ORIGINAL ARTICLE

Modeling climate change impact on the hydropower potential of the Bamboi catchment

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Abstract

Understanding climate change impacts helps adaptation efforts in the energy sector. This study evaluates the impact of future climate change on the hydropower potential (HPP) of the Bamboi catchment in West Africa combining the HBV-light rainfall-runoff model and a hydropower generation model. Two regional climate simulation datasets MPI-ESM-REMO and WASCAL under RCP 4.5 were applied to the validated HBV light to simulate the catchment discharge. Based on reference and future simulated discharges, a 1.3 MW run-of-river hydropower plant was designed to evaluate the HPP of the catchment. Hydrological and HPP changes were expressed as the difference between two future periods (2020–2049 and 2070–2099) and a reference period (1983–2005). The climate datasets projected a mean annual precipitation increase by 8.8% and 7.3% and discharge increases by 11.4% and 9.735% for the 2020–2049 and 2070–2099 periods, respectively. However, an overall decrease of hydropower generation by − 9.1% and − 8.4% for the 2020–2049 and 2070–2099 periods, respectively, was projected. These results stem from an increase in discharge for the rainy season not convertible into hydropower, combined with a decrease in discharge during the dry months that leads to important HPP losses.

Keywords Climate change · Hydropower · Run-of-river · Hydrological modelling

Introduction

Hydropower is a reliable renewable and economically competitive source of energy (Berga 2016). Currently it has a share of 16% of the world's generated electricity and contributes 78% of the renewable electricity generation (Berga 2016). Hydropower and climate change have a two-way relationship where by hydropower mitigates climate change by hindering emission of greenhouse gases to the atmosphere and climate change can affect hydropower generation by increasing the potential evaporation leading to rivers discharge reduction and the reduction of hydropower potential (Boadi et al. 2017). Hydropower is the leading source of renewable energy in West Africa and it offers many benefits

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to the community and facilitates regional and economic development (Hamududu et al. 2012). However, due to its low adaptive capacity, West Africa is one of the regions which will be severely affected by climate change (IPCC 2014).

Several studies (e.g. Badou et al. 2018; Yira et al. 2017; Mbaye et al. 2015; Obahoundje 2015) have already assessed the impacts of climate change on water resources in West Africa although not much work was done on its impacts on hydropower potential. Both Oyerinde et al. (2016) and Obahoundje (2015) undertook researches on the potential impact of climate change on hydropower generation at the Kainji dam (the Niger Basin) and the Bui dam (Black Volta basin) respectively; and results showed that while climate change is projected to decrease the hydropower potential of Bui, the opposite is expected for Kainji. At Bamboi catchment (Black Volta), a strong reduction in the rainfall occurrence has been experienced in the Basin since 1960s notably the 1973/1974 and 1983/1984 dramatic droughts (Boadi et al. 2017). These reductions have led to strong fluctuations in the river discharge with generally a negative trend from 1960 to 2000. The majority of climate models in West Africa predicts an overall warming trend throughout the region with an estimated temperature increase of 0.5 °C per decade (Sylla et al. 2016). These rising temperatures cause a further reduction of river discharge as a result of increased evaporation.

Understanding climate change impacts helps adaptation efforts (Coulibaly et al. 2020; Cronin et al. 2018). However, the vast majority of the above aforesaid information ascertains the unclear signal for the future hydropower potential in the region, and implies further assessments on the future climate impacts on the hydropower potential of the region. Furthermore, scientific evidences about how climate change will impact hydropower generation in the Bamboi catchment specifically are less documented which creates a gap that need to be filled; while increasing consumption of fossil fuel call for reducing greenhouse gas (Kassem et al. 2020). This study is novel as many of the previous investigations carried out in the region assessed only the impact of climate change on water resources and not explicitly on the hydropower potential. Second, the studies that assessed the hydropower potential mainly focused on dam and not on run-of-river systems. The current study combines climate impact assessment on water resources and hydropower potential of a run-of-river hydroelectricity system.

The aim of this research is to assess the impacts of climate change on hydropower potential of Bamboi catchment. Accordingly, it has the following three objectives: (i) set up the conceptual hydrological simulation model HBV light for the Bamboi catchment; (ii) assess the impact of future climate change on the hydrological regime of the catchment through scenario (RCP4.5) application comparing a reference period (1983–2005) to two future periods (2020–2049

and 2070–2099); and (iii) assess the impact of climate change on the hydropower potential of the catchment.

Materials and methods

Figure 1 shows the general methodology that was applied to model climate change impact on the hydropower potential of the catchment. Detailed descriptions of the steps are provided in the next sessions.

Study area

This study was carried out in the Bamboi catchment covering a total area of 134 200 km^2 (Fig. 2). The catchment spans across Mali, Burkina Faso, Ghana and Ivory coast (Obahoundje 2015). The main river in the basin is the Black Volta river which originates as Mouhoun in Burkina Faso and as Sourou in Mali (UNEP-GEF 2013) and it has a length of 1325 km and the total drainage is 154,900 km^2 (Atulley 2013). Temperature in the basin ranges from 15 to 44 °C and it increases from south to north. March and April are the hottest months whereas the coolest month is August. Rainfall ranges from 4000 to 1400 mm and it increases from North to South likewise humidity (Obahoundje 2015). The basin experiences unimodal rainfall (in the north) and bimodal rainfall (in the south) as a result of inter tropical convergence zone.

Hydrological modelling

The hydrological modeling was carried out with the HBV-light model (Seibert and Vis 2012). HBV light is a rainfall-runoff simulation model that requires four inputs for a classic application: (1) reference evapotranspiration-ETo, (2) observed discharge for the calibration and validation, (3) precipitation, and (4) air temperature. Only three modules of the model structure were applied: (i) soil, (ii) routing, and (iii) response. The built-in Genetic Algorithm and Powell optimization-GAP were adopted for the calibration of the model. During the calibration phase, the period from 1979 to 2001 Jan was used for warming, and 01 Jan 2001 to 01 Jan 2004 was used for parameters optimization. The best parameter set was found at 50 000 Monte Carlo simulations after a series of repeated iterations. Statistical criteria and visual inspections of simulated (Qsim) and observed (Qobs) discharge plots were the two techniques used in this study to evaluate the performance of the model. Statistical criteria were done by considering the Nash–Sutcliffe efficiency—NSE, the coefficient of determination—R^2 and the Kling–Gupta efficiency—KGE (Gupta et al. 2009). For the validation process, the warm up period was taken from 01 Jan 1979 to 01 Jan 2004 and the validation period ranged
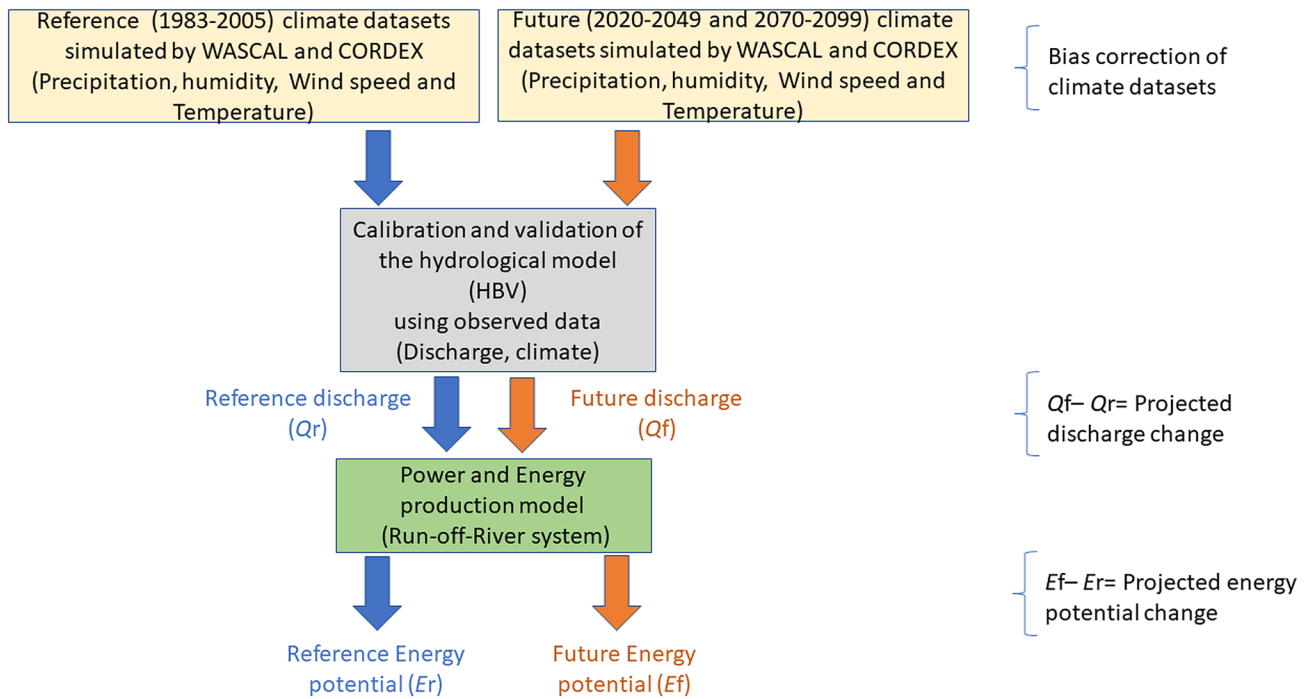
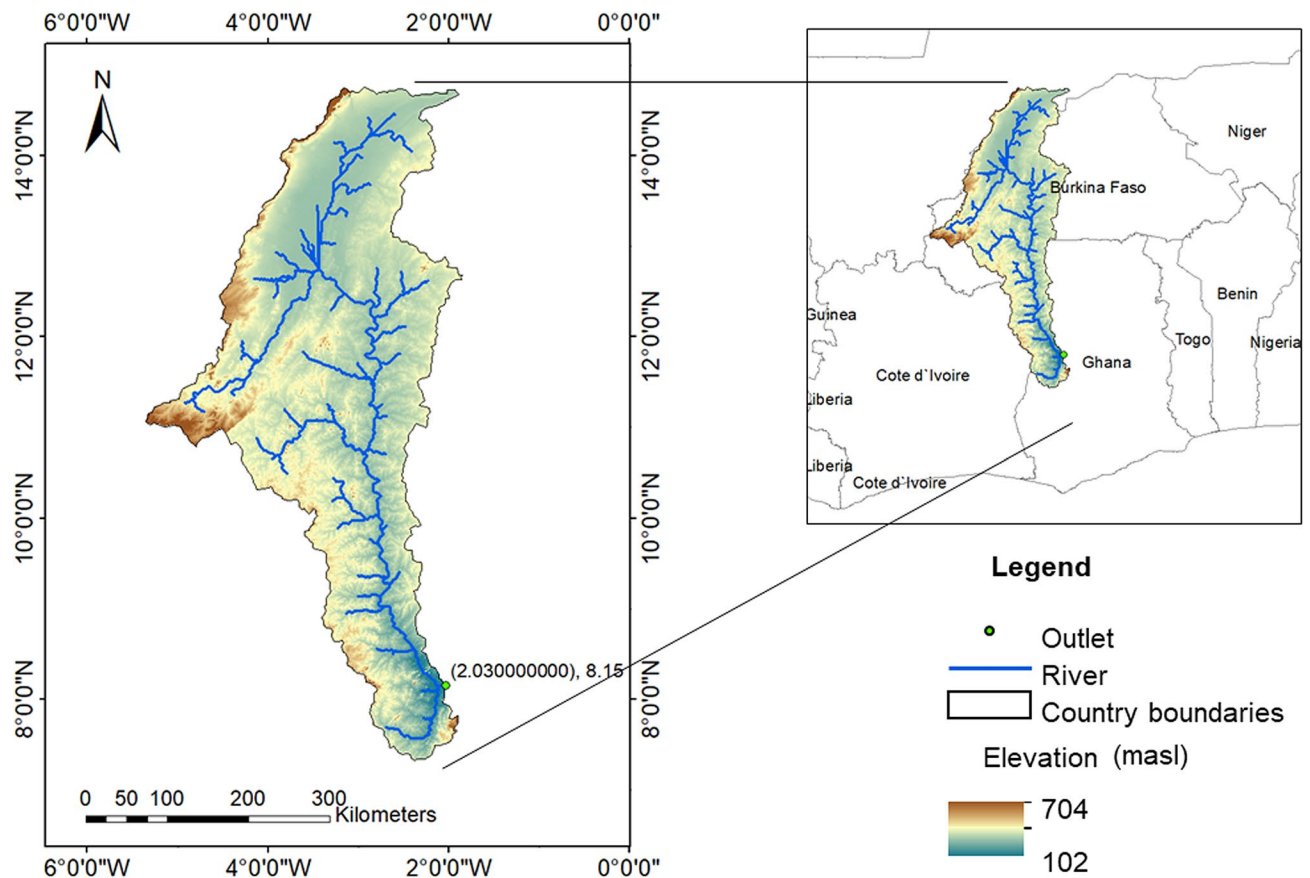**Fig. 1** Flowchart of the general methodology

Fig. 2 Location of the Bamboi catchment

from 2004 Jan 1 to 2007 Feb 28. Table 1 provides the type and source of the applied datasets in the study.

Climate impact assessment on the hydrology and hydropower potential of the catchment

For climate impact assessment, two RCM GCM climate datasets developed by WASCAL at 12 km spatial resolution using WRF and the CORDEX climate product (0.44° spatial resolution) with the same concentration pathway RCP 4.5 were applied in this study (Table 2). The climate dataset developed by WASCAL is only available for scenario RCP 4.5. It is noteworthy that the difference between RCP 4.5 and RCP 8.5 became meaningful only after 2040 and that RCP4.5 is a reasonable scenario according to COP 21 agreement (Heinzeller et al. 2018). Scenario RCP.5 refers to a radiative forcing of about 4.5 Wm^2 at stabilization after 2100 (Moss et al. 2010). Climate data bias correction was applied to both RCMs–GCMs following the non-parametric quantile mapping using the empirical quantiles method (Gudmundsson et al. 2012). The

empirical quantiles method implies that for each variable, a transfer function is derived using its observed and simulated data for the reference period; afterwards the transfer function is applied to the projected period. Figure 3 shows that for all variables, biases are in general reduced by the applied bias correction method. The bias corrected climate data (reference_1983–2005 and future_2020–2049 and 2070–2099) were used as inputs for the hydrological model to simulate both historical and projected discharges. Power and energy production were calculated from the simulated discharges using the hydropower equations (Eq. 1 and Eq. 2).

$$P = e\rho QgH \tag{1}$$

$$E = P * \Delta t \tag{2}$$

where P is power (W), E is energy in watts (W/h), e is the efficiency of the turbine (set to 80%), ρ is the density of water (kg/m^3), Q is the water released to the turbine (set to Q_{80}—the 20 percentile flow—of the mean simulated historical and projected discharges, m^3/s), g is the gravitational force (m/s^2), H set to 20 m is the water level above the turbine (mm), and Δt is time (hour).

Table 1 Applied datasets

Data set	Resolution	Detail/source	Processing
Observed climate	Daily	Climate forecast system reanalysis–CFSR, precipitation, humidity, wind speed and temperature (https://globalweather.tamu.edu/)	Spatial average
Simulated climate	Daily	Precipitation, humidity, wind speed and temperature—WASCAL (Heinzeller et al. 2018)	Bias correction
Simulated climate	Daily	Precipitation, humidity, wind speed and temperature—CORDEX (https://esg-dn1.nsc.liu.se/search/cmip5/)	Bias correction
Observed discharge	Daily	Runoff-Global Runoff Data Center—GRDC (station 153 1100)	None

Fig. 3 Comparison between bias corrected and uncorrected simulated climate data of the study area
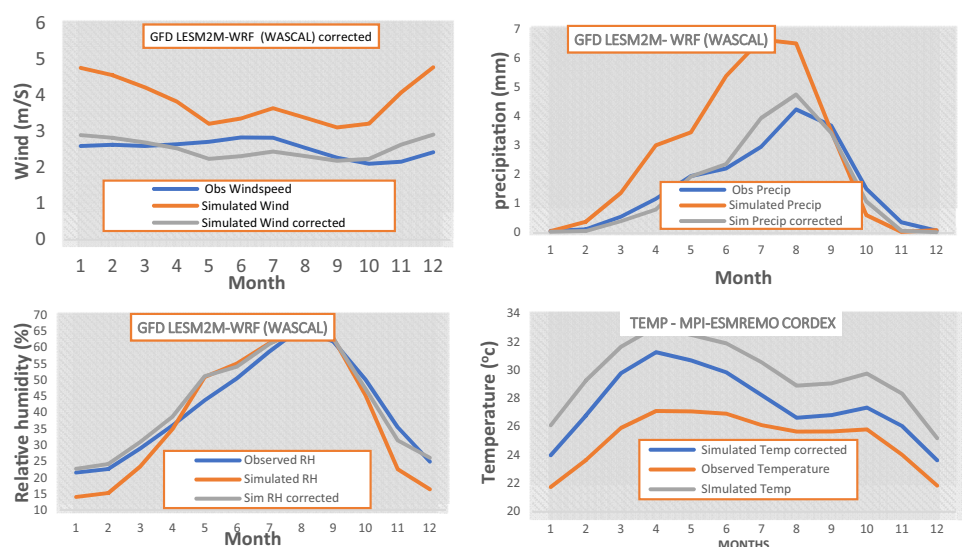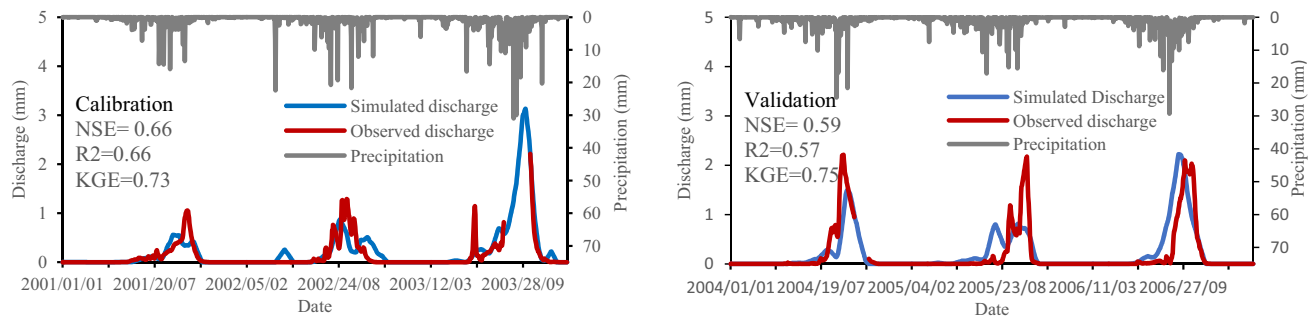
Fig. 4 Calibration and validation results of the HBV model for Bamboi catchment for the period 2001–2004 and 2004–2007, respectively

Table 2 RCM–GCM products and the corresponding label used in the study

Framework	RCM	Driving GCM	Label used in the study
CORDEX	REMO	MPI-ESM	MPI-ESM-REMO & CORDEX
WASCAL	WRF	GFDL-ESM2M	GFDL-ESM2M-WRF & WASCAL

Results

Hydrological model calibration and validation

Goodness of fit for the calibration and validation periods is shown in Fig. 4. The quality measures achieved during calibration equal 0.66, 0.66 and 0.73 for R^2, NSE and KGE, respectively, indicating a satisfactory to good agreement between observed and simulated discharges. As for the validation phase, the KGE efficiency is within the same range as during the calibration. NSE and R^2, however, dropped by 0.07 and 0.09 points compared to the calibration phase. The visual inspection of the hydrographs shows a broad agreement between simulated and observed discharges (Fig. 4).

Hydrological and hydropower potential changes

Future discharges simulated with GFDL-ESM2M–WRF (WASCAL) and MPI –ESM REMO (CORDEX) with both bias corrected and non-bias corrected climate data, were compared to the reference (historical) discharge. The comparison indicates an increase in the annual discharge by both climate models (Table 3). With bias corrected climate data, and for the mid-century (2020–2049), GFDL-ESM2M–WRF (WASCAL) projects a 14.4% increase in annual discharge, which is a consequence of relative increase in precipitation of around 11%. However, for the end of century (2070–2099), there is a slight decrease in discharge as compared to mid-century (2020–2049). These trends are similar with non-bias corrected climate data, and also apply to the MPI–ESM-REMO (CORDEX) climate dataset.

Figure 5 indicates that the maximum amount of hydropower power will still be generated in wet season and the minimum will occur during the dry season. Figure 6 further shows that the projected discharge increase will span from Jun to November. Runoff, therefore, increases with precipitation in the wet season. Figure 6 also indicates a slight decrease in discharge from December to May. Both climate datasets project a decrease in the average hydropower generation in the future as compared to the baseline period (1983–2005). The projected hydropower potential

Table 3 Projected discharge change between the reference (1983–2005) and future periods (2020–2049) and (2070–2099)

Climate model	Reference discharge (mm)	Projected change_2020-2049 (%)	Projected change_2070-2099 (%)
Bias corrected			
GFDL-ESM2M-WRF	200.890087	+ 14.4	+ 14.2
MPI–ESM-REMO	218.9933	+ 8.4	+ 5.27
Mean of the ensemble	209.94	+ 11.4	+ 9.735
Non-bias corrected			
GFDL-ESM2M-WRF	314.8618	+ 54.2	+ 35
MPI–ESM-REMO	673.4019	+ 14.3	+ 15
Mean of the ensemble	494.13185	+ 34.25	+ 25

trends by CORDEX climate product is in agreement with the WASCAL climate product, only slight differences in the magnitude of the changes can be noticed.

It is evident from Table 4 that the average annual hydropower generation will decrease in the future for both climate datasets. For the mid-century (2020–2049) period a decrease in the average annual hydropower production by − 9.1% for bias-corrected data and − 7.6% for uncorrected data climate ensemble is projected. By end of century (2070–2099), the average annual power production shows a slight increase as compared to the (2020–2049)

period; however, the amount is still lower compared to the reference period. These changes are not consistent with the simulated annual discharges as the increase in discharge is generally expected to lead to an increase in hydropower generation.
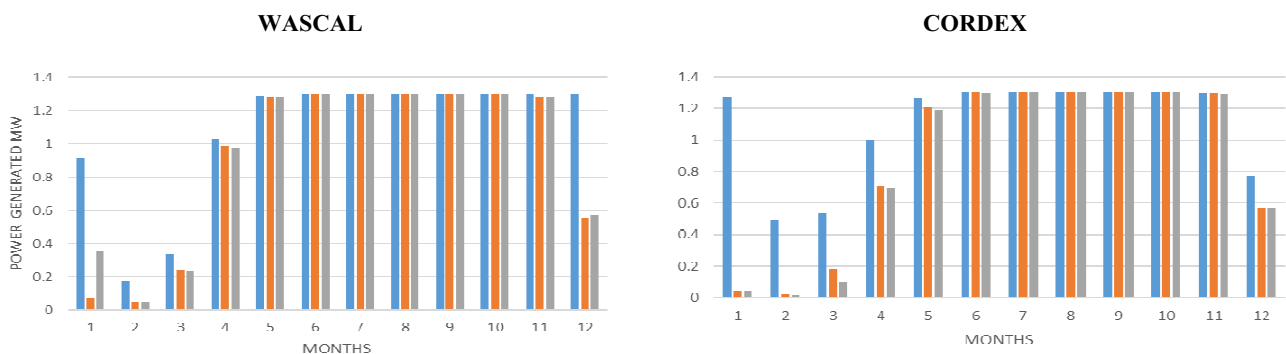

Fig. 5 Projected and historical power by WASCAL and CORDEX data sets (corrected data). Blue represent the reference period (1983–2005), orange is the future period (2020–2049), and grey represents the future period (2070–2099)

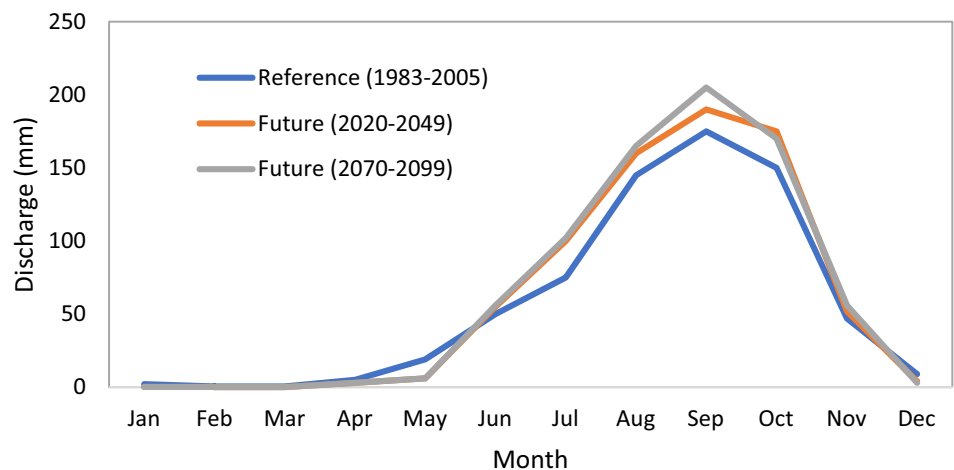**Fig. 6** Change in the annual discharge pattern (CORDEX dataset)

Table 4 Annual average projected energy generation

Period		Energy (MWh)			Change (%)	
		1983–2005	2020–2049	2070–2099	2020–2049	2070–2099
CORDEX	Corrected	7917.1	7726.5	7636.3	− 2.4	− 3
	Uncorrected	8667	7726	8582	− 10.9	− 0.9
WASCAL	Corrected	9440.5	8050.6	8257.2	− 15.4	12.5
	Uncorrected	84,000	8050.6	8314	− 4.2	− 1.02
Average	Corrected	8678.8	7888.6	7946.7	− 9.1	− 8.4
	Uncorrected	8533.5	7888.3	8448	− 7.6	− 1

Discussion

Hydrological model calibration and validation

During both the calibration and validation phases, good agreement between simulated and observed discharges was achieved. This is supported by fair model statistical quality measures. However, several discrepancies can be observed; notably, (i) some peaks are not well reproduced in 2001 and 2002, (ii) peaks are underestimated in 2001, 2002, 2004 and 2005 and (iii) peaks are overestimated in 2003. Beside model imperfection, important gaps in the GRDC runoff time series combined with the use of reanalysis climate data (CFSR) can reasonably explain these discrepancies (Poméon et al. 2017). The suitability of the HBV model to simulate the hydrology of some West African catchments is reported by Yira et al. (2019). The often-mentioned misrepresentation of peak flow by the model is usually attributed to measurement errors during high discharge events as overbank flow characterizes many rivers in the region.

Hydrological and hydropower potential changes

Projected increase in the annual discharge by the middle and end of the twenty-first century as a consequence of precipitation increase is reported for the West African region (Badou et al. 2018; Yira et al. 2017). For Sylla et al. (2015), the projected large patterns of increased precipitation in the Sahelian region is due to intensification of the hydrological cycle by increasing atmospheric temperatures. Due to the water limited environment feature of catchments in the region, precipitation (and soil moisture) dictates their hydrological behavior.

A decrease in the average annual hydropower generation in the future is also reported by several previous studies in the region (e.g. Obahoundje et al. 2015). Such a decrease is, however, attributed to a decrease in precipitation and the resulting impact (reduction) of runoff inflow into the hydroelectric dam. Conversely, the simulated annual increase in discharge as achieved in the current study does not lead to an increase in hydropower generation. As the designed run-of-river system in the current study has a fixed maximum capacity, only a discharge increase leading to an increase in the flow duration over the dry period would induce an increase in hydropower generation potential. This stems from the fact that the system already operates at its full potential (1.3 MW) during the rainy season (this is not the case in the dry season), and increasing the river discharge does not affect this potential (while a decrease lower than this potential would affect

the HPP). Both WASCAL and CORDEX climate datasets projected an increase in precipitation and discharge in the rainy season for the future periods. However, this increase in discharge occurs during the wet season where the power plant already operates at its full potential. As a consequence, the discharge increase does not translate in additional energy production. The annual discharge increase is overshadowed by a decrease in monthly discharge during the dry season. This decrease of discharge over the dry season will lead to a loss of HPP.

Conclusion

A statistical bias correction was applied to two RCM-GCM datasets, GFDL ESM 2 M of WASCAL high resolution climate product and MPI ESM REMO of CORDEX Africa project both under scenario RCP 4.5 to assess the impacts of climate change on the hydropower potential of the Bamboi catchment comparing two future periods 2020–2049 and 2070–2099 to a reference period (1983–2005). Projected historical and future discharges data were converted to hydropower potential following a run-of-river hydroelectricity generation model. The results showed that the hydrological simulation model HBV was successful in simulating the hydrological regime of the Bamboi catchment as evidenced by the statistical quality measures producing minimum values of 0.57 for Nash–Sutcliffe efficiency, 0.73 for Kling–Gupta efficiency, and 0.59 for R^2 during the calibration and validation. All these values indicate a good agreement between observed and simulated variables making the model reliable in climate impact assessment.

The results further indicated that precipitation will increase in both future periods (so is temperature); however, the hydropower potential will decrease for both future periods, it is projected to decrease in the dry season December to May while the discharge increase in the wet season May to August is not convertible to hydropower as these discharges exceed the maximum capacity of the turbines. Both climate datasets, considering uncorrected and corrected climate data, are agreeing that hydropower production is projected to decrease towards end of the century 2070–2099, while the decrease in the mid-century is even higher.

Author contributions The authors made equal contributions to the design and writing of this manuscript.

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