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Impacts of climate change on water resources availability in Zambia: implications for irrigation development

Byman H. Hamududu[1] · **Hambulo Ngoma**[2,3]

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Abstract

The Zambian economy is predominantly based on exploitation of its natural resources. The water resources in particular are important for the socioeconomic development of the country. Managing 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 study assesses the spatial and temporal distribution of water resources and the impacts of projected climate change on water resource availability in Zambia. The study employs statistical downscaling of future climate scenarios and a water balance model in a hydrological modeling framework to assess the impacts of climate change on water availability. Unlike past studies done at national, regional or global levels, analysis in this study was done at the local river basin level. The main results indicate that temperature is projected to increase by 1.9 °C and 2.3 °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% toward the end of the century across the country. These changes in rainfall and temperature will decrease water availability by 13% by the end of the century in 2100 at national level. At the river basin level, the northern basins are projected to stay the same or experience slight gains in water resources compared to those in the southern and western parts of Zambia where reductions up to 9% are projected. In particular, Zambezi, Kafue and Luangwa River basins are projected to have less water resources available due to reduced rainfall and higher temperatures. Two main implications for irrigation development follow in Zambia. More water-efficient irrigation technologies are needed and water resources will need to be better managed and regulated to cope with the projected water stresses due to climate change.

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✉ Hambulo Ngoma
hambulo.n@gmail.com

[1] Norwegian Water Resources and Energy Directorate, Middelthuns gate 29, 0368 Oslo, Norway

[2] Indaba Agricultural Policy Research Institute (IAPRI), 26A Middle Way Road, Kabulonga, Lusaka, Zambia

[3] Department of Agricultural, Food and Resource Economics, Michigan State University, 446 West Circle Drive, East Lansing, MI 48824-1039, USA

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1 Introduction

The impacts of climate change on livelihoods are larger for rural households that depend on rainfed agriculture. Dependence on rainfed agriculture exposes rural households and makes them vulnerable to climate shocks such as floods and droughts (Hallegatte et al. 2016; Niang et al. 2014). Smallholder rainfed farming systems in sub-Saharan Africa (SSA) and Zambia in particular are prime examples. Over 90% of smallholder agriculture is rainfed in Zambia (Wineman and Crawford 2017). This, coupled with low capacities to adapt and cope with climate shocks, makes 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). It affects crop production and therefore agricultural incomes and food security, asset acquisition and returns on assets. More subtly, climate change affects output prices, wages, off-farm and alternative livelihood opportunities, health and nutrition outcomes, and food systems (Niang et al. 2014; Olsson et al. 2014; Porter et al. 2014; Serdeczny et al. 2017).

Rainfed farming systems in SSA need to transform in order to respond to increasing climate shocks, while raising agricultural productivity to meet rising food demands. Smallholder irrigation is widely considered part of the solution to this challenge (Niang et al. 2014). Irrigation facilitates all-year-round production, better water management and agricultural intensification, and it was central in the success of the Asian Green Revolution (Binswanger-Mkhize and Savastano 2017; Boserup 1965; Koundouri et al. 2006). Combined, these factors imply that irrigation if widely adopted has the potential to increase household incomes and build the resilience of smallholder farming systems to rainfall variability and other climate shocks.

Irrigation development is necessary to the global sustainable development agenda and in particular in the attainment of Sustainable Development Goal number six, which aims to ensure that water is available and sustainably managed for all. Irrigation is part of the Comprehensive African Agriculture Development Program (CAADP) at the regional level. Irrigation is also part of the Southern African Development Cooperation (SADC) regional agricultural policy, which among other things targeted to increase area under irrigation to 7% of arable land by 2015, improve agricultural water management and build water infrastructure (Akayombokwa et al. 2015).

In Zambia, irrigation is promoted as a means to build the resilience of farmers to, and as an adaptation option to climate change, and for agricultural development. Irrigation is a key strategy highlighted in the Second National Agricultural Policy (SNAP), the National Agricultural Extension and Advisory Services Strategy (NAEASS), the National Investment Plan (NAIP) and the Seventh National Development Plan (7NDP) (GRZ 2004, 2013, 2016a, b, c, 2017).

The National Irrigation Policy and Strategy of 2004 whose objective is “a well-regulated and profitable irrigation sector that is attractive to both private investors and Zambia’s development partners” provides overall policy guidance for irrigation development in the country. Among other things, the policy aims to remove constraints for existing irrigators and encourages new private investments. Unlike developed countries such as Mexico (Rap 2006), where irrigation is decentralized, commercialized and led by the private sector, the main policy thrust in Zambia still hinges on building irrigation infrastructure, which is then handed over to small-scale farmers (Akayombokwa et al. 2015). This is unsustainable. Not only are such investments in irrigation costly to government, they do not take into account the likely impacts of climate change on water availability and, accordingly, adapt the types of irrigation technologies promoted among smallholder farmers.

1.1 The problem

Despite having nearly 2.75 million hectares (ha) of irrigable land and holding an estimated 45–60% of surface and underground water supplies in southern Africa, irrigation remains low in Zambia. Only 6% or 155,000 ha of the 2.75 million ha of irrigable land is irrigated (GRZ 2013). Irrigation among smallholder farmers is largely informal and applied mainly for fruits and vegetables grown in close proximity to water sources. Ngoma et al. (2017) show that irrigation is used by nearly 16% of smallholders for fruits and vegetables and only by about 1% for field crops in Zambia. 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, water availability and its subsequent use may not be guaranteed in Zambia because most of the major river systems are shared watercourses with riparian countries. Moreover, the lack of data on availability and distribution of water resources, and on the likely impacts of climate change on these aspects at subnational level can impede irrigation development.

Most studies on the impacts of climate change on agriculture or water resources/hydropower generation have been carried out at relatively low spatial resolutions, such as national and regional levels (see Hachigonta et al. 2013; Hamududu and Killingtveit 2012, 2016; Niang et al. 2014; Schlenker and Lobell 2010; Serdeczny et al. 2017). While useful, such analysis may be too coarse (generalized impacts) to guide subnational decision making. This study contributes toward addressing this gap and responds to the call in the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) for more research on the impacts of climate change on water resources. The study aims to quantify the impacts of climate change on water availability at subnational level and draw implications for irrigation development in Zambia. It applies a water balance model in a hydrological modeling framework to assess the spatial and temporal distribution of water resources and uses 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 (Bank 2010; Bates et al. 2008; Beilfuss 2012; Hamududu and Killingtveit 2012; Serdeczny et al. 2017; Ebinger and Vergara 2011) and does the analysis at the river basin level in order to capture salient subnational differences.

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

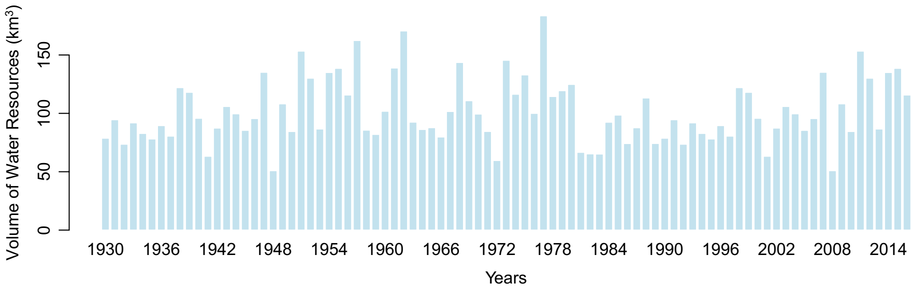

Fig. 1 Available annual water resources in Zambia, 1930–2015. *Note*: Figure was created in R using river flow and rainfall data from various sources. *Source*: Authors

2 Background on climate and water resources distribution in Zambia

Covering some 752,610 km^2 in southern Africa, Zambia is largely a plateau with an average elevation of 1138 meters above sea level (masl). The country has a unimodal rainy season influenced by the location of the Inter-Tropical Convergence Zone and has an uneven rainfall distribution. Rainy seasons span November to April annually with average rainfall of more than 1000 mm in the high-rainfall areas in the north and less than 800 mm in the south. Zambia has high seasonal rainfall variability, creating additional water supply problems. For example, there was reduced water availability in drought years of 1972, 1982, 1992, 1995, 2001 and 2008 (Fig. 1). This has implications on food security and on efforts to reduce poverty and buttresses the need to improve water resources management in Zambia as highlighted in the 2016 National Policy on Climate Change.

Zambia is drained by two major river systems: the Zambezi and Congo River Basins. The Zambezi basin covers about 77% 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 1,359,000 km^2, making it the largest of the African river systems flowing into the Indian ocean. The total area of the Kafue River basin is estimated to be 156,340 km^2 with a total length of around 1300 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. The Luangwa river basin covers an estimated 145,690 km^2.

Table 1 presents summary statistics for Zambia's major rivers basins, showing basin size, proportion of the basin that is in Zambia, length of rivers found in the basins and runoff.

The Luapula and the Chambeshi rivers feed the Congo River in the north, which flows northward (Fig. 2). 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 Lake Tanganyika but the Lufubu River is the main river that drains much of Zambia into the lake. The Lufubu basin is also known as Lake Tanganyika basin. The Chambeshi River is another major river of the Congo basin in Zambia.

Temperatures in Zambia are highest, averaging above 25 °C between August and October in the dry season. This period is associated with increased water scarcity due to evapotranspiration. It is cooler from May through July with temperatures averaging about 18 °C.

Table 1 Zambia's main river basins: size, proportion in Zambia and runoff. *Source*: Authors

Main basin	River	Basin size (km^2)	Basin in Zambia (%)	River length (km)	Mean annual runoff (m^3/s)	Runoff percent (%)
Zambezi	Zambezi	268,235	39	1700	1325	8
	Kafue	156,995	100	1300	315	9
	Luangwa	144,358	98	850	681	17
	Others	8658	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				

Table compiled using data from various sources

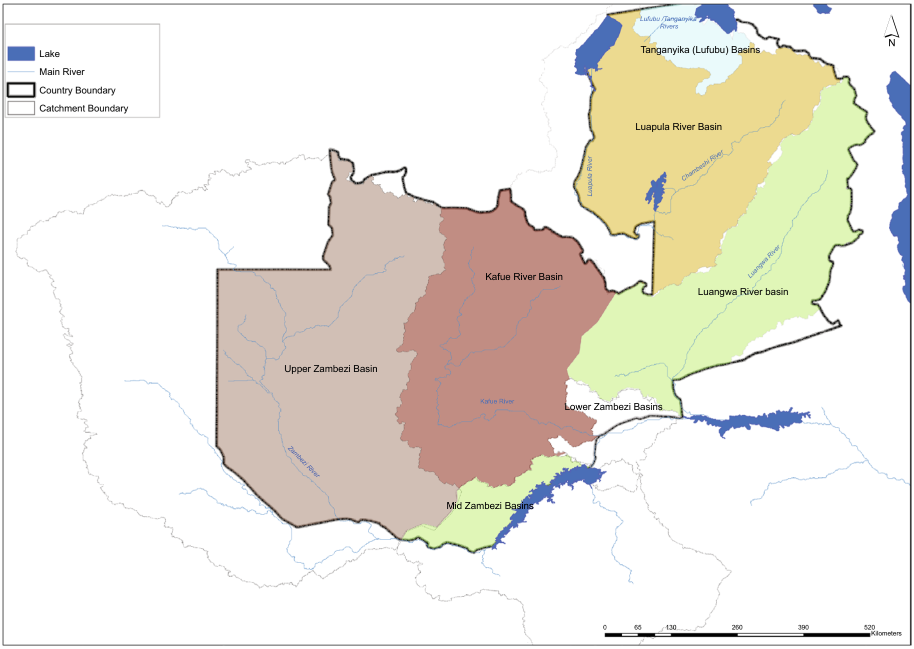

Fig. 2 The main river basins in Zambia. *Note*: Figure was compiled in *R* using data from Hydroshed (https://hydrosheds.cr.usgs.gov/dataavail.php, accessed November 2017). *Source*: Authors

3 Materials and methods

3.1 Data sources

The climate and river flow data used in the biophysical assessments were obtained from various sources. Observed river flow or discharge data for the five major basins for the period 1930–2016 were obtained from the Water Resources Management Authority

(WARMA) in Lusaka, Zambia. The WARMA data were supplemented with data from the Global Runoff 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 (50°S to 50°N) with a resolution of 0.05° (Funk et al. 2014).

This gridded data were downloaded and processed using the *R* software to extract data for each river basin for the period 1980–2015. Where necessary, data from the Zambian Meteorological Department were also used. Other spatial data products such as the World Bank climate portal and the Climate Research Unit at University of East Anglia were also used for climate data (Harris et al. 2014). Some data for comparison were obtained from the Climate Information Portal of the Climate Systems Analysis Group.[1]

3.2 Data analysis

Data analysis proceeded in two parts. In the first part, current (observed) rainfall and temperature data were used to calibrate a water balance model that was then used to compute water resource availability for the five main river basins in Zambia. In the second stage, future climate variables (temperature and rainfall) from General Circulation Models were used in the water balance model to compute water resource availability from current periods until end of the century in 2100.

3.2.1 Computing future river basin water resources

A water balance model was calibrated based on current climate and river flows. The main input data in a water balance model are temperature, rainfall and the georeferenced spatial location of the sites of interest, e.g., water basins in this case. Other important parameters used for model calibration, such as the runoff coefficient, direct runoff and soil moisture capacity, were obtained from secondary sources. The water balance model runs on a monthly time step, and the runoff is given out in millimeters. The resulting runoff was then compared to the observed discharge data in order to assess the accuracy of the calibrated model. The model was then applied on the projected climate data to simulate the future runoff for different river basins. The resulting runoff was then summarized on monthly basis and aggregated to annual values. Other output variables such as potential evaporation and soil moisture were computed in addition to runoff. Figure 3 shows a schematic overview of a typical water balance model.

The general water balance model used in computing runoff can be represented as:

$$\mathbf{Ro_u t} = \mathbf{Rn}_{\mathrm{b}} + \mathbf{Rn}_{\mathrm{lk}} - \mathbf{Evp}_{\mathrm{b+lk}} \pm \mathbf{Sto}_{\mathrm{lk}} \tag{1}$$

where $\mathbf{Ro_u t}$ is the outflow measured in the river draining the basin; $\mathbf{Rn}_{\mathrm{b}}$ is the total amount of rainfall received in the basin; $\mathbf{Rn}_{\mathrm{lk}}$ is rainfall received in reservoirs in the basin; $\mathbf{Evp}_{\mathrm{b+lk}}$ is the water lost through evaporation over the entire basin (evaporation from open water bodies, main reservoirs, vegetation, etc.); and $\mathbf{Sto}_{\mathrm{lk}}$ refers to changes in the reservoir and groundwater storage. Equation 1 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.

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

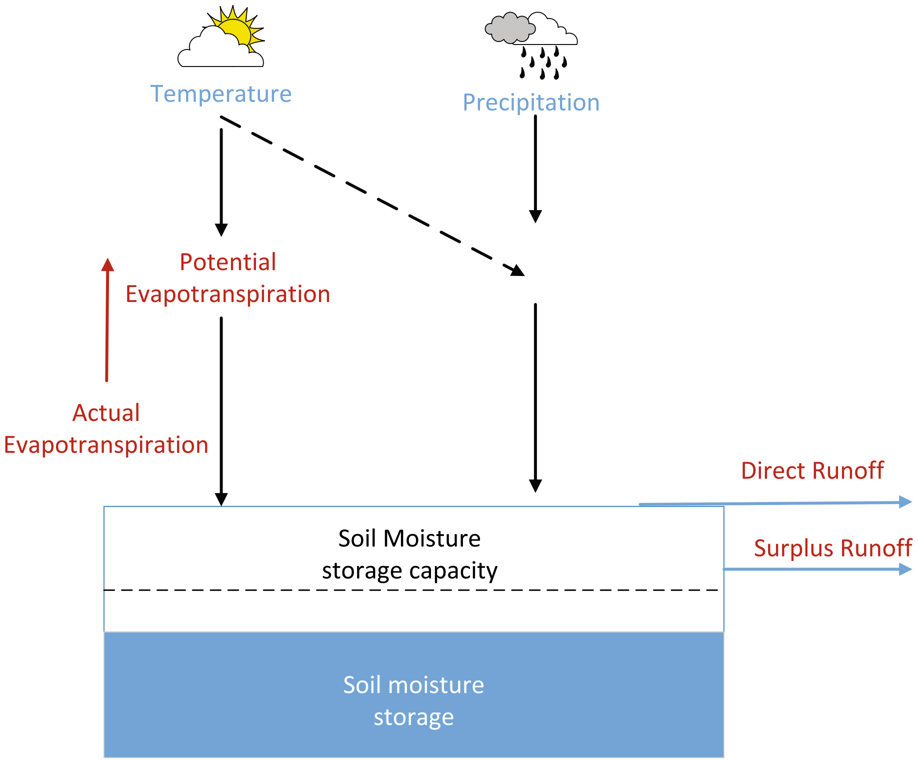

Fig. 3 Structure of the monthly water balance model. *Note*: Model inputs are shown in blue, while outputs are shown in red. Figure modified from McCabe and Mark (2010)

3.2.2 Computing the impacts of climate change on water resources

To estimate the impacts of climate change on water resources, statistical downscaling was used to compute the changes in future rainfall and temperature, and the resulting changes in water resources from current periods until end of the century in 2100.[2] Statistical downscaling uses the global circulation model (GCM) outputs from different future climate scenarios under varying representative concentration pathways (RCPs). 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). The emissions trajectories under different RCPs are shown in Fig. 4. RCPs were adopted by the IPCC AR5 in 2014.

Statistical downscaling develops a statistical regression between the local observed climate variables and projected future climate variables from the GCM models. Using this relationship, local future temperature and rainfall are then projected. Benestad (2011)

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[2] 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.

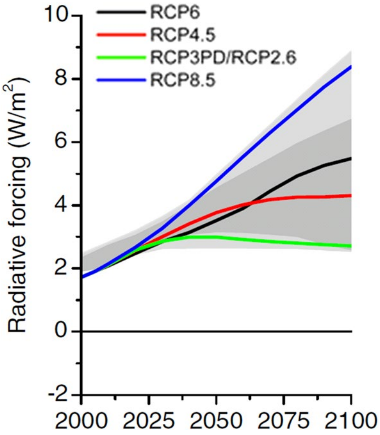

Fig. 4 Representative concentration pathways under AR5 of the intergovernmental panel on climate change. *Source*: Meinshausen et al. (2011)

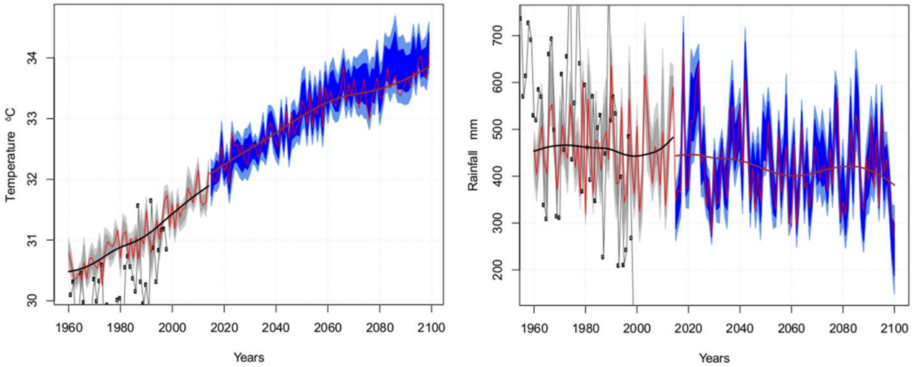

Fig. 5 Historical and future maximum temperature and rainfall for the Zambezi River basin. *Note*: Unless otherwise stated, this and the rest of similar figures on temperature and rainfall were created in *R* using historical and projected rainfall and temperature data. The gray part is the historical 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. *Source*: Authors

describes the statistical downscaling process in detail. Precipitation, temperature and pressure variables were selected for use as predictors for local rainfall and temperature. In total, 14 GCMs[3] and 2 RCPs[4] were used in the downscaling process. These GCMs were chosen on the basis that the projections agreed with no major contradictions and were consistent with each other. The GCM models used in this study are the common ones applied in the African setting, especially in SSA.

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[3] see Table A2 with list of GCMs.

[4] RCP4.5 and RCP8.5.

Table 2 Current and future available water resources in the Zambezi River basin. *Note*: Unless otherwise stated, 2030 represents the period 2020–2050, 2050 represents the period 2050–2070 and 2080 represents 2080–2100 for this table and the rest of similar tables on water resources availability. The table was compiled using data generated from observed and simulated water resources availability. RCP 4.5 is an optimistic climate scenario, where as RCP 8.5 is a pessimitc scnario which assumes that climate change will worsen. *Source*: Authors

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

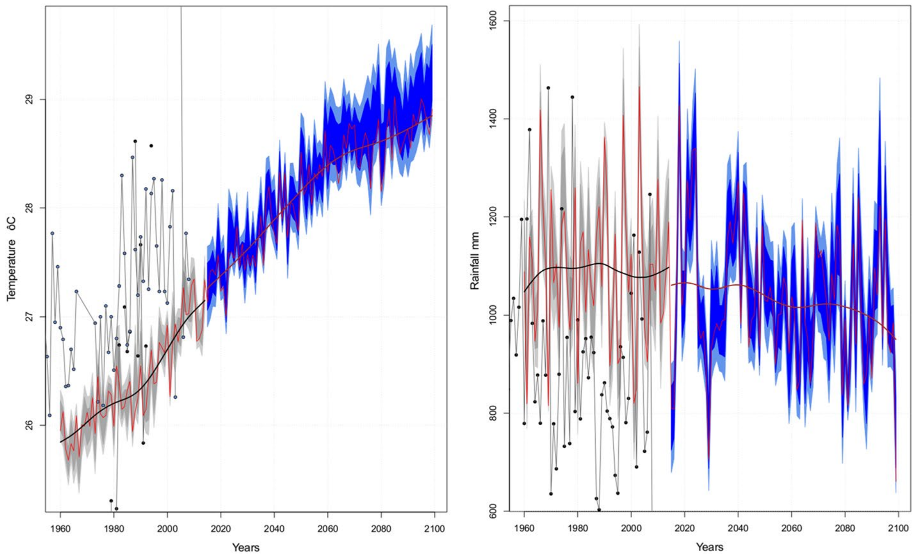

Fig. 6 Historical and future maximum temperature and rainfall for the Kafue River basin. *Source*: Authors

4 Results and discussion

4.1 Water resources availability at river basin level: past, present and future

Overall, results under the optimistic RCP 4.5 and a somewhat pessimistic RCP 8.5 climate scenarios indicate that temperature will rise, while rainfall will decrease in Zambia from present times until the end of the century in 2100. These results are in line with other findings (Bank 2010; Beilfuss 2012; Hamududu 2012; IPCC 2014; Kanyanga et al. 2013; Niang et al. 2014). This study also highlights differences in the magnitude of the changes for different basins that is not found in most current literature. In general, the projected changes will reduce the amount of water resources available in the future.

Table 3 Current and future available water resources in the Kafue River basin. *Source*: Authors

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

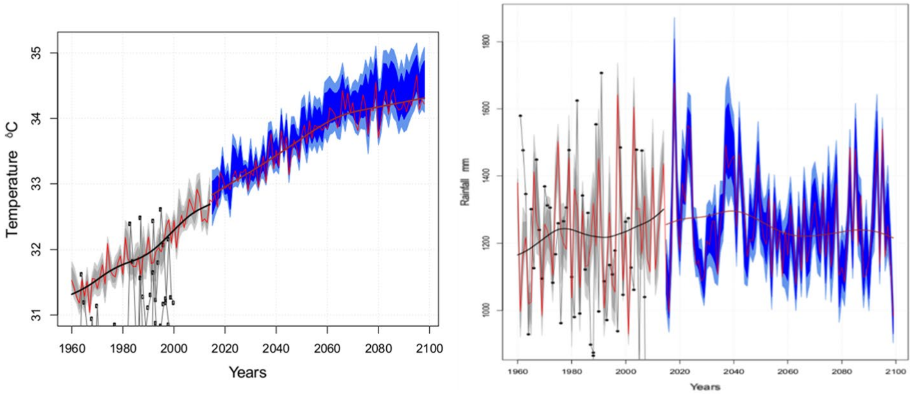

Fig. 7 Historical and future maximum temperature and rainfall for the Luangwa River basin. *Source*: Authors

Table 4 Current and future available water resources in the Luangwa River basin. *Source*: Authors

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

4.1.1 Impacts of climate change on the Zambezi River basin

Figure 5 presents the results on the historical and projected maximum temperature and rainfall in the Zambezi basin. As can be seen from the figure, temperature under RCP 4.5 will continue to increase through 2100 but at a reduced rate toward the end of the century, while rainfall is projected to decrease. The month-on-month changes in temperature and rainfall from present times through to 2100 given in supplementary tables (Tables S1–S2) show that the projected changes in temperature and rainfall are higher during the rainy seasons between November and March of every year.

Simulated results based on future climate change under RCP 4.5 indicate that there will be a 6.3% reduction in water resources available in the Zambezi basin from the current 48 km^3 to 45 km^3 toward the end of the century in 2100 (Table 2).

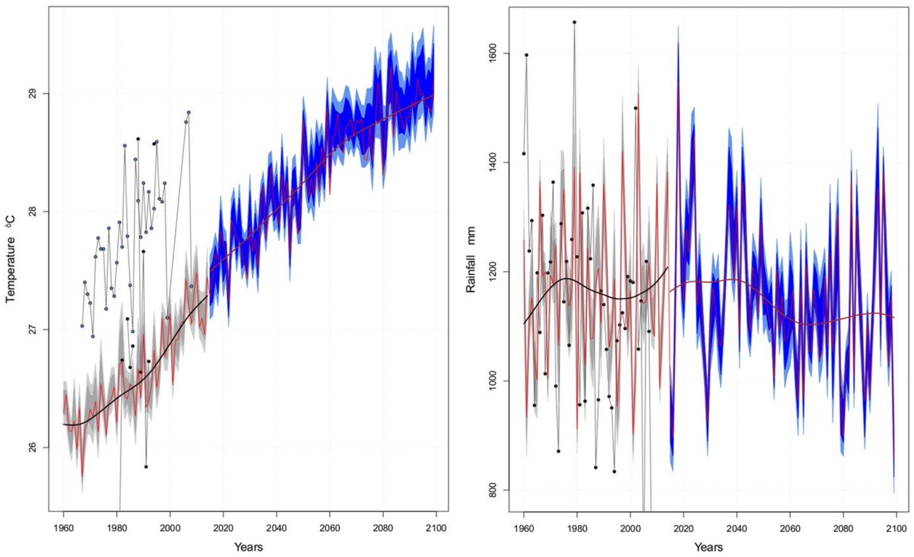

Fig. 8 Historical and future maximum temperature and rainfall for the Chambeshi–Luapula River basin. *Source*: Authors

Table 5 Current and future available water resources in the Chambeshi–Luapula River basin. *Source*: Authors

	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

4.1.2 Impacts of climate change on the Kafue River basin

Figure 6 shows that rainfall is projected to reduce, while temperature will increase in the Kafue River basin.

Based on projected climate data, results indicate that there will be a 9% reduction in water resources availability in the Kafue River basin compared to the 6% in the Zambezi River basin toward the end of the century (Table 3).

4.1.3 Impacts of climate change on the Luangwa River basin

Figure 7 shows the historical and future temperature and rainfall changes under RCP4.5 in the Luangwa basin. Average temperature is projected to increase, while rainfall will reduce.

Table 4 shows that there will be a 5% reduction (under RCP 4.5) in water resources availability in the Luangwa River basin toward the end of the century. The smaller reduction in available water resources in the basin 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.

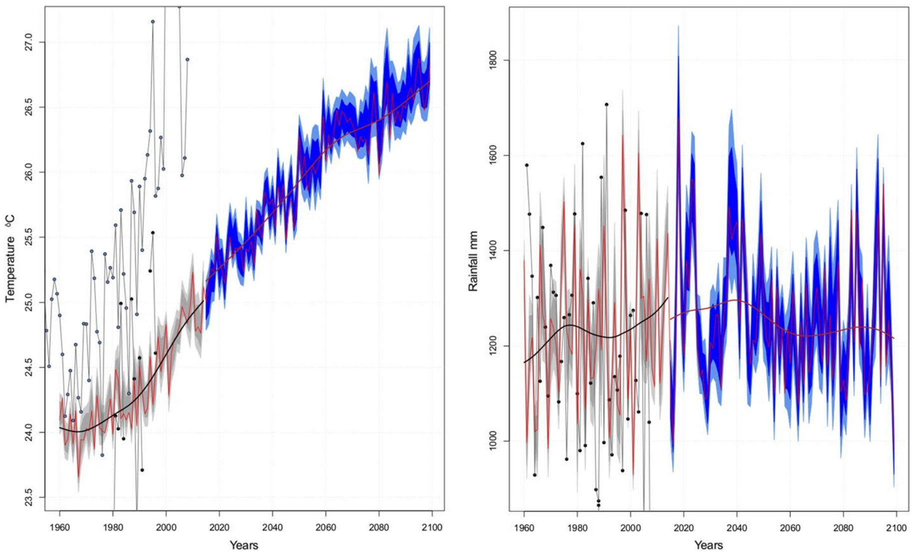

Fig. 9 Historical and future maximum temperature and rainfall for the Lufubu River basin. *Source*: Authors

Table 6 Current and future available water resources in the Lufubu River basin. *Source*: Authors

	Water resources (km^3)			
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

4.1.4 Impacts of climate change on the Chambeshi–Luapula River basin

As with other basins, rainfall is projected to reduce but maximum temperature is likely to increase in the Chambeshi–Luapula River basin (Fig. 8).

The total water resources in the Chambeshi–Luapula basin are projected to reduce by 3% by 2100 under RCP 4.5 (Table 5). This will be driven mainly by rising temperature which in turn will increase evapotranspiration from the vast water bodies in the basin. At 3% reduction in available water, climate change will have less impacts impacts on water availability in the Chambeshi–Luapula basin. Partly, this is because the basin has several reservoirs and because rainfall is projected to stay the same or slightly increase in the northern parts of Zambia. As such, the effects of high temperature on water resource availability will be moderated by good rains in the northern region. This shows and confirms that the water resources in the northern part of the country will nearly remain the same even with climate change.

4.1.5 Impacts of climate change on the Lufubu River basin

Figure 9 shows the historical and projected maximum temperature and rainfall in the Lufubu basin. Even though rainfall is projected to decrease, the decrease is marginal under

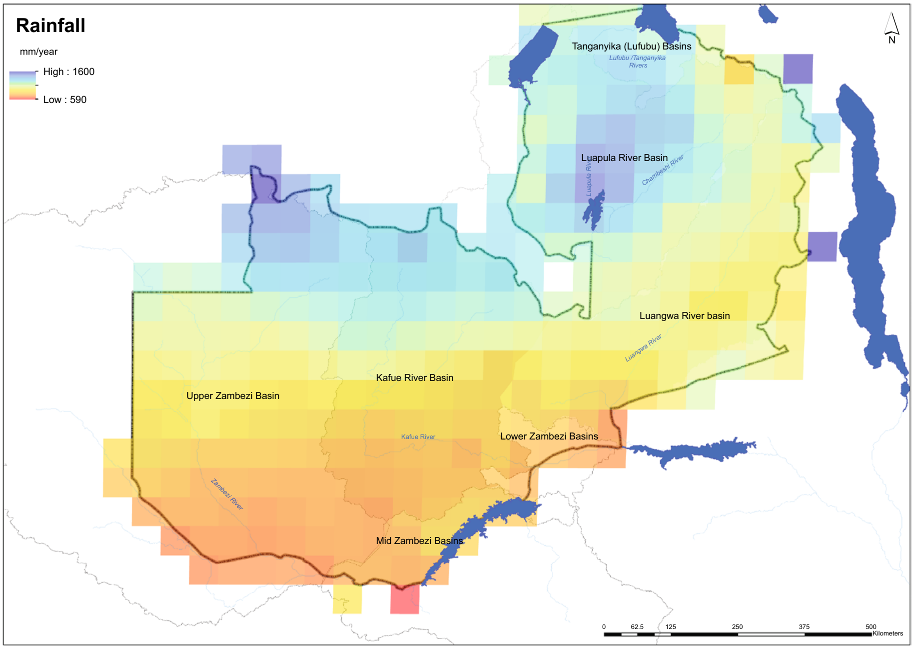

Fig. 10 Spatial distribution of the historical average rainfall from 1961 to 1990 in Zambia. *Note*: Figure was created in *R* using historical rainfall data. *Source*: Authors

RCP 4.5 and not as much as in other river basins. However, maximum temperature will increase in similar manner to the other basins.

The Lufubu River basin is located in the high-rainfall areas of the country. As such, climate change will have minimal impacts on water resource availability. In fact, Table 6 shows that water resources will remain unchanged in the Lufubu basin by the end of the century in 2100. Because the Lufubu basin is small relative to other basins, marginal changes in the water levels in the basin will have no or limited impacts over the water resources flowing into the Tanganyika and the country at large.

The foregoing results suggesting that Zambia will experience a reduction in rainfall and an increase in temperature are in line with the previous literature. This agrees with the IPCC's projections that there will be reduced rainfall and runoff in southern Africa and sub-Saharan Africa (Bates et al. 2008) and several other studies come to similar conclusions for the region (Bank 2010; Beilfuss 2012; CIAT and WorldBank 2017; Hamududu 2012; Kanyanga et al. 2013; Serdeczny et al. 2017). We add to this burgeoning literature by explicitly localizing these projections at river basin level and by showing that there will be significant differences across the different regions of Zambia. Further, results showing month-on-month changes in temperature and rainfall from present times through to 2100 for each basin are given in supplementary online materials (Tables S1–S9).

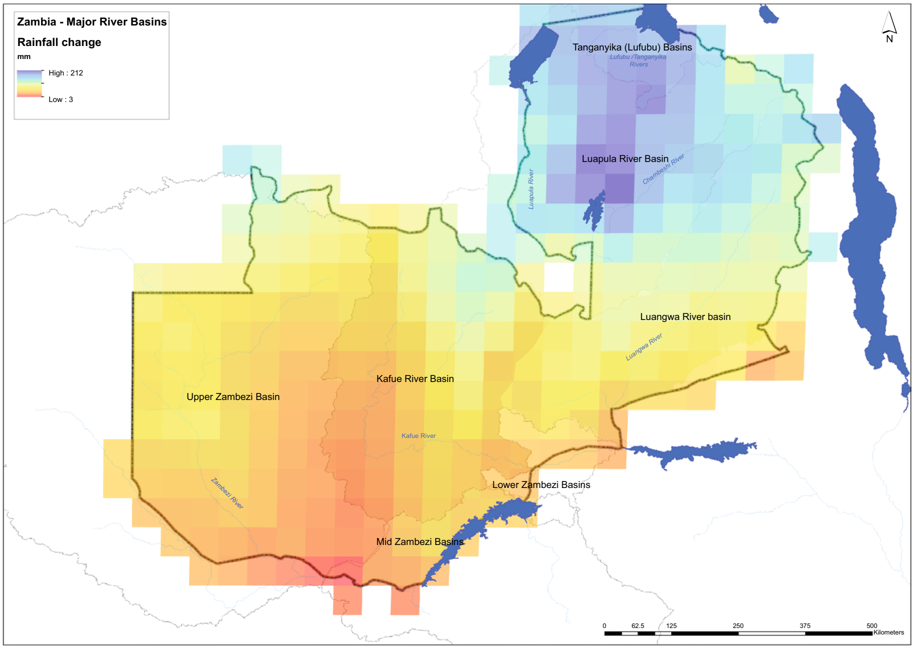

Fig. 11 Spatial distribution of the projected rainfall changes by mid-century (2050) in Zambia. *Note*: The changes in rainfall were computed as differences between projected climate output variables from global circulation models (GCM) and long-term averages over the observed historical reference period 1960–2000. *Source*: Authors

Fig. 12 Projected percentage changes in rainfall in Zambia by 2030, 2050 and 2080. *Note*: These are aggregate average changes for the 30-year periods 2030 (2020–2050), 2050 (2050–2070) and 2080 (2080–2100). The figure was created in Stata software. *Source*: Authors

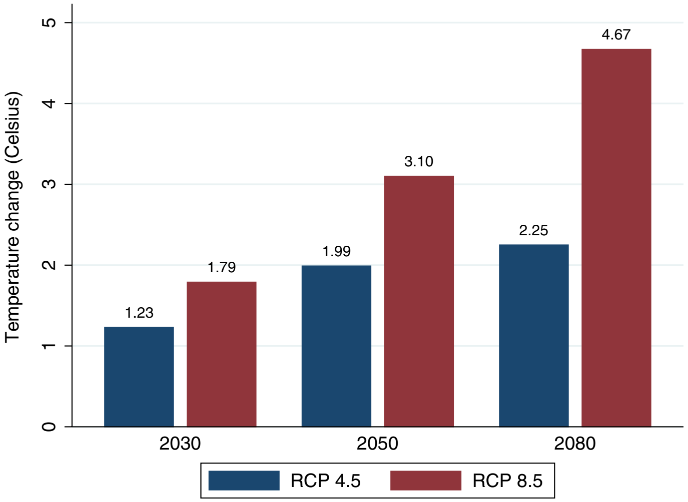

Fig. 13 Projected changes in maximum temperature in Zambia by 2030, 2050 and 2080. *Note*: These are aggregate average changes for the 30-year periods 2030 (2020–2050), 2050 (2050–2070) and 2080 (2080–2100). The figure was created in Stata software. *Source*: Authors

5 Impacts of climate change on water resource availability in Zambia

While the preceding section has presented the projected changes in climate and the impacts on water availability at river basin level, this section presents indicative national level estimates. These results are aggregated averages across all the main river basins in Zambia. The spatial distribution of rainfall has changed from the historical reference period in the 1960s–2000s and the present, and it is projected to change even further by mid- to end of the century in 2100. Compared to the past (Fig. 10), Zambia is projected to be drier with significantly less rainfall in the southern, eastern and western parts of the country (Fig. 11) by mid-century (ca. 2050). The northern parts will be less affected with positive gains in some areas.

At the temporal scale, rainfall will reduce at the beginning of the rainy season, thereby delaying the onset of the rainy seasons. Projections also show that rainfall will slightly increase toward the end of the rainy season in March and April. These findings are in line with smallholder farmer perceptions of climate change trends in Zambia (Mulenga et al. 2017).

Figures 12 and 13 summarize the average changes in rainfall and temperatures over the next three 30-year periods until the end of the century in 2100 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% toward the end of the century. The projected reductions are higher under the more pessimistic RCP 8.5 scenario.

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 (Fig. 13).

Figure 14 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 as shown in Fig. 15. The overall result indicates that water

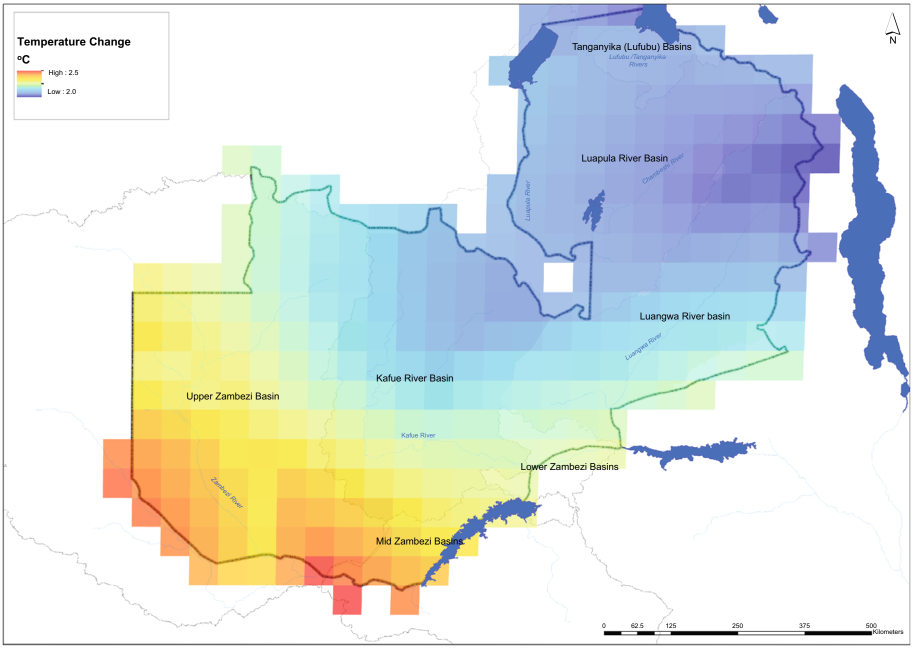

Fig. 14 Projected changes in maximum temperature by 2050 in Zambia (°C). *Note*: The changes in temperature were computed as differences between projected temperature from global circulation models (GCM) and long-term averages over the observed historical reference period 1960–2000. The figure was created in *R*. *Source*: Authors

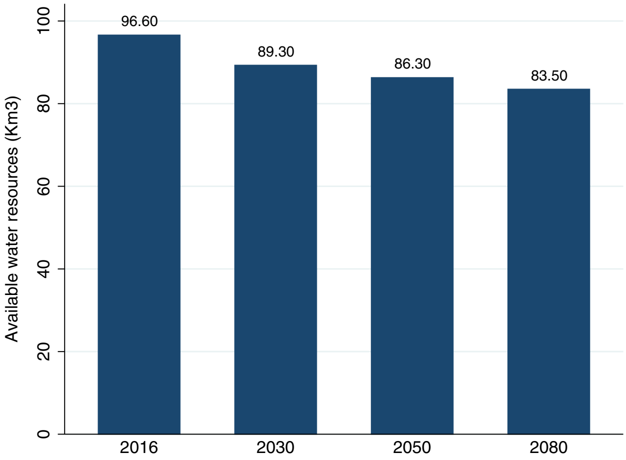

Fig. 15 Projected water resources availability in Zambia (km^3). *Note*: The values in this figure are aggregates of the projected water resource availability in all the basins in Zambia in future 30-year periods 2030 (2020–2050), 2050 (2050–2070) and 2080 (2080–2100). The figure was created in Stata software. *Source*: Authors

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.

The foregoing national level results mask differences at the subnational levels. At basin level, the northern basins are likely to stay the same or experience slight increases in rainfall. 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, will lead to reduced available water resources. Moreover, projected high temperatures will result in high loss of 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 transfer the abundant water resources in the north to the south?

5.1 Implications of climate change on irrigation development in Zambia

The main findings suggesting that climate change will reduce water availability by 13% have implications for irrigation development in Zambia. First, the projected shortening of the rainy season implies that rainfed agriculture will be adversely affected. This will likely result in poor agriculture production, which in turn threatens household, and national food and nutrition security, and resilience. Second, the projected increase in water stress will negatively affect irrigation development due to reduced water resources availability. And, lastly, the projected increase in average temperatures will raise crop water requirements. Given this scenario, both rainfed and irrigated agriculture production will be affected, and farmers have to adapt in one way or another. Part of this adaptation will include using drought resistant or tolerant crop varieties and animal breads, and early maturing crop varieties. Although irrigation is seen as an adaptation option, results in this paper imply that irrigation will be negatively affected by climate change. Better targeted investments in irrigation are needed.

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 has been 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, a rating curve equation 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 are then put through a hydrological model—another 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 inputs in policy decisions. The assessment conducted in this study does not include detailed computations for groundwater resources. It is an important component but also requires a lot of investments to measure it properly.

7 Conclusion

This study evaluated the spatial and temporal distribution of water resources and the impacts of climate change on water resource availability in Zambia at national and subnational levels.

The main results suggest that temperature in Zambia is projected to increase by 1.9 °C and 2.3 °C by 2050 and 2100, respectively. Rainfall is projected to decrease by about 3% by mid-century and only marginally by about 0.6% toward the end of the century across the country. The reductions in rainfall will be larger in the southern, western and eastern parts compared to the northern region of Zambia.

On aggregate, the changes in rainfall and temperature are projected to reduce water availability by about 13% from current (observed) levels of about 97 km^3 to about 84 km^3 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 basins are all projected to have less water resources available due to reduced rainfall and higher temperatures. Thus, we conclude in line with the fifth assessment report of the Intergovernmental Panel on Climate Change that climate change will worsen water stress in Zambia and that there will be significant differences at river basin level.

Two implications for smallholder irrigation development in Zambia follow. *First*, 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 in order to improve water resource management. And, *second*, 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. A thorough inventory of ground water resources is needed to guide water resource management in Zambia.

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Appendix A: Additional outputs

See Tables 7 and 8.

Table 7 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 (km2)	418,814	0	3,264	0	60,073	–
Gauging station (km^2)	513,780	96,239	140,922	34,745	161,275	9027
Gauging station name	Victoria Falls	Hookbridge	Roadbridge	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	1320	170	536	77
February	1200	619	1920	307	1000	112
March	1900	774	1860	461	1700	161
April	2700	709	1120	471	1700	149
May	2500	428	420	294	1200	77
June	1700	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	3200	1100	4250	582	2000	301
High	1700	469	849	280	1000	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	1189	308	639	185	741	66
Runoff depth (mm)	119	101	139	168	161	221
Rainfall (mm)	–	1184	877	1323	1167	1141
Runoff percent (%)	–	8.8	16.7	12.7	13.8	19.4

Table 8 List of global circulation models (GCM) used in the analysis

Model name	Full name	Center	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_esm2 m	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_chem	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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