Impacts of Climate Change on Water Resources and Hydropower Systems in central and southern Africa

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Doctoral Thesis

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by

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In memory of my late father, Hichuunga B. Hamududu

Abstract

Climate change is altering hydrological processes with varying degrees in various regions of the world. This research work investigates the possible impacts of climate change on water resource and Hydropower production potential in central and southern Africa. The Congo, Zambezi and Kwanza, Shire, Kafue and Kabompo basins that lie in central and southern Africa are used as case studies.

The review of climate change impact studies shows that there are few studies on impacts of climate change on hydropower production. Most of these studies were carried out in Europe and north America and very few in Asia, south America and Africa. The few studies indicate that southern Africa would experience reduction in precipitation and runoff, consequently reductions in hydropower production. There are no standard methods of assessing the resulting impacts.

Two approaches were used to assess the impacts of climate change on water resources and hydropower. One approach is lumping changes on country or regional level and use the mean climate changes on mean annual flows as the basis for regional changes in hydropower production. This is done to get an overall picture of the changes on global and regional level. The second approach is a detailed assessment process in which downscaling, hydrological modelling and hydropower simulations are carried out.

The possible future climate scenarios for the region of central and southern Africa depicted that some areas where precipitation are likely to have increases while other, precipitation will reduce. The region northern Zambia and southern Congo showed increases while the northern Congo basin showed reductions. Further south in southern African region, there is a tendency of decreases in precipitation. To the west, in Angola, inland showed increases while towards the coast highlighted some decreases in precipitation.

On a global scale, hydropower is likely to experience slight changes (0.08%) due to climate change by 2050. Africa is projected for a slight decrease (0.05%), Asia with an increase of 0.27%, Europe a reduction up to 0.16% while America is projected to have an increase of 0.05%. In the eastern African region, it was shown that hydropower production is likely to increase by 0.59%, the central with 0.22% and the western with a 0.03%. The southern, and northern African regions were projected to have reductions of 0.83% and 0.48% respectively.

The basins with increases in flow projections have a slight increase on hydropower production but not proportional to the increase in precipitation. The basins with decreases had even high change as the reduction was further increased by evaporation losses. The hydropower production potential of most of southern African basins is likely to decrease in the future due to the impact of climate change while the central African region shows an increasing trend. The hydropower system in these regions will be affected consequently.

The hydropower production changes will vary from basin to basin in these regions. The

Zambezi, Kafue and Shire river basins have negative changes while the Congo, Kwanza and Kabompo river basins have positive changes. The hydropower production potential in the Zambezi basin decreases by 9 - 34%. The hydropower production potential in the Kafue basin decreases by 8 - 34% and the Shire basin decreases by 7 - 14 %. The southern region will become drier with shorter rainy seasons. The central region will become wetter with increased runoff. The hydropower production potential in the Congo basin reduces slightly and then increases by 4% by the end of the century. The hydropower production potential in the Kwanza basin decreases by 3% and then increases by 10% towards the end of the century and the Kabompo basin production increases by 6 - 18%. It can be concluded that in the central African region hydropower production will, in general, increase while the southern African region, hydropower production will decrease.

In summary, the analysis has shown that the southern African region is expected to experience decreases in rainfall and increases in temperature. This will result in reduced runoff. However the northern part of southern Africa is expected to remain relatively the same with slight increase, moving northwards towards the central African region where mainly increases have been registered. The southern African region is likely to experience reductions up to 5 - 20% while the central African region is likely to experience an increase in runoff in the range of 1 - 5%.

Lack of data was observed as a critical limiting factor in modelling in the central and southern Africa region. The designs, plans and operations based on poor hydrological data severely compromise performance and decrease efficiency of systems. Climate change is expected to change these risks. The normal extrapolations of historical data will be less reliable as the past will become an increasingly poor predictor of the future. Better (observed) data is recommended in future assessments and if not better tools and methods for data collection/ should be used. Future designs, plans and operations should include and aspect of climate change, if the region is to benefit from the climate change impacts.

Preface

Electricity production in southern Africa is mainly dependent on run-off from rivers. Runoff depends on rainfall, therefore changes in rainfall resulting from climate change will affect run-off in rivers and consequently have an impact impact on hydropower production. Changes in hydropower production capacity have large economic effect on the countries in southern Africa.

Assessing the future hydrological regimes is a chain process where changes in external forcing by greenhouse gas emissions are introduced into general circulation models and consequently in regional climate models. The results from climate models simulation are applied in driving the hydrological models that define time series of hydrological state variables and fluxes for current and future climate conditions. The time series and their statistics are a useful way of communicating the results from modelling hydrological impacts of climate change.

This doctoral work has been performed at the Department of Hydraulic and Environmental Engineering, NTNU, Trondheim, with Professor Ånund Killingtveit as main supervisor and with Professor Knut Alfredsen providing support. This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfilment of the requirements for the doctoral degree (PhD).

The work was carried out while the author was employed as a PhD (Stipendiat)candidate at the Faculty of Engineering Science and Technology, Department of Hydraulic and Environmental Engineering at NTNU. During the research time, the position was 100% with 25% assigned duties by the department. The Research funds were obtained mainly from the Research Council of Norway's external funding.

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Byman Hikanyona H. – August 2012– Trondheim, Norway

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List of Abbreviations

AGCM	Atmospheric General Circulation Model
ANN	Artificial Neural Networks
AOGCM	Atmosphere-Ocean General Circulation Model
AR4	Fourth Assessment Report of IPCC
CERA	Climate and Environmental Retrieving and Archiving
ENSO	El Nino Southern Oscillation
GCMs	Global Circulation Models
GHCN	Global Historical Climatological Network
GHG	Green House Gas
GRDC	Global Runoff Data Centre
HBV	HBV hydrological Model from Hydrologiska Byråns Vattenbalansavdelning
IEA	International Energy Agency
IHACRES	Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data hydrological model
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
MMD	Multi Model Dataset
MW	MegaWatts
nMag	nMag Hydropower Simulation Model

PCMDI	Program for Climate Model Diagnosis and Inter comparison
PITMAN	PITMAN hydrological model
RCM	Regional Climate Model
SADC	Southern African Development Community
SAPP	Southern African Power Pool
SLP	Sea Level Pressure
SLURP	Semi-Distributed Land Use-based Runoff Processes
SRES	Special Report on Emission Scenario
SRREN	Special Report on Renewable Energy and Climate Change Mitigation (IPCC)
TF	Transfer Function
TWh/a	TerraWatts per Annum
WG	Weather Generator
Z	Geopotential Height

Chapter 1

Introduction

The increase in the world's population over the last century, complemented by the rise in the standards of living, has resulted in a rise in the demand for energy. The ever–increasing use of fossil fuels (coal, oil and gas), the main sources of energy so far, has led to a rise in carbon dioxide emissions (a significant share of GHG). Recent data confirm that the use of fossil fuels accounts for a significant share of global anthropogenic greenhouse gas emissions. Emissions continue to increase and the CO_2 concentration had increased to over 390 ppm, or 39% above pre–industrial levels, by the end of 2010. It is now evident that the planet is warming rapidly and there is scientific evidence that the major contributor of this warming is the increase in heat–trapping GHG emitted during the combustion of fossil fuels, and also from other processes. While there are many options that can be used to reduce the emissions, the most important option is increasing the renewable energy proportion (12.9% in 2008) in the total energy supply and thus reducing the share of fossil fuels. Hydropower constitutes a large portion of the renewable energy sources (35%).

The scientific literature as seen in the Intergovernmental Panel on Climate Change (IPCC) is clear in that climate change is likely to pose a significant challenge to the goals of sustainable development as well as seriously impinge on the ability of key ecosystems to maintain their current levels of service. The long-term trends behind global climate change are on top of natural multi-annual oscillations, which in the short term may mask the absolute net effects of global warming. Some of these oscillations do have some degree of predictability. The strength of El Nino Southern Oscillation,for example, can be predicted based on measurements of the temperature dipoles in the Pacific Ocean. Predictions on a longer time scale, however, are generally not feasible, other than by reference to past events. In general, the consequences of different paths of global GHG emissions give the clearest signals for the distant future, where anthropogenic forcing is the largest compared to the internal fluctuations of the climate system. Projections of climate define possible outcomes of the future climate pathways, but will not necessarily show the climate that will actually be realized.

The IPCC in its Fourth Assessment Report (AR4) concluded that climate change is occurring faster than earlier, as reported (Bates et al., 2008; Arnell et al., 2003; IPCC, 2007). Climate change will result in changes in various river flow conditions such as timing and quantity of flow, sediment load, temperature, and biological/ecosystem changes (Madani, 2011). Climate change has been reported to be one of the great challenges of the 21st century reports (IPCC, 2001). The International Energy Agency (IEA) report of 2011 projected that renewable–based electricity generation would triple between 2008 and 2035 under the "increasing use of renewable" scenario. Hydropower generation makes a substantial contribution to meeting today's increasing world electricity demands. The report adds that the share of renewable in global electricity generation will increase from 19% to almost a third (nearly the same as coal). The primary increase is said to come from hydropower and wind but hydropower remains dominant over the projection period. It is projected that global hydropower production might grow by nearly 75% from 2008 to 2050 under business-as-usual but that it could grow by roughly 85% over the same period in a scenario with aggressive action to reduce greenhouse gases (GHG) emissions. According to the IEA, a realistic potential for global hydropower is 2 to 3 times higher than the current production, with most remaining development potential in Africa, Asia, and Latin America (IEA, 2011).

It is been reported that in 2009, hydropower accounted for about 16% (approximately 3,551 TWh) of total global electricity production and has reached 26% of the total installed capacity for electricity generation (Bartle, 2010). Global production of hydropower has grown steadily by about 2.3% per year on average since 1980 while some reports increases of up to 3.1% per year for the European Union (SRREN-IPCC, 2011; Kumar et al., 2011). Global average growth rates of hydropower generation in the future are estimated to continue in the range of 2.4 - 3.6% per year between 1990 and 2030 (IEA, 2011). The highest growth rates are expected in developing countries which have high unexploited hydropower potential, but also in other countries, for example, parts of Eastern Europe. In Western Europe, only 1% annual increase is estimated (Lehner et al., 2005) . In contrast to the above, there are also indications that the annual energy production of some existing hydropower stations in some parts of the world has decreased since the 1970s, for example in some parts of Europe (Milly et al., 2008). The reductions have generally been attributed to changes in average discharge, but it is not clear whether they reflect cyclic fluctuations, steadily rising water abstraction for other uses, or the consequences of long–term changing climate conditions. Projections of changes in runoff are supported by the recently–demonstrated climate models. The global pattern of observed annual stream flow trends is unlikely to have arisen from unforced variability and is consistent with a modelled response to climate forcing (Milly et al., 2005).

1.1 Problem Outline

Climate change will cause changes in the patterns of the water cycle and geographical distribution of water resources in future. The impacts will be seen in climatic factors such as temperature, precipitation, wind speed, humidity. The impact of interest here is on river flow which is the resource for hydropower. The resulting flow effects could be in the form of changes in average flows (amount), variability of flow, or seasonal variability, increases in extremes, droughts and floods leading to changes in sediment transport, posing serious threat to reservoirs, safety of dams, and efficiency of the hydropower systems. The IPCC has stated that between 2000 and 2005, climate change accelerated faster than predicted, with the consequence that the water cycle could change in an unpredictable way, resulting in increases in extreme weather (IPCC, 2007). The major concern is that with all these changes, even if the quantity of water in the world does not change, the level of accessibility of the available water may be altered. The global circulation models projection over Africa highlights a gloomy scenario especially in water resources planning and management. The region already experiences droughts and floods almost every 8 years (Shahin, 2002). Climate change will further complicate the already difficult water–related issues. Further, hydropower remains the main source of electricity in the region, although access to electricity in Southern Africa is very low. Over 60% of the rural population relies on traditional biomass energy sources such as wood, charcoal, crop waste, manure, for cooking and heating, candles and kerosene for lighting.

Africa is projected to warm more than the global annual mean warming in all seasons. Annual rainfall is likely to decrease in much of the northern parts of the continent (Mediterranean and Sahara) and in the southern region. However the east Africa region is likely to have increased mean annual rainfall (IPCC, 2007). The southern Africa region receives 500 mm to 1200 mm annual rainfall per year in only 5 months, and with decreased mean annual rainfall and high temperatures, water management is likely to be difficult. The World Summit on sustainable Development, IPCC, the World Water Forum and many other institutions have highlighted the need for detailed regional assessment on climate change impacts. There is also a realization that perturbations in climate parameters, particularly rainfall, are largely amplified by the hydrological system and that if climate changes were to be seen in the manner international science is predicting, this would add a further layer of concern to the management of southern Africa's already high–risk and stressed water sector. The critical challenge that the region is facing today is effective management of the available scarce water resources in very few reservoirs to meet the power supply needs.

Even though there is marked progress in climate research in recent years, the climate of many parts of Africa is still not fully understood. Further derived climate scenarios are very coarse and do not usually adequately capture important regional variations that exist in Africa's climate. With regard to research gaps and priorities, the (IPCC, 2007) reports there is very little detailed information on the impacts and vulnerabilities of the energy sector in Africa specific to climate change and variability, particularly using and applying scenarios and outputs of GCM.The greatest challenge is that hydropower while being attractive is dependent on runoff, which in turn is dependent on precipitation. Precipitation in Africa is highly variable (unreliable) and unreliability may worsen with climate change. It is this dependence on runoff that makes hydropower one of the most vulnerable industries to changes in climate.

The impacts of climate change on hydropower production are very important in the Southern African Development Community region because of the prominent role that hydropower development plays in regional development plans. Most of the region's power systems are almost entirely dependent on hydropower except for Botswana, and South Africa. The Southern African Power Pool's (SAPP) integrated expansion plans include more than 6,300 MW of new, large–scale hydropower between the years 2010 and 2015, and at least another 6,500 MW are under discussion within the Zambezi River basin alone. The plans for these investments, however, do not generally include an assessment of long–term climate change impacts on the technical and economic viability of these hydropower plants. Moreover, electricity blackouts are common and widespread in the region, resulting in economic losses due to frequent droughts and stressed water resources.

The Sub-Saharan Africa (excluding South Africa and Botswana) is about 60% dependent on hydropower for its electricity supply, and most countries individually are much more dependent. The region has experienced recurring drought in the 50 years, which has become a leading contributor to power shortages in countries in the region.

In general, the region is endowed with enormous hydropower potential that needs to be harnessed. Despite this potential which is currently enough to meet all the electricity needs of the continent (if developed), only a small fraction has been exploited. Hydropower being a water resources–based source faces the challenge of climate change in the future. A region such as southern Africa, whose economies are based on water (rainfall), is likely to be affected by climate change.

With a total technical potential of 1,750 TWh of electricity production, Africa accounts for only 12% of the global hydropower potential. Out of this estimated technically feasible hydropower potential 9.3% is currently developed and another 58% of technically and economically feasible hydropower potential could be exploited. Another 37% of technically feasible hydropower potential could become economically viable in the future. Small hydropower plants will be part of the solution for the electrification of rural Africa. However, the growing population of Africa will also require the construction of medium and large hydropower plants to cover Africa's growing energy needs. Yet hydropower exploitation of major African rivers such as the Zambezi, Congo, Nile and Niger could meet the rising demand and increase access to electricity in Africa. Small run-of-river hydro plants remain undeveloped for many reasons in Africa (Rosenlund and Hamududu, 2011).

It is therefore necessary that future water resources and hydropower scenario are developed based on a climate change scenario. This would highlight likely implications that may result from future climate change. Although a great deal of research has been undertaken in global climate change worldwide, very few studies have focused on this region. Climate change could affect the water volume and seasonality of runoff in rivers consequently impacting on power production.

Enhanced knowledge of climate change impacts in the region is required to add to the relatively inadequately researched and understood impacts. This knowledge provides an insight into capacities of the future water resources and how they differ from the past and present variability. The study adds to increased knowledge base on the region on climate change and water resources through various results. The research increases our understanding of the impacts of changes in water resource systems, and the vulnerability of water usages such as hydropower systems.

1.2 Research Context

There is an emerging literature on the effects of both climate variability and long–term climate change on hydropower (SRREN-IPCC, 2011; Kumar et al., 2011; Bates et al., 2008; IPCC, 2007; Christensen et al., 2004; Harrison and Whittington, 2002; Mukheibir, 2007). The scope of this research is to evaluate the impacts of climate change on hydrological processes and regimes, and on water resources.

The topics that will be included in this research include: Climate systems, Re-analysis of GCMs, Natural Climate Variations, Regional Rainfall -Runoff Modelling, Water Balance, Hydropower and Production Simulations.

Research of this nature is limited firstly by the study methods employed and their outputs. Secondly, the region of Southern Africa lacks reliable historical (time-series) data for such a research. These limitations will have a significant bearing on the results of this study. Further, the research will be limited to analyses that affect hydrological systems while knowing that there are other important issues that need to be understood. Due to the time and specificity of the research, the study will be restricted to water resources and hydropower. The basis of this study lies mainly on the use of suitable GCM simulation outputs. This research will use the already–developed methods for downscaling and hydrological modelling but will be mindful of the assumptions and limitations these methods have.

1.3 Research Objectives

The research goal is to assess the potential impacts of climate change on water resources, and hydropower systems. This will contribute to strengthening knowledge on how climate changes will affect the water resources in the southern African region. It is aimed at providing information about water resources availability, to evaluate overall impacts on water resources and hydropower. The primary aim of this research is to contribute to reducing vulnerability to climate change through enhanced understanding.

The specific purposes of the research are presented in Table 1.1:

	Objectives
1	Analyse the historical trends and variability of climate and hydrology in the region
2	Analyse regional climate system in the context of future changes
3	Carry out downscaling from selected GCMs to regional / local level
4	Carry out hydrological Modeling under present and future scenarios (Case studies)
5	Assess impacts on hydrologic regimes from simulated climate changes.
6	Assess impacts on hydropower systems through hydropower simulations

Table 1.1: *Research Objectives*

1.4 Research Design

The research has been undertaken within the planned research schedule. The work started late 2007 and was completed in early 2012 as planned. The following were the steps taken to achieve the above listed objectives.

1.4.1 Literature Review

A review was carried out to assess best practice on assessment of the impacts of climate change. The purpose of the first part was to assess best practice in hydrological analysis for the hydropower system (reservoir capacity, economy and handling of extremes). The most peer reviewed documents, are the IPCC assessment reports, were studied in depth and the findings listed. Gaps were identified and best practice was noted for use. The second part of the review focused on how climate change influences the resource availability and how it is incorporated in current hydropower planning.

1.4.2 Data Collection and Analysis

In this step, different types of data were collected from various sources. The data included raw precipitation, temperature, and evaporation. data from meteorological institutions, from national offices (Zambia Meteorological Department) within the region. In addition, data from the Global Historical Hydrological Network was obtained via the internet. The other data types, river flow / discharge data were obtained from the national water resources departments and Global Runoff Data Centre The hydropower systems data was obtained from electricity utility companies and the Southern Africa Power Pool (SAPP). The climate change data were obtained from the two (2) IPCC online sites World Data Centre for Climate and Program for Climate Model Diagnosis and Inter comparison, All these data were checked for consistency and accuracy.

Climate change scenarios are generated for the region up to 2050 / 2100, depending on availability and fed into a hydrological model to assess impacts on each river basin. The modelling is based on a number of processes from emission scenarios to assessment via GCMs, the RCM, with additional bias correction and downscaling to the sub–basin level and hydrological modelling. The hydrological modelling is performed using either the HBV , IHACRES or PITMAN hydrological models. By using RCM data instead of GCM data, the spatial gridded data are greatly increased, providing more variability in these basins. Finally, the hydropower simulations are carried out using mainly the nMAG hydropower simulation model to yield the hydropower outputs. The results of hydropower simulations for different periods are compared to highlight the impacts of climate change.

1.4.3 Downscaling

The climate change data from the global climate model were then downscaled using various methods as described later to obtain regional or local future climate scenarios. Due to the large number of models, only a few (five) models were chosen based on specific performance criteria. The selected GCMs (CGCM3, CSIRO3, ECHAM5,CCSM3 and HADCM3) based on one scenario (SRES A1B) are the basis for most of the computations, although in some cases, some GCMs did not have data or the scenario data were missing, in that case, the number of GCMs is reduced or another scenario is used. SRES A1B is a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality Nakicenovic (2000).

1.4.4 Hydrology and Water Balance

Water balance through hydrological modelling is then carried out from downscaled data and observed data. Subsequently, the future climate variables were used to obtain the future river flows. This was carried out at different levels, global, regional and basin. Detailed analysis of the process for a few selected basins is presented in the respective chapters.

1.4.5 Hydropower Simulations

Finally, the resulting water balances (river flows) were then used as inputs into hydropower simulations, starting with the historical /current period to the future scenario. These simulations were the bases for the conclusions and recommendations

1.5 Thesis Structure

The thesis, is structure as a monograph and consists of nine chapters . Each chapter has one of the central themes in this research. The general flow follows the research process from literature review through to summary and conclusions. The research starts with a general review and assessment at a global hydropower scale through regional and large basins to local small basins (hydropower systems).

Chapter 1 is this introduction to the research, with definitions of the problems, and the objectives and methodology of the research. The work plan followed is also presented in this chapter at the end.

Chapter 2: Background, gives the general information about climate change, and the state–of–the–art of the science, methods and findings in climate change impacts on hydropower. The chapter also highlights the general problems caused by climate change, the different climate scenarios for the area of study. The chapter ends with challenges that the region may face as a result of climate change. The review of existing studies delves into published literature, grey literature of research groups and scientists who have assessed climate change impacts on hydropower. Further the chapter outlines the known impacts in different parts of the world from the literature.

Chapter 3: Methodology, describes the approaches that can be used for assessing climate change impacts on hydropower. The chapter further highlights possible applications of each of the methods described, in addition to stating the advantages and disadvantages of each of them. Further, the chapter describes where each of these approaches could be applied.

Chapter 4: Climate Change Modelling. The chapter on modelling describes in detail the process of climate modelling, from GCMs to local impacts on hydropower plants. The steps followed are explained and the data needs of each step are discussed in detail. Data sources are also given.

Chapter 5: Testing the Methodologies. The chapter uses the developed methodology to assess the impacts of climate change on global hydropower production, African hydropower production and a more detailed basin level assessment. The chapter also discusses the process and results of these analyses that were performed on different scales. It shows how different methodologies, from simple to detailed methods could be used to assess climate change impacts and also gives an important global picture of the impacts on hydropower from changes in climate change.

Chapter 6: Introduction to the Study Area. The chapter begins with a general introduction to the study area, Africa, highlighting pertinent issues with regard to climate and hydropower. The sampled basins are also introduced here with key characteristics or description data. The selected basins are the Congo, Zambezi, Kwanza, Shire, Kafue and Kabompo basins

Chapter 7: Future Climate Scenarios. The chapter discusses the general climate scenario of the region as given by GCMs. Mainly this chapter provides the results from the selected basins with the region to show the differences in impacts. Hydrological modelling is carried out on the Congo, Zambezi, Kwanza, Shire, Kafue and Kabompo basins.

Chapter 8: Hydropower Simulation. This chapter highlights the results of hydropower simulations and the changes that could be expected in the future on the regional hydropower systems. The methods used on each basin are highlighted and the results discussed for each of these basins.

Chapter 9: Summary and Conclusion. As the last chapter, the summary of the findings are presented here and conclusions are then drawn based on these findings. This chapter also addresses topics for further research.

Appendices In addition there are attachments and appendices to the thesis in the appendices section. These include some detailed results from downscaling as additional plots that could not be included directly into the main document.

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Chapter 2

Review of studies on Climate Change Impacts on Water Resources and Hydropower

2.1 Introduction

Climate change is one of the great challenges of the 21st century (Kumar et al., 2011). The International Energy Agency (IEA) report of 2011 projected that renewable-based electricity generation would triple between 2008 and 2035 under the increasing-use-of-renewable scenario (IEA, 2011). Hydropower generation makes a substantial contribution to meeting today's increasing world electricity demands. The report adds that the share of renewable in global electricity generation will increase from 19% to almost a third (nearly the same as coal). The primary increase is said to come from hydropower and wind but hydropower remains dominant over the projection period. According to the IEA, a realistic potential for global hydropower is 2 to 3 times higher than the current generation, with most remaining development potential existing in Africa, Asia, and Latin America. IEA also notes that, while run-of-river hydropower plants could provide as much as 150 to 200 GW of new generating capacity worldwide, only 5% of the world's small-scale hydropower potential has been exploited (EIA, 2011).

Climate change and the resulting changes in precipitation and temperature regimes will affect hydropower generation. It is reported that hydropower systems with less storage capacities are more vulnerable to climate change, as storage capacity provides more flexibility in operations (Bates et al., 2008). Although hydropower systems may benefit from more storage and generation capacity, expansion of such capacities may not be economically and environmentally justified. These changes would affect hydropower generation in all regions of the world. Given the significant role of hydropower, the assessment of possible impacts of climate changes on regional discharge regimes and hydropower generation is of interest and importance for management of water resources in power generation.

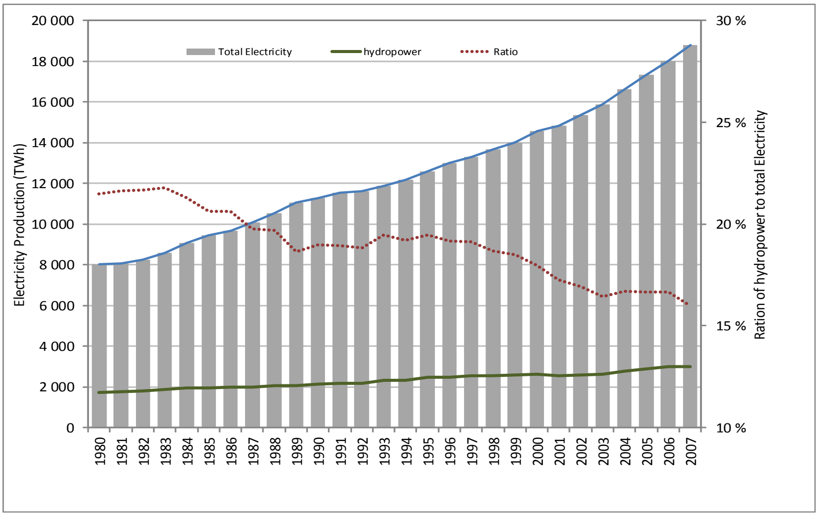


Figure 2.1: *Global Total Electricity Generation Trends (TWh) in the last 20 years. The bar graph shows the total global electricity generated and the green line shows the global hydropower produced. The inset (red line) shows the reducing ratio of global hydropower to the total electricity from over 21% in 1980 to 16% in 2008. Data source: (Bartle, 2010)*

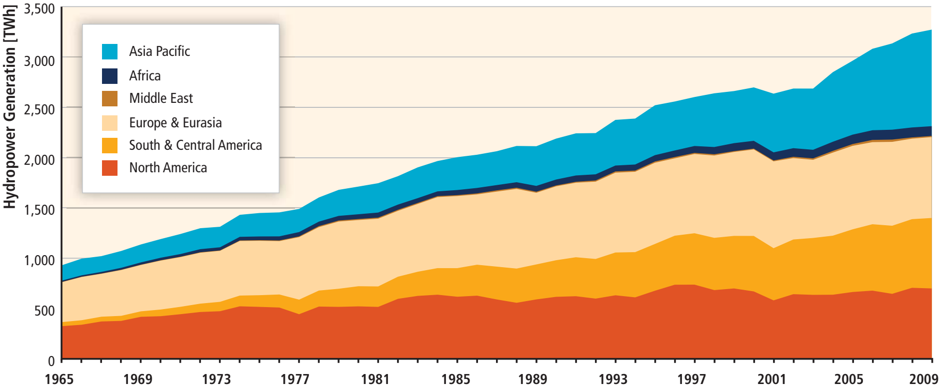


Figure 2.2: *Hydropower generation (TWh) by region. The production capacity has been increasing especially in Asia and South America. Africa has not increased its installed capacity, it remains relatively the same over the period (Kumar et al., 2011), Chapter 5, page, 444 Figure 5.1*

Global hydropower generation capacity has been increasing steadily over the last 30 years, and the past few years have shown an increased growth rate. Figure 2.1 presents the ratio of hydropower to the total electricity generation from 1980 to 2008. Although the ratio is reducing (21%– 16%), figure 2.2 shows that hydropower generation is also increasing till year 2005. The global hydropower productions from various continents/regions of the world are presented in Figure 2.2. Europe, America, and Asia have sizable shares of hydropower capacities. The hydropower production for Europe and Northern America, though large, has not been increasing much during this period while that in Southern/Central America and Asia/Oceania has greatly increased during this period as seen in Figure 2.2. Table 2.1 gives the regional hydropower characteristics in terms of hydropower in operation, under construction, planned and number of countries with more than 50% of their total electricity demand supplied by hydropower.

Table 2.1: *World Hydropower in operation (2009), under construction and planned from (Bartle, 2010).*

Region	**Hydropower in Operation**	**Hydropower under construction**	**Hydropower Planned**	**Countries with 50% of electricity supply**
	MW	**MW**	**MW**	**#**
Africa	23,482	5,222	76,600	23
Asia[1]	401,626	125,736	141,300	9
Europe[2]	179,152	3,028	11,400	8
North & Central America	169,105	7798	17,400	6
South America	139,424	19,555	57,300	11
Australiasia/Oceania	13,370	67	1500	4
World-Total	926,159	161,406	305,500	61

Table 2.2 shows regional hydropower statistics on hydropower potential. The table highlights the technically feasible, annual average potential, and possible increase achievable. The capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time and its output if it had operated at full capacity the entire time. The lowest capacity factor is in Europe and clearly shows that hydropower in Europe is used mainly for peaking purposes than in the other regions, (Bartle, 2010).

Table 2.2: *Regional Hydropower Potential (2009). The table highlights the technically feasible, annual average potential, annual generation capacity, and feasible increase (Bartle, 2010).*

Region	**Technically Feasible Potential**	**2009 Generation**	**Capacity Potential**	**Installed Capacity**	% of Total **Potential**	**Capacity Factor**
	TWh/y	**TWh/y**	**MW**	**MW**	**%**	
Africa	1750	98	424,277	23,482	9.3	0.47
Asia	6800	1514	1,928,286	401,626	17.8	0.40
Australasia/Oceania	200	37	55,351	13,370	53.9	0.41
Europe	1140	542	352,804	179,152	34.3	0.37
North America	1510	689	360,397	169,105	26.3	0.48
Latin America	2968	671	596,185	139,424	20.1	0.57
Total/Average	14,368	3551	3,722,930	926,159		0.44

2.2 Hydrology and Climate Change

The hydrological cycle links climate and water resources and plays a vital role in the climate system. The vulnerability of hydrology due to climate changes has been outlined by several assessment report, the most recent is IPCC–AR4 (IPCC, 2007; Bates et al., 2008; Kumar et al., 2011). The changes in climate could intensify the hydrological cycle depending on the scale of focus. The sun provides the energy for this cycle and redistribution of the fluxes of moisture be it on land, in the ocean or the atmosphere. The various processes of the hydrological cycle are sensitive to climate change in different ways. If temperature increases as a result of climate, the amount of water vapour that can be held in the atmosphere increases. Precipitation, the source of renewable water occurs on a range of space and time scales. Thus, climate change through changes in evaporation may alter the redistribution of precipitation between what returns to the atmosphere, runs in rivers and oceans or infiltrates into the ground. It is reported that with a rise in temperature, precipitation amounts will increase in high latitudes (Bates et al., 2008). Precipitation will actually decrease in the lower latitudes. The water resource, runoff, is the water that remains available for use after precipitation. With the increasing temperature and evaporation, the general observations are that runoff generally is reducing but not everywhere (Bates et al., 2008). Africa is one region where reductions have been observed while in Europe and North America the trends generally show an increase. It is this water resource that hydropower potential is based on and therefore any changes in runoff could be translated, though not in similar magnitude to hydropower production. Possible changes to the hydrological cycle (associated with an increased concentration of GHG in the atmosphere and the resulting changes in climate) include:

- Changes in the amount of precipitation (and temporal distribution).
- An increase in precipitation intensity under most situations.
- Changes in the form of precipitation (snow or rain).
- Increased evapo–transpiration and a reduction in soil moisture.
- Changes in vegetation cover resulting from changes soil moisture.

2.3 Observed Changes

Observations, best available (global) baseline over which to assess future climate changes, from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases (IPCC, 2007). Globally, the IPCC report many significant observed changes in physical variables many of which are consistent with warming (IPCC, 2007). From this evidence, the following general conclusions are made:

- "The global average surface temperature has increased, especially since about 1950. The temperature increase from 1850-1899 to 2001-2005 is 0.76^{o}C – 0.19^{o}C

. The rate of warming averaged over the last 50 years (0.13°C – 0.03°C per decade) is nearly twice that for the last 100 years" (IPCC, 2007).

- Some extreme weather events have changed in frequency and/or intensity over the last 50 years. Cold days, cold nights, and frosts have become less frequent over most land areas, while hot days and hot nights have become more frequent. The frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) has increased over most areas. The incidence of high sea level has increased in several sites worldwide since 1975 (IPCC, 2007).
- There is emerging evidence of an increase in variability of climate parameters (temperature, precipitation, extreme events). This is supported by the observed trends in storm intensification, increased frequency of extreme events, and above-record temperatures.

2.3.1 Impacts on Hydropower

The climate change impacts on hydropower system has not been fully mapped and assessments vary in the way they use the available climate data and assessment procedures. These differences make comparison of results in some case to be difficult. Below are examples to illustrate some past climatic events that have caused serious disruptions in hydropower production and delivery in Africa.

- Kariba, which contributes 50% of the electricity needs in the region, dropped hydropower production by 8% due to drought in 1992
- Kenya and Tanzania were forced in 2000 to ration electricity since the hydroelectric plants has been affected by persistent drought (IEA, 2011).
- After the drought in 2004, all of Tanzania'Šs hydroelectric plants were operating at half capacity (IEA, 2011). This fell to 50% in 2005 and then to below 30% in 2006 due to severe drought conditions. During February 2006, of the installed capacity of 561 MW of hydropower, only 140 MW was available, and this fell to as low as 50 MW in March 2006 (Casmiri, 2009).

2.4 Observed Changes in Precipitation and Runoff

2.4.1 Precipitation, Intensity, Runoff

There are contradicting results from different regions of the world on global trends on precipitation over the last century. Different periods show different trends. There are also reported large discrepancies between datasets (Milly et al., 2005). A summary of the observed global precipitation variations since 1900 is given in Figure 2.3. However there are also downward trends in other parts of Africa and south Asia.

Generally intense precipitation has been reported to be increasing even in areas where total precipitation is reported to be decreasing. Most of the rainfall statistics are dominated by inter–annual to decadal variations and trend estimates are spatially incoherent (IPCC, 2007; Griffiths et al., 2003; Herath and Ratnayake, 2004). Seasonal shifts have been reported that vary between regions with stronger increases in warm seasons in America while Europe has notable changes in the cool season (Bates et al., 2008).

In a more general sense, studies have indicated that runoff trends are not always consistent with changes in precipitation. However, there is more concrete evidence on changes on the timing of river flows in many regions. There is a pronounced shift in high latitudes where winter precipitation may fall as rain instead of snow and snow-melt begins earlier than before (Bates et al., 2008).

2.4.2 Precipitation and Temperature

For a mid century warmer climate, the AR4 generation of climate models indicate that precipitation generally increases in areas of regional tropical precipitation. There is also a general decrease in the subtropics, and an increase at high latitudes as a consequence of a general intensification of the global hydrological cycle (Meehl et al., 2007).

The AR4 reports that there is close agreement of globally averaged surface air temperature multi-model mean warming for the early 21st century for concentrations derived from the three Emission Scenarios (B1, A1B and A2) scenarios. The warming averaged for 2011 to 2030 compared to 1980 to 1999 is between 0.64^oC and 0.69^oC. The mid-century (2046 - 2065), the choice of scenario makes a difference for the magnitude of multi-model globally averaged surface air temperature warming, with values of 1.3^oC, 1.8^oC and 1.7^oC for B1, A1B and A2, respectively. Global patterns of the three scenario and time periods are given in Figure 2.4

2.4.3 Changes in Runoff

It has been estimated from historical discharge records that it is likely that for each 1^oC rise in temperature, global runoff will increase by 4% (Labat et al., 2004). Applying this projection to changes in evapo-transpiration and precipitation leads to the conclusion that global runoff is likely to increase by 8% towards the end of the century. Changes in runoff based on GCMs show increases up of 10 – 40% in eastern equatorial Africa. They also predict 10–30% decreases in runoff in southern Africa by 2050, (Milly et al., 2005). Milly et al. also compared the end of the 20th century with a future period at the end of the 21st century. Figure 2.6 shows the relative changes based on this comparison. The multi-model ensemble was used to predict the complex pattern of streamflow change that can be anticipated in the 21st century. As shown in figure 2.6 results from the models predict 10 to 40% increases in runoff in eastern equatorial Africa, the La Plata basin and high latitude North America and Eurasia by the year 2050. They also predict 10 – 30% decreases in runoff in southern Africa, southern Europe, the Middle East and mid-latitude western North America by the year 2050. Globally, for all the regions there is a ’runoff

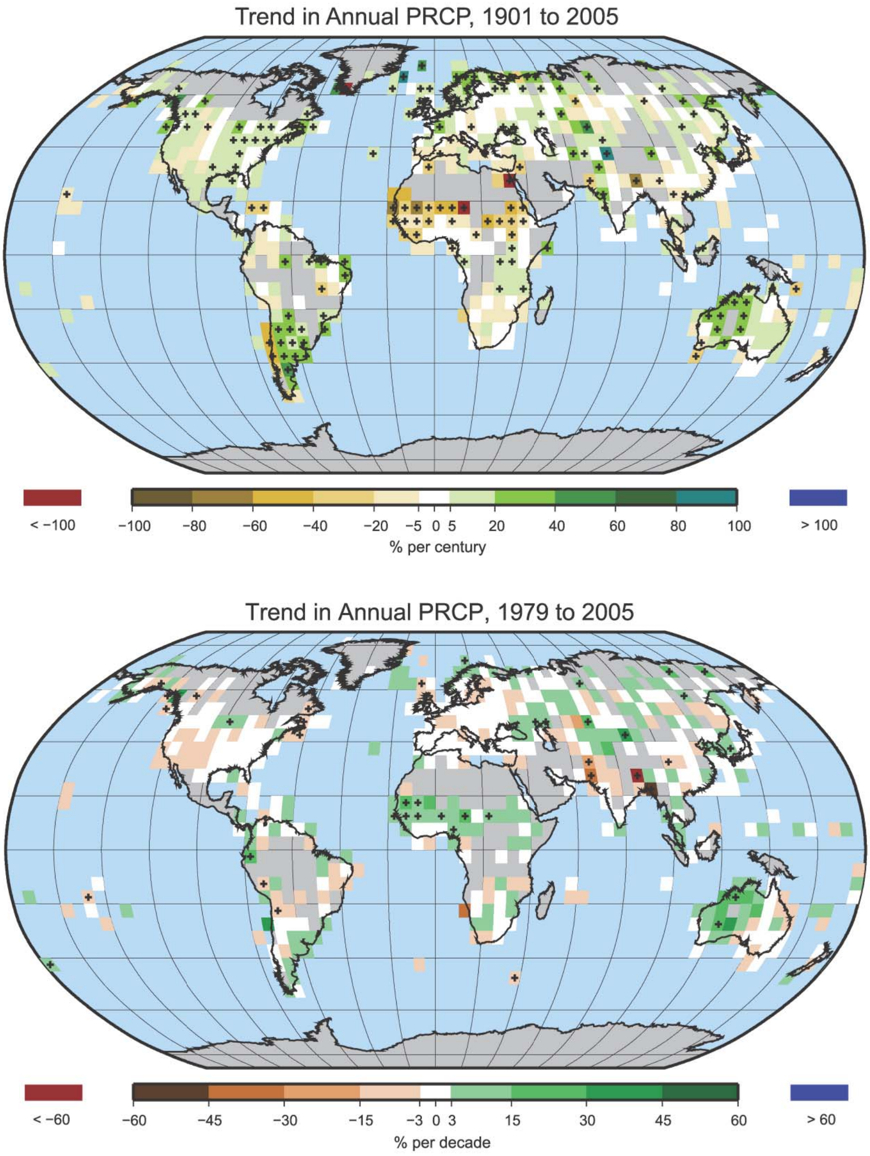


Figure 2.3: *Trend of annual precipitation amounts, 1901 - 2005 (upper, % per century) and 1979-2005 (lower, % per decade), as a percentage of the 1961-1990 average, from GHCN station data. Grey areas have insufficient data to produce reliable trends. from (Bates et al., 2008) Chapter 2, page 17 figure 2.3.*

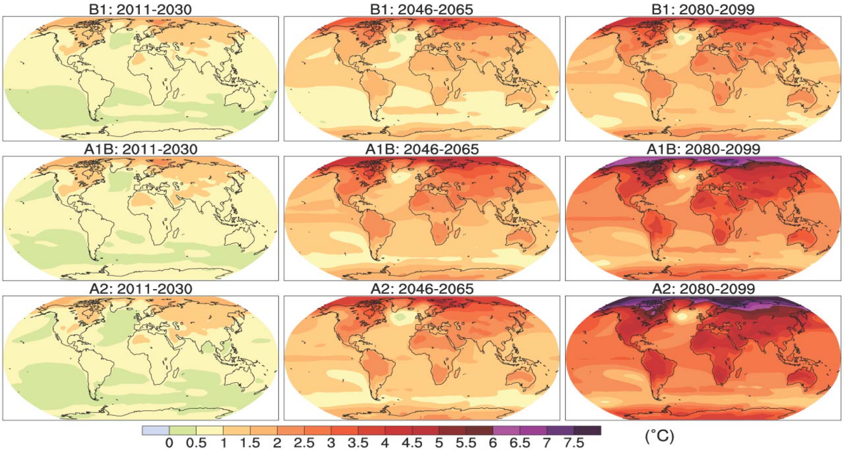


Figure 2.4: *Multi-model mean of annual mean surface warming (surface air temperature change, řC) for the scenarios B1 (top), A1B (middle) and A2 (bottom), and three time periods, 2011 to 2030 (left), 2046 to 2065 (middle) and 2080 to 2099 (right). Anomalies relative to the average of the period 1980 to 1999. from (IPCC, 2007). Chapter 10, page 766 Figure 10.8*

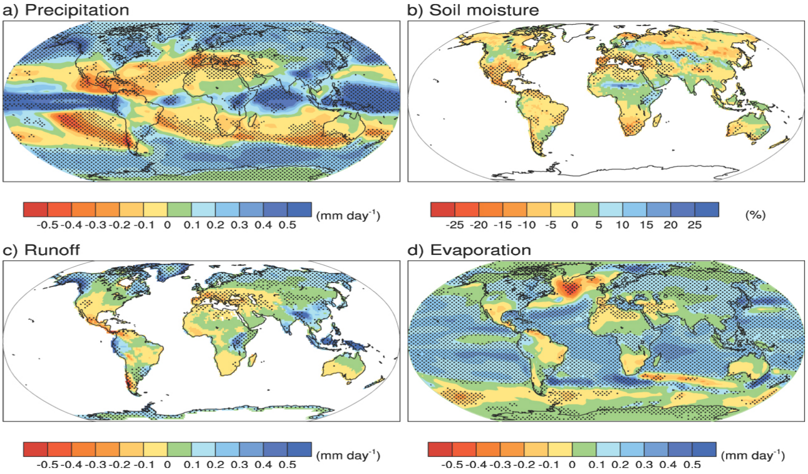


Figure 2.5: *Fifteen-model mean changes in (a) precipitation (mm day^{-1}), (b) Soil Moisture (%), (c) runoff (mm day^{-1}) and (d) evaporation (mm day^{-1}). Regions are stippled where at least 80% of models agree on the sign of the mean change. Changes in annual means for the scenario SRES A1B for the period 2080 - 2099 relative to 1980 -1999. from (IPCC, 2007) Chapter 2 page 27 Figure 2.8*

multiplier' such that a small percentage change in precipitation yields a much higher percentage change in runoff. This runoff 'multiplier effect' occurs because runoff (R) is the difference between precipitation (P) and evapo transpiration (E). If, for example, P is 1000 mm and E is 800 mm, R will be 200 mm. If P now increases by 10% to 1100 mm with no change in E, runoff will increase from 200 mm to 300 mm, or by 50%, a multiplier effect of 5.

2.4.4 Projections for Africa

The projections for Africa are mixed with increases in some region and decreases in other region. For the region of southern Africa, IPCC projected changes in the near surface temperature between the period 1980 – 1999 and the period 2080 – 2099 in the (MMD) under A1B scenario is shown in figure 2.7. The mean temperature is projected to increase by 3 – 4^{o}C. This is higher than the projected global mean temperature increase and hence the region is projected to warm more than the average global warming towards the end of the century. Figure 2.8 illustrates some aspects of temperature and precipitation from MMD-A1B scenario projections. Much of Southern Africa is projected to be drying up and models show some agreement on this trend. This is a result of the larger picture of drying in the subtropics on the global scale. This is said to be a hydrological response to a warmer atmosphere that is a result of increased water vapour and the resulting vapour transport in the atmosphere from regions of moisture divergence to regions of moisture convergence (IPCC, 2007). In this region, the drying is a result of processes of shifts in the circulation across the south Atlantic and Indian oceans. This is further modified by the orographic forcing further inland. The projections point to delays in the onset of rainy season for this region.

However in regions like southern Africa, where rainfall is mostly of a small–scale convective nature, GCMs due to their coarse resolutions are not able to accurately bring out the differences within a grid cells typically currently at 200 x 300 km. This calls for the use of data with finer resolution or point (station–based data). The RCMs, although have been said to introduce more uncertainties on top of uncertainties from GCM, have added value for climate scenarios for such regions. Regional climate modelling has been carried out based on RCMs (Bergstrom et al., 2001).

The IPCC (2007) reported that there are several climate projections based on RCM available for Southern Africa but not so much for other parts of Africa. Among these focusing on Southern Africa are (Tadross et al., 2006:) and (Hewitson and Crane, 2006). Tadross et al. examined 2 RCM nested over Southern Africa driven by HadCM3 under emission scenario A2. It was observed from this study that the western part of the region is expected to be drying up while the eastern part of the region is expected to receive increased rainfall. Hewitson and Crane used empirical downscaling to provide projections for precipitation using six GCM simulations.

A more recent study in east Africa concluded that the rate of change was uncertain but all evidence pointed to a wetter climate with more intense wet seasons and less severe

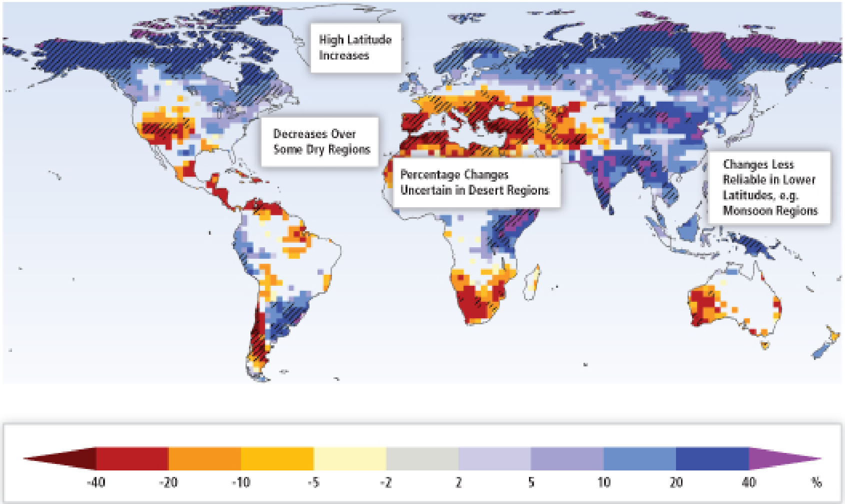


Figure 2.6: *Large-scale changes in annual runoff (water availability, in percent) for the period 2090 to 2099, relative to 1980 to 1999. Values represent the median of 12 climate model projections using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change. (from (SRREN-IPCC, 2011; Kumar et al., 2011), Chapter 5, page 448 Figure 5.4*

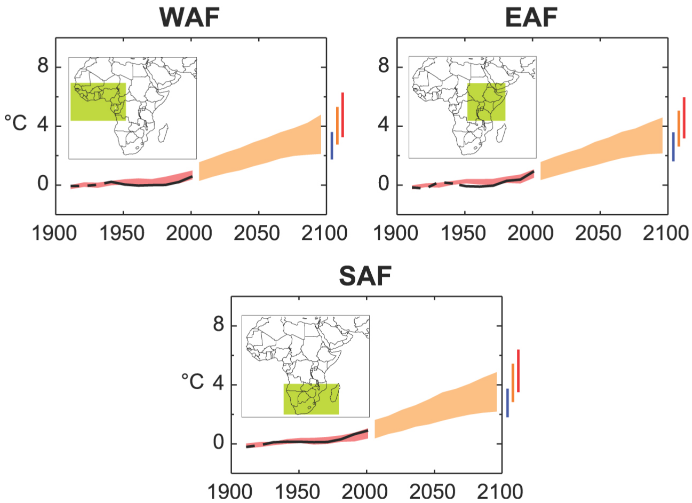


Figure 2.7: *Temperature Anomalies with respect to 1901–2005 for Southern Africa Region. The black line is 1906–2005, red envelope simulated by MMD models (with forcings) and Orange is projected 2001–2100 by MMD models under A1B emission scenario. The bars on the right side of the plot represent projection under different emission scenarios (Blue for B1, Orange for A1B and red for A2) from (IPCC, 2007) Chapter 11, page 868 Figure 11.1*

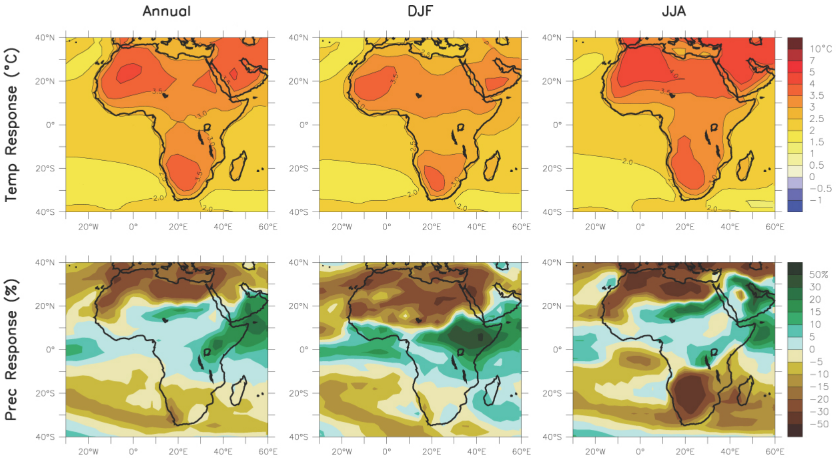


Figure 2.8: *Temperature and Precipitation changes over Africa from the MMD model–A1B simulations. On top row, Annual, DJF, JJA temperature changes between 1980–1999 and 2080–2099 (Average of 21 Models). The bottom row is precipitation changes in percentage, from (IPCC, 2007),Chapter 11, page 869 Figure 11.2*

droughts, (Shongwe et al., 2011). They noted that although their analysis of simulated precipitation show upward trends from early in the beginning of the 21st century, parts of East Africa could still be experiencing drier conditions. An example is given of local trends in Rwanda and Burundi that have been negative over the last decades of the 20th century. This is attributed to natural variability or model deficiencies in this complex region, (Shongwe et al., 2011). Another study of sub-regional hydropower planning programme, under the Nile Equatorial Lakes Subsidiary Action programme (NELSAP), included some sensitivity analyses to study the impact of climate change on the different hydropower projects.

In a similar study in southern Africa (like East Africa), Shongwe et al. observed that over the western parts of southern Africa, an increase in the severity of dry extremes paralleled a decrease in the mean precipitation during austral summer months. There is a notable delay in the onset of the rainy season found in almost the entire region of southern Africa. Early ending was found in many parts of the region implying shortening of the rainy season. Reduction in moisture influx from the southwestern Indian Ocean during the austral spring is projected in their analysis implying delayed rainfall onset in southern Africa. The northeasterly shift of the tropical temperate cloud band is likely to cause more severe droughts in the southwest of southern Africa and enhanced precipitation farther north in Zambia, Malawi, and northern Mozambique. This study showed that changes in the mean annual rainfall vary on relatively small spatial scales in southern Africa and differ between seasons. Changes in extremes often, but not always, parallel changes in the mean precipitation, (Shongwe et al., 2009a,b).

Changes in Africa Runoff

There are very few studies that have attempted to make future runoff projections. Changes in temperature, wind speed, humidity and the nature and distribution of vegetation will also affect water availability. Higher temperatures are likely increase both potential and actual evapo-transpiration. Changes in the inter- and intra-annual variability of rainfall may lead to significant impacts on the spatial and temporal distribution of runoff. Gleick and Elizabeth Gleick (1993) examined how the shared water resources of international river basins may be affected by climate change. The results suggest that runoff in the semi-arid areas of the continent is highly sensitive to fluctuations in rainfall and temperature. A study in West Africa's Niger Basin showed runoff increases of 30-50% and in other regions decreases of 15-59% were reported. The Nile Basin could have a 50% reduction in runoff in the Blue Nile catchment (Hulme et al., 1995). A study on the Zambezi River used a simple rainfall-runoff analysis driven by three climate model scenarios; runoff decreased due to climate change. Elsewhere it has been reported that just a slight rise in temperature resulted in a fall in river flows of at least 10% and increases in open water evaporation of 14%. There are other basin-wide studies published in literature (Gosling et al., 2011). Generally it may be concluded that the nature of future runoff projection for Africa is not well known. A recent study on projected reductions in the runoff in most of the sub-basins (Yamba et al., 2011).

2.5 Future Projections of Hydropower Production

Hydropower production, depending on river flow, is sensitive to both total runoff and to its variability and seasonality. Therefore an increase in climate variability even with no change in average annual runoff could impact hydropower output and performance. Many assessments have been done around the world on the impacts of climate change on hydropower. The next sections summarize some of the studies at regional levels.

The electricity production potential of hydropower plants existing at the end of the 20th century will increase by 15–30% in Scandinavia and northern Russia, where currently between 19% (Finland) and almost 100% (Norway) of the electricity is produced by hydropower, (Lehner et al., 2005). In the south decreases of 20–50% in Portugal, Spain, Ukraine and Bulgaria (Lehner et al., 2005). For the whole of Europe (with 20% share of hydropower), hydropower potential is projected to decrease by 7–12% by the 2070s (Bates et al., 2008).

Another example in the south of Europe, studies in the Swiss Alps predict total runoff reductions, (Schaefli et al., 2007). A Scandinavia-wide study concluded that increases in hydropower production in most areas is expected, but changes in winter seasons would have practical implications for the design and operation of many hydroelectric power plants, (Bergstrom et al., 2001) (Bergström et al., 2012) . These findings on increased hydropower have also been replicated by other studies, for example (Graham et al., 2007) (Strzepek and Yates, 1997) and (Klein et al., 2002).

Studies in the USA have indicated reductions for example, Ontario's Niagara and St. Lawrence - 25–35% and Colorado River hydropower, California's high-elevation hydropower and Pacific Northwest although other studies (St. Lawrence River by 1–7%) showed a small gain in hydropower potential (+3%) (Bates et al., 2008), (Christensen et al., 2004), (Moulton and Cuthbert, 2000) (Lofgren et al., 2002)),(Markoff and Cullen, 2008) (Vicuna et al., 2008). In southwestern USA it was shown that temperature rise would lead to increased draw-down of reservoirs, (Robinson, 1997). In the northern Canadian regions increase in spring or winter floods the projected and could lead to excessive spills that could jeopardize the integrity and operations of certain hydropower stations, (Filion, 2000).

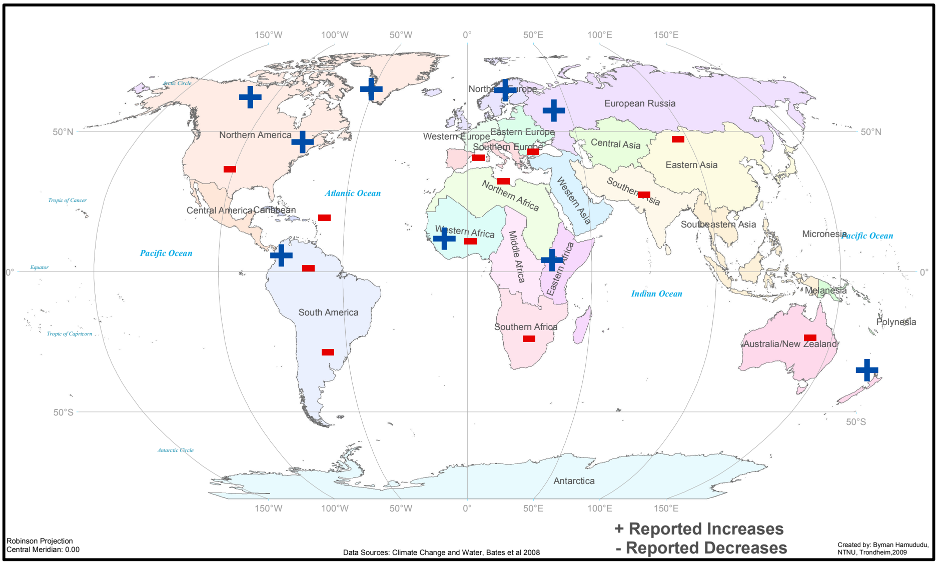
There are few published studies focused on hydropower in the context of climate change in Africa. Much of the impact on hydropower can be deduced (with reservation) from studies of precipitation and temperature as well as climate model predictions on the same. Most of the outlook for Africa is pointing to reduced hydropower production except in eastern Africa. In east Africa most climate models predict increases in precipitation. This projected increase in hydropower potential needs to be confirmed through detailed analysis on small spatial scales which should include downscaling of climate model results, (Shongwe et al., 2006; Arnell et al., 2004).

In the Zambezi Basin, Harrison and Whittington applied a water balance model for the basin of the proposed Batoka Gorge project to climate change scenarios from two GCMs (without downscaling). Harrison and Whittington predicted reductions in river flow levels (10 - 35%) and consequently changes in potential electricity production (6 -21%), with declines in the dry seasons twice as much as the annual change (Harrison and Whittington, 2002). A reduction in hydroelectric power is also anticipated elsewhere, when river flows are expected to decline (Whittington and Gundry, 1998; Magadza, 2000).Another study on the Zambezi showed that hydropower production potential tended to reduce in most of existing and proposed hydroelectric power schemes owing to climate change and increasing water demand (Yamba et al., 2011)

2.6 Hydropower in the Future

The current estimates of hydropower potential are based on observed data for the prevailing climatic conditions. There are various reasons for the likely change in hydropower production potential but the most important are river flow changes, changes in extreme events and changes in loads of sediments transported. Runoff changes related resulting from changes in local climate (precipitation and temperature) in the catchment area may lead to changes in runoff volume, variability of flow and seasonality of the flow, directly affecting the resource potential for hydropower generation. Increased sediment load could also fill up reservoirs faster and decrease the live storage, reducing the degree of regulation and decreasing storage services (Hamududu and Killingtveit, 2012; Kumar et al., 2011; Bates et al., 2008; IPCC, 2007).

It has been reported that the average global or continent-wide impacts of climate change



Data Sources: Climate Change and Water, Bates et al 2008

Created by: Byman Hamududu, NTNU, Trondheim,2009

Figure 2.9: *Future Global Hydropower Production changes. Regions with (+) are regions projected with increase and those with (-) are regions where studies have projected decreases in power production inferred from research studies reviewed. The studies vary a lot in methodology and scale. See Appendix C for the list of studies and methodologies used.*

on hydropower resource potential are expected to be relatively small, but significant regional and local effects can be expected (Hamududu and Killingtveit, 2012). The hydropower resource potential depends on factors such as topography and the volume, variability and seasonal distribution of runoff. Not only are these regionally and locally determined, but an increase in climate variability, even with no change in average runoff, can lead to reduced hydropower production unless more reservoir capacity is built and operations are modified to account for the new hydrology that may result from climate change (Kumar et al., 2011). In order to make more accurate quantitative predictions of regional effects it is therefore necessary to analyse both changes in average flow and changes in the temporal distribution of flow, using hydrological models to convert time series of climate scenarios into time series of runoff scenarios.

In Africa, the electricity supply in a number of countries is largely based on hydroelectric power. However, few available studies examine the impacts of climate change on the hydropower resource potential in Africa. Observations deducted from general predictions for climate change and runoff point to a reduction in hydropower resource potential with the exception of east Africa (Hamududu et al., 2010).

2.7 Discussions

Reduced hydropower production is expected in many areas where precipitation is projected to decline. In other areas with increased precipitation, an increase in production is projected. Figure 2.9 summarizes the findings regarding global projections for hydropower. Changes in seasonal timing, and increased variability will affect hydropower system operation. The impact of this could be offset by increasing storage and/or capacity, subject to other economic and environmental considerations. The change in seasonality could reduce operation problems in some high latitude areas where winter runoff will increase and problems associated with ice will decrease.

More stress from competing water uses such as increases in the demand for domestic and irrigation water may be encountered and/or there may be more interest in protecting waterways and landscapes which conflicts with future efforts to develop new sites. This could lead to the reduced role of hydropower in contributing to the mitigation of climate change. There could also be increased difficulty in system operation. There is need to carry out an assessment of the robustness of current systems in a future with altered conditions. The uncertainty in the planning process is high because different climate models and scenarios give varying projections. Quantifying the uncertainty across models and improving skill in modelling climate and climate change precipitation has the potential to greatly improve decision making and make the planning process more robust. Otherwise there would be need to review how to deal with the hydrological risks if climate change was to exacerbate it.

Globally there is need for more climate change studies specifically targeted to hydropower systems and targeted for specific regions or systems. In some regions such as Africa, there is a greater need for focused studies. Some information can be gleaned from studies focused on precipitation and temperature, but without detailed precipitation-runoff modelling, conclusions drawn from such analysis have limited applicability.

There is need for uniform assessments employing multi–models, both for climate and hydropower systems, on a scale of catchments and individual power plants in order to establish the true type and variation of the impacts, the correct magnitude, the associated uncertainty and the needed interventions and investments for adaptation. Climate change should form a part of conventional project appraisal where it can be used to describe the uncertainty in the hydrology and give better inputs to technical, environmental, economic and financial analyses. Such integrated climate-hydrological-hydropower modelling is the main topic and tools for further analysis in the chapters that follow.

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Chapter 3

The Methodology for Assessing Climate Change Impacts on Hydropower

3.1 Approaches to Assessing Impacts of Climate Change on Hydropower

There are several conceptual steps in the process of assessing climate change impacts on hydropower generation systems, as can be seen in Figure 3.1. The framework revolves around the procedure used in the development of input data (often time series) in hydrological modelling for impacts assessment. The first procedures involves using the GCM simulated data directly in the hydrological modelling or hydropower simulation. This has been applied in very large basins or regions. The second procedure uses the change signal of the GCM simulated through the delta approach, explained in section 3.2.2. The delta change is usually applied on the observed data (time series). The third procedure applies downscaling from the GCMs and derives the delta change from the downscaled results. The fourth method involves downscaling and deriving the time series ensembles from the downscaled data. In this procedure new time series are developed based on the observations and GCMs. The ensembles are then used as inputs in the hydrological or hydropower modelling. The use of any of these procedures depends on many factors such as: (i) the objective of the assessment, (ii) the level of detail required, (iii) the geographical coverage, (iv) availability of hydropower system description data and (v) availability of observation data. The procedures can be seen as stepped analyses, the modelling begins to be complex as are the detail and data requirements, beginning at the global scale down to small basin scale.

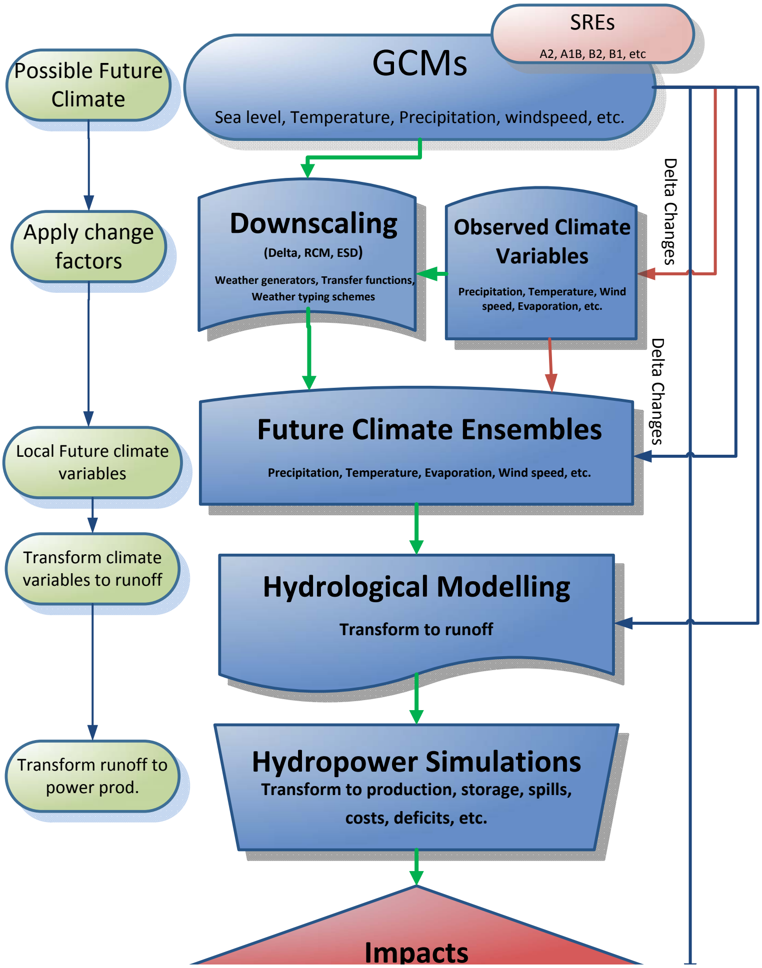

Figure 3.1: *Climate Change Impact Assessment modelling process required to assess impacts on Hydropower Systems.*

3.1.1 GCMs Direct

The procedure at this level is a quick assessment of future impact scenarios. As mentioned before, the future GCM/s data are used directly as the input into modelling. The procedure takes the location of interest and data are retrieved from GCMs. This procedure usually uses the mean annual values of precipitation, temperature and runoff. The mean annual runoff is the average value of all annual runoff amounts estimated from the period of record or during a specified base period from a basin. This is the average amount of water on the surface of the basin that can be utilized in a year. The mean annual runoff is used to characterize changes in runoff in a region / basin. Although this estimate is not very accurate, it serves as rapid indicative estimate of the likely impacts of climate change on the discharge from a basin. This is a useful quick estimate of changes that may be carried out in scooping papers or reports. Later, a more detailed and accurate analysis may be carried out to gain insights in the details. It is has been pointed out that many decisions affecting water resources over the long term are being made in regions where detailed assessments have yet to be made.

At this low resolution level, hydropower systems are combined at the national or state levels with the changing climate. In this way, the process will avoid complex individualized assessment of hydropower plants, that would be expensive and time consuming to carry out. The mean annual flow for the current period is taken as the basis and the future flow obtained from future mean flow is used as the main driver. While there are several assumptions, it is a practical, easy and quick way to asses the impact on such a large scale. Here, changes in the mean annual flows (Q_{mean}) are sufficient to gain insights into the expected changes. The current and future mean annual flows are then used as the current and future water resources respectively. These are applied to the hydropower simulation model to obtain the future production from the hydropower systems. The capacity factor is added to find out if the hydropower system is able to cope with increased or reduced water resources. This gives a general picture of the global view of impacts. This approach is applied in Chapter 5 - Assessment of impacts of climate change on global hydropower. The climate change scenarios will be used to assess the impact on mean annual flows. With these changes in mean annual flow, the general picture of the future production of hydropower systems is then generated.

The direct use of GCM output from control simulations into hydrological model simulations typically leads to considerable deviation in river discharge from observations due to systematic biases (Graham et al., 2007). GCMs have demonstrated a significant skill at the continental and hemispheric spatial scales and incorporate a large proportion of the complexity of the global system. The spatial scale on which a GCM operates in resolution ranges of 2.5^o x 3.75^o (HadCM3) representing a grid of 300 - 400 km (Wilby et al., 2002). GCMs are inherently unable to represent local sub-grid scale features and dynamics. Moreover, the accuracy of GCMs in general decreases from climate–related variables, such as wind, temperature, humidity and air pressure to hydrological variables such as precipitation, evapo–transpiration, runoff and soil moisture. These limitations of the GCMs restrict the direct use of their output in hydrology.

However there are cases where GCM outputs have been used directly to project river runoff (Landman et al., 2001), (Milly et al., 2005). The observations for large–scale basins are not adequate to represent the entire basin accurately both in quantity and quality especially in Africa where observations are generally poor. As GCMs cover the entire globe, they are thought to provide an alternative data source for hydrological modelling.

The use of GCM outputs as hydrological outputs for macro-scale basins has been carried out by many researchers in hydrology (Xu, 1999). The analyses are based on the fact that GCMs have a simple bucket model for water balance, i.e. for each cell. If the precipitation exceeds evaporation, then soil is filled up and runoff occurs and as long as this is close to saturation, the actual evaporation is equal to potential evaporation rate . The studies found agreements for river basins with a mean annual runoff between 200 and 600 km^3/year but poor agreements for large basins with small total runoff (Xu, 1999). The conclusion was that using GCMs to predict runoff was poor due to many factors such as the treatment of water excess and other feedback mechanisms that exist in the hydrological cycle (Kite et al., 1994),(Kite, 1998).

Another method of using GCM outputs directly is to use the precipitation and temperature from GCM directly as input in the hydrological model. A study on Mackenzie and Columbia River basin used GCM output temperature and precipitation as input into the hydrological model. In this study, it was concluded that the GCM output could be used in areas with inadequate observations but this should be restricted to very large basins (Kite and Haberlandt, 1999).

Scaling Approach

A suggested way of making more use of information from climate models while producing reasonable hydrological simulations for the present climate is to use a scaling approach. Scaling implies an adjustment of specific variables to reduce systematic biases. The scaling factors derived for the control simulation of a particular climate model are applied to adjust scenario simulations. Mean annual GCM/RCM precipitation and temperature are scaled to mean annual observations with constant scaling factors.

3.1.2 Delta Approach

The second method is the derivation of the delta and applying the delta change on the observed data. The concept in this method is that a change signal (delta) in the GCMs when applied to the observations would transform the existing records to likely future records. This is the most used method as it is simple and quick. The most common transfer method used hitherto - delta approach (Arnell and Reynard, 1996; Lettenmaier et al., 1999; Bergstrom et al., 2001; Graham et al., 2007), often referred to as 'delta change' or the 'change factor' method (Wilby et al., 2002). The signal of climate change from climate models to hydrological models or other impact models is the 'delta change' approach, where differences in climate variables are extracted from the GCM control and scenario simulations and projected into an observed database (Bergstrom et al., 2001). This is achieved by applying these change factors, or perturbations to historical data and this produces a set of historical records adjusted for climate change perturbations for future 30 year periods: 2020-2050, 2050-2080 and 2070-2099. These 'delta' factors are the GCM simulated value for a particular quantity relative to the GCM value over the 'current period' period (1960–1990), and therefore represent the relative change in a quantity as simulated by the GCM. The delta method is useful for large global or regional climate change impacts assessment or for quick assessment of basins.

The delta method assumes that future model biases for both mean and variability will be the same as those in present-day simulations. The delta method has the advantage that climate changes are relative to the historic record and this is relatively easy for water resources managers to interpret and incorporate in existing planning processes. The same factors are used for all years and for all precipitation events, and therefore this method does not alter the current period statistics, like the number of rainy days. The delta approach, does not also include changes in variability between GCM control period and scenario simulations.

The above method is still applicable to large regions like Africa, the difference being that the level of detail increases. In this case the data can be taken on provincial or state level, thereby revealing more details and differences within large units. This methodology is presented in Chapter 6 for Africa. However, at this level it is still time–consuming and expensive to get into hydrological modelling and hydropower simulations may be voluminous and the number of hydropower systems large. As the resolution gets higher and the study area becomes smaller, the data may be summarized and duration curves may be used to assess the changes. A flow duration curve is useful for predicting annual energy potential for any site. It also permits the incorporation of a number of years of data into one data set, presented in form of a curve. The different years provide more information about the variability and occurrence of flows. More importantly, it provides a basis for computing energy output and the percentage of time that a specific energy output can be generated.

3.1.3 Delta Approach from Downscaled Data

A third method, is a variant of the second procedure. It is still the delta approach but differs from the second method in the derivation of the change signal. In this procedure, the delta is derived from the downscaled data as opposed to the deriving it from the GCMs. The application of the delta method is similar to the procedure described above.

3.1.4 Full Detailed Assessment

The last procedure involves carrying out all the steps described in Figure 3.1. These steps are downscaling from GCMs to generate future climate ensembles, using the ensembles in hydrological modelling and applying the results of hydrological modelling in hydropower simulations. In order to explore, the range of possible climate change impacts on the hydropower system in detail, the modelling steps are processed step by step. It is necessary that the steps are followed in order to realize realistic future scenarios of hydropower systems. This is the thorough procedure that is expected to give detailed results with reduced uncertainty. As has been mentioned before, either a simpler way of estimating altered climate variables or a sensitivity analysis for hydrological analysis is used. This results in rough estimates of either of the processes. When this methodology is followed reasonable weight is given to both approaches and the results will be more realistic.

Flow duration curve method

A flow duration curve provides suitable information for understating the regime of the basin. This is a way of incorporating any number of years of data onto a single plot. The high and low flows are preserved and these are very important for aspects of hydropower system design, e.g. storage, spillway and turbine size. The duration curve also permits the computation of the annual energy potential and the percentage of time such a pre-determined production level is exceeded. Although the flow duration curve reveals the time during the year, a particular flow is above or below, it does not show when these events occur. In climate change impacts, the current and future flow duration curves are plotted together and the annual energy production can be re-evaluated based on the future duration curve. The annual energy output is determined by calculating the area below the curve and the runoff.

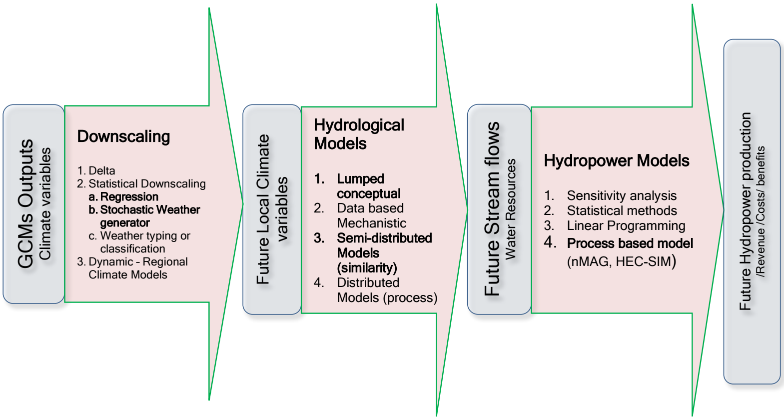

Figure 3.2: *Climate Change Impact Assessment Procedure on Hydropower system. The assessment process moves from left to right, applying modelling at each stage. This figure is part of the main procedural framework in Figure 3.1*

3.2 The Approach

The framework for assessment is a process-based approach throughout the assessment process based on Figure 3.1. The various levels/steps of application will require different methodologies at different levels. The process begins with the GCM outputs at the top and ends with the impacts on hydropower production.

First, GCM outputs for the 21st century under various emission scenarios are selected together with a set of chosen GCMs based on some criteria, in most cases the model/s that perform/s best (Taylor, 2001) .

The second step is to interpolate GCM outputs to the area of interest through the downscaling process to produce a set of regional or local climate perturbations. These local climate variables will represent the local future climate.

The third step is to use local variables (time–series) as inputs for hydrological modelling which is used to simulate stream flows under the perturbed climate.

The last step uses future river flow data in hydropower simulations in order to assess hydropower generation of the hydropower system under the changed climate. Hydropower production is taken to estimate revenue from hydroelectric generation and calculate the changes in revenue relative to non-perturbed operations.

3.2.1 Downscaling

For studies that do not deal with very large basins, it is imperative that downscaling is carried out to have meaningful future scenarios from the GCMs. There are different techniques for downscaling that range from simple to complex and expensive methods. Regional Climate Models have become extremely important in investigating the characteristics of surface parameters, e.g. soil moisture, and their interaction with the atmosphere, which may vary significantly over periods of several days. Dynamic downscaling for climate studies utilizes a regional climate model (5000 x 5000 km) that is nested within a global climate model (GCM). The GCM drives the RCM as initial and time-dependent lateral boundary conditions.

Empirical or statistical downscaling is an alternative approach to obtaining regional-scale climate information (Wilby et al., 1998). It uses statistics to find linkages / resolved behaviour in GCMs with climate in a local station or basin. As long as significant statistical relationships occur, empirical downscaling yields regional information for any desired variable such as precipitation and temperature. This approach encompasses a range of statistical techniques from simple linear regression to more complex applications such as those based on weather generators (Wilby et al., 1998), canonical correlation analysis (Zorita and von Storch, 1999), or artificial neural networks (Hewitson and Crane, 2006).

3.2.2 Hydrological Modelling and Water Resources

The next step in the assessment process deals with translating the future climate variables (from GCMs /RCMs or from statistical downscaling outputs) into stream flows. Hydrological models are simplified, conceptual representations of a part of the hydrological cycle. They are used for hydrological prediction river flows using the climate variables like temperature and precipitation. Two major types of hydrological models can be distinguished: stochastic hydrological models i.e. black box systems, based on data and using mathematical and statistical concepts to link inputs (precipitation, temperature and the like) to the output (runoff). The second type is process-based models i.e. represent the physical processes observed in the real world. These models are known as deterministic hydrology models. The models are further distinguished by how the represent the various hydrological processes. Two basic types result, the lumped and distributed hydrological models. Lumped conceptual models, despite their limitations, are widely used for climate change impact assessment and water resource planning. This is mainly due to their simplicity in implementation and the reduced demand for input parameters when compared to other types of models. It has been observed that uncertainties in simulated stream flow projections are a result of the choice of model calibration period, model structure, and non- uniqueness of model parameter sets. On the other hand, distributed models have the advantages that changes can be implemented in a spatial context. This is true for large basins where input parameters vary across the basin; in this case these changes can be implemented in their spatial context by the model. The lack of complete data to use as input and validate distributed-complex models is making the application of these models difficult. The proposed approach is to use the simplest model that would satisfy the goals of the assessment. The emphasis here is to use a simulation model to obtain runoff.

Even if the GCMs /RCMs have hydrological components, the use of the runoff data from GCMs is discouraged, due to the limitations (Beven, 2003). It is therefore necessary to use hydrological models with better physical parametrization. Here, as in any stage of the assessment process, one is faced with a choice of many rainfall – runoff models with different structures, input parameter requirements and model types. Which of these models is best depends on many factors (Beven, 2003). When time-series data are readily available, hydrological modelling is the best approach to transform the climate variables into changes in runoff. Although this can vary from simple to complex modelling, it is the most accurate way of assessing the climate change impacts on runoff.

3.2.3 Hydropower Simulations - Power Generations and Income

In order to obtain the change in hydropower production that results from climate change, production calculations are necessary and these are carried out using hydropower simulation models. The simulation model normally reflects the main features of the existing hydropower system and is thus run over a number of years to get stable average estimates, first in the current period and then in the future. There are not so many hydropower simulation models when compared to hydrological models. The simplest and statistical way of computing power production is correlation between historical records of flow and production. However, this does not work in all cases. The best approach is to use a process-based hydropower simulation in which most of the important components of the hydropower system are defined. HydroSim (HEC), nMAG (NTNU) (Killingtveit, 2004) and other correlation methods have been used as hydropower simulation models.

3.2.4 Discussion

There are many ways of assessing climate change impacts on hydropower generation systems. The use of an approach depends on many factors such as the level of detail required, the geographical coverage, hydropower system description, and observation data availability. For example, the level of detail required for a global assessment differs from that needed for basin level assessments. Many studies have carried out assessment of hydropower generation in different parts of the world in various ways. Usually basin level assessment involves downscaling from GCMs through detailed hydrological modelling and hydropower simulations, while on a regional level assessment, details begin to be reduced. The methods can be seen as stepped analyses, whereas the modelling begins to be complex, the detail and data requirements also do, beginning at the global scale down to small basin scale. (Medellan et al., 2008) used downscaled hydrological data in a customized modelling scheme to assess the adaptability and adaptations of California's entire water supply system to dry climate warming. (Madani and Lund, 2010) used an energy-based hydropower optimization model, avoiding the conventional modelling (simulation/optimization) methods, due to the large number of hydropower plants in California. The model used was developed for low-resolution, system-wide hydropower studies. In a rather more detailed study of the Danube basin, development of hydropower was modelled using a specially–coupled physically based hydrological model for three hydropower plants, (Koch et al., 2011). Another study on changes to whitewater recreation in California's Sierra Nevada used only elevation and runs as the predictors in identification, mapping and geomorphic classification to anticipate changes in runoff volume and timing from climate warming, (Ligare et al., 2011). Another example of detailed studies was carried out in the northern catchment in Norway (Jerko and Killingtveit, 2010) and recently a very comprehensive region wide assessment of the Nordic region (Fenger, 2007). This study cover various basins ranging from small to large over the entire Nordic region. Different methods of assessment were also applied.

In another approach, a method of modelling high elevation hydropower systems was developed and applied in California, (Madani and Lund, 2009). The method is energy-based and optimization was carried out on energy generation data on a monthly time scale and seasonal energy storage capacities. However there are some limitations. The method is a simplified approach where detailed hydropower data are unavailable. It is a simple approach for developing a good representation of an extensive hydropower system with little time or resources for policy and adaptation studies. Based on the results of some applications, the method is said to be useful for studying large hydropower systems when the level of detail needed is lower. The developed method can be used for studying the effects of climate change on a large hydropower system. In the above method, a large hydropower system (national or regional, large basin) can be modelled. However at the global scale, a more simplified approach is necessary not only to reduce on the complexities but due to lack of data for such a thorough detailed approach.

Lastly different approaches used in this research have been formulated during the research period. These approaches are applicable at different levels of detail required and the amount of available data. At the very top level is an approach used in Chapter 5, which aggregates different types of hydropower systems from various climates to highlight the larger global picture is used. The approach is based on the fact that the current hydropower generation system may only be limited by water availability. The main assumption is that if water inflow reduces, the hydropower systems will likewise reduce generation and vice versa, assuming that current systems can be upgraded. With this approach, changes in annual mean flows are the main predictors of hydropower generation in each unit. The next level, with higher resolution, in Chapter 6 is a similar approach applied with more detail at the regional scale. And finally in Chapter 8, a more detailed approach is applied on several selected basins (large and medium). This is a more thorough approach that uses more detailed hydrological data, hydropower description and future climate variables.

It should be mentioned here that climate modelling is limited by uncertainty at all stages of the assessment process. Uncertainty comes from the whole range of emission scenarios (global socio-economic development), the range of climate models used for a given scenario, the downscaling of climate effects to local/regional scales, hydrological modelling, hydropower simulations and feedbacks from adaptation and mitigation activities. Limitations in observations and understanding restrict our current ability to reduce these uncertainties. Climate change may have a substantial effect on the supply of electricity; however, climate change may also affect demand. Uncertainty should be treated as risk, like many others in water resource projects.

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Chapter 4

Modelling - Climate Change

There are many factors that govern the Earth's climate, but essentially the driving process is the energy supply from the Sun and the interactions of the solar radiations with the Earth and its atmosphere. Figure 4.1 depicts the Earth's energy balance while Figure 4.2 shows how the greenhouse effects affect the energy balance. The alteration of the energy flows /amounts would cause the Earth's climate to change. The most important processes are: properties of solar radiation and the Earth's radiation; the Earth's surface and atmosphere's ability to absorb or reflect the energy; and how these processes and parameters vary with time. The total incoming radiation from the Sun is balanced in general over time (IPCC, 2007).

Greenhouse Gases

The Earth's atmosphere is made up mostly of nitrogen (78%) and oxygen (21%), with a small amount of "trace gases" (1%) mixed in. The tiny percentage of trace gases (carbon dioxide, ozone, methane, and carbon monoxide) and water vapour contribute in a significant way to changes in the Earth's climate. The trace gases, (GHG), allow energy from the Sun (shortwave radiation) to reach the Earth's surface, but absorb energy emitted from the Earth (long-wave radiation); this affects the surface energy balance of the planet by warming the atmosphere directly above it resulting in long-term changes to the global climate. Although an excess of greenhouse gas results in global warming, naturally occurring greenhouse gases are beneficial in keeping our planet at a comfortable temperature.

Aerosols

Small particles in the atmosphere (smoke, dust, manufacturing, etc.) affect how the Earth system behaves. Aerosols absorb and scatter radiation, which cause either warming or cooling of the atmosphere. They also are important to the formation and behaviour of

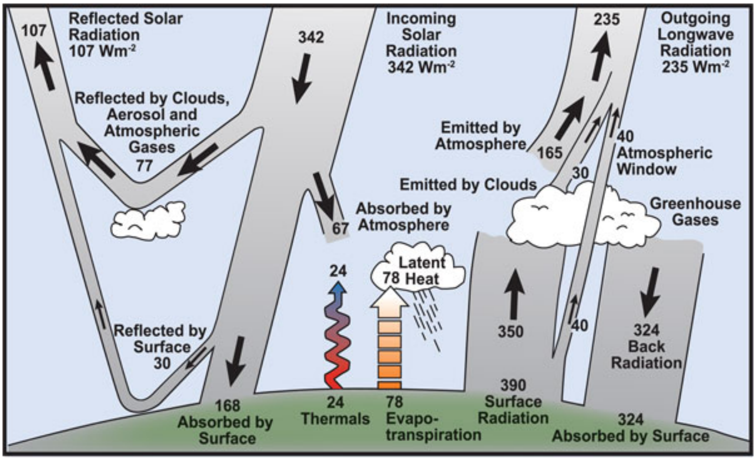

Figure 4.1: *Estimate of the Earth's Mean Energy balance from (IPCC, 2007), Chapter 1, page 96, FAQ 1.1 Figure 1*

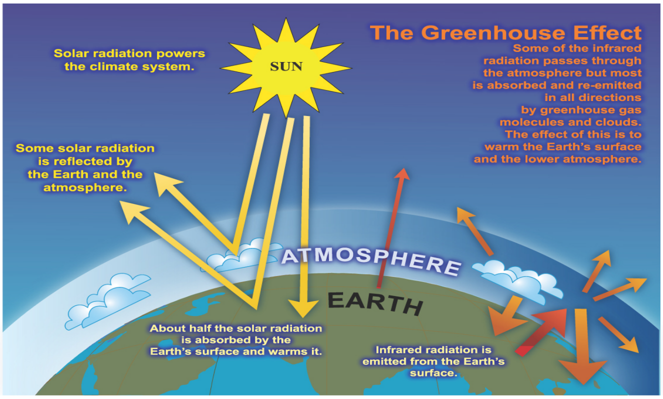

Figure 4.2: *Greenhouse Effect from (IPCC, 2007), Chapter 1, page 115, FAQ 1.3 Figure 1*

clouds, and influence the water cycle and the Earth's radiative balance.

Emission Scenarios

IPCC SRES (Special Report on Emissions Scenarios - SRES) scenarios were constructed to give likely future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. The IPCC SRES scenarios contain various driving forces of climate change, including population growth and socio-economic development (Nakicenovic, 2000). Future levels of global GHG emissions are a product of very complex, incompletely-understood dynamic systems, driven by forces such as population growth, socio-economic development, and technological

Table 4.1: *Scenario Story lines and their descriptions,source: (Nakicenovic, 2000)*

StoryLine	Description of Scenario
A1	The **A1storyline** and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. This scenario develops into four groups depending on technological and energy system change.
A2	The **A2storyline** and scenario family describes a very heterogeneous world. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storyline.
B1	The **B1storyline** and scenario family describes a convergent world with the same low population growth as in A1, but with rapid changes in economic structures towards a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.
B2	The **B2storyline** and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in B1 and A1.

progress among others (Nakicenovic, 2000).Emissions scenarios are a central component of any assessment of climate change. The scenarios are based on story lines that can be summarized as follows in Table 4.1.

Figure 4.3 highlights the estimates about how much warming results from each of the future forcing family scenarios. The effect of each storyline can be seen in the CO_2 emissions which result into temperature rise

4.0.5 Global Circulation Models

Global Circulation Models (GCMs) are numerical models representing physical processes in the atmosphere, ocean, cryosphere and land surface. They are the most advanced tools currently available for simulating the response of the global climate system to increasing GHG concentrations. While simpler models have also been used to provide globally- or regionally-averaged estimates of the climate response, only GCMs have the potential to provide geographically and physically consistent estimates of regional climate change which are required in impact analysis. Table 4.4 lists the GCMs used by the IPCC, (IPCC, 2007). Climate models are the only means to estimate the effects of increasing GHGs on future global climate.

4.1 Climate Scenarios

Climate scenarios developed for impact studies usually require that some estimate of climate change be combined with baseline observations of climate data (IPCC, 2007). These future scenarios may be reported as an ensemble of GCMs or few selected GCMs or sometimes one GCM.

The *first method* is simple interpolation of the climate model data to a finer spatial resolution. In this approach, changes in climate at a fine spatial scale (for example 0.5^o x

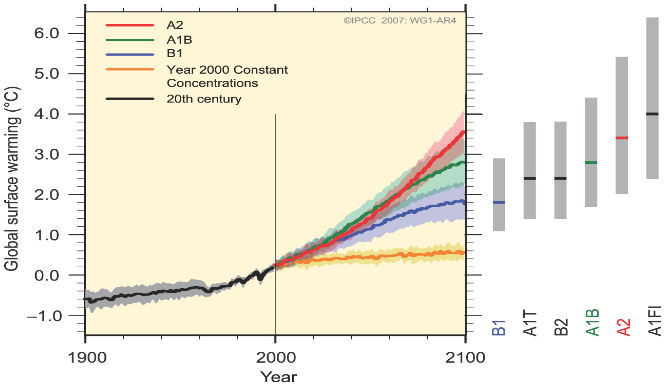

Figure 4.3: *Temperature Change based on scenarios. Depending on the scenario chosen, the expected rise in GHG-concentrations varies. The envelope shows the region covered by several models with SRES. from (IPCC, 2007)*

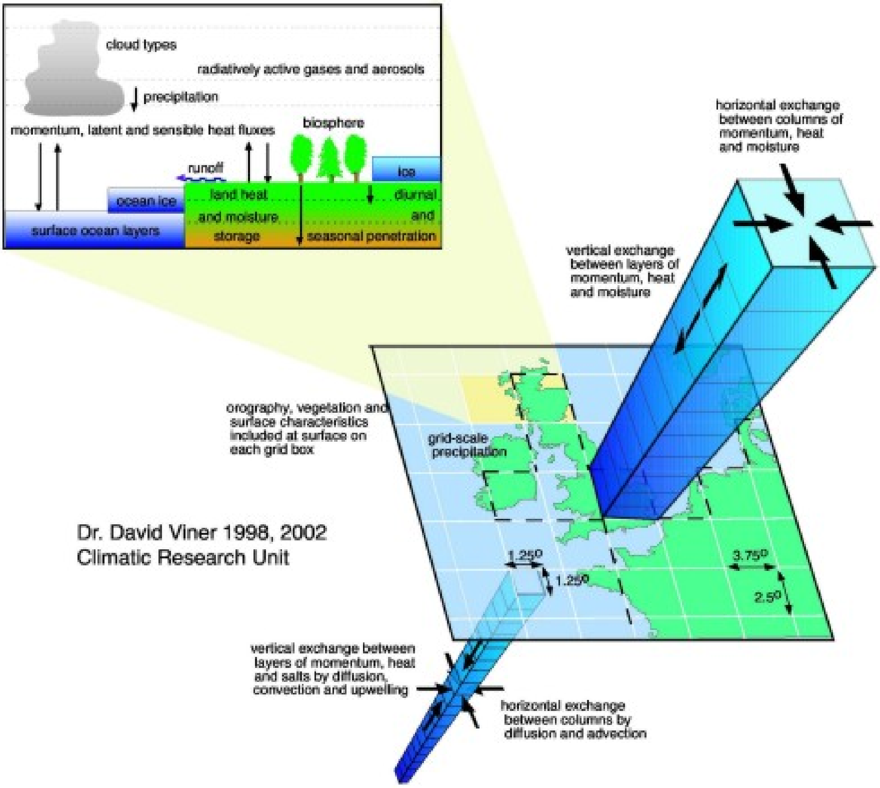

Figure 4.4: *The coupled GCM extends from the bottom of the ocean to the upper atmosphere with several layers. These are modelled in the 3D based on each grid cell from (IPCC, 2007)*

Table 4.2: *List of Global Circulation Models used in the AR4 (from (IPCC, 2007))*

	Name	Model	col Lon	row lat	Time units days since	Center	City	Country
1	BCM2	bccr bcm2 0	128	64	1800-1-1	BCCR	Bergen,	Norway
2	CGMR	cccma cgcm3 1	96	48	1850-1-1	CCC	Victoria,	Canada
3	CGHR	cccma cgcm3 1 t63	128	64	1850-1-1	CCC	Victoria,	Canada
4	CNCM3	cnrm cm3	128	64	1860-1-1	CNRM	Toulouse,	France
5	CSIRO3.0	csiro mk3 0	192	96	1860-1-1	CSIRO	Melbourne,	Australia
6	CSIRO3.5	csiro mk3 5	192	96	1860-1-1	CSIRO	Melbourne,	Australia
7	GFCM20	gfdl cm2 0	144	90	1861-1-1	GFDL	Princeton,	USA
8	GFCM21	gfdl cm2 1	144	90	1861-1-1	GFDL	Princeton,	USA
9	GIAOM	giss aom	90	60	1850-1-1	GISS	New York	USA,
10	GIEH	giss model e h	72	46	1880-1-1	GISS	New York	USA
11	GIER	giss model e r	72	46	1880-1-1	GISS	New York	USA
12	FGOALS	iap fgoals1 0 g	128	60	1850-1-1	IAP	Beijing,	China
13	ECHAM4	ingv echam4	320	160	1870-1-1	INGV	Bologna,	Italy
14	INCM3	inmcm3 0	72	45	1871-1-1	INM	Moscow,	Russia
15	IPCM4	ipsl cm4	96	72	1860-1-1	IPSL	Paris,	France
16	MIHR	miroc3 2 hires	320	160	1850-1-1	CCSR	Tokyo,	Japan
17	MIMR	miroc3 2 medres	128	64	1850-1-1	CCSR	Tokyo,	Japan
18	ECHO G	miub echo g	96	48	1860-1-1	MIUB	Bonn,	Germany
19	ECHAM5	mpi echam5	192	96	1860-1-1	MPI	Hamburg,	Germany
20	MRCGCM	mri cgcm2 3 2a	128	64	1801-1-1	MRI	Tsukuba,	Japan
21	CCCSM3	ncar ccsm3 0	256	128	0000-1-1	NCAR	Boulder,	USA
22	NCPCM	ncar pcm1	128	64	0000-1-1	NCAR	Boulder,	USA
23	HADCM3	ukmo hadcm3	96	73	1860-1-1	UKMO	Exeter,	UK
24	HADGEM	ukmo hadgem1	192	145	1860-1-1	UKMO	Exeter,	UK

0.5^o) are interpolated from the climate model resolution using some form of interpolation procedure. The approach is simple, but it is difficult to apply to anything other than mean climate.

The *second method* is statistical downscaling using empirical relationships between coarse-scale and local climate. This approach develops empirical relationships between the two scales using observed climate data, and applies these relationships to simulated coarse-scale climate data.

The *third method* is the use of a regional climate model. This approach uses a RCM nested within the coarse-scale global model to simulate climate over a region at a finer spatial resolution (typically of the order of (0.5^o x 0.5^o).

The *fourth method* is use of a (GCM) in a 'time-slice' experiment. This approach runs the AGCM for a defined time-slice, with just the sea surface temperature determined from a coarse-scale fully coupled atmosphere-ocean model (AOGCM) .

Statistical downscaling is a method that is quick and inexpensive. It is an appropriate method for generating long time series and for exploring a range of different GCM results.

4.2 GCM Selection

Depending on the region, it is likely that some GCMs simulate the climate of the region better than the others. Irrespective of the method of realizing future climate scenario, due to the large number of GCMs and outputs, it is often necessary to select a few GCMs or one out of the total number of twenty-four (Table 4.2). This is normally done to reduce the amount of work and to have good consensus (agreement) regarding future scenarios from the GCMs. The difficulty then lies in selecting the GCMs suitable for the local area under study. Often, the GCM is selected because the data are easily accessible (in easy format) and have been used by many researchers in that region. However it can be argued that the selected GCMs may not be the most appropriate ones for the region and the results may be erroneous. This is not necessarily the best GCM but suitable GCM/s. In this way it would be expected that the results are a better representation of the likely future climate. Thirty-year mean present day (1961 –1990) regional precipitation fields simulated by the GCMs were compared to observed data, using the gridded rain gauge (CRU) dataset (Hulme, 1992). Based on this type of analysis, GCMs that showed better performance were selected. Based on the above analysis, 5 GCMs that consistently performed well were selected. In this region and for each of these groups (clusters) the following GCMs (selected) consistently performed well. The selected models are B - CGCM3, E - CSIRO3, S - ECHAM5, T - CCSM3 and V - HADCM3. Though not the best for many stations, the scores from these models remained high in most stations. Consequently, these are the models that were used in the analyses that follow in the coming chapters. CRU datasets were used as reference (observed) data. For the rest of the analysis in this work, the selected GCMs (see Table 4.2) are the only ones that have been applied unless where there is no data. The common thirty-year periods for which changes are often grouped to simplify the presentation of results. The common periods used are current or baseline, 2020s, 2050s, 2080s and these represents the periods between 1961 - 1990, 2011 - 2039, 2041 - 2069 and 2071-2099 respectively.

Clustering

In order to select GCMs for use, it is necessary to subject the GCMs to performance tests. However before the tests are carried out, the climate system was categorised into groups so that GCMs are assessed based on the climate zone they belong to. In order to uncover the groups of precipitation types, stations were subjected to the correlation and cluster analysis. The climate stations with data were then grouped into climate zones using a method called clustering. Ward's method in cluster analysis of a general hierarchical cluster method was used. The Ward's method calculates the distance between two clusters as the sum of squares between the two clusters added up over all the variables. At each generation, the within-cluster sum of squares is minimized over all partitions obtainable by merging two clusters from the previous generation. The main difference between this method and the other linkage methods consists in the unification procedure.

The classification method is similar to the analogue model in many respects, but a pool of historical data is now distributed into different classes according to the corresponding large-scale circulation pattern (Zorita and von Storch, 1999). The clustering is applied here on the understanding that precipitation patterns occur on mesoscale clusters in association with mesoscale convective systems. Distance measure and clustering methods may vary, but clustering bears similarities to the analogue approach. Clusters tend to consist of points in a K (e.g. number of EOFs) dimensional space which are close to each other compared to members of other clusters.

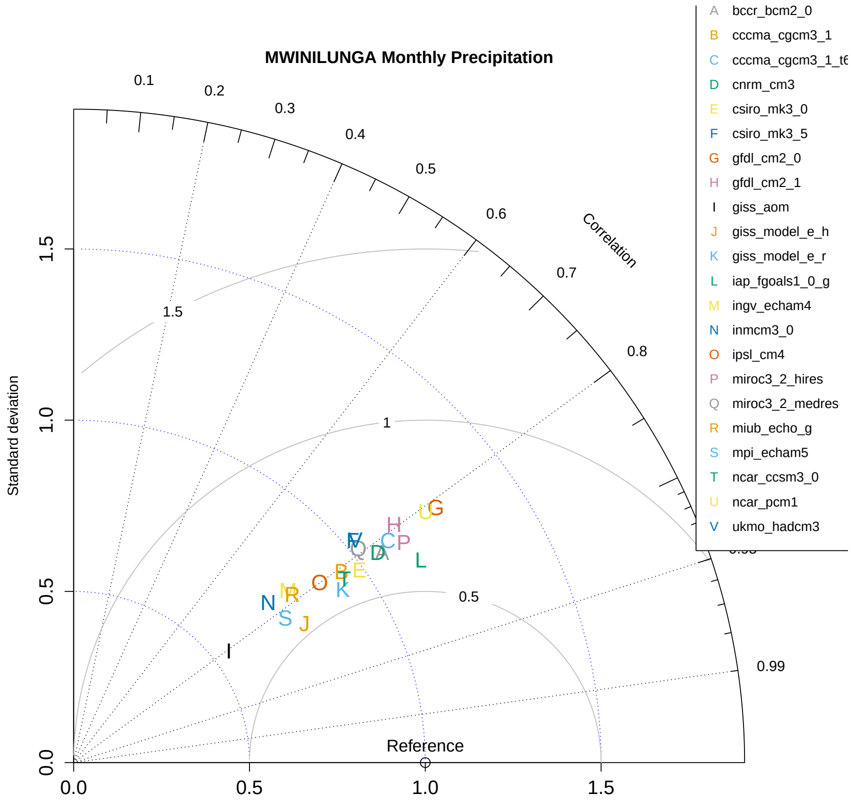

Figure 4.5: *The performance of GCM: Each alphabetic letter represents a GCM. The reference point is the observed data. Along the axes is the standard deviation while the radial lines from the reference represents the root mean square error and the angle of tilt from the y-axis is the correlation. The GCMs represented in this diagram shows relative similar correlation but the standard deviation varies a lot compared to the reference.*

GCM Performance - The Taylor Diagram

The Taylor diagram provides a good way of graphically summarizing how closely a pattern (set of patterns) matches observations (Taylor, 2001). The comparison is based on similarities in patterns between two sets of data. The similarity between patterns is quantified in terms of their correlation, centred root mean square error, and the amplitude of their variations. The Taylor diagram shown in Figure 4.5 displays the quality of model predictions against the reference values, typically direct observations. A diagram is built by plotting one model against the reference, then adding other model points. Often the data is normalized when for easy comparison between the reference and the models. The diagram is used to summarize the degree of correspondence between simulated and observed fields. The correlation coefficient and the root mean square difference between the two sets are represented in one plot by a single point two–dimensional. The limits to agreement between models and observations are different for different fields and generally will vary with the time and space-scales considered. The geometric relationship between the root mean square difference, the correlation and the standard deviation, provide some guidance in devising skill scores that appropriately penalize for discrepancies in variance and differences in pattern similarity. The precipitation data generally give low performance on most models when compared to temperature. This is attributed perhaps to tropical rainfall and location at mid–latitude which produce high intensity storms. This is also responsible for the seemingly relationship between mean annual rainfall and performance of the GCM; the higher the mean annual rainfall the better the performance (Taylor, 2001). The diagram shows the 22 models (excluding BCM2) and how the models compare with reference, in this case ERA40 monthly data. The variable used during the evaluation is precipitation.

4.3 Downscaling

As discussed in section 3.2, downscaling provides a link between GCM outputs to observations using re–analysis data such as NCEP or ERA40 or other historical records. Methods for downscaling range from statistical downscaling model (SDSM, ASD tool) on daily time steps, LARS-WG, Empirical Statistical Downscaling (ESD) daily and monthly, dynamic downscaling (Regional Climate Models) and the sensitivity analysis (delta) method. The methods give the future climate scenarios for a given location or basin.

Dynamic Downscaling
Dynamic downscaling for climate studies utilizes a regional climate model that is nested within a global climate model (GCM) or global re–analysis. The GCM together with the global re–analysis data is interpolated to the RCM's grid and used to drive the RCM as initial and time-dependent lateral boundary conditions. The basic idea behind regional climate modelling is that a GCM can provide correct large–scale circulation in response to global climatic forcing and the RCM can represent sub–GCM grid scale forcing due to complex topography adequately. Most regional climate modelling studies use 50 km resolution following the initial RCM studies.

Statistical Downscaling
Statistical downscaling uses statistical relationships to link GCM simulated results with climate in a targeted area. This approach encompasses a range of statistical techniques from simple linear regression (Wilby et al., 2002) to more-complex applications such as those based on weather generators (Wilby et al., 1998), canonical correlation analysis (Storch and Navarra, 1993; Zorita and von Storch, 1999), or artificial neural networks (Hewitson and Crane, 2006). There are several tools available for empirical-statistical downscaling, among them is SDSM, (Wilby and Wigley, 2000), ASD and ESD (Benestad, 2004; Benestad Rasmus E, 2008). The first two methods work on daily data while the third can be used on both. For the larger part of this work, the ESD has been

employed. The SDSM is a stand-alone programme in MS–Windows while the ESD is a bundle of R–functions available in MS–Windows and Linux and other operating systems. The process of downscaling is based on the following assumptions:

- The predictors are variables of relevance to the local climate variable being derived, and are realistically modelled by the GCM. Variables such as temperature or geo-potential height are more skilfully represented than derived variables such as precipitation at the regional or grid scale.
- The transfer function is valid under altered climatic conditions. This cannot be proven in advance, as it would require the observational record to span all possible future realizations of the predictors.
- The predictors fully represent the climate change signal. Most downscaling approaches to date have relied entirely on circulation-based predictors and, therefore, can only capture this component of the climate change.

All downscaling methods are based on one of the three techniques described below to derive future climate variables.

Weather generators (WG), are random data generators of realistic looking sequences of local climate variables based on the approach to model daily precipitation occurrence, and usually these rely on stochastic processes. Transfer functions (TF) , is where a direct quantitative relationship is derived through, e.g, regression derived from regression-like techniques or piecewise linear or non-linear interpolations as illustrated in Figure 4.6. These include spatially–distributed variables, principal components analysis, Canonical Correlation Analysis (CCA) and redundancy analysis, Singular Value Decomposition and piecewise linear or non-linear interpolation and Artificial Neural Networks (ANNs) based approach.

Weather typing (WT) are schemes based on the more traditional synoptic climatology concept and which relate a particular atmospheric state to a set of local climate variables. The WT approach relates weather-classes to local and regional climate variations. The weather classes are either defined synoptically or fitted specifically for downscaling purposes by constructing indices of airflow (IPCC, 2001).

Predictor Variables

Most downscaling applications have dealt with temperature and precipitation. In most cases, mean sea level pressure (SLP) and geopotential heights (Z) have been the most widely used predictors of temperature and precipitation (Storch and Zwiers, 1999). The reason for this is that circulation dynamics are responsible for a significant proportion of the local climate variance, and these variables have a long temporal record, and the relative skill with which GCMs are able to simulate them.

Predictand

The station data (the predictand) were taken from the Global Historical Climatology Network (GHCN V2), of the National Climatic Data Centre, US Department of Commerce and retrieved using the function scripts in R-package. The longer series spanned the period 1900–2000 but this temperature record also differed from the climate data archive record during the late 1990s.

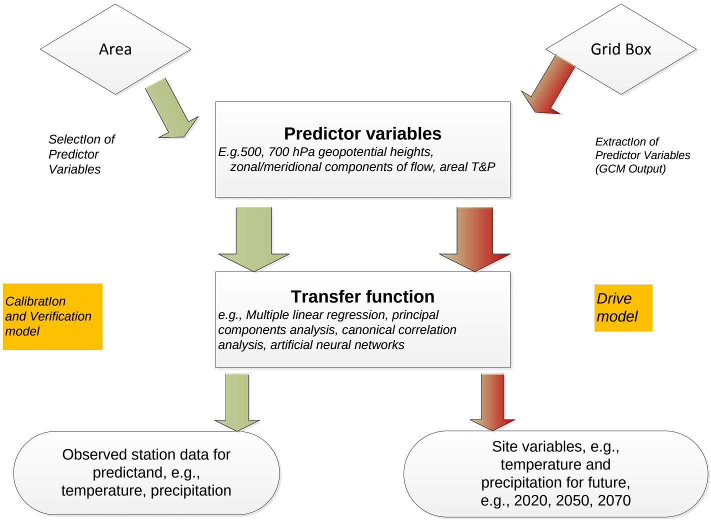

Figure 4.6: *General Transfer functions illustration, after (Wilby and Harris, 2006)*

SDSM / ASD

SDSM is a freely accessible and user-friendly statistical regression downscaling method, used to downscale a large-scale atmospheric variables to catchment level. It is a tool for assessing local climate change impacts using statistical downscaling technique. The model facilitates the rapid development of multiple, low–cost, single–site scenarios of daily surface weather variables under present and future climate forcing (Wilby et al., 2002), (Wilby and Harris, 2006). Prior to carrying out the downscaling of large-scale atmospheric variables, ancillary tasks are performed with it, such as data quality control, transformation of observed data and pre-screening of predictor variables. Screening is used to get potential predictor variables for further downscaling at a site. The ASD has however automated this process by employing MATLAB some results of daily downscaling are shown in Figure 4.7 and Figure 4.8.

Clim.pact

The method on which these results are based has been used in several previous studies and is therefore well-documented. This study uses similar approach as those used in Benestad (2008b) to downscale Norwegian regional climate series, Engen-Skaugen et al. (2007) to downscale river run-off, Figure 10: Global percentage changes in future (2050) runoff by country and Engen-Skaugen et al. (2008) where catchment-scale temperature and precipitation were downscaled. The implementation of the ESD is also documented in Benestad (2005), explaining how each GCM were downscaled for each calendar month separately. Large-scale precipitation was used to downscale the local precipitation, as in Benestad et al. (2007), and large-scale temperature was used to estimate the local temperature pact, developed and maintained by Benestad offers several advantages over direct global climate model (GCM) output or nested model output based on regional climate models (RCM) (Benestad, 2004). It is more suitable in regions with complex physiography, e.g. high mountains, heterogeneous vegetation and landscape structures, deep valleys and fjords, there are often pronounced small-scale structure in climatic variables such as temperature and rainfall. *Clim.pact* has some additional advantages as it involves an analysis that gives diagnostics which can be used to assess the GCM skill and the degree of realism. GCMs are said to give a better representation of the upper-air fields than the near-surface data, and *clim.pact* uses upper-air fields rather than surface fields as predictors.

The tool clim.pact was used to carry out the calculations, using a common empirical orthogonal function (EOF) based framework and linear multiple regression as a basis for the empirical-statistical model. The ESD was based on a 'finger-print' type technique whereby spatial patterns describing the large-scale anomalies correlated with the local variations were identified in the gridded observations (reanalysis) and then matched with the same spatial structures found in the model results.

A common EOF framework combined large-scale gridded temperature or precipitation anomalies estimated from the ERA40 re-analysis with corresponding anomalies from a simulation performed by a GCM (interpolated onto the same grid as the former). An ordinary EOF analysis is applied to this combined data set. The common EOF framework yields both the spatial structures (referred to as âĂŹEOFsâĂŹ or âĂŹmodesâĂŹ) as well as weights describing their temporal evolution/ variation (referred to as 'principal components'). By combining anomalies rather than the total values, constant biases are removed, however, the constant level of the end results become more arbitrary. The principal components (PCs) describing the temporal variations of the different modes (dominant spatial precipitation pattern) represent exactly the same spatial structures for GCMs and the ERA40.

A step-wise regression analysis was employed that used the part of the PCs describing the ERA40 data together with the predictand (temperature or precipitation series) to calibrate the model. This calibration returns R2-statistics, describing how well the local series can be reproduced with the statistical model if the ERA40 data is used as predictor.

The clim.pact tool makes predictions based on the calibration data (ERA40) as well as the GCM (either 20th century or the 21st century). However, the ESD-results derived from ERA40 are not independent and only serves as a visual check of the quality of the statistical downscaling model. The downscaling for the 20th century, on the other hand, provides independent data which can be used. GCMs regional variable spatial pattern correlation using the Canonical Correlation Analysis (CCA) the validation against the actual observations. This validation tests whether the ESD-model is good (here the R2-statistic is also a measure of skill). Many of the series were short, which may have reduced the quality of the ESD analysis. The ESD for both the temperature and the precipitation yielded weak results (low R2) for some locations, and most of the precipitation at the stations exhibited secular variations which were not captured by the ESD. The figure shows best-fit linear trend as a function of calender month (season), with trend estimate along the y-axis and the month on the x-axis. The year has been repeated, showing two cycles, in order to provide a good description of the change from December to January. The filled regions mark the confidence intervals of the trend coefficient estimates, and the blue curve shows the R2 scores associated with ESD for the particular month. As can be seen in the figures, the area is likely to experience increased precipitation. The figure further shows the months with significant level in the analysis.

$Clim.pact$ has incorporated a post-process quality control in order to attach less weight to the least realistic results, hence adopting a Bayesian-type approach. This post-processing step graded the quality of the results according to the realism of the spatial regression weights, how the trends of adjacent months relate to each other, realistic seasonal values and variability, strong $E - SDS$ regression results, and unrealistic size of the predictor domain. Typical results of downscaling from clim.pact are presented in Figure 4.9 for rainfall and Figure 4.10

Figures 4.9 and 4.10 depicts some of the results that were obtained from downscaling using the clim.pact downscaling tool. These plots include all the data as it was produced from the downscaling. Later, it was possible to filter the data so that only the data within 95 $\%$ confidence interval is retained and used further on. Changes for each season was carried out and changes highlighted through the probability empirical distribution function plots and box plots for each season. It is clear for this station (Malanje in Angola), rainfall is projected to increase slightly on annual basis though there are differences in seasons. Some climate stations' results are appended in the appendices A. This post downscaling analysis process has been carried out on the several stations where there was good data.

4.4 Rainfall Runoff Modelling

The most important requirement of any hydrological modelling process is an evaluation of the input data that are available to set up, calibrate and use the model. The availability of continuous and good quality data is vital for effective calibration. A model would not be optimized adequately in the absence of good quality input data with associated observed flows for calibrations. This is especially true in parts of Africa, where warfare and economic limitations of the past and present have largely precluded the collection of spatially and temporally representative water resource information.

In climate change studies, the above is compound by the fact that climate change impact assessments based on the simulations from GCMs. The GCMs generate monthly weather data more accurately than daily data. In order to study climate change better, the monthly weather data seems to be ideal. This is also helpful when studying in catchments where input data is problematic. No matter how good a model may be, its results are heavily dependent on input data. Any successful model application therefore will be influenced by the type of the catchment response characteristics, available inputs, and

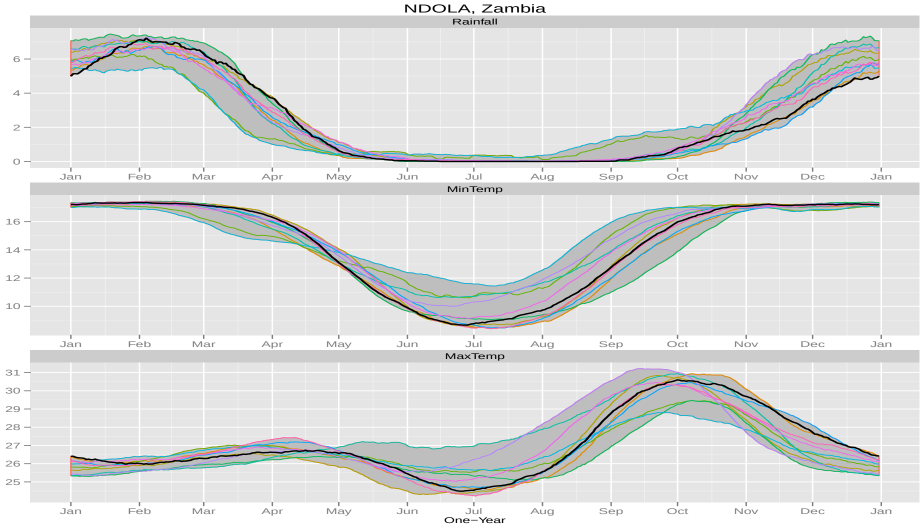

Figure 4.7: *Ndola - An ensemble of GCMs was used to downscale for this single location. Different lines represent different GCMs compared. Grey (shading) area represents the range covered by different models,black is the observed data.*

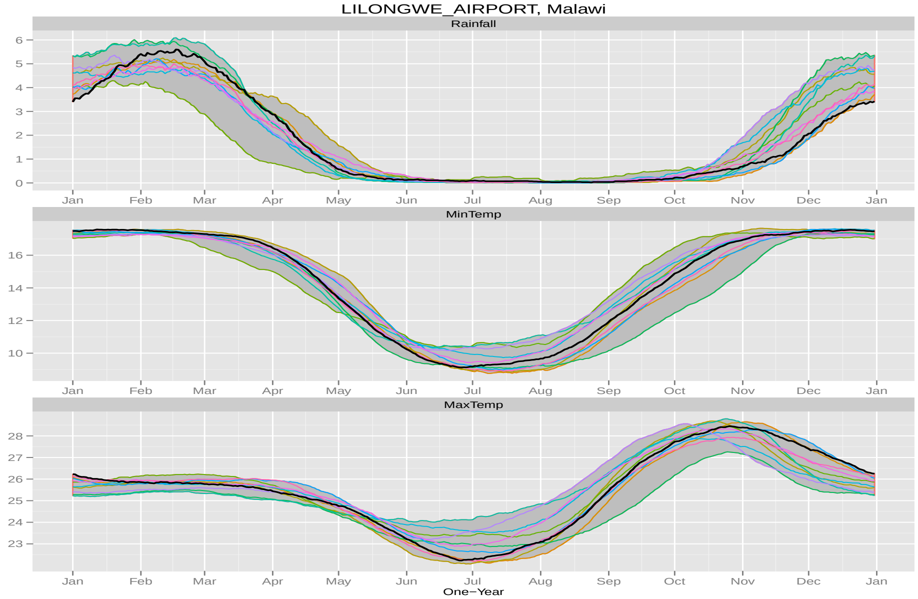

Figure 4.8: *Lilongwe - An ensemble of GCMs was used to downscale for this single location. Different lines represent different GCMs compared. Grey (shading) area represents the range covered by different models,black is the observed data.*

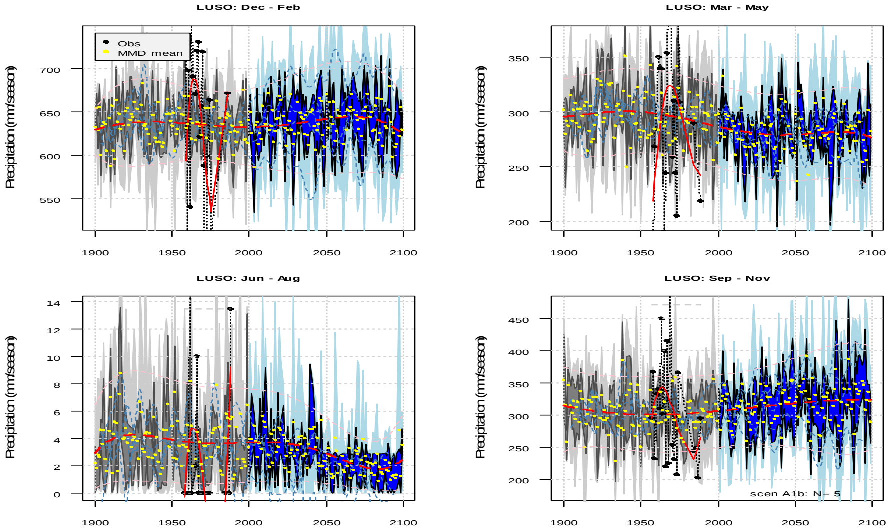

Figure 4.9: *Luso, Angola, A five MMD ensemble was used to downscale precipitation for this single location. Grey is represents 20th century part and blue for the 21st century part of the downscaling. The shading levels indicate the confidence interval, i.e. dark blue with 95 confidence interval.*

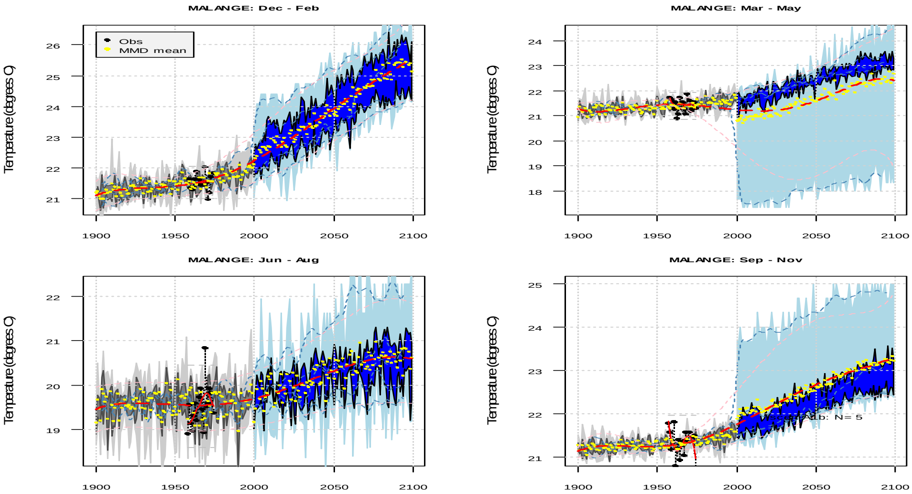

Figure 4.10: *Malanje, Angola. A five MMD ensemble was used to downscale temperature for this single location. Grey is represents 20th century part and blue for the 21st century part of the downscaling. The shading levels indicate the confidence interval, i.e. dark blue with 95 confidence interval.*

the type of results required and the availability of data with which to evaluate parameter values. (Bergstrom et al., 2001) listed the requirements of hydrological models for Climate Change applications as; 1) data demands must be realistic, 2) complexity must be justified by the results required, 3) sound and understandable structure and 4) valid in a new climate scenario.

Table 4.3: *Some Hydrological Models used in Climate Change impacts*

Hydrological Model	Time scale	Region applied	Reference
WBM (Water Balance – uncoupled to GCM)	Monthly	Global model	(Engeland et al., 2001; Gleick, 1987; Vorosmarty et al., 1998; Dooge, 1992)
Thornthwaite monthly water-balance model	Monthly	UK, China, West Africa, Greece, India, USA,	(McCabe and Ayers, 1989; Vorosmarty and Moore, 1991)
Simple bucket scheme	Monthly	Europe	(Yates, 1997)
Water balance model (penman)	Monthly	USA, Europe	(Jolley and Wheater, 1996)
PITMAN	Monthly	Africa, South America, USA	(Pitman and Basson, 1980; Gosling et al., 2011; Hughes et al., 2006, 2010)
STREAM	Monthly	Netherlands, India, Vietnam	(Hurkmans et al., 2008)
VIC	Daily	Europe, China, USA, Africa	(Guo et al., 2009) (Shrestha et al., 2012)
HBV	Daily	Sweden, France, Finland, Norway, China, Germany, Africa	(Bergström, 1992), (Bergstrom et al., 2001) (Bergstrom, 2006) (Beldring et al., 2006)
IHACRES	Daily	Norway	(Dye and Croke, 2003//), (Croke and Littlewood, 2005) (Croke et al., 2006)
LANDPINE	Daily	Norway	(Rinde, 1998)
ENKI	Daily	Norway	(Rinde, 1998)
TOPMODEL	Hourly/ Daily	Norway, Europe, China, Canada	(Beven, 1997; Kirkby, 1997; Yong et al., 2009; Xu et al., 2010)
WGHM – WaterGap	Daily	Global model	(Alcamo et al., 2003)
Sacramento model	Daily/monthly	USA, Kenya	(Gleick and Elizabeth, 1999),(Gleick, 1987),(Najafi et al., 2011),(Yates and Strzepek, 1998)
SWAT	Hourly/daily	USA, Asia, Norway, Europe	(Gosling et al., 2011) (Joh et al., 2011),(Gu et al., 2010)
HSPF model	Hourly	Canada	(Nassim and Munjed, 2008),(Goncu and Albek, 2010)
SHE	Hourly	Europe, USA,	(Abbott et al., 1986a),(Abbott et al., 1986b) (Dai et al., 2010),(Zhang et al., 2008), (DHI)

The modelling process can improve to our understanding of hydrological processes, but the problems that relate to the availability and quality of the input data may hinder this enhanced understanding. In recent years there has been an increasing trend towards the development of physically based but complex models (Beven, 1989). Evidently, there are problems associated with the application of physically based models (Hughes, 1998). It would appear that future developments in hydrological modelling techniques face a dilemma (Xu, 1999). While daily data may be available in some parts of the world, in other areas such data is not available and if it is available it is not be continuous. Any model user is therefore faced with a choice of using either a sophisticated model with less than perfect input data or a less complex model, based upon a simpler conceptualization of known reality, for which the data requirements are less demanding. The objective of this section was to investigate applicability of monthly hydrological models in modelling dry climate catchments in assessment of climate change impacts.

The model of the river basin is applied to both ’present day’ historical conditions and also various development and climate change scenarios to assess the impact of these on river flows. The most problematic aspect of the use of precipitation-runoff models for climate change assessment is the implicit assumption that parameter estimates obtained from historical data are applicable to alternative climates. As long as the differences between current and altered climate are modest compared to the observed inter–annual and inter–seasonal variability in the historical records of the atmospheric forcing, which is usually the case, this should not be a serious issue. Furthermore, for assessments that use the perturbation method of climate scenario development, changes are interpreted relative to a base case hydrological simulation using historical observed data.

Regardless of the hydrological model used, calibration is first performed by running the model with observed time series of precipitation and temperature (for at least a five-ten-year period) and comparing observed and simulated stream flow. Model parameters are adjusted within physically plausible ranges so that the daily stream flow peaks, base flow recession, monthly flow volumes and long-term average flow volumes matched as closely as possible.

4.4.1 Simple Lumped Models

The simplest model is a deterministic lumped time dependent model. The model should represent the most important processes and be able to show change in the important processes, in particular runoff. The results of such a model should be useful as input for hydropower modelling. As far as climate change is concerned, the simpler the model the better since it is necessary to run the model a number of times for different GCMs and different scenarios. In the category of hydrological models the HBV (Bergstrom, 1972) is one of the models that is most widely used for planning of hydropower operation, forecasting of inflows given the weather forecasts. HBV combines both the forecasting and planning characteristics which are very important in hydropower systems. Other models include the IHACRES(Jakeman et al., 1990), and the monthly PITMAN (Hughes et al., 2006) models 4.3. The IHACRES works well in tropical climates and is easier to calibrate since it is data-based, only very few parameters need to be changed while the PITMAN model has the advantage of having the monthly time and has been applied widely in tropical Africa.

4.4.2 Complex Detailed Models

These kinds of models allow different predictions of a system under various conditions because of physical process and measurable system characteristics. They are the basis for determining the behaviour of a system in a physical based model. Due to the fact that these models are grid-based, they sometimes preferred for large-scale continuous modelling, such as for climate investigations. An example (extreme) of these are the physically-based models SHE (System Hydrologique European) (DHI)and the ENKI (Kolberg and Bruland, 2010) model that is detailed and complex 4.3. However, the most difficult issue about such models is the demand for input data: they require a lot of data which should be gridded. These data may not be easily obtainable for the future. Most of the time these models are used for sensitivity analysis, where variables can be changed for different scenarios and the results can been seen.

4.5 Hydropower Simulations

The planning, design, operations and financial evaluation of hydropower systems are based on hydrological time series. Normally periods ranging between 20 to 50 years are used for evaluations. The procedure so far has been generating design time series based on observed data. The time series (duration curves) would then be fed into a hydropower simulation model for optimization of design and / or operation. The results of such an optimization is the need for a certain firm generation of the hydropower plant which in turn will determine the sizes of hydraulic structures (reservoirs, water ways) of the system. Hydropower operational planning also requires future periods though a bit shorter (25-30). Often the operations simulation is carried out to evaluate the performance of the hydropower system under varying climatic or other conditions. The impacts of climate change likely affect future planning and operation period. In order to estimate the potential impacts of a climate scenario, corrected stream flows are run through a hydropower model that considers the rules for regulating flows through the system's dams and calculates resultant power generation. Analysis of water management operations using a water management (reservoir) model can be simulated using the resulting stream flows. Changes in the availability of river flow and hydropower system constraints will impact on the ability of the hydropower system to meet average and peak demands. Annual hydropower output can thus also be assessed for future climate simulations. Various climate scenarios have been used to suggest possible impacts, but the results indicate a range of outcomes, good and poor, depending not only on the climate but also on the operation of the utility itself.

In order to evaluate hydropower production from a system, it is necessary to simulate the hydropower scheme. this is normally carried out by a hydropower simulation model. A hydropower modelling approach, based on water balance concepts is desired. It is important that the model takes into account the most important water balance details of the hydropower system. All computations are carried out, routing flow from inflow rivers into the reservoirs, bypass, tunnels, etc. downstream the river system. The model should be adaptive to any specific individual hydropower system. When the model has been set up, a simulation is run for a number of years in the future (20 -50). The model set up should be able to give useful parameters that assist in evaluation the system. Such a model should be generate results such as include average annual production, firm energy, average income, reservoir water levels and total water released downstream of the hydropower system.

For hydropower stimulations,the nMAG (Killingtveit, 2004) was taken to represent a model that would be sufficient to give the above parameters.This model is based on a detailed description of hydrological conditions (as inputs) and production systems. The model is useful for development planning.

4.6 Discussions

Downscaling from GCMs is a necessity, although it is difficult to say which of the two common methods of downscaling should be used for a specific location. The choice between statistical and dynamical downscaling depends on many factors, such as availability and quality of observational records and the local performance of statistical methods, availability and performance of RCM model results. From a modelling point-of-view, the use of continuous simulations is preferred over time-slice simulations. Use of multiple GCMs should be made and where possible multiple emissions scenarios. The delta-approach methods is sufficient for assessing mean responses (but should not be used for extreme events). Use of scaling methods may be preferred where extreme events are to be evaluated, as such methods have much better potential to include changes in variability. Estimating evapo-transpiration for future climates is a critical step in hydrological assessment.

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Chapter 5

Testing the Methodologies of Impacts Assessment

In Chapter 4, a procedure for assessing climate change impacts on hydropower production was formulated. Some of the published literature reviewed earlier in Chapter 2 were the basis for formulating this procedure. In this chapter, the procedure has been put to test for three different test cases. The first test case is the application in assessing the impacts of climate change on global hydropower production. The case involves making simplification in process of deriving the impacts of climate change on water resources and hydropower production.

The second test case is the assessing the impacts of climate change on water resources and hydropower production on a region hydropower production. The focus here is the region of Africa. The third case is the basin level (detailed assessment) impacts study. The test case is the Awash basin in Ethiopia. This case used the full detailed process for evaluating the impacts of climate change on hydropower. This chapter comprises of the descriptions of the cases and results from these cases.

In the preceding sections, three cases where different methodologies for assessing climate change impacts on hydropower production have been evaluated before being applied in the analyses in Chapter 7 and Chapter 8. The first case, on the global hydropower production, is incorporated in this report in Appendix A1, the second case, on a regional scale (Africa), the results are included in this chapter and the third case is more detailed on the basin level is also included Appendix A2. The case on global assessment has been published and the paper is in the Appendix A and the third case presented is in a paper that is under review and is likely to be published soon. This paper is also in Appendix A. The second case however, even though it is highlighted in the published paper, is presented below in a more detailed manner.

5.1 Impacts of Climate Change Impacts on Global Hydropower

This case provides an overview of present (existing) global hydropower generation and its future prospects with respect to climate change. The focus of this work is global (all countries) i.e. low resolution (less detail) although for clarity's sake, some large countries like Australia, Brazil, Canada, China, India, and the USA, had to be subdivided into provinces or states. Assessment of climate change impacts on hydropower can be done at various levels of detail with different methods. On a global scale, low resolution analysis is acceptable as detailed modelling may be costly and tedious. While recognizing the fact that climate change impacts hydropower in different ways: volume of flow, timings of flow, etc., the analysis has been confined to changes in mean flows (volume of flow). In addition, there is no estimate of the future hydropower development as doing so would require more detailed data (national development plans or trends)for each state and country. The study aimed to answer questions related to national, regional and global hydropower generation and the expected increases or decreases in the same due to future changes in climate and water availability, and the extent of such changes. In order to answer the above, GIS analysis has been utilized to understand and visualize regional scenarios of hydropower generation. The present work makes no attempt to analyse the impact of climate change on electricity demand, as it focuses on the generation side. The GIS has been used here as a tool to merge and analyse different databases in order to gain insights into the anticipated changes. The database included data on countries hydropower capacities, generation, global water resources, global runoff, dams, hydropower plants, etc. Table 2.2 on shows regional hydropower statistics and the installed capacity and hydropower generation in 2009 which is of special interest. The table highlights the technically feasible, annual average potential, and feasible increase. The capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time and its output if it had operated at full nameplate capacity the entire time. The lowest capacity factor is in Europe and clearly shows that hydropower in Europe is used more for peaking purposes than in the other regions (Bartle, 2010)

The approach used in this analysis aggregates various types of hydropower systems from different climates to highlight the larger global picture. The approach is based on the fact that the current hydropower generation system may only be limited by water availability. The main assumption is that if the water supply is reduced, the hydropower systems will likewise reduce generation and vice–versa, assuming that current systems can be upgraded. With this approach, changes in annual mean flows are the main predictors of hydropower generation in each unit. The delta changes were directly derived from the GCM unto the flows in major river basins globally, with continuous data of more than 30 years. Based on this association the changes were remapped back to the GCMs and the maps of expected changes by 2050 in river flows were generated. The changes in river flows was aggregated on country basis. The hydropwer production was correlated to the water resources for each country. Based on this relationship, hydropower production changes were mapped on country basis.

5.2 Impacts on Climate Change on African Hydropower

Table 5.1: *African Regions and Countries in detail.*

Region	Country	Runoff (mm/yr)	Installed Capacity (MW)	Hydropower generation 2005 (GWh)	Changes in Hydropower %
East Africa	Burundi	132	32	98	13.1
	Comoros	723	1	2	
	Djibouti	14	0		
	Ethiopia	97	669	2,805	
	Kenya	52	677	2,996	
	Madagascar	567	105	653	−4.5
	Mauritius	1,081	59	113	
	Reunion	1,941	125	575	
	Rwanda	206	35	129	15.1
	Somalia	21			
	Tanzania	96	557	1,760	12.9
	Uganda	272	306	1,839	14.9
Central Africa	Centr. Afr. Rep	232	19	83	
	Cameroon	612	805	3,874	0.0
	Chad	37			
	Congo	2,409	92	351	−4.2
	Guinean	960	3	3	
	Gabon	627	170	806	−6.6
	Sao tome	2,100	6	11	
	Zaire DRC	549	2,410	7,322	−0.1
North Africa	Algeria	6	280	549	
	Egypt	59	2,745	12,518	
	Libya	0			
	Morocco	72	1,498	1,398	
	Sudan	26	308	1,227	7.1
	Tunisia	30	66	144	−30.8
	Western Sahara	3			
Southern Africa	Angola	147	498	2,197	−7.4
	Botswana	25			
	Lesotho	99	76	350	−8.8
	Malawi	145	283	1,369	−0.4
	Mozambique	274	2,136	13,131	−9.5
	Namibia	22	249	1,641	−21.2
	South Africa	41	661	903	−11.6
	Swaziland	262	41	158	−12.7
	Zambia	139	1,698	8,794	−4.5
	Zimbabwe	51	850	5,776	−10.4
West Africa	Benin	213	1	1	
	Burkina Faso	46	32	99	
	Ghana	222	1,198	5,573	−1.6
	Guinea	918	129	436	−2.9
	Guinea-Bissau	922			
	Ivory coast.	251	604	1,423	−6.2
	Liberia	2,409			
	Mali	80	155	240	
	Mauritania	11	97	49	
	Nigeria	314	1,938	7,871	0.4
	Senegal	200	0	264	
	Sierra Leone	2,206	4	0	6.1
	Togo	257	67	73	

The approach used in this case is similar to assessing climate change impacts on global hydropower approach above. The main difference here is details of the results. Countries individually are mapped and the results on country basis can be also seen. The method was used to assess the impacts on Africa's hydropower systems. The section below highlights the details at national level on the results. In Africa, there are some countries with increasing hydropower generation and others with decreasing hydropower generation, as illustrated in Table 5.1. The eastern African region shows increases in almost all countries except Ethiopia where there were disagreements among the GCMs. The southern and northern regions show decreases in hydropower generation. The western region remains nearly the same but there are some countries with increases while others have decreases, and again in most countries there were disagreements among the GCMs regarding future runoff. The results in Table 5.1 are plotted on to a map in Figure 5.1. The map shows where the likely changes are going to occur and how big this expected change could be. The larger hydropower producers in Africa generally show decreases and the increases can be expected in the east Africa states.

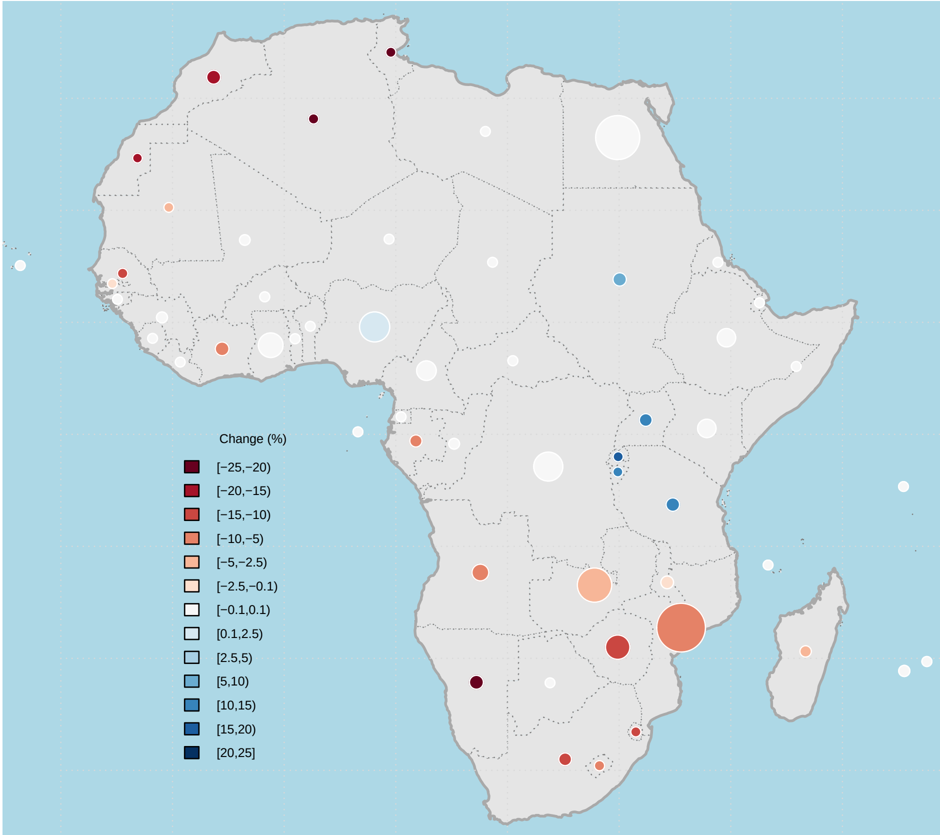

Figure 5.1: *Installed capacities and relative changes due to climate change. The size of the dots represents the country's installed capacity while the colours represent the changes. Brown/red represents negative changes while blue represents the positive changes. The shading level is indicative of the level of change*

5.3 Assessing Impacts of Climate Change on a small basin

The last case details a thorough method for assessing impacts of climate change on hydropower production. The method follows the methodology described in Chapter 3. The main difference from other methods is that the time series used in hydrological modelling are realized from the downscaling, a result of input data from the GCMs. As the basin is reasonably small the downscaling brings out the likely local changes based on the local climate station observations. Hydrological modelling is carried used the realized future climate ensembles of temperature and precipitation. Further the hydropower system is set up in detail with nearly all components included. The results for such a case study are more detailed as well. The results of this analysis is included in Appendix A.

5.3.1 Discussions

The application of the formulated procedure has been carried out and proved to be very useful at this level. At the level, it was possible to depict globally the likely impacts of climate change on current hydropower system. However this was done with many assumptions and simplifications.

The amount of electricity produced by a hydropower system depends on: 1) the discharge / flow (amount of water passing through the turbine per unit time); 2) the site head (the height of the water source), and 3) the turbine generating capacity and efficiency.

There could be some differences when the results presented in the assessment of impacts on the global scale compared to a more local detailed analysis of climate change impact on one or two hydropower systems, where more plant data, time series data and detailed down-scaling is carried out. However the results were not very different (within ranges).

There are many factors that could be used to mitigate impacts on climate change on hydropower especially in operations. These have not been dealt with in this current study. Such factors include the storage capacity, pumped storage system and operation rule curve changes. These were considered to be outside the scope of this study.

This first case study, published in Energies volume 5 issue 2 (Hamududu and Killingtveit, 2012). The results presented in Table 5 (see Appendix A) have been used as reference in the SRREN report (SRREN-IPCC, 2011) and Table 5.1 (full details in Appendix B) was used in a report on Climate impacts on energy systems by World Bank report in 2010 (WB, 2010). The third case study (Awash, Ethiopia) has been submitted to Climatic Change and is under second review.

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Chapter 6

Study Area – Africa

6.1 Introduction

Africa is the second largest continent in the world and is homeland to nearly a billion people. It lies between 40^o North and 37^o South. The is continent divided by the equator, the north being bigger 68%. The major landmass is located between the Tropics of Cancer and Capricorn, making Africa essentially a tropical continent. The continent is surrounded by the Mediterranean Sea to the north, both the Suez Canal and the Red Sea along the Sinai Peninsula to the northeast, the Indian Ocean to the southeast, and the Atlantic Ocean to the west. Some notable mountains are the Kilimanjaro (5,895 m), Meru (4,565 m), Elgon (4,300 m), Ethiopian highlands (3,620 m), Lesotho highlands (3,200 m), and the Ruwenzori Range (5,120 m). The surface covered by swamps is estimated at about 1.1% of the total area of Africa. The swamps are distributed around the drainage basins of major rivers like the Zambezi, Congo, and the Upper Nile, as well as lakes Victoria, Kyoga, Chad and Mweru. Until the mid-1990s, Europe had been the second most populous region of the world, but in 1996 the population of Africa surpassed that of Europe for the first time (see Figure 6.2). Africa's population growth rate is estimated at 2.3 per cent per year during 2010-2015 (double that of Asia). The population of Africa is more than a billion since 2009 and is expected to add another billion in just 35 years (by 2044). Whereas in 2010 Asia's population was four times larger than that of Africa (4.2 billion vs. 1.0 billion), by 2100 it may be only 28% higher than that of Africa (4.6 billion in Asia vs. 3.6 billion in Africa). By 2100, Africa's population, which in 2011 is equivalent to 61% of the population of the Americas, Europe and Oceania taken together, might surpass them by 83%. The percentage of Africans constituting the total world population has kept growing: 9% in 1970 and 15% by the year 2011. Figure 6.3 depicts the population of Africa on a region wise basis. The eastern and western regions of Africa have the largest populations; these are also growing at a brisk rate.

Figure 6.1: *Political Countries of Africa with major water bodies and rivers. Country boundaries are in grey and the rivers, lakes, swamps are blue*

The general climate of Africa is mainly influenced by its geographical location. Most of Africa is characterized by hot tropical climate for most of the year. The Indian Ocean SST tends to dominate in the rainfall variability of Africa in the warm phase of ENSO and the Atlantic Ocean controls the rainfall of Africa in the cold phase. The average air temperature at sea level for January and July varies from less than 15^{o}C to more than 35^{o}C, depending on the geographical location and the season of the year. The climate of Africa ranges from tropical to subarctic on its highest peaks. Its northern half is primarily desert or arid, while its central and southern areas contain both savanna plains and very dense jungle (rainforest) regions. In between, there is a convergence where vegetation patterns such as sahel, and steppe dominate. Africa is the hottest continent on earth; drylands and deserts comprise 60% of the entire land surface. The mean daily range of temperature does not exceed 10^{o}C for the coastal strips as well as along the Equator. This range increases with distance towards the heart of the continent to reach or exceed 20^{o}C.

The mean annual rainfall in Africa varies from less than 100 mm to more than 3,000 mm. The remarkable feature is that the climatic divisions can be approximated by more or less parallel bands extending from west to east, with the heaviest rainfall (tropical wet climate) around the Equator. It has been suggested that these bands can be classified according to the annual rainfall into desert (100 – 150 mm), sub-desert (150 – 300 mm), sahelian (300 – 750 mm), tropical (750 – 1,200 mm) and tropical-equatorial (more than 1,200 mm). Figure 6.4 shows the mean annual rainfall of Africa.

There are several factors that influence the climate of Africa. First is the activity of the Sun. A second factor is the fact that Africa is almost surrounded by water bodies, Atlantic and Indian Ocean, the Red Sea and Mediterranean Sea. These water bodies have huge effect on the humidity of Africa's landmass. Third is the Inter Tropical Convergence Zone (ITCZ) , whose location separates a general warm dry air mass and a cooler moist mass. The nature of precipitation and its annual variation is linked to the movement of the ITCZ and the airflow patterns. The last factor is relief; Africa is bordered by mountains, the atlas range in the north. The west, the east and the south all have mountain ranges.

Extreme spatial and temporal variability of climate and rainfall in the continent has far-reaching consequences for water resources management, especially with the imbalance in geographical distribution of rainfall across the continent. Northern and southern Africa receive 9 per cent and 12 per cent, respectively, of the continent's rainfall, the Congo River watershed in the central humid zone, with 10 per cent of Africa's population, alone has over 35 per cent of the continent's annual runoff and combined with the humid equatorial zone in the Gulf of Guinea records Africa's highest annual rainfall. The greater part of Africa consists of a very ancient mass originating from the Precambrian crystalline and metamorphic rocks. These are the Lower Precambrian, predominantly consisting of granitoids and granite gneisses; the Middle Precambrian, essentially schist quartzic and eruptive material; and the Upper Precambrian with schist, sandstone, lava and conglomerates. The strain exerted on the rigid mass of Africa for a long time resulted in the rift system. The rift extends from Jordan and the Red Sea in the north down to South Africa. The western rift runs through or very closely parallel to Lakes Albert, Edward, Tanganyika and Malawi. Soils are the product of all processes exercised by the prevailing climates on the parent materials. As such, African soil types are widely variable, and for each climatic type there can be rich as well as poor soils. In general sands, gravels and pebbles cover desert regions. The soils of the highly elevated areas are usually shallow and mostly covered with stones. The dry and wet climates alternate, i.e. seasonally well-watered areas called savannas are common but are unfavourable lands for drainage conditions. Savannas cover at least one-third of the African tropics. The African equatorial rainforest together with savanna occupy more than half the area of Africa. Some of the significant rivers of tropical Africa are fed from the runoff of the equatorial forest area. Highland grasses and mountain forests are found in volcanic areas and where the elevation of the ground is at or above 1500 m.

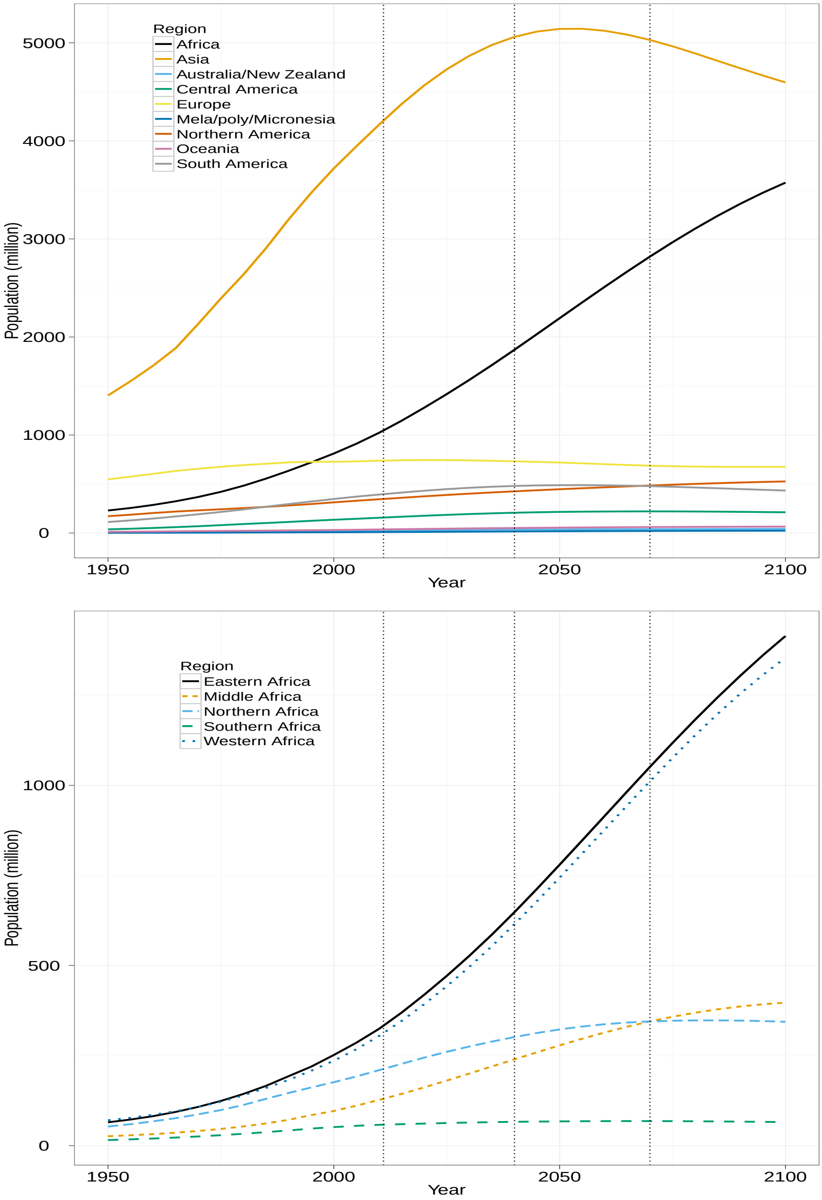

Figure 6.3: *Population of Africa by Region. The dotted lines mark the years 2010, 2040 and 2070. Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2010 Revision, http://esa.un.org/unpd/wpp/index.htm*

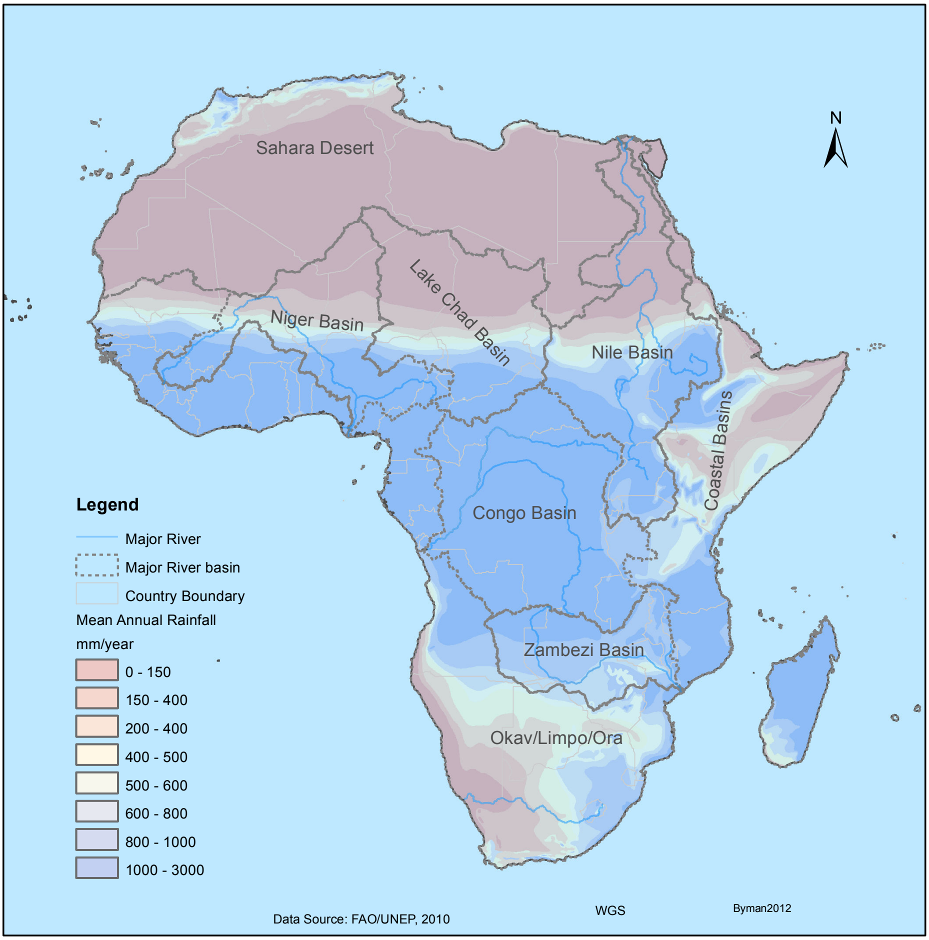

Figure 6.4: *Mean Annual Rainfall for Africa, with major river basins*

Water Resources

Africa is endowed with abundant water resources in the form of large rivers, lakes, wetlands and limited but widespread groundwater. Much of this is located in central Africa with huge hydropower potential in the equatorial region and the sub-humid East African Highlands along the Rift Valley. The total water withdrawn for various uses is still very low compared to the renewable resources (UNECA, 2001). There are many threats to sustainable use of water and land resources grouped into natural and human factors; including factors as the transboundary water basins, climate and rainfall variability, water scarcity from shrinking water bodies, drought and desertification and depletion of water resources (Shahin, 2002).

Africa's share of global freshwater resources withdrawal is only 213 km^3/yr (6%) and

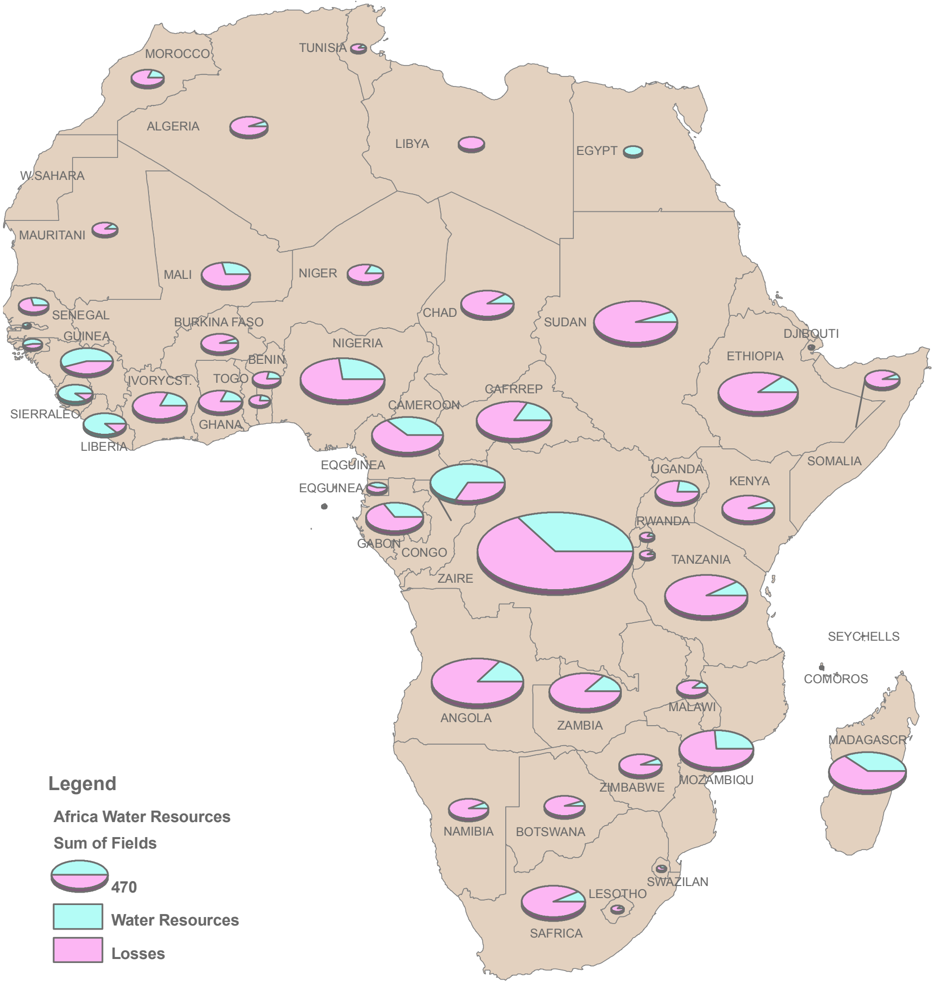

Figure 6.5: *Ratio of Water Resources to Precipitation in Africa. The size of the pie indicates relative total amount precipitation (annual) while the green slice shows the ratio that is converted to runoff (FAO, 2011)*

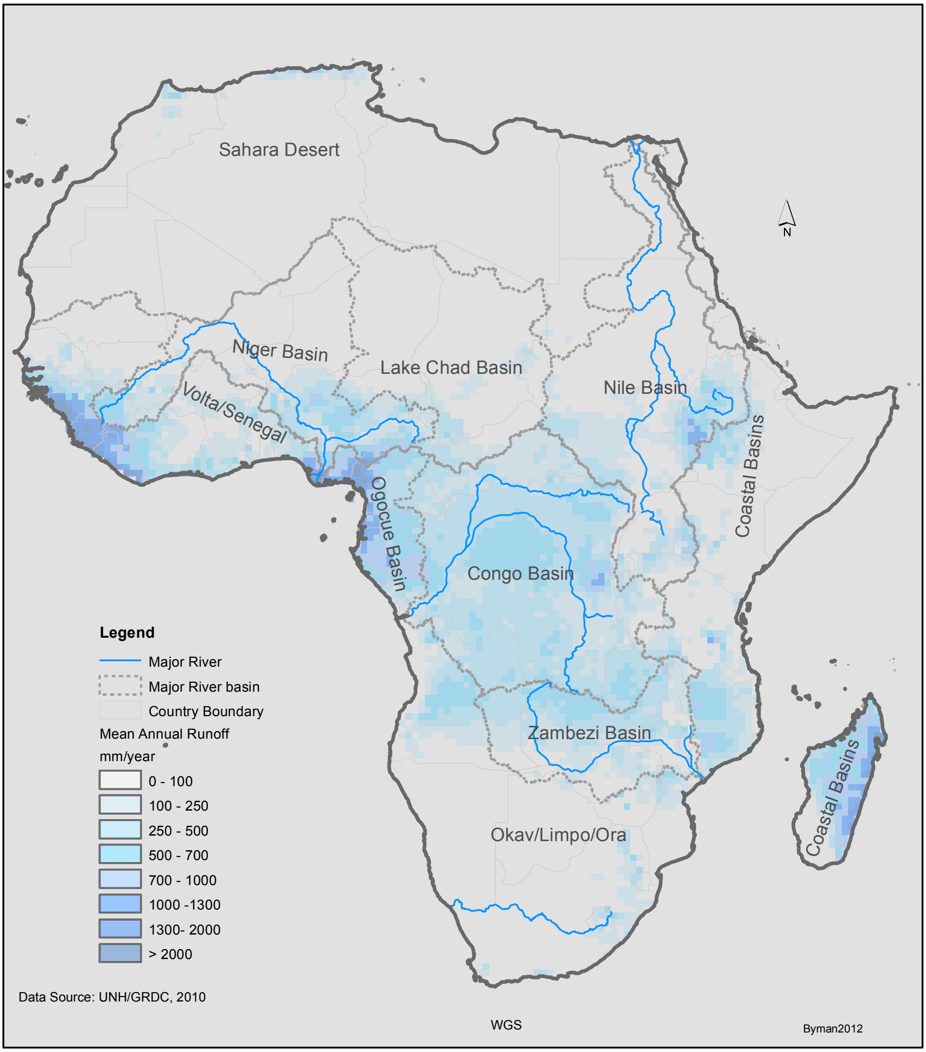

Figure 6.6: *Mean Annual Runoff (mm/yr). The highest runoff is around the central region where the Congo basin lies. This sub-region is also expected to experience further variability in rainfall, reduced precipitation and increased evaporation, as a result of climate change. Central Africa rarely experiences problems of water availability, because rainfall is high and generally predictable. Most western African countries are well-endowed with freshwater, except for those bordering on the Sahel, which frequently experience drought. Table 6.1 gives statistics for 13 major river basins of Africa.*

only 25% of this is in the eastern and southern regions of the continent (Gleick, 2008). It receives 12,000 km^3 of precipitation per year and produces runoff of 2600 km^3 (25%) per year. Out of the 1777 dams in Africa, 1277 dams are located within in the eastern and southern parts, with total reservoir capacity of 493 km^3 but only 95 of these dams are used for hydropower generation (ICOLD). Figure 6.6 presents the mean annual run-off across Africa. Problems with freshwater availability in Africa are complicated by highly variable levels of rainfall. In the north, the major issue of concern is, therefore, freshwater availability for domestic, agricultural and industrial consumption. In the east, there is also competition for access to water resources between user groups and between countries. Some of the countries are not only dependent on freshwater for domestic, agricultural and industrial consumption, but also for hydropower generation. The southern Africa region is mostly semi-arid, and experiences the largest variation in rainfall, both over time and countries.

Table 6.1: *Some of the major Characteristics of Major Rivers in Africa, data source (FAO, 2010)*

	Congo	Nile	Niger	Zambezi	Orange	Chari	Juba	Senegal	Limpopo	Volta	Rufiji	Cuanza
Drainage Area 10^3km^2	3680	2870	2090	1330	1020	880	750	441	440	394	178	149
Length km	4370	6670	4160	2660	1860	1400	1600	1430	1600	1600	1400	630
Average Discharge m^3/s	41250	1696	4217	3519	486	1252	546	545	824	1288	119	946
Runoff Vol. km^3/yr	1300	53.5	133	111	15.3	39.5	17.2	17.2	26	40.6	35.3	29.8
Runoff mm	353	18.6	63.4	83.4	15	44.9	22.9	39	59.1	103	198	200

With a rapidly growing population and demands for water, freshwater availability is a challenge for Africa. Human actions contribute to reducing natural water quantity and quantity through widespread contamination from pollution, poor sanitation, wastes and decay of aquatic weeds and salinization, a problem compounded by poor land use and agricultural practices (UNECA, 2001).

A key water resource challenge in Africa is the multiplicity of international water basins, about 80, with weak cooperation and institutional regulatory instruments. Virtually all sub-Saharan African countries share at least one international water basin (ADB, 2010). Some countries have several international rivers passing through them. In the midst of a plentiful water resource situation at the continental level, some African sub–regions and countries are experiencing growing water scarcity. The dry and wet hydro–climatic periods are common in most historical discharge records of the African rivers. The discharge fluctuations and alternations (dry and wet) flows in the Southern hemisphere show similarity, lag and even oppositions between the hydroclimatic periods when compared to those of the rivers in the Northern hemisphere. Some studies have shown the cyclic variations in rainfall in South Africa in depth, and from that study long-term and about '9-year' cycles have been identified Shahin (2002). These cycles have been linked to physical phenomena such as ocean temperatures, atmospheric pressure oscillation in the Southern hemisphere and solar activity, through the rainfall activities.

6.2 Energy in Central and Southern Africa

Generally, Africa is a major net energy exporter with each sub region, except East Africa, being a net exporter of energy. North Africa is the largest, (oil and gas), West Africa (oil), southern Africa (oil and coal) and central Africa (oil). East Africa is a net energy importer (mainly oil). The vast majority (80%) of energy consumption in Africa is either

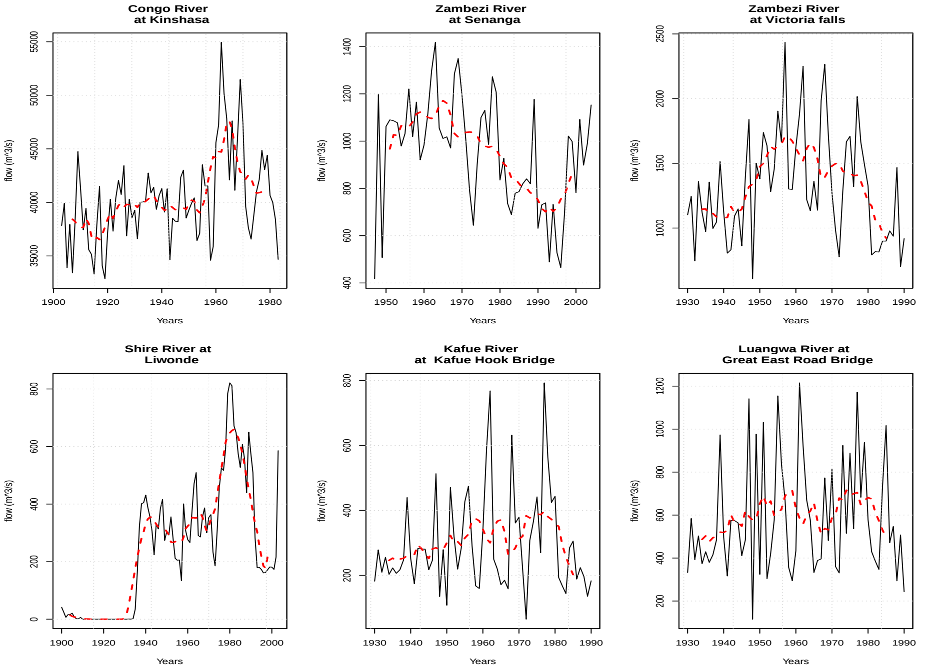

Figure 6.7: *Annual flows (anomalies) for the main river basins in the southern African region. Historical trends for some main discharge stations in Africa. The dotted red line shows the 10-year moving average*

in northern or southern Africa. Hydroelectric capacity accounts for about 22% of total electric generating capacity in Africa. Hydroelectricity represents the primary source of electricity in East Africa and Central Africa (and nearly half in West Africa).

Reliance on hydropower is 80% or greater in Cameroon, the DRC, Ghana, Mozambique, Rwanda, Uganda, and Zambia. Hydropower reliance is greater than 70% in many other African countries. Hydropower has an enormous potential to contribute to the growing energy needs of the African continent without emitting greenhouse gases. Although Africa has one of the biggest hydropower potentials in the world, it currently uses only a fraction of its rich potential. The total installed capacity of hydropower in Africa, 24 GW. More than half of the installed hydropower capacity of Africa is concentrated in the Democratic Republic of Congo, Egypt, Mozambique, Nigeria and Zambia. Another 5 GW was under construction at the end of 2009. In 23 African countries, 50% of the total power supply is provided by hydropower.

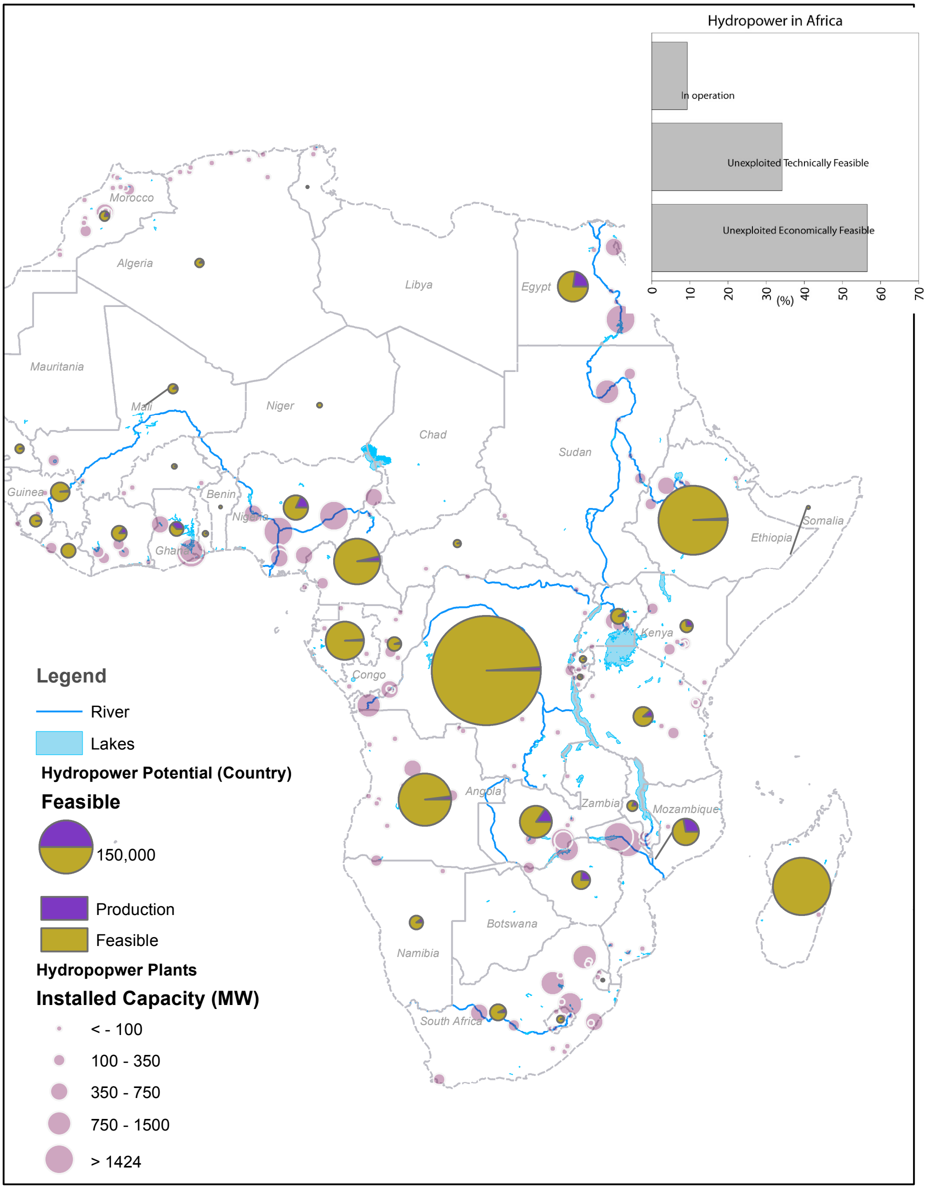

Figure 6.8: *Status of Hydropower in Africa. Data source Bartle (2010)*

Yet only about 9.3% of Africa's enormous hydropower potential has been harnessed and hydropower continues to be the main electricity supply to the region Bartle (2010). With most economies in the region struggling to advance, hydropower is still and will remain the most economical option for electricity supply (IHA, 2000). According to the

Table 6.2: *Central and Southern African Regional Energy Statistics, values in TWh (2009). data source: IEA 2011*

Country	Thermal	Hydro	Nuclear	Others	Total	%hydro
Angola	0.88	2.6	0	0	3.5	75
Botswana	0.98	0.0	0	0	1.0	0
Congo (DR)	0.02	7.2	0	0	7.2	100
Lesotho	0	0.2	0	0	0.2	100
Malawi	0.03	1.1	0	0	1.1	97
Mozambique	0.04	14.6	0	0	14.6	100
Namibia	0.05	1.6	0	0	1.6	97
South Africa	216	1.1	10	0.3	228	1
Swaziland	0.27	0.2	0	0	0.4	36
Zambia	0.05	9.2	0	0	9.3	99
Zimbabwe	3.97	5.5	0	0	9.5	58
Region (2009)	223	43	10	0.3	276	16
World Total (2009)	11,943	2,997	2,660	414	18,015	

Africa Development Bank, hydropower contributed 15.9% of Africa's total electricity production, 4.0% was nuclear, 0.3% was geothermal and 79.8% was thermal in 2005. Figure 6.8 shows recent (2010) Africa's annual hydro generation as a percentage of the 1750 TWh/yr technically feasible. The inadequacy of energy has been attributed to slow economic development in the region. However population growth and planned industrialization are putting a lot of pressure on energy demand within the region. In many countries, plans are under way to develop some of the remaining hydropower potential and in many countries there are some hydropower projects under construction. Apart from South Africa and Botswana, almost all countries in southern Africa have more than 50% hydropower as a source of energy. In fact without South Africa, the average regional dependency on hydropower for electricity supply is more than 62%. Economies of most of southern African countries rely on hydropower exports. More hydropower plants are planned or being constructed in east and southern African countries. Figure 6.9 highlights the top ten hydropower producers in Africa. The technical, economic hydropower potential and the most recent hydropower production is plotted. As can be seen the Egypt and Mozambique have the highest production (2009) where as the highest potential lies in Congo (DR) and Ethiopia with a lot of potential both technically and economically feasible to be developed.

It is estimated that 90% of Africa's hydropower potential is concentrated in Angola, Cameroon, Congo (DR), Egypt, Ethiopia, Gabon, Madagascar, Mozambique, Nigeria and Zambia. The Congo alone accounts for almost 50% of the total African hydropower potential. The high up-front costs of hydropower investment have been a barrier to the development of this energy source in Africa, where financial resources are scarce. The lack of adequate political framework conditions and good governance policies, the suboptimal general investment climate and local conflicts hamper the exploitation of Africa's hydropower potential.

The hydropower production in Africa is low relative to the continent's high hydropower potential. The southern African region has the highest production when compared to other regions in the continent. In the mid-1990s the production level was at par with other regions but the region has increased sharply its hydropower production. As can

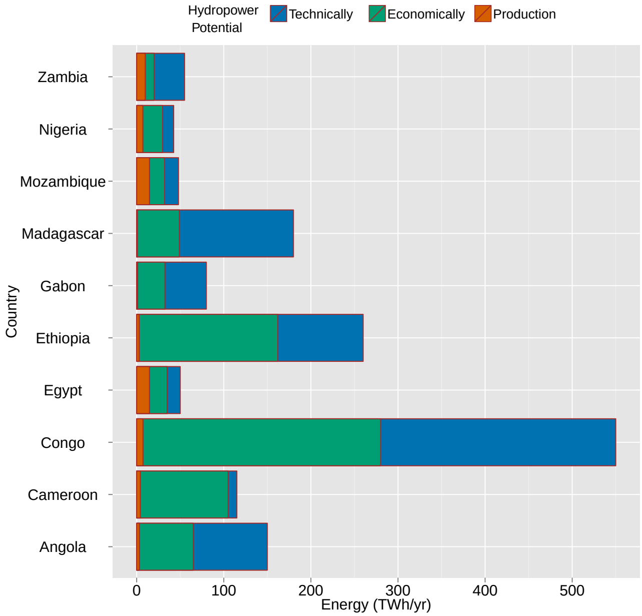

Figure 6.9: *Africa's top 10 hydropower producers (Potential) and their hydropower production. The total length of the bar represents the technical feasible hydropower potential, part of that is economically feasible in green, and hydropower production in brown. The remaining blue is the technical feasible hydropower but is currently uneconomically feasible. Data source (Bartle, 2010)*

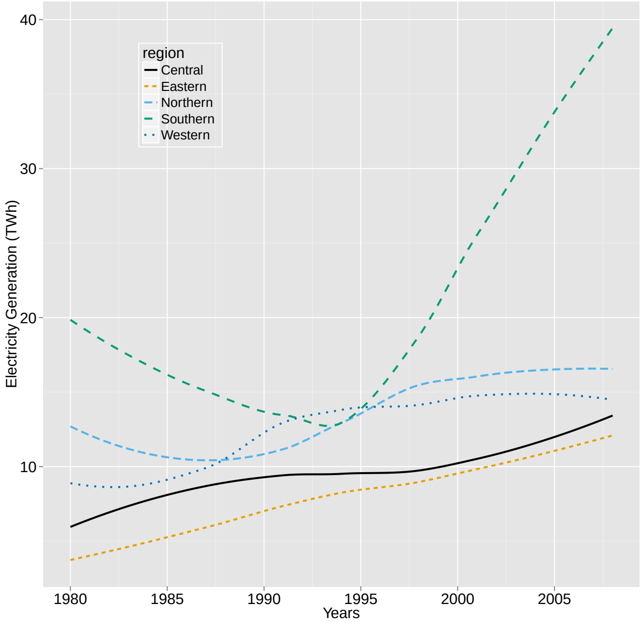

Figure 6.10: *Africa hydropower production trend by region. The southern Africa region has the largest share of hydropower production Africa with a dip in the mid 1990s and has since increased the production. As new hydropower plants are developed this is likely to change, since much of southern Africa has developed a large portion its potential. It is expected the central and eastern region will increase production in the near future based on the current projects under construction. data source (Bartle, 2010)*

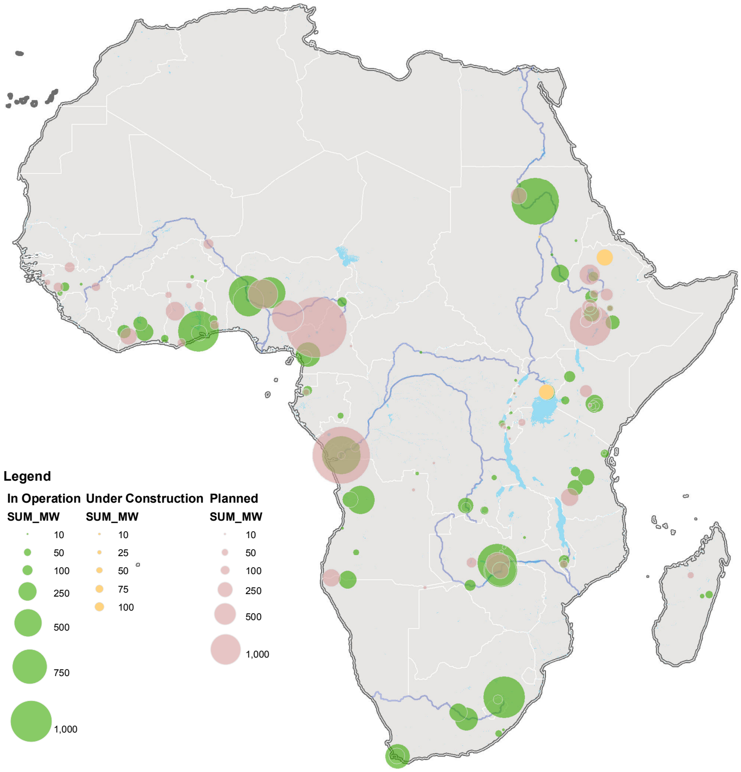

Figure 6.11: *Hydropower plants (>10 MW) in Africa, The size of the dots represents the relative size of installed capacity, power in operation are represented by green dots, yellow under construction and cyan for planned*

be seen in the figure 6.10, other region are increasing their hydropower production and the growth is likely to triple in a few years time. There are 168 hydropower plants with installed capacity larger than 10 MW in Africa (2009). These include the plants under construction, as well as plants which are planned and on the anvil. Out of the 168 hydropower plants, 93 plants are in operation, 3 under construction, and 52 planned for immediate construction. There are about 20 plants in different statuses such as abandoned, in a state of disrepair and vandalized.

6.3 Historical Variations in Climate in Southern Africa

The historical time-series analyses are very important in studies about climate change impacts. These analyses form a basis for possible trend detection and also establish knowledge about the natural variability of climatology and hydrological parameters that exist in the region. This section assesses the observed changes and trends within the region. It is therefore important that regional assessment of these trends and patterns be carried out to be able to show a trend, and magnitude of the trend, if any.

The main test for trend detection used in environmental data analysis is the non-parametric Mann Kendall test. The Mann–Kendall test is a rank-based method and the results of the trend test are used to determine whether the observed time series for a variable exhibit a number of trends that is greater than the number that is expected to occur by chance. All the trend results in this research are evaluated at the 5% level of significance to ensure an effective exploration of the trend characteristics of the study area. The Mann-Kendall test, also called Kendall's tau test is the rank-based non-parametric test for assessing the significance of a trend, and has been widely used in hydrological trend detection studies (Xu et al., 2005; Hamed, 2008; Chen et al., 2007; Burn et al., 2002). The Mann-Kendall test is used to estimate the magnitude of the trends in this analysis. The slope in the Mann-Kendall is the median over all combinations of record pairs for the whole data set. It is therefore unbiased estimator of the trend magnitude.

6.4 Regional Observed Temperature Trends

The observed data from these selected stations were analysed. The temperature data, like the rainfall data were taken from the GHCN and Zambia Meteorological Department. The stations apart from stations in Zambia were all downloaded from the GHCN. Figure 6.12 shows the locations of the selected stations. The temperature data are of very short periods with a lot of missing data and therefore only a few stations with relative long periods of data could be used in this analysis. The results are present in Figure 6.13 for stations with recorded observation longer than 30 years, 60 years, and 80 years respectively. The individual stations are plotted in different colours and a median of all station is plotted in black. As can be seen from the plots, the records show an increasing trend from all the stations and even the median too has a clear upward trend. In several stations, the period 1920 - 1940s shows relatively higher temperatures, the trend going downward in 1950 - 1970s and relatively steep upward trend towards the 1980 - 2010s. These variations are present in all the three plots for different length of observations. The conclusion is that the records in the region indicate increasing higher temperatures and the slope seems to be increasing towards the latter period. It may also be said that regional warming is intensifying.

6.4.1 Observed Precipitation Trends

Most of the precipitation datasets were obtained from GHCN and supplementary datasets, Zambian station data was obtained from the Zambian meteorological department. All the stations used in the analysis lie within and/or around the Zambezi River Basin and therefore encompass Angola, Botswana, DR Congo, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe. Figure 6.13 shows a number of time–series plots for some stations for the same period of time across the basins. The variability is already apparent here both in amounts and temporal differences. The rainfall records were not as good as the temperature records and as such only a plot of stations with records longer than

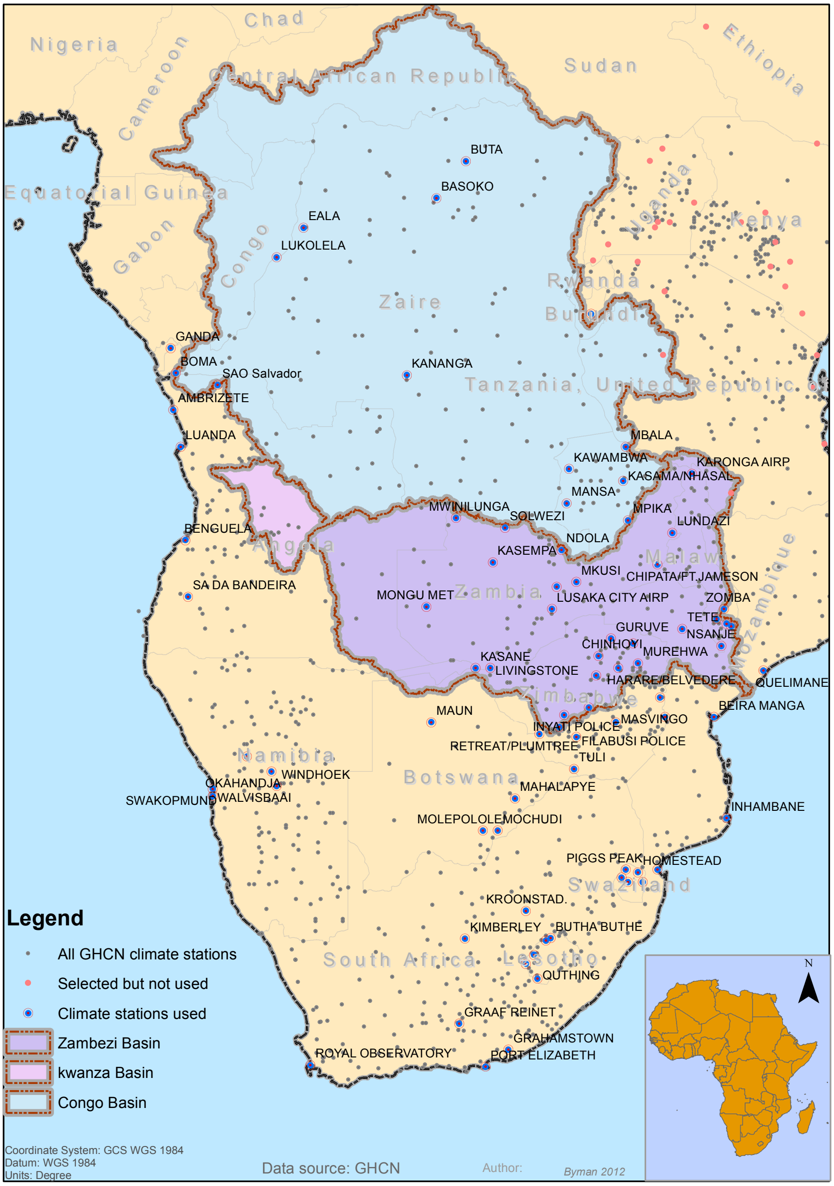

Figure 6.12: *Selected Climate Stations in central in southern Africa. The red dots are climate stations that were selected for trends analysis. These stations have long and continuous (>30 years) data for temperature or rainfall. The gray dots are stations registered with GHCN but data is either short or has a lot of gaps (unusable) and therefore quality is not good*

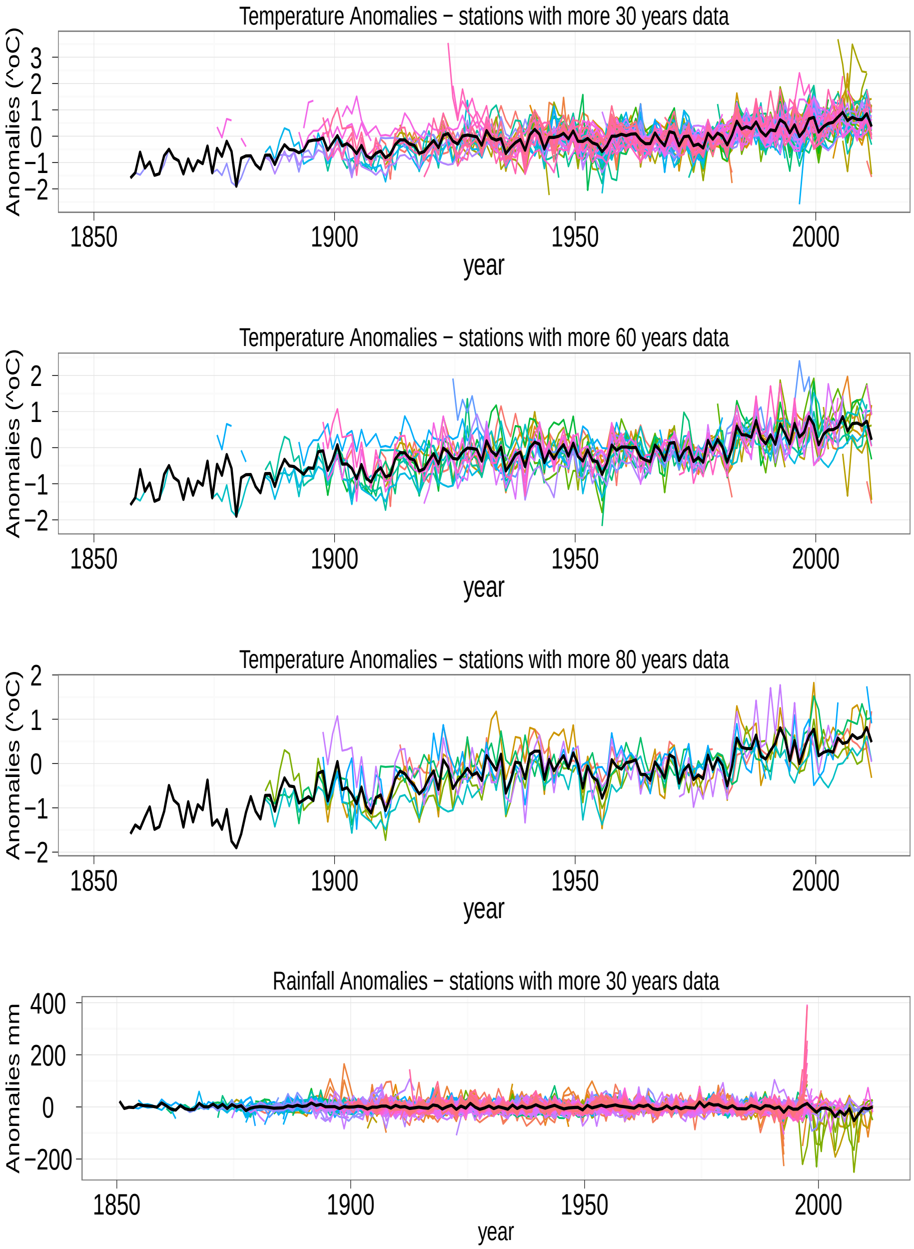

Figure 6.13: *Plot on Anomalies of station with greater than 30 years (no. 73 stations), 60 years(no. 26 stations) and 80 years (no. 7 stations) for temperature and the bottom shows the rainfall anomalies. The black line is the median for each plot*

30 years is shown in Figure 6.13. The trends in rainfall was not as clear as in temperature, however a slight decline is noticed from the figure. However the rainfall stations when analysed individually highlighted different trends although there are fewer stations with trends that was significant. Some rainfall stations showed neither increasing or decreasing trends (remained the same) while with those stations with trends, it was not significant.

6.4.2 Observed River Flow Trends

The discharge data were obtained from GRDC and the Department of Water Affairs, Ministry of Energy and Water Development in Zambia. The annual and monthly discharge data were inspected and selected based on the continuity in data and falling within the Zambezi Basin. There was no filling of missing data in order to avoid disturbing natural patterns and trends. Figure 6.7 shows the time-series plot of discharge datasets and the variability between stations is very visible. The discharge records are very short except for some major rivers at certain gauging stations in the region. As can be seen in Table 6.3, only a handful of stations have significant slopes. However, the remaining stations highlighted decreasing runoff in these rivers.

Table 6.3: *Trend and slope estimation of the river flows. The sign (negative or positive) on slope column indicates where it is increasing or decreasing. It is clear most of the rivers in the region have negative trends. The slope is the trend for the period used in the analysis. The slope was computed using the SEN's slope estimator. Sen's slope estimator is a method for linear regression that selects the median slope among all lines through pairs of two-dimensional sample points. The slope (%) was the computed for the entire period, although different period have different slopes.*

Country	River	Gauging station	trend τ	Slope (%)	Signif.level
South Africa	VAAL	DE HOOP 65	-0.16	-0.47	0.02
South Africa	WONDERBOOM	DIEPKLOOF BURGERSDORP	-0.23	-0.64	0.00
South Africa	ORANGE	ALIWAL NOORD	-0.37	-0.99	0.00
South Africa	BREE	CERES TOEKEN GEB.	-0.15	-0.39	0.05
South Africa	INCOMATI	HOOGGENOEG	-0.51	-1.88	0.00
Zimbabwe	INSIZA	FILABUSI UPPER WEIR	-0.29	-3.27	0.03
Zambia	LUCHECHE	BELOW LAKE CHILA	-0.49	-2.73	0.00
Zambia	ZAMBEZI	SENANGA	-0.26	-0.64	0.00
Zambia	KAFUE	NYIMBA	-0.26	-1.28	0.08
Zambia	KAFUE	MACHIYA FERRY	-0.20	-1.12	0.07
Zambia	KALEYA	WATER VALLEY ROAD	-0.30	-2.83	0.00
Zambia	LUANGINGA	KALABO	-0.39	-1.87	0.00
Zambia	LUAPULA	CHEMBE FERRY	-0.20	-1.26	0.04
Zambia	LUFUBU	GREEN WATER FALLS	0.52	1.62	0.00
Zambia	NGONA	NTUMBACHUSHI FALLS	-0.19	-0.38	0.05
Malawi	SOUTH	CHIMSEWEZO	0.47	5.82	0.00
Malawi	SHIRE	LIWONDE	0.60	5.32	0.00
Malawi	SHIRE	CHIROMO	0.51	2.85	0.00

6.5 Selected Basins - Highlights

The basins selected for climate change impacts assessments are Congo, Zambezi, Kwanza, Shire, Kafue and Kabompo River Basins as shown in Figure 6.14. All these basins lie

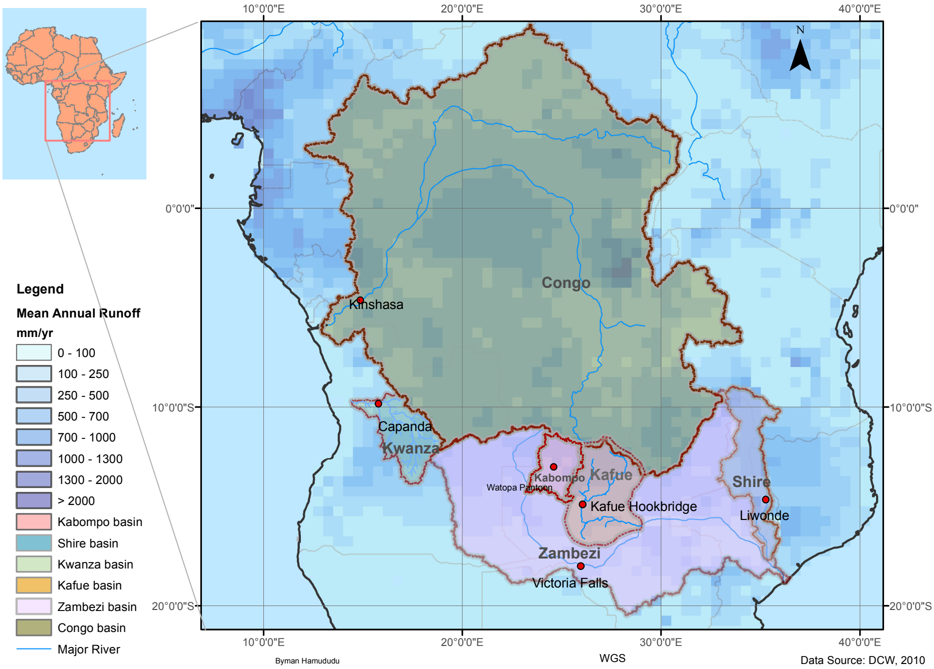

Figure 6.14: *Selected Basins for Case Study. The red dots with names denotes the guaging stations where each river basin is been modelled.*

in the central and southern African region, where this analysis is focusing. The basins were selected due to the hydropower potential that exist on these river basins and the importance of the hydro power to the regional hydro power production. There are other important basins that could have been included in the analysis, but availability of data also limiting factor. The choice of these basins also covered the different range in size, from large to small.

6.5.1 Congo River Basin

The Congo River Basin is located in central Africa within 13^{o}24' South and 9^{o}20' north and 12^{o} 04' and 34^{o} 06' east. The Congo River is the second largest river in the world after the Amazon: 4,400 km long and draining a basin of 3,800,000 km^2 see Figure 7.1. The river accounts for an estimated 30% of the African continent's total water resources. This slope gives the falls very high potential for hydroelectric power generation. It is the largest waterfall in the world in terms of volume. The Congo River originates in highlands located in eight sub–basin states. However, most of the contribution to the runoff at the mouth of the Congo River is generated in the middle courses of the river in the central tropical rainforests on the equator. The annual average runoff in the Congo is 1,260,000 Mm ^{3}, and the average flow is 42,000 m^3/s. The central part of the catchment where the equator passes is very important for the study, since high amount of precipitation is available throughout the year in the area. The Democratic Republic of Congo has plans to create the world's largest hydropower scheme of 39,000 MW. The site is located 150 kilometres upstream from the mouth of the Congo River and 225 kilometres downstream from Kinshasa, DR Congo's capital. There are two existing hydropower plants on Congo River located at Inga falls, the first hydropower station at the falls: Inga I (1972), with an installed capacity of 351 MW (2.4 TWh/y) and Inga II, (1982) with an installed capacity of 1424 MW (10.4 TWh/y).

The total presently installed generating capacity is more than 2500 MW which includes other smaller hydropower plants in the upper parts of the basin. The future plans for the Inga hydropower scheme is to first add Inga III, a large dam that would produce 3500 MW of electricity, then eventually dam across the entire Congo River to create the Grand Inga Dam, with an installed capacity of 39,000 MW (288 TWh/y). On completion of the Grand Inga Dam, it will be the largest hydropower facility in Africa. There are large wetlands and lakes in the Congo Basin within Zambia and Tanzania which provide important grazing, fish, and wildlife resources to the population. There are about 20 large dams that have been built on the tributaries of the Congo River within Congo. Most of these dams are used for water supply and hydropower generation.

6.5.2 Zambezi River Basin

The Zambezi River Basin is located in south central Africa within 8^o 42' and 21^o 35' south and 18^o 11' and 36^o 17' east. The basin has a total area of 1,390,000 km^2. The Zambezi River Basin is the largest of the African river systems flowing into the Indian Ocean (Figure 7.7). It is shared by eight basin countries and supports a population of more than 30 million people. The major tributaries of the Zambezi rise in Angola, Malawi, Tanzania, Zambia, and Zimbabwe. There are five major swamps, the Barotse, the Eastern Caprivi, the Kafue, the Busanoa, and the Lukanga, covering an area of 20,000 km^2 at high flood periods.

Apart from a number of smaller lakes, the most significant natural lake is Lake Malawi (28,750 km^2), but there are also two major artificial lakes, namely Kariba (5,180 km^2) and Cahora Bassa (2,660 km^2). Other reservoirs with large surface areas are the Kafue Dam (809 km^2) and the Itezhi–tezhi Dam (365 km^2). Although the available water resources in the Zambezi Basin, in general, exceed the demand at present, this situation may deteriorate as a result of the increase in population, more industrial and mining development, increased irrigated food production, a higher standard of living of the population, including the environmental water demand of the system. However, it is estimated that the most significant increase in water consumption will most probably be a result of large-scale irrigation projects for food production. More than 28 dams with a storage capacity in excess of 12 million m^3 , of which Kariba is the largest (160,000 million m^3) and Cahora Bassa the second largest (52,000 million m^3), have been built for domestic, industrial, and mining water supply, irrigation and power generation. At present the major hydropower facilities in the Zambezi Basin are at Victoria Falls (108 MW), Kafue Gorge (990 MW), Kariba (1266 MW), Cahora Bassa (2075 MW) and on the Shire River at Nkula A and B (124 MW), Tedzani (90 MW), and Kapichira (125 MW).

6.5.3 Kwanza River Basin

The Kwanza Basin is located in Angola within 7^o 40’ and 13^o 55’ south and 13^o 10’ and 19^o 15’ east. The basin has a total area of 157,000 km^2 and borders the catchments of the Cuito and Cubango rivers on the south and southeast. These rivers, contrary to the Kwanza, flow towards the Kalahari Desert. The basin also borders the basins of some of the Zambezi right bank tributaries. On the north and northeast it is bordered by the large Congo Basin. The Kwanza River, approximately 1000 km long, has its source in the Angola highlands, in the Bie district, above 1500 metres above sea level. It initially flows from south to north and then changes course to the west, near Malanje. After changing its course, turning to the west for an extension of 200 km corresponding to the Middle Kwanza, the river rapidly flows down from the Angolan highlands to elevations near sea level, at Cambambe about 60 km south of Luanda, showing an average slope of 0.005. After this reach located between mostly steep slopes with churning waters due to numerous rapids and falls, the Kwanza spreads out on the coastal peneplain flooding vast areas during the rainy season. Monthly average rainfall normally reaches the highest values during the months of November-December and February-March. As regards the flood peaks observed in run-off at Cambambe, maximum monthly average rainfalls occur less than one month in advance, according to the flood concentration time estimated based on other data. The highest value for annual rainfall was 1490 mm corresponding to the largest flood recorded at Cambambe. The lowest rainfall value was recorded is 828 mm. During the dry season, normally in June, July and August, there is no rainfall for two to three months. Generally rainfall increases in the northeast direction from the south west. The highest rainfall areas are bordering with Congo in the northern part of the country. The Kwanza catchment lies in the centre of the country and therefore enjoys medium to high rainfall. Figure 6.14 shows the Mean Annual Rainfall over Angola and the Kwanza catchment. The lowest mean rainfall for Kwanza catchment is about 400 mm/year (towards to outlet) while the highest point at source has mean annual rainfall of 1400 mm/year. The Kwanza hydropower system has two existing hydropower plants. The first one up is the Capanda hydropower plant, it comprises of a reservoir with a capacity of 4450 million m^3. The installed capacity is 620 MW utilizing 640 m^3/s with a head of 84 metres. The second is the Cambambe hydropower plant with a smaller reservoir of 20 million m^3. The capacity installed is 260 MW using 670 m^3/s with a head of 51 metres. There are plans to construct two more hydropower plants between the two existing hydropower plants. These are Nhangue hydropower plant with another reservoir of 3300 million m^3, 1325 MW installed capacity and will use 625 m^3/s and a head of 193 metres. The second planned hydropower plant is the Cacula Cabasa with installed capacity of 1025 MW from a head of 191 metres using 600 m^3/s of flow.

6.5.4 Shire River Basin

The Shire River Basin is located in Malawi within 8^{o}20' and 17^{o}25' south and 32^{o}20' and 36^{o}10' east. The Lake Malawi and Shire River Basin lies in southern part of the Great East African Rift Valley system, which has significantly influenced its shape and morphology. The entire basin area of Lake Malawi/Shire River system is about 150,000 km^2 and is a tributary of Zambezi River. The lake has an unusually low land/lake catchment ratio of 17 - 5 and relatively deep lake with an average depth of about 250 metres to a deepest point of 702 metres below surface. The lake surface is about 28,750 km ^{2}, 590 km long and a maximum width of 80 km, with average observed water level of 474.15 masl. To the east the Shire Basin forms the national boundary with Mozambique and covers the entire Lake of Malawi. A large part (20%) of this basin is covered by the lake making the basin special for hydrological modelling. The largest tributary is Ruhuhu River (14,070 km^2) in Tanzania followed by South Rukuru (12,110 km^2) in Malawi and the Bua and Linthipe rivers, all in Malawi with 10,700 and 8,560 km^2, respectively. The other significant tributaries include Songwe, Kiwira and North Rukuru rivers and others, which are all less than 5,000 km^2 each

The Shire River is the outlet of the lake Malawi and flows about 410 km from Mangochi to Ziu Ziu in Mozambique, where it drains into Zambezi River. The reach is divided into the upper, middle and lower sections. The Upper Shire is between Mangochi and Matope, with a total channel bed drop of about 15.0 m, over a distance of 130 kilometres. However, within this reach the upper most reach from Mangochi to Liwonde is almost flat with the channel bed dropping to about 1.5 m over a distance of 87 km. The hydropower potential for Malawi lies in the section from Matope to Chikwawa, where the river drops about 384 metres.

6.5.5 Kafue River Basin

The Kafue River Basin is located in Zambia within 11^{o}24' and 17^{o}35' south and 25^o 31' and 29^{o}45' east. The basin has a total area of 157,000 km^2. The Kafue River Basin forms the left bank tributary of the Zambezi River Basin It rises in the North–western part of Zambia, where Zambia shares a border with the Democratic Republic of Congo. The source the river is at an elevation of 1370 metres above sea level and runs to the point where it joins Zambezi at an elevation of 500 metres above sea level, covering a distance of 1568 kilometres. The middle Kafue is mainly the plains (Kafue flats) and marshland occupying an area of about 7000 km^2. This part of the basin supports other uses such as agriculture, fishing, dry season cattle grazing, municipal water supplies and commercial sugar growing. The length of the river in this part is about 450 km and has a gentle slope, taking close to six weeks from the Itezhi-Tezhi Dam to the Kafue power station.The northern part of the basin receives up to 1400 mm of rainfall annually while the southern part of the basin receives as low as 800 mm annually. The average discharge before the first reservoir is 308 m^3/s, with the highest peaks of 800 m^3/s in the months of March and April. The Kafue Basin has runoff coefficient of about 9%.

The Kafue Gorge Hydropower Station is consists of two dams: Itezhi–Tezhi (6000 million m^3) and Kafue Gorge dams (785 million m^3), 10 km tunnel and power station utilizing 450 m drop from Kafue Gorge Dam. Its installed capacity was 900 MW (6 no. x 150 MW) but has been upgraded to 990 MW (6 no. x 165 MW). The power station is designed for minimum flow of 120 m^3/s to maintain its firm energy target of 430 MW at 99.5% reliability. Along with the construction of the current Kafue Gorge Hydropower Station, the Itezhi-Tezhi Dam was built about 230 kilometres upstream and formed a reservoir with a capacity of 6 billion cubic metres. This reservoir levels the flow of the Kafue, which varies with the season (wet versus dry) and contributes to the efficient operation of the Kafue Gorge Hydropower Station. Another plant is being constructed on the Itezhi Tezhi reservoir. There is also construction of hydropower plant at a site downstream of the Kafue Gorge plant. Annual pan evaporation value is in the range of 2547 mm, applying the pan–to–lake coefficient of 0.7 gives 1783 mm per year. The climatology for Kafue Basin is like the typical tropical climate, with uni-modal rainfall season and dry the rest of the year. However, there are differences in the magnitudes of the rainfall within the basin. The basin receives most of the rainfall from the upper part of the catchment in the north.

6.5.6 Kabompo River Basin

Kabompo River Basin is located in North-Western Province of Zambia within 11^o12’ and 14^o35’ south and 22^o55’ and 26^o15’ east. The basin has a total area of 2,300 km^2 . The Kabompo River is one of the main tributaries of the upper Zambezi River. It flows entirely in Zambia, rising to the east of the source of the Zambezi, in North-Western Province along the watershed between the Zambezi and Congo river basins which also forms the border between Zambia and DR Congo. The Kabompo River flows south-west through Miombo woodland, then a remote dry forest eco-region, with the West Lunga National Park on its west bank. After flowing past the town of Kabompo, it develops a swampy floodplain up to 5 km wide. The river enters the Zambezi north of the town of Lukulu, at the north end of the Barotse Floodplain. Its main tributaries are the Western Lunga River which flows from the north, and the Dongwe River from the east.

The Kabompo hydropower Project has installed capacity of 40 MW in the Kabompo Gorge on the Kabompo river. The annual generation is 176 GWh/year from a mean discharge of 24 m^3/s, net head of 160 m, plant factor of 59% and connected to a dam of 68 m high and reservoir capacity of 289 million m^3 of storage and surface of area of 28.1 km^2. The project supplies power to four districts in North Western Province namely; Kabompo, Mufumbwe, Zambezi, and Chavuma as well as have extra power for export to Angola through Chavuma Boarder Post at Chingi.

In order to have a good overview of the temporal distribution of flows in these basins, the individual flows were analysed. The box plot in Figure 6.15 was used to depict the variability of flow on monthly basis over the observations period. The figure shows the interquartile range of flows between 25th and 75th percentile for each of the six basins selected. The line inside the box shows the median flow for each month. The upper

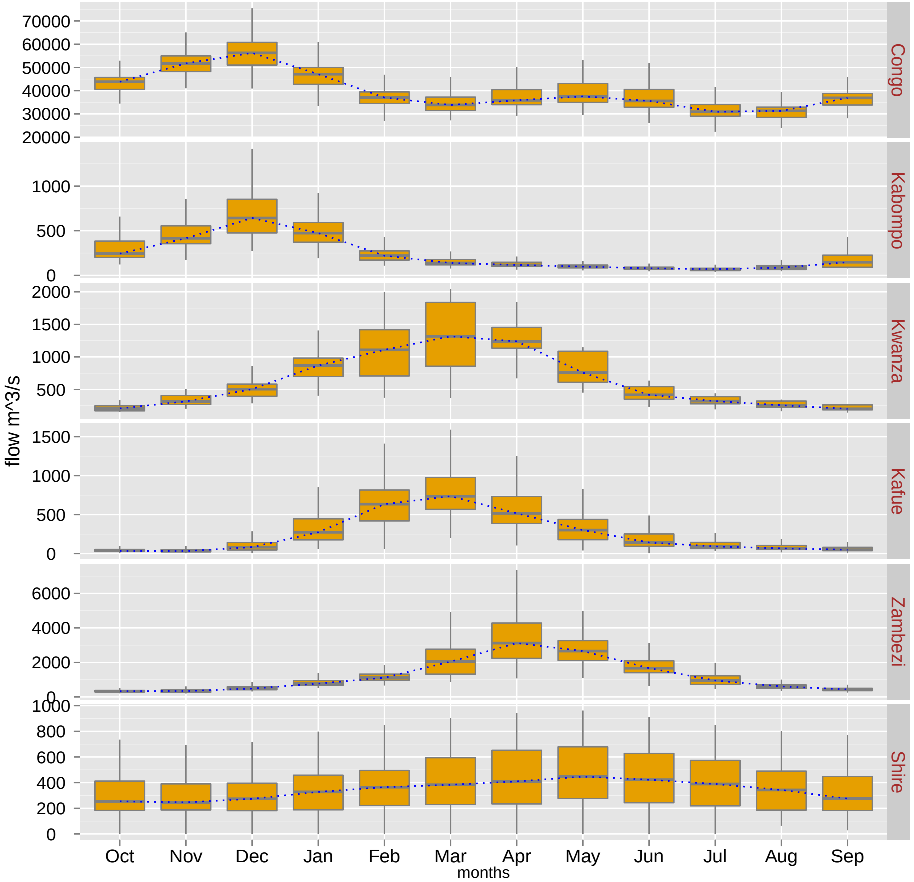

Figure 6.15: *Variations in river flow analysis. The blue bands show the variation between the highest and lowest recorded for each month. from top to bottom: Congo, Zambezi, Shire, Kwanza and Kafue rivers.* (Data source: (GRDC, 2011))

adjacent value (upper mark) is the largest flow that is less than or equal to the upper quartile plus 1.5 the length of the interquartile range. The lower flows (lower mark) is the flow of the smallest flow that is greater than or equal to the lower quartile less 1.5 times the length of interquartile flow range. The red dots are outliers (flows) beyond lower-upper mark range and these represent the recorded flows beyond the normal range (upper and lower). The Congo river has lower variabilities in flow when compared to Shire river. However for the other rivers, the variability is higher in high flow months than the months with low flows.

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Chapter 7

Future Scenarios

7.1 Introduction

The first step was to access the simulation data of the global circulation models. GCM simulations run in large international climate research centres world wide and the resulting data are published on servers where free downloads can be made. As mentioned before, the number of GCMs was large, it was necessary to select a few GCMs (manageable) during the selection process. The selection process was described in chapter 4 where CGCM3.1, CSIRO3.0, ECHAM5, CCSM3.0 and HACDM3 models were selected for this purpose. Though there are many emission scenarios available (see section 4.1.1), only one emission scenario (SRES A1B) was selected. The basis for this selection was the fact that this emission scenario lies between the low (B1) and high (A2) emission scenarios. This decision also reduced the number of future ensembles of the climate variables generated. In the rest of this work the emission scenario used is A1B unless otherwise stated.

The GCMs were selected by applying the Taylor diagram (Taylor, 2001) as described in detail in Chapter 4.3.2. Five GCMs were selected for the region; CGCM3, CSIRO3, ECHAM5, CCSM3, HADCM3. The data simulated from these GCMs were used for downscaling for each of the catchments and the mean / median of the results used as the future variables.

Using the procedures outlined in Chapter 3 and Chapter 4, downscaling were carried out on selected stations within these basins. The downscaling method used was mainly statistical downscaling on daily time step and others on monthly time step. For stations where daily data were available daily statistical downscaling was carried out using the SDSM procedure described earlier. For monthly downscaling, clim.pact package (described under section 4.4.2) was used. The statistical downscaling was carried out by using the SDSM for daily data and clim.pact for monthly data to assess the expected changes on temperature and precipitation. The results of the downscaling were derived future time series for the three future periods of 30 years each was derived from from downscaling. The reference period sometimes referred to as current period, is the 1961 -1990 and the three periods are called 2020s, 2050s and 2080s, representing 2011 - 2039, 2040 - 2069, and 2070 - 2099 respectively.

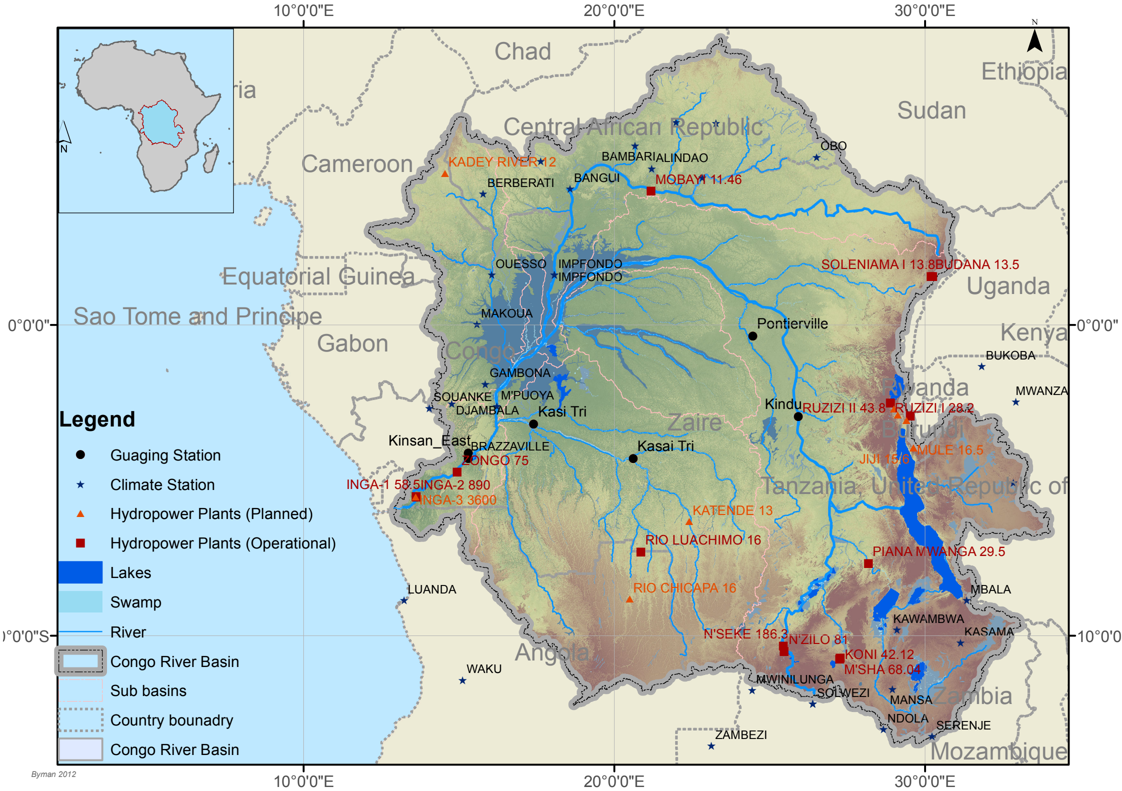
In order to provide perturbed scenarios of runoff, results from downscaling of GCMs were applied in hydrological models to identify climate change impacts. Simplified post-processing of global simulations and statistical downscaling were carried out prior to hydrological modelling.

7.2 Modelling the Selected River Basins

7.2.1 Congo River Basin

The historical meteorological data used for the study of climate change impacts were obtained from the GHCN (Global Historical Climatology Network) database on a daily basis at 10 stations in the Congo Basin catchment. The data were obtained from CRU (gridded observations for temperature and rainfall), GRDC (river flow) and GHCN (climate station observations). The stations used for the study are all located in the northern and southern parts of the catchment, which are in Central Africa Republic and Zambia respectively. No data (with good quality) could be found /accessible in the central part of the catchment which includes dense river networks and areas with high amounts of precipitation. The central part of the catchment where the equator passes is very important for the basin, since high amount of precipitation occurs throughout the year in this part of the basin. The stations with climate data, flow gauging stations, hydropower plants, along with major water bodies and other features are shown in figure 7.1

Downscaling of large scale GCM outputs to a finer spatial resolution was carried out in the catchment. Downscaling using the SDSM principle (Wilby et al., 2002) was carried out with the help of ASD downscaling tool for single-site scenarios of daily surface weather variables under current and future climate forcing. The HadCM3, the Climate model developed at the Hadley Centre, UK and CGCM3 from the Canadian Climate Centre were obtained at the Canadian Climate Impacts Scenarios website. From an initial 33 stations (see Figure 7.1) selected from the GHCN dataset, only 19 stations were found to have data that could be used in downscaling. The results from the selected 19 stations for the downscaling from the SDSM are presented in Table 7.1 and Table 7.2. Later, the clim.pact (Benestad, 2004) was also used on a few selected stations on a monthly time step. Some example of results of the downscaling using the clim.pact in Figure 7.2. Most of the stations were dropped as the calibration during the downscaling failed completely. However of these stations that could be downscaled were located to the northern and



Byman 2012

Figure 7.1: *Congo Basin with climate stations that were used in downscaling with gauging stations and climate stations*

Table 7.1: *Downscaling results for Rainfall - Congo Basin*

Name	Station code	Scode	Latitude	Longitude	Elevation	Changes (%)		
						2020	2050	2080
BERBERATI	CT000004600	CT 04600	4.22	15.78	583	–8	–15	–12
BRAZZAVILLE	CF000004450	CF 04450	–4.25	15.25	314	13	34	48
BOSSEMBELE	CT000004605	CT 04605	5.27	17.63	674	–24	–30	–26
BANGUI	CT000004650	CT 04650	4.38	18.57	381	–10	–11	–8
BRIA	CT000004655	CT 04655	6.53	21.98	548	–22	–29	-28
BANGASSOU	CT000004656	CT 04656	4.73	22.83	500	–19	–29	–33
BAMBARI	CT000004660	CT 04660	5.77	20.67	448	–20	–28	–30
YALINGA	CT000004661	CT 04661	6.5	23.27	602	–20	–26	–26
ALINDAO	CT000004662	CT 04662	5.02	21.2	447	–37	–45	–39
ZAMBEZI	ZA000067531	ZA 67531	–13.53	23.12	1077	–3	0	10
LOBO	CT000004659	CT 04659	5.4	26.5	660	–16	–15	–6
MWINILUNGA	ZA000067441	ZA 67441	–11.75	24.43	1363	12	34	43
SOLWEZI	ZA000067551	ZA 67551	–12.18	26.38	1386	12	31	31
KAWAMBWA	ZA000067403	ZA 67403	–9.8	29.083	1324	9	18	35
MBALA	ZA000067413	ZA 67413	–8.85	31.33	1673	-8	-8	1
MANSA	ZA000067461	ZA 67461	–11.1	28.85	1382	10	20	41
KASAMA	ZA000067475	ZA 67475	–10.22	31.13	1384	4	12	34
NDOLA	ZA000067561	ZA 67561	–13	28.65	1270	4	13	35
SERENJE	ZA000067571	ZA 67571	–13.23	30.22	1384	7	18	36

Table 7.2: *Downscling results for maximum temperature Congo Basin*

Name	Station code	Scode	Latitude	Longitude	Elevation		Changes (%)	
						2020	2050	2080
BERBERATI	CT000004600	CT 04600	4.22	15.78	583	1.4	2.5	3.8
BRAZZAVILLE	CF000004450	CF 04450	–4.25	15.25	314	1.7	3.0	4.6
BOSSEMBELE	CT000004605	CT 04605	5.27	17.63	674	1.9	3.3	5.1
BANGUI	CT000004650	CT 04650	4.38	18.57	381	1.3	2.3	3.6
BRIA	CT000004655	CT 04655	6.53	21.98	548	0.2	0.3	0.5
BANGASSOU	CT000004656	CT 04656	4.73	22.83	500	–0.1	-0.2	-0.3
BAMBARI	CT000004660	CT 04660	5.77	20.67	448	1.5	2.7	4.0
YALINGA	CT000004661	CT 04661	6.5	23.27	602	1.5	2.6	4.0
ALINDAO	CT000004662	CT 04662	5.02	21.2	447	0.0	0.0	–0.1
ZAMBEZI	ZA000067531	ZA 67531	–13.53	23.12	1077	1.5	2.8	4.4
OBO	CT000004659	CT 04659	5.4	26.5	660	0.0	–0.1	–0.2
MWINILUNGA	ZA000067441	ZA 67441	-11.75	24.43	1363	1.5	2.8	4.3
SOLWEZI	ZA000067551	ZA 67551	–12.18	26.38	1386	1.6	3.0	4.7
KAWAMBWA	ZA000067403	ZA 67403	–9.8	29.083	1324	1.0	1.8	2.7
MBALA	ZA000067413	ZA 67413	–8.85	31.33	1673	1.9	3.6	5.6
MANSA	ZA000067461	ZA 67461	–11.1	28.85	1382	1.9	3.6	5.5
KASAMA	ZA000067475	ZA 67475	–10.22	31.13	1384	1.3	2.5	3.8
NDOLA	ZA000067561	ZA 67561	–13	28.65	1270	1.7	3.1	4.8
SERENJE	ZA000067571	ZA 67571	–13.23	30.22	1384	1.8	3.3	4.9

southern part of the catchment.

Table 7.1 depicts that the rainfall changes in future over the northern part of Congo Basin will be reduced while in the southern part will increase. The central part of the Congo Basin may remain the same, the results excludes this region. In Chapter 6, it was observed that the middle part of the Congo basin contributes most of the runoff of the Congo River. For this method only a few stations are presented to show the type of results. In the northern part of Congo Basin the rainfall increases between January and May but there a slight decrease for the rest of the year, resulting in a total decrease on annual basis. The northern part of the Congo basin receives rainfall throughout the year but the rainy season can be divided into two parts, March – May and second (main) season is September – November. Although there are changes in all seasons, the changes in the two rain seasons have more impacts than the other seasons. Unlike the northern part of the Congo Basin, these stations lie in the zone with uni-modal rainfall pattern. The rainfall season is only in the months of December-February, although rainfall begins in late October and can last till end of April. In terms of changes in rainfall amounts, the December-February changes are more significant than any other seasons.

The maximum temperatures results are presented in Table 7.2, both the northern and southern sides of the Congo Basin, have increases although the increase is high on the maximum temperature than the minimum temperature. Unlike rainfall the temperature variation over the Congo basin is relatively low, but the increasing trends are more consistent. The results of downscaling are shown in Figure 7.2 and Figure 7.3.

Hydrological Modelling

The hydrological modelling was carried out using the PITMAN rainfall runoff model.

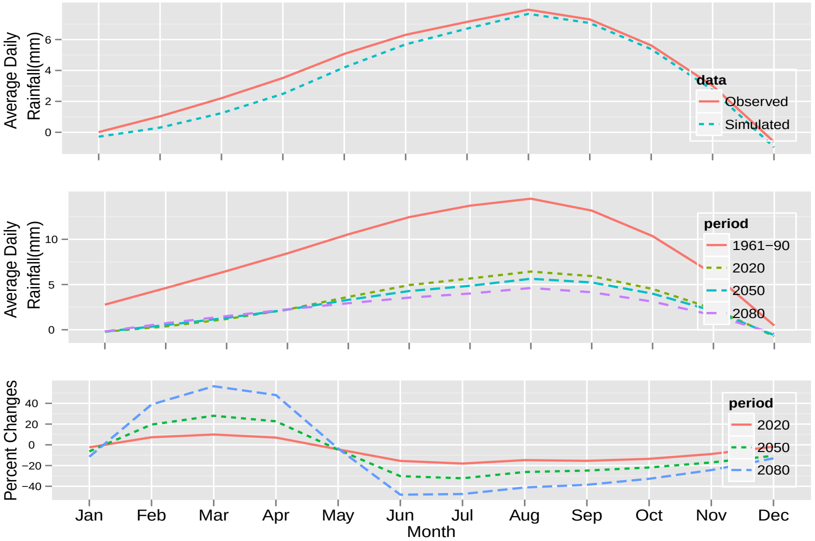


Figure 7.2: *Downscaling results for Yalinga Station Central African Republic, Yalinga is located in the northern part of Congo basin. The annual rainfall at Yalinga is about 1100 mm.*

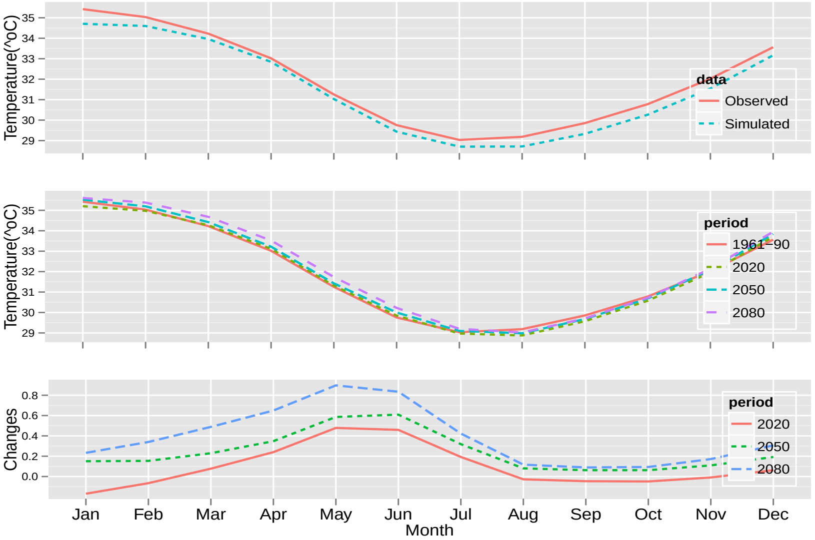


Figure 7.3: *Downscaling results for Yalinga Station Central African Republic, Yalinga is located in the northern part of Congo basin.*

The Pitman model evaluates a catchment as having two storages, which are the interception storage, and subsurface storage (Figure 7.4). Pitman originally referred to the subsurface storage as soil moisture storage which combined soil moisture and groundwater. The model simulates four processes which are; interception, surface runoff, evaporation from the subsurface storage, and runoff from the subsurface storage.

The model assumes that all the rainfall that is intercepted on a particular day evaporates on the same day. The interception loss is a function of interception capacity, and the amount of daily rainfall. The interception model assumes that the rate of increase of interception gradually decreases as the rainfall increases.

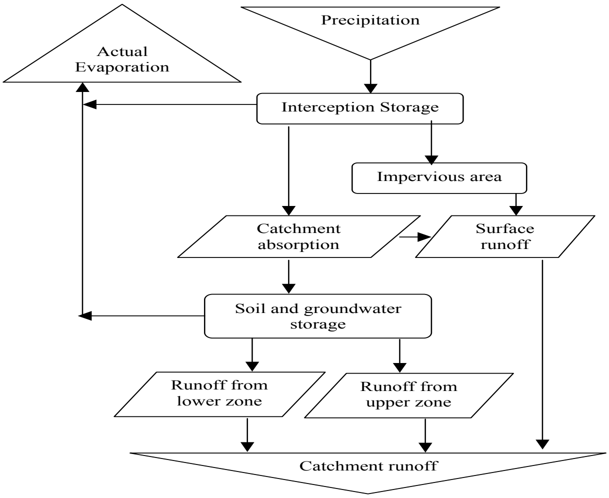


Figure 7.4: *The Structure of the PITMAN monthly rainfall runoff model*

The model assumes that surface runoff is generated from two processes. Firstly, all the rainfall on impervious areas of the catchment will form surface runoff. This runoff can only contribute to stream flows if they discharge goes directly into streams, otherwise runoff generated on these parts of the catchment will be absorbed by the surrounding soils. Secondly, surface runoff can be formed as a result of rainfall which does not infiltrate on pervious parts of the catchment. The absorption rate of rainfall into the subsurface storage is considered to vary spatially because of variations in vegetation, soils and geology. It is assumed that as the rain all increases, it will increasingly exceed absorption rates of increasing proportions of the catchment and therefore contribute to surface runoff.

When the subsurface storage has the maximum amount of water, the actual evaporation rate equals the potential evaporation rate. But when the subsurface storage declines below this maximum amount, the actual evaporation rate declines from the potential rate. A power curve is assumed to describe the rate at which water drains from subsurface storage to streams. It is assumed that all the water is coming from the lower zone of the subsurface storage. Water coming from the lower zone of the subsurface storage will take longer time to reach the catchment outlet than originating from the upper zone.

The results from the downscaling were then used as inputs into the hydrological modelling process. The PITMAN hydrological model was used on a monthly time step. The monthly time was ideal for a large basin of the size of the Congo. The required input data for the Pitman model are basin area, a time series of basin average rainfall, seasonal distributions of evaporation (fractions), irrigation water demand (mm), other water demands (fraction) and monthly parameter distribution factors. Optional data requirements includes optimisation ranges for parameters (ZMIN, ZMAX, ST, POW and FT), and time series of basin average potential evaporation, upstream inflow and transfer inflow. The Pitman model is no different from most conceptual models in that there is rarely an optimum solution based on a unique combination of parameter values for a specific basin. This presents a real challenge with respect to calibration.

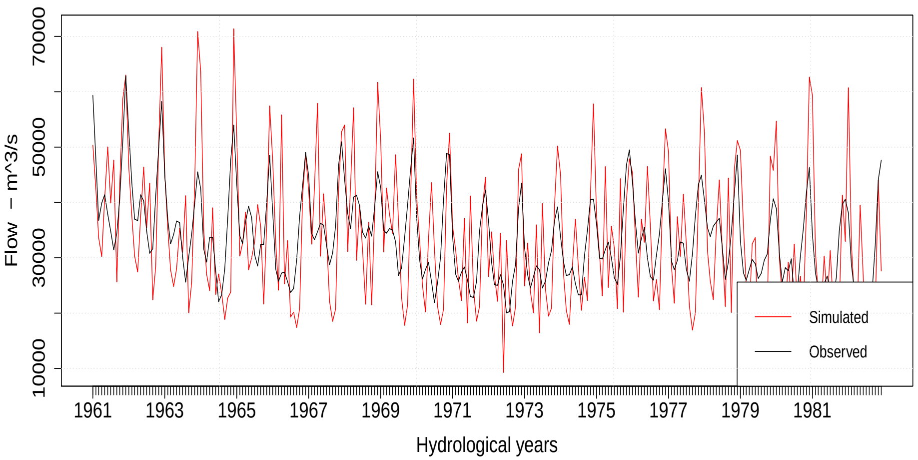


Figure 7.5: *PITMAN model calibration results - Congo Basin at Kinshasa gauging. The PITMAN hydrological model was set up with several (9) sub basins. The discharge observations were only available at Kinshasa. The blue line represents observed data, red line for simulated, and the green line is the simulated data from GCMs*

The model was first calibrated manually (with internal hints calibration improvements) using the observed data and then later with the current period (1961 -1990) and the future time period as described earlier. The results of the hydrological modelling are presented in Figure 7.5 and Figure 7.6. The period 1961 - 1982 had observations for both temperature and precipitation and discharge data. The model was calibrated based on this period and the results of the downscaling. The calibrated model represented the hydrological response of the basin adequately based on the historical hydrological data. Consequently, it was used to assess the impact of future development scenarios, given that likely water abstraction scenarios were represented by the model.

The typical monthly calibration of the hydrological model is shown in Figure 7.5. The figure shows that the modelling process had some problems in simulating the high flows (over estimated) and the low flows (underestimated). This can be attributed to the missing data in the centre of the Congo Basin, which is the main contributor to runoff of the river. The runoff data was limited in the Congo river. The calibration was only based on the runoff data at Kinshasa gauging station. As such, the calibration parameters in the PITMAN model was assumed to be the same throughout the basin, even if the basin was subdivided into 12 modules, the sub basin modules lacked observed flow data for calibration independently. Table 7.3 shows the parameters that were optimum for the model calibration. The parameters are defined below the table. The quality of calibration process was assessed using the Nash-Sutcliffe R2 for optimal model parameters by manual model calibration. The average R2 value is 0.58, not a very good calibration. Figure 7.5 shows that the model simulations for the calibration period were good enough although some low runoff years and some peaks are not well simulated. Table 7.3 summarises the calibration parameters of the PITMAN hydrological model for basin. This was attributed to short periods of data, stations located outside the catchment and poor runoff data available for the basin.

Table 7.3: *PITMAN Model calibration parameters for the Congo River simulations. The period used for calibration is 1961 - 1982. POW - Power of soil moisture/subsurface flow equation, SL - Soil moisture state when subsurface flow=0, ST - Soil moisture capacity in mm, FT - Subsurface flow at soil moisture capacity, GW - Maximum groundwater flow in mm/month, ZMIN - Minimum catchment absorption in mm/month, ZMAX - Maximum catchment absorption in mm/month, PI - Interception storage in mm, TL - Lag of flow (excluding groundwater), GL - Lag of groundwater flow in months, and R - Coefficient in evaporation/soil moisture equation.*

Module	POW	SL	ST	FT	GW	ZMIN	ZMAX	PI	TL	GL	R
1	0	0	50	99	99	0	600	1.5	0.99	20	0.5
2	0	0	50	99	99	0	600	1.5	0.99	20	0.5

The changes in per cent are shown in Table 7.4. The first row is the average of the observed flows and the rest of the values are changes of flow as a percentage of the current period. The reduction appears to be more pronounced in the period between March - May while there are increases in the period between June -September. However, the annual values show that there is tendency of increases in flow in the future although the first period 2011 - 2040 shows a slight decrease. Figure 7.6 presents the changes graphically. Based on these results, the Congo River Basin flow is likely to increase slightly from 1 to 4 % towards the end of the century.

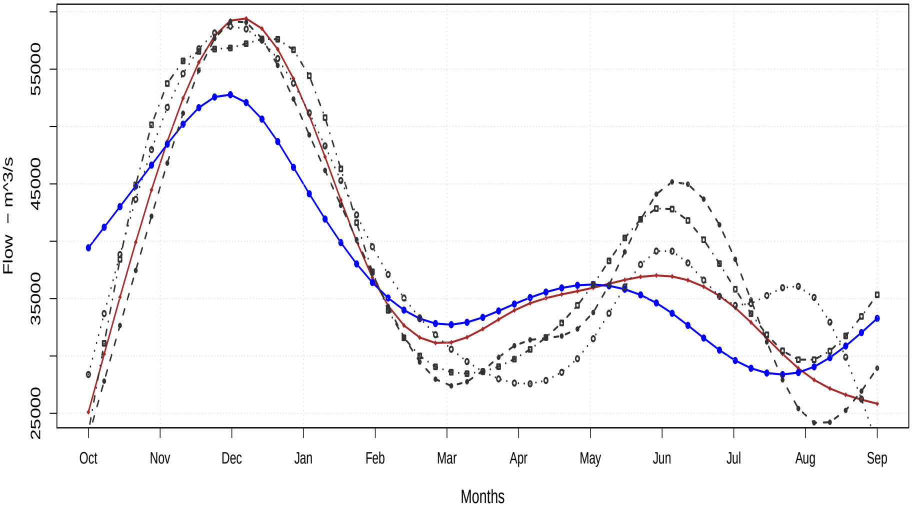


Figure 7.6: *Annual hydrographs for different periods for Congo Basin. Blue represents observed while red is the simulated current period. Other colours represent different periods*

Table 7.4: *Changes in flow - Congo River. The first row is the average of the observed annual monthly flows. The changes are expressed as percentage (%) of the current monthly flows*

Period	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Flow ('000)	44	53	59	50	40	36	39	41	38	33	32	37	45
2020s	91	96	100	97	101	88	91	93	121	113	87	112	99
2050s	113	107	99	100	108	99	81	87	106	100	126	86	101
2080s	93	112	96	106	101	92	88	100	116	105	104	137	104

7.2.2 Zambezi River Basin

The Zambezi basin lies in the uni-modal rainfall zone and therefore there is not much difference in rainfall pattern between the different parts of the basin except the reduction in amounts from north to south. Most of the data used in this analysis were obtained from Zambia Meteorological Department and as a result there were more number of stations with data in the Zambezi basin. The station data were supplemented by the data from GHCN for other countries (Zimbabwe and Malawi) within the basin and consistencies were checked. The average annual rainfall over the upper catchment is 1100 - 1200 mm, with considerably higher rainfall near the source (northern part). The monthly and annual distribution of rainfall is given in Table 7.5. Rainfall season occurs during the period from November to March, with peak rainfall occurring in December and January. Runoff peaks in February or early March. Mean annual runoff from the region is about 26.8 x 10^9 m^3, providing an average annual flow of 850 m^3/s.

Figure 7.7: *Zambezi Basin with climate stations that were used in downscaling with climate and gauging stations and hydropower plants*

The peak runoff typically reaches Lukulu by February-March but this runoff takes one and half months to pass through the Barotse Plain and peak discharge near the downstream outlet (Senanga) is often delayed until April or early May. Flood-waters recede slowly from the Barotse Plain during the six-month dry season, with high evaporation losses throughout the year. Figure 7.8 shows the climate (rainfall and evaporation regimes) on the top plot and the lower plot shows the effect of the flood plain on flows.

The downscaling process for the Zambezi river basin was carried out on the stations with long continuous data. The downscaling technique used is clim.pact (Benestad, 2004) on a monthly time step. The reason for this choice was uniformity since some stations (in Zimbabwe and Malawi) had only monthly data. Mean temperature and precipitation were downscaled for this basin. The results of the downscaling are presented in Table 7.6. In total number of 40 stations had data that could be used for downscaling. These stations are located all over the basin however only the stations in the upper part of the catchment were used. Most of these stations are shown on the previous map of the Zambezi River Basin.

The mean temperature results shows an increasing trend in the future, and this is consistent in most of the stations; it varies only in magnitude. There are reductions in rainfall amounts in some stations while in others there is no change or slight increase. The stations in the northern part of the basin show some increases in rainfall amounts, while the

Table 7.5: *Mean monthly and annual rainfall (mm) for selected stations in the northern highlands. The stations locations are shown in Figure 7.7*

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Mwinilunga	91	209	264	239	213	255	96	10	1	0	2	17	1396
Zambezi	48	135	228	239	208	170	42	3	0	0	0	0	1074
Kabompo	37	193	219	243	209	166	43	5	1	0	0	3	1120
Kasempa	39	142	255	248	212	171	38	3	0	0	1	4	1106
Kaoma	34	111	217	210	192	128	42	3	0	0	0	4	943
Average	50	158	237	236	207	178	52	5	0	0	1	6	1128

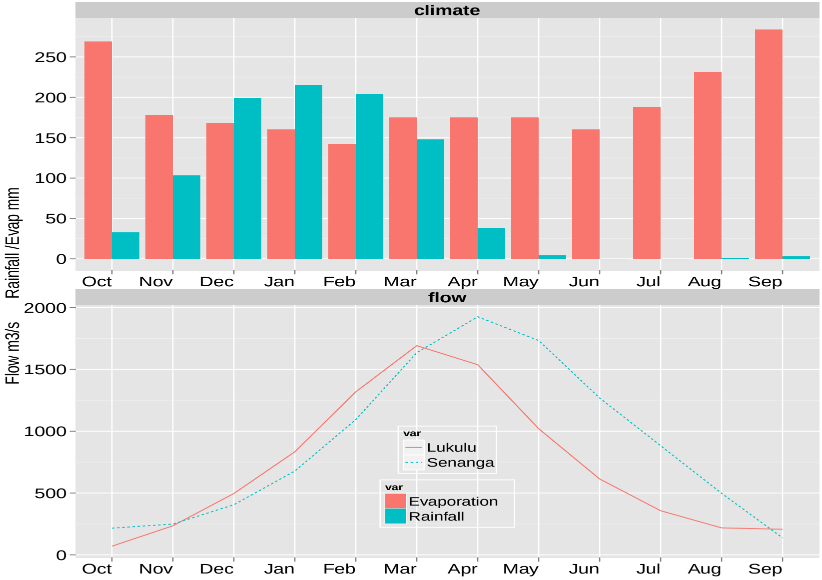


Figure 7.8: *Mean monthly rainfall in the Zambezi headwaters region (top), and hydrographs of mean monthly runoff upstream and downstream of the Barotse Plain, 1950-99, showing attenuation of peak runoff. The top plot is the rainfall (blue) and potential evaporation (mm). The lower plot shows the effect of the Barotse flood plain. The continuous line is the Zambezi flows at Lukulu and the broken line (purple) is flows at Senanga*

stations in the southern part of the basin show decreasing amounts of rainfall. In general, the results show that rainfall on average will decrease to 94% by the 2020s, 92% by the 2050s and 90% by the 2080s compared to the current climate. The mean temperature results show that there will be an average increase in temperature of 1.4^{o}C by the 2020s, 2.3^{o}C by the 2050s and 3.2^{o}C by the 2080s. In conclusion, the basin will experience higher temperatures and reduced rainfall. As the number of stations were relatively many for Zambezi basin, an additional check was carried out. The correlation between the mean annual rainfall and the change was investigated for each time period. There seemed to show, though weak, relationship between the changes and the mean annual rainfall. The high rainfall stations registered increases or lower reductions.

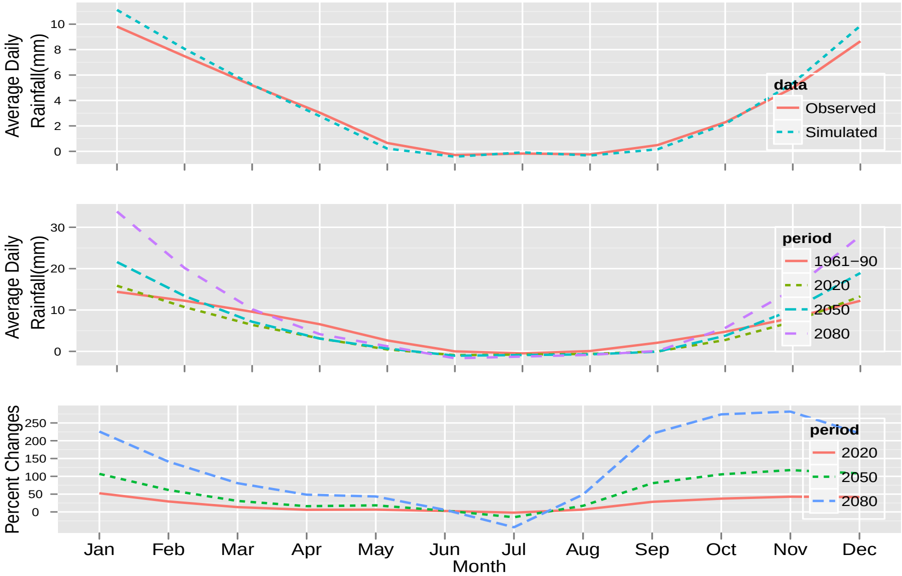


Figure 7.9: *Downscaling results for Zambezi, northern western Zambia. The plots depicts the changes in seasons, JJA,SON, DJF and MAM. The annual rainfall at Zambezi is 1200 mm*

Figure 7.9 show the results of downscaling for two climate station, one (Zambezi) in the upper part of the basin and the second in the middle part. The rainfall in the middle part of the basin (Livingstone climate station) is expected to reduce while the upper section is expected to have increase (Zambezi climate station).

Figure 7.9 show the results of downscaling for two climate station, one (Zambezi) in the upper part of the basin and the second in the middle part. The rainfall in the middle part of the basin (Livingstone climate station) is expected to reduce while the upper section is expected to have increase (Zambezi climate station)

Hydrological modelling

Hydrological modelling was carried out using the PITMAN model (described in the previous section), on a monthly time step. Evapo-transpiration was computed using the Hargreaves method (Hargreaves and Allen, 2003) that uses mean temperature and location of the station. The basin was subdivided into sub-basins (modules). For each of these modules temperature, rainfall and evapo-transpiration were estimated from the downscaled results. Where runoff data was available for the modules, calibration was carried out to get optimal parameters. In Figure 7.10, the calibration of one of the modules (upper Zambezi) is presented. The runoff data at Victoria Falls (pump station) was used for this calibration. There were six sub-basins, among them Kabompo, Lwanginga, Zambezi upper and Cuando. Another module that was set up was the mid Zambezi. However,

Table 7.6: *Downscaling results for rainfall Zambezi Basin. The values in the table represents the change (%) for each period relative to reference period. The changes are in percentages of the current period, while the annual is the observed mean annual rainfall per year in mm*

NAME of STATION	Mean Annual Rainfall (mm)	2020s %	2050s %	2080s %
SOLWEZI	1243	0.12	0.12	0.31
MWINILUNGA	1439	0.12	0.24	0.34
KABOMPO	1027	0.28	0.36	0.36
CHOMA	785	-0.13	-0.17	-0.22
KAOMA	924	0.03	-0.06	-0.12
LUSAKA	788	-0.17	-0.18	-0.19
LIVINGSONE	765	-0.17	-0.18	-0.22
KALOMO	726	-0.21	-0.19	-0.2
HWANGE	512	-0.22	-0.23	-0.15
HARARE	787	-0.05	-0.07	-0.02
GWERU	653	-0.15	-0.23	-0.15

because there was no runoff data for mid-Zambezi model parameters from Kafue river basin were used. The Kafue module has runoff data and was calibrated. The calibration was done for Kafue Hook Bridge runoff data. The model parameters were also used for other modules which did not have runoff data. Figure 7.10 illustrates the results of calibration. In order to get the runoff series in the future, the calibration model was run using the downscaled future temperature and runoff and the computed evapo-transpiration. In Figure 7.11, it can be seen that the runoff for this module decreases in the future. From the current runoff data, the runoff decreases by 8% in the 2020s, 13% by the 2050s and 21% by the 2080s, see Figure 7.11.

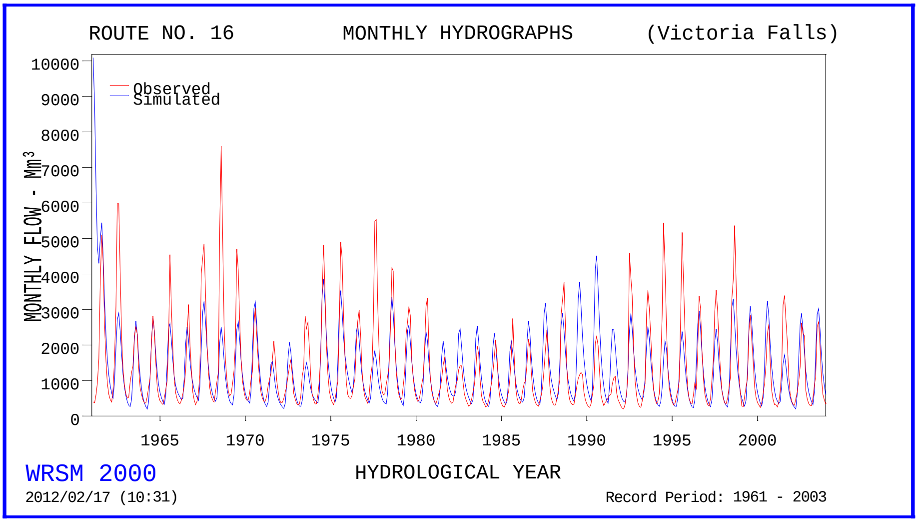


Figure 7.10: *Calibration of Hydrological Model. PITMAN Calibration Results - Zambezi Basin at Victoria Falls gauging station. The PITMAN hydrological model was set up with several (5) sub basins. The discharge observations were only available at Victoria Falls (Pump station). The blue line represents observed data, red line for simulated, and the green line is the simulated data from GCMs.*

The calibration of the hydrological model for Zambezi basin is shown in Figure 7.10. The figure shows that the modelling process with a good fit though there are some problems in simulating the high flows (over estimated). The calibration was only based on the runoff data at Victoria falls, pump station for Livingstone town water supply - gauging station. The calibration parameters in the PITMAN model was assumed to be the same throughout the basin, even if the basin was subdivided into 8 modules, the sub basin modules lacked observed flow data for calibration independently. Table 7.3 shows the parameters that were optimum for the model calibration. The parameters are defined below the table. The quality of calibration process was assessed using the Nash-Sutcliffe R2 for optimal model parameters by manual model calibration. The average R2 value is 0.79, a good calibration. Figure 7.10 shows that the model simulations for the calibration period were good. Table 7.7 summarises the calibration parameters of the PITMAN hydrological model for basin.

Table 7.7: *PITMAN Model calibration parameters for the Zambezi River simulations. The period used for calibration is 1961 - 1982. POW - Power of soil moisture/subsurface flow equation, SL - Soil moisture state when subsurface flow=0, ST - Soil moisture capacity in mm, FT - Subsurface flow at soil moisture capacity, GW - Maximum groundwater flow in mm/month, ZMIN - Minimum catchment absorption in mm/month, ZMAX - Maximum catchment absorption in mm/month, PI - Interception storage in mm, TL - Lag of flow (excluding groundwater), GL - Lag of groundwater flow in months, and R - Coefficient in evaporation/soil moisture equation.*

Module	POW	SL	ST	FT	GW	ZMIN	ZMAX	PI	TL	GL	R
1	2.2	0	150	99	20	200	1100	1.5	0.25	2.5	0.5
6	2.2	0	150	99	20	200	1100	1.5	0.25	2.5	0.5

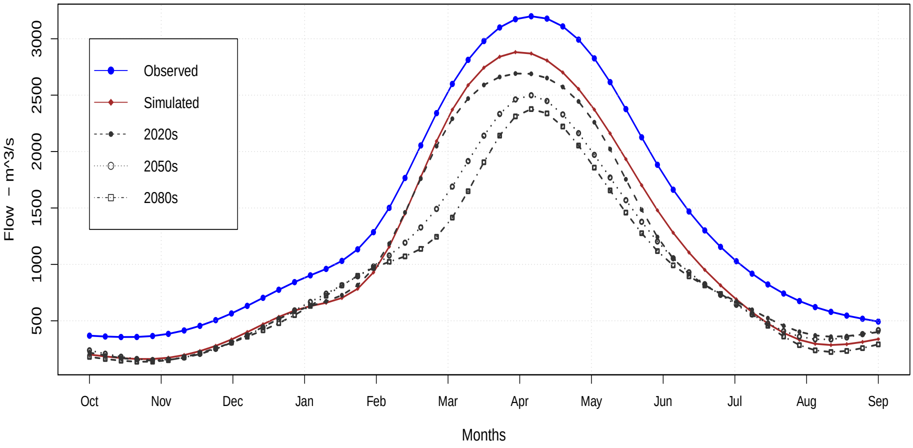


Figure 7.11: *Monthly flow changes. Changes in flow - Zambezi River at Victoria Falls - Pump station*

Table 7.8: *Monthly flow changes in Zambezi River at Victoria Falls*

PERIOD	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Current (m^3/s)	368	374	571	882	1320	2533	3185	2860	1799	1039	649	493	1339
2020s (%)	108	90	92	99	103	97	93	95	83	97	123	119	100
2050s (%)	118	92	92	104	104	71	86	83	82	93	111	123	96
2080s (%)	90	86	91	97	102	59	81	79	76	95	83	86	85

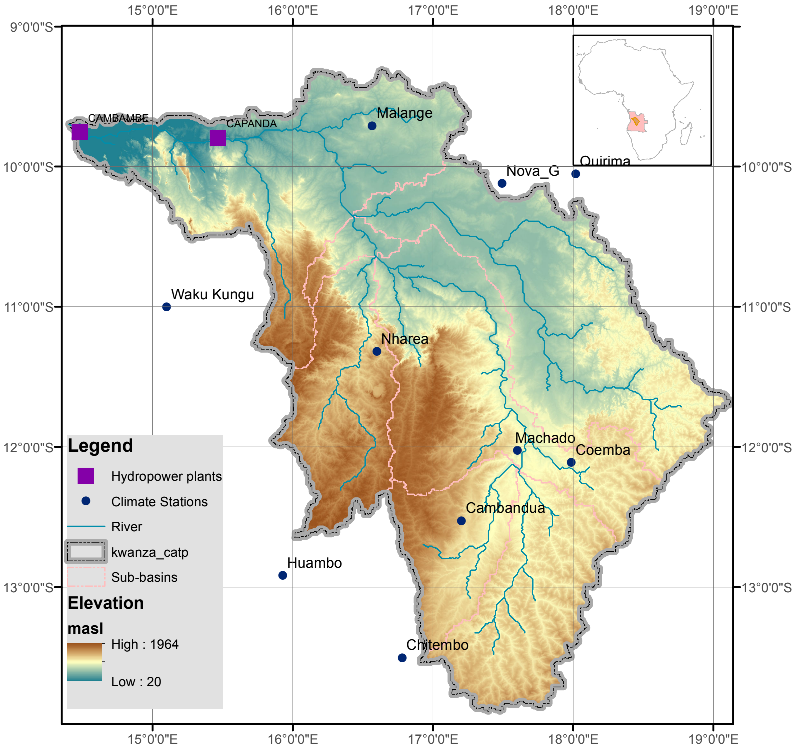


Figure 7.12: *Kwanza River Basin with sub–catchments with climate stations and location of hydropower plants. The river basin, located in Angola flows north and then west towards the Atlantic Ocean*

7.2.3 Kwanza River Basin

The Kwanza Basin, Angola was modelled like the Congo and Zambezi basins. The Kwanza Basin did not have any long continuous climate data in most stations in the basin. Although the data were not as good (few years of data and quality), downscaling was carried out. The data was filled and corrected where there were apparent errors. Climate data were filled in where there were gaps with neighbouring stations from Zambia. Most of the stations with data where outside the basin. The SMHI RCA datasets were used as input data to hydrological modelling. Later the hydrological modelling, and hydropower simulations were carried out. As shown in Figure 7.12, most of the climate stations are located in the outside or downstream of the river system. The results for precipitation are shown in Table 7.9. The temperature increases by 1.2°C by the 2020s, 2.1°C by the 2050s and 3.2°C by the 2080s. Rainfall increases by 4% by the 2020s, 6% by the 2050s and 12% by the 2080s. The Kwanza Basin, is expected to have increased rainfall as can be seen from Figure 4.8 in Chapter 4. The changes in tabular form of rainfall and temperature are given in Table 7.9.

Table 7.9: *Results of downscaling - Angola (Kwanza) Stations. The values in the table represents the changes (%) for each period relative to reference period. The changes are in percentages of the current period, while the annual is in mm of rainfall per year*

NAME	Mean Annual mm	2020s %	2050s %	2080s %
CARMONA	1599	0.03	0.25	0.24
COEMB	1319	0.04	0.05	0.07
DUNDO	1614	0.05	0.19	0.20
GANDA	1565	0.24	0.45	0.45
LUSO	1208	0.32	0.31	0.31
MALANJE	1151	0.1	1.04	0.12
MALUDO	1487	0.17	0.2	0.19
MOCIMBA	1014	0.22	0.22	0.22
NOVA	1322	0.07	0.15	0.1
PORTO AMBOIM	672	0.07	0.08	0.12
SA DA BANDEIRA	1428	0.18	0.18	0.17
SILVAPORA	1428	0.18	0.18	0.17
		0.24	0.19	0.19

Hydrological modelling

The HBV hydrological model was used for hydrological modelling (Bergstrom, 2006; Bergstrom et al., 2001; Bergström, 1992; Bergstrom, 1972; Saelthun, 1996). The HBV hydrological modelling was used to assess the impact of climate change on the stream flow. The model is a conceptual rainfall-runoff model, originally developed for Scandinavian catchments but now extensively used in Europe and other parts of the world in a wide range of applications. It considers the main runoff generating process using simple structure. The HBV-model is a conceptual lumped precipitation-runoff model, which is used to simulate the runoff process in a catchment based on data for precipitation, air temperature and potential evapotranspiration.

The model computes snow accumulation and snowmelt, actual evapo-transpiration, storage in soil moisture and groundwater and runoff from the catchment. In general, it is a mathematical model of the hydrological processes in the catchment. The soil moisture routine, which is based on simple equations with only three empirical parameters, determines actual evapotranspiration and is controlling runoff formation based on the level of the soil moisture content in the system. The runoff response routine transforms excess water from the soil moisture routine into runoff. It consists of two linear tanks called Upper zone and Lower zone which are connected in series by a constant percolation rate. The Upper zone represents the quick runoff components, both from overland flow and from groundwater interflow. The lower zone represents the groundwater and lake storage that contribute to base flow in the catchment.

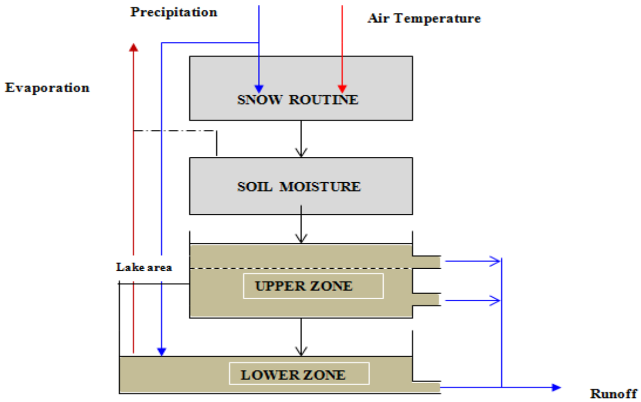


Figure 7.13: *The structure of HBV daily rainfall runoff model*

The main structures of HBV model is presented in Figure 7.13. The model contains a relatively smaller number of parameters which can further be divided into confined and free parameters. Free parameters are determined during the process of calibration whereas confined parameters are determined from maps, field surveys or from other sources of information about the catchment.

The model use daily Precipitation (P), Air temperature (T) and Potential evaporation (PET) as input data. P and T are based on observations while PET is usually computed from other climatic data. Precipitation input is usually computed as Areal precipitation (PA) for the catchment, by combining observations from several stations in or around the catchment, depending on availability. The basin areal temperature and rainfall were computed using the thiessen polygon method. In this process it is necessary to find the optimal weighting between different stations. In addition, precipitation data was corrected since there is usually a loss of precipitation in the measurement process. In most cases a positive precipitation-elevation gradient will also be used in the model. Air temperature data similar to precipitation was also based on observations at several stations. Since the air temperature decreases with increasing elevation, it was necessary to correct the measurements to obtain air temperature in higher elevations in the catchment. This decrease (Lapse rate) is usually in the order of -0.6 oC/100 m elevation increase. Increasing or decreasing air temperature will also bring a change in the potential evaporation (PET). Potential evaporation can be computed by different methods, depending on data availability. In the simplest case, it is possible to use only air temperature. The evapo-transpiration was computed using the Hargreaves method (Hargreaves and Allen, 2003). Due to lack of runoff data, only 12 years of data was the only data available for calibration on this basin. Potential evapo-transpiration for present climate was computed to be 898 mm/year. For future climate simulations (2020, 2050 and 2080) the monthly change in potential evapo-transpiration were computed with respect to temperature for each period.

Figure 7.14 shows the calibration results of the model for Kwanza basin for a few number of years in order to give an impression of the quality of the model fit. Model calibration quality was assessed by a combination of graphical and numerical criteria, using plots of observed and simulated flows together with Nash-Sutcliffe R2 parameter corrected with water balance deviation. R2 is a measure of how good the model performs, a perfect model has R2=1.0, and the closer to 1, the better the model. Optimal model parameters have been determined by manual model calibration. Some results of the model calibration is given. The average R2 value is 0.68, a medium good result. Figure 7.14 shows that the model simulations for the calibration period were good although some low runoff years and some peaks are not well simulated. Table 7.10 summarises the calibration parameters of the HBV model for basin. This was attributed to short periods of data, stations located outside the catchment and poor runoff data available for the basin.

Table 7.10: *Kwanza Catchment HBV calibration parameters for different RCM datasets*

Description	Parameter	CCSM3 A1B	ECHAM4 A1B	ECHAM4 B2	Mean
Rain Correction	PKORR	1.1	1.1	0.95	1.05
Elevation Correction	HPKORR	0	0	0	0
Field Capacity	FC	850	400	350	333.33
Beta	BETA	1.2	1.2	1.6	1.33
Evaporation threshold	LP	20	10	30	20
Fast Drainage	KUZ2	0.02	0.02	0.02	0.02
Slow Drainage	KUZ1	0	0	0	0
Threshold	UZ1	10	5	20	11.67
Percolation	PERC	0.2	0.1	0.2	0.17
Drainage Coeficient	KLZ	0.01	0.01	0.01	0.01
	R^2	0.66	0.66	0.6	0.63
	Q	202	201	205	204

The results are generally good although the model underestimates peak flows in some years. Good quality data within the catchment could reduce these deviations even more. Despite these deviations, it is concluded that on average, the runoff in the catchment can be simulated with the HBV-model with acceptable accuracy. For further analysis and comparison the simulated flow series is used as representative for the present hydrology (1990s). By using the simulated flow instead of the observed flow, the change in flow will be related only to the change in climate. For each the future periods of 30 years, input data based on future rainfall and temperature and computed potential evapo-transpiration were used. The changes in runoff based on the hydrological simulations for each period is summarised below.

The future runoff was simulated using the downscaled future rainfall and temperature. As shown in Figure 7.15, runoff increases by 2% in the 2020s, 4% by the 2050s and 8% by the 2080s. The source of the runoff in this basin lies in the highlands where temperature is relatively lower and as such evaporation losses are lower when compared to other basins (Zambezi) in the south-east. Table 7.11 summarizes the changes on month to month basis for the future periods.

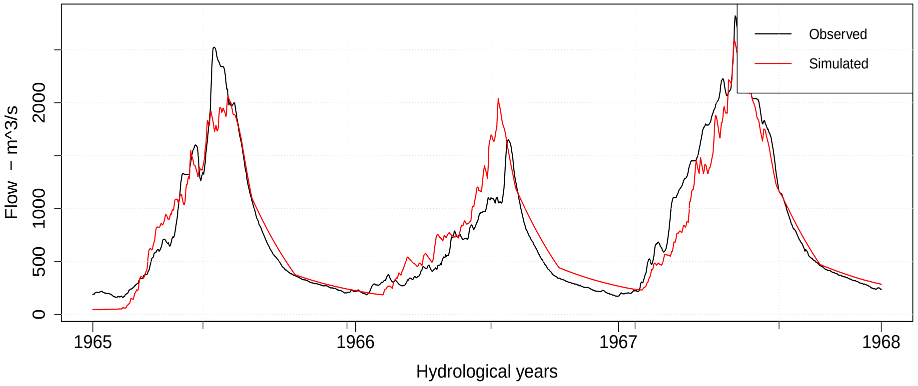


Figure 7.14: *Calibration of Hydrological Model. Calibration Results - Kwanza Basin at Capanda gauging station. The discharge observations were available at Capanda station.*

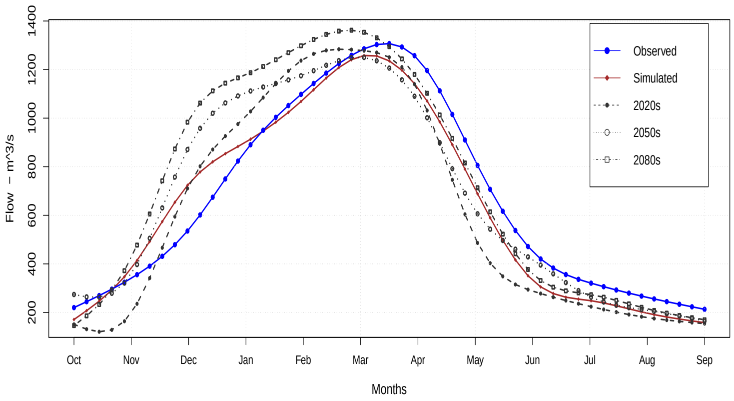


Figure 7.15: *Annual hydrographs - flow changes. Mean changes in flow - Kwanza River. The RCMs data was averaged to get the plotted values.*

Table 7.11: *Monthly flow changes for different time periods for Kwanza River Basin*

PERIOD	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Current (m^3/s)	220	341	541	867	1106	1279	1243	824	451	322	262	213	639
2020s (%)	88	52	99	112	115	102	99	71	87	90	91	97	92
2050s (%)	96	94	121	123	109	100	104	88	126	106	106	104	106
2080s (%)	115	112	122	120	121	100	103	111	117	118	109	108	113

7.2.4 Kafue River Basin

The Kafue Basin data for most of the stations were obtained from the Zambia Meteorological Department and therefore were of longer duration than other basins. However there were some errors found in the data and corrections were performed where possible.

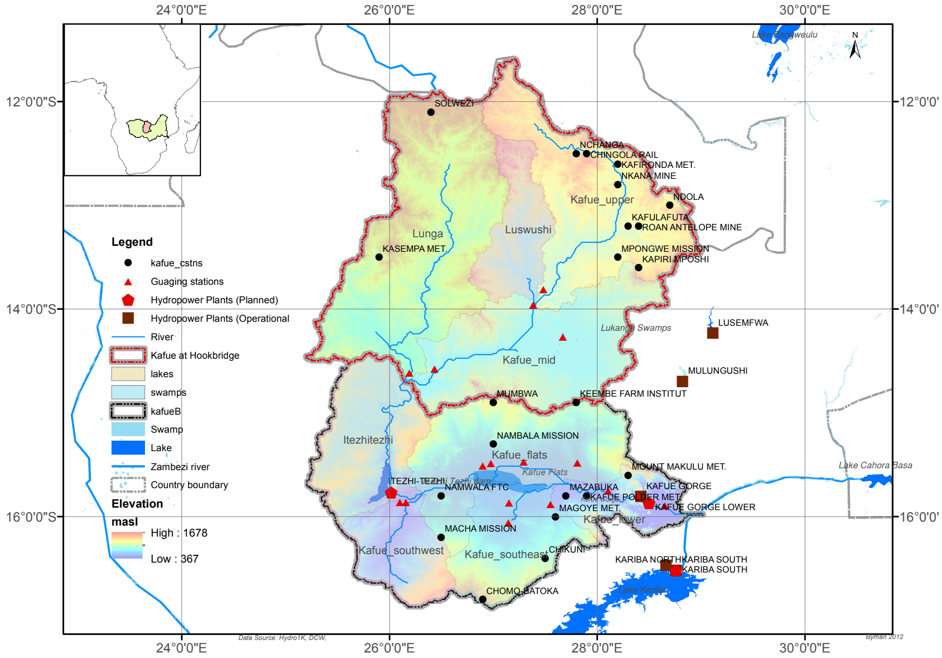


Figure 7.16: *Kafue River Basin with climate stations, gauging stations, major water bodies and hydropower plants.*

Figure 7.16 gives the location, climate stations, discharge gauging stations, hydropower stations both planned and operational and the sub-basins. All climate stations in Kafue Basin are located in the Zambezi Basin, since Kafue lies in the Upper Zambezi basin. A total of six stations were used for Kafue Basin. Like the other basins, the future climate for the basin was generated by downscaling using the SDSM method of statistically downscaling and some stations had already been downscaled using the clim.pact method. This downscaling methodology was problematic especially for downscaling rainfall. It was difficult to get predictors that were agreeing with the observations for most of the stations.

Climate stations used in the downscaling in the Kafue Basin are shown the river basin map for Kafue. Generally these stations result show reductions in the amount of rainfall in future. The downscaling showed that temperature will increase by 1.3^{o}C by the 2020s,

Table 7.12: *Downwscaling results from Kafue Basin rainfall using the SDSM. The values in the table represents the changes (%) for each period relative to reference period. The changes are in percentages of the current period, while the annual is mean annual rainfall in mm of rainfall per year*

NAME	ANNUAL	2020s %	2050s %	2080s %
SOLWEZI	1243	12	12	31
MWINILUNGA	1439	12	24	34
KABOMPO	1027	28	36	36
NDOLA	1209	-4	-8	-5
KAOMA	924	3	-6	-12
NAMWALA	778	-8	-11	-18

2.3^{o}C by the 2050s and 3.7^{o}C by the 2080s. Rainfall decreases by 1% in the 2020s, 5% by the 2050s and 7% by the 2080s. Table 7.12 shows the rainfall results of the downscaling for some stations in Kafue basin. These stations were used in the derive the area precipitation for the basin for each future time period.

Hydrological modelling

The modelling strategy adopted HBV hydrological model for transforming rainfall (and temperature) into runoff. The input data was available through the climate stations within the basin. The stations with long data obsevations were Ndola, Kafironda, Kabwe, Solwezi and Kasempa stations. The basin areal temperature and rainfall were computed using the Theissen polygon method. In addition, precipitation data was corrected since there is usually a loss of precipitation in the measurement process. In most cases a positive precipitation-elevation gradient will also be used in the model. Air temperature data similar to precipitation was also based on observations at several stations. Since the air temperature decreases with increasing elevation, it was necessary to correct the measurements to obtain air temperature in higher elevations in the catchment. This decrease (Lapse rate) is usually in the order of -0.6 ^{o}C/100 m elevation increase. Increasing or decreasing air temperature will also bring a change in the potential evaporation (PET). Potential evaporation can be computed by different methods, depending on data availability. In the simplest case, it is possible to use only air temperature. The evapotranspiration was computed using the Hargreaves method (Hargreaves and Allen, 2003). Potential evapo-transpiration for present climate was computed to be 1970 mm/year. For future climate simulations (2020, 2050 and 2080) the monthly change in potential evapotranspiration were computed with respect to temperature for each period.

The model calibration was assessed by a combination of numerical criteria, using plots of observed and simulated flows together with Nash-Sutcliffe R2 parameter corrected with water balance deviation. Optimal model parameters have been determined by manual model calibration. Some results of the model calibration is given. The average R2 value is 0.75, a reasonable fit. The results are good although the model fit get poor towards the 1990s. The likely reason for the poor fit is the deterioration od data quality towards the 1990s. It was concluded that on average, the runoff in the catchment can be simulated with the HBV-model with acceptable accuracy. For further analysis and comparison the simulated flow series is used as representative for the present hydrology (1990s).

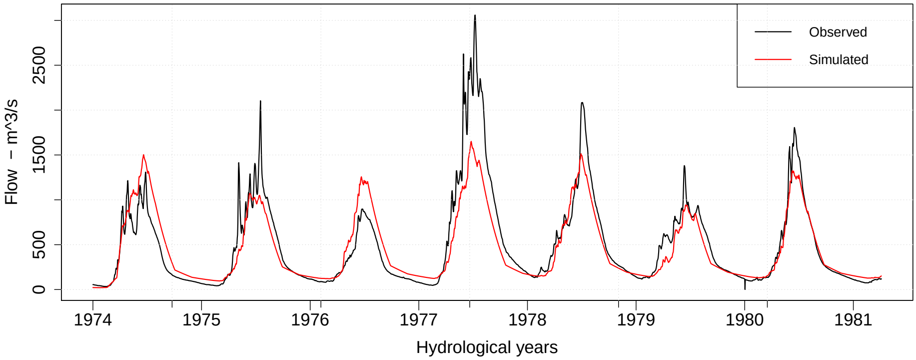


Figure 7.17: *Calibration of Hydrological Model. HBV Calibration Results - Kafue Basin at Kafue Hook bridge gauging station. The HBV hydrological model was set up with several (4) sub basins. The discharge observations were only available at Kafue Hook bridge. The blue line represents observed data, red line for simulated, and the green line is the simulated data from GCMs.*

By using the simulated flow instead of the observed flow, the change in flow will be related only to the change in climate. For each the future periods of 30 years, input data based on future rainfall and temperature and computed potential evapo-transpiration were used. The changes in runoff based on the hydrological simulations for each period is summarised below.

For the current period, temperature and rainfall from the six stations were used to drive the model. Figure 7.17 shows the calibration of the model for Kafue Basin. Future climate variables were then used to drive the model to obtain future runoff series. The results in Figure 7.18 show that runoff will decrease by 12% in the 2050s, 17% by the 2050s and 23% by the 2080s. Figure 7.18 and Table 7.13 summarize the changes in future periods in Kafue river basin on monthly basis.

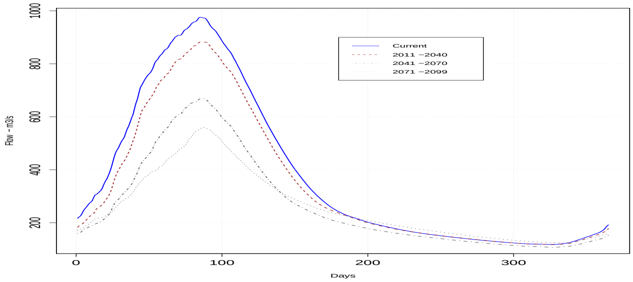


Figure 7.18: *Mean monthly flow changes. Changes in flow - Kafue River at Kafue Hook bridge. The upper plot shows the calibration of the observed and the simulated monthly flows while the low plot shows the flows for different time periods*

Table 7.13: *Monthly flow changes in Kafue River at Hook bridge gauging station. The Kafue hook bridge gauging station is located just before into the Itezhi-tezhi reservoir*

PERIOD	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Current (m^3/s)	70	57	185	313	356	672	515	246	114	121	100	45	233
2020s (%)	84	95	79	91	89	94	93	85	89	91	93	79	88
2050s (%)	66	75	88	86	89	94	87	75	94	83	75	59	81
2080s (%)	31	56	74	82	83	89	85	67	86	69	65	39	69

7.2.5 Shire River Basin

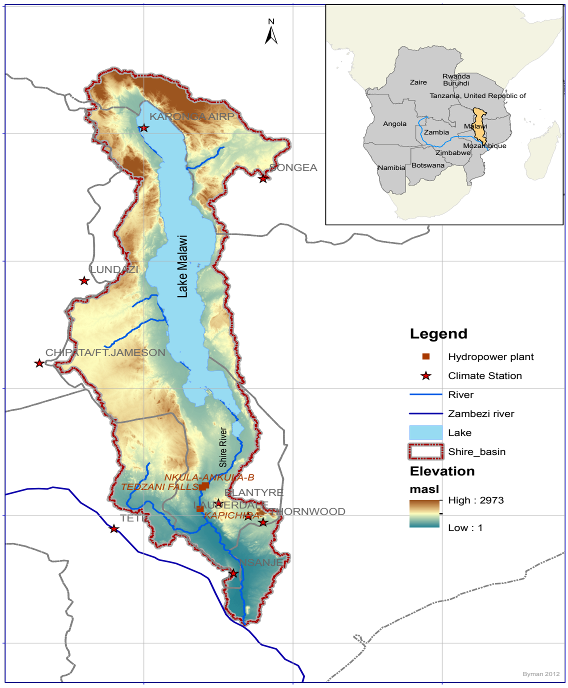


Figure 7.19: *Location of Shire Basin in the region with climate stations and some hydropower stations. The basin is near the Zambezi Delta.*

The climate data for Shire River Basin was obtained from GHCN. There are few climate stations with good data in the basin. Downscaling was carried out on the stations that surround Lake Malawi as there are no climate stations with observations on Lake Malawi (Figure 7.19). The downscaling was carried out on a monthly basis using the clim.pact method. While there are many climate stations with data, most stations had lots of gaps in the observation records. This discontinuous observations (data) on climate leads to difficulties during downscaling. As a result, only a few stations were used in downscaling. The downscaling was extended to stations which were even towards confluence of the Shire and Zambezi rivers. This was done to get an overall picture the likely future climate in the basin.

For each the future periods of 30 years, input data based on future rainfall and temperature and computed potential evapo-transpiration were used. The changes in runoff based on the hydrological simulations for each period is summarised below. The results showed that temperature in the Shire Basin increases by 1.2^{o}C by the 2020s, 2.3^{o}C by the 2050s and 3.8^{o}C by the 2080s, while rainfall in Table 7.14 decreases by 6% in the 2020s, 8% by the 2050s and 11% by the 2080s.

Table 7.14: *Downscaling results for Shire Basin. The values in the table represents the changes (%) for each period relative to reference period. The changes are in percentages of the current period, while the annual is in mm of rainfall per year*

NAME	ANNUAL mm	2020s %	2050s %	2080s %
ZOMBO	1088	-0.15	-1.18	-0.19
NKHOTA KOTA	1595	0.17	0.17	0.1
MCHINJI	1094	-0.11	-0.1	-0.1
MBEYA	927	-0.1	-0.15	-0.08
LIVINGSTONIA	1538	0	-0.1	-0.11
LILOGWE	841	-0.03	-0.02	-0.02
LAUDERDALE	1976	-0.02	-0.12	-0.16
CHILEKA	879	-0.04	-0.07	-0.04
CHIPATA	1041	-0.04	-0.05	-0.03
BLANTYRE	526	-0.19	-0.29	-0.38
MANGOCHI	829	-0.03	-0.1	-0.04

Hydrological modelling strategy

The hydrological modelling of the Shire Basin is different from the other basins due to the large amount of rainfall that falls directly on Lake Malawi. It was decided that the ordinary hydrological modelling process would not be suitable for this basin. The water balance computation was carried out. The method uses estimate of total precipitation (direct rainfall on the lake), evaporation, runoff from rivers flowing into the lake and the outflow from the lake through the Shire river. The free water (difference between the incoming, that is precipitation plus inflow, and evaporation) was correlated to the outflow. This set up was also used for future simulations based on the downscaling results. The simulations for the future periods indicate that runoff will decrease by 8% in the 2020s, 14% by the 2050s and 23% by the 2080s as shown in Figure 7.20. Table 7.15 summarise the changes on monthly basis for different time periods in per cent.

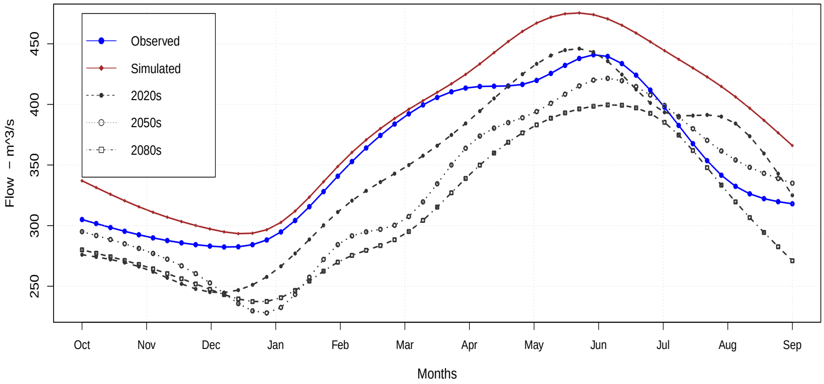


Figure 7.20: *Calibration and monthly flow changes. Changes in flow - Shire River. The upper plot shows the calibration of the observed and the simulated monthly flows while the low plot shows the flows for different time periods*

Table 7.15: *Monthly flow changes in Shire River at Liwonde*

PERIOD	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Current (m^3/s)	337	313	297	300	351	394	427	466	473	445	411	366	382
2020s (%)	90	91	87	90	91	89	93	103	100	99	115	102	96
2050s (%)	97	96	89	79	83	78	89	94	95	100	106	105	93
2080s (%)	92	91	87	82	79	75	83	91	90	97	97	85	87

7.2.6 Kabompo River Basin

Kabompo River Basin (Figure 7.21) is the smallest of all the basins analysed. Only two stations for which downscaling was carried out were used. The downscaling technique used was SDSM method. The results of downscaling for theses stations indicate that temperature will increase by 1°C in the 2020s, 2.1°C by the 2050s and 2.4°C by the 2080s. Rainfall will increase by 6% in the 2020s, 9% by the 2050s and 12% by the 2080s. This basin lies in the northern part of the Zambezi Basin where the increase in rainfall is expected.

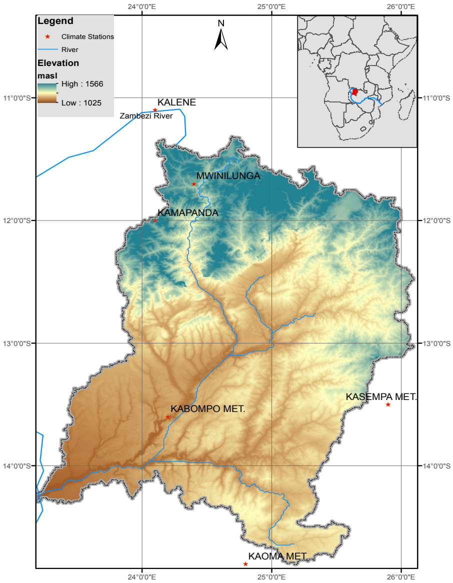


Figure 7.21: *Location of Kabompo Basin in the region. The basin is near the source of Zambezi River.*

Hydrological modelling

The hydrological model used in Kabompo is the IHACRES model (Croke and Littlewood, 2005; Croke et al., 2006; Dye and Croke, 2003//). IHACRES is a catchment-scale rainfall-streamflow model. The IHACRES model is a conceptual-metric model, using the simplicity of the mathematical model to reduce the parameter uncertainty inherent in hydrological models while representing more detail of the internal processes than is typical for a mathematical model.

The model uses rainfall, maximum temperature as input and observed runoff for calibration purposes. It was run on a daily times step. The areal rainfall and temperature were estimated from the two stations using the Thiessen polygon method. The model characterises the catchment by a small set of parameters. Calibration has two methods; a non-linear loss module and a linear unit hydrograph module. The linear relationship between effective rainfall and streamflow allows the application of unit hydrograph theory. This unit hydrograph theory conceptualises the catchment as a series of linear storages acting in series and/or parallel. The non-linearity observed between rainfall and streamflow is accommodated in the (non-linear loss) module which converts rainfall to effective rainfall. The model takes as input, once calibrated, time series of rainfall and either temperature or potential evapotranspiration. The output was a time series of modelled stream flow.

For the calibration period and the validation period, observed stream flow is required to measure of performance to be computed. The data from Kabompo, Kasempa, Kaoma, Mwinilunga climate stations were used for calibration. The calibration was carried out using the manual and semi automatic calibration embedded in the model. The calibration was carried out by specifying the calibration periods, and then choosing between the linear and non linear module. The linear module performs a cross correlation for delay time between rainfall and stream flow and then the instrumental variable function or fixed function was used to regulate the linear module. For this catchment the linear module was good for the calibration and yielded good results. This was done in a semi automated process.

The calibration period from 1962 - 1980 was successful with the highest performance (r^2) of 0.76. The worst period was between 1975 and 1980 but in general, the calibration parameters were considered to be reasonable. The model was then used in the future climate scenarios. Future runoff series were simulated from the downscaled future variables. Figure 7.23 and Table 7.16 show the calibration and the flow changes on monthly basis for future time periods.

The results are good although the model fit misses the peak flows and the cause of this was poor data quality located outside the basin. Better quality within the basin would improve the model performance. It was concluded that on average, the runoff in the catchment can be simulated with the HBV-model with acceptable accuracy. For further analysis and comparison the simulated flow series is used as representative for the present hydrology (1990s). By using the simulated flow instead of the observed flow, the change in flow will be related only to the change in climate. The results show that runoff in this basin will increase by 4% in the 2020s, 7% by the 2050s and 10% by the 2080s.

Table 7.16: *Monthly flow changes in Kabompo River at Watopa*

PERIOD	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Current (m^3/s)	25	29	75	193	317	378	315	160	83	59	45	33	143
2020s (%)	96	133	129	119	103	106	110	91	79	124	89	74	104
2050s (%)	133	200	142	135	107	90	121	133	72	126	58	55	114
2080s (%)	183	311	160	158	112	93	126	151	66	87	53	61	130

7.3 Discussion

Future local impacts of climate change on runoff was estimated by using HBV and IHACRES,on a daily time steps and PITMAN model on a monthly time step. The ensembles of temperature and precipitation for future periods were used as inputs to these hydrological models. For all the hydrological modelling, the challenge remained in estimating the potential evapo-transpiration which is a very important variable in hydrological modelling. The required potential evapo-transpiration was computed using the simple Thornthwaite and Hargreaves method based on future mean temperature. The IHACRES model requires maximum temperature to estimate the potential evapo-transpiration. Both of these methods depend on temperature and location to estimate the potential evap-transpiration. In this region observations (data) are scarce and even when data exist, there are gaps, either filled (roughly) or unfilled. Implementation of

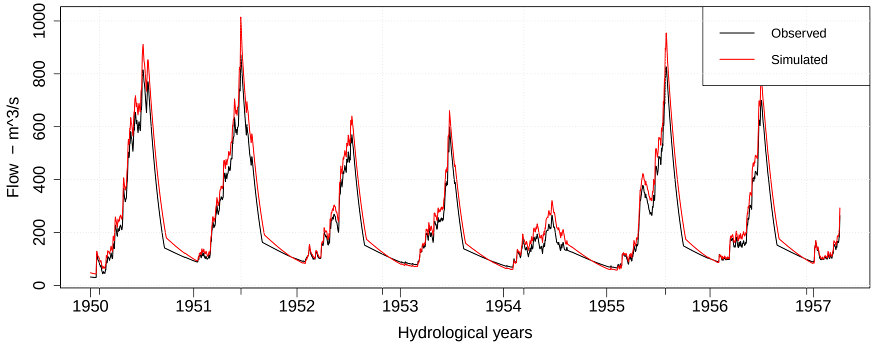


Figure 7.22: *Changes in flow - Kabompo River. The upper plot shows the calibration of the observed and the simulated monthly flows while the low plot shows the flows for different time periods*

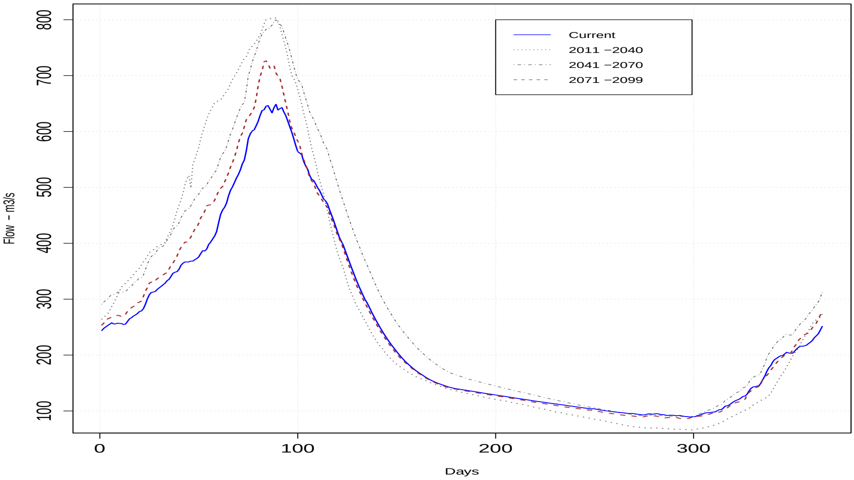


Figure 7.23: *Changes in flow - Kabompo River. The upper plot shows the calibration of the observed and the simulated monthly flows while the low plot shows the flows for different time periods*

hydrological models with high temporal resolution is remains a challenge. For example in Angola, the Kwanza basin was could only be modelled for 6 years on daily time step (HBV) while with a monthly model (PITMAN), it was possible to get data up to 12 years for modelling.

Table 7.17 shows the overall changes on the selected basins for various variables, temperature, precipitation and finally runoff. The runoff is further plotted graphically to show the changes.

Different hydrological models and simulations have been used in this analysis of river basins. Lack of good quality data was a challenge and calibrations in most basins proved to be very difficult because of the same. The results of these simulations despite the above challenge show that river regimes will change by different magnitudes.

There is both increasing and decreasing tendency in runoff in the river basins considered here. The Congo,the Kwanza in Angola, and Kabompo basins show an increase. The Congo, Kwanza and Kabompo basins are in the region where the climate change projections are not very conclusive since it is difficult to get agreement between GCMs in this region. However based on the GCMs, the results indicate a slight decrease in the 2020s and small increase towards the mid century and more increase to the end of the century for the three basins.

For the rest of the basins, (Zambezi, Shire, and Kafue basins) the results show a continuous decrease in flow. The decreases continue to -20% towards the end of the century(2080s). In this region there is better agreement among the GCMs. The details are depicted in Table 7.17.

Downscaling of climate scenarios was possible and good on monthly basis. However downscaling on daily basis was very challenging. AS such only very few stations were successfully downscaled on daily time step.

These changes are mainly due to climate change based on 5 GCMs and one emission scenario. The interpretation of these results should be done with care as these result are from a sample of the GCMs thought to be representing the region well.

The changes in flow regimes in these selected river basins highlight the basin level impacts. The difference in pattern and magnitude of changes depict the difference that exist between future climate scenarios.

The central and southern African region will be affected by climate change. The southern African region seems to be affected negatively while the central region seems to increase or nearly remain the same.

Table 7.17 shows the overall changes on the selected basins for various variables, temperature, precipitation and finally runoff. The runoff is further plotted graphically to show the changes.

Table 7.17: *The results of the simulation from future climate for different periods. Results of the changes computed from the hydrological modelling.*

Basins	Period	Mean Annual Rainfall mm/yr	Change in Rainfall %	Change in Temperature ^{o}C	Mean Annual Flow m^3/s	Change in flow %
Congo	obs	1600			37548	
	sim				37210	
	2020		0	1.1	36909	-1
	2050		3	2.1	37492	1
	2080		3	3.5	38584	4
Zambezi	obs	960			1339	
	sim				1053	
	2020		-1	1.2	978	-4
	2050		-9	2.3	918	-12
	2080		-14	3.7	841	-20
Kwanza	obs	1400			640	
	sim				607	
	2020		6	1.2	589	-3
	2050		4	2.1	649	7
	2080		12	3.2	692	12
Shire	obs	1100			382	
	sim					
	2020		-6	1.2	351	-4
	2050		-8	2.1	326	-7
	2080		-12	3.9	298	-12
Kafue	obs	1000			143	
	sim				132	
	2020		-0.3	1.3	115	-12
	2050		-4.5	2.3	110	-17
	2080		-6.8	3.7	102	-23
Kabompo	obs	1200			233	
	sim				227	
	2020		12	1.1	236	4
	2050		16	2.2	245	8
	2080		18	3.5	261	15

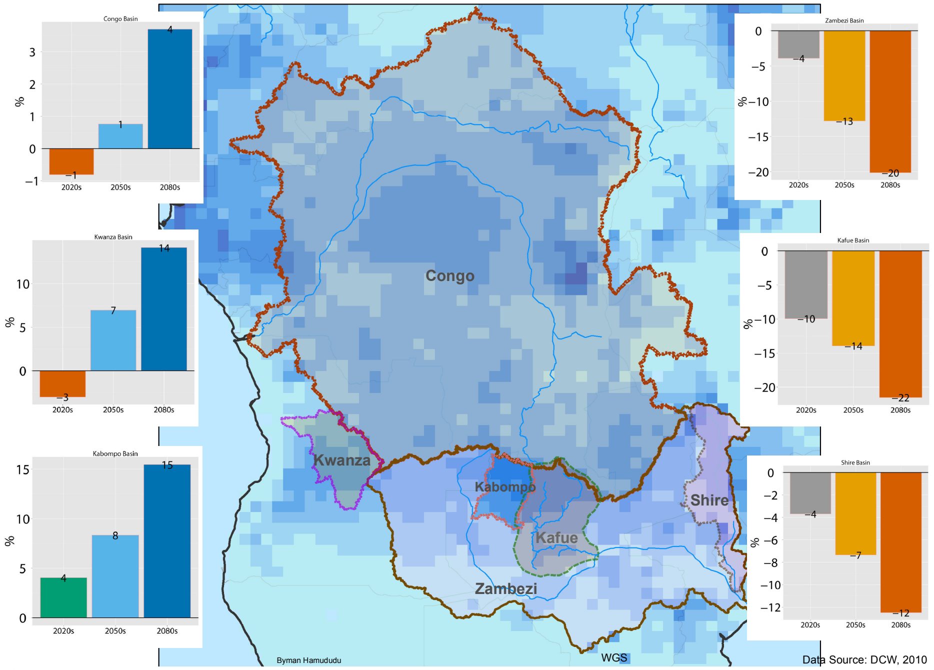


Figure 7.24: *Change in runoff as a percentage in the selected basins. The different future periods are represented on the x-axis and changes in percent %*

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Chapter 8

Hydropower Production Simulations

8.1 Introduction

In order to analyse the impact of changed flows on hydropower productions a model that describes the hydropower system is required to simulate the system with future flows. While it is sometimes tempting to assume that the changes in runoff are directly related to changes in hydropower production, this assumption should be used for only in large (regional or global) areas analysis or run-of-river systems. However, where there is storage it is necessary to carry hydropower simulations to ascertain the changes that may result from computed changes in runoff. Since the basins selected all have reservoirs with varying sizes, the hydropower production simulations were deemed necessary.

8.2 Analysis Approach

The hydropower systems, with technical and operational parameters, were used to set up and simulate the power generation. The impacts of concern were with the potential annual hydropower production using the current installed capacities. The hydropower simulations required a model that could represent the important components of the hydropower system, and the nMag was the hydropower simulation model selected.

8.2.1 Hydropower Simulation Model

The hydropower simulations were carried out using the nMAG hydropower simulation model (Killingtveit and Saethun, 1995). This model was developed in 1984 at the Norwegian Institute of Technology (NTH), Trondheim, Norway and has been improved since then (Killingtveit, 2004). The modelling system can simulate several reservoirs, power plants, inter-basin transfer, and control points. The model is primarily intended for operation simulation to estimate the production and economic benefit of the system under varying hydrological conditions. In addition, it is capable of simulating reservoir operation strategies for water supply, irrigation, and flood control projects. The system can simulate the production and the economic benefit of the system under given data on inflow conditions, production system, consumer system and operation strategy. The model is helpful to study the economic feasibility of a proposed project under varying hydrological and operational conditions. However, in the present work the focus was on future simulation of power production to see the change in potential due to the impact of climate change (Jerko and Killingtveit, 2010) (Haile et al., 2010).

8.2.2 Model Structure

The model contains nodes from four different module types where all or some are contained in a system at a time. These are termed as: Regulation reservoirs, Power plant, Water transfer (Diversions) and Control point. The set up for simulation involved creating modules that are interconnected by links defining the address of water from one module to another by using transport lines or paths. Three different release options: production release, bypass release and flood spill are available for water transferring from one module to the next, and the first priority is given for production release. To run the model, compulsory and optional data are needed for the modules as input. Another input for the model is a time series of hydrological data with a time step which may be daily weekly or monthly depending on the purpose of the simulation. Reservoir and power plant physical data, and information about the operational strategy of the plant are other inputs needed for simulation. All the input data must be fed to the model at the modules, and the addresses of water from one module to the next should be specified by the user.

8.2.3 General Procedure

The applications of the hydropower simulations on each of these basins was done using a standard procedure. First, the model is run using the observed inflow data and the hydropower produced is checked against the reported hydropower production for that system. All processes along the section of the basin were represented through various nodes. When the production matched the reported production, the hydropower model was accepted to represent the processes in the existing system. The second step was to introduce the future river flow, evaporation and other parameters and the system was run again. The results were then reported as the future production of the hydropower system. Evaporation losses from reservoirs are important factors in water balance. In the tropical climates with high temperatures and reservoirs dominate the hydropower systems, evaporation losses could be significant. For that case estimates of the evaporation in the reservoir was an important step. The estimated evaporation rates in the major reservoir are presented in Table 8.1

Table 8.1: *Mean monthly evaporation rates in the major reservoirs on the Zambezi Basin. Evaporation data were obtained from the Meteorological Department. The figures in this table were computed based on these observations. Data source (Zambia Meteorological Department and Institute of Hydrology, UK (IH, 1994).)*

Month	Kafue	Kariba	Itezhi Tezhi	Cahora Bassa
January	149	164	140	177
February	130	147	131	143
March	164	183	153	165
April	162	174	160	200
May	150	164	156	198
June	138	138	142	175
July	155	152	156	193
August	189	195	193	246
September	219	240	222	304
October	233	288	245	310
November	201	213	211	246
December	158	189	166	200
Annual	2048	2248	2075	2556

8.3 Congo Basin - Inga Hydropower System,

Table 8.2: *Characteristics of Inga hydropower site. Four hydropower plants with Inga I and II, already existing While Inga III and the grand Inga are still under study.*

	Inga I	Inga II	Inga III	Grand Inga
Water Head (m)	50	58	60	150
Turbine Flow (m3/sec)	780	2,800	6,300	26,400
Number of Power Generators	6	8	16	52
Installed Capacity (MW)	351	1,424	3,500	39,500
Energy Production (TWh/a)	2.4	10.4	23.5	288

The Inga hydropower site and the its future development figures are shown in Table 8.2. The site has been investigated for a long time now, and it is believed that the hydropower potential on the site may be more than previously thought. The refinement in technology development and efficiencies in modern machinery (turbines, generators, etc.) may also prove to have an added effect on the potential.

For hydropower simulations, Inga I and Inga II were set up in nMag model as a unit. In the model set-up, the two plants have been combined for simplicity in computation and analysis with one reservoir. The existing system consisting of Inga I and Inga II was simulated with a total production of 12.8 TWh/y. The flows resulting from hydrological simulations of the control period (1961–1990) were used to simulate the current production levels and later the flows from future periods were used. The summary results are presented in Table 8.3 .

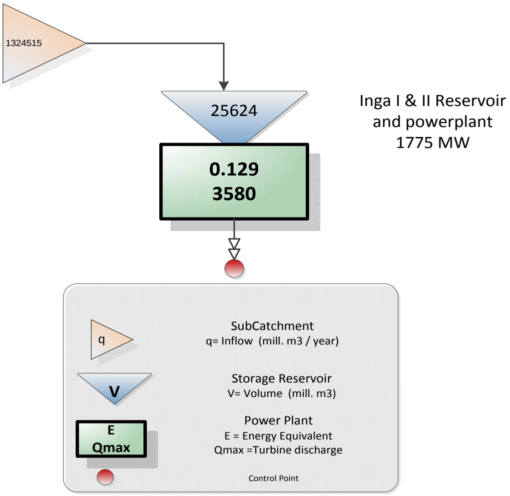

Figure 8.1: *Diagramatic representation of the nMag Hydropower simulation model set up for Congo hydropower system for Inga I & II. The figures in the diagram represent some of the actual data that was used in the simulations*

Table 8.3: *Results of nMag simulations summarised as changes in hydropower production in Congo river basin*

Period	Inflow mill.m^3	Inflow Change %	Energy production TWh/y	Change %
Current	25,624		12.8	
2020s	25,368	-1	12.7	-1
2050s	25,880	1	12.8	0
2080s	26,649	4	13.3	4

8.4 Zambezi - Kariba Hydropower System

The Zambezi River Basin has a total of 4684 MW of hydropower currently installed. Table 8.4 contains a lists the exiting hydropower in the river system. The total hydropower production is about 32,993 GWh annually. The hydropower system on the Zambezi was modelled according the major tributaries. In this part, only the main Zambezi, at Victoria falls for Kariba and Cahora Bassa hydropower system were modelled. The Kafue, and Shire are modelled separately.

Modelling strategy

The nMag model for Zambezi hydropower system is shown in Figure 8.2. The Cahora Bassa hydropower was included since it lies downstream of Kariba, Kafue and Luangwa river systems. Data for the hydropower model is given in Table 8.4. Main input data are summarised in Table 8.5, these were used in the nMag set-up for simulations.

Table 8.4: *List of Existing hydropower plants and their characteristics in Zambezi River Basin*

Power		Plant	Capacity MW	Generation GWh	Discharge m^3/s 1)	Commission. year
Cahora Bassa	Zambezi	Storage	2,075	17,000	2,260	1975
Nkula A	Shire	RoR	24	171	51	1966
Nkula B	Shire	RoR	100	411	195	1981
Tedzani I+II	Shire	RoR	40	211	120	1977
Tedzani III	Shire	RoR	52	291	156	1995
Kapichira I	Shire	RoR	64	2)	135	1999
Wovwe	Wovwe	RoR	5	9	1	1995
Mulungushi	Mulungushi	Storage	20	80	11	1924
Lusemfwa	Lusemfwa	Storage	18	113	16	1944
Lusiwasi	Lusiwasi	Storage	12	105	3	1970
Victoria Falls A	Zambezi	RoR	8	52	11	1934
Victoria Falls B	Zambezi	RoR	60	390	64	1968
Victoria Falls C	Zambezi	RoR	40	260	43	1972
Kariba North	Zambezi	Storage	600	3,800	744	1977
Kariba South	Zambezi	Storage	666	4,200		1960
Kafue Gorge	Kafue	Storage	900	5,900	252	1977
			4,684	32,993		

The hydropower simulations for Zambezi were combined into one set-up for modelling. This is a large system for modelling in terms of flow volumes but the nMag was able to handle this very well. Although it is possible to give all the results for the hydropower plants in the system, only the overall Zambezi system will be summarized. The rest of the basins were summarized in their respective sections. The Kafue, and Shire systems are described later in this chapter.

The results from the simulations for the Zambezi hydropower system are summarised in Table 8.6 for the different periods. It clearly shows the years when there are droughts, with low production levels and higher production level during the high rainfall years.

Table 8.5: *List of hydropower plants on the Zambezi Hydropower System Simulations*

NAME	Reservoir	Power Plant	Reservoir Volume Mm^3	Max. Power MW	Max. Flow m^3/s	Production GWh/yr
Itezhi–Tezhi	Reservoir		5624	0	10000	0
Kafue	Reservoir	Powerplant	785	990	252	3783
Victoria Falls		Powerplant	0	121	128	140
Kariba	Reservoir	Powerplant	64800	1440	850	6564
Lusiwasi	Reservoir	Powerplant	72	11	3	42
Lusemfwa	Reservoir	Powerplant	14	16	16	38
Mulungushi	Reservoir	Powerplant	300	18	11	45
Cahora–Basa	Reservoir	Powerplant	54853	2270	1000	17000
Nkula A		Powerplant	0	22	51	
Nkula B		Powerplant	0	88	195	126
Tedzani I		Powerplant	0	36	120	95
Tedzani II		Powerplant	0	46	158	110
Kapichira		Powerplant	0	67	158	210
Wovwe		Powerplant	0	5	1	45
Total			126 500	5 130		23 160

The year 1978 for example was one of the wet years recorded and the system clearly highlights that production is responded to high flows resulting from a high level of rainfall. The results of the effects of climate change are summarised in Table 8.6 for Kariba hydropower system and Table 8.7 for the Cahora Bassa hydropower system.

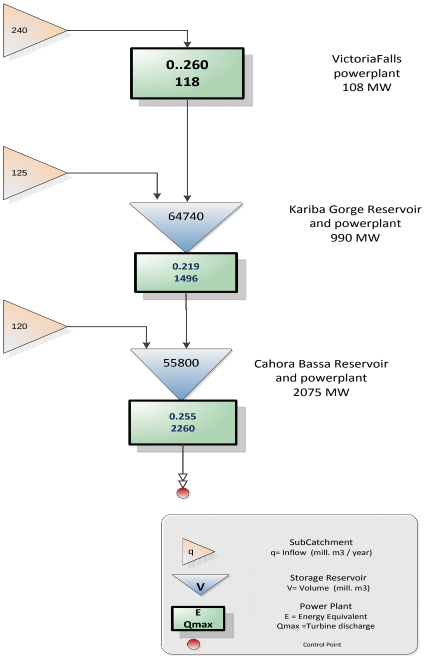

Figure 8.2: *Diagram representation of the nMag Hydropower simulation model setup for Zambezi hydropower system*

Table 8.6: *Changes in hydropower production in Zambezi River Basin for both the South (Zimbabwe) and North (Zambia) hydropower plants. The hydropower production at Victoria Falls would nearly remain the same as the plant only uses a small proportion of the total discharge.*

Period	Inflow mill.m^3	Inflow Change %	Energy production TWh/y	Change %
Current	64800		6564	
2020s	62208	-4	6038.9	-8
2050s	60912	-6	5382.5	-18
2080s	51840	-20	4332.2	-34

Table 8.7: *Changes in hydropower production - Cahora Bassa*

Period	Inflow mill.m^3	Inflow Change %	Energy production GWh/y	Change %
Current	74800		17000	
2020s	71060	-5	15470.0	-9
2050s	68068	-9	13940.0	-18
2080s	57596	-23	10540.0	-38

8.5 Kwanza River - Capanda Hydropower System,

The Kwanza hydropower system has two existing hydropower plants (Capanda and Cambambe) and several hydropower plants are planned between the existing plants. The river goes through several rapids between the Capanda hydropower plant and the Cambambe plants. The planned hydropower plants between these existing plants will use the changes in elevation through the rapids. The modelling set-up is shown in Figure 8.3 and other details are in Table 8.8

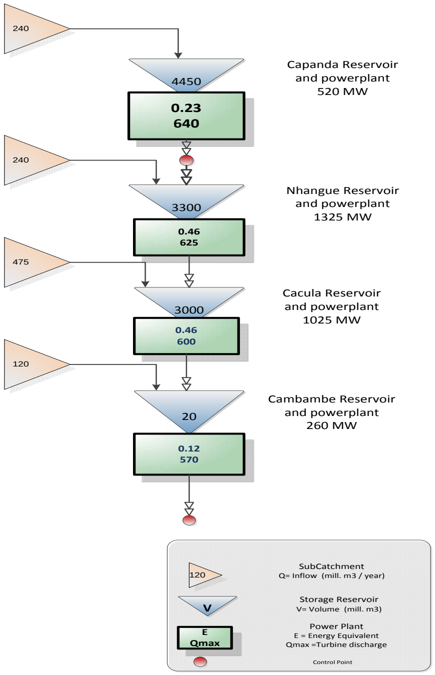

Figure 8.3: *nMag Hydropower simulation model setup for Kwanza hydropower system*

Table 8.8: *Kwanza Hydropower Plants*

Name	Status Operation/Planned	Reservoir million m^3	Installed Capacity MW	Design Flow m^3/s	Head metres (m)	Production TWh/y
Capanda	Operational	4450	520	640	84	2880
Nhangue	Planned	3300	1325	625	193	5732
Cacula Cabasa	Planned		1025	600	191	5440
Cambambe	Operational	20	260	670	51	1440

The first and the last are the existing hydropower plants while the ones in between are planned. The nMag hydropower simulations model was set up using the observed data from 1963 – 1975. The tables below show that set up and some configuration parameters in summary for Kwanza Basin.

The analysis here shows that the future climate within and around the Kwanza catchment

Table 8.9: *Hydropower simulations set up and results for Kwanza Basin*

Name	Reservoir Volume	Max. Power	Max. Flow	Production	Total Flow	Through flow	Bypass flow	Spillage	Spillage
	mill. m^3	MW	m^3/s	GWh		mill. m^3	mill. m^3	mill. m^3	%
Capanda	3560	520	640	3740	19700	14560	0	4964	25.4
Cambambe	20	260	570	1817	19525	15410	0	4055	20.8

in Angola will get slightly wetter with higher temperatures than the current period. The northern catchment shows an increase in the precipitation while the southern shows a decrease in precipitation. The temperature in all places indicates an increase up to 3.2^{o}C by end of the century. The resulting effect of these climate changes on water resources is a decrease in the first period (2020s) but increase are projected for other periods

The results show that there is a slight increase in the in hydropower production towards the end of the century as can be seen in Table 8.10. The results of changes in hydropower production are summarized in Table 8.11.

Table 8.10: *nMag simulation water balance results in Kwanza hydropwer system (all values in million m^3) due to climate change*

	Current	2020	2050	2080
Average Inflow	19,579	19,344	19,853	20,029
Actual Inflow	19,700	19,464	19,976	20,153
Reservoir Evaporation	220	231	243	255
Reservoir change per year	-93	-96	-92	-88
Outflow	19,572	19,136	19,641	19,810
Demand Coverage	85	84	87	88

Table 8.11: *Changes in hydropower production Kwanza basin. The changes were computed on the existing Capanda and Cambambe hydropower plants. These power plants are on the same river and lie in series. More plants are planned between the two power plants. The hydropower system could have increased hydropower production*

Period	Inflow mill.m^3	Inflow Change %	Energy production GWh/y	Change %
Current	19700		4320	
2020s	19306	-2	4190.4	-3
2050s	21079	7	4492.8	4
2080s	22064	12	4752.0	10

8.6 Shire Basin - Hydropower System

The Shire hydropower system is the backbone of the Malawi electricity system. Malawi remains isolated in terms of grids interconnections. The total hydropower installed capacity for river system is 300 MW, producing 1085 GWh annually (See Table 8.12). The first part (top) of the table shows the existing while the latter shows the planned hydropower systems. The existing system was analysed through modelling in order to assess the impacts of climate change.

Table 8.13 shows the expected changes in the hydropwer production of the Shire system. The estimates are that by the end of the century the system will produce two thirds of its current level. The reductions are 7 % by 2020s, 9% by 2050s and 14% by the 2080s.

Table 8.12: *List of hydropower plants Shire river Basin and the planned projects in the lower part of the table*

Power plant	River	Plant type	Capacity (MW)	Generation (GWh)	Discharge (m3/s))	Com. year
Nkula A	Shire	RoR	24	171	51	1966
Nkula B	Shire	RoR	100	411	195	1981
Tedzani I+II	Shire	RoR	40	211	120	1977
Tedzani III	Shire	RoR	52	291	156	1995
Kapichira I	Shire	RoR	64	2)	135	1999
Wovwe	Wovwe	RoR	5	9	1	1995
			285			
Kapichira II	Shire	RoR	64		135	
Kholombidzo	Shire	RoR	2)			
Nachimbeya	Shire	RoR	2)			
Mpatamanga	Shire	RoR	2)			
Lower Fufu	S. Rukuru/	RoR	90	570	30	

Table 8.13: *Changes in hydropower production Shire basin. The results indicate a reduction in hydropower production in the system*

Period	Inflow mill.m^3	Inflow Change %	Energy production GWh/y	Change %
Current	572		1095	
2020s	526	-4	963.6	-7
2050s	498	-7	919.8	-9
2080s	440	-12	810.3	-14

8.7 Kafue Basin - Kafue Gorge Hydropower System

The current Kafue Gorge Hydropower Station, uses the Itezhi-Tezhi Dam, about 230 kilometres upstream and forms a reservoir with a capacity of 6 billion cubic metres. This reservoir levels the flow of the Kafue, which varies with the season (wet versus dry) and contributes to the efficient operation of the Kafue Gorge Hydropower Station.

Table 8.14: *Main data used including current demands on middle Kafue River Basin*

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Firm power	319	309	319	319	291	391	309	319	309	319	319	309
Peak Power	900	900	900	900	900	900	900	900	900	900	900	900
Irrigation	19	16	9	5	5	8	15	17	15	15	17	17
Water supply	6	6	6	6	6	6	6	6	6	6	6	6

The operation of the reservoir and power generation depends on the amount of water in the reservoir. As the year progresses into the dry season, even though demand increases (cold season), power production is reduced as water may not be enough to last the remainder of the dry season. The reservoir is nearly emptied in November just before the next rain season and reaches the maximum level in May after which all power production is using the reservoir volume from both the reservoir and the upper Itezhi–Tezhi Dam. Table 8.16 shows the nMag results of various parameters for the current period.

Table 8.17 shows the expected changes in the Kafue hydropower system. The current production levels are likely to be reduced by 8% by 2020s, 18% by 2050s and 34% by the 2080s. The larger reductions can be attributed to extensive evaporation losses in the reservoirs and the flood plains, in addition to increased abstractions to sugar irrigation

Table 8.15: *nMag set up (Input data) for Kafue Hydropower System*

Name	Reservoir Volume mill. m^3	MAX Power MW	MAX. Flow m^3/s	Prodn GWh	Local flow %	Total flow mill. m^3	Thru flow mill. m^3	Bypass mill. m^3	Spillage mill. m^3
Itezhi–Tezhi	5,624	0	10,000	0	5,910	5,910	5648	0	0
Downstream of ITT	0	0	10,000	0	0	5,648	5,648	0	0
Abstractions	0	0	10,000	0	0	5,648	4,187	1,461	0
Kafue Gorge	785	900	252	3,431	1,884	6,071	3,681	0	1,629
Downstream of KGHP	0	0	10,000	0	0	5,310	5,310	0	0

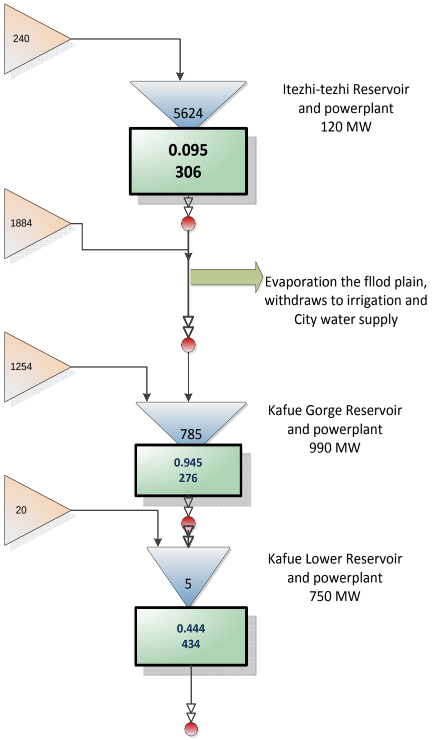

Figure 8.4: *nMag model setup for Kafue hydropower system*

Table 8.16: *Overall results from the simulations of Kafue Hydropower system*

Parameter	Current	future
Average Inflow into the system (mill. m^3)	9050	7794
Actual Inflow into the system (mill. m^3)	9050	7794
Reservoir Evaporation (mill. m^3)	1094	1188
Initial Reservoir Level (masl)	5768.1	5768.1
Final Reservoir level (masl)	4341.7	4341.7
Reservoir Change per year	-67.9	-64.8
Outflow from the system	8023.9	6770.8
Firm Power Costs (mill.MT/yr)	2	8
Operation Costs (mill.MT/yr)	-247.66	50.613
Net Benefits (mill.MT/yr)	249.6605	42.613

Table 8.17: *Changes in Hydropower production in Kafue River with only the existing Kafue Gorge hydropower plant highlighted in these results.*

Period	Inflow mill.m^3	Inflow Change %	Energy production GWh/y	Change %
Current	9050		5034	
2020s	7964	-12	4631.3	-8
2050s	7512	-17	4127.9	-18
2080s	6969	-23	3322.4	-34

and city water supply.

8.8 Kabompo Basin - Kabompo Hydropower System

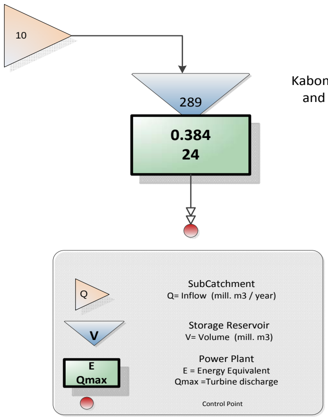

Figure 8.5: *nMag Hydropower simulation model setup for Kabompo hydropower system*

The last system is Kabompo Project, located in North-Western Province of Zambia. The Kabompo River is one of the first major tributaries of Zambezi. As specified in Chapter 6, the installed capacity is 34 MW. The catchment area of the basin is 2,300 km^2 with a maximum generation discharge of 24 m^3/s utilizing a net head of 160 metres and generation capacity of 176 GWh per year. A reservoir, is formed by a 68 m dam and contains 289 million m^3. Unlike the other hydropower system in the Zambezi basin, perhaps due to its location, Kabompo is poised to have increased hydropower production. Table 8.18 indicates that the hydropower could increase by 6%, 10% and 18% by 2020, 2050 and 2080 respectively.

Table 8.18: *Changes in hydropower production - Kabompo Basin*

Period	Inflow mill.m^3	Inflow Change %	Energy production GWh/y	Change %
Current	60		176	
2020s	62	4	186.6	6
2050s	65	8	193.6	10
2080s	69	15	207.7	18

8.9 Discussion

In this chapter, the future runoff time series developed in the previous chapter (Chapter 7) were used to drive the simulations of the hydropower systems. The nMag hydropower simulation model was used. As earlier mentioned it is simple to use and yet adequate to represent most of the essential components of the hydropower system. Other input data including system reservoir, power plant, bypass, and operation strategy were used to describe the hydropower system for each site. Reservoir evaporation and environmental requirements were specified as well. The time steps of the runoff time series were on monthly time step for some basins and daily time step for the others. The simulation model was run on monthly and daily time step depending on input data. The hydropower simulations were carried out with assumptions. These assumptions have an impact on the results. Some of the assumptions are; 1) most of data describing the hydropower system was assumed to remain the same in the future periods. 2) Water demands from other users was also assumed to remain at current levels in the future periods, 3) environmental requirements also remain unchanged and 4) production capacity is at the current levels. The results of the simulations highlighted the changes (ranges) that can be expected to impact the hydropower production potential in the two regions of central and southern Africa. The results also showed the need for basin-level assessment for each basin as the changes were different within large basins (e.g. Zambezi basin). The Congo, Kwanza in Angola and Kabompo hydropower system in Zambia showed slight increase (10%) in the hydropower production potential while the Zambezi, Shire and Kafue hydropower systems were negatively affected (34%) by climate change in the future periods. The simulations results depicted the future systems production potential and how these would be impacted by climate change. The tabulated and plotted results shows only some of the information that was generated by the using the methodology formulated in chapter 4.

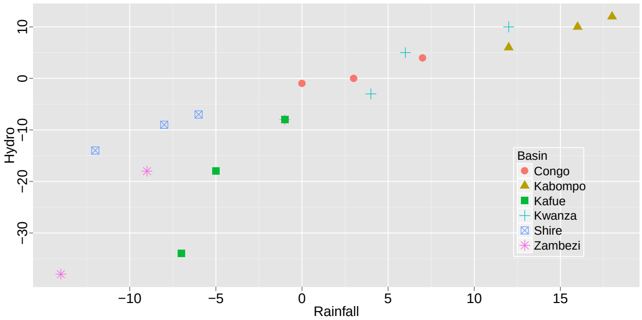

Figure 8.6: *Correlation between runoff changes compared to hydropower changes*

With all the systems analysed, the separate changes in rainfall, runoff and hydropower production were pooled and possible relationship between changes analysed. There seems to be correlation between the changes in rainfall, runoff and Hydropower. This is illustrated in Figure 8.6 and Figure 8.7. In this figures, it is possible to estimate the changes in hydropower production based on changes in rainfall and runoff

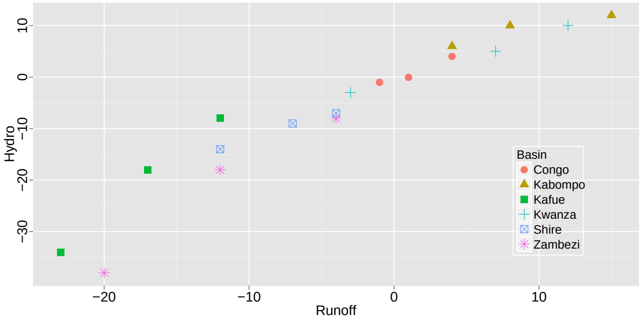

Figure 8.7: *Correlation between runoff changes compared to hydropower changes*

Above of these results, it is worth noting that differences in impacts occur from basin to basin even a region like southern Africa. The differences highlight the need for more wide spread basin level assessments in the region. In the central African region, only the main Congo basin was assessed and similarly it is expected individual basin within the Congo would result in differences from basin to basin. Table 8.19 shows a short comparison of the results of the two methodologies used in this work. While the comparison is not fitting well, it can be used as a quick estimate to the likely changes in the region, in the absence of detailed basin level study. The results also highlight the differences between basins. In Zambia for example the Zambezi, the main basin is projected to have different change from Kafue and Kabompo which are sub basin of Zambezi.

Table 8.19: *Comparison of estimates from country based computation and basin level assessment*

Country	Country level change	Basin Level Change	Basin
Angola	-7	4	Kwanza Basin
Congo	N/A	0	Congo basin
Malawi	-0.4	-9	Shire Basin
Zambia	-5	-9	Zambezi Basin
Zambia	-5	-12	Kafue Basin
Zambia	-5	10	Kabompo Basin

8.10 Concluding remarks

There is no doubt that the hydropower systems of central and southern African region will be affected by climate change projections. Based on the above scenarios and case studies, in general, the potential for hydropower production in the central African region is predicted to increase. The potential for hydropower production in the southern Africa region is projected to reduce. All the system that have been analysed use reservoir/s for reliability. The impact of these reservoirs in the face of reduced inflow has not been analysed.

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Chapter 9

Summaries and Conclusions

9.1 Summary

Increasing levels of greenhouse gases like CO_2 in the atmosphere since pre-industrial times are well-documented and the effects of this is well known. Climate model projections summarized in the AR4 by the IPCC indicated that during the 21st century the mean surface temperature is likely to rise a further 1.1 to 2.9^{o}C and 2.4 to 6.4^{o}C for the lowest and highest emissions scenarios respectively. This will result in changes in water resources to levels that may not have been recorded. This demands that the state of our knowledge of the river flow regimes in rivers be adopted to take into account these changes.

Impacts assessments on water resources and hydropower have been carried out globally although the number of impact studies on hydropower varies greatly from region to region.

The impact of climate change on global hydropower production has been estimated to be very small. However there are regions that will be greatly affected. The global hydropower production is one of the sectors that will not be negatively impacted by changes in climate. In Africa, most areas will have reduced hydropower production except for east Africa and some part of west Africa. In summary, all regions of the world will be impacted by changes in climate resulting in alterations in hydropower production potential.

The detailed analysis of the assessment of climate change impacts on hydropower in Africa as a region revealed further differences even among the countries and basins. At the continental level, the impacts of climate change on hydropower are slightly negative for Africa. Large differences in impacts emerge when basin level assessments are carried out. Local variations in impacts from climate change could be large even in areas that may seem to be homogenous in climate.

The downscaling of GCMs simulated scenarios to local climate revealed that station-based statistical downscaling is ideal in Africa where data with long continuous (with minimal) records is limiting.

The HBV, IHACRES and PITMAN hydrological models have been used for translating climate scenarios into runoff in this analysis. These models have been used before in climate change impact assessments. All these models proved to be relatively simple for repeated runs with few parameters. Future scenarios of flow regimes in six basins were carried out and the results presented. The basin sizes ranged from 2300 - 3,800,000 km^2 sampling basins from central and southern Africa.

The Zambezi, Kafue and Shire river basins have negative changes while the Congo, Kwanza and Kabompo river basins have positive changes. The hydropower production potential of most of southern African basins is likely to decrease in the future due to the impact of climate change while the central African region shows an increasing trend. The hydropower system in these regions will be affected consequently. The hydropower production changes will vary from basin to basin in these regions. The central African region hydropower production is likely in general increase while the southern African region, hydropower production will decrease.

Even though this work did not assess all the basins in central and southern Africa, there is a general reduction in the basins that were analysed in the southern African region. These, though small number of basins, show that future climate change and the impacts on water resources and hydropower are expected. Much of central Africa depicted increases in river flow although there are stations where reductions in rainfall were depicted. In general, the central African region may experience increase or nearly remain the same. It can be seen from these results that there are differences within the region and it is expected that impacts on different basins will vary.

The study shows that there can be variations across a region, and even within a region. Hydropower generation is mainly influenced by runoff although there are other limiting factors. Changes in runoff will therefore lead to changes in hydropower generation. In its most accurate form, basin hydropower analysis for individual basins gives a better picture of future generation. However, when an assessment is carried out on the global level, scale becomes an important issue. Central and Southern African regions with inadequate gauging records (climate and hydrology) that require filling up of large gaps, generalised methods could be useful. These few short data confirm the changes and variability in climate and natural water resources availability.

9.2 Recommendations for Future Research

Climate change is taking place and will continue. This is the reality. Water resources designers, planners and managers need to take into account the likely changes in water resources availability in the future.

The current generation of GCMs has coarse resolutions even if this keeps on improving, it still lacks important climatic variables necessary for hydrological modelling. As GCMs improve both in resolution and parametrization, these kinds of assessments process are required. The CODEX project promises better resolution all over the world (including Africa).

From the downscaling procedure, precipitation downscaling was more challenging than temperature, use additional downscaling methods to get a better result. Finally, for the hydropower simulation, more recent data for the hydropower plants and for the other demands (irrigation and water supply) should be used in a future analysis.

Downscaling on daily time step proved to be problematic. The discontinuous data complicated by short length on daily records was a daunting task. Further work is here recommended to use monthly data-sets and better data collection methods of climate data.

More basin-level assessment of impacts should be carried out, if possible even for small basins. This would better the understanding of the impacts and get a more comprehensive picture of the regional vulnerability. The reservoir optimisation (including other water users) would be need to be carried out to ensure that changes in management of reservoir (rules) do not infringe the environment requirements of the hydropower system.

It is recommended that future work would incorporate future land use scenarios. Estimating potential evapo-transpiration or evaporation remains a challenge for future scenarios. In current analysis, evaporation is computed based on temperature. It is recommended here that better methods for estimating evapo-transpiration for future periods should be developed.

The historical observations has been assumed to cover all the statistical parameters of the local climate and river flow and that the future climate would be similar to the past (stationarity notion). The future flow regimes are likely to change to levels that have not be recorded (no longer stationery) as a result of climate change. The existing design rules need to be changed so that shifts in design floods as a result of changes in climate can be taken into account.

Lack of good observed data highlighted some of the challenges the region faces. The downscaling and hydrological modelling were affected by the lack of the data. Future work is required to collect more data through means that are sustainable. Otherwise, hydrological modelling on monthly time step is recommended. It is highly recommended to improve both climate and hydrological monitoring system in these regions.

While this study attempted to take into account the main water users (water supply, irrigation), the future estimates proved difficult to estimate. Future developments and the estimation of water demand need to be taken into account when similar analyses carried out.

Appendix A

Appendices

A.1 Published /Under-Review Papers

A.1.1 Assessing Climate Change Impacts on Global Hydropower

The paper presented here has been published in the Energies. It is included in its published form.

A.1.2 Impacts of Climate Change on Hydropower Potential of Upper Awash Basin, Ethiopia

The paper presented here has been submitted for publishing with Journal of Climatic Change and has been reviewed by the journal, awaiting the final approval. It is presented in its revised form forwarded to the reviewers.

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Article

Assessing Climate Change Impacts on Global Hydropower

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Abstract: Currently, hydropower accounts for close to 16% of the world's total power supply and is the world's most dominant (86%) source of renewable electrical energy. The key resource for hydropower generation is runoff, which is dependent on precipitation. The future global climate is uncertain and thus poses some risk for the hydropower generation sector. The crucial question and challenge then is what will be the impact of climate change on global hydropower generation and what are the resulting regional variations in hydropower generation potential? This paper is a study that aims to evaluate the changes in global hydropower generation resulting from predicted changes in climate. The study uses an ensemble of simulations of regional patterns of changes in runoff, computed from global circulation models (GCM) simulations with 12 different models. Based on these runoff changes, hydropower generation is estimated by relating the runoff changes to hydropower generation potential through geographical information system (GIS), based on 2005 hydropower generation. Hydropower data obtained from EIA (energy generation), national sites, FAO (water resources) and UNEP were used in the analysis. The countries/states were used as computational units to reduce the complexities of the analysis. The results indicate that there are large variations of changes (increases/decreases) in hydropower generation across regions and even within regions. Globally, hydropower generation is predicted to change very little by the year 2050 for the hydropower system in operation today. This change amounts to an increase of less than 1% of the current (2005) generation level although it is necessary to carry out basin level detailed assessment for local impacts which may differ from the country based values. There are many regions where runoff and hydropower generation will increase due to increasing precipitation, but also many regions where there will be a decrease. Based on this evaluation, it has been concluded that even if individual countries and regions may experience significant impacts, climate change will not lead to significant changes in the global hydropower generation, at least for the existing hydropower system.

Keywords: climate change; global; water resources; hydropower generation

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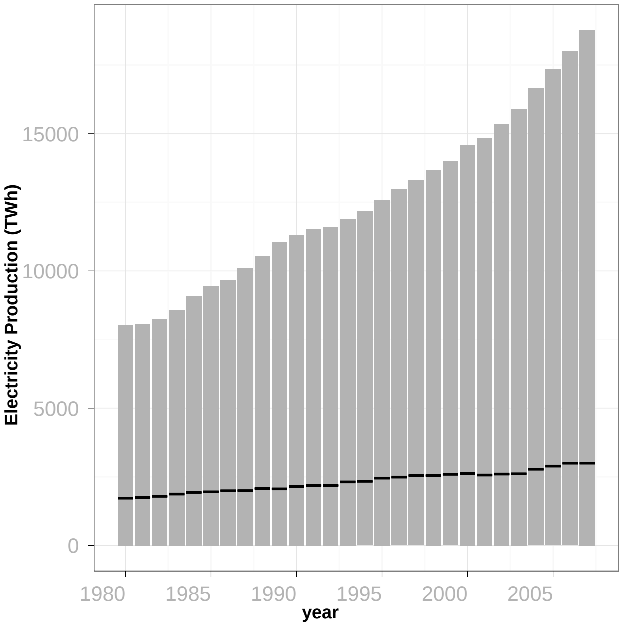
1. Introduction

Climate change is one of the great challenges of the 21st century [1]. The International Energy Agency (IEA) report of 2011 projected that renewables based electricity generation would triple between 2008 and 2035 under the increasing-use-of-renewables scenario. Hydropower generation makes a substantial contribution to meeting today's increasing world electricity demands. The report adds that the share of renewables in global electricity generation increases from 19% to almost a third (nearly the same as coal). The primary increase is said to come from hydropower and wind but hydropower remains dominant over the projection period. It is projected that global hydropower generation might grow by nearly 75% from year 2008 to year 2050 under business-as-usual scenario but that it could grow by roughly 85% over the same period in a scenario with aggressive action to reduce greenhouse gas (GHG) emissions. However, even under this latter scenario, increased hydropower generation is projected to provide only about 2% of the total GHG emission reductions from the global electric power sector compared to business-as-usual by year 2050 (with all renewable technologies nonetheless providing nearly 33.5% of GHG abatement from the power sector). According to IEA, a realistic potential for global hydropower is 2 to 3 times higher than the current generation, with most remaining development potential existing in Africa, Asia, and Latin America. IEA also notes that, while run-of-river (smaller) hydropower plants could provide as much as 150 to 200 GW of new generating capacity worldwide, only 5% of the world's small-scale (*i.e.*, small, low, and hydro) hydropower potential has been exploited [2].

In year 2009, hydropower accounted for about 16% (approximately 3551 TWh/a) of total global electricity generation and has reached 26% of the total installed capacity for electricity generation [3]. Global generation of hydropower has been growing steadily by about 2.3% per year on average since 1980 while the EU reports increases of up to 3.1% per year for the European Union. Global average growth rates of hydropower generation in the future are estimated to continue in the range of 2.4–3.6% per year between 1990 and 2030 (EIA, 2009). The highest growth rates are expected in developing countries which have high unexploited hydropower potentials, but also in other countries, for example, parts of Eastern Europe. In Western Europe, an annual increase of only 1% is estimated [4]. In contrast to the above, there are also indications that the annual energy generation of some existing hydropower stations in some parts of the world has decreased since the 1970s, for example in some parts of Europe [5]. The reductions have generally been attributed to changes in average discharge, but it is not clear whether they reflect cyclic fluctuations, steadily rising water abstractions for other uses, or the consequences of long-term changing climate conditions. Recent climate studies have pointed out that the time has come to move beyond the wait-and-see approach in future climate scenarios. Projections of changes in runoff are supported by the recently demonstrated climate models. The global pattern of observed annual stream flow trends is unlikely to have arisen from unforced variability and is consistent with modeled response to climate forcing [6].

The IPCC in its AR4 concluded that climate change is occurring faster than earlier reported [7–9]. Many future climate scenarios point to the fact that the climate is changing rapidly although there are many arguments over the causes of these changes. Climate change will result in changes in various river flow conditions such as timing and quantity, sediment load, temperature, biological/ecosystem changes, and fish responses [10]. Climate change and the resulting changes in precipitation and temperature regimes will affect hydropower generation. It is reported that hydropower systems with less storage capacities are more vulnerable to climate change, as storage capacity provides more flexibility in operations. Although hydropower systems may benefit from more storage and generation capacity, expansion of such capacities may not be economically and environmentally justified. These changes would affect hydropower generation in all regions of the world. Given the significant role of hydropower, the assessment of possible impacts of climate changes on regional discharge regimes and hydropower generation is of interest and importance for management of water resources in power generation.

Figure 1. Global Total Electricity Generation Trends (TWh) in the last 20 years.



Global hydropower generation capacity has been increasing steadily over the last 30 years, and the past few years have shown an increased growth rate. Figure 1 shows the ratio of hydropower to the total electricity generation from year 1980 to year 2008. Although the ratio is reducing from 0.20 to 0.16, the Figure shows that hydropower generation is also increasing and is projected to continue increasing till year 2050. The global hydropower capacities and the contributions from various continents/regions of the world from 1980 to 2008 are presented in Figure 2. Europe, America, and Asia have sizable share of hydropower capacities. The installed capacity for Europe and Northern America, though large, has not been increasing much during this period while that in Southern/Central America and Asia/Oceania has greatly increased during this period as seen in Figure 2. However, the continental potentials are different, large in other regions like Africa. Table 1 shows regional hydropower characteristics in terms of hydropower in operation, total potential, under-construction, planned and countries with more than 50% of their total electricity demand supplied by hydropower.

Figure 2. Trends in Global Installed Hydropower Capacities (1980–2006).

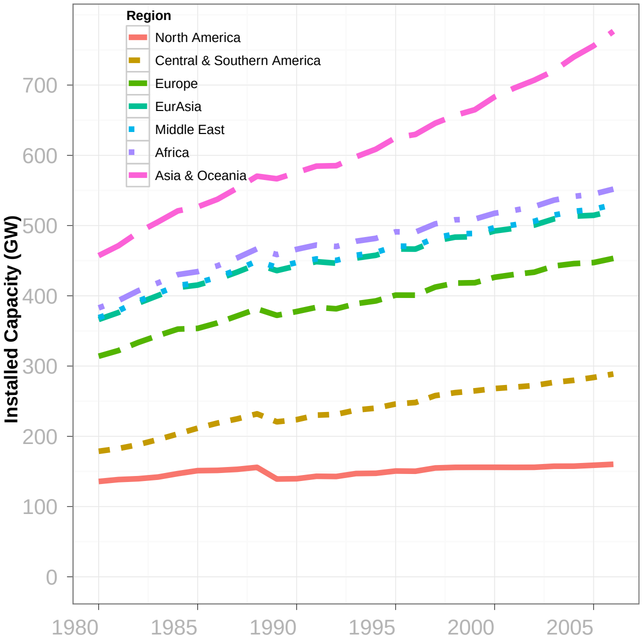


Table 1. World Hydropower in operation, under construction and Planned [3].

Region	Hydropower in Operation	% of Total Potential hydropower	Hydropower under construction	Hydropower Planned	Countries with 50% of electricity supply
	MW	%	MW	MW	#
Africa	23,482	9.3	5,222	76,600	23
Asia [1]	401,626	17.8	125,736	141,300	9
Europe [2]	179,152	53.9	3,028	11,400	8
North & Central America	169,105	34.3	7798	17,400	6
South America	139,424	26.3	19,555	57,300	11
Australiasia/Oceania	13,370	20.1	67	1500	4
World-Total	926,159		161,406	305,500	61

[1] Includes Russia and Turkey; [2] Excludes Russia and Turkey.

This study provides an overview of present (existing) global hydropower generation and its future prospects with respect to climate change. The focus of this work is global (all countries) *i.e.*, low resolution (less detail), although for clarity's sake, some large countries like Australia, Brazil, Canada, China, India and USA had to be subdivided into provinces or states. Assessment of climate change impacts on hydropower can be done at various levels of detail with different methods. On a global scale, low resolution analysis is acceptable as detailed modeling may be costly and tedious. While recognizing the fact that climate change impacts hydropower in different ways—volume of flow, timings of flow, *etc*., the analysis has been confined to changes in mean flows (volume of flow). In addition, there is no estimate of the future hydropower development as doing so would require more detailed data (national development plans or trends) for each state and country. The study aims to answer questions related to national, regional and global hydropower generation and the expected increases or decreases in the same due to future changes in climate and water availability, and the extent of such changes. In order to answer the above, GIS analysis has been utilized to understand and visualize regional scenarios of hydropower generation. The analysis makes no attempt to analyze the impact of climate change on electricity demand, as it focuses on the side of generation. The GIS has been used here as a tool to merge and analyze different databases in order to gain insights into the anticipated changes. The database included data on world countries hydropower capacities, generation, global water resources, global runoff, dams, hydropower plants, *etc*. Table 2 shows regional hydropower statistics and of special interest is the installed capacity and hydropower generation in 2009. The table highlights the technically feasible, annual average potential, and feasible increase. The capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time and its output if it had operated at full nameplate capacity the entire time. The lowest capacity factor is in Europe and clearly shows that hydropower in Europe is used mainly for peaking purposes than in the other regions [3].

Table 2. Regional Hydropower Potential (2009). The table highlights the technically feasible, annual average potential, annual generation capacity, and feasible increase [3].

Region	Technically Feasible Potential	Capacity Potential	Installed Capacity	2009 Generation	Capacity Factor	Feasible Capacity Increase
	TWh/y	MW	MW	TWh/y		%
Africa	1750	424,277	23,482	98	0.47	1925
Asia	6800	1,928,286	401,626	1514	0.4	670
Australasia/Oceania	200	55,351	13,370	37	0.41	408
Europe	1140	352,804	179,152	542	0.37	214
North America	1510	360,397	169,105	689	0.48	225
Latin America	2968	596,185	139,424	671	0.57	464
Total/Average	14,368	3,722,930	776,760	3551	0.44	

There are many methods of assessing climate change impacts on hydropower generation systems. The use of a method depends on many factors such as the level of detail required, the geographical coverage, hydropower system description, and observation data availability. For example, the level of detail required for a global assessment differ from that needed for basin level assessments. Many studies have carried out assessment of hydropower generation in different parts of the world in various ways. Usually basin level assessment involves downscaling from GCMs through detailed hydrologic modeling and hydropower simulations, while on a regional level assessment, details begin to reduce. The methods can be seen as stepped analyses, where as the modeling begins to be complex, the detail and data requirements also do, beginning at the global scale down to small basin scale. Medellin-Azuara *et al.* [11] used downscaled hydrologic data in customized modeling scheme to assess the adaptability and adaptations of entire California's water supply system to dry climate warming. Madani and Lund [12] used an energy-based hydropower optimization model, avoiding the conventional modeling (simulation/optimization) methods, due to the large number of hydropower plants in California. The model used was developed for low-resolution, system-wide hydropower studies [12]. In a rather more detailed study of the Danube basin, development of hydropower was modeled using a special, coupled-physically-based hydrological model for three hydropower plants [13]. Another study on changes to whitewater recreation in California's Sierra Nevada used only elevation and runs as the predictors in identification, mapping and geomorphic classification to anticipate changes in runoff volume and timing from climate warming [14].

In a non-conventional approach, a method of modeling high elevation hydropower systems was developed and applied in California [15]. The method is energy-based and optimization was carried out on energy generation data on a monthly time scale and seasonal energy storage capacities. However there are some limitations as pointed out [15]. The method is a simplified approach where detailed hydropower data is unavailable. It is a simple approach for developing a good representation of an extensive hydropower system with little time or resources for policy and adaptation studies. Based on the results of some applications, the method is said to be skillful and useful for studying large hydropower systems when there is less details required. The developed method can be used for studying the effects of climate change on a large hydropower system [15]. In the above method, a large hydropower system (national or regional, large basin) can be modeled. However at the global scale, a more simplified approach is necessary not only to reduce on the complexities but due to lack of data for such a thorough detailed approach.

The approach used in this analysis aggregates different types of hydropower systems from different climates to highlight the larger global picture. The approach is based on the fact that the current hydropower generation system may only be limited by water availability. The main assumption is that if water supply reduces, the hydropower systems will likewise reduce generation and *vice versa*, assuming that current systems can be upgraded. With this approach, changes in annual mean flows are the main predictors of hydropower generation in each unit.

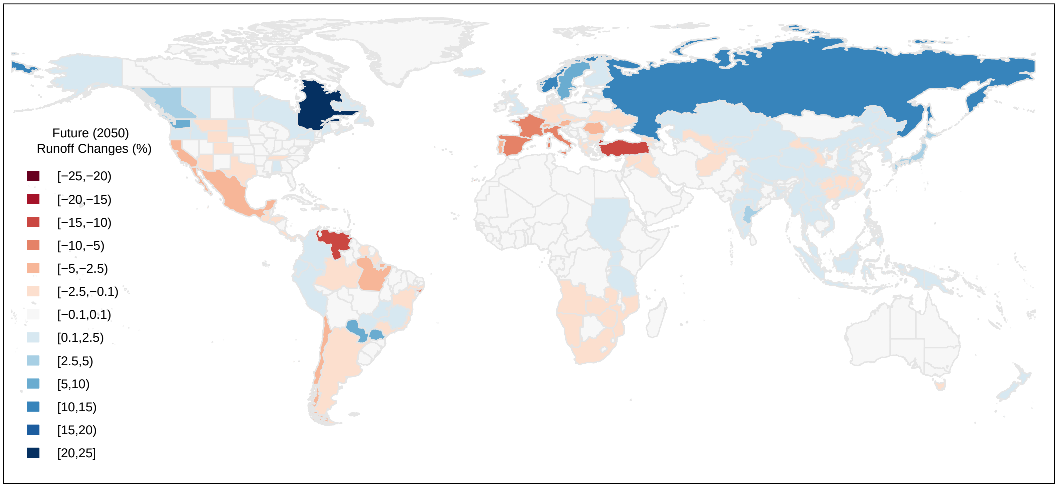
2. Methodology

The runoff baseline data is taken from the IPCC AR4 (2007), which is based on data supplied by Milly *et al.* [6]. An ensemble of 12 climate models was used with qualitative and statistically significant skill to simulate observed regional patterns of twentieth-century multi-decadal changes in streamflow. The realism of hydroclimatic simulations varies across models, so an ensemble from a subset of the models with the selection based on performance was used. The GCMs were ranked with respect to root-mean-square (r.m.s.) error (over the 165 basins and all runs) of the logarithm of long-term mean discharge per unit area; the logarithmic transform is commonly used in hydrology because flows can range over several orders of magnitude. A total of 12 GCMs were retained (35 runs of 20C3M) with the lowest error for use in the ensemble analyses [6]. Changes are expressed in terms of percentage variation from current runoff figures. The runoff changes are assessed at a national scale. On average, runoff can be thought of as the difference between the precipitation and evaporation over long periods of time and this makes it the available water for use, be it for hydropower, irrigation, domestic consumption, *etc*. In order to assess the future water availability, 12 GCMs with 20th century GRDC data [6] and future (A1B scenario) were used to evaluate the global trends of runoff. A total of 165 global basins with more than 28 years of data (greater 10% missing data) were used in regression analyses to predict the future resource availability. The model ensemble was in agreement in most regions, but there were some instances where the model ensembles did not produce similar trends and these were excluded from the analysis [6]. The agreement criteria were based on 60% of the GCM agreeing on the trends of future runoff. In the countries where the GCM predictions did not agree, *i.e.*, less than 66%, GCM having the same sign of increase or decrease were left out. The 12 GCMs results were tabulated and based on the above; a single value (median) was assigned to each country or state. The important measure of agreement was the trend, either positive or negative. The median was chosen as representing the mid-trend line of the GCMs for the particular unit, and so is not affected by the outliers. The mean was thus avoided, and the median was used in this analysis [6].

These estimated changes in runoff are the bases for country values (GCM estimates) and used as predictors in projecting hydropower generation for each country or state. The process data indicated that large changes in water resources can be expected in the coming decades due to climate changes across the globe. However, from this analysis, it is not possible to show the changes in seasons or in the timing of the water resources, which in some regions may be more pronounced. The changes are not weighted or did not have any spatial detail to represent the spatial variability in runoff areas within each country or state, and as such the results are generalized. The climate models do not simulate the high spatial resolution/detail in terms of projected climate change variables because of their large grid sizes. The runoff changes provided in this study are meant to provide a broad indication of the likely country based median changes.

Using GIS, the hydropower generation by countries were mapped into a GIS database system where different tables were merged for analysis. A GIS database management expedites the analysis on various tables that make up the database. The analysis was carried out on a national basis although some countries were subdivided into states due to their size; *i.e.*, United States, Canada, Brazil, China, India and Australia. The countries or sub-regions were taken as units on which further analysis was based. The computed runoff changes is also mapped on a different layer. Computed future (2050) changes in runoff are based on results from 12 GCMs [6]. The GCMs differ in their future projections but a single value was sought by analyzing whether the general changes were positive or negative from most models. In all countries or states where the GCM agreed, in terms of trends, a median of the forecast of the GCMs was computed and the median value was then applied to annual hydropower generation for each of these units. The changes are then mapped to produce the future (year 2050) generation based on the current generation levels.

Figure 3. Future (2050) Runoff changes (%) based on 12 GCMs under A1B scenario.

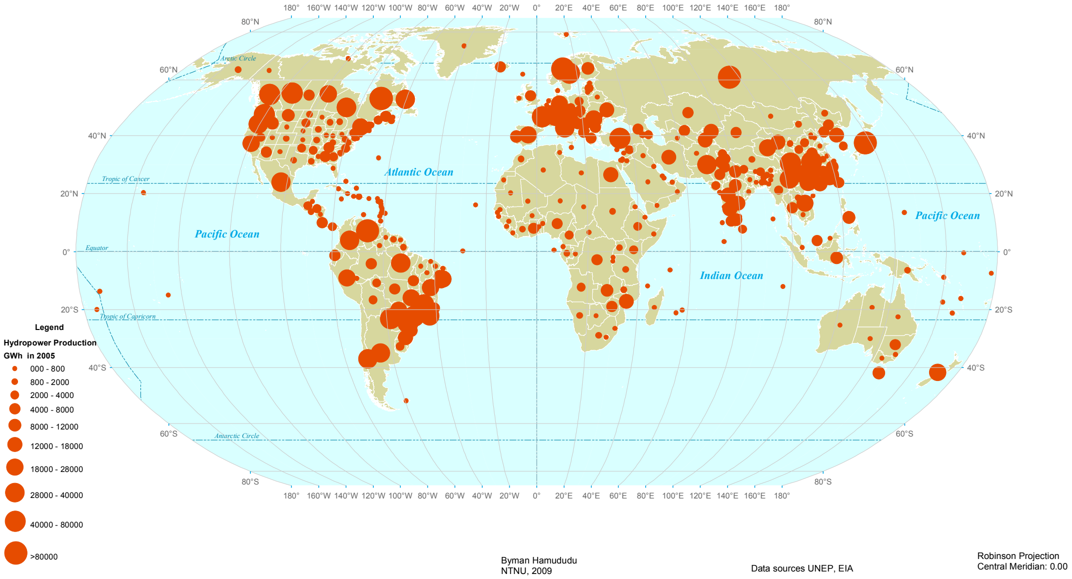


Based on the above data, the analysis was carried out to convert changes in water resource availability to changes in hydropower generation. The runoff was assumed to be the main determinant of or limitation to hydropower generation. Results are given in the next section. The computational details are illustrated by a more detailed table for Africa (Table A1 where the database and computations can be seen for individual countries. The same level of detail has been applied for all other countries and sub-regions. The methodology is based on the fact that hydropower generation (N) is a function of flow (Q, in m^3s^{-1}), head (H, in m) and efficiencies. The most varying factor is the flow (Q), referred to as water resources for every unit.

$$N = 9.81QH_\eta \tag{1}$$

The procedure uses the flow (Q) for the water resources for each country and assumes that the changes in water resources for that unit will impact the hydropower produced in the future. It is further assumed that most of the new hydropower developments will take place in the same regions where the existing systems are located. The results are expressed in percentage change relative to the generation of the existing system. This same percentage change is likely to occur even when the generating capacity is increased. Figure 4 shows data on hydropower generation; the sizes are proportional to the hydropower production for that country or state in year 2005.

Figure 4. Hydropower generation (GWh) in 2005.



Byman Hamududu
NTNU, 2009

Data sources UNEP, EIA

Robinson Projection
Central Meridian: 0.00

3. Data

Data were obtained from various sources and transformed where necessary into GIS layers. Most of the data of hydropower and energy were obtained from Energy Information Administration (EIA) of US, which is the official energy statistics of the US government freely available from their website [16] (Department of Energy 2009). Other national-level energy data were obtained directly from national websites and integrated into one database. GIS-related data like political boundaries and maps were obtained from UNEP geodata portal [17] (UNEP/DEWA/GRID-Europe, 2006), the data on dams from International Commission on large dams (ICOLD), national-level water resources data from Food and Agriculture Organization (Water Development and Management Unit, FAO) [18]. Data for trends and projections are based on a global runoff analysis by Milly (2005). Milly *et al.* showed global pattern of trends in stream flow and water availability in a changing climate. The study highlighted the variations in changes in runoff over the entire globe from region to region [5]. The following GCMs in Table 3 were used in the analysis. Runoff increases are predicted for the mainly northern regions of America, Canada, Europe and Russia as well as parts of India and Bangladesh, East Africa and a few countries in Southern America. The rest have reductions while for much of Central and West Africa, forecast cannot be made with certainty.

Table 3. GCMs used in the projections of future 2050 runoff changes after [5].

#	Model	Version	Modelling Centre	Country
1	CGHR	CGCM3.1 (T63),	Canadian Centre for Climate Modeling & Analysis	Canada
2	ECHOG		Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group,	Germany/ Korea
3	FGOALS	FGOALS-g1.0, LASG/	Institute of Atmospheric Physics,	China
4	GFCM20	GFDL-CM2.0	US Dept. of Commerce/NOAAA/Geophysical Fluid Dynamics Laboratory	USA
5	GFCM21	GFDL-CM2.1	US Dept. of Commerce/NOAAA/Geophysical Fluid Dynamics Laboratory	USA
6	GIEH	GISS-EH, NASA	Goddard Institute for Space Shuttles	USA
7	HADCM3	UKMO-HadCM3	Hadley Centre for Climate Prediction and Research/Met Office	UK
8	HADGEM	UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research/Met Office	UK
9	MIHR	MIROC3.2 (hires),	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan
10	MPEH5	MPEH5:	ECHAM5/MPI-OM, Max Planck Institute for Meteorology	Germany
11	MRCGCM	MRI-CGCM2.3.2	Meteorological Research Institute	Japan
12	NCCCSM	CCSM3	National Center for Atmospheric Research	USA

Table 4 shows the regions of the world and the countries grouped according to UNEP (2009). Note that some countries are unconventionally placed in regions, for example Russia and Turkey are grouped along with other Asia countries and not Europe. This changes the regional statistics *i.e.*, adding the generation from Russia and Turkey to the already high hydropower production in Asia.

Table 4. Global Regional Groupings of the Countries according to UNEP(2009), after [17].

Continent	Region	Countries within the Region
Africa	Eastern	Burundi, Comoros, Djibouti, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Seychelles, Somalia, Tanzania, Uganda,
	Central	Central African Rep, Cameroon, Chad, Congo, Eq. Guinea, Gabon, Sao tome
	Northern	Algeria, Egypt, Libya, Morocco, Sudan, Tunisia, W. Sahara
	Southern	Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia, Zimbabwe
	Western	Benin, Burkina Faso, Cape Verde, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory coast., Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo
Asia	Central	Kazakhstan, Kirgizia, Tadzhikstan, Turkmenistan, Uzbekistan, Russia
	Eastern	China, Hong Kong, Japan, North Korea, South Korea, Mongolia, Taiwan
	South Eastern	Papua New guinea, Brunei, Burma, Indonesia, Kampuchea, Laos, Malaysia, Philippines, Singapore, Thailand, Vietnam
	Southern west	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
	Western	Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arab, Syria, Turkey, United Arab Emirates Yemen
Australasia		Australia, New Zealand

Table 4. *Cont.*

Continent	**Region**	**Countries within the Region**
Europe	Eastern	Belarus, Bulgaria, Czech republic, Estonia, Hungary, Latvia, Lithuania, Moldavia, Poland, Romania, Slovakia, Ukraine
	Northern	Denmark, Faroe island ., Finland, Iceland, Ireland, Norway, Sweden
	Southern	Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Macedonia, Malta, Portugal, San marino, Serbia, Slovenia, Spain
	Western	UK., Austria, Belgium, France, Germany, Liechtenstein, Luxembourg, Netherlands, Switzerland
America	Caribbean	Anguilla, Antigua & b, Bahamas, Barbados, Cuba, Dominica, Domrep, Grenada, Guadalupe, Haiti, Jamaica, Martinique, Nantilles, Puerto Rico, St Chrs-nv, St Lucia, Stvinc & gr, Trinidad & Tobago, Turks & c.i,
	Central	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Bermuda,
	Northern	Canada, USA
	Southern	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Falkland, French Guiana, Guyana, Paraguay, Peru, Surinam, Uruguay, Venezuela
Oceania		New .Caledonia, Solomon, Vanuatu, Cooking island, Guam, Kiribati, Nauru, Tuvalu, Fiji, French Polynes, Tonga, Hawaii, West Samoa

4. Results and Discussion

The results from the analysis are shown in Figure 5. The size of the dots indicates the installed capacity while the colour (red for reduction ad blue for increase) indicate the changes for each country/state where GCM prediction on runoff data were consistent and reliable (in agreement). Most of the highlights are in line with many site-specific studies on hydropower and climate in most of the regions of the world. The regions of Europe, US and Canada all have projections similar to results obtained in the studies [19–26].

Table 5 shows that 2931 TWh of hydro-electricity were produced in year 2005. From the analysis, based on 2005 global hydropower generation, it can be said that by year 2050, the hydropower generation would be affected differently in various regions of the world. There are regions where hydropower generation will increase and there are also regions where hydropower generation will decrease.

In Africa, there are some countries with increasing hydropower generation and others with decreasing hydropower generation, as illustrated in the appendix. The Eastern African region shows increases in almost all countries except Ethiopia where there were disagreements among the GCMs. The Southern and Northern regions show decreases in hydropower generation. The Western region remains nearly the same but there are some countries with increases while others have decreases, and again here in most countries there were disagreements among GCMs on future runoff.

Figure 5. Percentage Changes in Global Hydropower generation resulting from 12 GCMs (AR4 2007) under A1B scenario.

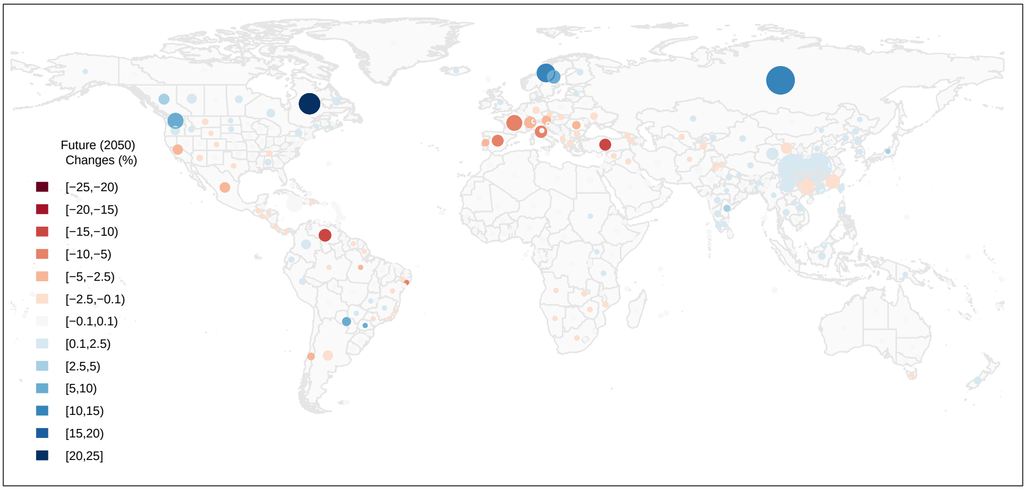


Table 5. Summary of Regional (2050) Changes in Hydropower generation.

Continent	Region	Generation TWh	Change TWh	% Change of total
Africa	Eastern	10.97	0.11	0.59
	Central	12.45	0.04	0.22
	Northern	15.84	−0.08	−0.48
	Southern	34.32	−0.07	−0.83
	Western	16.03	0.00	0.03
		89.60	0	−0.05
Asia [1]	Central	217.34	2.29	2.58
	Eastern	482.32	0.71	0.08
	South Eastern	57.22	0.63	1.08
	Southern	141.54	0.70	0.41
	Western	70.99	−1.66	−1.43
		996.12	2.66	0.27
Australasia/Oceania		39.8	−0.03	0
Europe [2]	Eastern	50.50	−0.60	−1.00
	Northern	227.72	3.32	1.46
	Southern	96.60	−1.79	−1.82
	Western	142.39	−1.73	−1.28
		517.21	−0.8	−0.16
America	Northern, Central/ Caribbean	654.7	0.33	0.05
	Southern	660.81	0.30	0.03
		1,315.5	0.63	0.05
Global		2,931	2.46	0.08

[1] Includes Russia and Turkey; [2] Excludes Russia and Turkey.

For Asia, positive trends owing to climate change have been projected for most countries. An exception is the Middle East (here grouped under Asia) which has decreasing trends. This continent shows the largest increases vis-a-vis the others. In fact, all the parts of this continent show increases apart from western part, which does not produce a lot of hydropower.

The Americas have a continental net increase with major producers having increases (south and north) and only central America having a reduced generation in the future. The northern part of America shows (mostly) increases and this changes southward with the central region of America showing decreases. Changes in the America nearly cancel out as decreases in some parts are offset by increases in others.

Southern, Eastern and Western Europe have reductions while the Northern part shows increased generation, and with increased generation in high-producing regions, the regional net growth is positive. The large producers are in the Northern region, and as such, the continental changes show net increases in hydropower generation.

Most of Australasia has reduced generation while Oceania shows an increase. There are disagreements among the GCMs on future projections over Australia. There are only a few states where there are agreements. This makes it difficult to make a good picture of future hydropower generation of this region.

From the results, it can be seen that most of the high hydropower-producing countries in the north (Canada, US and parts of Europe and Russia) will have increased generation, while for most of the south, whether big or small, hydropower generation will decrease.

It should be stated here that the analysis was carried out on a national basis (states for the largest countries), while this papers summarizes the results at a regional level. There are many differences within each region. Even when the overall region may register an increase, it is likely that some countries within the region may experience reductions. Table 5 has been appended to show intra-regional variations for one continent, Africa. Africa has been chosen to highlight these internal differences in changes due to its high hydropower potentials (undeveloped) and its having the greatest variations and the highest necessity for development in the future due to increasing population.

The global change in future hydropower generation due to climate change shows a slight increase over the current global hydropower generation (0.46 TWh). This could be improved by bringing on-stream fresh capacity either already under construction or on the anvil.

5. Limitations

The overall objective of this study was to present a global picture of impacts of climate change on hydropower generation. In order to do this efficiently, a lot of simplifications were made. These included ignoring the impacts such as changes in timing of flow, changes in sediment transport, *etc*. These are important factors in hydropower operation, but were not included in this analysis. In addition there were no adaption and/or mitigation on operations included in the analysis, and as such, no storage analysis or non-storage analysis was performed.

The changes are computed on the current hydropower generation and no future hydropower development has been included, firstly due to the fact that these data are difficult to obtain for each country or state for the whole world, and secondly because the analysis would become more complex, requiring more resources.

Another simplification is that changes are computed at country level (except for very large countries). The study recognizes that climate change impacts can vary spatially and sometimes over short distances, but again, the simplification that for each country, an average change is assumed may seem acceptable. The objective was to show the bigger global picture and the direction of change on the global scale.

The amount of electricity produced by a hydropower system depends on: (1) the discharge/flow (amount of water passing through the turbine per unit time); (2) the site head (the height of the water source); and (3) the turbine generating capacity and efficiency. In order to evaluate the impacts of climate change on hydropower globally, only the mean discharge/flow has been used as a factor to hydropower generation, which is also a simplification.

The above simplification would lead to some differences when the results presented in this study are compared to a more local detailed analysis of climate change impact on one or two hydropower system, where more plant data, time series data and detailed down-scaling is carried out. However a few comparisons made so far showed that the results were not very different (within ranges).

There are many factors that could be used to mitigate impacts on climate change on hydropower especially in operations. These have not been dealt with in this current study. Such factors include the storage capacity, pumped storage system, operation rule curve changes, *etc*. These were considered to be outside the scope of this study.

The primary function of a hydropower system is to generate power. However in many countries, the hydropower systems play important roles as general purpose water handling facilities. The multipurpose use of water and demand is important as the impacts of climate threaten the agreements that exist between many users of water. In areas projected with decrease, as the water resources decrease, competition and re-examinations of agreements may result. This ultimately would result in changes in the hydropower generation.

This study has not examined the impact of increased frequency of droughts and floods, as forecast in many places with climate change. If droughts and floods become more frequent, this scenario would severely impacts hydropower production. These extreme events would reduce the reliability of hydropower system to produce power. In regions where mean annual flow does not change, it is still possible that hydropower production would be severely affected if the droughts become more frequent. The impacts of changes in extreme events should be examined carefully on a local scale.

6. Conclusions

Hydropower generation is mainly influenced by runoff although there are other limiting factors. Changes in runoff will therefore lead to changes in hydropower generation. In its most accurate form, hydropower-plant based analysis for individual stations gives a better picture of future generation. However, when one is considering the global level, scale becomes an important issue.

The overall impacts on the global technical potential is expected to be slightly positive. However, results also indicate the possibility of substantial variations across regions and even within countries. Globally, hydropower generation computations show a very slight increase around year 2050 of about 0.46 TWh per annum. However, different countries and regions of the world will have significant changes; some with positive and others with negative changes. This study therefore provides general estimates of regional and global perspectives of the probable future hydropower generation scenarios.

Climate change is a challenge for the entire hydropower sector; the challenge is to come up with mitigation measures for hydropower operations and designs against these effects. Some regions have minimal infrastructure to act as a buffer the impacts of change.

The hydropower sector is one of the sectors least adversely affected on a global scale. Although the various regions will have varying changes, at the global level, there could be a slight gain in total global hydropower generation. It is worth mentioning here that after factoring in the uncertainty through the whole analysis process, it can be said that hydropower generation will remain nearly the same for some time into the future—till year 2050.

Investment (construction of new plants) in the hydropower sector could help reduce the gap (deficit) that may be created by effects of climate change on power generation in areas where there is still untapped potential. In other areas where the potential is nearly exhausted, better technology (e.g., high efficiencies) on existing systems would help mitigate the impacts or boost the contribution of hydropower to global electricity generation.

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Appendix

Table A1. African Regions and Countries in detail.

Region	Country	Runoff (mm/yr)	Installed Capacity (MW)	Hydropower generation 2005 (GWh)	Changes in hydropower %
East Africa	Burundi	132	32	98	13.1
	Comoros	723	1	2	
	Djibouti	14	0		
	Ethiopia	97	669	2,805	1.6
	Kenya	52	677	2,996	
	Madagascar	567	105	653	−4.5
	Mauritius	1,081	59	113	
	Reunion	1,941	125	575	
	Rwanda	206	35	129	15.1
	Somalia	21			
	Tanzania	96	557	1,760	12.9
	Uganda	272	306	1,839	14.9
Central Africa	Centr. Afr. Rep	232	19	83	
	Cameroon	612	805	3,874	0.0
	Chad	37			
	Congo	2,409	92	351	−4.2
	Guinean	960	3	3	
	Gabon	627	170	806	−6.6
	Sao tome	2,100	6	11	
	Zaire DRC	549	2,410	7,322	−0.1
North Africa	Algeria	6	280	549	
	Egypt	59	2,745	12,518	
	Libya	0			
	Morocco	72	1,498	1,398	
	Sudan	26	308	1,227	7.1
	Tunisia	30	66	144	−30.8
	Western Saharan	3			
Southern Africa	Angola	147	497.5	2,197	−7.4
	Botswana	25			
	Lesotho	99	76	350	−8.8
	Malawi	145	283	1,369	−0.4
	Mozambique	274	2,136	13,131	−9.5
	Namibia	22	249	1,641	−21.2
	South Africa	41	661	903	−11.6

A.2 Downscaling Results in Plots

A.2.1 Introduction

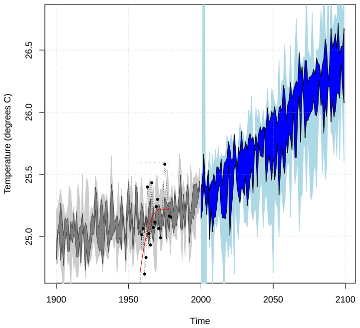
The results of empirical-statistical downscaling (clim.pact) for monthly mean temperature and precipitation are presented in the appendices for a multi-model ensemble of the GCMs from AR4 with one emission Scenario of A1B. The post downscaling analysis involves evaluation of results by incorporating common EOF analysis. The downscaling incorporated local information for climate stations.

The predictors for the temperature and precipitation were mean temperature and total precipitation respectively from the monthly mean large-scale anomalies from the ERA40 re-analyses. The gridded reanalysis ERA40 data were mixed with 5 GCMs of IPCC SRES A1B-based climate scenarios. CSIRO.MK3.0, ECHAM5/MPI-OM, CGCM2.3.2, CCSM3, and UKMO-HadCM3 were selected and used in the downscaling. The clim.pact tool involved a stepwise multiple regression between the 8 leading common EOFs for the mixed data and one time series representing monthly temperature of precipitation for each station. The area was automatically picked from the African region of positive anomaly correlation between the predictand (station data) and the predictors ERA40 on monthly basis.

The plots in the following pages are a result of post-processing that graded the quality of the results as example from a selected number of climate stations. The trends of adjacent months were related to each other, realistic seasonal values and variability. The plots common known as 'plume plots' for some selected stations are showing the E-SDS results for the 20th century (grey) and 21st century (blue) together with the actual observations (black points). The first plots are for mean temperature followed by plots of precipitation for selected stations in central and southern Africa. The first page contains examples of downscaling results of temperature and the last page is precipitation results.

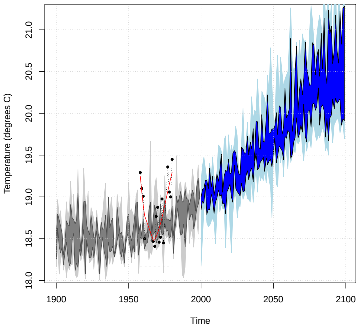
Temperature

CABINDA: Jan − Dec



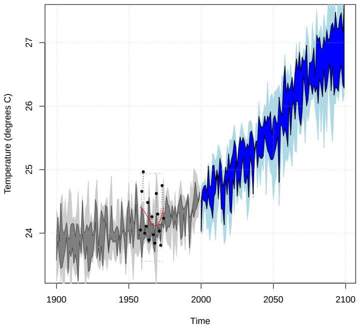
IPCC AR4: 20C: N=5, sresa1b: N=5

HUAMBO: Jan − Dec



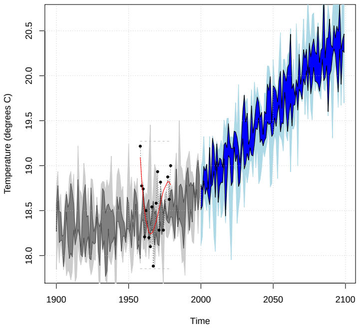
IPCC AR4: 20C: N=4, sresa1b: N=5

LUANDA: Jan − Dec



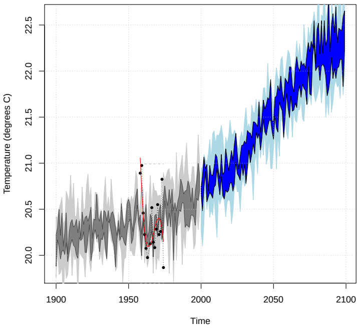
IPCC AR4: 20C: N=5, sresa1b: N=5

LUBANGO: Jan − Dec



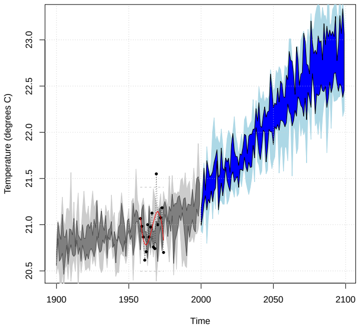
IPCC AR4: 20C: N=5, sresa1b: N=5

LUSO: Jan − Dec



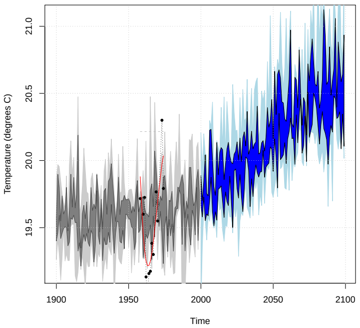
IPCC AR4: 20C: N=5, sresa1b: N=5

MALANGE: Jan − Dec



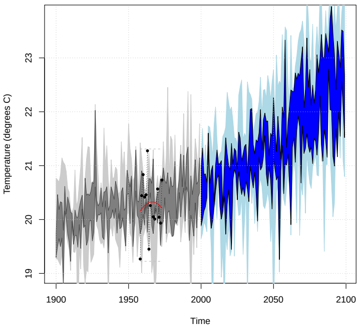
IPCC AR4: 20C: N=5, sresa1b: N=4

MENONGUE: Jan − Dec



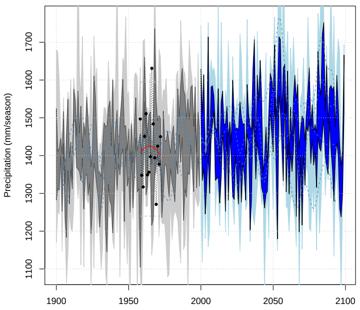
IPCC AR4: 20C: N=5, sresa1b: N=5

MOCAMEDES: Jan − Dec



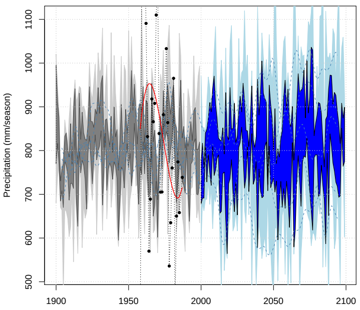
IPCC AR4: 20C: N=5, sresa1b: N=5

ANDRADA6: Jan − Dec



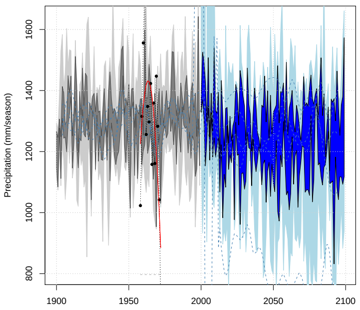
IPCC AR4: 20C: N=5, sresa1b: N=4

CABINDA6: Jan − Dec



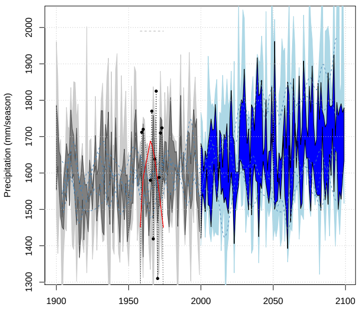
IPCC AR4: 20C: N=4, sresa1b: N=5

CACONDA6: Jan − Dec



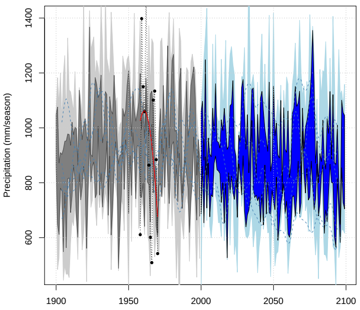
IPCC AR4: 20C: N=5, sresa1b: N=5

CARMONA6: Jan − Dec



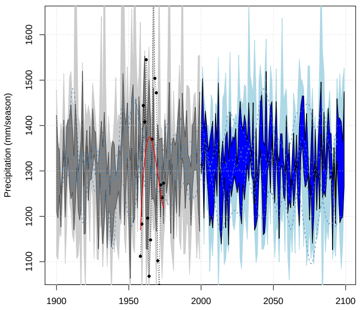
IPCC AR4: 20C: N=5, sresa1b: N=5

CATENGUE6: Jan − Dec



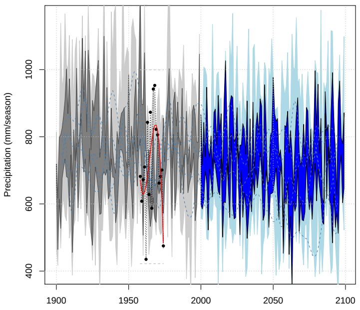
IPCC AR4: 20C: N=5, sresa1b: N=5

CEILUNGA6: Jan − Dec



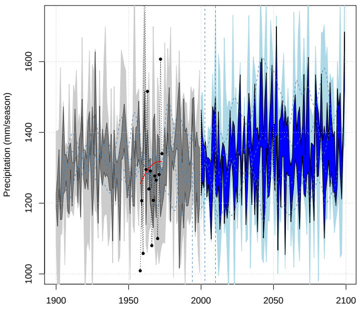
IPCC AR4: 20C: N=5, sresa1b: N=5

CHIBEMBA6: Jan − Dec



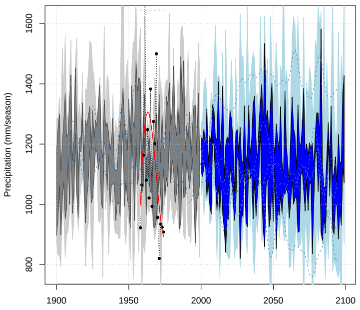
IPCC AR4: 20C: N=5, sresa1b: N=5

CHINGUAR6: Jan − Dec



IPCC AR4: 20C: N=5, sresa1b: N=4

CHITEMBO6: Jan − Dec



IPCC AR4: 20C: N=5, sresa1b: N=5