
        Write(iunito,996)
                Write(40,996)
```

```
        Go to 999
        Endif
        Endif
c
c       check if the output data is concurrent with the rest
c
        If(iyear.ne.ii(1).and. imon.ne.ii(2).and. iday.ne.ii(3))then
        Write(iunito,995)
                Write(40,995)
995     Format(/,20x,'Output is not concurrent with the inputs')
        Write(iunito,996)
                Write(40,996)
        Go to 999
        Endif
        If(ny.ne.ii(4))then
        Write(iunito,991)
                Write(40,991)
991     Format(/,20x,'Output is of different length than input')
        Write(iunito,996)
                Write(40,996)
        Go to 999
        Endif

c       Choose the calibration period.
c
        Write(iunito,55)n
                Write(40,55)n
55      Format(/,2x,'The total length of data is = ',i4,
     1  /,2x,'The program assumes that the calibration starts',/,2x,
     2  'from the beginning of the available data.',//,2x,
     2  'How many days for calibration ?',t60,'=>')
        Read(iuniti,*)nc
                Write(40,*)nc
        If(nc.gt.maxx)then
        Write(iunito,990)nc
                Write(40,990)nc
990     Format(/,20x,'DIMENSIONAL ERROR -- Increase Maxx to ',i5)
        Write(iunito,996)
                Write(40,996)
        Go to 999
        Endif
c
```

```
c       Calculate the mean outflow during the calibration period.
c
        ybar = 0.0
        Do 60 j = 1,nc
        ybar = ybar+y(j)
60      continue
        ybar = ybar/nc
c
c       ______________________________________________________________
        Write(40,820)n
820     Format(5x,'Total data points are = ', i5)
        Write(40,821)iyear,imon,iday
821     Format(5x,'Starting date = ',i4,'/',i4,'/',i4)
        Write(40,822)nc
822     Format(5x,'Calibration data points are = ', i5)
        Write(40,823)ybar
823     Format(5x,'Mean of the calibration = ', F10.2 )
c       ---------------------------------------------------------------
-
        Do 90 j = 1,number
        Do 95 k = 1,n
        d(k) = x(j,k)
95      continue
        Call Clear
        Write(iunito,100)j
100     Format(///,5x,'Processing input number ',i2,'.....')
                Write(40,100)j
c
c       Calculate the seasonal mean of this input.
c       yr array in subroutine LPM3 is used as a workspace
c
        Call LPM3(d,nc,sx,l29,yr)
c
c       assume 4 harmonics are sufficient for smoothing.
c
        mm = 4
120     ier = 0
        nprint = 1
c
        Call LPM7(sx,365,mm,ssx,a0,a,b,c,nprint,ier)
        If(ier.ne.0)then
        Write(iunito,994)ier
```

```
                Write(40,994)ier
994     Format(/,20x,'Error detected in LPM7 -- ier =  ',i3)
        If(ier.gt.900)then
        Write(iunito,996)
                Write(40,996)
        Go to 999
        Endif
        Endif
                iunito = 40
                Call LPM7(sx,365,mm,ssx,a0,a,b,c,nprint,ier)
                iunito = iunitf
                Write(40,839)j
839             Format(/,2x,'Smoothed seasonal mean input no.',i2)
                Write(40,837)(ssx(i),i=1,365)
837             Format(2x,7f10.3)

c
c       Check if the number of harmonics used are correct.
c
        Write(iunito,105)
                Write(40,105)
105     Format(/,2x,'Would you like to change the number',/,2x,
     1  'of chosen harmonics (y/n) ?',t60,'=>')
        Read(iuniti,1)iy
                Write(40,1)iy
        If(iy.eq.iyes.or.iy.eq.iycs)then
        Write(iunito,110)
                Write(40,110)
110     Format(/,2x,'Revised number of harmonics ?',t60,'=>')
        Read(iuniti,*)mm
                Write(40,*)mm
        If(mm.gt.maxh)then
        Write(iunito,986)maxh
                Write(40,986)maxh
986     Format(/,20x,'Dimensional error __ Too many harmonics',/,20x,
     1  'The number of harmonics is restricted to ',i2)
        mm  = maxh
        Endif
        Go to 120
        Endif
c
c       Calculate the perturbations of each input.
```

```
c
        Call LPM4(d,yr,n,ssx,l29)
c
        Do 65 k = 1,n
        xr(j,k) = yr(k)
65      Continue
90      Continue
c
c       Process the outflow series ; calculate its perturbations.
c
        Write(iunito,125)
125     Format(///,5x,'Processing outflow ....')
                Write(40,125)
c
c       Calculate the seasonal mean
c
        Call LPM3(y,nc,sy,l29,yr)
c
c       yr is still used as workspace.
c       choose 4 harmonics initially
c
        mm = 4
130     ier = 0
        nprint = 1
        Call LPM7(sy,365,mm,ssy,a0,a,b,c,nprint,ier)
        If(ier.ne.0)then
        Write(iunito,994)ier
                Write(40,994)ier
        If(ier.gt.900)then
        Write(iunito,996)
                Write(40,996)
        Go to 999
        Endif
        Endif
                iunito = 40
                Call LPM7(sy,365,mm,ssy,a0,a,b,c,nprint,ier)
                iunito = iunitf
                Write(40,841)
841             Format(/,2x,'Smoothed seasonal mean discharge ')
                Write(40,837)(ssy(i),i=1,365)

        Write(iunito,105)
```

```
                Write(40,105)
        Read(iuniti,1)iy
                Write(40,1)iy
        If(iy.eq.iyes.or.iy.eq.iycs)then
        Write(iunito,110)
                Write(40,110)
        Read(iuniti,*)mm
                Write(40,*)mm
        If(mm.gt.maxh)then
        Write(iunito,986)maxh
                Write(40,986)maxh
        mm = maxh
        Endif
        Go to 130
        Endif
c
c       calculate the outflow perturbations
c
        Call LPM4(y,yr,n,ssy,l29)
c
c       Guess the initial memory lengths for each input
        Write(iunito,135)
                Write(40,135)
135     Format(/,2x,'Initial guess of the memory lengths?')
210     Do 140 k  = 1,number
        Write(iunito,145)k
                Write(40,145)k
145     Format(27x,'Input ',i1,t60,'=>')
        Read(iuniti,*)m(k)
                Write(40,*)m(k)
140     continue
c
c       check the total memory lengths
c
        mtotal = 0
        Do 150 k = 1,number
        mtotal = mtotal+m(k)
150     continue
        If(mtotal.gt.maxz)then
        Write(iunito,992)mtotal
                Write(40,992)mtotal
992     Format(/,20x,'Dimensional error. Increase maxz to ',i5)
```

```
        Write(iunito,996)
                Write(40,996)
        Go to 999
        Endif

c       Find the maxm. memory length.

        mmax = m(1)
        Do 160 k = 2,number
        If(m(k).gt.mmax)mmax = m(k)
160     continue
c
c       Call the subroutine to estimate the Pulse response functions.
c
        ier = 0
        nprint = 1
        Call
LPM9(xr,maxi,nc,yr,nc,h,maxi,mmax,m,number,mtotal,a1,maxz,
     1  c1,yestmt,cgm2,se,wk1,gf,nprint,ier)
c
c       Perform the convolution
c
        Do 170 i = 1,n
        yestmt(i) = 0.0
170     continue
        Do 175 k = 1,number
        Do 180 i = 1,n
        Do 185 j = 1,m(k)
        If((i-j+1).le.0.or.(i-j+1).gt.n)Go to 185
        yestmt(i) = yestmt(i)+(h(k,j)*gf(k))*xr(k,i-j+1)
185     continue
180     continue
175     continue
c
c       Add the the seasonal mean discharge to the perturbations.
c
        Call LPM5(yhat,yestmt,n,ssy,l29)
c
        Write(iunito,1234)
1234    Format(5(/),40x,'Press return to continue =>')
        Read(iuniti,1)iy
c
```

```
      Call Clear
      Write(iunito,200)
200   Format(5(/),5x,'>>>CALIBRATION PERIOD RESULTS<<<')
              Write(40,200)
              Do 838 k = 1,number
              Write(40,829)K
829           Format(///,5x,'Input Number = ',i2,/,5x,16('-'))
              Write(40,840)m(k)
840           Format(/,5x,'The chosen memory length = ',i5)
              Write(40,851)gf(k)
851           Format(5x,'The gain factor of the OLS = ',f12.4)
              Write(40,842)
842           Format(5x,'Standardised OLS pulse response')
              Write(40,843)(h(k,j),j=1,m(k))
              Write(40,844)
844           Format(5x,'Standard error')
              Write(40,843)(se(k,j),j=1,m(k))
843           Format(5x,10f7.3)
838           continue

      Do 701 j = 1,mmax-1
      yhat(j) = -9.9
701   continue

      Do 176 k = 1,number
      If(area(k).ne.0.0)then
      factor = 86.4/area(k)
      gf(k) = gf(k)*factor
      Endif
      Write(iunito,177)k,gf(k)
              Write(40,177)k,gf(k)
177   Format(/,5x,'Non dimensional gainfactor for input',i2,' is',
     1 f10.4)
176   continue
c
      ier = 0
      nprint = 1
      Call LPM6(y,mmax,nc,yhat,ybar,f0,f,rsqr,nprint,ier)
      If(ier.ne.0)then
      Write(iunito,985)ier
              Write(40,985)ier
985   Format(/,20x,'Error detected in LPM6  - ier = ',i3)
```

```
      If(ier.gt.900)then
      Write(iunito,996)
              Write(40,996)
      Go to 999
      Endif
      Endif
              iunito = 40
              Call LPM6(y,mmax,nc,yhat,ybar,f0,f,rsqr,nprint,ier)
              iunito = iunitf
      nprint = 1
      Write(iunito,205)
              Write(40,205)
205   Format(/,2x,'Are the assumed memory lengths correct (y/n)?',
     1 t60,'=>')
      Read(iuniti,1)iy
              Write(40,1)iy
      If(iy.ne.iyes.and.iy.ne.iycs)then
      Call Clear
      Write(iunito,215)
              Write(40,215)
215   Format(/////,2x,'The revised memory lengths are ? ')
      Go to 210
      Endif
c
c     Check if the verification data is in continuation .
c
      nverc = 0
      nleft = n-nc
      If(nleft.gt.0)then
      Write(iunito,305)nleft
              Write(40,305)nleft
305   Format(/,2x,'The remaining',i6,' values after the calibration'
     1 ,/,2x,'may be use as a verification period.',//,2x,
     2 'Is it desirable to do  so (y/n)? ',t60,'=>')
      Read(iuniti,1)iy
              Write(40,1)iy
      If(iy.eq.iyes.or.iy.eq.iycs)then
      nc1 = nc+1
      Write(iunito,300)
300   Format(5(/),5x,'>>>VERIFICATION PERIOD RESULTS<<<')
              Write(40,300)
      ier = 0
```

```
        nprint = 1
        Call LPM6(y,nc1,n,yhat,ybar,f0,f,rsqr,nprint,ier)
        If(ier.ne.0)then
        Write(iunito,984)ier
                Write(40,984)ier
984     Format(/,20x,'Error detected in LPM6  - ier = ',i3)
        If(ier.gt.900)then
        Write(iunito,996)
                Write(40,996)
        Go to 999
        Endif
        Endif

                iunito = 40
                Call LPM6(y,nc1,n,yhat,ybar,f0,f,rsqr,nprint,ier)
                iunito = iunitf

        nprint = 1
        Endif
        If(iy.ne.iyes.and.iy.ne.iycs)then
        nverc = 1
        Endif
        Endif
c
c       Write the estimated discharge in a file.
c       If the verification data is in continuation with the
calibration
c       data and it was decided to carry out the verification also,
then
c       the estimated discharge in the file will include the
c       verification period also.
c
        If(nverc.eq.1)then
        nver = nc
        Else
        nver = n
        Endif
        Write(iunito,700)
                Write(40,700)
700     Format(/,2x,'Name of the file to store the',/,2x,
     1  'estimated discharges ?',t60,'=>')
        Read(iuniti,2)fyle
```

```
        Write(iunito,805)
        Read(iuniti,810)(ititle(i),i=1,16)
        ier = 0
        nprint = 0
        Call LPM2(yhat,nver,maxx,fyle,ititle,iyear,imon,iday,ihour,
     1  imin,isec,idt,l29,icode,iunity,nprint,ier)
        If(ier.ne.0)then
        Write(iunito,982)ier
982     Format(/,20x,'Error detected in LPM2 - ier = ',i3)
        If(ier.gt.900)then
        Write(iunito,996)
        Go to 999
        Endif
        Endif
c       --------------------------------------------------------------
999     Stop
        End
```

Subroutines for the Linear Pertubation Model

Subroutine for reading data LPM1

```
Subroutine LPM1(x,nx,idimx,fyle,ititle,iyear,imon,iday,ihour,
     1  imin,isec,idt,l29,icode,iunit,nprint,ier)
         DIMENSION X(IDIMX),ITITLE(16),MONS(12)
         Character*20 fyle,uname(5)
         COMMON /SYSPAR/IUNITI,IUNITO,IDEBUG
        DATA MONS/31,28,31,30,31,30,31,31,30,31,30,31/
        DATA UNAME / 'Not given','mm.','Cumecs.','inches','Cusecs.'/
c
OPEN(UNIT=30,FILE=FYLE,STATUS='unknown')
c
c       Read the first line. It should explain the contents.
c
READ(30,100)(ITITLE(I),I=1,16)
100     FORMAT(16A4)
if(nprint.eq.1)WRITE(IUNITO,200)FYLE,(ITITLE(I),I=1,16)
200     FORMAT(/,5x,' File:',a20,/,5x,' contains : ',16A4)
c
c       Read the second line. This should be the file-type 1.
c
READ(30,300)I,IFREE
300     FORMAT(2(1X,I1))
```

```
IF (I.EQ.1) THEN
c       Time series file.
c       Read the third line. It should have the misc. information.
c
IER=0
READ(30,400)NX,IYEAR,IMON,IDAY,IHOUR,IMIN,
     1             ISEC,IDT,L29,ICODE,IUNIT
READ(30,*)(X(I),I=1,NX)
c600     FORMAT(2X,6E13.5)
RETURN
END
```

Subroutine for writing results LPM2

```
        Subroutine LPM2(x,nx,idimx,fyle,ititle,iyear,imon,iday,ihour,
     1                imin,isec,idt,l29,icode,iunit,nprint,ier)
c
        DIMENSION X(IDIMX),ITITLE(16),MONS(12)
        Character*20,fyle,uname(5)
        COMMON /SYSPAR/IUNITI,IUNITO,IDEBUG
        DATA MONS/31,28,31,30,31,30,31,31,30,31,30,31/
        DATA UNAME / 'Not given','mm.','Cumecs.','inches','Cusecs.'/
c

        open(unit=20,file=fyle,access='append',status='old',err=805)
go to 806
805open(unit=20,access='sequential',file=fyle,status = 'new')
806continue
c
c        write the first line. It should explain the contents.
c
        write(20,100)(ITITLE(I),I=1,16)
100        FORMAT(16A4)
        if(nprint.eq.1)WRITE(IUNITO,200)FYLE,(ITITLE(I),I=1,16)
200        FORMAT(/,5x,' File:',a20,/,5x,' contains : ',16A4)
c
c        write the second line. This should be the file-type 1.
c
        itp = 1
        itp1 = 0
        write(20,300)itp,itp1
300        FORMAT(2(1x,i1))
c        write the third line. It should have the misc. information.
```

```
c
                write(20,400)NX,IYEAR,IMON,IDAY,IHOUR,IMIN,
     1           ISEC,IDT,L29,ICODE,IUNIT
400               FORMAT(1X,I6,1X,I4,1X,5(I2,1X),I9,1X,I4,2(1X,I1))

c        Now write the data.
c
                        write(20,600)(X(I),I=1,NX)
600                        FORMAT(2X,6E13.5)
c
        RETURN
        END
```

C Subroutine for calculating seasonal mean

```
        subroutine LPM3(x,n,sx,l29,y)
c
        dimension x(n),y(n),sx(365)
        common /syspar/ iuniti,iunito,idebug
        ny = n/365
        nl = n-(ny*365)
c
90      do 75 j = 1,n
75      y(j) = x(j)
c
c       Adjust the values of the 28th and the 29th february.
c
        if(nl1.eq.0)go to 40
        ls = l29
        do 25 j = 1,nl1
        if(ls.eq.1)go to 35
        y(ls-1) = 0.5*(y(ls)+y(ls-1))
35      y(ls+1) = 0.5*(y(ls)+y(ls+1))
        ls = ls+1461
25      continue
c
c       Remove the 29th feb. from the data.
c
        l = 1
        ls = l29
        do 45 k = 1,n
        if(k.eq.ls)go to 50
        y(l)  = y(k)
```

```
        l = l+1
        go to 45
50      ls = ls+1461
45      continue
c
c       Find the daily seasonal mean from the adjusted series.
c
40      do 60 k = 1,365
        sx(k) = 0.0
        kk = k
        do 70 j = 1,ny
        sx(k) = sx(k)+y(kk)
        kk = kk+365
70      continue
        sx(k) = sx(k)/ny
60      continue
        l = 365*ny
        do 80 k = 1,365
        l = l+1
        if(l.gt.(n-nl1))go to 999
        sx(k) = ((sx(k)*ny)+y(l))/(ny+1)
80      Continue
999     Return
        end
```

Subroutine for calculating perturbations

```
        Subroutine LPM4(x,xr,n,sx,l29)
c
        dimension x(n),xr(n),sx(365)
        common/syspar/iuniti,iunito,idebug
c
        ny = n/365
        nl = n-(ny*365)
c
c       nl is the number of leap years
        nl1 = 0
        if(l29.eq.0)go to 20
        ls = l29
15      if(ls.gt.n)go to 25
        ls = ls + 1461
        nl1 = nl1 +1
        go to 15
```

```
25      continue
        ny = ny+1
c
c       Subtract the seasonal means.
c
        ls = 129
        l = 1
        do 45 j = 1,ny
        do 50 i = 1,365
        xr(l) = x(l) - sx(i)
        l = l+1
        if(l.gt.n)go to 999
        if(l.eq.ls)go to 55
        go to 50
55      xr(l) = x(l) - 0.5*(sx(i)+sx(i+1))
        l = l+1
        ls = ls+1461
        if(l.gt.n)go to 999
50      continue
45      continue
c
999     return
        End
```

Subroutine for calculating estimated series

```
        Subroutine LPM5(x,xr,n,sx,l29)
c
c
        dimension x(n),xr(n),sx(365)
        common/syspar/iuniti,iunito,idebug
c
        ny = n/365
        nl = n-(ny*365)
        ny = ny+1
c
c       Add the seasonal means.
c
        ls = 129
        l = 1
        do 60 j = 1,ny
        do 65 i = 1,365
        x(l) = xr(l) +sx(i)
```

```
        l = l+1
        if(l.gt.n)go to 999
        if(l.eq.ls)go to 70
        go to 65
70      x(l) = xr(l) + 0.5*(sx(i)+sx(i+1))
        l = l+1
        ls = ls+1461
        if(l.gt.n)go to 999
65      continue
60      continue
999     return
        end
```

Subroutine for calculating sum of squares of differences between observed and estimated and model efficiency

```
subroutine LPM6(x,n1,n2,xhat,ybar,f0,f,rsqr,nprint,ier)
        Dimension x(n2),xhat(n2),y11(10),y22(10),fmse(10)
        common /syspar/iuniti,iunito,idebug
c
c       calculate the mean of x series and xhat series.
c
n = n2-n1+1
sxhat = 0.0
sx = 0.0
do 15 j = n1,n2
sx = sx +x(j)
sxhat = sxhat + xhat(j)
15      continue
sx = sx/n
sxhat = sxhat/n
c
c       calculate the initial variance and the residual variance after
c       fitting the model expressed /day.
c
f = 0.0
f0 = 0.0
do 20 j = n1,n2
f0 = f0+(x(j)-ybar)**2
f = f+(x(j)-xhat(j))**2
```

```
20      continue
f = f/n
f0 = f0/n
c
c       Calculate the index rsqr.
c
rsqr = (1-(f/f0))*100.0
c
c       check if printing of the results are required.
c
if(nprint.eq.1)then
Write(iunito,500)
500     Format(///,10x,'TABLE',/,10x,15('-'),//,10x,'Catchment',/,10x,
     1  'Model',/,10x,'Calibration/verification period',/,10x,
     2  'Design/updating mode',//)
ratio = sxhat/sx
write(iunito,505)n,n1,n2,ybar,sx,sxhat,ratio,f0,f,rsqr
505     Format(/,10x,'Short summary of the results',/,10x,29('-'),
     1  //,10x,'(for',i5,' values, from',i5,' to',i5,' )',/,
     2  10x,60('-'),/,10x,'1. Mean of the outflow in calibration'
     3  ,t50,'=',e13.6,//,10x,'2. Mean of the observed series',t50,
     4  '=',e13.6,/,10x,'3. Mean of the estimated series',t50,'=',
     5  e13.6,/,10x,'4. Ratio of the estimated to the ',
     6  /,10x,'   observed mean of the outflow',
     7  t50,'=',f10.4,//,10x,'5. The initial S.O.S per unit time',t50,
     8  '=',e13.6,/,10x,'6. The final S.O.S per unit time',t50,'=',
     9  e13.6,/,10x,'7. The performance index (R sqr.
%)',t50,'=',f10.2
     1  ,/,10x,60('-'))
endif
c
If(nprint .eq. 2)then

nband = 3
write(iunito,510)
510     format(//2x,'Enter the band limits (2 values):',t60,'=>')
read(iuniti,*)y22(1),y22(2)
y22(3) = 1.0e10
y11(1) = 0.0
do 600 i=2,nband
y11(i) = y22(i-1)
600     continue
```

```
do 720 j=1,nband
fmse(j) = 0.0
num = 0
do 710 i=n1,n2
if(x(i) .ge. y11(j) .and. x(i).lt.y22(j))then
fmse(j) = fmse(j) + (x(i)-xhat(i))**2
num = num + 1
endif
710     continue
if(num .gt. 0)then
fmse(j) = fmse(j)/num
else
fmse(j) = -9.9
endif
write(6,640)j,num,j,fmse(j)
640     format(/2x,'Number of flows in zone-',i1,' = ',i5,
     $         /2x,'MSE of zone-',i1,' flows = ',e13.6)
720     continue

Endif
999     return
end
```

c **Subroutine for estimating the standardised pulse response**

```
c       functions along with their standard errors by the method of
c       ordinary least squares
c
        subroutine LPM9(x,ix,nx,y,ny,h,ih,mmax,m,number,mtotal,a
     1  ,ia,c,yestmt,cgm2,se,wkspce,gf,nprint,ier)
c
        dimension x(ix,nx),y(ny),h(ih,mmax),a(ia,mtotal),c(mtotal),
     1  yestmt(ny),se(ih,mmax),wkspce(ia),m(number),gf(number)
        common /syspar/ iuniti,iunito,idebug
c       Carry out some spot checks mainly on the dimensions.
        ier = 0
        if(number.le.ix)go to 111
        ier = 999
        write(iunito,997)ier
997     Format(/,20x,'Error detected in LPM9 - ier = ',i3)
        go to 999
111     If(ia.ge.mtotal)go to 222
```

```
        ier = 998
        write(iunito,997)ier
        go to 999
222     smm = 0.0
        do 994 j = 1,number
        smm = smm+m(j)
994     Continue
        if(smm.eq.mtotal)go to 333
        ier = 997
        write(iunito,997)ier
        go to 999
333     do 991 j = 1,number
        if(m(j).le.mmax)go to 991
        ier = 996
        write(iunito,997)ier
        go to 999
991     Continue
c
c       Carry out initialisation of some matrices.
c
        Do 5000 i = 1,ih
        do 5001 j = 1,mmax
        h(i,j) = 0.0
        se(i,j) = 0.0
5001    Continue
5000    Continue
        do 5002 i = 1,ny
        yestmt(i) = 0.0
5002    continue
        do 5003 i = 1,ia
        wkspce(i) = 0.0
        do 5004 j = 1,mtotal
        c(j) = 0.0
        a(i,j) = 0.0
5004    Continue
5003    Continue
        do 5005 j = 1,number
        gf(j) = 0.0
5005    Continue
c
        minitl = mmax
c
```

```
C         CALCULATION OF XTX
c
100      M01 = 1
         DO 200 I=1,NUMBER
         M02=M01
         DO 300 J=I,NUMBER
         DO 400 II=1,M(I)
         II1=M01+II-1
         DO 500 JJ=1,M(J)
         JJ1=M02+JJ-1
         A(II1,JJ1)=0.0
         DO 600 K=MINITL,NY
         K1=K-II+1
         K2=K-JJ+1
         IF(K1.LE.0.OR.K1.GT.NX.OR.K2.LE.0.OR.K2.GT.NX)GOTO 600
         A(II1,JJ1)=A(II1,JJ1)+X(I,K1)*X(J,K2)
600      CONTINUE
500      CONTINUE
400      CONTINUE
         M02=M02+M(J)
300      CONTINUE
         M01=M01+M(I)
200      CONTINUE
         M01=1
         DO 210 I=1,NUMBER
         M02=1
         IF((I-1).EQ.0) GOTO 205
         DO 220 J=1,I-1
         DO 230 II=1,M(I)
         II1=M01+II-1
         DO 240 JJ=1,M(J)
         JJ1=M02+JJ-1
         A(II1,JJ1)=A(JJ1,II1)
240      CONTINUE
230      CONTINUE
         M02=M02+M(J)
220      CONTINUE
205      M01=M01+M(I)
210      CONTINUE
c
cCALCULATION OF XTY
c
```

```
        M01=1
        DO 700 I=1,NUMBER
        DO 800 II=1,M(I)
        II1=M01+II-1
        DO 900 K=MINITL,NY
        K1=K-II+1
        IF(K1.LE.0.OR.K1.GT.NX) GOTO 900
        C(II1)=C(II1)+X(I,K1)*Y(K)
900     CONTINUE
800     CONTINUE
        M01=M01+M(I)
700     CONTINUE
c
c       Calculate the Matrix inversion.
c       Subroutine used is LPM8.
c
750     Ifail = 0
        call LPM8(a,mtotal,ia,ifail)
        if(ifail.ne.0)then
        write(iunito,988)ifail
988     Format(/,20x,'Error detected in LPM8 - ier = ',i3)
        ier = 995
        go to 999
        endif
c
C       START TO CALCULATE THE COEFFICIENTS OF MULTIPLE
C       REGRESSION LINEAR MODEL: H
c
1150    M01=1
        DO 1400 I=1,NUMBER
        DO 1500 I1=1,M(I)
        I2=M01+I1-1
        DO 1600 J=1,MTOTAL
        H(I,I1)=H(I,I1)+a(I2,J)*C(J)
1600    CONTINUE
1500    CONTINUE
        M01=M01+M(I)
1400    CONTINUE
c
cSTART TO CALCULATE THE STANDARD ERRORS
c
        DO 1700 I=1,NY
```

```
1700    YESTMT(I)=0.0
        DO 1800  K=1,NUMBER
        DO 1900  I=1,NY
        DO 2000  J=1,M(K)
        IF((I-J+1).LE.0.OR.(I-J+1).GT.NX) GOTO 2000
        YESTMT(I)=YESTMT(I)+H(K,J)*X(K,I-J+1)
2000    CONTINUE
1900    CONTINUE
1800    CONTINUE
        E=0.0
        DO 2100 I=MINITL,NY
        E=E+(Y(I)-YESTMT(I))**2
2100    CONTINUE
        CGM2=E/(NY-MINITL+1-MTOTAL)
        DO 2200  I=1,MTOTAL
        WKSPCE(I)=SQRT(a(I,I)*CGM2)
2200    CONTINUE
        M01=1
        DO 2300 K=1,NUMBER
        DO 2400 I=1,M(K)
        I1=M01+I-1
        SE(K,I)=WKSPCE(I1)
2400    CONTINUE
        M01=M01+M(K)
2300    CONTINUE
c
c       Carry out the standardisation.
c
        Do 2500 k = 1,number
        gf(k) = 0.0
        do 2600 j = 1,m(k)
        gf(k) = gf(k)+h(k,j)
2600    continue
2500    continue
c
        do 2700 k = 1,number
        do 2800 j = 1,m(k)
        h(k,j) = h(k,j)/gf(k)
        se(k,j) = se(k,j)/gf(k)
2800    continue
2700    continue
c       Check the print control
```

```
        if(nprint.eq.1)then
        Write(iunito,505)
505     format(/,10x,'LPM9 RESULTS',/,10x,12('-')///)
        Do 3000 k = 1,number
        Write(iunito,501)k
501     format(/,10x,'TABLE:',/,10x,12('-'),////
     1         /,10x,'The Estimated Pulse Response Function',/,10x,42
     2         ('-'),///,10x,'METHOD: Ordinary Least Squares',
     3         /,10x,'DATA: Concurrent Time Series',
     4         /,10x,'      (Multiple Input-Single output System)',/
     5         /,10x,'CATCHMENT:',////,10x,'Input number = ',i3,/,
     6     10x,42('-'),/,12x,'NUMBER',4x,'ORDINATES',5x,'STANDARD',
     7         /,37x,'ERROR',/,10x,42('-'))
        do 503 i=1,m(k)
        write(iunito,502) i,h(k,i),se(k,i)
502     format(10x,i4,3x,f13.4,f13.4)
503     continue
        write(iunito,504) gf(k)
504     format(10x,42('-'),/,11x,'GAIN FACTOR (Dimensioned) =',e14.7
     1  ,/,10x,42('-'),////)
3000    continue
        Endif
999     return
        End
```

c ## Subroutine for Fourier series smoothing

```
        Subroutine LPM7(x,n,mm,xh,a0,a,b,c,nprint,ier)
c
        Dimension x(n),xh(n),a(mm),b(mm),c(mm)
        common/syspar/iuniti,iunito,idebug
c
c       calculate the harmonic coefficients and
c       estimate the smoothed series.
c
        a0 = 0.
        var = 0.
        do 10 l = 1,n
        a0 = a0+x(l)
10      continue
        a0 =a0/n
        if(mm.le.0)then
```

```
        do 15 j = 1,n
        xh(j) = a0
15      continue
        go to 999
        endif
        do 20 i = 1,n
        x(i) = x(i)-a0
        var = var+x(i)*x(i)
20      continue
        var = var/n
c
c       Maximum number of harmonics = n/2
c
        if(mm.gt.(n/2))then
        if(idebug.ne.0)then
        write(iunito,998)
998     Format(/,20x,'Illegal parameter mm in LPM7')
        endif

        ier = 1
        mm = n/2
        endif
c
        do 25 j = 1,mm
        a(j) = 0.0
        b(j) = 0.0
        do 30 kk = 1,n
        an = 2.*3.1415926*kk*j/n
        a(j) = a(j)+x(kk)*cos(an)
        b(j) = b(j)+x(kk)*sin(an)
30      continue
        a(j) = a(j)*2./n
        b(j) = b(j)*2./n
        c(j) = (a(j)*a(j)+b(j)*b(j))/2./var*100.
25      continue
        do 40 j = 1,n
        x(j) = x(j)+a0
40      Continue
        do 35 im = 1,n
        xh(im) = a0
        do 35 in = 1,mm
        al = 2.*3.1415926*im*in/n
```

```
        xh(im) = xh(im)+a(in)*cos(al)+b(in)*sin(al)
35      continue
c
c       Check the negativity constraint.
c
        Do 45 j = 1,n
        if(xh(j).lt.0.0)go to 50
45      continue
        tvol = 0.0
        go to 70
50      ncnt = 0
        svol = 0.0
        do 55 j = 1,n
        if(xh(j).lt.0.0)then
        svol = svol+xh(j)*(-1.0)
        xh(j) = 0.0
        ncnt = ncnt+1
        endif
55      continue
        tvol = (svol/(n*a0))*100.0
        sv = svol/(n-ncnt)
        do 60 j = 1,n
        if(xh(j).ne.0)then
        xh(j) = xh(j)-sv
        endif
60      continue
c
c       check if printing is required.
c
70      if(nprint.eq.1)then
        write(iunito,500)
500     Format(5(/),10x,'SMOOTHING VIA FOURIER SERIES',/,10x,28('-
'),//,
     1  10x,46('-'),/,11x,'Number',5x,'Fourier  Coefficients
Variance'
     2  ,/,11x,'of',t46,'accounted',/,11x,'Harmonics',t46,'by the
jth.',
     3  /,t46,'harmonics',/,t23,21('-'),/,t27,'a(j)',t38,'b(j)',t49,
     4  'c(j) %',/,10x,46('-'),/)
        do 510 j = 1,mm
        write(iunito,505)j,a(j),b(j),c(j)
505     Format(13x,i3,t21,f10.2,t32,f10.2,t47,f6.2)
```

```
510     continue
        write(iunito,515)a0,var
515     Format(/,10x,46('-'),//,11x,'Coefficient a0 (the mean)  = '
     1  ,e13.6, /,11x,'The initial variance =       ',e13.6)
        Write(iunito,520)tvol
520     Format(11x,'Negative volume as % total = ',e13.6,/,10x,46('-
'))
        endif
c
999     return
        End
```

c **Subroutine for finding the inverse of a matrix**

```
c       by Gaussian-Jeodan elimination procedure.
c
        subroutine LPM8(a,n,maxn,ier)
c
        dimension a(maxn,n)
        common/syspar/iuniti,iunito,idebug
c
c       Carry out some spot checks mainly on the dimensions.
c
        if(n.gt.maxn)then
        ier = 999
        write(iunito,997)ier
997     Format(/,20x,'Error detected in LPM8 - ier = ',i3)
        go to 999
endif
        do 10 k=1,n
        if(a(k,k).eq.0.0) then
        ier=998
        write(iunito,20)k,k
20      format(/,15x,'Fatal Error detected in LPM8',
     1  /,15x,'because a(',i3,1h,,i3,') is a zero element.',/)
        go to 999
        endif
10      continue
c
        do 800 k=1,n
        do 400 j=1,n
        if(j-k) 300,400,300
```

```
300     a(k,j)=a(k,j)/a(k,k)
400     continue
        a(k,k)=1.0/a(k,k)
        do 800 i=1,n
        if(i-k) 500,800,500
500     continue
        do 700 j=1,n
        if(j-k) 600,700,600
600     a(i,j)=a(i,j)-a(i,k)*a(k,j)
700     continue
        a(i,k)=-a(i,k)*a(k,k)
800     continue
        ier=0
c
999     return
        end
```