Climate change and hydrological analysis of Tekeze river basin Ethiopia: implication for potential hydropower production

Abebe G. Adera and Knut T. Alfredsen

ABSTRACT

Climate change is expected to intensify the hydropower production in East Africa. This research investigates the runoff and energy production in the current and future climate for the Tekeze hydropower plant located in the Tekeze river basin in the northern part of Ethiopia. The rainfall-runoff model HBV and the hydropower simulator nMAG were used to generate runoff and energy production in the current and future climate. A combination of five regional climate models and seven global climate models from the Coordinated Regional Climate Downscaling Experiment were used to generate bias-corrected scenarios for the future climate. The result shows an increase in future runoff which was shown to be due to an increase in precipitation. However, the current operational strategy of the power plant did not utilize the future runoff in an optimal way. Therefore, based on the projected future inflow, we have developed a new reservoir operational strategy to preserve water for power production. As a result, the energy production was increased, and the flood spill from the reservoir reduced. This shows the need to adapt the hydropower production system to the future flow regimes to get the most out of the available water.

Key words | climate change, climate change adaptation, reservoir operational strategy, Tekeze hydropower, water resources

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INTRODUCTION

Ethiopia is a country with abundant water resources that can be harnessed to meet the fast growing demands for energy for sustainable development of the society. The country is endowed with hydropower potential of 45,000 megawatt (MW), which is the second largest in Africa. At the time of writing, more than 83% of the population in Ethiopia does not have access to electricity, and more than 94% of the population relies on wood as the main energy source for cooking and heating (Tegenu 2006).

Hydropower production is projected to increase in some regions and decrease in other regions of the world (Hamududu & Killingtveit 2012). Hamududu *et al.* (2010), in a review of hydropower and climate change, found that the scenarios for East Africa showed increased hydropower production while most of Southern and West Africa would have a reduction of hydropower production. Results from a previous study in Ethiopia linking climate change, hydrology and hydropower showed that lack of adaptation of the climate change for energy development will lead to a potential loss in hydropower production (Block & Strzepek 2012). Kim & Kaluarachchi (2009) found that the hydropower potential of the northern part of the Blue Nile Basin will increase due to an increase in the mean annual runoff and a joint dam operation management practice will benefit both downstream countries and the Blue Nile Basin in terms of hydropower, water supply and water storage. Management of water resources will be important in the future, and here reservoir operation is important for hydropower,

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irrigation, water supply and flood control. King & Block (2014) developed a reservoir filling policy and assessment tool to show dam performance and downstream flows for Africa's largest hydropower project Grand Ethiopia Renaissance Dam (GERD), and such tool can be used to estimate the impacts on hydropower production, reservoir filling time and downstream flow that helps politicians and regional water managers.

The Coordinated Regional Climate Downscaling Experiment (CORDEX) initiated by World Climate Research Program (WCRP) aims at generating high-resolution regional climate projections that can be used to carry out analysis of the future climate on a global, regional and local scale (Giorgi *et al.* 2009). An assessment of the performance of 10 regional climate models (RCMs) from CORDEX in simulating rainfall over the eastern part of Africa showed that most RCMs simulates rainfall reasonably well and can also reproduce the major responses to El Nino–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) forcing over the northern East Africa, eastern East Africa and southern East Africa regions (Endris *et al.* 2013).

Uncertainties in projected changes in the hydrological systems arise from internal variability in climate, uncertainty about future greenhouse gas and aerosol emissions, the translations of these emissions into climate change by global climate models (GCMs), the spatial scale and hydrological model uncertainty (Bates *et al.* 2008). The biases in precipitation simulated by the RCMs should be post-processed, so that it produces trustworthy results at local scale. The common approaches of climate post processing are mainly to correct the climate data, so that it shows statistical similarity with the observed data, a technique usually termed downscaling (Teutschbein & Seibert 2013). Gudmundsson *et al.* (2012) found the non-parametric transformation to give the best performance in minimizing RCM biases for precipitation.

According to Mengistu & Sorteberg (2012), among the three Eastern Nile basins (Abbay, Baro-Akobo and Tekeze), Tekeze was more sensitive to an increase in rainfall, while Baro-Akobo showed sensitivity signs for a reduction in rainfall, and the sensitivity of discharge to rainfall and temperature changes is different among the three basins. Recently, a paper by Gebremicael *et al.* (2017), a work done for the Tekeze river basin, showed that the changes in streamflow were not affected only by rainfall but also by other catchment characteristics such as changes in land use and upstream watershed managements. The hydrological response to climate change for Gilgel Abay river, in the lake Tana basin of Ethiopia using HadCM3 GCM and the A2a and B2a climatic scenarios for the period 2010–2100, showed that the mean annual rainfall at lake Tana will decrease in the period 2010–2040 and increase during 2070–2100, and the seasonal rainfall will increase during the rainy months June–September (Dile *et al.* 2013). For the upper Blue Nile river basin, Gebre & Ludwig (2015) found that the ensemble mean of monthly and seasonal precipitation will increase in the future over the basin, and the historical mean monthly precipitation from GCMs showed good agreement with the observed data. Results from two different lumped conceptual hydrological models, a total of 17 GCMs for A1B and B1 GHG emission scenarios for Nyando and lake Tana catchments in the Nile river basin, showed a wide range of simulated results in rainfall, maximum and minimum temperature (Taye *et al.* 2011). Furthermore, wider signals were shown for rainfall than temperature and the study concluded that using few GCMs will result in an unreliable outcome due to uncertainties in the model results and recommended using ensemble mean of several models to better reduce the uncertainty of the climate models (Taye *et al.* 2011).

The aim of this paper is to assess the hydrology and energy production of the Tekeze hydropower system in the current climate and the inflow and potential production for the future climate. Based on this, the need to develop a new operational strategy for future climate aiming at improving the energy production given future inflow and the possibility to adapt the Tekeze hydropower system to the future will be discussed.

METHODS AND ANALYSIS

Description of the study area

The Tekeze river basin is one of the 12 river basins located in the northern part of Ethiopia between latitude 12.5–14.1°N and longitude 37.6–39.7°E. It is a part of the Nile river system, flowing towards Sudan and terminating in the Mediterranean Sea. Tekeze hydropower plant is constructed in this river basin, utilizing water from the Embamadre sub-catchment. The Embamadre catchment has an area of 44,845 km^2 and its elevation ranges from 869 to 4,502 m.a.s.l. The annual rainfall ranges from 500 mm to 1,700 mm, the mean temperature is 18 °C and the mean annual runoff around 1,100 m^3/s. For this study, a total of six precipitation and temperature gauging stations and the stream flow data from Embamadre discharge station were used. The catchment was delineated using a Digital Elevation Model of 30 arc s (1 km × 1 km) resolution from the HYDRO1 K database (https://earthexplorer.usgs.gov/). The location of gauging stations, the discharge station, the Tekeze hydropower and the delineated catchments is shown in Figure 1.

Tekeze Dam is a double curvature concrete arch dam with an overall height of 185 m. The power plant has an underground powerhouse with four Francis turbines and four 75 MW generators. The construction period was from 2002 to 2007 and the power plant started operation in 2009. The reservoir has maximum storage capacity of 9.3 billion m^3 in which the live storage capacity is 5.3 billion m^3 (Humphreys *et al.* 1997).

The main steps or frameworks followed in this study are: (1) checking the quality of all observed data and fill missing values. (2) Calibration and validation of the rainfall-runoff model (HBV) for the Embamadre catchment in the current climate by utilising historical unregulated streamflow data. (3) Prepare the bias-corrected climate model output for the Tekeze catchment. (4) Using the calibrated and validated HBV model from step 2, simulate the discharge in the catchment for the current and future climate based on climate model data. (5) Simulate the energy production and flood spill from Tekeze hydropower plant using the existing reservoir operational scheduling for the current and future climate. (6) If needed, modify reservoir operational

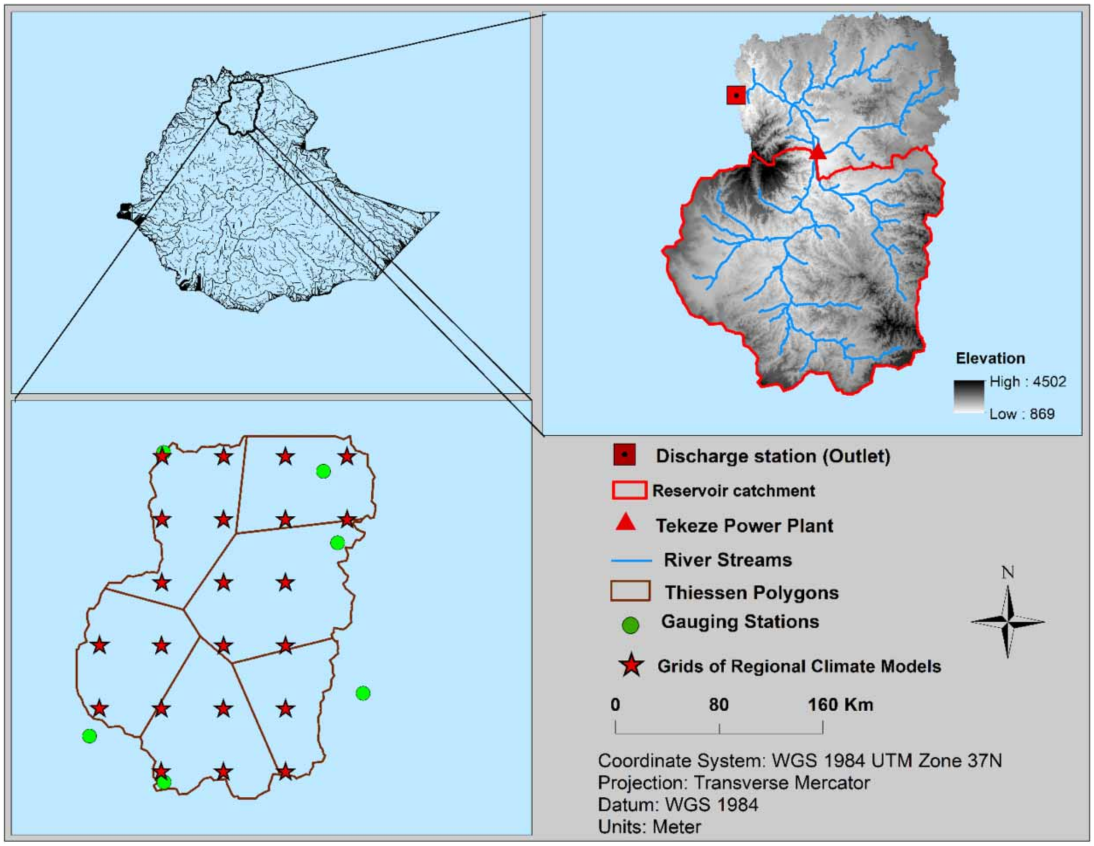

Figure 1 | Location of Embamadre catchment, gauging stations, discharge station, RCM grids within the boundary and Tekeze hydropower plant.

scheduling and re-simulate energy production and flood spill, to evaluate if a changed operational schedule is needed to increase the benefit from future production.

Hydrology model

The HBV model (Bergström 1976) has been used by many researchers in the Blue Nile basin for assessment of climate change impacts on hydrology (Abdo *et al.* 2009; Enyew *et al.* 2014; Worqlul *et al.* 2018) and in other African countries (Hamududu & Killingtveit 2016a, 2016b), and it was also selected for this research study. The HBV model is a conceptual precipitation-runoff model used for simulating inflow forecasts to hydropower systems and streamflow records for hydrological analysis. The specific HBV version used in this study is described by Killingtveit & Sælthun (1995). In HBV, runoff from the catchment is computed from precipitation and temperature. The actual evapotranspiration in the model is computed based on the computed soil moisture deficit and potential evapotranspiration which is given as input. In this study, the daily precipitation and temperature from six gauging stations within Tekeze river basin were collected from the National Meteorology Agency of Ethiopia, and the daily discharge data were obtained from the Ministry of Water and Energy of Ethiopia. The observed precipitation and temperature data from six gauging stations were available for the period 1981–2005, and the few months missing data were filled by constructing correlations between the available stations and the best-correlated station was selected to complete the data series. The monthly potential evapotranspiration for present and future climate scenarios was computed using a temperature index method based on Thornthwaite's approach (Thornthwaite 1948). The origin, name and other details of the six gauging stations used in this study are presented in the supplementary material (Table S1).

The areal precipitation was computed using Thiessen polygon-based weights from the six gauging stations and the areal average precipitation was used as input for the HBV model. The observed discharge was available from 1995 to 2001. The first four years were used to calibrate the model and the remaining three years were used for model validation. The model performance was evaluated using the Nash-Sutcliffe criterion together with visual inspection of plots of observed and simulated discharge, and by evaluating accumulated difference between observed and modelled discharge.

Integrating current and future climate

The CORDEX data from the Earth System Grid Federation (https://esg-dn1.nsc.liu.se/search/esgf-liu/) were used for climate change analysis. For this study, five different RCMs are used in combination with seven driving models

Table 1 | List of GCM–RCM combinations from AFR-CORDEX for Rcp4.5 and Rcp8.5 on 0.44° grid, and their abbreviations used in this study (https://esg-dn1.nsc.liu.se/search/esgf-liu/)

No.	GCM model	RCM model	Abbreviated as	Origin of GCM	Origin of RCM
1	CanESM2	RCA4	Can-RCA4	CCCma, Canada	SMHI, Sweden
2	CNRM-CM5	RCA4	CNRM-RCA4	CNRM, France	SMHI, Sweden
3	CSIRO-Mk3	RCA4	CSIRO-RCA4	CSIRO-QCCCE, Australia	SMHI, Sweden
4	EC-EARTH	HIRHAM5	EC-HIR	ICHEC, Europe	DMI, Denmark
5	EC-EARTH	RACMO22T	EC-RAC	ICHEC, Europe	KNMI, Netherlands
6	EC-EARTH	REMO2009	EC-REM	ICHEC, Europe	MPI-CSC, Germany
7	MIROC5	RCA4	MIROC5-RCA4	JAMSTEC, Japan	SMHI, Sweden
8	MPI-ESM-LR	CCLM4-8-17	MPI-CCL	MPI, Germany	CLMcom, Switzerland
9	MPI-ESM-LR	REMO2009	MPI-REM	MPI, Germany	MPI-CSC, Germany
10	MPI-ESM-LR	RCA4	MPI-RCA4	MPI, Germany	SMHI, Sweden
11	NorESM1-M	HIRHAM5	Nor-HIR	NCC, Norway	DMI, Denmark
12	NorESM1-M	RCA4	Nor-RCA4	NCC, Norway	SMHI, Sweden

(GCMs) in total of 12 different GCM–RCM combinations. These 12 combinations were used as a basis for the hydrological analysis to provide a range of output to quantify the uncertainties. The GCM and RCM models and institutions running the models with their abbreviations used in this study are presented in Table 1. All models used in this study are run with two emission scenarios (Rcp4.5 and Rcp8.5) for the African domain.

In this study, the resolution of RCM grids was ~50 km by ~50 km, and an average precipitation and temperature of each grid cell that falls within the catchment boundary was computed for the historical period (1981–2005) and for the projected scenarios (2025–2049, 2050–2074 and 2075–2099). The data were corrected for bias errors using the Quantile mapping (Quant method) from the qmap R package (Gudmundsson *et al.* 2012). In this study, each sub-catchment contains minimum two and maximum five RCM grids falling within the boundary (Figure 1). The quantile mapping was then applied for each sub-catchment with regard to the number of RCM grids, and the catchment average was used as an input to the HBV model to simulate discharge.

Bias correction methods were used to correct the mismatch between the GCM–RCM model output and observed data. The most commonly used bias correction methods are delta change approach, multiple linear regression, variance scaling, power transformation, local intensity scaling and distribution mapping (Sorteberg *et al.* 2014). In this study, we used a distribution mapping bias correction method called Quantile mapping, which matches an empirical distribution of the RCM data with the distribution of observed data. Even though most statistical transformation methods are capable of removing biases from RCM, the non-parametric transformation (Quantile mapping) is recommended for reducing biases as it does not make any assumptions about an underlying distribution (Gudmundsson *et al.* 2012). Quantile mapping uses an empirical cumulative distribution instead of parametric distributions, and it is approximated using tables of empirical percentiles. The values between the percentiles are interpolated using linear interpolation. In this study, the quantile mapping was computed for the 25 years of the observed data and climate models for the historical reference period (1981–2005). This was then applied on the future climate scenarios, so that the future climate data will have similar statistics as the present data. For assessing the quality of the output from the quantile mapping, an equiratio cumulative distribution function (ECDF) matching method between bias-corrected and -observed historical data (Wang & Chen 2014; Wagena *et al.* 2016) was used and the plots are shown in supplementary material Figures S1–S12. Besides, the mean absolute error (MAE) was also used to evaluate the accuracy and it is shown in Table 2. This shows that the quantile mapping bias correction method applied in this study was reasonable.

Hydropower simulation

The purpose of hydropower is to meet electricity demand, but supplying water, control floods and other objectives may also be important in a multipurpose reservoir goal. To achieve such goals, storing of water in reservoirs is vital, and a regulation reservoir typically follows a certain strategy of filling and releasing of water. This is defined as the operational strategy of the hydropower production system, and this strategy should handle the varying inflow and demands throughout the year. For assessing the change of flow due to climate on hydropower production, we used the hydropower simulation program nMAG (Killingtveit 2005). The nMAG hydropower simulation program has been used in Norway (Chernet *et al.* 2013; Timalsina *et al.* 2015) and also in other African countries (Hamududu & Killingtveit 2015, 2016a, 2016b; Jjunju & Killingtveit 2015). The main components of nMAG are hydrological input, reservoirs, power plants, a description of the energy market, restriction data (e.g. environmental constraints) and operational strategies. The hydrological data of the simulation should include the length and time step of the simulation period, data for each catchment in the hydropower system, and runoff time series.

The reservoir components include data on lowest and highest regulated water level of the reservoir, and the reservoir volume. The power plant components include maximum capacity, the level of the intake, the tail water level, the head loss coefficient, and the total efficiency. The energy market component defines firm power level, power price, the seasonal distribution of power, and the cost functions that defines limits for excess power

Table 2 | MAE between the observed of each station and the output of each RCM–GCM for the baseline (1981–2005) after Quantile mapping

Gauging stations	**Addis zemen**	**Agere genet**	**Alamata**	**Hawzen**	**Mekelle**	**Shire**
Models	MAE	MAE	MAE	MAE	MAE	MAE
Can-RCA4	3.7	5.2	4.7	2.3	2.3	4.2
CNRM-RCA4	3.8	5.2	3.4	2.2	2.4	3.7
CSIRO-RCA4	3.8	4.9	3.4	2.2	2.4	3.6
EC-HIR	4.0	5.1	3.5	2.2	2.5	3.7
EC-RAC	4.1	5.1	3.5	2.3	2.6	4.0
EC-REM	4.1	5.2	3.4	2.2	2.5	3.8
MIROC5-RCA4	3.8	4.9	3.3	2.1	2.4	3.6
MPI-CCL	4.3	5.1	3.6	2.3	2.5	3.9
MPI-REM	3.9	4.7	3.4	2.2	2.5	3.8
MPI-RCA4	3.8	4.7	3.3	2.2	2.5	3.6
Nor-HIR	4.0	4.8	3.4	2.2	2.5	3.9
Nor-RCA4	3.7	5.1	3.4	2.2	2.4	3.6
Average	3.9	5.1	3.5	2.2	2.5	3.8

production and external power needed during low production and rationing. The reservoir operational strategy defines how the reservoir is to be operated and can use an unconditional production strategy and a reservoir guide curve which takes into account the historical inflow regime and reservoir release to control releases and to minimize loss of water due to floods (flood spill). The program simulates production due to variation of inflow within a given year or between different years under different conditions (inflow conditions, power demand, energy prices, water consumption and operational strategy of reservoir). The model supports multiple reservoirs, water transfers and power plants. The Tekeze hydropower system is a simple one-reservoir system, which will have a reservoir module and a power plant module. The nMAG program was set up using daily runoff time series based on the Embamadre gauge scaled down to the Tekeze reservoir catchment.

Two different operational strategies on a daily time step were used to define the reservoir operation in nMAG. The current operational strategy of the Tekeze hydropower system is unconditional power production in which the program tries to meet the target power demand on a day-to-day basis. The target power is the actual energy production or the firm power level to be available from the production system. In this condition, unless the reservoir is full or empty, the reservoir releases enough water to meet the target power demand. The second strategy uses a guide curve that steers the reservoir operation over the year by ensuring that the reservoir content stay close to the defined guide curve thereby avoiding a too low or too high reservoir filling for the time of the year which reduces the risk of rationing due to shortage of water or flood spill in situations with excess water. The reservoir guide curve is constructed by using the mean monthly discharge, the highest reservoir level, the lowest reservoir level and the consumption to define how release and filling is distributed over the season.

RESULTS

The calibration (1995–1998) gave an NSE value of 0.81, −28 mm of accumulated difference and −4.2 percent bias (PBIAS). The model validation (1999–2001) results gave an NSE value of 0.78 and −59 mm of accumulated difference. The first two years (1995 and 1996) the observed flow showed high daily fluctuations which the model could not simulate properly. This is similar to the previous works in Tekeze basin (Mengistu & Sorteberg 2012; Gizaw *et al.* 2017).

During the first two years, the model underestimates the flow which could be due to the reason that the climate stations are located on the boundary that indicates less representation of the catchment and another reason could be due to errors in measurement from the discharge station. The observed (1995–2001) and simulated (1995–2001) mean annual volume discharges which are important for hydropower production are 7,455 and 7,607 million m^3 (2% difference), respectively. Besides, the mean annual volume discharge for the extended reference period (1981–2005) is 4,940 million m^3, and since the volumes are similar, we do expect the production simulation to be reasonable. However, the overall simulated discharge reproduces the observed discharge reasonably well, and the results after validating the model over a different period show that the parameter set performing well in the calibration period also performed well in the validation period. The model calibration and validation results are shown in Figure 2.

Current and future model water balance of Tekeze catchment

Three water balance components (rainfall, discharge and evapotranspiration) were analysed to investigate the current and future model water balance of Tekeze catchment. The model simulated discharge is reasonable as compared to observed discharge. The current water balance showed that the model is able to simulate the water balance component quite well, and we do expect the model to simulate the future water balance reasonable. However, there is large deviation between the observed and simulated discharge during the validation period due to an increase in rainfall. Overall evapotranspiration is higher than the discharge for the Tekeze catchment, which is shown to be due to an increase in temperature, and it increases in the majority of the climate models in the future period as

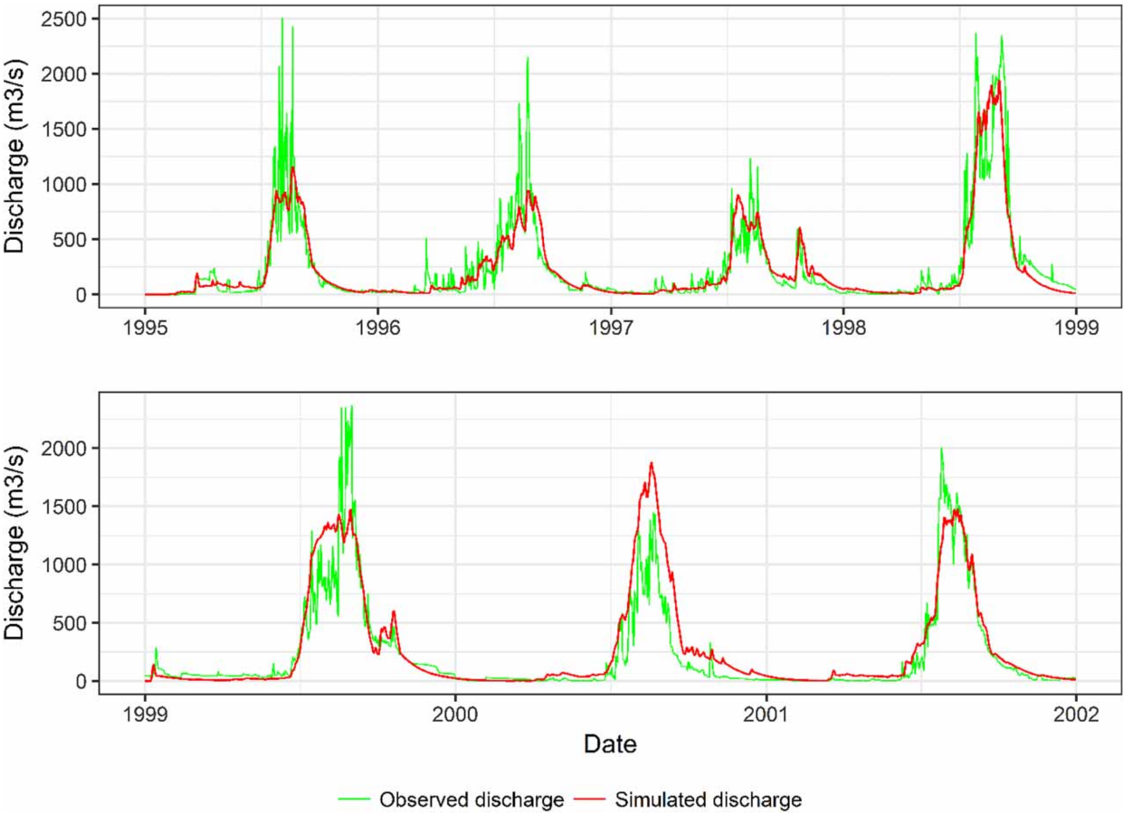

Figure 2 | Calibration results (1995–1998) and model validation (1999–2001). First row is the result after calibrating the model with NSE of 0.81 and accumulated difference of −28 mm. The second row is the model validation result (NSE = 0.78 and accumulated difference = −59 mm).

Table 3 | Current and future model water balance for Tekeze catchment

Type	Calibration period (1995–1998)	Validation period (1999–2001)
Rainfall (mm/yr)	557	641
Evapotranspiration (mm/yr)	450	407
Simulated discharge (mm/yr)	161	236
Observed discharge (mm/yr)	167	165

	2025–2049					
	Rcp4.5			Rcp8.5		
Model	Rainfall (mm/yr)	Discharge (mm/yr)	Evapotranspiration (mm/yr)	Rainfall (mm/yr)	Discharge (mm/yr)	Evapotranspiration (mm/yr)
Baseline (1981–2005)	**566**	**187**	**342**	**566**	**187**	**342**
Can-RCA4	688	216	469	728	239	484
CNRM-RCA4	676	238	419	664	224	423
CSIRO-RCA4	525	171	348	481	149	329
EC-HIR	612	198	406	576	182	391
EC-RAC	535	162	391	567	179	380
EC-REM	550	173	371	563	179	371
MIROC5-RCA4	680	254	401	706	265	407
MPI-CCL	541	165	372	546	170	373
MPI-REM	535	171	354	562	188	359
MPI-RCA4	523	174	336	595	214	358
Nor-HIR	580	194	371	579	192	373
Nor-RCA4	684	256	407	674	250	403
Ensemble mean	594	198	387	604	203	388
Model	**2050–2074**					
Can-RCA4	745	249	481	758	251	491
CNRM-RCA4	648	228	394	684	244	410
CSIRO-RCA4	391	107	284	453	137	308
EC-HIR	563	175	375	569	181	373
EC-RAC	560	176	373	586	187	381
EC-REM	580	185	377	548	166	377
MIROC5-RCA4	759	299	415	800	332	430
MPI-CCL	520	156	353	519	158	350
MPI-REM	518	162	340	498	155	330
MPI-RCA4	519	169	331	556	193	340
Nor-HIR	596	203	365	597	204	366
Nor-RCA4	703	260	402	728	276	410
Ensemble mean	592	198	374	608	207	381
Model	**2075–2099**					
Can-RCA4	710	216	484	742	238	481

(*continued*)

Table 3 | continued

Type	Calibration period (1995–1998)			Validation period (1999–2001)		
CNRM-RCA4	719	270	410	795	318	430
CSIRO-RCA4	359	93	265	397	112	278
EC-HIR	575	179	383	582	184	384
EC-RAC	562	175	384	609	203	385
EC-REM	530	161	358	539	164	358
MIROC5-RCA4	737	295	405	924	403	445
MPI-CCL	542	166	363	468	136	325
MPI-REM	498	155	329	391	106	281
MPI-RCA4	532	176	337	494	160	317
Nor-HIR	603	205	372	536	175	339
Nor-RCA4	654	242	387	752	293	414
Ensemble mean	585	194	373	602	208	370

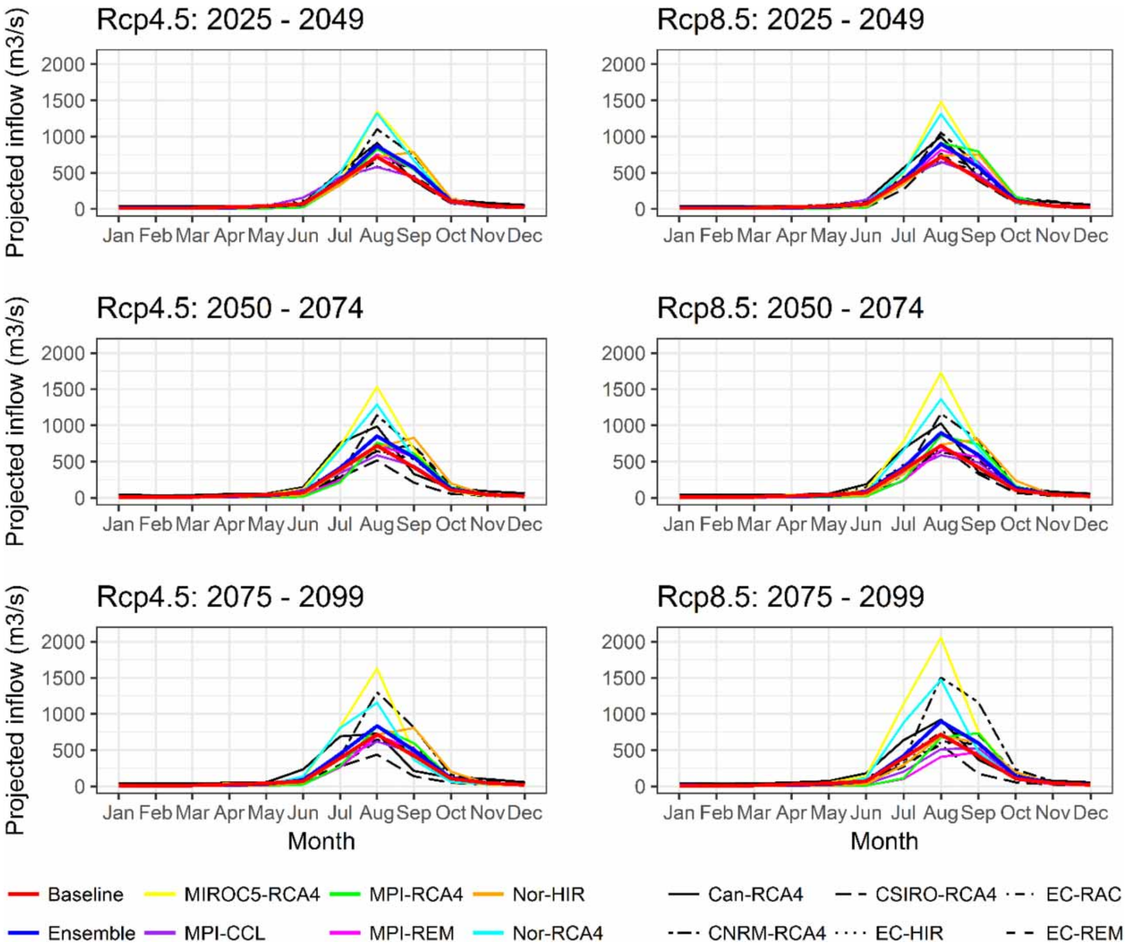

Figure 3 | Projected mean monthly streamflow (m^3/s) for Tekeze river basin. The results on the left column shows projected inflow for Rcp4.5 and the right column for Rcp8.5.

compared to the baseline. Similarly, rainfall increases in the future period, which results an increase of discharge. The current and future water balance components for all climate models are shown in Table 3.

Changes in streamflow for Tekeze river basin

The results of mean monthly runoff for three future periods (2025–2049, 2050–2074 and 2075–2099) for all driving models and scenarios are presented in Figure 3. From these results, RCP8.5 predicts a higher streamflow to Tekeze river basin than the RCP4.5. In the middle period (2050–2074), MIROC5-RCA4 shows an increased mean monthly inflow during the rainy season, while EC-REM shows a decreased inflow. This pattern is also similar in the last period (2075–2099) as compared to the other models. The other models fall between these two. The average annual inflow volume increases for the majority of the models in the future as compared to the baseline and the results are shown in Table 4. The increase in mean monthly inflow and mean annual volume is shown to be due to an increase in the future rainfall predicted by the climate models.

Table 4 | Average annual inflow volume for Tekeze reservoir (4,940 million m^3 is for the baseline 1981–2005)

	Average annual inflow volume (million m^3)					
	Rcp4.5			**Rcp8.5**		
Model	**2025–2049**	**2050–2074**	**2075–2099**	**2025–2049**	**2050–2074**	**2075–2099**
Can-RCA4	6,262	7,227	6,275	6,941	7,287	6,898
CNRM-RCA4	6,896	6,608	7,828	6,510	7,069	9,233
CSIRO-RCA4	4,945	3,115	2,696	4,310	3,987	3,247
EC-HIR	5,752	5,071	5,189	5,275	5,243	5,331
EC-RAC	4,699	5,113	5,070	5,198	5,411	5,895
EC-REM	5,019	5,373	4,670	5,196	4,804	4,748
MIROC5-RCA4	7,364	8,677	8,564	7,692	9,623	11,675
MPI-CCL	4,795	4,526	4,806	4,916	4,586	3,958
MPI-REM	4,969	4,704	4,481	5,462	4,498	3,088
MPI-RCA4	5,049	4,904	5,117	6,218	5,583	4,642
Nor-HIR	5,640	5,889	5,941	5,564	5,930	5,066
Nor-RCA4	7,431	7,532	7,018	7,259	7,997	8,494
Ensemble Mean	5,735	5,728	5,638	5,878	6,001	6,023

Changes in future energy production and flood spill for Tekeze hydropower plant

Using the current operational strategy, the nMAG program was tested against observed production for the observed discharge. The results show that the mean annual simulated production using seven years of discharge (1995–2001) was 1,276 Gigawatt hours (GWh), the simulated energy production over the extended historical baseline period (1981–2005) was 1,171 GWh, and the observed/measured energy production of five years (September 2009–August 2014) was 1,151 GWh which is 2% lower than the simulated production. The modelled production is therefore considered to be in good agreement with observations. With the current operational schedule, the ensemble mean of climate models showed a slight increase in future energy production as compared to the current period. Similarly, using the current operational schedule, the mean monthly flood spill from the reservoir increases during the long rainy season (July–October). As a result, a new reservoir operational strategy in the form of a reservoir guide curve (Killingtveit & Sælthun 1995) was developed by using the future inflow from the ensemble mean of models as a basis (Figure 4). The reservoir guide curve starts at a filling of about 60% in early January and draws down the reservoir until early June to have capacity to store the inflow during the rainy season with a full reservoir expected in early September and then a reduction to 60% filling at the end of the year. The current operational schedule (unconditional power production) in the nMAG model was modified by the new

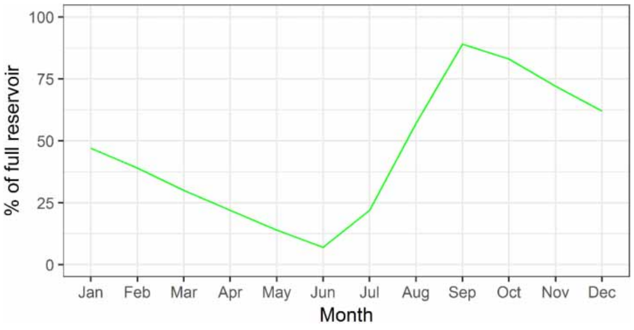

Figure 4 | Reservoir operational scheduling curve developed for the future inflow. The curve is developed using inflow from the ensemble mean of models, and it is the technique used to modify the current operational scheduling.

reservoir operational rule curve, and the simulations of production and flood spill were redone.

Using the newly modified operational schedule, all GCM–RCM combinations showed an increase in mean annual energy production as compared to the production from the current operational schedule. The results of the mean annual energy production for the future compared with the current and modified reservoir operational strategy are shown in Figure 5. Besides, the percent increase in energy production due to the implementation of the newly developed reservoir operational strategy is summarized in Table 5.

On the other hand, after modifying the current operational strategy, the flood spill from the reservoir decreases for all driving models. In all future periods, the flood from the reservoir is available only in the rainy and late rainy months (July–October). In all future periods, during this rainy season, the reduction in mean monthly flood spill for Rcp4.5 ranges from 4% to 100%. Similarly, for Rcp8.5, the mean monthly flood spill reduces from 1% to the highest

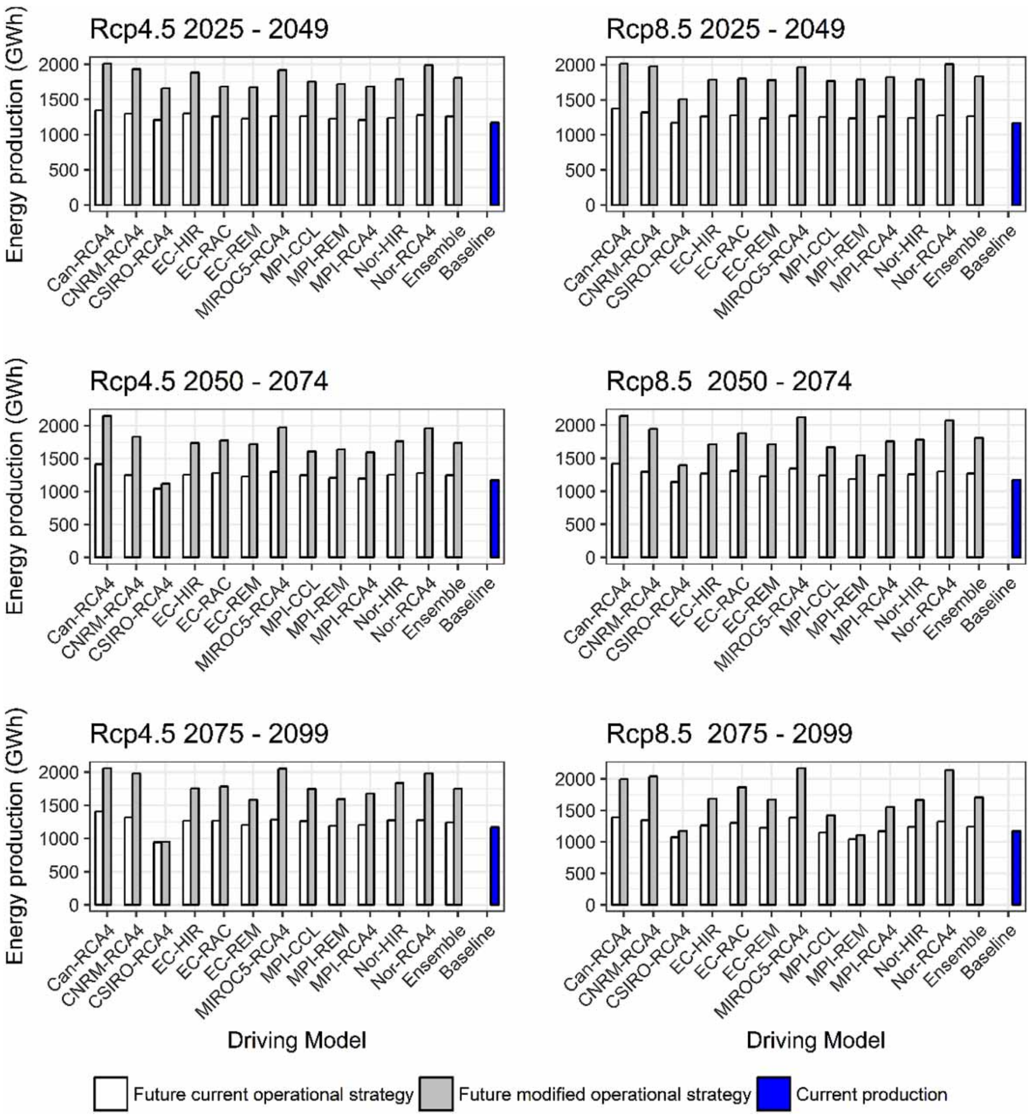

Figure 5 | Projected mean annual energy production in GWh for Tekeze power plant on the current and modified operational scheduling. Results showed on the left column are for Rcp4.5 and the right column for Rcp8.5.

reduction 100%. The percent of reduction in flood spill after modifying the operational scheduling is summarized in Table 6.

DISCUSSION AND CONCLUSIONS

The rainfall-runoff model (HBV) calibration results were satisfactory for this study as the main purpose was to simulate discharge at the outlet of the catchment as inflow to the hydropower model. The overall model performance shown here are similar to previous work but with a different hydrological model done on the same catchment by Mengistu & Sorteberg (2012). The model simulates a slight increase of annual volume +2% as compared to the observed discharge, and the water balance deviation between the observed and modelled discharge was −28 mm. Thus, we found it reasonable to use the HBV model for simulating discharge for the 25-year extended period (1981–2005) used in this study.

We found out that the future runoff will increase slightly in 2025–2049 but more in 2050–2074 and 2075–2099, which is associated with the increase in precipitation over the Tekeze river basin. The mean monthly increase in runoff is similar to previous studies (Taye *et al.* 2011; Dile *et al.* 2013; Enyew *et al.* 2014). The bias-corrected precipitation for driving the hydrological models selected in this study showed good agreement with the observed data, and for the comparable climate models showed similar results as found by Gebre & Ludwig (2015). The projected runoff for MIROC5-RCA4 is higher compared to the other models during the long rainy season, while EC-REM predicts lower runoff, and this results found out to be similar to findings in Wagena *et al.* (2016).

Table 5 | Percentage change increase of energy production after modifying the existing reservoir operational scheduling

	% Increase of energy production for scenarios					
	Rcp4.5			**Rcp8.5**		
Model	**2025–2049**	**2050–2074**	**2075–2099**	**2025–2049**	**2050–2074**	**2075–2099**
Can-RCA4	49	52	47	47	51	44
CNRM-RCA4	49	47	50	50	50	51
CSIRO-RCA4	38	7	10	29	22	9
EC-HIR	45	38	38	41	35	34
EC-RAC	34	39	40	41	44	44
EC-REM	36	40	32	44	39	36
MIROC5-RCA4	52	52	60	54	58	57
MPI-CCL	39	29	39	41	34	23
MPI-REM	40	36	34	45	31	6
MPI-RCA4	40	33	39	45	41	33
Nor-HIR	44	40	44	44	42	34
Nor-RCA4	55	53	55	57	59	61
Ensemble Mean	44	39	41	45	43	37

To show the wider range of variability, we used five different RCMs in combination with seven GCMs. Endris *et al.* (2013) used an ensemble of 10 different RCMs to assess the rainfall simulation performance, and Rummukainen *et al.* (2001) found that the RCM rainfall patterns follows and highly affected by the biases in GCM-driving models. In our study, the variability of climate models was shown in these 12 GCM–RCM combined simulations. The GCMs from the current CMIP5 projected that the RCP scenarios will show little change of precipitation in the rainy season July–October (IPCC 2013). According to recent paper by Gizaw *et al.* (2017), the mean annual streamflow is projected to increase 3–6% in Tekeze river basin and this increase in streamflow is in line with our study at the same river basin. However, much detailed high resolution of RCMs will provide more reliable estimation of future rainfall and runoff.

The future energy production from Tekeze hydropower plant was assessed, and we found that there is no significant change in production in the future period using the same reservoir operational strategy as today. The main reason for this is the increased flood spill from the reservoir during the rainy season. These results were shown to be due to an increase in future inflow to the system, and running the hydropower on the current operational strategy will not utilize the water in an efficient way with a large amount of water spilled from the reservoir. This shows the need to develop a better hydropower scheduling strategy to adapt the future inflow. For this purpose, we developed a new reservoir operational strategy based on the future inflow pattern which is used to manage the incoming flow. Thus, the newly modified reservoir operational strategy made it possible for the hydropower system to utilize most of the incoming future inflow for both energy production

Table 6 | Percentage reduction of flood spill from Tekeze reservoir after modifying the operational scheduling

	% Reduction of flood spill for scenarios							
	Rcp4.5				**Rcp8.5**			
Model	**July**	**August**	**September**	**October**	**July**	**August**	**September**	**October**
2025–2049								
Can-RCA4	100	71	19	10	97	45	28	22
CNRM-RCA4	81	66	23	7	100	77	25	19
CSIRO-RCA4	10	88	49	50	10	90	81	100
EC-HIR	100	90	45	15	100	95	51	12
EC-RAC	100	98	81	54	100	98	65	23
EC-REM	100	99	52	29	100	95	63	17
MIROC5-RCA4	100	66	6	0	100	53	10	10
MPI-CCL	100	100	86	43	100	100	76	40
MPI-REM	100	97	63	30	100	98	46	18
MPI-RCA4	100	95	47	8	100	82	30	6
Nor-HIR	100	98	47	10	100	100	50	10
Nor-RCA4	100	61	12	10	96	65	10	25
Ensemble mean	90	86	44	20	91	83	45	24
2050–2074								
Can-RCA4	96	42	7	15	93	44	14	6
CNRM-RCA4	100	68	34	15	100	78	11	6
CSIRO-RCA4	10	100	93	10	10	96	65	100
EC-HIR	100	98	70	12	100	86	43	17
EC-RAC	100	100	65	29	100	98	68	38
EC-REM	100	100	53	10	100	100	73	77
MIROC5-RCA4	90	35	6	10	95	35	10	10
MPI-CCL	100	100	84	33	100	100	85	77
MPI-REM	100	100	72	14	10	96	66	36
MPI-RCA4	10	88	58	18	100	87	41	11
Nor-HIR	100	99	38	3	100	96	39	19
Nor-RCA4	95	50	7	10	100	56	5	10
Ensemble mean	82	82	49	12	82	81	42	32
2075–2099								
Can-RCA4	94	55	16	8	90	45	7	10
CNRM-RCA4	88	61	7	6	100	57	4	3
CSIRO-RCA4	10	10	10	10	10	100	82	10
EC-HIR	100	99	58	15	100	92	45	11
EC-RAC	100	100	69	15	100	91	44	21
EC-REM	100	100	67	37	100	98	76	63
MIROC5-RCA4	92	38	4	10	78	16	1	4
MPI-CCL	100	98	87	93	100	100	94	64

(*continued*)

Table 6 | continued

Model	Rcp4.5 July	Rcp4.5 August	Rcp4.5 September	Rcp4.5 October	Rcp8.5 July	Rcp8.5 August	Rcp8.5 September	Rcp8.5 October
	% Reduction of flood spill for scenarios							
MPI-REM	10	100	81	67	10	100	96	38
MPI-RCA4	100	100	84	88	10	98	71	35
Nor-HIR	100	97	45	9	100	96	60	17
Nor-RCA4	93	51	9	10	92	42	3	21
Ensemble mean	81	75	44	28	72	78	49	23

The 100% reduction shows that there is no flood from the reservoir after implementing the new operational strategy.

and thereby reduce flood spill. This shows the importance of adaptation to the changes in future inflow. According to Jjunju & Killingtveit (2015), the increase in inflow due to climate change observed in East Africa cannot be fully utilized on the present system and the existing reservoir operational rules have to be upgraded to exploit the increased future inflow.

A reservoir filling policy has been suggested as a crucial strategy for regional policy makers and stakeholders to uphold the function of reservoirs in the future climate by King & Block (2014), and the findings from this study confirm that view. There was not much research done on adaptation strategies in the region and in our study, we developed a climate adaptation mechanism or strategy that is based on the projected streamflow and it showed strong signs of the need for future adaptation mechanisms. The management practices could further be integrated with sediment, flood, irrigation and water supply practices. Therefore, for better management and operation of future inflow, an assessment tool like the nMAG model applied in this project should be used to evaluate energy production and reservoir performance, and to provide a basis for finding the best adaptation strategies. Such an integrated assessment tool will provide benefits both for developers and regional managers.

In this study, the land use and hydrological parameters for future time simulations are considered the same as the present time. There is uncertainty in our modelling results, which is due to the uncertainty in the GCM–RCM, and to address this we have used as many models as we can so that it will be possible to visualize the wider range of uncertainties due to climate models. Another uncertainty is related to hydrological parameters, and excluding potential land use change in the future time could lead to an increase in evapotranspiration. The potential evapotranspiration is computed based on the temperature index (Thornthwaite 1948) approach for both the current and future periods, and this method might result in deviation from other methods. The equation was used and evaluated by previous researchers in the northern highlands of Ethiopia (Woldeamlak 2002; Walraevens *et al.* 2009). However, we do believe this study shows potentially interesting results in future hydropower production with a new adaptation method to the future climate.

Our results show large potential for hydropower production, which is in line with Hamududu & Killingtveit (2012). Van Vliet *et al.* (2016) recommended an adaptation method as a key solution to changes in climate, and we have found that adaptation to future climate is important to get the most out of the available water, which is necessary for countries like Ethiopia that use hydropower as the main source of energy. Besides, different modelling tools can be used to asses this and can be extended to other reservoir uses.

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