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IMPACTS OF CLIMATE CHANGE ON WATER AVAILABILITY IN ZAMBIA: IMPLICATIONS FOR IRRIGATION DEVELOPMENT

By

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Food Security Policy *Research Papers*

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EXECUTIVE SUMMARY

Water resources are important for current and future socioeconomic development of any country. To manage water resources sustainably requires a good understanding of the current and future availability of these resources at local level: how much water is available, where is it available and when?

This paper assesses the spatial and temporal distribution of water resources and the impacts of projected climate change on water resource availability, and draws implications for irrigation development in Zambia. Unlike past studies done at national level, this study is at river basin level. Using a water balance model in a hydrological modeling framework and statistical downscaling of future climate scenarios from the Intergovernmental Panel on Climate Change, the paper simulates the impacts of climate change on water availability in Zambia's main river basins from current periods until the end of the century in 2100.

The main results indicate that temperature increases in Zambia are projected to reach 1.9o C and 2.3o C by 2050 and 2100, respectively. Rainfall is projected to decrease by about 3% by mid-century and only marginally by about 0.6% towards the end of the century across the country. However, there are large differences across the different regions, with the southern, western and eastern regions projected to be much more affected compared to the northern region.

These changes in rainfall and temperature will reduce water availability by about 13% from current (observed) levels of about 97 km3 to about 84 km3 by the end of the century at national level. At the river basin level, the northern basins are likely to stay the same or experience slight increases in water resources compared to those in the southern and western parts of Zambia. In particular, Zambezi, Kafue, and Luangwa River Basins are projected to have less water resources available due to reduced rainfall and higher temperatures

.

These findings have implications for smallholder irrigation development in Zambia.

First, this implies that contingent on costs, current and future irrigation schemes will need to adopt more water efficient technologies such as overhead irrigation systems (e.g., center pivots and drip irrigation) as opposed to the prevalent surface irrigation methods.

Second, reduced water availability will increase access and irrigation costs, which in turn may reduce its profitability among smallholder farmers as they tend to have limited capital and capacity to adapt to higher cost structures.

Third, competition for the reduced available water resources will disadvantage the smallholder farmers. Policies to protect them against the large scale users are required. Options for bulky water transfer from low-demand, high-water areas in the north to the high-demand, low-water areas in the south should be explored.

Fourth, water resources management and regulation need to be strengthened, for example by ensuring that water user rights and fees become mandatory, even among smallholder farmers. There is also need to improve rain water harvesting and storage by investing in more efficient reservoirs. How these reservoirs should be managed to ensure equitable access to water resources and to reduce water loss due evapotranspiration requires further thought.

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ACRONYMS AND ABBREVIATIONS

CEC	Copperbelt Energy Company
CHIRPS	Climate Hazard Group Infrared Precipitation
CSAG	Climate Systems Analysis Group
CSO	Central Statistical Office
CRU	Climate Research Unit
ESD	Empirical Statistical Downscaling
GCM	Global Climate Models
GRDC	Global Runoff Data Centre
GRZ	Government Republic of Zambia
IAPRI	Indaba Agricultural Policy Research Institute
IPCC	Inter-government Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
MWBM	Monthly Water Balance Model
MW	Mega Watts
NAIP	National Investment Plan
NGO	Non-Government Organization
RCP	Representative Concentration Pathways
SNAP	Second National Agriculture Policy
SSA	Sub Sahara Africa
WARMA	Water Resources Management Authority
ZESCO	Zambia Electricity Supply Corporation

1. INTRODUCTION

The impacts of climate change on livelihoods are larger for rural households that depend on rainfed agriculture. For these households, dependence on rainfed agriculture amounts to double tragedy: they are more likely to be affected (exposed) and tend to lose more when affected (vulnerable) by shocks such as floods and droughts (Hallegatte et al. 2016). Smallholder rainfed farming systems prevalent among rural households in sub-Saharan Africa (SSA) and Zambia are prime examples. Rural households in SSA have low capacities to adapt and cope with climate shocks (Hallegatte et al. 2016), making climate change a major threat to poverty alleviation.

Climate change has both direct and indirect impacts on the livelihoods of rural households (Porter et al. 2014). Directly, it affects crop productivity and production, and therefore agricultural rent and food security. Climate change also affects the ability of households to acquire assets and returns on these assets. Indirectly, climate change affects output prices, wages, off farm employment and alternative livelihood opportunities, and food systems.

The challenge for the region, therefore, is the one hand to build the resilience of smallholder rainfed farming systems to raise productivity and production to meet rising demand for food and food diversity while on the other hand cope with and adapt to climate shocks. Smallholder irrigation is widely considered part of the solution to the dual challenge: it facilitates all-year round production and thus increases household incomes and builds the resilience of smallholder farming systems to rainfall variability.

For its socioeconomic and environmental/climate merits, irrigation development is a key policy priority highlighted in the Second National Agricultural Policy (SNAP), National Agriculture Investment Plan (NAIP) and Seventh National Development Plan (7NDP) as a means to both increase the resilience of farmers to climate change and for agricultural development, and to diversify the Zambian economy from copper dependence (GRZ 2013; GRZ 2016a; GRZ 2016b; GRZ 2017).

There are several irrigation models in Zambia including (i) informal irrigation at individual household level, (ii) smallholder irrigation schemes (e.g., community based, farmer, or cooperative operated schemes), (iii) quasi-government schemes, and (iv) private or commercial irrigation schemes. However, there are several gaps in our understanding of what works and is best suited for smallholder farmers, how best to scale up those models that work and on the impacts of current and future climate change on water resource availability at local scales such as river basin.

1.1. The Problem

Out of the potential 2.75 million hectares (ha) irrigable land, of which 523, 000 ha or 19% is economically viable, only about 155, 000 ha (about 6% of the total land area or about 1/3 of irrigable area) is irrigated in Zambia (GRZ 2013). Moreover, it is often argued that Zambia is richly endowed with water resources, holding an estimated 45 - 60% of surface and underground water supplies in southern Africa (GRZ 2013). The annual runoff is estimated at about 100 billion m^3 and about 60 billion m^3 stored underground in rivers, lakes, streams and swamps. Combined, the under exploited irrigation potential and the abundant water resources suggest that Zambia, like several other SSA countries, has enormous potential to expand irrigation (Xie et al. 2014).

However, there are peculiarities: since most of the major river systems in Zambia are shared watercourses with riparian countries, there is no guarantee of water availability and its subsequent use. This is exacerbated by climate change, which on average is likely to reduce water availability. This begs the question, is Zambia really richly endowed in water resources?

Several stakeholders, including government, the donor community, non-government organization (NGOs), and the private sector support some form of irrigation development in Zambia. Ngoma et al. (2017) shows that about 17 and 15% of the smallholder farmers in Zambia irrigated some of their fields in 2010/2011 and 2012/2013 agricultural seasons, respectively. The authors further show that the most prevalent method of irrigation is rudimentary at best, with more than 80% of the households having used manual bucket irrigation.[1] Understanding the socioeconomic constraints to irrigation uptake is an interesting area for future research and one that is beyond the scope of this paper. Interested readers are referred to Ngoma et al. (2017) and Simfukwe (2014).

In addition to the socioeconomic constraints to irrigation development in Zambia, biophysical challenges—a focus of this paper—abound. It is well known that optimal use of available water resources is key to reducing the country's dependency on copper production and enhance the resilience of smallholder farming systems to climate variability. However, it is not very clear how to do so because several factors impede the full exploitation of water resources for increased production through irrigation in Zambia. These include: (i) lack of accurate data on availability and distribution of water resources and the likely impacts of climate change on these aspects; (ii) poor resource management, regulation and enforcement of legislation mechanisms; (iii) unclear water abstraction and use rights; (iv) lack of an integrated approach to water resource management; (v) inadequate investment in water infrastructure; (vi) recurring droughts and floods; and (vii) lack of clear understanding on the most suitable and feasible irrigation development approaches.

This paper contributes towards filling these gaps and addresses some of these factors. It applies a water balance model in a hydrological modeling framework to assess the spatial and temporal distribution of water resources and uses the Intergovernmental Panel on Climate Change (IPCC) future climate scenarios to assess the medium- and long-term impacts of climate change on water resource availability in Zambia. This study complements past studies done at national or regional levels (Bates et al. 2008; African Development Bank 2010; Beilfuss 2012; Hamududu and Killingtveit 2012; Ebinger and Vergara 2015) and does the analysis at the local scale - at the river basin level in order to capture the subnational differences.

Specifically, the study attempts to answer the following questions:

1. How much of the precipitation received ends up in rivers, what are the trends, and how do seasonal inflows and outflows from selected basins vary from year to year?
2. What are the likely impacts of projected climate change on water resources availability and what is the likely risk on the water resource availability and use?

The rest of the report is structured as follows. Section 2 presents a brief overview on the distribution of the water resources in Zambia and characterizes Zambia's historical and future climate. The data and methods are presented in Section 3; Section 4 presents and discusses the results; and section 5 draws implications of the impacts of climate change on water availability on smallholder irrigation development in Zambia. Study limitations are laid out in Section 6 and the paper concludes in Section 7.

[1] This is a system of irrigation where households manually draw water from wells or streams or rivers using buckets to irrigate crops.

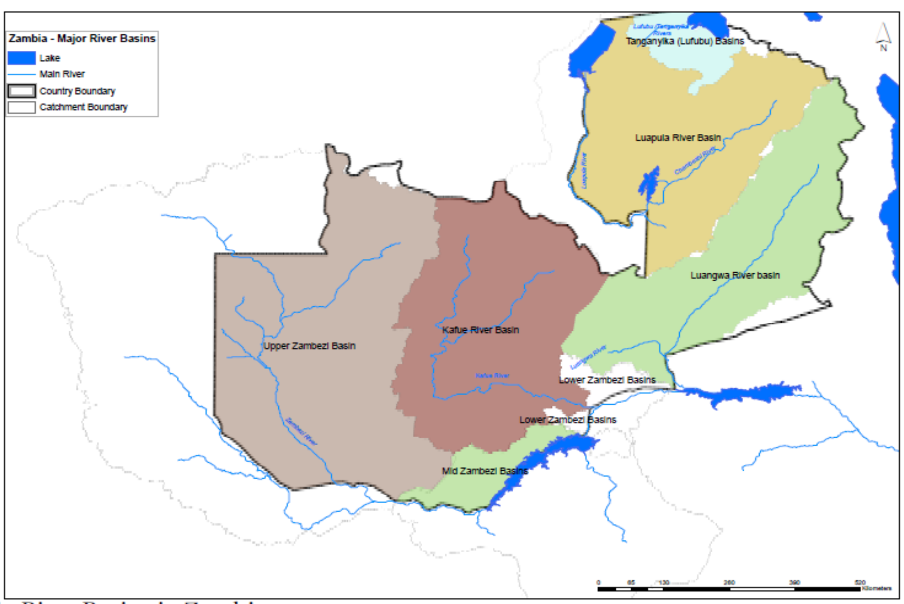
2. WATER RESOURCES DISTRIBUTION IN ZAMBIA

Water resources of a country constitute one of its vital resources that can significantly contribute to socioeconomic development and poverty eradication. However, this resource, in most cases, is not evenly distributed over time and space. This often times limits the availability and use of the water resources. Zambia is not an exception. The main source of water resources in Zambia is direct rainfall, which has been experiencing variability, further threatening water distribution. The distribution of water can be viewed at macro-level groupings such as provinces and districts but it is often easier to follow the watershed boundaries as shown in Figure 1. The watershed boundary is considered to be the natural distribution of water resources although groundwater may not follow these above surface divisions.

Following this typology, Zambia is drained by two main river systems, the Zambezi River and the Congo River basins. The Zambezi covers a larger portion of the country and is fed by three rivers—Upper Zambezi, Kafue, and the Luangwa rivers. The Zambezi River is Africa's fourth largest river after the Nile, Congo, and Niger Rivers. The Zambezi basin has a total area of about 1,390,000 km^2, making it the largest of the African river systems flowing into the Indian Ocean. It is shared by eight countries and supports a population of more than 40 million people. The main economic activities within the riparian states are mining, agriculture, tourism, fisheries, and manufacturing. Most of these activities depend mainly on the electricity produced in the hydropower plants of the basin, as well as on other sources of energy (primarily coal and oil).

The Kafue River originates in Copperbelt Province near Kitwe and North-western Province near Solwezi. It flows down in a southerly direction across the Kafue Flats and finally to the confluence of Zambezi River south-east of the basin. The total area of the Kafue River basin is estimated to be 157,000 km^2 with a total length of around 1,300 km. The Kafue Flats sub-basin occupies a major part of the Lower Kafue Basin and is located between the Itezhi-Tezhi Dam and Kafue Gorge Dam.

Figure 1. The Main River Basins in Zambia



Source: Authors.

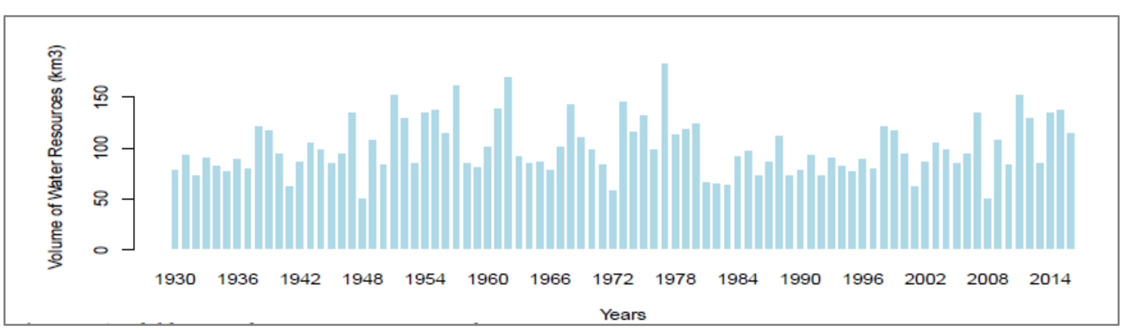
The Luangwa River has its origins in the Mafinga Hills of the Luangwa Malawi catchment boundary in north eastern Zambia. It flows in the eastern part of Zambia in the south western direction. The main tributary is the Lusemfwa River before the Luangwa joins the Zambezi River. The river flows on the floor of a large flood plain in the rift valley trough between two escarpments. It has few tributaries with a narrow shaped catchment.

The Luapula and the Chambeshi rivers feed the Congo River in the north, which flows northwards (Figure 1). Much of the water flowing into the Congo River is barely utilized while the Zambezi flowing southwards is highly utilized for various purposes, including irrigation and hydropower generation. There are several small rivers that flow into the Lake Tanganyika but the Lufubu River is the main river that drains much of Zambia into the lake. Lufubu basin is also known as Lake Tanganyika basin.

The Chambeshi River is another major river of the Congo Basin in Zambia. This river originates in Mbala highlands near the border of Zambia and Tanzania. Together with a number of small tributaries, the river flows south west into northern Zambia. Downstream after the confluence with Lukulu River, the river changes its name to Luapula as it enters Luapula province. The basin is on the high plateau with mountains resulting in many small tributaries. The Luapula river (from Chambeshi river) whose origins are in Lake Bangweulu and the Chambeshi river flows in the southerly and westerly directions before flowing in the
northern direction into Lake Mweru. Luapula River flows between Zambia and Congo and forms the boundary line between the two countries.

According to the World Bank water resources database, Zambia has abundant available water resources when compared to some of her neighboring countries like Zimbabwe, Botswana, and Namibia.[2] The African Water Development Report of 2006 estimates the total amount of water that flows annually through Southern Africa to be 399 km^3, of which only 80 km^3 (ca. 20%) flows through Zambia. The total internal renewable water resources per capita has reduced to 4,947 m^3/person /year as of 2014, down from 17,886 m^3/person /year in 1962 in Zambia.
Figure 2 shows the annual available water resources in Zambia from the 1930s to 2015. It is apparent from the figure that water resource availability is highly variable from year to year. Zambia has sufficient water resources during normal rainy seasons, but high climate variability coupled with inadequate storage infrastructure and management result in water scarcity during years of low rainfall.

Figure 2. Available Annual Water Resources in Zambia, 1930 – 2015



Source: Authors.

[2] https//data.worldbank.org

For example, there was reduced water availability in drought years of 1972, 1982, 1992, 1995, 2001, and 2008 (Figure 2). This has implications on food security and on efforts to reduce poverty and reinforces the need to improve water resources management in Zambia as highlighted in the 2016 National Policy on Climate Change. Further, the demand for water and the exploitable water resources of the country are unevenly distributed. The greatest demand for water occurs in the south, but most of the available water is in the north.

2.1. Current Uses of Water Resources

This section highlights the main different water uses and user categories in Zambia.

2.1.1. Water Supply

Most of the water supply in Zambia is from surface water resources, predominantly from rivers. The bulk of this water is used for urban water supply in cities and towns. Surface water accounts for about 90% of the water supplied to all sectors (agricultural, domestic, industrial, and tourist). Rainfall is the primary source of water in the country, providing flow in the streams. In some rural areas, rain water is harvested, stored, and used for various purposes including for household water reticulation in small communities or for small scale backyard irrigation.

2.1.2. Domestic Water Supply

It is the policy of the Government that potable water should be available to all citizens in such quantity and at such quality as to sustain life, irrespective of the citizen's ability to pay. According to the 2015 Central Statistics Office (CSO) annual report, about 65 % of the population has access to piped water, while about 34.7 % of the population uses untreated water from rivers, springs, and ponds.[3] Deep wells and boreholes have become very common in urban areas and in most cases these sources are not treated.

Rural residents obtain water through a variety of sources, such as hand pumps, streams, dams, and rain water. Only about 1.6 % of the rural population have piped water. The lower population density and sparse settlement patterns in rural areas means that the cost of water provision is often higher than in urban areas, while lower incomes in many rural areas make it hard for some customers to meet the full cost of high-quality services.

2.1.3. Industrial and Commercial Water Use

Large industries in major Zambian towns obtain surface water from nearby rivers especially in the Copperbelt area. Small industries with low water requirements are supplied from the township water supply systems. The bulk of the industrial water is used by the mining and processing, and sugar companies.

2.1.4. Agriculture Water Use

The agricultural sector is the major water user in the country, and is one of the key sectors of the Zambian economy. The irrigation potential for the country is estimated to be 523,000 ha. In 1985 an estimated 681.5 million m^3 were supplied to this sector, representing 75% of the total water supply

[3] Accessed from www.zamstats.gov.zm

for the country in that year. The bulk of the irrigation water (ca. 88%) in Zambia relies on surface water compared to only 12% from underground sources (GRZ 2013).
Of the 523,000 ha economically viable irrigable land, only 155, 000 ha (ca. 6% of the total land area or about 1/3 of irrigable area) is irrigated in Zambia (GRZ 2013). Thus, there is a 70% irrigation gap that can be explored in the country. Several factors undermine irrigation water use, including underdeveloped water supply sources and infrastructure for distribution and increasing salinity of ground water. Irrigation in Zambia is characterized by inefficient and low-tech methods such as furrow irrigation with significant water wastage. Conveyance of water from source to farmland is hindered by the poor condition of many of the existing waterworks, and unlined canals result in huge water losses.

2.1.5. Hydropower Water Use

The Zambia Electricity Generation and Supply Corporation (ZESCO) is responsible for providing electricity for public use. However, there are other private organizations, such as the Lunsemfwa, Lunzua, and Copperbelt Energy Corporation (CEC) and sugar estates that supply electricity for their own use. Nearly all hydropower plants are owned and operated by ZESCO throughout the country. These plants have a total installed capacity of 2,337 MW, which supplies 99 % of Zambia's energy needs (Table 1). Zambia has about 6,000 MW unexploited hydropower potential, while only about 37% has been developed. Of the total power output, Kariba North Power on the Zambezi River and Kafue Gorge on the Kafue River are the country's main power stations. This again shows that the water resources in the south are utilized more than those in the north.

2.1.6. Transport and Tourism

Most of the rivers in Zambia are not navigable for long stretches except where there are lakes. Lake Kariba, Mweru, Bangweulu, and Tanganyika are the best known water bodies that are usually used for transport. Other rivers are used for transport but for short distances. Several waterfalls are a huge attraction for tourists and boat cruises are also very common on most lakes in the country.

Table 1. List of Hydropower Stations in Zambia

Basin	Hydropower Station	Generation Capacity (MW)
Zambezi	Kariba North Bank	1,080
	Victoria Falls	108
Kafue	Kafue Gorge	990
	Itezhi Tezhi	120
Luangwa	Mulungushi	32
	Lusenfwa	24
	Lusiwasi	12
Luapula	Chishimba	6
	Musonda	5
	Shiwang'andu	1
Lufubu	Lunzua	15
Total		2,394

Data source: ZESCO. http://www.zesco.co.zm/ourBusiness/generation.

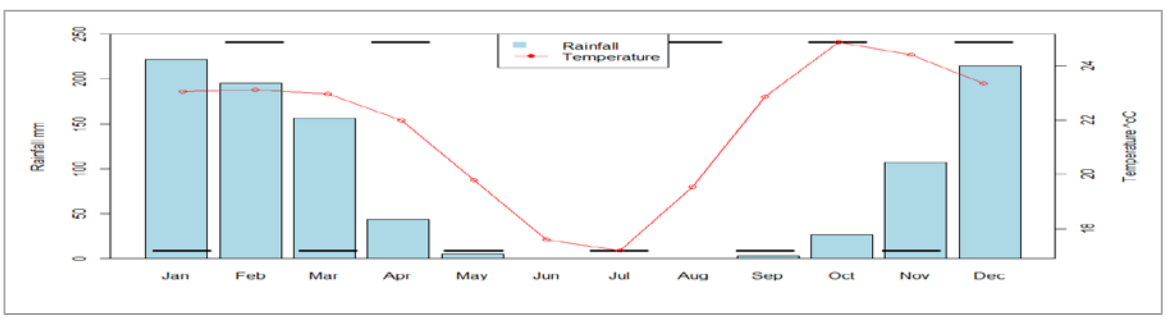
2.2. Climate

Covering some 752,610 km^2 in Southern Africa, Zambia is largely a plateau with an average elevation of 1,138 m.a.s.l. The country has a unimodal rainy season influenced by the location of the Inter-Tropical Convergence Zone (ITCZ) and has uneven distribution of rainfall. Rainy seasons span November to April of every year with average annual rainfall of more than 1,000 mm in the high-rainfall areas in the north and less than 800 mm in the south. Zambia experiences high seasonal rainfall variability, creating additional water supply problems.
The temperatures are highest during the last months of the dry season of August to October, averaging above 25^{o} C (Figure 3). This also corresponds to a period of increased water scarcity due to heightened evapotranspiration. It is cooler in May through July with temperatures averaging about 18^{o} C. This period presents a very good scenario for reduced evapotranspiration loss. The general average historical annual rainfall and temperature variability over the period 1960-2000 is shown in Figure 3.

Observed rainfall and temperature over the last 10 decades in Zambia reveal changes. Figures 4 and 5 show the long-term annual rainfall and temperature deviations from the average reference period between 1960 - 2000. It was colder in the 1900s to 1960s and generally hotter from the 1980s (Figure 4).

The rainfall generally reveals a decreasing trend from the 1980s onwards although there are some years with positive rainfall amounts post 2000 (Figure 5). Droughts and floods have become more frequent and are more severe than before. The rain season is shorter and more intense rainfall is recorded (Mulenga, Wineman, and Sitko 2017).

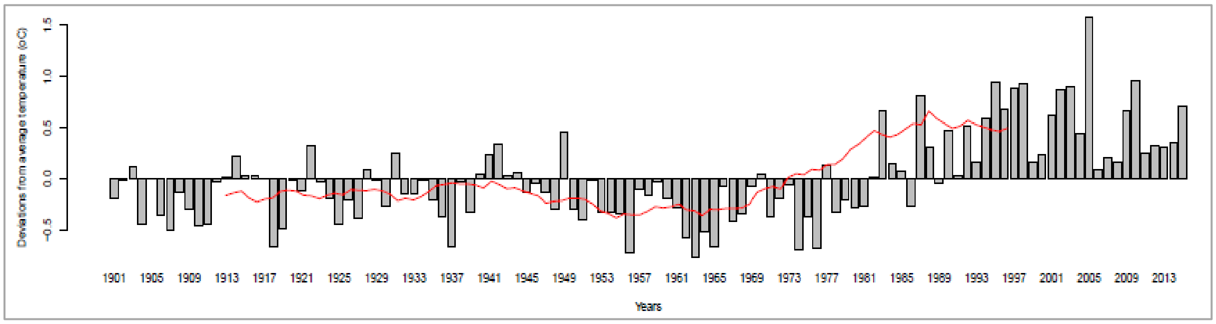
Figure 3. Average Long-term Monthly Rainfall and Temperature over the Reference Period 1960-2000 in Zambia



Source: Authors.
Figure notes: The monthly values are averages over the period 1960-2000.

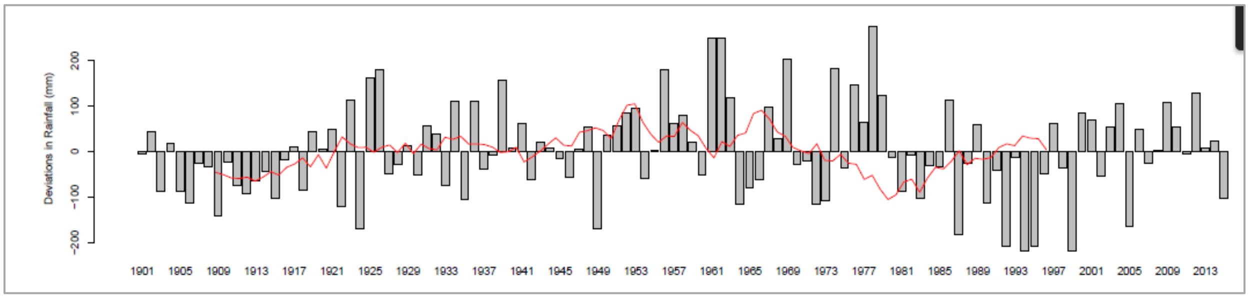
The projected rise in temperature will lead to high water losses from water bodies due to increased evapotranspiration. This is worsened by the fact that rainfall, the main source of water resources, is reducing, as can be in seen in Figure 5. The annual rainfall has not only reduced but also the difference has become larger in the last few years. According to the World Bank, the rainfall in Zambia has decreased by 1.9 mm/month/year since 1960 while the temperatures have increased by 1.3°C.

Figure 4. Long-term Temperature Deviations from the Average Reference Period (1960-2000) between 1901 - 2013 in Zambia



Source: Authors.
Figure notes: The red line show the general trend.

Figure 5. Long Term Rainfall Deviations from the Average Reference Period (1960-2000) between 1901 - 2013 in Zambia



Source: Authors.
Figure notes: The red line show the general trend.

3. DATA AND METHODS

3.1. Data

The climate and river flow data used in the biophysical assessments were obtained from various sources. Observed river flow and discharge data for the main river systems for the period 1930s – 2016 were obtained from the Water Resources Management Authority (WARMA) in Lusaka, Zambia. These data were supplemented with data from the Global Run off Data Centre. Temperature and rainfall data were obtained from the Climate Hazards Group Infrared Precipitation with Station database (CHIRPS). CHIRPS is a quasi- global spatial database (50º S to 50º N) with a resolution of 0.05º (Funk et al. 2014).

This gridded data was downloaded and processed using *R* to extract data for each river basin for the period 1980 - 2015. Where necessary, data from the Meteorological department of Zambia, e.g., on evaporation, were also used. Other spatial data products such as the World Bank climate portal and the Climate Research Unit (CRU) (Harris et al. 2014) at University of East Anglia were also used for climate data. Some data for comparison was obtained from the Climate Information Portal (CIP) of the Climate Systems Analysis Group (CSAG).[4]

3.2. Methods

This study has two main objectives: first to assess the spatial temporal availability of water resources in Zambia, and second to assess the impacts of climate change on water availability. In answering these objectives, the paper applied a hydrology model in a water balance framework. The main focus of the water resources assessment is on aspects of national and sub-national water availability rather than water allocation, or quality although there is mention of quality of surface streamflow and ground water.

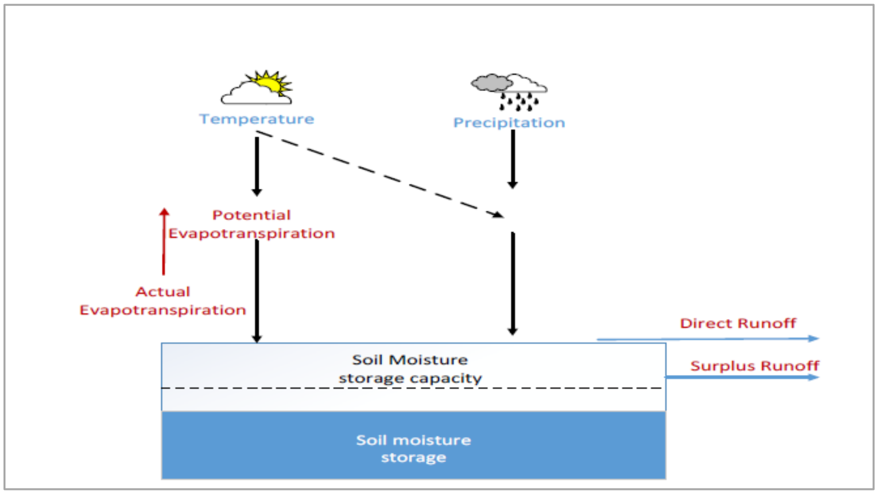
3.2.1. Computing the Basin Water Resources

A water balance model in hydrological modelling is required to produce river flows in the future based on the projected climate data. The water balance model was calibrated based on today's climate and river flows and then later applied on the projected climate to simulate the future runoff for different river basins and evapotranspiration. The resulting runoff was then summarized on monthly basis and aggregated to annual values. Other output variables such as potential evaporation, soil moisture and surplus or deficit were computed in addition to runoff (outflow).

The model structure and processes are shown in Figure 6. The input data required is temperature and rainfall, and the location of the site given in latitude north or south. There are other parameters that are used for calibration like the runoff coefficient, direct runoff, soil moisture capacity, etc. The resulting runoff can be compared to the observed discharge. The monthly model runs on monthly time step and the runoff is given out in millimeters.

[4] http://www.csag.uct.ac.za/climate-services/cip/

Figure 6. Structure of the Monthly Water Balance Model



Source: Figure modified from McCabe (2010).
Figure notes: Model inputs are shown in blue, while outputs are shown in red.

The computation of the water resources follows the understanding of the natural process in the water distribution in a single basin. The projected monthly and annual flows were used in computing the available water resources in each river basin using the general water balance equation (Equation 1) applied in a water balance accounting process. The rainfall is input while the evaporation is a loss and runoff is output with storage accounting for the difference. The evaporation was calculated based on the observed values around the main reservoirs. These values were then summed up to get the total water resources available for the country. The following equation was used in computing the water resources for every basin:

$$Ro_ut = Rn_b + Rn_{lk} - Evp_{b+lk} \pm Sto_{lk} \quad (1)$$

where Ro_ut is the outflow measured in the river draining the basin; Rn_b is the total amount of rainfall received in the basin; Rn_{lk} is rainfall received in reservoirs in the basin; Evp_{b+lk} is the water lost through evaporation over the entire basin (evaporation from open water bodies, vegetation, etc.); and Sto_{lk} refers to changes in the reservoir and groundwater storage. The equation was modified for basins which have no or very small reservoirs to account for missing components in the computation. In this way, the general methodology remained the same but depending on the conditions in the basin, the computation was carried out accordingly. This water resources assessment does not include detailed computations for groundwater resources. It is an important component but also requires a lot of measurement (investment) to measure it properly.

3.2.2. Computing the Impacts of Climate Change on Water Resources

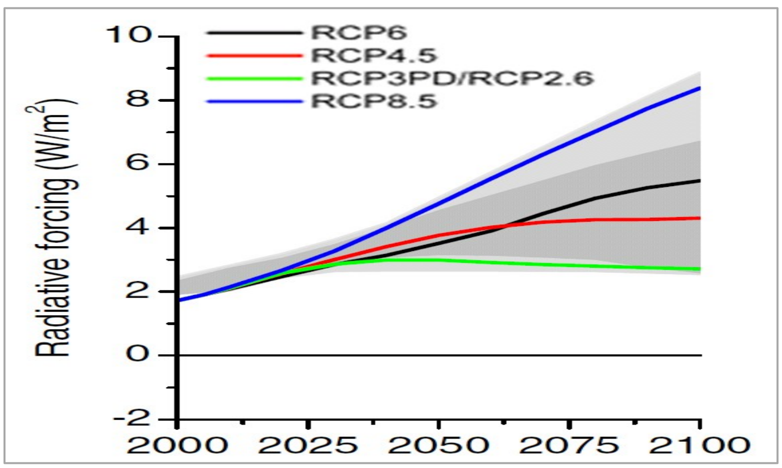
To estimate the climate change impacts on water resources, statistical downscaling was used to compute the changes in future rainfall and temperature, and the resulting changes in water resources.[5] The statistical downscaling process uses the Global Circulation Models (GCM) outputs

[5] Downscaling refers to a process of taking global information on climate response to changing atmospheric composition, and translating it to a local finer spatial scale, e.g., at river basin level.

from different IPCC future climate scenarios under varying Representative Concentration Pathways (RCPs) shown in Figure 7. RCPs describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come (Meinshausen et al. 2011). These were adopted by the IPCC in the 5th assessment report in 2014. The GCM outputs are projected future climate variables. GCMs are the most comprehensive physically-based models of climate change available and referenced by the IPCC AR4 and AR5.

Statistical downscaling develops a statistical regression between the local observed climate variables and the GCM output variables. Using this relationship, local future temperature and rainfall can be projected. The statistical downscaling process is described in Benestad (2011). Precipitation, temperature, and pressure variables were selected for use as predictors for local rainfall and temperature. There were 14 GCMs[6] and 2 RCPs[7] used in the downscaling process. These GCMs were chosen on the basis that the projections talk to each other i.e., they agree with no major contradictions and are consistent with each other. The GCM models used in this paper are the common ones applied in the African setting, especially in SSA.

Figure 7. Representative Concentration Pathways under AR5 of the Intergovernmental Panel on Climate Change



Source: Meinshausen et al. (2011).

[6] See Table A2 with list of GCMs

[7] RCP4.5 and RCP8.5

4. RESULTS AND DISCUSSION

The analysis carried on the various river basins indicate similar results but with varying levels of change. The largest changes are in the Zambezi River basins in the southern parts of Zambia.

4.1. Water Resources Availability: Past, Present and Future

The result of the water resources assessment is a sum of the water resources for each basin and changes that are likely to occur in the various basins around the country. The water resources and likely changes starting with temperature and rainfall are given in each of the respective sections below. Overall, results under the RCP 4.5 (an optimistic scenario) and RCP 8.5 (a somewhat pessimistic scenario) climate scenarios indicate that temperature will rise while rainfall will decrease in Zambia from present times onwards towards the end of the century.

There are some differences in the magnitude of the changes among the basins but the direction of change is negative for all the basins, suggesting high temperatures and lower rainfall. These projected changes in temperature and rainfall will reduce the amount of water resources available in the future periods. Table 2 summaries the results for the major rivers basins in the country, showing changes in temperature, rainfall and the resulting changes in runoff.

4.1.1. Zambezi River Basin

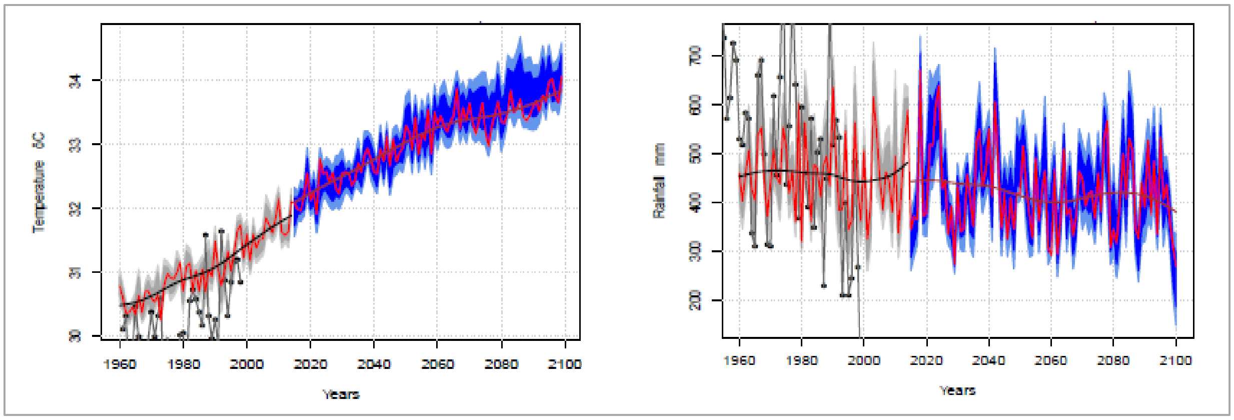
The average discharge from the (Upper) Zambezi River at Victoria Falls is 1187m^3/s. It starts to increase from November through April and reaches its peak around April with flows up to 2,700 m^3/s during wet years. October has the lowest flows with average discharge of 296 m^3/s which is about a tenth of the highest flows.

Table 2. Zambia's Main River Basins: Size, Proportion in Zambia, and Runoff

Main Basin	River	Basin size (km2)	Basin in Zambia (%)	River length (km)	Mean annual runoff (m3/s)	percent (%)
Zambezi	Zambezi	268,235	39	1,700	1,325	8
	Kafue	156,995	100	1,300	315	9
	Luangwa	144,358	98	850	681	17
	Others	8,658	100			
Congo	Chambeshi	44,427	100	560	185	15
	Luapula	113,323	65	615	741	14
	Lufubu	15,856	6	250	66	19
	Total	751,852				

Source: Authors.

Figure 8. Historical and Future Maximum Temperature and Rainfall for Zambezi River Basin



Source: Authors.

Figure notes: The gray part is the historical period and the blue part is the projected values. The black dots are observed values while red lines are median values with levels of gray and blue indicating the confidence intervals.

Impacts of Climate Change on the Zambezi River Basin: Figure 8 presents the results on the historical and projected maximum temperature and rainfall in the Zambezi River Basin. As can be seen from the figure, temperature under RCP 4.5 will continue to increase through 2100 but at a reduced rate towards the end of the century. Table 3 presents the month-on-month results for changes in temperature and rainfall from present times through to 2100. The temperature is projected to increase throughout the years in all months. The RCP 8.5 scenarios indicates changes in the range of 5ºC per month by 2100. Future rainfall is projected to decrease in the Zambezi basin.

The rest of the downscaling results are summarized in Tables 3, 4, and 5. These tables show monthly changes for the following 30-year future periods: 2030 represents the period 2020 - 2050, 2050 represents the period 2050 - 2070 and 2080 representing 2080 - 2100. Temperature is projected to increase while rainfall will reduce more significantly during the agricultural seasons (November - March).

Table 3. Future Changes in Maximum Temperature in the Zambezi Basin Relative to the 1960-2000 Historical Averages (ºC)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	2040	1.7	1.9	2.2	2.4	2.9	4.2	4.2	2.7	1.9	1.2	1.4	0.9
	2060	2.3	2.5	2.8	3.1	3.7	5.2	5.2	3.7	2.7	2.2	2.5	1.8
	2080	2.7	2.8	3	3.5	4.2	5.6	5.6	4	3.1	2.5	2.6	2
RCP 8.5	2040	2.3	2.5	2.9	3.2	3.8	5.1	4.9	3.5	2.6	2	2.1	1.6
	2060	3.5	3.7	3.9	4.5	5.2	6.5	6.5	4.9	4.1	3.5	3.8	3.1
	2080	5.2	5.1	5.5	6.1	6.9	8.2	8.2	6.7	6	5.4	5.5	4.5

Source: Authors.

Table 4. Percentage Changes in Future Rainfall in the Zambezi Basin Relative to the 1960-2000 Historical Averages (ºC)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	2040	-27	-3	16	4	1	0	3	2	5	-43	-54	-36
	2060	-35	-15	10	4	0	3	0	0	15	-45	-48	-40
	2080	-32	-12	7	2	0	0	-1	0	30	-48	-51	-36
RCP 8.5	2040	-20	-2	3	10	4	-3	-5	18	-45	-45	-51	-40
	2060	-38	-13	6	4	0	1	-6	2	-48	-48	-50	-40
	2080	-36	-14	-2	0	0	11	-4	14	-48	-48	-55	-39

Source: Authors.

Table 5. Current and Future Available Water Resources in the Zambezi River Basin

	Water resources (km^3)			
RCP	Current	2030	2050	2080
4.5	48	46	45	45
8.5	48	45	43	41

Source: Authors.

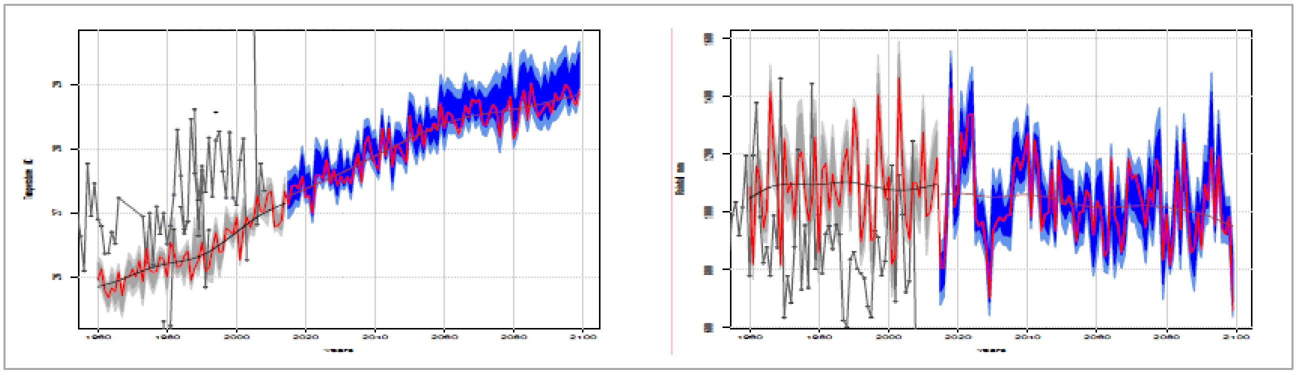
Simulated results based on future climate change under RCP 4.5 indicate that there will be a 6.7% reduction in water resources availability in the Zambezi basin from the current 48 km^3 to 45 km^3 towards the end of the century (Table 5).

4.1.2. Kafue River Basin

The water flow in the Kafue River Basin is controlled by the Itezhi-Tezhi Dam. A 30-year (October 1976 - September 2006) average discharge flow of Itezhi-Tezhi dam and water level shows that the average flow is 237 m^3/s and is regulated to keep a minimum flow of 150 m^3/s throughout the year. The lowest water level is 988m around December and January. The lowest discharge occurs in the month of October (66 m^3/s) and the high flow month is March with recorded flows of 1100 m^3/s. The outflow capacity of the Kafue Flats sub-basin is equivalent to the discharge flow at the Kafue Gorge Dam. The monthly average water flow from the dam ranged from 206 m^3/s in November to 530 m^3/s in May, and the annual average is 361 m3/s which is higher than the inflow average capacity of 237 m3/s.

Impacts of Climate Change on the Kafue River Basin: These results are qualitatively similar to those for the Zambezi Basin, but there are differences in the magnitudes of changes. Figure 9 show the general trends for temperature and rainfall in the Kafue Basin. Rainfall is projected to reduce, while temperature will increase. The changes in rainfall in the Kafue River Basin does not show as much reduction as in the Zambezi basin. However, increases in temperature and reductions in rainfall, no matter how small, are a cause for concern for future water resource availability.

Figure 9. Historical and Future Maximum Temperature and Rainfall for Kafue River Basin



Source: Authors.

Figure notes: The gray part is the historical period and the blue part is the projected values. The black dots are observed values while red lines are median values with levels of gray and blue indicating the confidence intervals.

Tables (6) and (7) summarize the rest of the downscaling results. These tables show monthly changes for the 30-year future periods 2020 - 2050, 2050 - 2070, and 2080 - 2100. The delta changes are then applied to the observed values to generate new times series of temperature and rainfall for the future periods.

Table 6. Future Changes in Maximum Temperature in the Kafue Basin Relative to the 1960-2000 Historical Averages (^{O}C)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	2030	1.7	1.9	2.2	2.4	2.9	4.2	4.2	2.7	1.9	1.2	1.4	0.9
	2050	2.3	2.5	2.8	3.1	3.7	5.2	5.2	3.7	2.7	2.2	2.5	1.8
	2080	2.7	2.8	3	3.5	4.2	5.6	5.6	4	3.1	2.5	2.6	2
RCP 8.5	2030	2.3	2.5	2.9	3.2	3.8	5.1	4.9	3.5	2.6	2	2.1	1.6
	2050	3.5	3.7	3.9	4.5	5.2	6.5	6.5	4.9	4.1	3.5	3.8	3.1
	2080	5.2	5.1	5.5	6.1	6.9	8.2	8.2	6.7	6	5.4	5.5	4.5

Source: Authors.

Table 7. Percentage Changes in Future Rainfall in the Kafue Basin Relative to the 1960-2000 Historical Averages (^{O}C)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	2030	10	15	64	0	8	1	-4	-10	0	16	6	-8
	2050	2	6	31	3	7	1	-31	-20	7	-8	4	-9
	2080	5	9	46	16	1	0	-32	-30	8	-8	0	-6
RCP 8.5	2030	13	15	64	11	-5	0	-31	-38	9	7	7	-6
	2050	4	10	32	11	24	1	-32	-46	0	-4	-11	-14
	2080	-4	1	41	24	10	0	-38	-39	-11	-5	-13	-17

Source: Authors.

Table 8. Current and Future Available Water Resources in the Kafue River Basin

	Water Resources (km^3)			
RCP	Current	2030	2050	2080
4.5	11	10.5	10.3	10
8.5	11	10.1	10.4	9.8

Source: Authors.

Based on projected climate, results indicate that there will be a 9% reduction in water resources availability in the Kafue River Basin compared to the 7% in the Zambezi River Basin towards the end of the century (Table 8). Although the basin is projected to experience high temperatures in future, there is no large reduction in the water resources of the basin, suggesting that evapotranspiration from reservoirs and swamps along the river will not have a large impact.

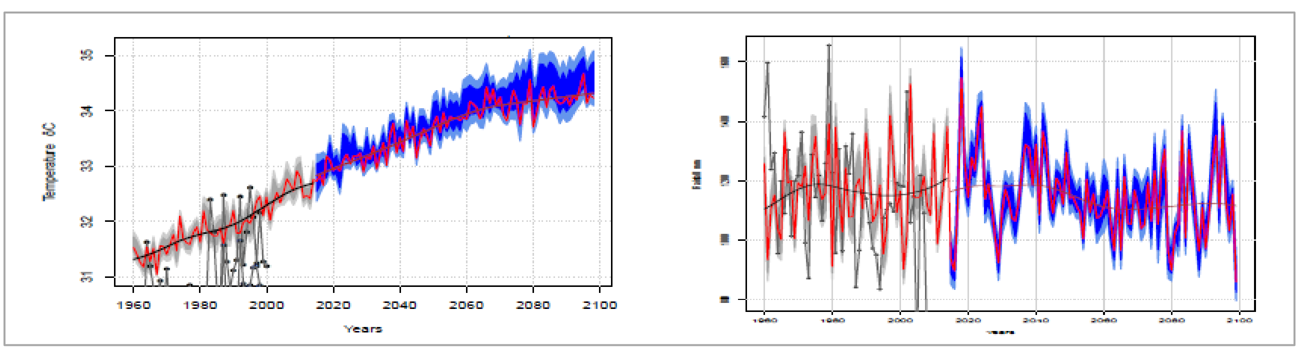
4.1.3. Luangwa River Basin

The average discharge at Luangwa Road Bridge on Luangwa River is 639 m^3/s. The lowest month is October with flows as low as 56 m^3/s and the highest flows occur in the month of February with highest recorded at 4,250 m^3/s. The minimum discharge recorded is as low as 36 m^3/s in Luangwa River. The Luangwa has a one of the highest runoff percentage at 17%.

Impacts of Climate Change on the Luangwa River Basin: As presented for other basins, here in Figure 10 are shown the historical and future temperature and rainfall changes under RCP4.5. Average temperature is projected to increase while rainfall will reduce. These projections are somewhat different for the pessimistic RCP 8.5 scenario.

Further results of projected changes in temperature and rainfall for the Luangwa River Basin are summarized in Tables 9 and 10. As with the other basins, rainfall is projected to decrease, while temperature will increase from present times on wards towards the end of the century.

Figure 10. Historical and Future Maximum Temperature and Rainfall for Luangwa River Basin



Source: Authors.
Figure notes: The gray part is the historical period and the blue part is the projected values. The black dots are observed values while red lines are median values with levels of gray and blue indicating the confidence intervals.

Table 9. Future Changes in Maximum Temperature in the Luangwa Basin Relative to The 1960-2000 Historical Averages (°C)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	2030	4.3	6.2	6.8	3.8	-1.8	-5.4	-4.5	-0.1	4.5	6.7	5	3.1
	2050	4.8	6.9	7.2	4.6	-1.1	-4.6	-3.7	0.6	5.2	7.6	6.1	3.9
	2080	4.9	6.9	7.5	4.8	-0.8	-4.4	-3.4	0.8	5.6	8	6.1	4
RCP 8.5	2030	4.6	6.6	7.3	4.5	-1.1	-4.8	-4	0.4	4.9	7.3	5.5	3.6
	2050	5.7	7.6	8.3	5.7	0.1	-3.5	-2.5	1.6	6.3	8.9	7.6	5.2
	2080	7.5	9.2	9.8	7.2	1.7	-1.9	-1	3.3	8.2	10.8	9.2	6.9

Source: Authors.

Table 10. Percentage Changes in Future Rainfall in the Luangwa Basin Relative to the 1960-2000 Historical Averages (°C)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	2030	-6	4	28	0	0	0	0	0	0	-32	-24	-11
	2050	-2	4	29	0	0	0	0	0	0	-22	-23	-10
	2080	-2	4	24	0	0	0	0	0	0	-38	-28	-14
RCP 8.5	2030	-1	3	33	48	20	-41	12	0	0	-17	-18	-9
	2050	-12	-2	7	46	0	0	-26	0	0	-45	-46	-16
	2080	-6	-5	10	50	0	-13	-18	0	0	-48	-29	-10

Source: Authors.

Table 11 shows that there will be a 5% reduction (under RCP 4.5) in water resources availability in the Luangwa River Basin towards the end of the century. This is partly because there are no major reservoirs or lakes in the basin that would result in large evapotranspiration losses. However, this might change with more hydropower developments planned in the basin.

4.1.4. Luapula - Chambeshi River Basin

The Chambeshi and Luapula rivers have an average discharge of 741 m^3/s. The lowest flows occur in October at 40 m^3/s and 237 m^3/s respectively, while the high month is April with flows of 471 m^3/s and 1700 m^3/s for Chambeshi and Luapula, respectively. The minimum flows recorded are 35 and 190 m^3/s. The runoff percentage is 13% for Chambeshi and 14% for Luapula River.

Table 11. Current and Future Available Water Resources in the Luangwa River Basin

	Water Resources (km^3)			
RCP	Current	2030	2050	2080
4.5	17	16.4	16.2	16.2
8.5	17	16.3	16	15.8

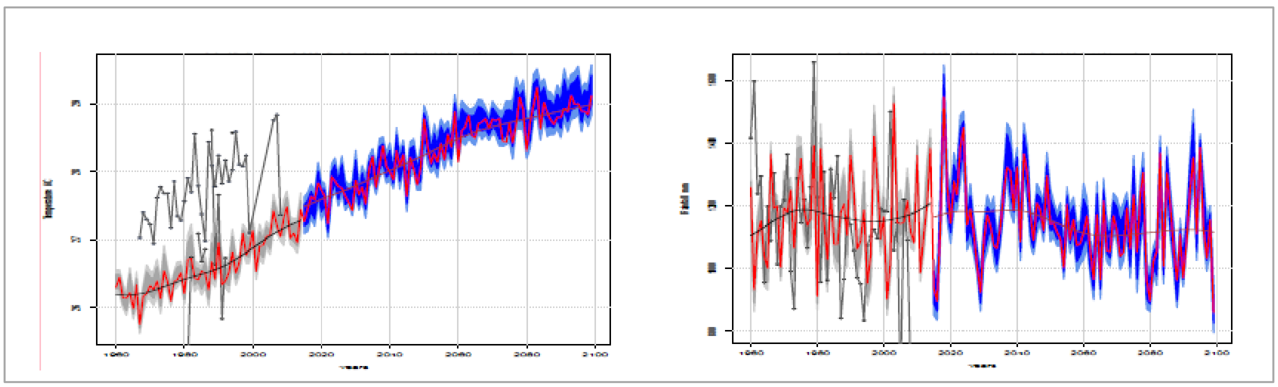
Source: Authors.

Impacts of Climate Change on the Chambeshi - Luapula River Basin: The total water resources in the Luapula-Chambeshi basin will reduce as indicated in Table 14. However, because of the main reservoirs and the fact the basin is located in the high rainfall areas of the country, projected climate change will have less impact on water availability (Table14). Even if evapotranspiration losses would increase with high temperatures and with slight reduction in rainfall, the total water loss in Luapula will not be as large as in other basins such as the Zambezi basin. This shows and confirms that the water resources in the northern part of the country will nearly remain the same even with climate change.

The downscaling results for Luapula and Chambeshi Basin in Figure 11 give insights on the projected changes in rainfall and temperature. As with other basins, it is clear from the figures that rainfall is projected to reduce (much more under the RCP 8.5 compared to RCP 4.5) but maximum temperature is likely to increase.

Additional results of projected changes in temperature and rainfall for the Luapula River Basin are summarized in Tables 12 and 13. Again, the main story is somewhat preserved: rainfall is projected to decrease towards the end of the rainy season (January to April) but will increase or stay the same towards the end of the season (October to November), while temperature will increase from present times onwards towards the end of the century.

Figure 11. Historical and Future Maximum Temperature and Rainfall for Luapula River Basin



Source: Authors.

Figure notes: The gray part is the historical period and the blue part is the projected values. The black dots are observed values while red lines are median values with levels of gray and blue indicating the confidence intervals.

Table 12. Future Changes in Maximum Temperature in the Luapula Basin Relative to The 1960-2000 Historical Averages (ºC)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	2020	1.2	0.2	1.4	1.8	1.8	2	3.1	1.8	1.4	0.7	0.1	1.2
	2050	1.7	0.8	1.7	2.5	2.6	3	4	2.7	2.1	1.5	1.1	1.9
	2080	2	0.9	2	2.8	3	3.2	4.3	2.9	2.5	1.8	1.1	2
RCP 8.5	2020	1.6	0.6	1.8	2.4	2.5	2.7	3.6	2.4	1.8	1.2	0.5	1.6
	2050	2.6	1.5	2.7	3.6	3.8	4	5	3.6	3.1	2.7	2.4	2.9
	2080	4	2.9	4.1	5	5.4	5.7	6.8	5.5	5	4.4	3.8	4.4

Source: Authors

Table 13. Percentage Changes in Future Rainfall in the Luapula Basin Relative to the 1960-2000 Historical Averages (ºC)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	2020	-22	-33	-14	-27	-26	0	0	0	0	0	0	33
	2050	-27	-39	-24	-33	-30	-43	0	0	0	0	0	34
	2080	-31	-38	-19	-31	-26	-66	0	0	0	0	0	41
RCP 8.5	2020	-24	-33	-9	-36	-13	0	0	0	0	0	0	38
	2050	-32	-37	-27	-44	0	0	0	0	0	0	0	30
	2080	-31	-38	-22	-45	0	0	0	0	0	0	0	36

Source: Authors.

At basin level, the available water resources will reduce by 3% by 2100 under RCP 4.5 (Table 14). This will be driven mainly by rising temperature which in turn will increase evapotranspiration from the vast water bodies in the basin.

4.1.5. Lufubu River Basin

The average discharge in Lufubu River at Keso Falls is 66 m^3/s. The lowest month is October with flows as low as 17 m^3/s and the highest flows occur in the month of March with highest recorded at 301 m^3/s. The Lufubu River has a one of the highest runoff percentage in Zambia at 20%.

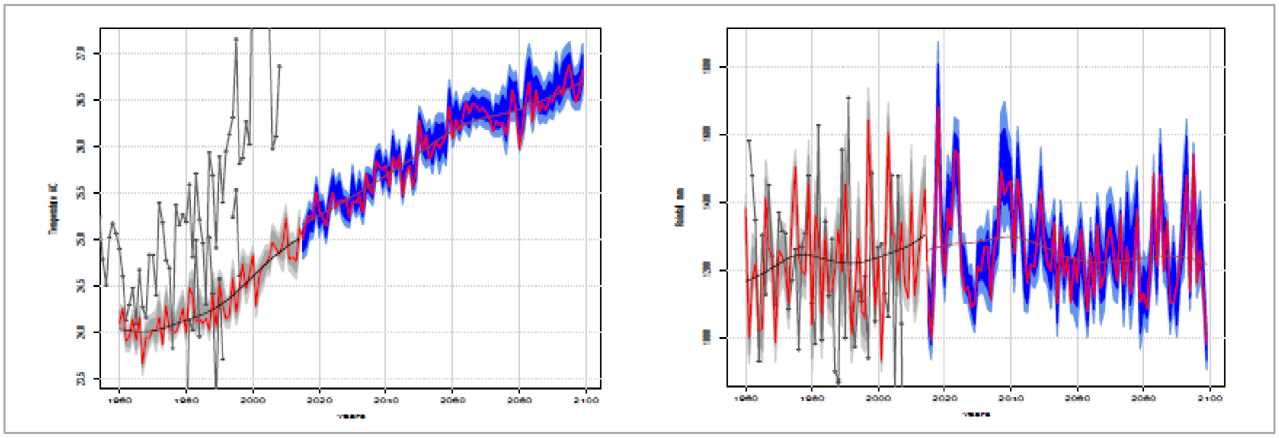
Impacts of Climate Change on the Lufubu River Basin: Figure 12 shows historical and projected maximum temperature and rainfall in Lufubu Basin. Even though rainfall is projected to decrease, the decrease is marginal under both the RCP 4.5 and RCP 8.5 and not as much as in other river basins. The conclusion could as well be that the rainfall remains the same for the basin. However, maximum temperature will increase in similar manner to the other basins (Figure 12).

Table 14. Current and Future Available Water Resources in the Luapula River Basin

	Water Resources (km^3)			
RCP	Current	2030	2050	2080
4.5	26	25	25.5	25.2
8.5	26	25.5	25.1	24.9

Source: Authors.

Figure 12. Historical and Future Maximum Temperature and Rainfall for Lufubu River Basin



Source: Authors.

Figure notes: The gray part is the historical period and the blue part is the projected values. The black dots are observed values while   red lines are median values with levels of gray and blue indicating the confidence intervals.

Further results of projected changes in temperature and rainfall for the Lufubu River Basin are shown in Tables 15 and 16. Again, the main story is somewhat preserved: rainfall is projected to decrease towards the end of the rainy season (December to April) but will increase towards the beginning of the season (October to November), while temperature will increase from present times on wards towards the end of the century under RCP 4.5.

Table 15. Future Changes in Maximum Temperature in the Lufubu Basin Relative to the 1960 - 2000 Historical Averages (°C)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	2030	1.2	0.1	0.9	1.7	1.9	0.3	-1.3	-0.1	2.4	3.9	3.5	1.2
	2050	1.7	0.7	1.2	2.3	2.6	1.1	-0.5	0.7	3	4.7	4.4	1.9
	2080	2	0.9	1.6	2.7	3.1	1.5	-0.1	1	3.4	4.9	4.5	2.1
RCP 8.5	2030	1.6	0.4	1.3	2.2	2.6	1	-0.6	0.6	3	4.4	3.9	1.6
	2050	2.5	1.4	2.1	3.3	3.8	2.3	0.6	1.8	4.2	5.8	5.4	2.9
	2080	4	2.7	3.4	4.6	5.2	3.8	2.1	3.4	5.8	7.3	6.8	4.2

Source: Authors.

Table 16. Percentage Changes In Future Rainfall in the Lufubu Basin Relative to the 1960-2000 Historical Averages (°C)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	2030	-4	-4	-9	15	13	-8	-7	0	-2	17	3	-8
	2050	-11	-11	-23	19	5	1	-2	6	-1	12	5	-12
	2080	-6	-7	-16	8	17	2	-1	3	-12	10	5	-7
RCP 8.5	2030	-5	-4	-8	9	-3	-2	0	-6	-13	-6	3	-9
	2050	-10	-8	-23	10	-2	-11	0	-14	-7	-6	2	-14
	2080	-12	-10	-18	5	0	-3	-2	0	-7	-9	2	-15

Source: Authors.

As was the case with the Luapula River Basin, the Lufubu River Basin is located in the high rainfall areas of the country and projected climate change will have less impact on water resource availability. Moreover, Lufubu Basin is small relative to other basins. Marginal changes in the water levels in the basin will have no or limited impact over the water resources flowing into the Tanganyika and the country at large (Table17).

Our foregoing results suggesting that Zambia will experience a reduction in rainfall and an increase in temperature are in line with previous literature. For example, IPCC projections suggest that there will be reduced rainfall and runoff in the southern Africa and sub Saharan Africa (Bates et al. 2008) and several other studies come to similar conclusions for the region (African Development Bank 2010; Beilfuss 2012; Hamududu 2012). We add to this burgeoning literature by explicitly localizing these projections at river basin level and show that there will significant differences across the different regions of Zambia.

Table 17. Current and Future Available Water Resources in the Lufubu River Basin

	Water Resources (km3)			
RCP	Current	2030	2050	2080
4.5	0.4	0.4	0.4	0.4
8.5	0.4	0.4	0.4	0.4

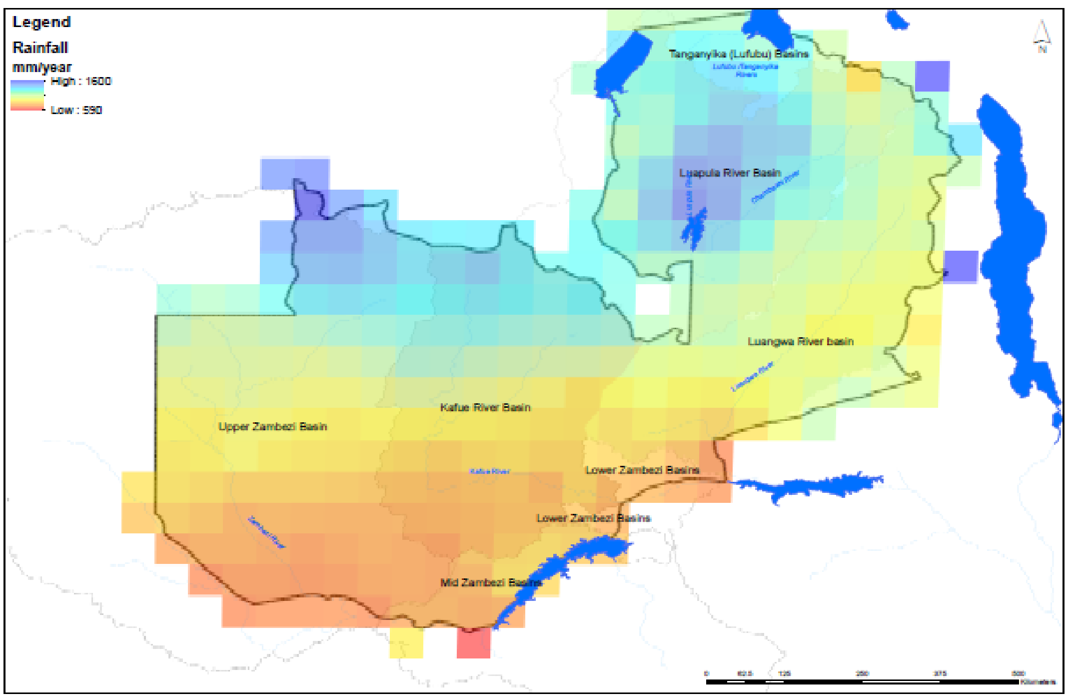
Source: Authors.

5. PROJECTED CLIMATE CHANGE AND IMPACTS ON WATER RESOURCE AVAILABILITY IN ZAMBIA

While the preceding section has presented the projected changes in climate and impacts on water availability at river basin level, this section presents indicative national level estimates. These are aggregated averages across all the main river basins in Zambia. The spatial distribution of rainfall has changed from the historical reference period of 1960 - 2000s and the present, and it is projected to change even further by mid- to end of the century. Compared to the past (Figure 13), Zambia is projected to be drier with significantly less rainfall in the southern, eastern and western parts of the country (Figure 14) by mid-century (ca. 2050). The northern parts will be less affected with positive gains in some areas.

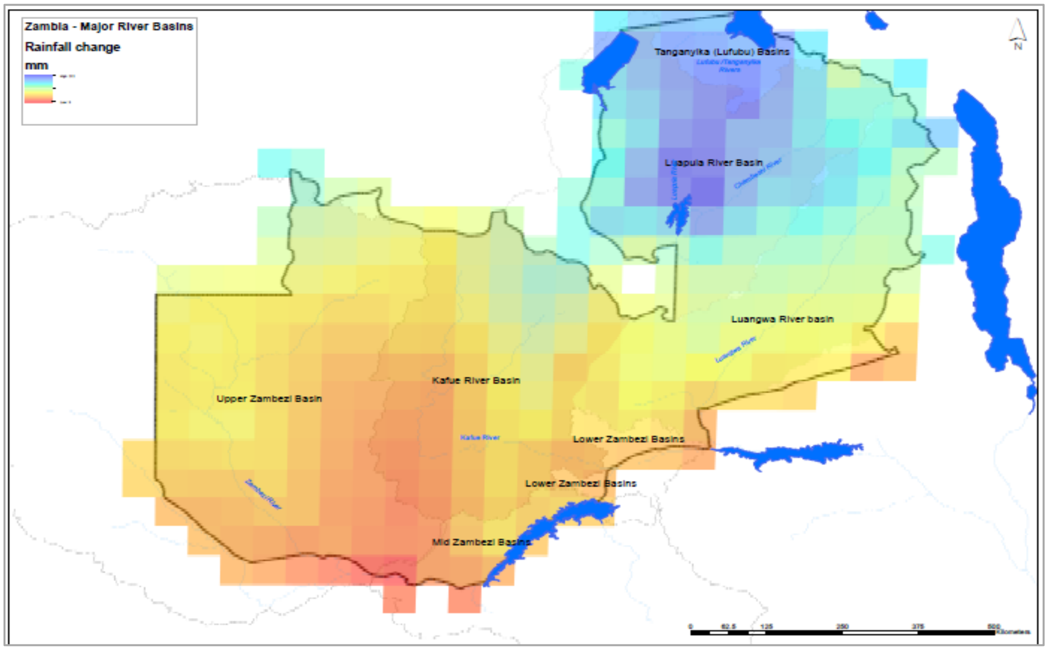
In terms of temporal distribution, the changes in rainy season shows that the rainfall reduces at the beginning of the season, meaning that, the rainy season is slightly delayed. However, it also shows that there is a slight increase at the end of the rainy season i.e., the last months (March and April) of rainy season show an increase in rainfall amounts. That is, there is a projected general delay of the rainy season.

Figure 13. Spatial Distribution of the Historical Average Rainfall from 1961 to 1990 in Zambia



Source: Authors.

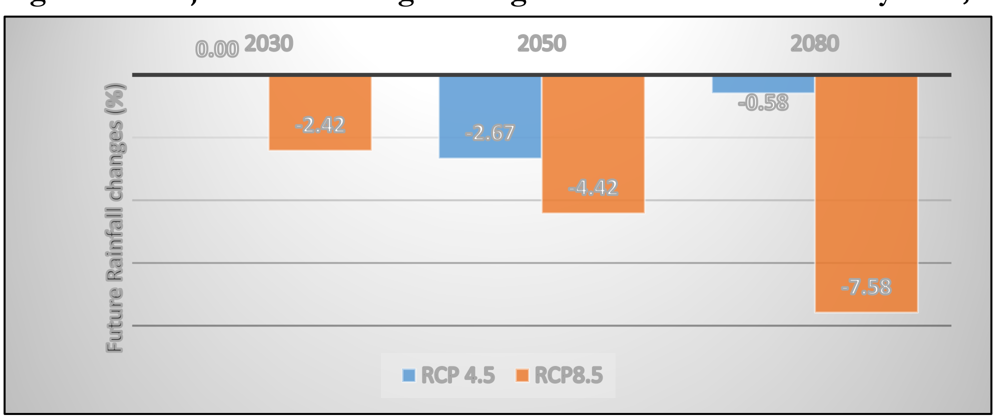
Figure 14. Spatial Distribution of the Projected Rainfall Changes by Mid-Century (2050) in Zambia



Source: Authors.
Figure notes: The changes in rainfall were computed as differences between projected climate output variables from Global Circulation Models (GCM) and long-term averages over the observed historical reference period 1960 - 2000 (Figure 3).

Figures 15 and 16 summarize the average changes in rainfall and temperatures over the next three 30- year periods until the end of the century under both RCP 4.5 and RCP 8.5 scenarios at national level. Under the more optimistic RCP 4.5, rainfall will reduce by about 3% by mid-century and only marginally by about 0.6% towards the end of the century. As expected, the projected reduction is higher under the more pessimistic RCP 8.5 scenario. Figure 14 shows the spatial distribution of the projected changes in rainfall in Zambia.

Figure 15. Projected Percentage Changes in Rainfall in Zambia by 2030, 2050, and 2080

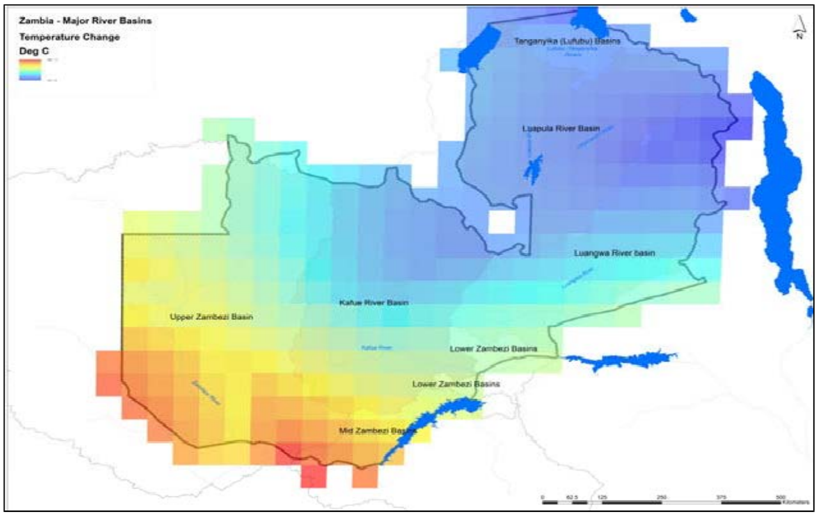


Source: Authors.
Figure notes: These are aggregate average changes for the 30-year periods 2030 (2020 - 2050), 2050 (2050-2070) and 2080 (2080 - 2100).

Temperature is projected to increase by 1.2° C in the next 30 years, reaching 1.9°C and 2.3°C by 2050 and 2100, respectively (Figure 16). Figure 17 shows the spatial distribution of the projected temperature changes.

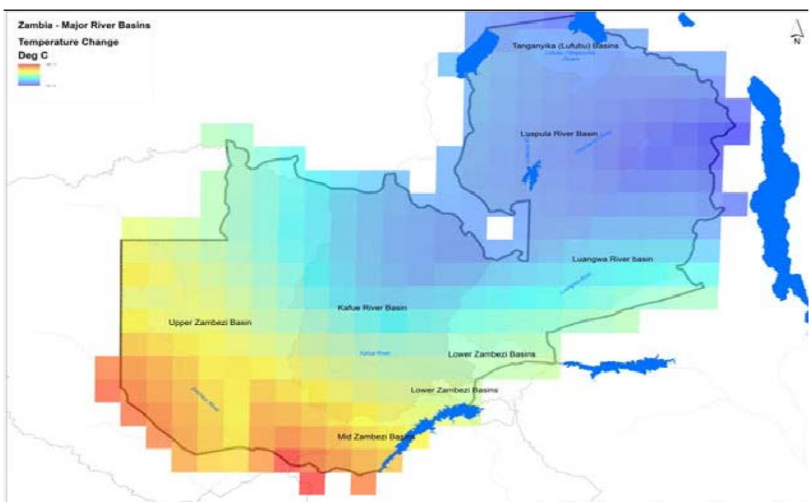
The projected changes in climate (rainfall and temperature) will directly affect water resources availability in the future. Figure 18 shows the aggregate changes in water resource availability in the future, while Table 18 presents the same results at basin level. The overall result indicates that water availability is likely to reduce by about 13% from current (observed) levels of about 97 km^3 to about 84 km^3 by the end of the century in Zambia.

Figure 16. Projected Changes in Maximum Temperature in Zambia by 2030, 2050, and 2080



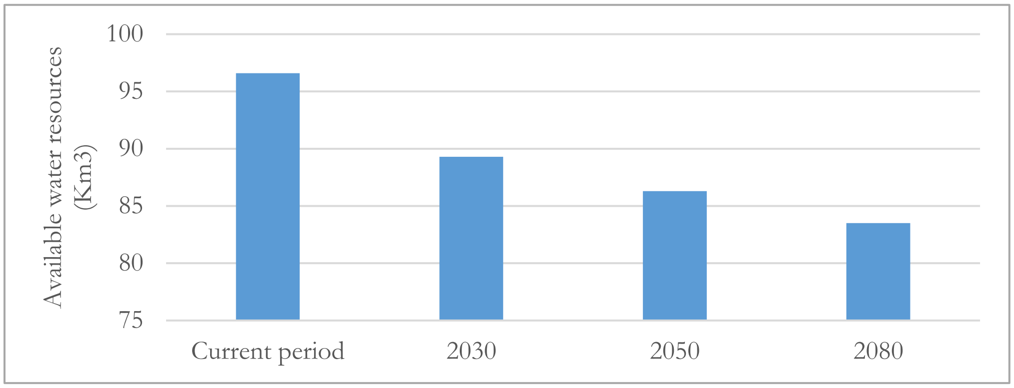
Source: Authors.
Figure notes: These are aggregate average changes for the 30-year periods 2030 (2020 - 2050), 2050 (2050-2070) and 2080 (2080 - 2100).

Figure 17. Projected Changes in Maximum Temperature by 2050 in Zambia (°C)



Source: Authors.
Figure notes: The changes in temperature were computed as differences between projected temperature from Global Circulation Models (GCM) and long-term averages over the observed historical reference period 1960 - 2000.

Figure 18. Projected Water Resources Availability in Zambia (km^3)



Source: Authors.

Figure notes: The values in this figure are aggregates of the projected water resource availability in all the basins in Zambia in future 30-year periods 2030 (2020-2050), 2050 (2050-2070) and 2080 (2080 - 2100).

Table 18. Water Resources Availability in Zambia (km^3)

	Zambezi River, Victoria Falls	Zambezi Lower, Kariba	Kafue River, Kasaka	Luangwa River, Road Bridge	Zambezi Lower, Chirundu	Luapula River, Chembe	Chambeshi River, Pontoon	Lufubu River
current	32.3	6.6	22.3	15	3.5	16.5	5.5	0.4
2030	30.7	6	19.6	13.5	3	16.1	5.5	0.4
2050	29.4	5.8	19.2	12.7	3	15.8	5.4	0.4
2080	28.7	5.4	18.8	12.1	2.8	15.3	5.4	0.4

Source: Authors.

The foregoing national level results mask differences at the sub-national levels. At basin level, the northern basins are likely to stay the same or experience slight increases in rainfall. This will see these basins maintain or slightly increase the annual amount of runoff in the rivers. However, the southern and western river basins show a different situation. The Zambezi, Kafue, and Luangwa basins are all projected to experience reduced rainfall and higher temperatures. This will result in increased evaporation and is likely to reduce river runoff. This in turn would lead to reduced available water resources. Moreover, projected high temperatures would result in heavy losses in water stored in reservoirs, further reducing the effectiveness of storage in these parts of the country. The foregoing discussion leaves one unanswered key question: is it feasible to move the abundant water resources in the north to the south?

6. LIMITATIONS

With a study of this nature, it is worth to note that there are uncertainties associated with the values obtained throughout the entire process. The main source of uncertainty is the input data. While all care was taken in collection of these observations, it is still very plausible that there are errors associated with the data collection process itself.

Such errors could result from the instruments used in data collection and any computations/processing carried out. For example, the river flows are measured as water levels (depth of water in the river) and later an equation—a rating curve—is used to obtain the corresponding discharge. Any hydrologist can tell how accurate this computation is.

As if this was good enough, the observed data with its uncertainty is then put through a hydrological model, another further approximation, further increasing the uncertainties. While this is very true, it important to note that these methods are used and have been used for making important decisions in water resources management the world over. Even though uncertainties remain thorny, the process gives indications of the likely values used for policy making. Coupled with experience, these values though full of uncertainties remain the most important pieces of decision making process.

7. CONCLUSION AND POLICY IMPLICATIONS

Coordinated development and management of water resources is important for current and future socioeconomic development. To do this properly requires a good understanding of the current and future availability of water resources: how much water is available, where is it available and when?

This paper assessed the spatial and temporal distribution of water resources and the impacts of projected climate change on water resource availability in Zambia at national and sub-national level. Using a water balance model in a hydrological modelling framework and statistical downscaling of future climate scenarios from the Intergovernmental Panel on Climate Change, the paper simulated the impacts of climate change on water availability in Zambia's main river basins from current periods until the end of the century in 2100. The following are the key results:

Temperature is projected to increase by 1.9o C and 2.3o C by 2050 and 2100, respectively, in Zambia. Rainfall is projected to decrease by about 3% by mid-century and only marginally by about 0.6% towards the end of the century across the country. The southern, western, and eastern parts will be much more affected compared to the northern region.

On aggregate, the changes in rainfall and temperature will reduce water availability by about 13% from current (observed) levels of about 97 km3 to about 84 km3 by the end of the century.

At basin level, the northern basins are likely to stay the same or experience slight increases in water resources. However, river basins in the eastern, southern, and western parts such as Zambezi, Kafue, and Luangwa are all projected to have less water resources available due to reduced rainfall and higher temperatures. Projected high temperatures in this region will result in high water loses from reservoirs. These results leave one key question unanswered: is it feasible to move the abundant water resources in the north to the south where demand is high?

We conjecture the following implications on smallholder irrigation development in Zambia:

- Current and future smallholder irrigation schemes will need to adopt more water efficient technologies such as overhead irrigation systems (e.g., center pivots and drip irrigation) as opposed to the prevalent surface irrigation methods. It is vital to understand the cost implications of such a switch to more water efficient technologies.

- Reduced water availability will increase access and irrigation costs, which in turn may reduce its profitability among smallholder farmers, as they tend to have limited capital and capacity to adapt to higher cost structures.

- Competition for the reduced available water resources will disadvantage the smallholder farmers. Policies to protect them against the large scale users are required.

- Management, regulation and monitoring of water use needs to be strengthened, for example by ensuring that water user rights and fees become mandatory and are enforced, and the process of acquiring water rights transparent.

- There is need to improve rain water harvesting and storage by investing in more reservoirs. How these reservoirs should be managed to ensure equitable access to water resources and to reduce water loss due evapotranspiration requires further thought.

- There is need for continuous monitoring of the water resources to track both the quantities and quality and assess suitability for irrigation.

- Generally, there is lack of data. Climate and water resources data have a lot of gaps. There is need for systematic collection of irrigation and other water use data for better analysis.

- There is need for feasibility studies on whether it is viable to transfer water resources from low-demand surplus areas in the north to high-demand deficit areas in the southern parts of the country.

APPENDIX: ADDITIONAL OUTPUTS

Table A1. Flow Characteristics of Main Rivers at Selected Gauging Stations in Zambia

River Basin	Zambezi	Kafue	Luangwa	Chambeshi	Luapula	Tanganyika
Area total *(km^2)*	687,049	156,995	147,622	44,427	173,396	15,856
Area Outside ZMB *(km^2)*	418,814	0	3,264	0	60,073	-
Gauging station *(km^2)*	513,780	96,239	140,922	34,745	161,275	9,027
Gauging station name	Victoria Falls	Hook Bridge	Road Bridge	Pontoon	Kashiba	Keso Falls
Monthly mean *(m^3/s)*						
October	336	66	56	40	237	17
November	354	70	67	40	195	20
December	507	142	424	75	265	41
January	777	338	1,320	170	536	77
February	1,200	619	1,920	307	1,000	112
March	1,900	774	1,860	461	1,700	161
April	2,700	709	1,120	471	1,700	149
May	2,500	428	420	294	1,200	77
June	1,700	229	214	155	931	48
July	919	147	146	96	712	34
August	579	113	104	68	488	25
September	423	86	73	51	323	19
Flow summary - *(m^3/s)*						
Maximum	3,200	1,100	4,250	582	2,000	301
High	1,700	469	849	280	1,000	89
Normal	777	173	202	108	606	41
Low	449	95	87	55	294	23
Drought	316	55	39	35	190	15
Minimum	298	49	36	33	174	14
Average	1,189	308	639	185	741	66
Runoff depth - *mm*	119	101	139	168	161	221
Rainfall -*mm*	-	1,184	877	1,323	1,167	1,141
Runoff percent - %	-	8.8	16.7	12.7	13.8	19.4

Table A2. List of Global Circulation Models (GCM) Used in the Analysis

Model name	Full name	Centre	Country
bcc_csm1_1_m	Beijing Climate Center Climate System Model	Beijing Climate Center (BCC)	China
ccsm4	Community Climate System Model	University Corporation for Atmospheric Research (UCAR)	USA
cesm1_ cam5	Community Earth System Model	National Center for Atmospheric Research (NCAR)	USA
csiro_mk3_6_0	Commonwealth Scientific and Industrial Research Org.	CSIRO Climate Science Centre	Australia
gfdl_cm3	Geophysical Fluid Dynamics Laboratory (GFDL)	NOAA	USA
gfdl_esm2m	Geophysical Fluid Dynamics Laboratory (GFDL)	NOAA	USA
giss_e2_h	Goddard Institute for Space Studies (GISS)	NASA's Goddard Space Flight Center	USA
giss_e2_r	Goddard Institute for Space Studies (GISS)	NASA's Goddard Space Flight Center	USA
ipsl_cm5a_mr	Institut Pierre Simon Laplace	Climate Modelling Center	France
miroc_esm	Model for Interdisciplinary Research on Climate	Center for Climate System Research	Japan
miroc_esm_che m	Model for Interdisciplinary Research on Climate	Center for Climate System Research, Tokyo	Japan
miroc5	Model for Interdisciplinary Research on Climate	Center for Climate System Research	Japan
mri_cgcm3	Meteorological Research Institute (MRI)	Meteorological Research Institute	Japan
noresm1_m	Norwegian Climate Center's Earth System Model	Bjerknes Centre for Climate Research	Norway

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