Hydropower Production in Future Climate Scenarios; the Case for the Zambezi River

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Hydropower Production in Future Climate Scenarios; the Case for the Zambezi River

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Abstract: Climate change remains a threat to water resources projects in southern Africa where impacts resulting from changes in climate are projected to be negative and worse than in most other regions of the world. This work presents an assessment of the impacts of climate change on water resources and hydropower production potential in the Zambezi River Basin. Future climate scenarios projected through the five General Circulation Model (GCM) outputs are used as input in the impact assessment. The future projected climate scenarios are downscaled to find local and regional changes, and used in the Hydrologiska Byråns Vattenbalansavdelning (HBV) hydrological model to assess climate change impacts on water resources in the river basin. According to the simulations, air temperature and potential evaporation are projected to increase, while rainfall is projected to decrease. The Zambezi hydropower system is likely to be affected negatively as a result of future climate changes. Increasing air temperature leading to increased evaporation, and reduced rainfall, both contribute to a decrease in resulting river flows and increased reservoir evaporation. Consequently, the decrease in water resources will lead to decreased hydropower production potential, by 9% in 2020s, 18% in 2050s and 28% in 2080s in the hydropower system, for a medium emission scenario, A1B.

Keywords: climate change; impacts; water resources; hydrology; hydropower production; Zambezi; Zambia; Mozambique; Malawi; Zimbabwe; Africa

1. Introduction

Climate change impacts present challenges of different dimensions to the development and management of water resources. In many parts of the world, especially Africa, water supply systems are already stressed and impacts of climate change will further complicate management of most of the systems. Across Africa, decrease in annual discharge will significantly affect present surface water supplies in large parts of the continent by the end of the century [1]. Southern Africa, due to its dependency on rain-fed water systems for food production, has been projected to be one of the regions of the world that will be negatively affected by climate change [2]. It follows therefore that water resource projects ought to consider climate change impacts for future planning, and management. Moreover, much of southern Africa depends on hydropower as a main source of electricity such that any changes in the water resources may result in changes in electricity supply. Timmermann et al. observed that climate change impacts are rarely explicitly considered in water resources planning, operations and management [3]. Although the available water resources in the Zambezi Basin, in general, exceed the demand at present, this situation may change as a result of the increase in population, more industrial and mining development, increased irrigated food production, a higher standard of living of the population, including the environmental water demand of the system. There are more than 28 relatively large dams with a storage capacity in excess of 12 million m^3 in the Zambezi River Basin, built for domestic, industrial, and mining water supply, irrigation and power generation. Kariba is the largest (160,000 million m^3) and Cahora Bassa the second largest (52,000 million m^3).

Historical observations of rainfall and temperature show that Africa in general is warming at the rate of about 0.05 °C per decade, with slightly larger warming in the June–November seasons than in December–May season [4]. The future projections for temperature in the region show increasing temperatures over the entire region. Temperature is expected to increase by 2–5 °C [5–7] by the end of the 21st century. These higher temperatures will increase the rate of evapotranspiration. Hewitson and Crane observed drying trends for the months of October–December (western side of southern Africa) and for January–March period. However an increase in precipitation to the south eastern part of the region was observed [8].

The Climate Systems Analysis Group (CSAG) and the University of Cape Town (South Africa), has developed comprehensive future climate projection scenarios for the southern African region. The future climate scenarios are based on GCMs used in the fourth report of the International Panel on Climate Change (IPCC—AR4), and recently using the IPCC—AR5 GCMs. The general direction of change—increasing temperatures and reduced precipitation—appears to be consistent [9,10]. These projections are likely to impact the water resources and hence the hydropower systems in the region.

There have been a few studies around the southern African region regarding climate change and its impact on water resources. Some of the most recent studies focused on the Zambezi River Basin [11,12], on the Okavango delta in Botswana [13–15], the Pungwe River Basin in Zimbabwe and Mozambique [16] and on the entire Zambezi River Basin, a risk assessment of the river system [17] and more recent Water Supply and Demand Scenarios for the Zambezi River Basin [18]. The Southern African Development Community (SADC) through the Global Carbon Capture and Storage Institute provides hydropower and hydrology simulations with quantification of elasticity [19]. Most of these studies indicate that the temperature is rising while precipitation is likely to reduce in the 21st century. Most of the studies highlight that impacts of these changes are reduced water resources (river flows in most rivers) in the southern African region as indicated through the following publications [2,20–29]. The southern African region has not yet been extensively studied as far as the climate change impacts on hydropower production potential are concerned.

On a global scale, the impacts of climate change on hydropower have been analyzed and the results indicate that at a global scale the impacts are minimal and slightly positive [30,31]. However, on the regional level of the southern Africa, there are negative impacts [2,30,31]. This is mainly due to declining river flows as observations already indicate. Other studies have suggested that also flow regulation and irrigation can alter local freshwater conditions. This can result in consistent effect like increasing evapotranspiration and decreasing temporal runoff variability from flow regulation [32]. In the southern African region, power is beginning to be pooled together through the Southern African Power Pool (SAPP) and more interconnections are planned to strengthen and improve the power exchange [33,34].

The objective of this study is to evaluate impacts of climate change on water resources in Zambezi River Basin and its implications on hydropower production potential. The following major hydropower projects were included: Victoria Falls, Kariba, Kafue, Cahora Bassa and Shire River. The Kariba hydropower system comprises of two hydropower plants on both sides of the dam wall. The hydropower plants lie in two countries, Zambia and Zimbabwe. In this study, these plants are analyzed as a unit. The study investigates the impacts of changes based on the changes in river flows. As such, the climate change is the main driver of change. The landscape drivers of change like land and water use and water storage can counter the effect of climate change [32], highlighting the importance of knowing the land and water use for future developments in the region from these related activities.

The process of assessing impacts of climate change involves selecting or defining possible future climate. Likely, future climate scenarios are generated by General Circulation Models (GCMs) and are the main tools for researchers [31,35–37]. The procedure in general is that GCMs simulations of future climate are used as inputs into hydrological models in order to study the impacts on river flows. As GCMs cannot provide the required spatial resolutions for hydrological model it is, most times, necessary to downscale to finer resolution suitable for hydrological modelling [38–43]. Downscaling is usually carried out through two different methods; dynamic downscaling, or statistical downscaling.

2. Study Area

The Zambezi River lies in south central Africa within 8°42′ and 21°35′ south and 18°11′ and 36°17′ east. It is Africa's fourth largest river after the Nile, the Congo and the Niger Rivers. The basin has a total area of about 1,390,000 km^2. The Zambezi River Basin is the largest of the African river systems flowing into the Indian Ocean (Figure 1). 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).

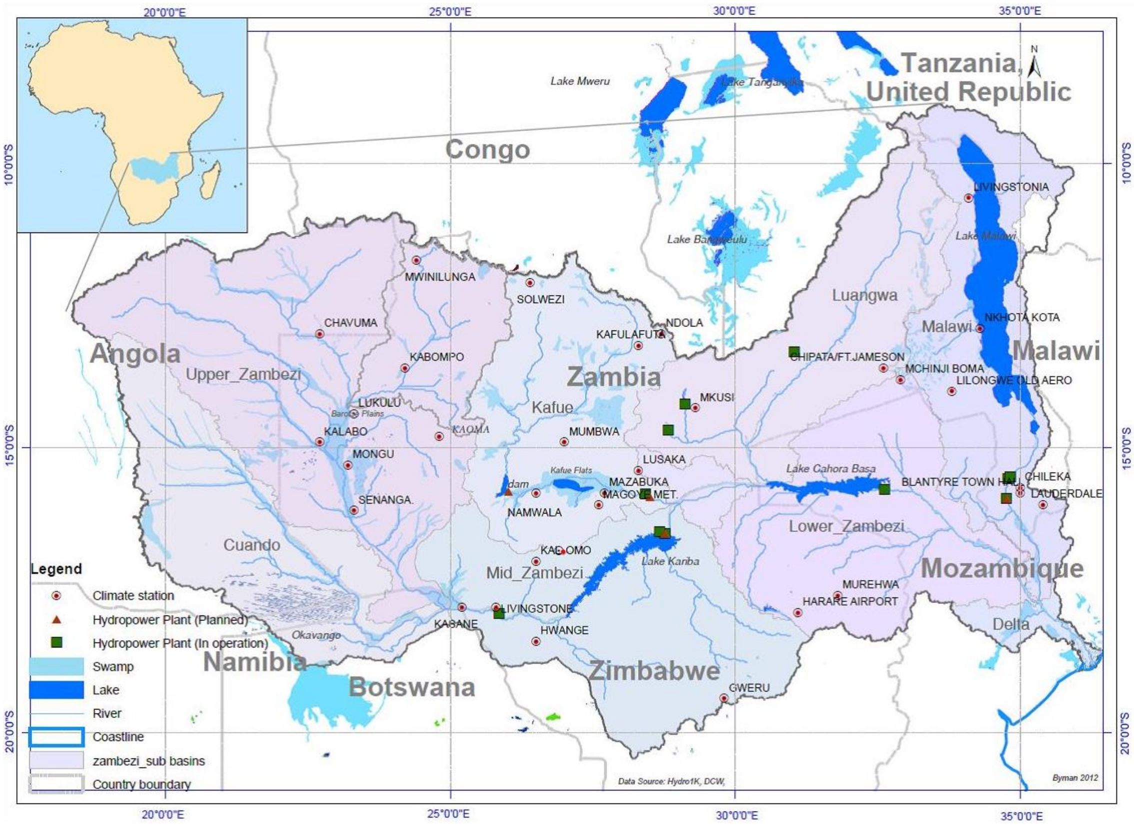


Figure 1. Zambezi River Basin with major sub basins. The red indicates the catchment that contributes to Victoria Falls and the green indicates the catchment that contributes to Kariba hydropower plants.

2.1. Climate and Hydrology

The Zambezi basin lies in the unimodal rainfall zone and therefore there is not much difference in rainfall pattern between the different parts of the basin except the reduction in amounts from north to south. Generally rainfall start in the September—November (SON) season, peaks in the December–February (DJF) season and ends in the March–May (MAM) season as illustrated in Figure 2. The June–August (JJA) season is dry though some of the northern parts of the basin may receive rainfall, also as early as August. The average annual rainfall over the upper catchment is 1100–1300 mm, with considerably higher rainfall near the Zambezi source area in Angola while in the southern low rainfall areas; it is as low as 500 mm/year. The seasonal distribution of rainfall is shown in Figure 2. Table 1 contains a list of selected meteorological stations and their precipitation patterns.

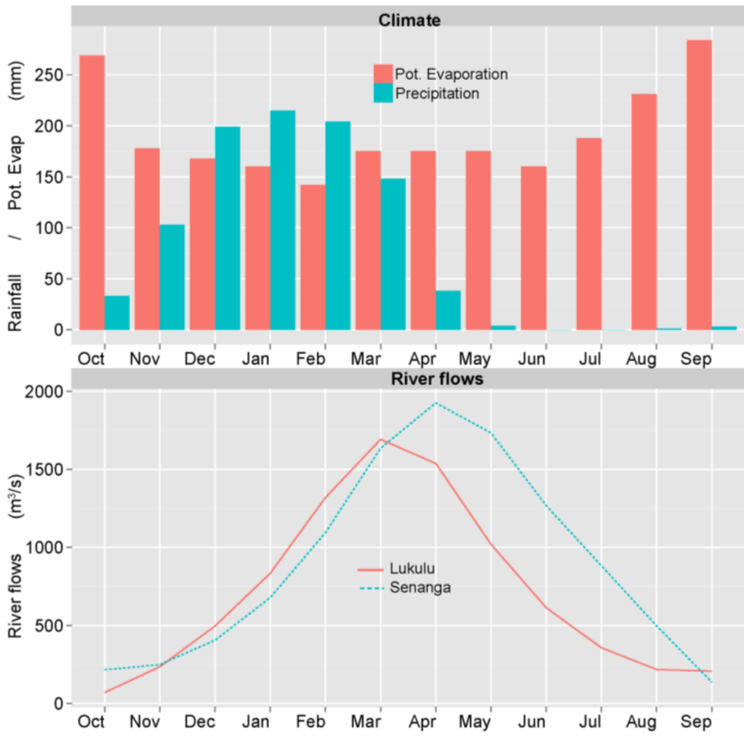


Figure 2. Climate and Hydrology in the Zambezi River Basin. The (**top**) is the mean monthly Rainfall and potential evaporation. The (**bottom**) plot is mean monthly runoff at Lukulu before the Barotse plains and Senanga after the Barotse plains, both are upstream of Victoria Falls.

Table 1. Mean monthly and annual rainfall (mm) for some selected stations in Zambezi River Basin. For location of individual stations, see Figure 1.

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Annual
Mwinilunga	91	209	264	239	213	255	96	10	1	0	2	17	1396
Zambezi	48	135	228	239	208	170	42	3	0	0	0	0	1074
Kabompo	37	193	219	243	209	166	43	5	1	0	0	3	1120
Kaoma	34	111	217	210	192	128	42	3	0	0	0	4	943
Senenga	37	87	188	221	187	121	25	3	0	0	0	1	870
Kalabo	29	86	213	255	177	178	51	0	0	0	0	2	992
Sesheke	25	82	159	175	169	98	23	2	1	0	0	3	738
Livingstone	24	75	168	178	143	85	20	3	0	0	0	2	700
Choma	15	45	105	160	165	89	14	4	0	0	0	6	603
Hwange	20	52	116	135	111	57	27	5	0	0	0	4	527
Gweru	35	96	159	139	125	56	29	8	0	0	2	9	661
Harare	40	93	183	191	176	99	37	7	0	1	1	7	840

The mean temperature over the basin is highest (26 °C) during the SON and DJF seasonal as shown in Figure 2. The hottest month is October, and sometimes November–December just before the rains begin. The dry season of JJA is also the cold season, and mean temperatures can be as low as 15 °C, while the MAM season is cool.

The largest natural lake in the basin is Lake Malawi (28,750 km^2). The largest artificial lakes (reservoirs) are Kariba (5180 km^2) and Cahora Bassa (2660 km^2). Other important reservoirs with large surface areas are the Kafue Dam (89 km^2) and the Itezhi-tezhi Dam (865 km^2). There are five major swamps, the Barotse, the Eastern Caprivi, the Kafue, the Busanga, and the Lukanga, covering an area of 20,000 km^2 at high flood periods. The mean annual discharge at the mouth of Zambezi River is 4200 m^3/s (130 $km^3/year$) as it enters the Indian Ocean. The main contributions to Zambezi river flow are from the tributaries grouped as; Upper Zambezi upstream of Victoria falls (25%), Kafue River (9%), Luangwa River (13%), and Shire River (12%) adding to a total of 60% of the Zambezi river discharge.

Figure 2 shows the climate (rainfall and evaporation regimes) on the top plot. The lower plot shows the annual runoff pattern in upper Zambezi, and the effect of the flood plains on flows. Runoff in the upper Zambezi is highest in period of March–May. Mean annual runoff from the region is about 26.8×10^9 m^3 providing an average annual flow of 850 m^3/s.

The peak runoff typically reaches Lukulu by February-March but this runoff takes one and half months to pass through the Barotse Flood plains and peak discharge near the downstream outlet (Senanga) is often delayed until April or early May. Flood-waters recede slowly from the Barotse flood plains during the six-month dry season, with high evaporation losses throughout the year.

2.2. Hydropower

The hydropower facilities are listed in Table 2. At present, the basin has 4833 MW of installed hydropower generation capacity along the main trunk Zambezi River and the two main tributaries Kafue and Shire. In addition there are a few smaller hydropower plants not included in this analysis and in Table 2. Potential plans for additional power plants and upgrading or expansion shows that the current average hydropower production of 31,598 GWh/year could be increased.

Table 2. List of existing hydropower plants and their characteristics within the studied part of the Zambezi River Basin.

Name	River	Plant Type	Capacity MW	Generation GWh/year	Discharge m^3/s
Victoria Falls A	Zambezi	RoR	8	52	11
Victoria Falls B	Zambezi	RoR	60	390	64
Victoria Falls C	Zambezi	RoR	40	260	43
Kafue Gorge	Kafue	Storage	900	5900	252
Kariba North	Zambezi	Storage	720	3282	744
Kariba South	Zambezi	Storage	750	3420	756
Nkula A + B	Shire	RoR	124	582	246
Tedzani I + II + III	Shire	RoR	92	502	276
Kapichira	Shire	RoR	64	210	135
Cahora–Bassa	Zambezi	Storage	2075	17,000	2260
Sum			4833	31,598	

3. Methodology

Assessment of climate change impacts on water resources and hydropower can be carried out at various levels of detail with different approaches. The main steps in the analysis we have done here for the Zambezi case are shown in Figure 3.

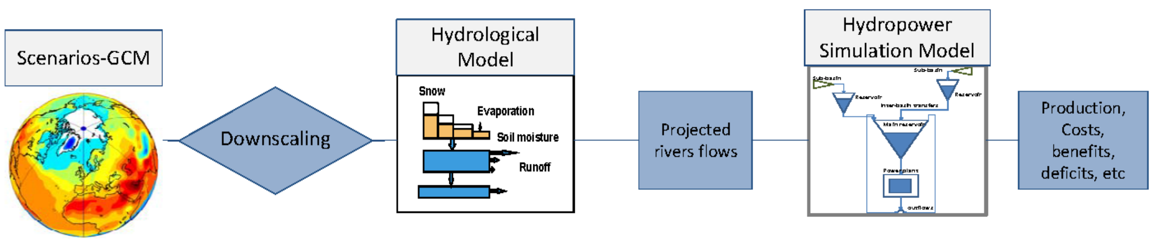


Figure 3. Main steps and methods used in assessing the impacts from future climate scenarios to hydropower production in Zambezi River.

Global Climate Models (GCMs) driven by future emission scenarios are the main tools used to develop future climate scenarios. It is common to use results from several different GCMs each with different emission scenarios to develop future climate scenarios. Next, by the process of downscaling, local future climate scenarios can be established for specific climate stations in the catchment. Statistical downscaling involves regression between GCMs outputs and local observations, resulting in projected future local climate for specific stations.

The first step was to access the data from several global circulation models. GCM simulations are produced by large international climate research centers worldwide (Table 3) and the resulting data are published on servers where free downloads can be made. In total there were 24 GCMs available during the fourth assessment report (AR4) by IPCC. This number of GCMs was too large for practical use, so it was necessary to select a few GCMs to be used during this analysis. The selection process employed the Taylor diagram method to compare the GCM data and observed data from Climate Research Unit (CRU) [18], and the five models Coupled Global Climate Model.

(CGCM3.1), Commonwealth Scientific and Industrial Research Office (CSIRO3.0), Max Planck Institute for Meteorology global Model, (ECHAM5), Community Climate System Model (CCSM3.0) and Hadley Centre Coupled Model (HACDM3) models were selected for further analysis. For more information about these models, see Table 3. Though there were many emission scenarios available, only three scenarios (A2, A1B, B2) were selected. These scenarios cover a wide range, both low (B2), middle (A1B) and high (A2) emission scenarios. This decision also reduced the number of future ensembles of the climate variables generated.

Table 3. List of selected GCMs (AR4, 2007) used in this study [23].

Model	Institute	City, Country
CGCM3.1/T47	Canadian Centre for Climate Modelling and Analysis (CCC)	Victoria, Canada
CSIRO3	Commonwealth Scientific and Industrial Research Office (CSIRO)	Melbourne, Australia
CCSM3	National Center for Atmospheric Research (NCAR)	Boulder, CO, USA
ECHAM5	Max Planck Institute (MPI)	Hamburg, Germany
HADCM3	Hadley Centre for Climate Prediction and Research, UK met. Office UKMO	Exeter, UK

In the Rest of This Paper the Middle Emission Scenario A1B is Used, Unless Otherwise Stated

Future climate within different regions in the basin were projected by downscaling the GCM results using the Empirical Statistical Downscaling (ESD) method of statistically downscaling [41,42]. Here, linear multiple regression is used to establish a statistical relationship between monthly values from station observations and the gridded GCM data outputs.

The simulated data from the five GCMs were used for downscaling to stations within the catchments and the mean/median of these results used as the future climate variables. The downscaling method used mainly daily data, in some cases data with monthly time step. For downscaling, the clim.pact package [41,42] was used to evaluate the expected changes on temperature and precipitation. The results of the downscaling were derived for the three future periods of 30 years. The reference period sometimes referred to as current period, is the 1961–1990 and the three future periods are called 2020s, 2050s and 2080s, representing 2011–2039, 2040–2069, and 2070–2099 respectively.

In order to provide corresponding scenarios of future runoff, results from downscaling of GCMs were applied in hydrological models to transform climate into runoff. The projected future climate scenarios were computed using change factors (see Section 5.2) between the historical period and future periods. This was done to reduce some systematic biases. In this approach, differences in relevant climate variables—typically precipitation, temperature and evapotranspiration—were extracted from the control and scenario simulations of the climate model and processed before being transferred onto an observed time series. The change factors (sometimes called the delta changes) are a common transfer method used [20].

Hydrological modelling was then used to transform the future climate scenarios to future river flows. The hydrological model was calibrated using the observed runoff data during the period representing 1961–1990. The study used five GCM models and the SRES emission (A2, A1B, B2) scenarios to project climate scenarios of temperatures and precipitation. The downscaling was performed at a monthly time step such that the generated output was monthly time series of downscaled mean monthly temperature (°C) and monthly precipitation amount (mm/month).

The HBV model was used for translating the climate scenarios, temperature, evaporation and precipitation, to hydrological changes. The HBV is a conceptual lumped rainfall runoff model originally developed for operational runoff forecasting [44,45]. It has also been used extensively to perform impact studies for climate change assessments [46]. The model, depicted in Figure 4 uses precipitation, air temperature and potential evaporation as input and is usually runs on a daily time-step. The model contains routines for snow accumulation and melt, soil moisture, and groundwater response. Potential evaporation was estimated based on temperature and precipitation series by the Hargreaves method, which is a modified Thornthwaite method [36,47,48].

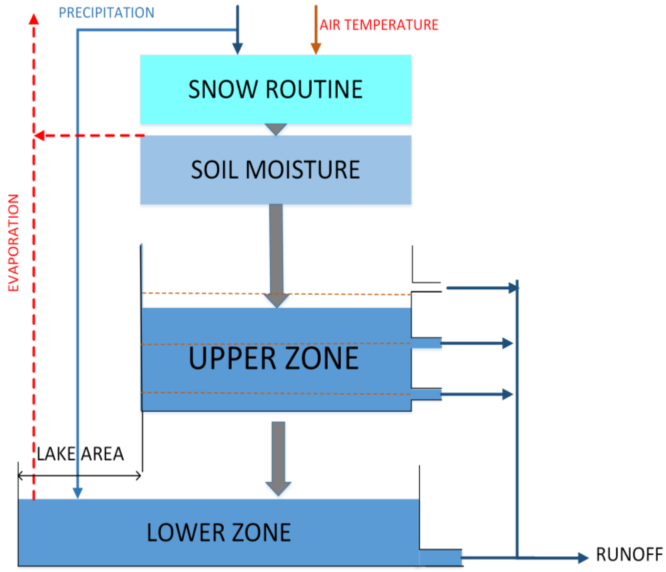


Figure 4. The simplified structure of the HBV rainfall-runoff hydrological model [11].

Typically calibration of HBV involves running the model and comparing the simulated results against river flow observations to obtain optimal performance. The model parameters were calibrated to fit the observed runoff at Victoria Falls gauging stations for the period 1962–2010 (hydrological years). The calibration was performed with a combination of manual calibration (manual adjustment of parameters and weighting of precipitation stations) and automatic calibration. Inflows to the ungauged catchments constituting (mid-Zambezi) were estimated based on the calibrated model for the upper-Zambezi using scaling techniques.

In order to analyze the impact of changed flows on hydropower productions, a model that describes the hydropower system is required to simulate the system with future flows. While it is sometimes tempting to assume that the changes in runoff directly relate to changes in hydropower production, this assumption should be used only in large (regional or global) areas analysis or run-of-river systems. However, where there is storage and other user demands it is necessary to carry hydropower simulations to ascertain the changes that may result from computed changes in runoff. Since the basins selected all have reservoirs with varying sizes, the hydropower production simulations were deemed necessary. In this case the results of the hydrological simulations (river flows) were inputs into the hydropower stimulations by an energy model. The energy model was used to highlight changes that are likely to occur given the changes in the river flows.

The nMAG hydropower simulation model was used to assess the impacts of climate change on hydropower potential. The nMAG model setup for Zambezi hydropower system is shown in Figure 5. The nMAG model was developed at NTNU [49] from 1984–2004 and was primarily intended for operation simulation to estimate the production and economic benefit of the hydropower system under varying hydrological condition. In addition, it is capable of simulating reservoir operation strategies for an integrated water resources system that includes water supply, irrigation, and flood control projects. The model contains nodes from four different module types where all or some are contained in a system at a time. These are termed as: Regulation reservoirs, Power plant, Water transfer (Diversions) and Control point. Input data including system reservoir, power plant, bypass, and operation strategy (reservoir operation rules) are used to describe the hydropower system for each site. Reservoir evaporation and environmental requirements are specified as well. A monthly time step was selected for the runoff time series.

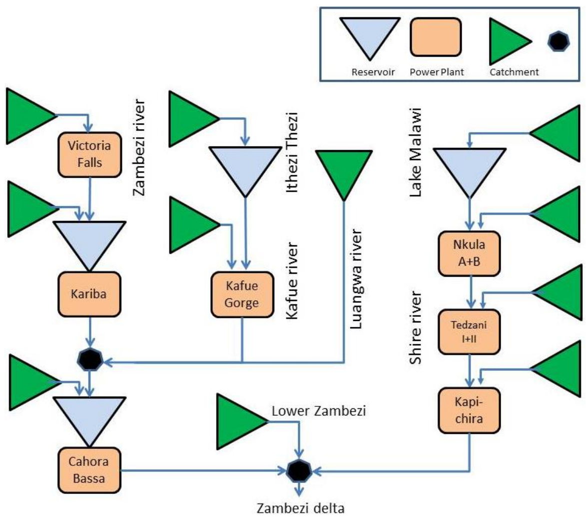


Figure 5. nMAG hydropower model setup for the Zambezi hydropower system.

4. Data

The GCMs results for the five different models (Table 3) and three different emission scenarios (B2, A1B and A2) was obtained from an InterGovernmental Panel on Climate Change IPCC data centre, the Program for Climate Model Diagnosis and Inter-comparison (PCMDI) [2,50]. The data access is free through its data portal [50] by user registration.

Most of the observed historical precipitation and temperature datasets were obtained from Global Historical Climatological Network (GHCN) [51]. Additional datasets, Zambian station data was obtained from the Zambian Meteorological Department. All the stations used in the analysis lie within the Zambezi River Basin. Observed temperature and precipitation data for the different climate stations (Table 1) were used as observed data (predictands) in the downscaling process.

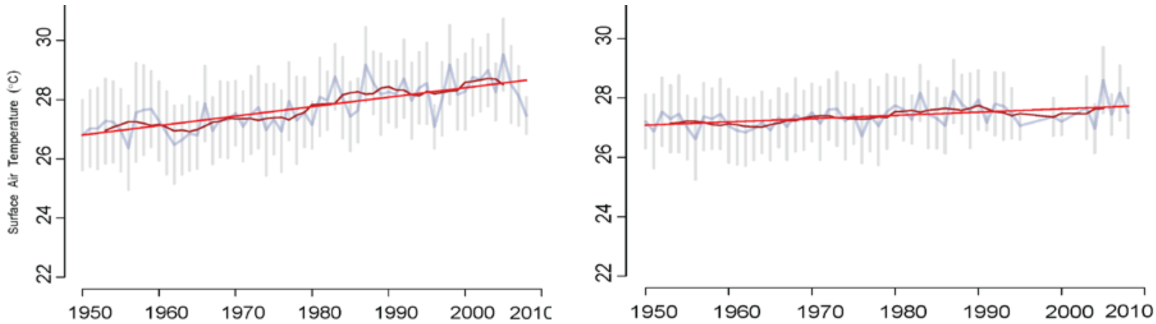
The discharge data were obtained from the Department of Water Affairs, Ministry of Energy and Water Development in Zambia. The annual and monthly discharge data were inspected and selected based on the continuity in data and position within the Zambezi Basin. The discharge data was used in the calibration of the hydrological model. This data set came with some gaps and therefore required some filling in for the missed values. The main gauging stations along the Zambezi River with data were Zambezi River at Kabompo, Zambezi River at Senanga and Zambezi River at Victoria Falls.

The hydrological description of the basin was derived based on Geographical Information systems (GIS) analysis of the basin. The data required was the basin area, sub basins, slope, and elevation zones among many parameters. Data for hydropower plants and their description was obtained from Zambia Electricity Supply Corporation (ZESCO), the electricity utility company in Zambia and from various reports. The hydropower system data required included reservoir size (area, volume), installed capacity, efficiency and other parameters.

5. Results

5.1. Current Climate

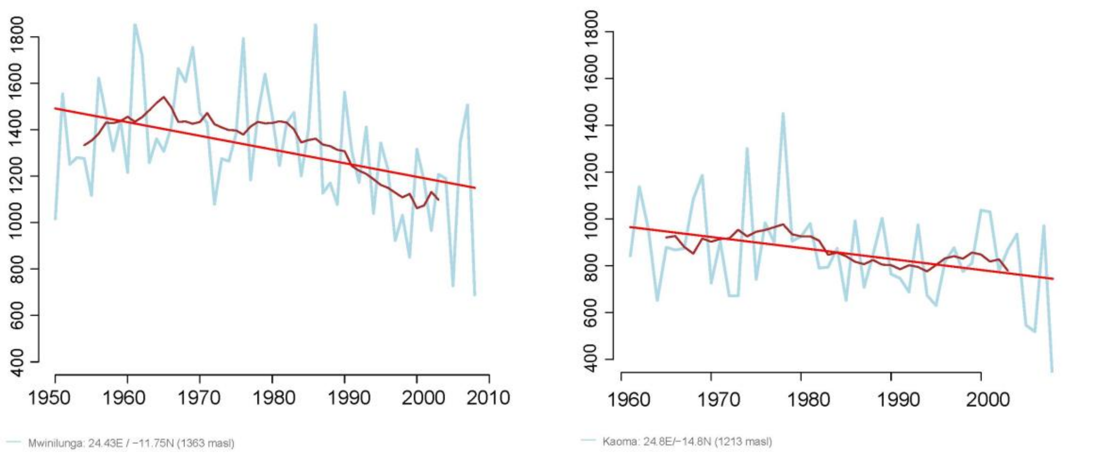
Our initial step was to have a general understanding of trends in the historical observations. The maximum temperature observations indicate that there has been a general increasing trend in temperature, as can be seen from Figure 6. This trend could be seen in all the climate stations within the basin, although rate differs slightly from station to station. The locations of meteorological stations can be seen in Figure 1.



(**a**) (**b**)

Figure 6. Observed trends (1950–2010) in observed annual maximum temperature at two climate stations within the Zambezi Basin: Mongu (**a**) and Mwinilunga (**b**). The y–axis is the temperature in degree Celsius (°C). The brown line represents the 5-year moving average while the red line is the simple linear trend line.

The rainfall observations from climate stations indicate that there has been a slight decreasing trend in rainfall as can be seen from Figure 7. The rate of decrease differs from station to station, with some stations showing no trend and even a positive trend on some stations. Jaramillo and Destouni in their supplementary materials also showed similar decreasing trends of rainfall in the upper Zambezi river basin [52,53].



(**a**) (**b**)

Figure 7. Observed trends (1950–2010) in annual rainfall at two of the climate stations within the Zambezi Basin, Mwinilunga (**a**) and Kaoma (**b**). The y–axis is the annual rainfall in mm. The brown line represents the 5-years moving average while the red line is the simple linear trend line.

5.2. Future Climate

We compared the GCMs data and the observations in the historical period. The selected GCMs' data matched the observed temperature during the historical period reasonably well though slightly underestimating the temperature. As for rainfall, most GCMs' data outputs overestimate the rainfall in the current period when compared to the observations. This is so for both the rainy season and the dry seasons. There is more agreement for temperature results among the models than for precipitation.

The downscaled GCM outputs of precipitation and temperature for period up to the end of the 21st century were taken from results of downscaling. The future changes are grouped into three distinct periods, namely, the 2020s (2010–2039), the 2050s (2040–2069) and the 2080s (2070–2099). For each station an ensemble of time series are generated with different GCMs and emission scenarios. In order to disaggregate the local climate projection into a daily time step, delta change factors from the downscaling process were calculated and added to daily time series of observation records. Calculations of change factors were based on the difference between the climatology of selected projection intervals (2020s, 2050s and 2080s) and a reference (baseline) period (1961–1990) using the Equations (1) and (2). Change factors for temperature were determined by:

$$\Delta T_{i,j,k} = \overline{T}_{i,j,k} - \overline{T}_{ref,k} \tag{1}$$

where ΔT = Temperature change factor (°C), $\overline{T}$ = Monthly mean temperature (°C), i = GCM, j = projection period, and k = month, ref = reference period. Similarly, the equation for estimating precipitation change factors reads:

$$\Delta P_{i,j,k} = \frac{\overline{P}_{i,j,k} - \overline{P}_{ref,k}}{\overline{P}_{ref,k}} * 100 \tag{2}$$

where ΔP = Precipitation change factor (%), $\overline{P}$ = Mean monthly precipitation (mm/month), i = GCM, j = projection period, ref = reference period and k = month.

5.3. Temperature

The mean temperature results from downscaling shows an increasing trend in the future, and this is again consistent in most of the stations; though it varies in magnitude. The mean minimum temperature results show that there is a likely average increase in temperature of 1.2 °C by the 2020s, 2.0 °C by the 2050s and 2.7 °C by the 2080s for the A2 scenario. The temperature results for the A1B and B2 scenarios also show an increasing trend in the future, though slightly lower. This is consistent for most of the stations. The mean temperature results from downscaling are shown in Table 4 for five individual GCMs and three emission scenarios. The results indicate that there are some differences between models and as mentioned earlier among emission scenarios. However, the general trends, all positive, are consistent in all the models and emission scenarios.

Table 4. Downscaling results for temperature in Zambezi Basin. Values in the table represent the Delta change (°C) relative to the reference period 1961–1990.

	2010–2039			2040–2069			2070–2099		
	A2	**A1B**	**B2**	**A2**	**A1B**	**B2**	**A2**	**A1B**	**B2**
CCCMA-CGCM3	1.4	1.1	0.9	2.0	1.3	0.9	2.8	2.2	1.3
CSIRO-MK3	1.0	0.9	0.6	1.9	1.2	0.8	2.6	2.0	1.2
MPI-ECHAM5	1.3	1.1	0.9	2.2	1.4	1.1	2.9	2.3	1.4
NCAR-CCSM3	1.2	0.9	0.7	2.1	1.2	0.9	2.7	2.1	1.3
UKMO-HADCM3	1.1	0.9	0.6	2.0	1.2	0.8	2.6	2.2	1.1
Average	1.2	1.0	0.7	2.0	1.3	0.9	2.7	2.2	1.3

5.4. Rainfall

The result for downscaling of precipitation are shown in Table 5. Most of the GCMs agree, and in general, there is a reduction in precipitation. The magnitude of change varies from month to month and from model to model and also from station to station not in shown the table. There are reductions in rainfall amounts in most stations. The stations with higher rainfall amounts in the northern part of the basin show some slight increases in rainfall amounts, while the stations in the southern part of the basin show decreasing amounts of rainfall. In summary, the basin is likely going to experience higher temperatures and reduced rainfall in general.

Table 5. Downscaling results for rainfall Zambezi Basin. Values in the table represent the Delta change (%) relative to reference period.

	2010–2039			**2040–2069**			**2070–2099**		
	A2	**A1B**	**B2**	**A2**	**A1B**	**B2**	**A2**	**A1B**	**B2**
CCCMA-CGCM3	−6	−4	−2	−14	−9	−4	−11	−6	−4
CSIRO-MK3	−4	−2	1	−8	−5	−1	−9	−5	−3
MPI-ECHAM5	−6	−4	−2	−18	−12	−7	−32	−21	−14
NCAR-CCSM3	−2	0	1	−6	−3	−1	−17	−10	−7
UKMO-HADCM3	−6	−4	−2	−12	−5	−3	−26	−16	−11
Average	−5	−2	−1	−12	−7	−3	−19	−12	−8

5.5. River Flows

5.5.1. Model Calibration

The hydrological model calibration was assessed by a combination of manual and numerical criteria, using plots of observed and simulated flows, together with Nash-Sutcliffe R2 parameter corrected for water balance deviation. The observed runoff at Victoria Falls (pump station) was used for this calibration for the period from 1989 to 2002 which had reasonable daily data coverage for both the runoff and rainfall and temperature. Optimal model parameters were determined by automatic model calibration, see Table 6 for the final parameters. Some model calibration result for Zambezi at Victoria Falls is shown in Figure 8. The average R2 value is 0.78 for the entire calibration period with accumulated volume difference of −11 mm, we consider this to be a reasonable good fit, see Table 6.

Table 6. HBV calibration parameters for Zambezi River at Victoria Falls. Dev. denotes the difference in observed total runoff and the simulated runoff during the calibration period.

Description	**Parameter**	**Value**	**Units**
Rain Correction	*PKORR*	0.94	-
Elevation Correction	*HPKORR*	0	-
Field Capacity	*FC*	288	mm
Beta	*BETA*	0.31	-
Evaporation threshold	*LP*	50	mm
Fast Drainage	*KUZ2*	0.03	mm/day
Slow Drainage	*KUZ1*	0.01	mm/day
Threshold	*UZ1*	51	mm
Percolation	*PERC*	2.7	mm
Drainage Coefficient	*KLZ*	0.01	mm/day
Model fit	*R2*	0.78	
Deviations	Q_{dev}	−11	mm

The results are reasonably good, although the model fit towards the 1990s was not so impressive. The likely reason for this poor calibration is the deterioration of data quality towards the 1990s. The HBV-model was also calibrated and used for Kafue River at Kafue Hook Bridge. The model performance was slightly lower here, with *R2* = 0.75. Also here, there was a tendency for decreasing model fit towards the 1990s.

The HBV-model was also set up for the mid Zambezi, however, because there was no runoff data available for mid-Zambezi to calibrate the model, parameters from upper-Zambezi were used. Models with the same parameters were also used for other catchments which did not have runoff data for calibration.

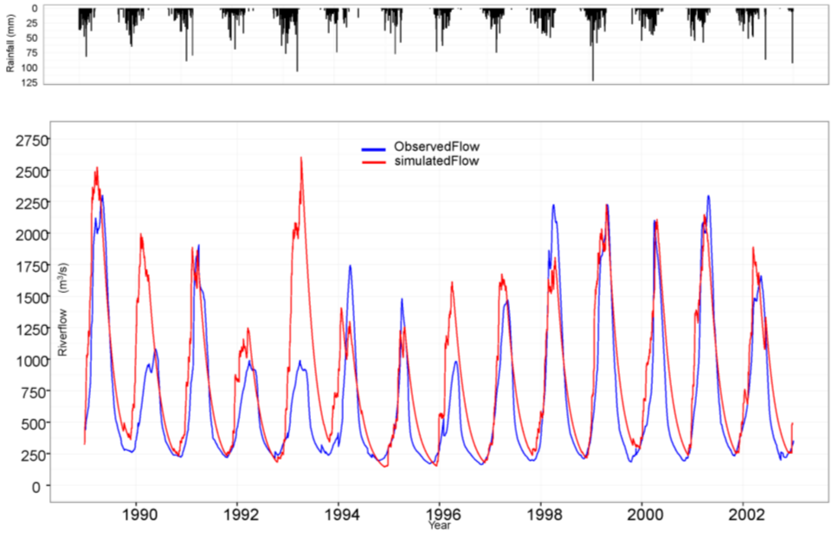


Figure 8. Calibration of Hydrological Model. HBV Calibration Results—Zambezi Basin at Victoria Falls gauging station. The HBV hydrological model was set up with several (5) sub basins. The discharge observations were only available at Victoria Falls (Pump station).

The hydrological modelling of the Shire River Basin is carried out in a different way. The Shire catchment is different because of its configuration, that is, the bigger portion of the catchment is Lake Malawi, (open water surface) and has many small rivers that flow into Lake Malawi, most of these have no discharge observations. The only discharge observations obtained were for outflow of the Lake Malawi at Liwonde barrage. The modelling is based on the water balance calculations. The method uses estimates of total precipitation (direct rainfall on the lake), evaporation, and runoff from rivers flowing into the lake compared to the outflow from the lake through the Shire River. The difference between the incoming precipitation on the lake plus inflow and evaporation is called "freewater". It is computed and correlated to the outflow. Using this method, the short non-continuous discharge data at the outflow of the Lake Malawi was extended.

Under various climate change scenarios precipitation and evaporation from the reference period were recomputed by using the corresponding delta-change values, and new runoff series computed.

5.5.2. Simulating Future Runoff

In order to get the runoff series in the future, the calibrated models were run using the future temperature, precipitation and evapotranspiration. For each of the future periods of 30 years, input data to the HBV-models were based on rainfall, temperature and potential evapotranspiration for the reference period, with corresponding Delta change corrections as given in Tables 4 and 5. For further analysis and comparison the simulated flow series is used as representative for the present hydrology (1990s). By using the simulated flow instead of the observed flow, the change in flow will be related only to the change in climate.

In Table 7 and Figure 9, with Victoria Falls as an example, it can be seen that the runoff for this part of the river decreases in the future. From the current runoff data, using emission scenario A1B, the runoff decreases by 4% in the 2020s, 11% by the 2050s and 16% by the 2080s. Runoff can further decrease even more due to the increasing evapotranspiration from the river basin once the other reservoirs for new hydro power projects that are developed in the basin [53] The changes in runoff based on the hydrological simulations for each period is summarized below in Figure 9.

For the current period, temperature and rainfall from the six stations were used to drive the model. Future climate variables were then used to drive the model to obtain future runoff series. The results shown in Figure 9 highlight that runoff will decrease by 12% in the 2050s, 17% by the 2050s and 23% by the 2080s. Figure 9 summarize the changes in future periods in Zambezi River basin on a monthly basis.

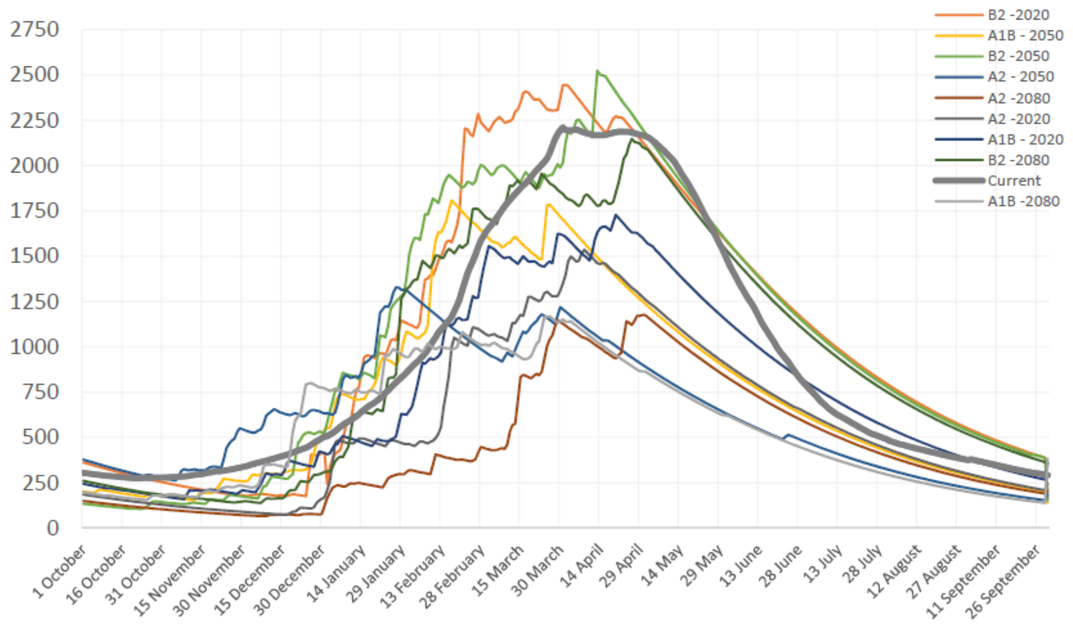


Figure 9. Average annual flow regimes in Zambezi River at Victoria Falls gauging station for the reference period 1961–1990 and for projected future periods for different emission scenarios. The y axis is flow in m^3/s.

Table 7. Monthly flow changes in Zambezi River at Victoria Falls. All figures in % of flow in the reference period 1961–1990. Emission scenarios A2, A1B and B2.

Period	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Annual
							A2						
2020s	96	89	92	99	103	88	90	87	90	94	101	104	94
2050s	88	86	88	89	90	71	85	83	82	89	93	92	86
2080s	84	80	83	82	84	59	71	76	76	83	83	86	79
							A1B						
2020s	102	91	92	99	103	94	90	87	90	97	124	119	96
2050s	99	89	90	97	99	90	86	83	82	93	111	110	89
2080s	90	86	88	94	95	88	81	79	76	88	83	86	84
							B2						
2020s	109	93	94	99	100	90	89	88	91	97	114	111	98
2050s	104	90	91	96	98	88	83	85	84	94	108	104	94
2080s	90	86	89	93	95	85	80	79	76	90	95	86	87

5.6. Hydropower Generation

The hydropower generation at Victoria Falls (A, B, C) were combined into one system (108 MW) although these vary in some detailed features such as total head. Similarly, Kariba North and South

Bank Power stations were combined into one system (1470 MW). Cabora Bassa hydropower is the last downstream in the series of hydropower plants simulated, this was also simulated as a unit. The nMAG setup model for Zambezi was first run on the reference period inflows with the observation runoff data or the HBV simulation data for the period 1960–1990 and the results compared to the records of power production. The model simulated the past years well.

The results of the simulations, shown in Table 8, show that the hydropower system at Victoria Falls does not change much over the simulated periods as it only uses a small percentage of the total volume of flow with some restrictions. It was not possible to get more information about how these restrictions would change with changes in total flow. The current restrictions are seasonally-based. However, the results of hydropower production simulations at Kafue, Kariba Shire and Cabora Bassa hydropower systems indicate that there will be a reduction in the production potential.

Table 8. Changes in production at selected groups of hydropower stations in the Zambezi basin for different emission scenarios.

	Period	Annual Inflow		% Change in Inflow for Scenarios			Annual Generation	% Change in Generation for Scenarios		
		m^3/s	$mill.m^3$	A2	A1B	B2	GWh	A2	A1B	B2
Victoria Falls	Current	1053	33207				702			
	2020s	1018	32211	−7	**−3**	0	702	0 *	**0 ***	0 *
	2050s	988	31215	−13	**−6**	−4	702	0 *	**0 ***	0 *
	2080s	891	28226	−20	**−15**	−13	702	0 *	**0 ***	0 *
Shire	Current	372	11731				1095			
	2020s	357	11262	−5	**−4**	−1	964	−9	**−7**	−4
	2050s	346	10910	−9	**−7**	−5	920	−14	**−9**	−8
	2080s	327	10324	−14	**−12**	−9	810	−21	**−14**	−12
Kafue	Current	287	9050				5034			
	2020s	253	7964	−15	**−12**	−6	4631	−17	**−8**	−8
	2050s	238	7512	−19	**−17**	−10	4128	−23	**−18**	−13
	2080s	221	6969	−26	**−23**	−15	3322	−37	**−34**	−19
Kariba	Current	1350	42500				7404			
	2020s	1296	40871	−6	**−4**	−1	6812	−9	**−8**	−3
	2050s	1161	36613	−15	**−14**	−5	6071	−19	**−18**	−8
	2080s	1094	34485	−24	**−19**	−10	5109	−30	**−31**	−13
Cahora Bassa	Current	2372	74800				17000			
	2020s	2253	71060	−11	**−5**	−2	15470	−12	**−9**	−4
	2050s	2158	68068	−21	**−9**	−6	13940	−21	**−18**	−9
	2080s	1826	57596	−34	**−23**	−15	12540	−32	**−26**	−15
Sum Zambezi	**Current**	2744	**86531**				**31235**			
	2020s	2610	**82322**	−10	**−5**	−2	**28579**	−12	**−9**	−4
	2050s	2504	**78978**	−16	**−9**	−6	**25761**	−20	**−18**	−9
	2080s	2154	**67920**	−26	**−22**	−14	**22483**	−31	**−28**	−15

* Assuming no change in generation since only a small part of the flow is used in the power plants.

Although there is a lot of detailed results from the simulations for the hydropower plants in the system, only the main five power plant groups in the overall Zambezi system will be summarized. This can be found in Table 8, for different emission scenarios and different periods.

As can be seen in Table 8, the expected changes in the Zambezi hydropower system varies somewhat depending on the choice of time and emission scenario used. Using the A1B (middle) emission scenario, the current production levels are likely to be reduced by 9% by 2020s, 18% by 2050s and 28% by the 2080s. Figure 10 highlights these variations in changes depending on the choice of scenario. Using the A2 ("aggressive") emission scenario, the current production levels are likely to be reduced by 12% by 2020s, 20% by 2050s and 31% by the 2080s. The reductions can be attributed to reduced rainfall amounts and increased evaporation, resulting in reduced runoff and increased evaporation losses in the reservoirs. The installation of more reservoirs for new hydropower plants in the future may even reduce more runoff [52,53].

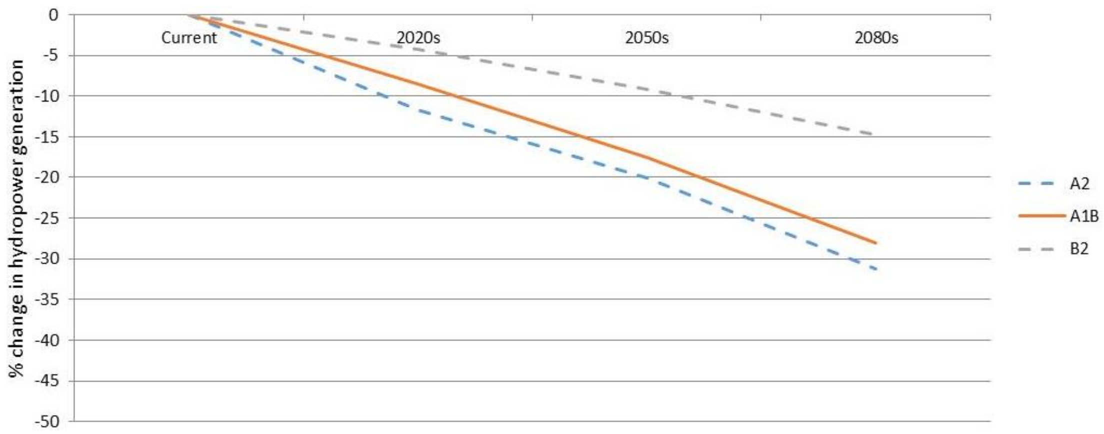


Figure 10. Change in generation capacity (%) for the Zambezi hydropower system for three different emission scenarios (A2, A1B and B2). Computed values for the 2020s, 2050s and 2080s compared to current climate (1961–1990).

6. Conclusions

The hydropower production system of southern African region is likely to be strongly affected by changes in climate. These results show that the future climate within and around the Zambezi catchment will get drier with temperatures higher than those in the current period. The temperature projections in the basin indicate an increase up to 2.7 °C by end of the century.

The rainfall analysis and projections show a decrease in the future precipitation which seem to continue the trend seen for current observations. The resulting effect of these climate changes on water resources is a gradual decrease in river flows, from 14% to 26%, towards the end of the century, depending on emission scenarios.

As a result of these changes, the water resources available for hydropower generation also decrease, and this will have a significant impact on the hydropower production potential. The results show that there could be a decrease up to 15%–31% in the hydropower production potentials towards the end of the century, again depending on emission scenario. Increased reservoir evaporation is a significant driver of the change in generation, in addition to the change in inflows. Sedimentation is another challenge for many reservoirs, but for the major reservoirs in Zambezi catchment, Lake Malawi, Kariba and the Cahora Bassa, the sedimentation rate is not as high and due to their sizes, it will take very long time for the reservoir volume to be affected by sedimentation.

This change is an indication that there will be large negative impacts on the hydropower system, and power deficits are likely with the current generation capacities, unless measures are taken. The scenarios presented in this study should serve as indications of direction of change and how large these could be, rather than exact predictions of the impacts of climate change in the basin.

This analysis has given a basis on which further detailed impact study on particular hydropower sites on the Zambezi basin can be evaluated. This is especially important for new hydropower development of sites that are planned within the Zambezi river basin.

There is significant uncertainty in the projections that are a result of many factors such as the lack of long climatic observations within the basin, uncertainty regarding future GHG emissions, the GCMs' ability to adequately simulate the future climate, and the adequacy of downscaling from global to local climate change.

We feel that these results, like many other impact studies, highlight the fact that planning, development and operation of water resource projects, especially the hydropower stations, need to take into account the impact of a changing climate and the changing land use and water use in this region. Ignoring the impacts resulting from changing climate could result in uneconomical and unsustainable development and operation of water related projects.

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