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ORIGINAL ARTICLE

Sensitivity of Hydropower Generation to Changes in Climate and Land Use in the Mono Basin (West Africa) using CORDEX Dataset and WEAP Model

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Abstract

The availability of water resources in a reservoir for electricity generation is strongly linked to climate and weather conditions. Also, the use of these water resources is influenced by the population size as well as anthropogenic activities. This research attempts to assess the combined effects of (i) climate change (CC), (ii) land use/land cover change (LULCC), and (iii) development (Dev) conditions on water resources and hydropower generation (HPGen) using Regional Climate Models (RCMs) from Coordinated Regional Downscaling Experiment (CORDEX) under the Representative Concentrated Pathways (RCP): RCP4.5 and RCP8.5. The RCMs considered are: CanRCM, CCLM, and WRF being drived by CanESM2, CNRM-CERFACS, and NorESM1, respectively. The Water Evaluation and Planning model (WEAP) tool is used to simulate the water availability and HPGen in the Mono basin under present and future conditions. The ensemble mean of the three-climate dataset analysis reveals that the temperature is projected to increase significantly while the precipitation change is uncertain under both RCPs in the near (2020–2050) and the far (2070–2090) futures. These changes in climate variables consequently affected simulated water availability for different water consumption sectors especially the HPGen in the near and far futures. Moreover, the Dev was found to exacerbate the burden that constitutes the CC for water availability and HPGen. Nevertheless, LULCC associated with either CC or both CC and Dev were projected by all the RCMs and their ensemble mean to reduce this burden. However, its side effects namely reservoir siltation and sedimentation need to be deeply investigated.

Keywords Climate change · CORDEX · Mono river basin · Hydropower generation · LULCC · WEAP model

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1 Introduction

Climate change (CC) is acknowledged as one of the major concerns for our societies, threatening all economic sectors. It is indeed expected to alter the temperature balance and rainfall regimes at global scale, leading to a major change in the regional hydrological cycle impacting several sectors of activities such as agriculture, water, and energy sectors (ACPC 2011). Thus, the role of energy sectors that rely on water resources for their operation is expected to be challenged under changing climate conditions (Raje and Mujumdar 2010; Schaeffer et al. 2012). This is more evident with water resources becoming scarce while the demand keeps increasing due to economic development and population growth (Yang et al. 2016). Indeed, multi-purpose reservoirs play a key role in supplying the population with drinking and irrigation water. They also mitigate impact of extreme events like floods and droughts (Lee et al. 2016). These reservoirs further ensure navigation, fishing (Yuksel 2009), and power generation. Even though hydropower (HP), as well as other renewable sources of energy (IPCC 2011), can be a key tool to mitigate and adapt to CC, they are also vulnerable to it and its variability (IHA 2019) due to their climate dependency. The dependency of energy sector on the climate system is likely to increase in the current context of global warming (IPCC 2011). CC is likely to impact water availability, stability, access, utilization, demand (ACPC 2011), and security (Brown and Crawford 2008) in most African countries.

Hydropower generation under climate conditions was demonstrated to be more sensitive to total runoff and reservoir level. For example, sub-Saharan Africa hydropower plants (HPPs) have experienced in the the past some CC and variability effects, and they have failed to deliver the power to meet the demand (Cole et al. 2014). To illustrate this, the Akosombo dam experienced a significant disruption in the generation of hydropower, which was due to reduced regular flow of water into the reservoir (Kabo-Bah et al. 2016), suggested to be directly linked to climate change (Boadi and Owusu 2017). Moreover, in Nigeria, the Kainji dam (Niger river basin) has faced the same challenges, as consequences of changes in climate and decrease in runoff (Salami et al. 2015), and resulting drop in reservoir stored water (Olofintoye and Adeyemo 2011). It was further reported that since 2013, hydroelectricity generation has fluctuated, largely due to the impact of droughts on the water availability at large dams in Zambia (Simon Trace 2019).

The future CC impacts on HP production may not be equally distributed and are suggested to vary according to the region and country (IPCC 2011). Some may experience an increase in production while others could experience a decrease. For example, in the Swiss Alps (Schaefli et al. 2007) and Mediterranean countries of Western Europe and Northern Africa, potential CC has a statistically substantial adverse effect on the hydropower system performance, while in Scandinavian countries (Norway, Sweden, and Denmark), a positive effect is projected (Turner et al. 2017). Generally, at continental (Africa) and regional (West Africa) levels, there are limited impacts of the changes in climate conditions on the HP generation (HPGen) (Blacksher et al. 2011; Hamududu and Killingtveit 2012). However, the magnitude of the impacts of CC on HPGen can be perceived at country level. Thus, somes studies suggested that CC could lead to a decline in the performance of hydropower systems accros Guinea (-12.9%), Mali (-13.17%), Togo (-14.4%), Ghana (-14.5%), Burkina Faso (-15.3%), Côte d'Ivoire (-15.3%) and Nigeria (-15.18%) over the period 2040–2069 relative to 1965–2000 (Turner et al. 2017). Other studies, on the other hand, projected an increase in runnof in some parts of West Africa (WA), especially in Guinea, Sierra Leone, Liberia, Western and southern part of Côte d'Ivoire (Kling et al. 2016; Stanzel et al. 2018), which may have a positive impact on HPGen.

Hydrological impacts of CC can exacerbate existing water stress (Raje and Mujumdar 2010) especially in Africa (van Vliet et al. 2016) and need to be considered in water management as reported by Amisigo et al. (2015). CC is suggested to cause a decrease in hydropower (existing and projected) technical performance across Ghana especially over the Volta basin (Amisigo et al. 2015; McCartney et al. 2012). Moreover, McCartney et al. (2012) found that the combined effects of the CC and different development conditions could add burden on water resources stress and affect negatively all activity sectors that consume water including hydropower plants.

In contrast to the Volta Basin, the assessment of CC impacts on Kainji dam in Niger river using the ensemble mean of eight GCM models projects an increase in HPGen under RCP4.5 and RCP8.5 scenarios (Oyerinde et al. 2016). Indeed, CC may lead to an increase in rainfall and streamflow over the Kainji Lake, thereby adding to untapped hydropower potential in the region (Oyerinde et al. 2016). This divergence in projected HPGen CC impacts between the Volta (Amisigo et al. 2015; McCartney et al. 2012) and Niger (Oyerinde et al. 2016) river basins underlines the importance to conduct such works at basin scale. Moreover, the potential water availability across the five major river basins (i.e., Senegal, Gambia, Volta, Niger and Chad) in WA is suggested to have a substantial decrease (from 10 to 40%) under RCP4.5 and RCP8.5 (Sylla et al. 2018a), which may severely affect HPGen. The vulnerability and resilience to CC of HPP in WA region is not well known as the projected precipitation (key driver of water availability in streamline and reservoir) remains uncertain (Riede et al. 2016). Although the effects of CC on HPGen has been widely investigated (Blacksher et al. 2011; Boadi and Owusu 2017), there are still few and rare works focusing on plant scale in WA. Hence, as the hydropower impacts of CC may depend on the hydrological condition and the geographical features of the basin where the dam is located; it is, therefore, necessary to drill down the analysis of CC impacts to the sub-national or local scale of HPGen (Shu et al. 2018).

Besides CC, there are other factors that can affect water availability in the river basin. Some studies suggest that CC in Africa will overall have a limited influence on future water availability relative to other drivers, such as population growth, urbanization, agricultural growth, and land use change (Niang et al. 2014). WA countries show rapid demographic growth which could further lead to significant land use change, such as urbanization and deforestation, providing additional cropland to feed the growing population. WA basins, as well as other regions of the continent, are also reported to be under a rapid change in land use and land cover (Cotillon 2017). This is the case for the Mono basin (Obahoundje et al. 2018).

There is a strong link between land-use dynamics, energy generation and CC (Dale et al. 2011). Thus, the HPGen depends on the land use/land cover (LULC) type of the river basin where the plant is located (Stickler et al. 2013). Indeed, the spatio-temporal variations of precipitation and temperature may be influenced by changes in LULC and climate system (Kabo-Bah et al. 2016). The land use/land cover change (LULCC) can modify the surrounding climate and precipitation patterns (Degu et al. 2011), subsequently altering local and regional hydrology regimes (Amoussou 2015; Faye et al. 2015). In hydrology, the land use dynamics (in the perspective of declining in vegetative cover) can impact the soil water holding capacity, resulting in a reduction of infiltration rate and increase in runoff generation (Mahe et al. 2005). Consequently, the streamflow will increase despite the reduction in rainfall. Two other paradoxes were experienced in WA region. The first paradox was observed during the 1968–1990s ‘Great Drought’ period, during which runoff significantly increased. The second started since the 1990s, during which the runoff coefficient continued to increase despite the general regreening of the Sahel (Descroix et al. 2018).

The hydrological impacts of LULCC has been shown to have a direct effect on hydropower schemes depending on the basin and the magnitude of changes. For example, in the Swiss Alpine Rhine basin in Europe, the LULCC is suggested to reduce the runoff generation and then the HPGen (Verbunt et al. 2005). In WA, on the other hand, the LULCC seems to have a positive impact on the runoff generation (Akpoti et al. 2016; Kouame et al. 2019). Thus, the LULCC effect could reduce the CC burden on HPGen as discussed by Obahoundje et al. (2017) over the dam of Bui in the Black volta basin.

The understanding of the combined effects of LULCC and CC on WA HPGen remain then at an early stage, highlighting the need for more studies at both regional and local scales. Also, the Mono river basin has never been studied in assessing future climate change impacts on HPGen. The current study is an attempt to assess, using CORDEX data, the effects of LULCC, development condition, and CC conditions on HPPGen and water availability in the Mono river basin. Specifically, this study evaluates how CC alone, combined CC and LULCC, CC under development conditions, and combined CC and LULCC under development conditions could potentially affect both HPPGen and water availability in the Mono river basin. The existing (Nangbeto) and planned (Adjarala) HPPs in the Mono river basin were considered. RCP4.5 and RCP8.5 of CORDEX data were used for CC conditions as input to WEAP model.

2 Materials and Methods

2.1 Study Area

Mono river basin is a transboundary catchment shared between Togo and the Benin Republic, covering an area of 24,282.26 km^2. It stretches between 0.8° -2°E longitude and 6.2°N-9.6°N latitude. The basin is drained by Mono river with a length of about 400 km (Fig. 1). The river originates in the North between the Sokodé town in Togo and the Benin border and flows southward to Grand Popo in Benin. A large part of the basin is rural and used for agricultural practices mainly for the cultivation of maize, yams, rice, cotton, and cassava (AfDB 1995). In the Mono river basin, the Nangbeto dam is built in Togo with a capacity of 65 MW, and the Adjarala dam (147 MW) is planned in Benin. The Mono basin land is covered typically by savannas (wooded and herbaceous), gallery forest, swampy areas and agricultural land (cropland and irrigation), as well as built-up areas (CILSS 2016a). Wooded savannas cover over two-thirds of the basin, mostly located from the central to northern part of the basin, while the swampy areas are found in the southern part and the gallery forest along the Mono river and its main tributaries (Obahoundje et al. 2018).

The basin geology is made of quartzites of the Atakorian in the North-East. The major part of the basin is made up of the Dahomean granito-gneiss locally with intrusions of granite and basalt while around 10% is quartzite (ORSTOM 1963).

The Mono river basin climate relies on the west African climate system which is controlled by the movement of the Inter-Tropical Convergence Zone and influenced by the Monsoon and Harmattan (Obahoundje et al. 2018). Its southern part located in the Guinean zone (transitional equatorial climate) of the basin, has a bimodal regime (March–June, and August–November as rainy seasons) with total annual precipitation between 1000

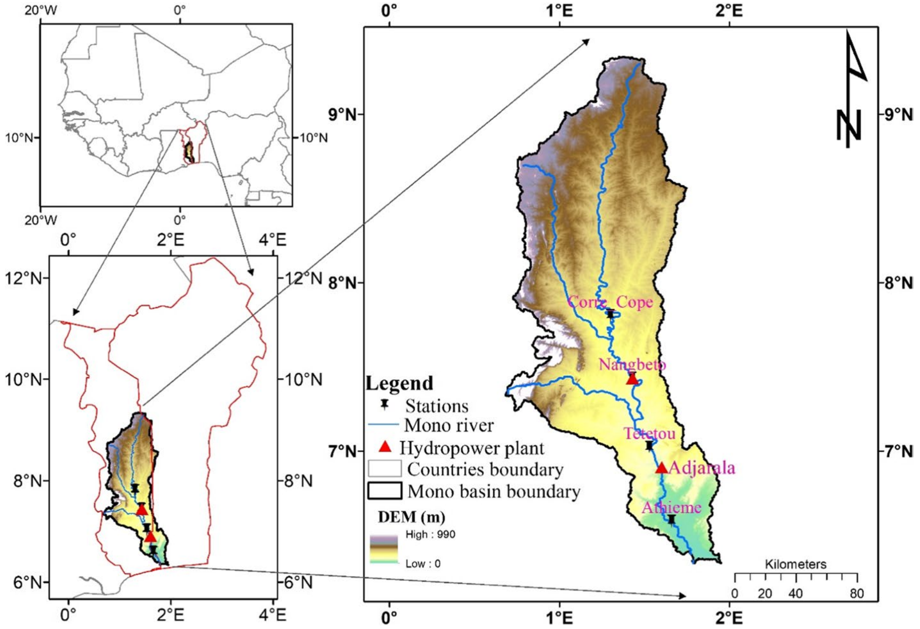


Fig. 1 Mono river basin shared between Togo and Benin Republic in West Africa

and 1100 mm (increasing Western-easterly ward). The Central and northern parts of the basin, located in the Sudanian zone, record a total annual precipitation between 1100 and 1900 mm (increasing eastern-westerly) (Amoussou et al. 2012). However, during December through May, the streamflow is almost null, while during the wettest months (June to October), the streamflow varies from 50 m^3/s to 400 m^3/s (Amoussou et al. 2012).

2.2 Data

2.2.1 Hydroclimatic Data

CORDEX is a global collaborative initiative that aims to develop the knowledge of regional downscaling of global climate scenarios, and provide and develop detailed, regional climate information necessary for vulnerability, impact, and adaptation studies at local and regional levels (Gutowski et al. 2016). CORDEX projections were extracted for the historical and future period following RCP4.5 and RCP8.5 (1970–2090) with a spatial resolution of 50 by 50 km. The analysis framework makes use of 3 Global Circulation Models (GCM) and 3 Regional Climate Models (RCM), as well as their ensemble mean. Table 1 shows the matrix of the simulations and the data used are open source available at Earth System Grid Federation (see https://cordex.org/). The chosen models were validated and widely used over WA for impact studies (Bichet et al. 2020; Sylla et al. 2018a, b). Daily precipitation, near-surface mean air temperature (2 m), near-surface wind speed, evaporation, and total cloud fraction have been extracted from the climate projection data and imported as input to the WEAP model.

All the climate historical data (precipitation, temperature, and wind speed) used to generate the baseline (Reference scenario) were extracted from Global Meteorological Forcing

Table 1 CORDEX climate projections used in the present research

Model number	Driving Global Climate Model (GCM)		Regional Climate Model (RCM)	
	GCM	Modelling Agency	RCM	Modelling Agency
(1)	CanESM2	CCCma	CanRCM	CCCma
(2)	CNRM_CERFACS	CNRM_CM5	CCLM	CLMcom
(3)	NorESM1	NCC	WRF	BCCR
(4)	Ensemble mean		Ensemble mean	

CanESM2 Second Generation Canadian Earth System Model, *CCCma* Canadian Center for Climate Modeling and Analysis, *CanRCM* Canadian Regional Climate Model, *CNRM* Centre National de Recherches Météorologiques, *CERFACS* Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, *CLMcom* Climate Limited-area Modelling Community, *NorESM1* Norwegian Earth System Model, *NCC* Norwegian Climate Centre, *WRF* Weather Research and Forecasting, *BCCR* Uni Research and the Bjerknes Centre for Climate Research

Dataset (GMFD) for land surface modelling. The GMFD data has a spatial resolution of 0.25 degrees (approximately 28 km) based on bias-corrected climate model output at the Princeton Data Source (Sheffield et al. 2006). GMFD was used to model the impact of climate change on water resources and agriculture demand in the Volta Basin using WEAP model (Amisigo et al. 2015). However, the relative humidity and evapotranspiration come from in situ observation. For more precision in spatial analysis in WEAP model, it is recommended to discretize a watershed into several small catchments depending on the data available (SEI 2015). In our case, the Mono basin was divided into four sub-basins namely Corre-cope, Nangbeto, Tetetou, and Athieme from North to South.

Observed streamflow data for four hydrological stations (Corre-cope, Nangbeto, Tetetou, and Athieme) were obtained from the Mono River Authority at daily timestep for 1970–2018. This data is used as input to the WEAP model basic scenario.

2.2.2 Land Use and Land Cover Data

The LULC classified by Obahoundje et al. (2018) was used as input for catchment land use data (Table 2). To run WEAP before 1988, we assume that land cover type has remained the same from 1970 to 2020 for all scenarios.

Table 2 Land use dynamic in Mono basin (Obahoundje et al. 2018)

Land Cover Types	Area (%) 1988	Area (%) 2002	Area (%) 2016	% Change (1988–2002)	% Change (2002–2016)	% Change (1988–2016)
Water Bodies	0.14	0.49	0.47	16.67	−0.23	8.2
Built-up	7.95	9.08	15.63	0.95	4.81	3.33
Agricultural Land	7.31	16.24	18.69	8.14	1.01	5.37
Herbaceous Savanna	47.98	55.63	38.97	1.06	−2	−0.65
Savanna	30.1	18.19	26.2	−2.64	2.93	−0.45
Forest	6.52	0.37	0.04	−6.29	−6.02	−3.43

The LULCC maps can be seen Fig. 3 of the study of Obahoundje et al. (2018)

2.2.3 Demography and Socio-economic Data

The municipal water demand was separated between urban and rural domestic demand. We assumed that 70% of the population within the Mono basin lives in a rural area while the remaining 30% lives in an urban area (e.g., in the cities Atakpamé, Sokodé, etc.). The estimated population per sub-catchment is shown in Table 3 for the years 2000, 2005, 2010, and 2015. Population data is obtained from the Gridded Population of the World version 4 (GPW) with an output resolution of 30 arc-seconds, or ~ 1 km at the equator (CIESIN 2016). Population increases for years in-between is interpolated using polynomial interpolation. A catchment population was then computed as the area of sub-catchment times the population density. The computed catchment population increases in the north-southern direction. This means that the Athieme catchment has the highest computed population and Corre-cope the lowest. In contrast, the population growth rate computed per sub-catchment increases from south to north.

UNESCO (1998) estimated that in developing countries in Asia, Africa and Latin America, public water withdrawal represents just 50–100 L per person per day. In WA, water use rate is estimated at 50–110 L/capita/day (lpcd) for urban demand and 20–50 lpcd for rural areas (WATAC 2000). Based on previous work in the Volta basin (Amisigo et al. 2015; McCartney et al. 2012), we assumed that the per capita daily water demands are 70 lpcd for urban and 37 lpcd for rural. This is applied to all four catchments and the assumed values under development conditions (described below) are presented in Fig. 2. Indeed, domestic water demand is expected to increase significantly over the 2010–2050 period especially in African and Asian sub-regions (UNESCO 2018).

The livestock data is extracted from Global Livestock Production Systems v.3 of Food and Agriculture Organization (FAO 2007a) (Table 3). Sub-Saharan Africa has a livestock growth rate of 3.2% for 1997–2015 and is expected to reach 3.3% for 2015–2030 (FAO 2007b). However, catchment density data (cattle, chicken, goats, pigs, sheep) was compiled using the growth rate of 3% at each catchment. The livestock density was multiplied by the catchment area, then the tropical livestock unit (TLU) was applied to each livestock category, and finally, summation gave the total livestock of a catchment. Tropical Livestock Units are livestock numbers converted to a common unit by multiplying by the following conversion factors: cattle = 0.7, sheep = 0.1, goats = 0.1, pigs = 0.2, chicken = 0.01 (HarvestChoice 2015). The daily water used per livestock is estimated as 50L/livestock/day (McCartney et al. 2012).

Table 3 Mono basin livestock, population, and irrigation data

Sub-catchment	Area (km^2)	Livestock	Population					Irrigation (ha)	
		2006	2000	2005	2010	2015	Growth Rate (%)	2000	2013
Corre-cope	10,277.6	90,847	337,106	403,808	487,262	592,094	5.04	0.00	0.00
Nangbeto	6,028.0	54,489	249,621	293,384	346,371	410,870	4.30	3,666.2	3,666.2
Tetetou	6,797.7	71,880	398,075	461,770	537,320	627,363	3.83	3,003.6	3,003.6
Athieme	1,178.9	23;267	288,905	333,019	384,040	443,054	3.55	6,222.7	6,222.7
Total	24,282.3	240,483	1,273,7	1,491,981	1,754,993	2,073,382		12,892.5	12,892.5

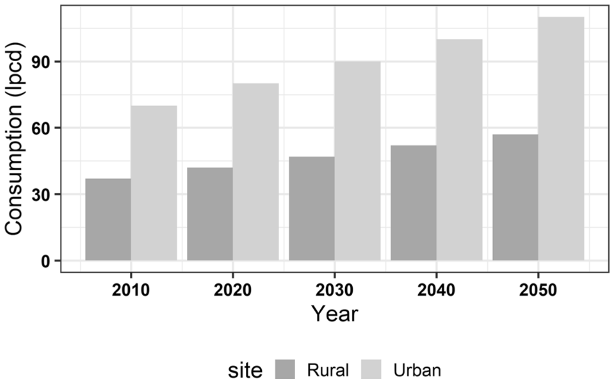


Fig. 2 Assumed per capita domestic water demand used in WEAP

The irrigated area data per catchment was extracted from the Permanent Interstate Committee for Drought Control in the Sahel (CILSS) LULC data (USGS and CILSS 2016) (Table 3). The irrigated crops in this basin were mainly rice and sugar cane. The annual water used per ha is estimated at 16,000 m^3.

2.2.4 Hydropower Plant Characteristics

Mono basin is a socio-economic zone for riparian countries. Within the Mono basin, the existing Nangbeto HPP is built in Nangbeto sub-basin (AfDB 1995) for electricity generation for Togo-Benin through CEB (Compagnie d'Electricité du Bénin) company. Due to demographic and economic growth, the energy demand has increased for both countries. To meet this demand another HPP at the Adjarala site (WAPP 2013) in Athieme sub-catchment is also planned. The characteristics of both hydropower schemes are summarized in Table 4.

2.2.5 Scenarios Development

Four scenarios are developed in addition to the reference one which is based on a combination of three conditions. The reference scenario is "business as usual" and is based on the observed hydroclimatic variables (1970–2010). The developed scenarios are climate change condition (CC), combined climate and LULCC condition (LULCC_CC), combined climate change and development condition (Dev_CC), and combined climate change, development, and LULC dynamics condition (Dev_LULCC_CC). The three used conditions are: (i) climate change based on projected CORDEX data RCP 4.5 and RCP 8.5; (ii) land use/cover change; and (iii) development (Dev) conditions. They are presented as follows:

Table 4 Hydropower plant characteristics

Hydropower plants	Install capacity (MW)	Volume (Mm^3)	Head (m)	Energy (Gwh/yr)	Maximum turbine flow (m^3)
Nangbeto (existing)	65	1710	30	170	2×120
Adjarala (planning)	147	680	54	367	3×105

- CC change condition is based on CORDEX output (Table 1) by considering RCP4.5 and RCP8.5;
- The LULCC refers to a change in an area exposed to anthropogenic activities. The LULCC condition assumes that the vegetative areas decrease by 1% per year and the land-use area (agricultural land and build up areas) increase by the same rate which is set in place as of 2020. Indeed, most WA countries have experienced change and degradation of vegetative areas over these last few decades, caused mainly by human activities such as agriculture expansion, bush fire, and timber extraction (Cotillon 2017; Atsri et al. 2018). A large part of natural vegetative covers has been converted to anthropised area in all WA countries. In WA, between 1975 and 2013, the forest areas have decreased by 24.6%, while settlement and agricultural land coverage have increased by 140% and 11.7%, respectively (Cotillon 2017). Togo and Benin as well as all WA countries have experienced a decline in vegetative cover (forests, woodland, savanna) and an increase in land use (agriculture and settlement). In Togo, within the same period, the agricultural land has increased by 14,000 km^2, or 266%, and had the highest annual expansion in WA (7%/year between 1975–2013) (CILSS 2016a). In Benin, within the same period, the agricultural land has increased from 9.2% to 27.1% (CILSS 2016b). It is important to highlight that the Mono river basin is transboundary shared between Togo and Benin.
- The development condition is expressed by increasing in municipal water demand by 1.42% per year (Fig. 2) as well as irrigated areas. Under such scenario, we assumed that the planned 43,000 ha irrigated area under the Nangbeto dam (AfDB 1995) will be fully developed by 2050. It will be set in place in the Nangbeto catchment progressively from 13,000 ha in 2020 by adding to this area 10,000 ha each decade. Besides, the Adjarala hydropower plant project will be set in place by 2020 in the model.

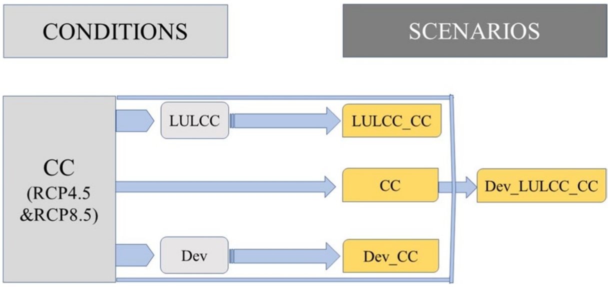
Developed scenarios are summarized by the flowchart in Fig. 3 and LULCC and Dev condition will be effective as of 2020. Also, a polynomial interpolation is used for extrapolating the population from 2016 to 2090 for all scenarios.

2.3 Methodology

2.3.1 WEAP Models Description

WEAP has been used widely for similar studies based on his ability to assess sectoral water demand analyses, LULC & CC impacts on hydrology, streamflow simulations as well as reservoir operations HPGen (Amisigo et al. 2015; McCartney et al. 2012; Allwaters Consult

Fig. 3 Flowchart of developed scenarios used in WEAP



Limited 2012). In WEAP, catchment processes such as evapotranspiration, runoff, infiltration, and irrigation demand are accounted for following four methods that are well described in the WEAP user guide (Sieber and Purkey 2011). These methods include: (a) the Rainfall Runoff; (b) the Irrigation Demands Only versions of the FAO Crop Requirements Approach; (c) the Soil Moisture Method; and (d) the MABIA Method.

The Soil Moisture Method was selected for the present work based on its ability to integrate climate variables, and the characterization of land use and/or soil type impacts to these processes (Obahoundje et al. 2017). The different time series and scenarios presented in Section 2.2.1 are used as input to WEAP to simulate dam operations, water withdrawal for irrigation and crop yields at monthly time step.

2.3.2 Data Adjustment

To evaluate the probable future change in climate variables (precipitation and temperature) over the basin the bias of the climate data of the model was adjusted. This was made based on the delta change method for precipitation and temperature, according to Eqs. (1) and (2), respectively, to compute the probable change (Eq. 3) for each variable. Also, the energy generation (simulated) of each model was normalized with a reference scenario generation using the delta change method. Indeed, the coefficient (δ) was computed by subtracting the mean generation of models from the reference scenario (Eq. 1). After the adjustment of the simulated energy, the rate of change for the near and far future are computed following Eq. (3). The relation to adjusting a bias in data using the delta change method is given by the two first following equations (Maraun 2016):

$$x^f_{i,adj} = y^p_i + \left(\overline{x}^f_i - \overline{x}^p_i\right) \tag{1}$$

$$x^f_{i,adj} = y^p_i \times \frac{\overline{x}^f_i}{\overline{x}^p_i} \tag{2}$$

$$Change_{future} = \frac{\overline{x}^f_{i,adj,future} - \overline{x}^f_{i,adj,hist}}{\overline{x}^f_{i,adj,hist}} \tag{3}$$

where, $\overline{x}^f_i$ and $\overline{x}^p_i$ are the mean of observed (reference scenario) and mean of simulation both for historical period, respectively; y^p_i is the model output simulation for future; and $x^f_{i,adj}$ refers to the adjusted output model.

2.3.3 WEAP Model Performance

Figure 4 presents the observed and simulated streamflow at Athieme (downstream of the basin in Fig. 4a) and Nangbeto (upstream of the dam in Fig. 4b) hydrological stations from 1990 to 2010 at monthly timestep. The model reproduces correctly the observed seasonal pattern and inter-annual variability. To explore how well the model reproduced streamflows as observed at any given gauging station, the Nash–Sutcliffe Efficiency (NSE) and the coefficient of determination (R^2) were computed for 1990–2000 and 2000–2010 periods for model calibration and validation, respectively. The NSE were 0.82 (0.86) and 0.81 (0.87) for calibration and

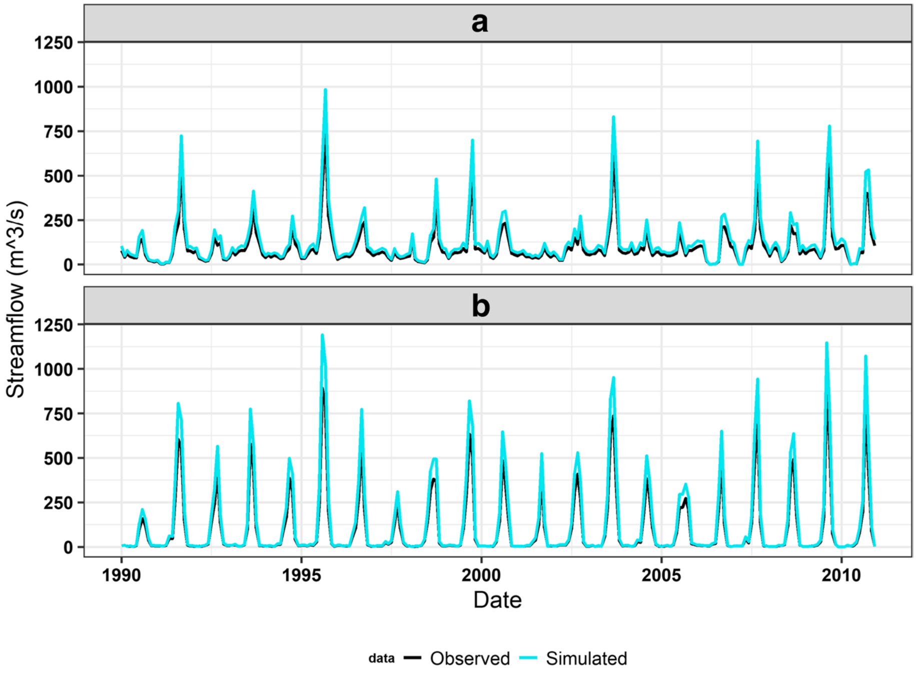


Fig. 4 Observed and simulated streamflow: **a** Athième and **b** Nangbéto hydrological stations (1990–2010)

validation at Athieme (Nangbeto) hydrological stations despite having some bias (overestimation 31% for both calibration and validation at Athieme, and 25.9% and 24.9% for calibration and validation, respectively, at Nangbeto). The observed and simulated monthly streamflow for calibration and validation periods are presented in Figs. 4 and 5.

3 Results and Discussion

3.1 Energy Simulated under Current Climate

Figure 6a, b exhibits the simulated energy generation (raw and adjusted respectively) for the historical period 1970 to 2000. Though the Nangbeto plant operation started in 1987 and for Adjarala is supposed to be in 2020, we consider the historical energy generation for 31 years (1970–2000) which are going to be compared with the future energy generation 2020–2090 period. This future period is subdivided into two sub-periods, namely: near future (2020–2050) and far future (2060–2090). In general, the energy generated under the historical period with all model scenarios is closer (with slight overestimation Fig. 6a) in the reference scenario. The mean annual (white star in Fig. 6), the minimum and maximum energy generation vary according to the model and HPP (Fig. 6a). The highest mean value is obtained from model1 for both HPPs. The raw energy generation simulated was then bias adjusted to the reference scenario (see Fig. 6b for 1970–2000 period).

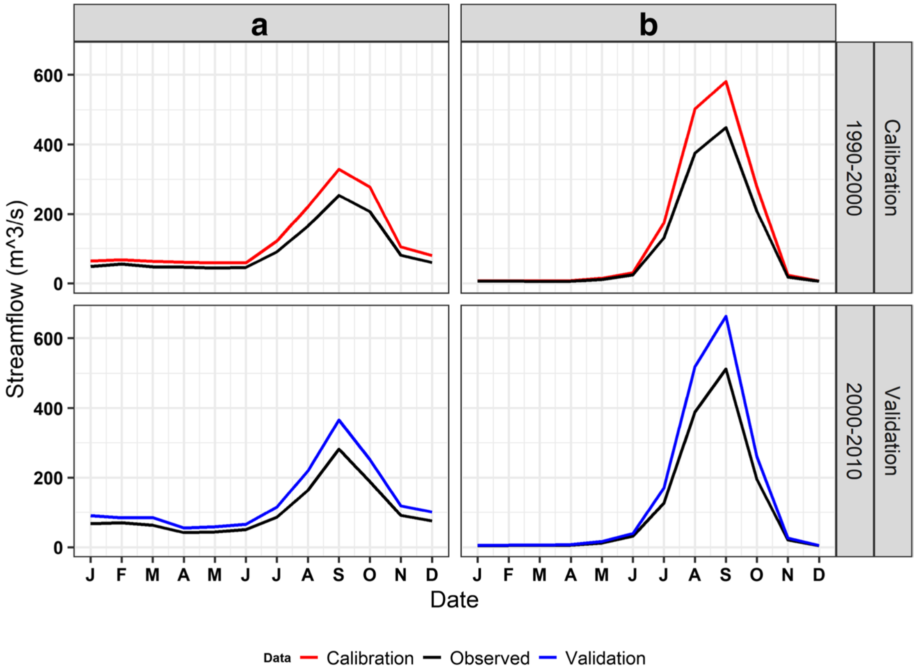


Fig. 5 WEAP calibration (1990–2000) and validation (2000–2010) (Calibration in first row subplots and validation in second-row subplots for Athiémé (first column) and Nangbéto (second column) hydrological stations. **a** Athieme and **b** Nangbeto

The reference scenario generation presents a negative skew distribution. However, model1 (CanRCM driven by CanESM2) and model3 (WRF driven by NorESM1) were positively skewed. All the scenarios under each model present the same Inter Quartile Range (IQR), the same minimum and maximum, and the same mean as well as the same first and third quantiles and outliers (Fig. 6a). Indeed, the effects of LULCC, as well as development (Dev) scenario, started as of 2020 and this could justify the same characteristics of generation observed under all scenarios of the same model for both power plants. These values (IQR, minimum and maximum, first and third quantiles and outliers) still vary according to the model after the bias adjustment but the mean annual energy generation becomes the same as the reference scenario (Fig. 6b).

3.2 Change in Climatic Variables

Figures 7 and 8 exhibit the probable annual change in CORDEX temperature and precipitation for the near (2020–2050) and far (2060–2090) futures. A bias adjustment based on the delta change method was applied for temperature and precipitation at monthly resolution before evaluating their probable change in the future (Maraun 2016; Chilkoti et al. 2017).

The difference between the near future and the historical period (1970–2000) on one hand and, on the other hand, the difference between the far future and historical period were computed for adjusted temperature (mean) and precipitation (total annual) based on Eq. (3). A Student test (t.test) was used to detect the statistical significance of this change.

All three models as well as their ensemble mean projected an increase in mean temperature for near and far futures with both RCP4.5 and RCP8.5 (Fig. 7). This change is

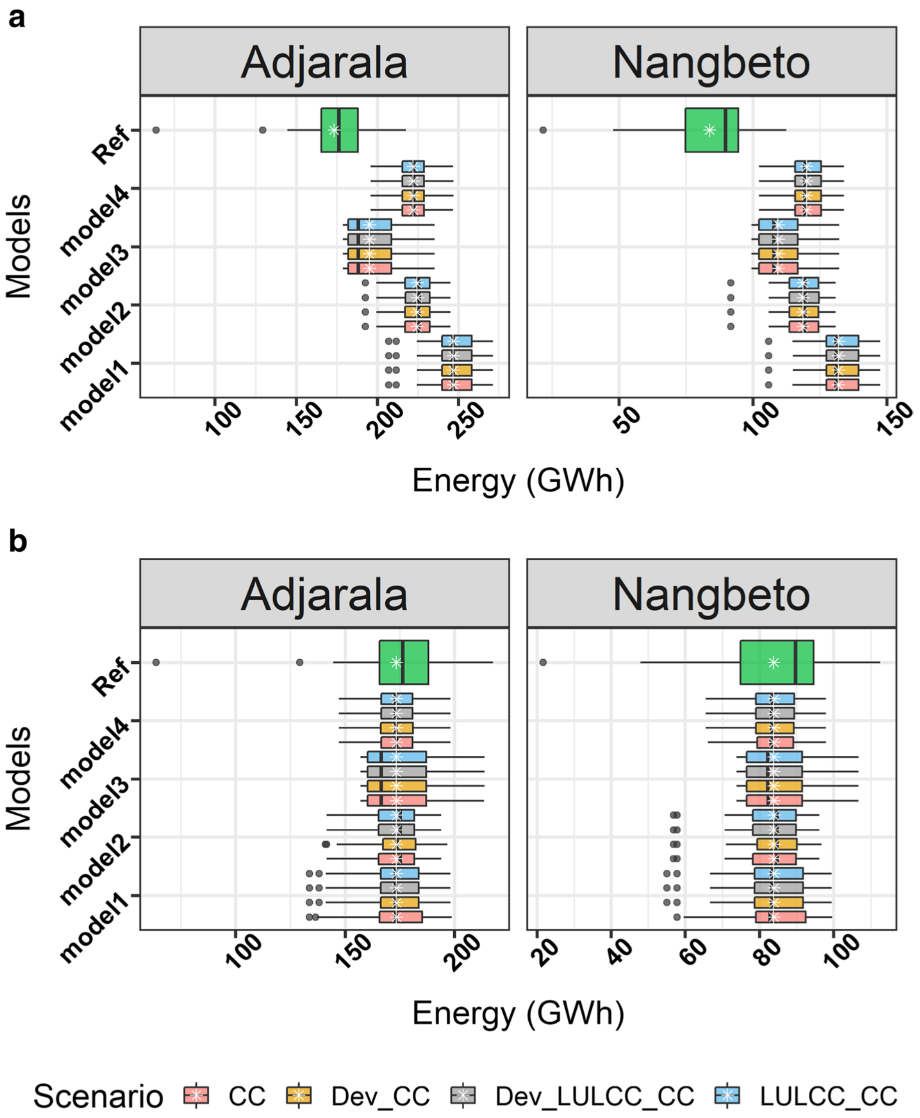


Fig. 6 Simulated hydropower plant under historical period 1970–2000: **a** raw energy; and **b** adjusted energy. (model1: CanRCM driven by CanESM2; model2: CCLM driven by CNRM_CERFACS; model3: WRF driven by NorESM1; model4: Ensemble mean

statistically significant at a 95% confidence level ($p < 0.05$; see Table SM1 in supplementary materials). The projected temperature changes with all models are greater under RCP8.5 than RCP4.5 for both periods (near and far future). The highest and lowest changes are given by model1 and model3, respectively, under both RCPs and for both periods. For instance, with RCP4.5 of near future (top-left plot), model1 estimates an increase of + 2.52 °C while model3 gives + 0.93 °C changes over the three decades. It is important to remember that the full model name is presented in Table 1.

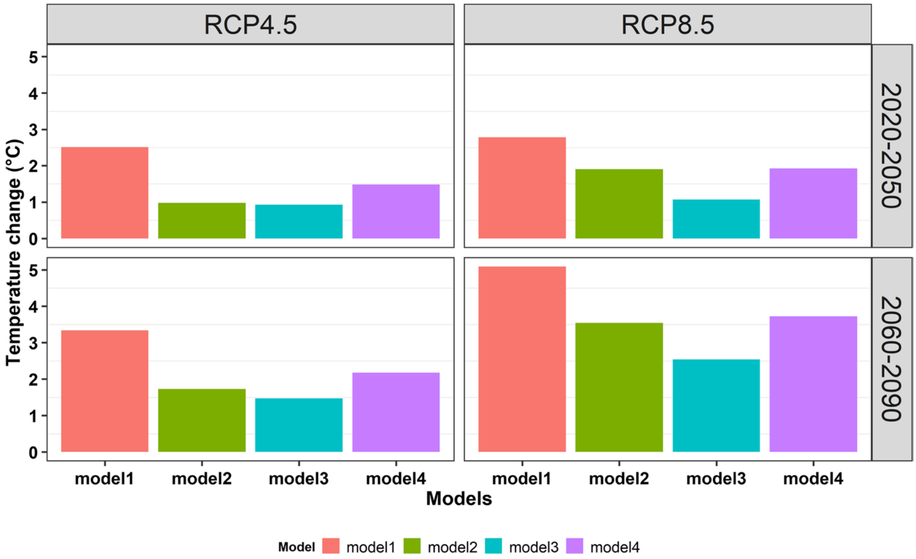


Fig. 7 Change in mean temperature (CORDEX) over Mono basin. (The changes were computed relative to 1970–2000 historical period)

This finding corroborates with the study of Lawin et al. (2019) in the same basin where they found an upward trend for both the minimum and maximum temperature. The projected change is going to be doubled in the far future compared to the near future. Over the same river basin, the air temperature is projected to increase in the range of + 1 °C and 1.5 °C by 2050 under AMMA-Ensemble (A1B), CMIP5 and CORDEX-AFRICA both under the RCP8.5 scenario (Amoussou et al. 2020).

The probable change in precipitation varies according to the model and RCP (Fig. 8). Among all models, only model1 (downward) and model4 (upward) gives agreement on the change trend under both RCPs. Under RCP4.5, only model1 in near future shows a significant trend while under RCP8.5 model1 and model4 (near future) and all models in far future except (model3) have projected a significant change (95% confidence level; see Table SM1 in supplementary materials). This finding in precipitation was also noted in a previous study (Amoussou et al. 2020) which showed that projected trends for cumulated precipitation are null or very moderate and diverge among models. The monthly precipitation could change by -32.4% and + 12% over 2061–2090 and 2071–2100, respectively (relative to 1981–2010) (Lamboni et al. 2019). Therefore, these projected changes in precipitation and temperature are suggested to directly affect the water availability and then HPGen in the future.

3.3 Hydropower Generation for Future Periods

Figure 9 presents the summary of the adjusted energy generation for the future period 2020–2090 for Adjarala and Nangbeto HPPs. The analysis of Fig. 9 reveals that statistical values (first and third quartile, median, mean, minimum, and maximum) of the

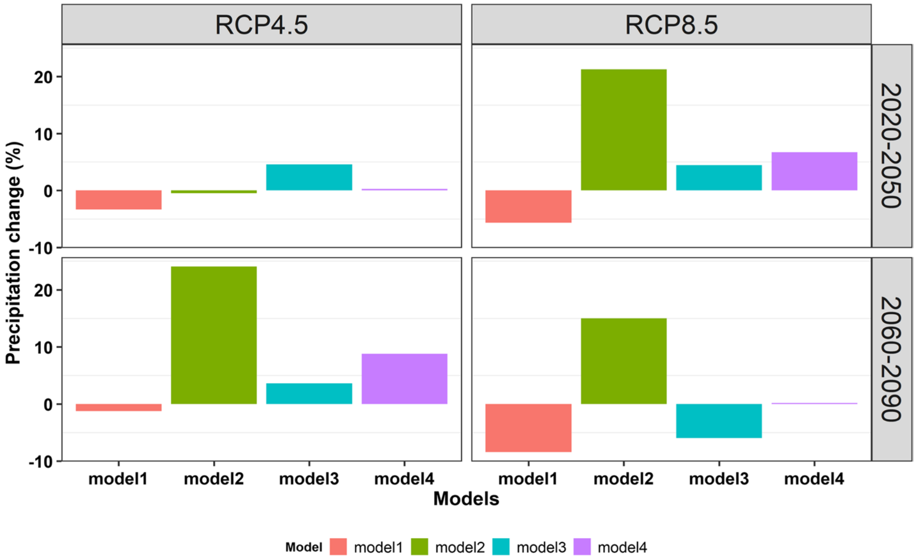


Fig. 8 Change in total annual precipitation (CORDEX) over Mono basin. (The changes were computed relative to 1970–2000 historical period)

simulated energy vary according to the HPP, model, scenario and RCPs. The greatest mean is obtained under the LULCC_CC scenario while the lowest is observed under Dev_CC scenario.

The analysis reveals that the mean observed energy generation over 1988–2010 (common period) is about 75 GWh while the simulated under reference scenario using observed hydroclimate variable is 90 GWh. The model overestimates the energy

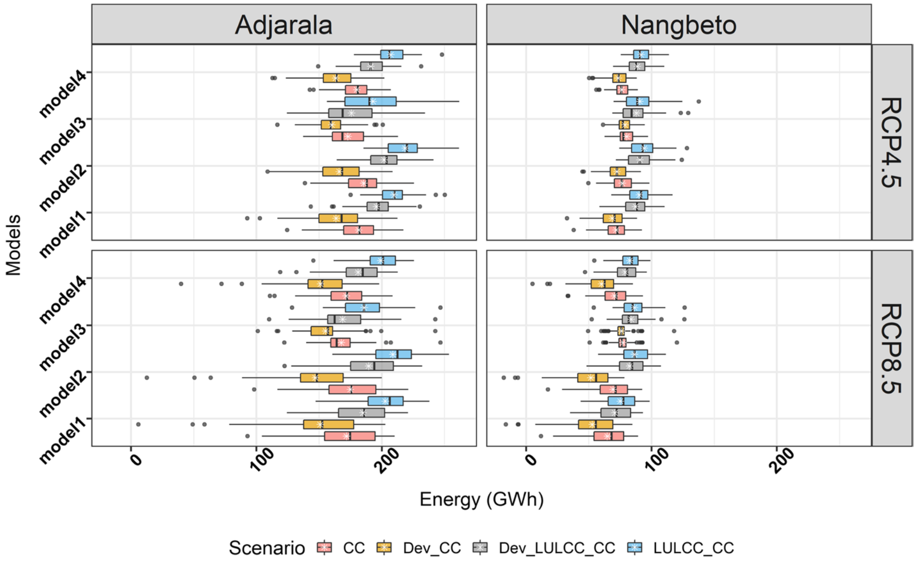


Fig. 9 Boxplot of adjusted Simulated energy under future period (2020–2090)

generation by about 19% and this could be explained by the overestimation of streamflow recorded.

Figure 10 summarizes the simulated energy generation adjusted for future near and far future periods for Nangbeto HPP relative to the mean annual production (observed over 1988–2010 period). The ensemble mean (model4) of all three models show that under CC condition, simulated energy over near (far) future could (could not) reach the mean of 1988–2010 period while considering both RCP. The energy generation compared to observed (1988–2010) reveals that the highest generation is noted under LULCC_CC followed by Dev_LULCC_CC scenarios while the lowest is simulated under Dev_CC followed by CC scenario. Thus, the development condition adding to changing climate conditions may be a threat to the energy generation in the future. Nevertheless, adding the LULCC effect on CC will mitigate the CC impacts as well as development condition threat on hydropower generation. This difference in magnitude of energy generation between CC and LULCC condition is suggested to be caused by LULCC incidence on streamflow.

Indeed, the upward trend of streamflow, as well as surface runoff induced by LULCC, were also projected in the Amazon watershed (Serrão et al. 2020). For instance, the increasing land use (urbanization and agricultural land) acts to reduce the infiltration rate of rainfall water while increasing the runoff generation capacity (Obahoundje et al. 2017). Its hydrological implication is widely discussed in the literature. In the Pra basin in Ghana, for instance, the variations in LULCC has caused an increment of surface runoff (124.51%) and water yield (40.13%), and reduced baseflow (30.08%) and evapotranspiration (13.248%) (Awotwi et al. 2019; Bessah et al. 2020). This effect has been recently discussed over Nyong river basin in Cameroon (Ewane and Lee 2020). The reverse change in land use is also found to have the inverse effect on hydrological

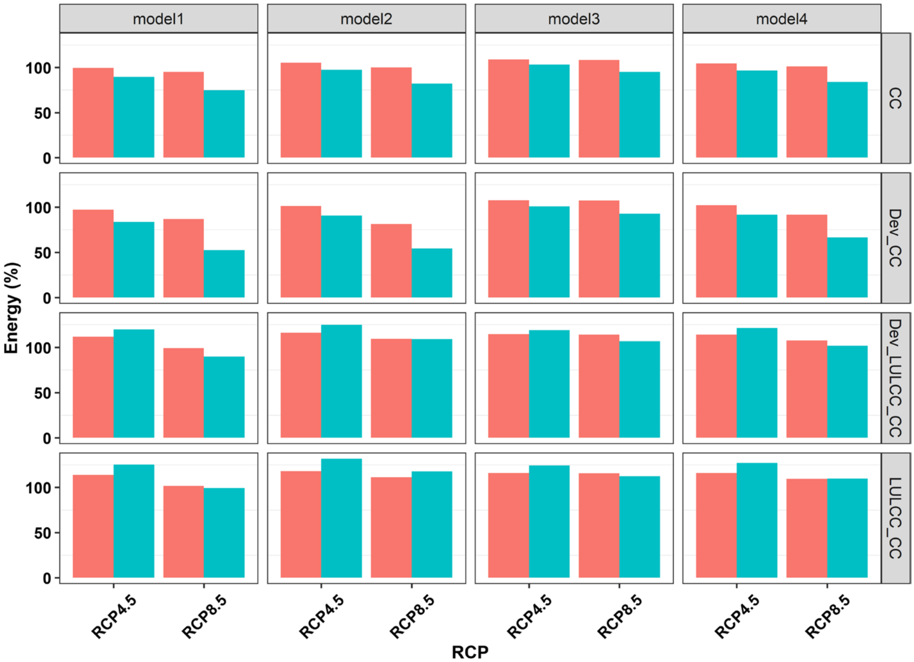


Fig. 10 Adjusted simulation of Nangbeto Hydropower generation under future periods compared to observed production (1988–2010)

system as well as on water resources availability, thus on energy generation. Lastly, this effect could be regressed by development condition.

Figure 11a, b illustrates the percentage change in hydropower generation relative to adjusted historical and future simulation of Nangbeto and Adjarala HPPs. The statistical analysis reveals that the projected change in energy generation is noted to be significant for model4 (model ensemble mean) in most cases (RCPs, periods and scenarios) (significant change at 95% confidence level; see Table SM2 in supplementary materials). The magnitude and trend of changes vary according to the RCP (RCP4.5 or RCP8.5), scenario (CC, Dev_CC, Dev_LULCC_CC, LULCC_CC), and the period (near or far future). In most cases, the probable change computed exhibits negative change for a generation under CC and Dev_CC scenarios for both plants. The ensemble mean (model4) presents a positive change under LULCC_CC and Dev_LULCC_CC scenarios which is greater in the far future. For illustration base on model4 and RCP4.5, increase of + 4.49% (+ 14.67%) and + 2.72% (+ 9.17%) in Nangbeto HPGen is projected for near (far) future under LULCC_CC and Dev_LULCC_CC scenarios, respectively. Under LULCC_CC and Dev_LULCC_CC scenarios at Nangbeto, the results display a negative change under RCP8.5 which is not the case under RCP4.5. Indeed, the CC condition reduces the expected energy production for both plants. However, the development conditions will worsen this production. Nevertheless, the LULCC will favour the generation under CC conditions. Despite this, combined development, LULCC, and CC will reduce the positive effect of LULCC on energy generation. For instance, under model 4 at Adjarala HPP, at far future with RCP4.5 are -0.6%, -13.21%, 21.33% and 8.9% under CC, Dev_CC, LULCC_CC and Dev_LULCC_CC scenarios, respectively.

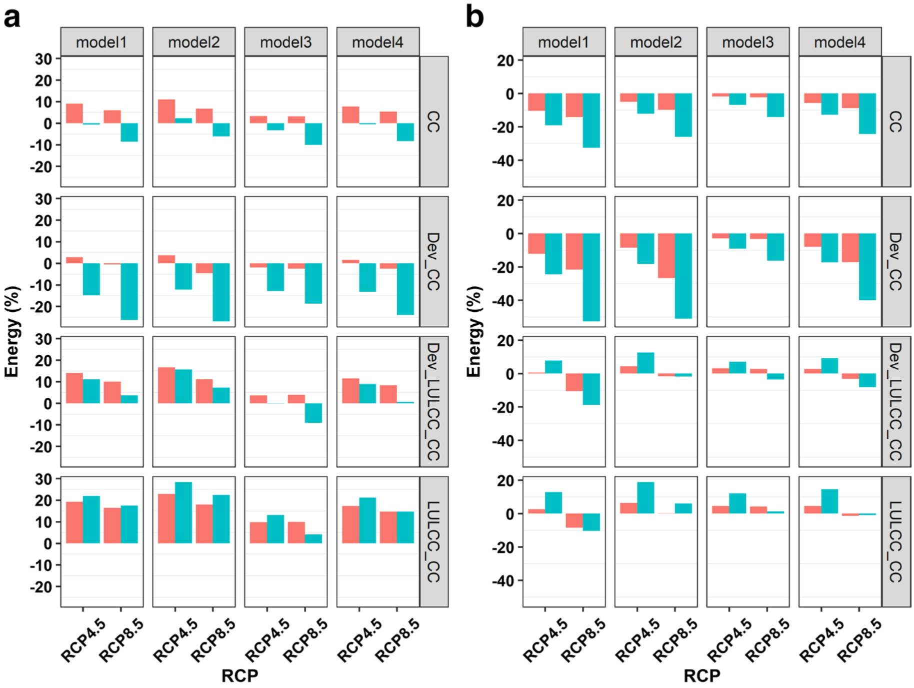


Fig. 11 Changes in mean annual hydropower generation for near (2020–2050) and far (2060–2090) relative to the control period (1970–2000). **a** Adjarala and **b** Nangbeto

Overall, the change in the future periods of HPGen is noted to be negative in most cases including ensemble mean under CC and Dev_CC scenarios. This change is noted to be positive in most conditions under LULCC_CC and Dev_LULCC_CC scenarios. Thus, the potential CC harms the hydropower system performance. However, considering the CC of ensemble mean (model4) scenario, the simulated energy generation changes of Adjarala HPP are + 7.5% (-0.6%) and + 5.34% (-8.37%) in near (far) future under RCP4.5 and RCP8.5, respectively. The positive trend in near future at Adjarala HPP is following the prediction of Kainji HPP for Niger river where an increase in annual change of 8.72% (8.63%) and 12.81% (24%) for near (2010–2035) and far (2036–2099) futures, respectively, were noted under RCP4.5 (RCP8.5) (Oyerinde et al. 2016). This upward change of Kainji HPGen for both scenarios was suggested to be associated with high flooding risk. In contrast, the Nangbeto HPGen change under CC condition is expected to be negative (-5.74% and -8.68% under RCP4.5 for the near and far future, respectively, and is likely to double under RCP8.5). Our findings for Nangbeto HPP are in line with the study of Amisigo et al. (2015) on Akosombo HPGen where around 80% of the demand will only be covered under climate change.

For both HPPs, the development condition (socio-economic) is simulated to add a burden on water resources by increasing unmet water demand for all sectors and by reducing the technical performance of reservoirs. McCartney et al. (2012) also confirmed the burden that constitutes the development condition. Under current development condition, only 77% (4,678 GWh/yr) of the potential average annual hydroelectricity will be delivered from all existing HPPs in the Volta basin, whereas only 53% (4,779 GWh/yr) and 30% (2,599 GWh/yr) could be generated under CC and intermediate development condition by the end of 2050 and 2100, respectively (McCartney et al. 2012). This reduction will be exacerbated under full development conditions where only 48% (5,673 GWh/yr) and 24% (2,701 GWh/yr) of the energy will be furnished (McCartney et al. 2012). Aside from water resources and HPGen, CC is likely to have serious consequences on economic development, food security and poverty in the region (McCartney et al. 2012). This is also confirmed by Djiby et al. (2018) in Lake Guiers of Senegal river basin where the combination of CC and population growth is projected to significantly increase the pressure on water resources (ACPC 2011). As raised earlier, LULCC under CC condition are projected to increase flow, and thus, mitigate the CC impacts on water availability and lead to a reduction of the amount of unmet demand caused by CC.

It is also found that the simulated HPGen in Mono is greater under LULCC than in other scenarios. This also confirms the previous work at Bui HPGen in the Black Volta basin (Obahoundje et al. 2017) and Amazon (the Tapajós River) river basin (Arias et al. 2020). It was found that CC could decrease dry season hydropower potential by 430–312 GWh per month (− 7.4 to − 5.4%), while combined effects of deforestation could increase interannual variability from 548 to 713–926 GWh per month (+ 50% to + 69%; Arias et al. 2020). Our finding in terms of HPGen is contrary to the findings of Serrão et al. (2020) in Amazon. Indeed, in Amazon, despite the increase in flow, there was no increase in the energy produced at the Tucuruí HP due to the inability of the turbines to convert excess water into energy and could consequently cause 30% per month losses in the HPGen and 65% in the annual balance (Serrão et al. 2020). Though LULCC may lead to increment in hydrological flow and then increase the power generation in Mono basin, it can also be associated with other phenomena (Sun et al. 2020), such as erosion and reservoir siltation, which could negatively affect the dam. These need to be deeply investigated.

The sediment yield attributed to anthropogenic activities may vary according to the catchment size. For instance, in semi-arid environments it may range from 130 ± 45 tonnes/

yr and 1130±230 tonnes/yr for the 8 km^2 and 100 km^2 catchments, respectively (Baade et al. 2012), while the mean annual sediment yield was estimated as 11.43 tonnes/ha/yr for the Kesem Dam watershed in Ethiopia with an area extent of 2808.22 km^2 (Tesema and Leta 2020). Lastly, the performance of this model could also be linked to the projected water availability of the basin, and thus, be related to unmet water demand.

3.4 Unmet Water Demand

Figure 12 exhibits the unmet water demand at the Mono river basin. Indeed, the water demand refers to the municipal, irrigation, livestock, industry, and dam water abstraction. The priority (ranging from 1 to 99) is assigned for each demand sector, then the model will supply all the demand sites with the lowest priority. Then, if water remains, the model will supply the other sites of water demand with the highest priority. For example, in this study, the HPP priority is 99 while the water demands for domestic (rural and urban), livestock and irrigation were set to priority 1. Thus, the hydropower plant is fed at the last position if water is available. If the available simulated streamflow is not enough to meet the demand, the model creates an unmet demand.

Overall, the water demand was not be fully met under most conditions. However, the highest unmet demand was projected to be under CC change and development scenarios, while the lowest unmet demand was under combined LULCC with CC. Moreover, the unmet water demand is expected to be greater under RCP8.5 than RCP4.5. Besides, the unmet water demand was projected worst in the far future (2060–2090) period.

These findings are in agreement with the results of the Amisigo et al. (2015) and McCartney et al. (2012) studies in the Volta and other river basins in Ghana. It is projected that, by the middle of the twenty-first century, basin-wide average annual rainfall, mean annual runoff, and mean groundwater recharge will all decline and significantly

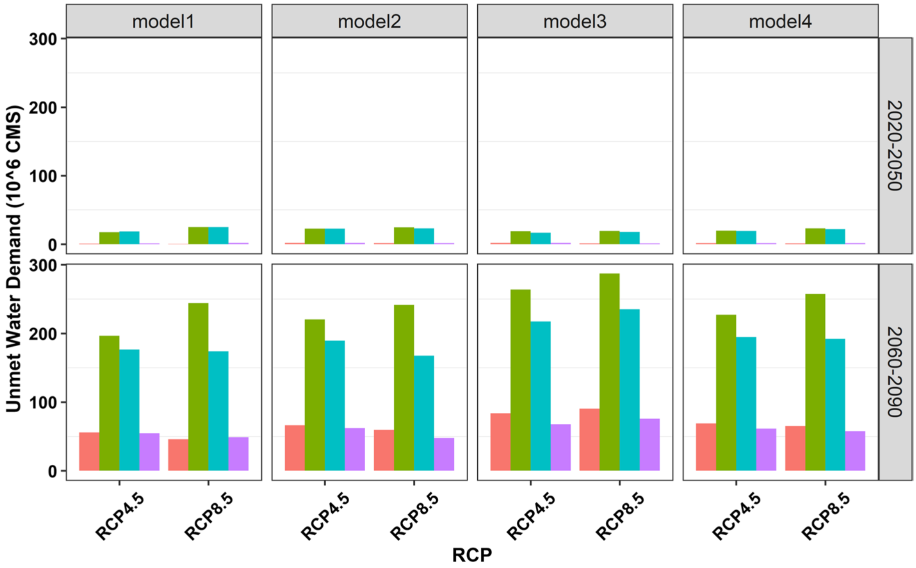


Fig. 12 Unmet water demand over Mono basin projected for the futures

undermine the technical performance of existing and planned reservoirs, which, in turn, will affect development outcomes (Amisigo et al. 2015). CC is projected to affect water availability in Mono river basin by affecting the runoff and increase the irrigation water needs, and then, undermine the basin irrigation potential (reduction ranging from -30% to -50% and -40% to -60% under 1.5 °C and 2 °C global warmings, respectively; Sylla et al. 2018b). CC is anticipated to cause a long-term increase in the amount of water shortage by adding pressure on water resources, leading to greater competition for surface water, and that domestic, tourist, livestock, and agricultural demands will not be met by the year 2100 (Rochdane et al. 2012) including HPP.

4 Conclusions

In this study, the joined impacts of (i) climate change (CC), (ii) land use/cover change (LULCC), and (iii) development (Dev) conditions on water resources and hydropower generation are assessed using CORDEX data under RCP4.5 and RCP8.5.

Overall, the results suggest that all the models projected a significant increase in air temperature over the Mono river basin in the near and far futures, while there is no agreement on precipitation trends. The changes in climate variables are suggested to impact the water availability and HPGen in the Mono river basin. The simulated unmet water demand and HPGen depended on the model, the RCPs (RCP4.5 or RCP8.5), and the types of scenarios (CC, CC and LULCC, CC and Development, combined CC, LULCC, and Development).

The results showed that all water demands (municipal, hydropower, and irrigation) could not be simultaneously met under any of the scenarios used, including the ensemble mean in the Mono river basin. CC is projected to create a shortage of water in the Mono river basin whereas the development condition was expected to add burden on this unmet water demand. The unmet demand was more perceived under RCP8.5 than RCP4.5. Nonetheless, the change in LULC condition is expected to reduce this increase in unmet demand created by CC and development scenario together. Also, the simulated generated hydroelectricity from Nangbeto and Adjarala plants could be affected negatively by CC condition as well as by adding development condition to it. Considering the CC condition alone, all models including their ensemble mean, projected a decrease in energy generation except model 1 and model 3 in near future at Adjarala station. However, the development condition is projected to add burden on already existing caused by CC condition on HPPs. LULCC is projected to reduce these burdens. Generally, while considering the ensemble mean models under LULCC_CC and Dev_LULCC_CC scenarios, the energy generation change is projected to be positive for both HPPs, periods, and RCPs except under RCP8.5 at Nangbeto station. The lowest hydropower generation could be observed under combined development condition and CC followed by CC, and the highest could be under LULCC_CC followed by Dev_LULCC_CC scenario. Indeed, the development condition is projected to exacerbate the effect of CC on water availability and energy generation, which could be alleviated by the LULCC condition.

This study focuses on the uses of raw output data of CORDEX Africa which has a spatial resolution of about 50 km by 50 km. It is, therefore, recommended to continue this work by processing a bias correction of the input climate data. As the unmet water demand is anticipated under all changing conditions, it is urgent to assess the effect on underground water resources as well as setting in places some water management measures. As the result shows an improvement in power production and water demand under changes in land use condition, it is suggested to assess all the negative impacts of LULCC in a streamline, in reservoirs, and on water quality for the short, mean, and long term over Mono river basin.

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Author Contributions S.O. conducted this research. A.D., E.A and M.Y.T. were the advisors: Conceptualization, S.O. and A.D.; Methodology, S.O., A.D., M.Y.T. and E.A.; Data Curation, K.K. and E.A.; Writing—Original Draft Preparation, S.O. and A.D.; Writing—Review & Editing, E.A., Y.M.K. and K.K. and M.Y.T; Funding Acquisition, A.D.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflicts of Interest The authors declare no conflict of interest.

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