

Assessing the Impacts of Climate Change on the Hydroelectric Power Plant of Kandadji, Niger

Inoussa Abdou Saley^{1*}, Amadou Lawali Djibo¹, Boubacar Abdou Boko^{2,3},
Harouna Sani Dan Nomao⁴, Mahamane Rabilou Iro Ousmane¹, Abdoul Aziz Saidou Chaibou¹

¹Département de Physique, Faculté des Sciences et Techniques (FAST), Université Abdou Moumouni (UAM), Niamey, Niger

²Laboratoire des Eaux Souterraines et Géo-Ressources, Faculté des Sciences et Techniques (FAST), Université Abdou Moumouni (UAM), Niamey, Niger

³Graduate Research Program on Climate Change and Water Resources, West African (Science Service Centre on Climate Change and Adapted Land Use (WASCAL)), Université D'Abomey Calavi, Cotonou, Benin

⁴Ecole National d'Ingénierie et des Sciences d'Energie de l'Université d'Agadez, Agadez, Niger

Email: *asinoussa@gmail.com

How to cite this paper: Saley, I.A., Lawali Djibo, A., Abdou Boko, B., Sani Dan Nomao, H., Iro Ousmane, M.R. and Saidou Chaibou, A.A. (2026) Assessing the Impacts of Climate Change on the Hydroelectric Power Plant of Kandadji, Niger. *Energy and Power Engineering*, 18, 651-669.
<https://doi.org/10.4236/epe.2026.1810030>

Received: August 19, 2026

Accepted: October 13, 2026

Published: October 16, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Debates regarding the climate change impacts on human societies and natural ecosystems remain a central concern for scientists and policymakers worldwide. Our study aims to contribute to this important research area by examining how climate change may affect the hydrological regime and energy production of the Kandadji hydroelectric power plant. We used *in-situ* observational data, climate model simulations and the outputs from the Community Water Model (CWatM), a hydrological model driven by three climate models. Quantile-quantile mapping was applied to the simulated discharge to adjust systematic biases in the hydrological model outputs. Two scenarios from the Representative Concentration Pathways (RCPs; RCP2.6& RCP8.5) and two scenarios from the Shared Socioeconomic Pathways (SSP126 and SSP370) were considered. Our results show that CWatM provides limited performance in representing both the seasonal cycle and inter-annual variability of the river discharge. Upward trends in the observed hydro-climatic parameters (total rain, rainy days, heavy rainfall events, maximum, minimum and mean discharges) were found meaning that we are facing an intensification of the observed hydrological cycle. These trends seem likely to continue over the future periods for all the scenarios. While changes in mean annual hydroelectricity generation potential are projected to be minor (<3%), tremendous changes at the seasonal scale are expected. Overall, these findings demonstrate promising prospects for future grid stabilization, energy service delivery and socio-economic benefits for the local communities, while emphasizing the need for adaptive reservoir management to navigate seasonal discharge extremes.

Keywords

Kandadji, CWatM, Hydro-Climatic, Hydroelectric Power Plant, Niger River

1. Introduction

Access to reliable and affordable electricity remains the fundamental pillar for the economic, social, and industrial development of any sovereign state. According to the global energy think tank, EMBER (<https://ember-energy.org/>), the majority of global electricity production (nearly 60%) in 2023 was derived from fossil fuels [1] [2] but the power mix is evolving. However, the consumption of these energy sources results in greenhouse gas (GHG) emissions, driving global warming, air pollution, and their associated impacts. In 2015, at the 21st Conference of the Parties (COP21), most countries committed to reduce global GHG emissions (mainly CO₂) and limiting temperature rise. To address this challenge, nations are actively seeking to increase the share of renewable energy sources in the global electricity generation, including hydropower, solar and wind power. In addition to being non-polluting and low-carbon, renewables are inexhaustible on a human time-scale making them critical for sustainable future. Recent data show that, for the first time in 100 years, renewables (33.8%) overtook coal power (33.0%) in 2025 [3]. Currently, beyond supporting grid stability in more than 150 countries, hydropower represents the third largest source of global electricity generation accounting for 14.3% of the total production in 2024, behind coal and gas [4]. This makes hydropower the leading renewable energy technology worldwide.

As stable and clean energy source, Hydropower is generated from hydroelectric dams that are structures built on waterways to store large quantities of water or through pumped storage systems [4]. Beyond power generation, the large water reservoirs support agricultural and livestock development while supplying drinking water to local communities. As a technically mature technology, hydropower is ranked as a primary source of renewable electricity that can offer crucial grid flexibility and storage capacity to balance electricity supply and demand [5]. Furthermore, it is among the most cost-effective electricity technologies characterized by low operation and maintenance costs though its deployment heavily depends on national, regional and global policies [6] [7]. Countries like Canada, China and the United States, which are among the world's largest economies, hold the largest installed hydropower capacities globally [8]. However, hydroelectricity generation relies directly on river discharge (runoff) making it highly sensitive to climate variability and climate change. According to the International Hydropower Association [9], changes in runoff and its seasonality and shifts in temperature and precipitation intensity directly influence hydroelectricity generation.

Indeed, it is well established that global warming and climate change will have significant repercussions on the hydrological regime of rivers [10]-[13]. Comparing streamflow across the largest African rivers, Aich *et al.* [14] stated that climate

change impacts are clearly visible in the mean discharge. For hydroelectric power plants, both operational and under construction, such as the Kandadji dam in Niger, this sensitivity poses major concerns for several reasons. First, temperature increases could trigger shifts in evapotranspiration, rainfall patterns, streamflow and overall water availability which can directly affect the hydropower generation. Analyzing three different dams, [15] revealed that the energy generation is highly sensitive to reservoir inflow and water level. Furthermore, they argued that the power of a given year is dependent on the total rainfall of current and/or the preceding year depending on the plant. Second, substantial uncertainties remain regarding the future rainfall changes particularly over West Africa and the Sahel regions. While recent studies have shown no clear trend in cumulative annual rainfall across West Africa and the Sahel [16] [17], clear signals of an increase in the frequency and intensity of heavy rainfall events have been identified [18] [19]. Regarding streamflow, despite high uncertainties across major African river basins, increasing trends have emerged in recent projections [5] [14] [20]. Finally, the Niger River Basin exhibits complex hydro-climatic dynamics, notably characterized by a distinct two-peak flow regime highly sensitive to climate variability and change across the Sahelian and Guinean headwater regions [21]–[24].

A severe water deficit could lead to a substantial decline in electricity generation whereas a significant increase in extreme flows would pose major risks to the dam infrastructure safety, surrounding populations, downstream ecosystems, and power production stability. Despite the strategic importance of this infrastructure for Niger's energy transition, agricultural systems, and climate resilience, quantitative assessments evaluating the impact of future climate change on Kandadji hydroelectric power plant remain limited. Therefore, analyzing future hydro-climatic parameters at the Kandadji station and their associated impacts on electricity generation is essential. This could promote better management and mitigate the possible negative impacts associated with climate variability and climate change. Our main objective is to quantify the potential impacts of climate change on the hydrological regime and the electricity production of Kandadji hydroelectric power plant. The remainder of this paper is organized as follows: Section 2 describes the materials and methods used; Section 3 presents and discusses the results; and Section 4 provides concluding remarks and policy recommendations.

2. Materials and Methods

2.1. Study Area and Data Used

2.1.1. Study Area

The Kandadji hydroelectric power plant is currently under construction on the Niger River, the third longest river in Africa (exceeding 4200 km of length) and the most important surface water resource in Niger [25]. Originating in the Fouta Djallon highlands of Guinea, the river flows through Mali, Niger, Benin and Nigeria before discharging into the Atlantic Ocean. The entire Niger River basin extends across nine states including Guinea, Côte d'Ivoire, Mali, Niger, Burkina

Faso, Benin, Cameroon, Chad, and Nigeria. Furthermore, the basin is divided into four hydrological sections: The upper basin (from the source in Guinea to Ségou in Mali); the inner delta (from Ségou to Tossaye in Mali); the Middle Niger (extending from Timbuktu in Mali to Malanville in Benin covering an area of approximately 900,000 km²) and the lower Niger [25]. **Figure 1** illustrates the geographical location of the Kandadji dam project site (14°36'32"N, 0°59'14"E). It is located near the village of Kandadji, approximately 61 km downstream from the Malian border and 187 km upstream from Niamey. The design nominal discharge of the Kandadji power plant is estimated at 237.5 m³/s for one turbine (yielding 950 m³/s for the four turbines) with a net head of 14.4 m with an expected power output of approximately 130 MW.

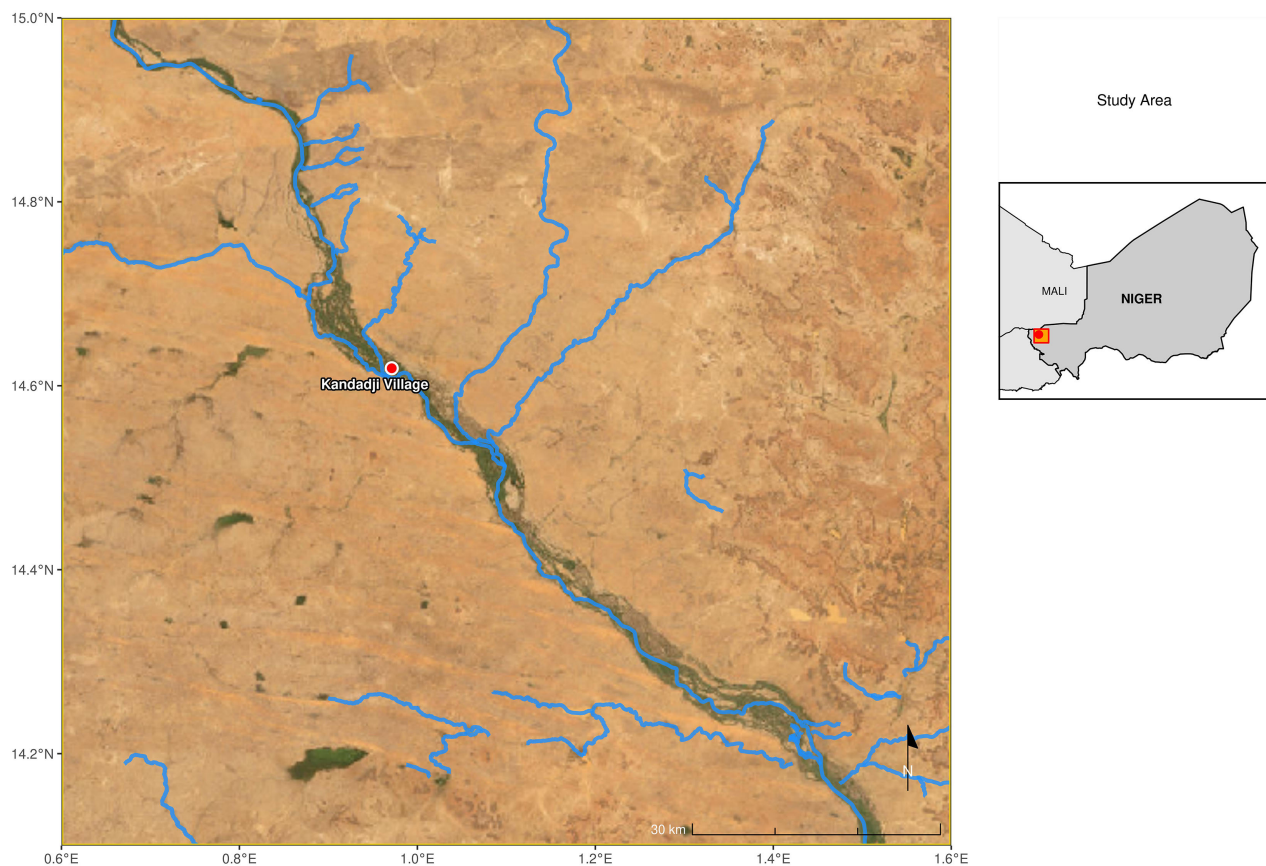


Figure 1. Localization of the study area of Kandadji hydroelectric power plant.

2.1.2. Data Used

1) Observational Data

Observational data used in this study include daily historical river discharge, rainfall and derived evapotranspiration at the Kandadji station. Daily river discharge records were obtained from the National Hydrological Service (NHS) of Niger for the period 1980-2019 (**Table 1**). To address missing values in the discharge series, gaps were filled using the most representative measure of central tendency for a sample (the median). Specifically, we calculated the median of the calendar day

corresponding to the missing day over a 10-year moving window (5 years prior and 5 years following the target year) centered on the target year.

Gridded daily precipitation data were extracted from the Climate Hazards Infrared Precipitation with Station data version 2 (CHIRPS; [26]) over the period 1981-2016 (Table 1). Precipitation values were extracted using the nearest-neighbor interpolation method at Kandadji station.

Table 1. Observation and hydrological model data from CWatM driven by climate model (GFDL, IPSL, HadGEM). 1981-2005 historical period common to observations and models for flow rate. The selected future periods are near (2025-2049) and far (2075-2099) futures.

Data Source	Parameters	Period	Resolution	Reference
Observation	Rainfall-CHIRPS	1981-2016	$0.05^\circ \times 0.05^\circ$	[26]
	Discharge (<i>In-situ</i>)	1980-2019	-	National Hydrological Service
Hydrological Model (CWatM)	Discharge (Historical)	(1951-2005)		
	Reference period	1981-2005		
	Discharge (Future)	(2006-2100)	$0.5^\circ \times 0.5^\circ$	https://cwatm.iiasa.ac.at/
	Pilots Models (GFDL, IPSL, HadGEM)	2025-2049		
	Scenarios (RCP2.6 and RCP8.5)	2075-2099		
Other Climate Model	Precipitation and temperature	(1951-2015)		
	Model (GFDL, IPSL)	(2016-2100)	$0.5^\circ \times 0.5^\circ$	https://www.isimip.org
	Scenarios (SSP1-2.6 and SSP3-7.0)	2025-2049 2075-2099		[29]

2) Model Simulations

a) Hydrological data

Hydrological simulations were extracted from the Community Water Model (CWatM). Developed and maintained by the International Institute for Applied Systems Analysis (IIASA), CWatM is an open-source hydrological model designed to simulate the daily water cycle at global and regional scales across historical and future periods [27]. The model is integrated into the Inter-Sectoral Impact Model Inter-comparison Project (ISIMIP, <https://www.isimip.org>) and assesses water availability, demand, and environmental flow requirements while incorporating human influences and water management. CWatM is particularly suited for evaluating how future water demand responds to socio-economic dynamics and how runoff changes under varying climate conditions. In this study, simulated daily discharge at the Kandadji station was analyzed.

As with all hydrological modeling frameworks, CWatM requires initial and boundary conditions derived from observational datasets or climate model outputs. In this study, outputs from three global climate models (GCMs) were used to drive CWatM over both historical (1951-2005) and the future (2006-2100) periods. These climate models are from the Institut Pierre Simon Laplace (IPSL-CM5A-LR), the Hadley Centre Global Environment Model (HadGEM2-ES), and the Geophysical Fluid Dynamics Laboratory (GFDL-ESM2M). The climate models output data for the future period are based on climate change scenarios [28]-

[30]. Two scenarios are considered from the Representative Concentration Pathways (RCPs) scenarios; the most extreme scenario (RCP8.5) and the mitigation scenario (RCP2.6) (Table 1). The scenarios selected would provide a broad range of potential impacts of climate change on streamflow and hydropower production for the Kandadji dam in Niger. Table 1 summarizes information on the data used in this study.

b) Climate data

Climate data from two global circulation models (GCMs) were also used in this study (Table 1). These are models from IPSL and the GFDL and have evolved within the Coupled Model Inter-comparison Project Phase 6 (CMIP6; <https://wcrp-cmip.org/cmip-phases/cmip6/>). They were downscaled and bias adjusted under the Inter-Sectoral Impact Model Inter-comparison Project (ISIMIP3b). They cover a historical period (1951–2015) and future period (2016–2100) under two selected scenarios from Shared Socioeconomic Pathways SSP1-2.6 (low emissions & sustainability) and SSP3-7.0 (medium to high emissions & regional rivalry). The climate variables considered in this study include rainfall as well as maximum and minimum temperatures. The latter two variables (maximum and minimum temperatures) were used to derive the potential evapotranspiration. Both models have been previously evaluated in representing rainfall patterns and extremes events over the Sahel region [19].

3) Data preparation

For all gridded datasets, values were extracted at the nearest-neighbor grid point of the Kandadji station. The advantages of this approach have been discussed and demonstrated in previous studies [19] [31]–[34]. The analysis was performed on the common longest period of all datasets and using ensemble mean for the models data. According to the observed discharge data, the hydrological model evaluation and bias correction were done over the period 1981–2005. The future analyses were conducted over the near future (2025–2049) and far future (2075–2099). Potential evapotranspiration (ET0) was estimated using the Hargreaves Reference Evapotranspiration Equation (1) based on the FAO Irrigation and drainage paper 56 guidelines [35] and implemented via the FAO56 R-package. As demonstrated by Mohawesh and Talazi [36], the Hargreaves formulation provides reliable ET0 estimates instead of using the FAO56PM method with acceptable accuracy.

$$ET0 = 0.0023 \times (T_{\text{mean}} + 17.8) \times R_a \times \sqrt{T_{\text{max}} - T_{\text{min}}} \quad (1)$$

where T_{mean} , T_{min} and T_{max} represent respectively the average, minimum and maximum temperatures in degree °C and R_a is the extraterrestrial radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$) and depends on the station position (latitude).

For climate impacts assessments, it is strongly recommended to perform bias corrections of the model data [37]. In this study, we applied the quantile-quantile mapping approach on the hydrological model data (discharge). It is based on a non-parametric function that modifies the mean, variability, and shape errors of the cumulative distribution function (CDF) of the simulated variables [38]. Spe-

cifically, the method proposed by Amengual *et al.* [38], was designed to adjust errors while preserving scaling signals and extreme flow variability.

2.2. Methods

2.2.1. Hydroclimate Parameters Used

Based on observational datasets, we analyzed recent historical trends in rainfall and streamflow at the Kandadji station. We assessed changes in the annual rainfall amount (PRCPTOT), the rainy days (days with rainfall exceeding 1 mm, RR1) and the occurrence of intense rainfall (days with rainfall above the 99th percentile, R99). For the streamflow, we evaluated the annual maximum, minimum, and mean discharge alongside two sector specific hydrological indices: the maximum number of hydrological consecutive dry days (HCDD), and the maximum number of hydrological consecutive wet days (HCWD). A hydrological dry day is defined when the streamflow drops below the minimum environmental flow threshold of 50 m³/s as stipulated in the Water Charter of the Niger Basin Authority (NBA) [39]. Conversely, a hydrological wet day is defined as a day when discharge reaches or exceeds the threshold of 950 m³/s, representing the nominal design discharge required for the continuous operation of all four turbines. The selection of these specific indices is particularly related to their potential influence on river dynamics and therefore on the resulting hydroelectricity generation. We also assessed future changes in mean annual accumulated evapotranspiration under the selected climate scenarios.

Statistical significance was assessed at the 5% level across all analyses: Student's t-test (Snedecor and Cochran, 1989) [40] was used to detect changes in the mean, the Mann-Kendall test (Kendall, 1975) [41] to evaluate monotonic trends, and Pearson's correlation coefficient to examine linear relationships. Model performance was evaluated using the mean bias (ME), coefficient of determination (R²), root mean square error (RMSE), and the modified Nash-Sutcliffe Efficiency (mNSE; Krause *et al.*, 2005) [42].

2.2.2. Determination of the Electricity Production

Using historical and projected streamflow series, the hydropower potential was calculated and the corresponding climate change impacts were quantified. The hydraulic, mechanical and electrical power were estimated using Equations (2)-(4), while the annual energy output and climate change impacts were derived using Equation (5) and Equation (6). Indeed, hydraulic power (P_h in Watt) supplied to the turbines by the water flow is expressed as:

$$P_h = \rho \times g \times H_n \times Q \quad (2)$$

where ρ is the water density [kg/m³], Q the daily streamflow [m³/s], g the gravitational acceleration [m/s²], H_n is the net head ($H_n = 14.4$ m for the Kandadji project).

The mechanical power (P_{mec}) is the power output of the turbine and given by Equation (3). In the case of the Kandadji dam, four Kaplan turbines were consid-

ered assuming a turbine efficiency of $\eta_t = 92\%$.

$$P_{\text{mec}} = 4 \times \eta_t \times P_h = 4 \times \eta_t \times \rho \times g \times H_n \times Q \quad (3)$$

The gross electrical power output (P_{elec}) delivered by the generator, assuming a generator efficiency of $\eta_G = 99\%$ is given by the formula (4):

$$P_{\text{elec}} = P_{\text{mec}} \times \eta_G = 4 \times \eta_G \times \eta_t \times \rho \times g \times H_n \times Q \quad (4)$$

The total annual electricity production E in GWh is obtained by integrating daily electrical power over the year:

$$E = \sum_{d=1}^N (P_{\text{elec},d} \times 24) \times 10^{-9} \quad (5)$$

where N represents the number of days in the given year (365 or 366).

For each of our variables, the impact of climate change was evaluated using the difference between the future and the reference periods of the considered variable. For example, the impact on the produced electrical energy is calculated using the Equation (6):

$$I_E^j = E_{\text{fut}}^j - E_{\text{ref}} \quad (6)$$

I_E^j is the change in the produced electrical energy over the future periods (2025-2049; 2075-2099) for the scenario j (RCP2.6; RCP8.5 or SSP126 and SSP370).

E_{fut}^j is the electricity production over the future period (2025-2049; 2075-2099) for the scenario j (RCP2.6; RCP8.5 or SSP126 and SSP370).

E_{ref} is the electricity production over the reference period 1981-2005.

3. Results and Discussion

3.1. Variability of the Observed Hydroclimate Indices

This section presents a detailed assessment of the historical evolution of hydro-climatic hazards observed at the Kandadji station. Specifically, **Figure 2(a)**, **Figure 2(b)** depict the historical trends of the maximum number of hydrological consecutive dry days (HCDD; consecutive days with discharge $< 50 \text{ m}^3/\text{s}$), the maximum number of hydrological consecutive wet days (HCWD; days with flow exceeding the threshold of $950 \text{ m}^3/\text{s}$), as well as the annual minimum, mean and maximum streamflows. The HCDD index reveals a clear shift between the period 1981-1990s and the post 2000 decades (**Figure 2(a)**). In the post 2000 period, the HCDD values reached their lowest levels (except for 2003 and 2018), driving a statistically strong downward trend. This shift indicates that we are currently experiencing a period with shorter durations of dry hydrological day sequences. In contrast to the HCDD pattern, HCWD values display a slight increasing trend (**Figure 2(a)**). Over the study period, the annual cumulative number of wet days consistently exceeded 60 days, confirming that streamflow remains above the $950 \text{ m}^3/\text{s}$ operational threshold for at least two months per year. Furthermore, annual minimum, mean and maximum discharge rates at Kandadji station exhibit a marked increase (**Figure 2(b)**), demonstrating a certain intensification of the river flow. While

higher flows promote reservoir fill up and enhance sustainable hydropower generation potential, they simultaneously elevate flood risks to dam infrastructure and surrounding riverine communities.

Regarding precipitation indices, **Figures 2(c)-(e)** illustrate the historical evolution of the annual total rainfall, the annual total of rainy days (RR1) and the annual total of heavy rainfall days (R99). All three indices exhibit significant upward trends, meaning that the Kandadji area is experiencing increasingly wetter conditions over recent decades. This finding strongly aligns with previous regional studies [18] [19] [43]. Increasing in these precipitation indices can favor higher runoff and river discharge, notably amplifying peak water levels during the local river flood.

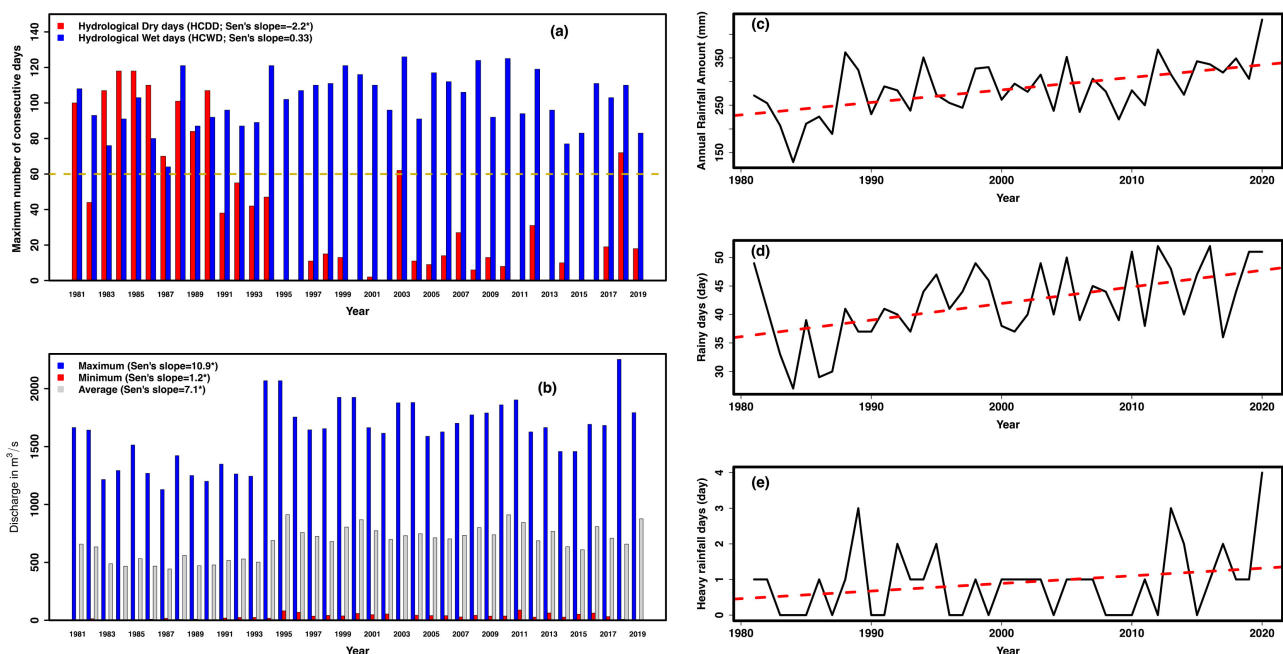


Figure 2. Inter-annual variability of observed (a) maximum number of consecutive wet (in blue color) and dry (in red color) days, (b) maximum (in blue color), minimum (in red color) and average (in gray color) variation of discharge (m³/s), (c) annual rainfall amount (mm), (d) rainy days and (e) heavy rainfall days.

The seasonal distribution of the average river discharge at the Kandadji station (**Figure 3**) indicates that the lowest flows occur between March and July. More particularly, May and June exhibit the lowest streamflows, less than or equal to the minimum environmental thresholds of 50 m³/s, making them the driest months hydrologically. During these two months, in the absence of a storage reservoir to store water and regulate its flow, the natural discharge is insufficient to operate even a single turbine for hydroelectricity generation. However, the period from November to January registers high sustained discharge corresponding to the period of the “black flood” or “Guinean flood”. It should be noted that flows exceeding the first vigilance threshold (1444 m³/s threshold at Niamey station) are recorded during the months of August and September linked to the occurrence of

heavy rainfall, leading to flash flood known as “red flood” or “local flood”. Overall, the observed hydrological seasonal cycle appears to be mainly influenced by the complex interplay between remote upstream rainfall and local Sahelian precipitation. This bimodal regime presents a notable challenge for hydrological models like CWatM, as simulating the long travel times and attenuation of remote precipitation signals requires accurate routing and wetland parametrizations [27] [44].

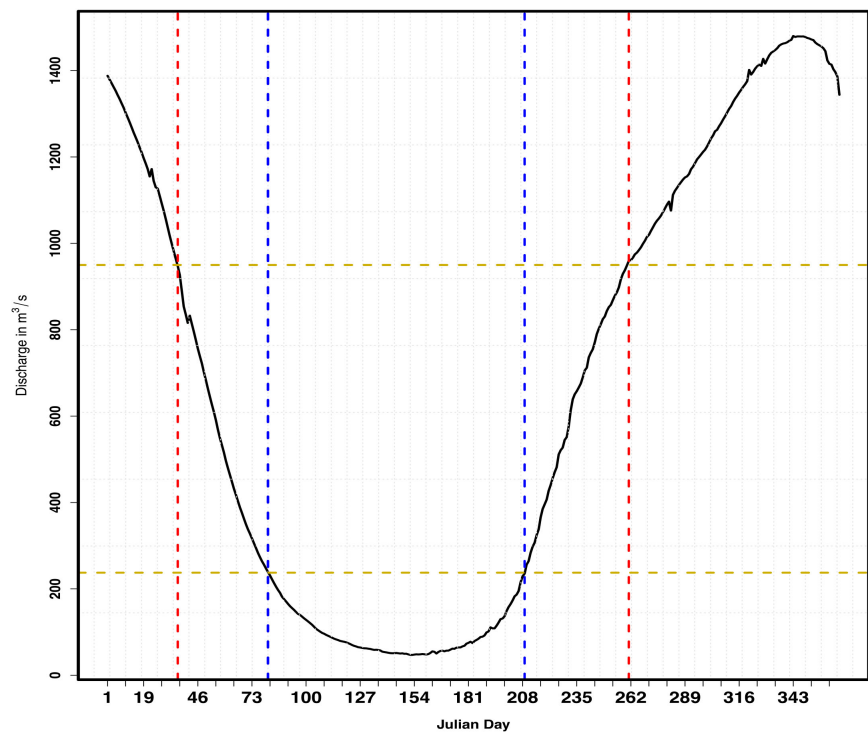


Figure 3. Seasonal cycle of observed discharge (m^3/s). The blue dash lines delimit the period of discharge lower than $237.5 \text{ m}^3/\text{s}$ and the red dash lines delimit the period with flow exceeding the threshold of $950 \text{ m}^3/\text{s}$.

3.2. Hydrological Model Validation

In this section, we present the evaluation of the performance of the hydrological model (CWatM) driven by three climate models (HadGEM, IPSL, and GFDL) in representing the observed features of the streamflow at Kandadji station. Quantile-Quantile mapping was applied to each model member before computing the ensemble mean. **Figure 4(a)**, **Figure 4(b)** present the simulated versus observed discharge regimes. It appears that the CWatM ensemble mean highlights a peak ($Q \geq 1000 \text{ m}^3/\text{s}$) during the period August-September (**Figures 4(a)**) which matches the local flood period. In fact, this peak corresponds to the monsoon seasonal rainfall peak over the Sahel region [45]. Thus, the discharge seasonal cycle of the CWatM ensemble mean denotes the strong influence of the rainfall in simulating the streamflow. Moreover, a study over two river basins in Côte d’Ivoire (West Africa) has shown that the inflow is highly dependent on rainfall [15]. Dur-

ing the Guinea flood period (October-January) the CWatM ensemble mean ($Q \sim 500 \text{ m}^3/\text{s}$) underestimates the observed ($Q > 1000 \text{ m}^3/\text{s}$) streamflow. However, the period of low water levels (March-June), the CWatM ensemble mean indicates the lowest streamflow but relatively higher than the observed. Meanwhile, the high CWatM discharge rates may be related to the bias correction method used as the approach does not capture new extreme dynamics (more intense event).

In terms of inter-annual variability (**Figure 4(b)**), CWatM ensemble mean overestimates the observation. This overestimation is particularly pronounced during the period 1981-1985 which is already characterized as a severe drought period [46]. This can be linked to the Sahelian paradox, which shows low rainfall, associated to high streamflow [21] [22]. Moreover, the land use land cover degradation in Kandadji area would favor CWatM to produce higher runoff and streamflow [21]. However, for some other years, the model strongly underestimates the observation (1990-1992). During the post 1994 period, CWatM ensemble mean seems to reproduce the observation. Over this period, the observation and ensemble mean model produce higher streamflow than the preceding period (1986-1993). The observed increase in rainfall and extreme rainfall over the Sahel region [18] [19] may favor the increase in streamflow during the post 1990 period.

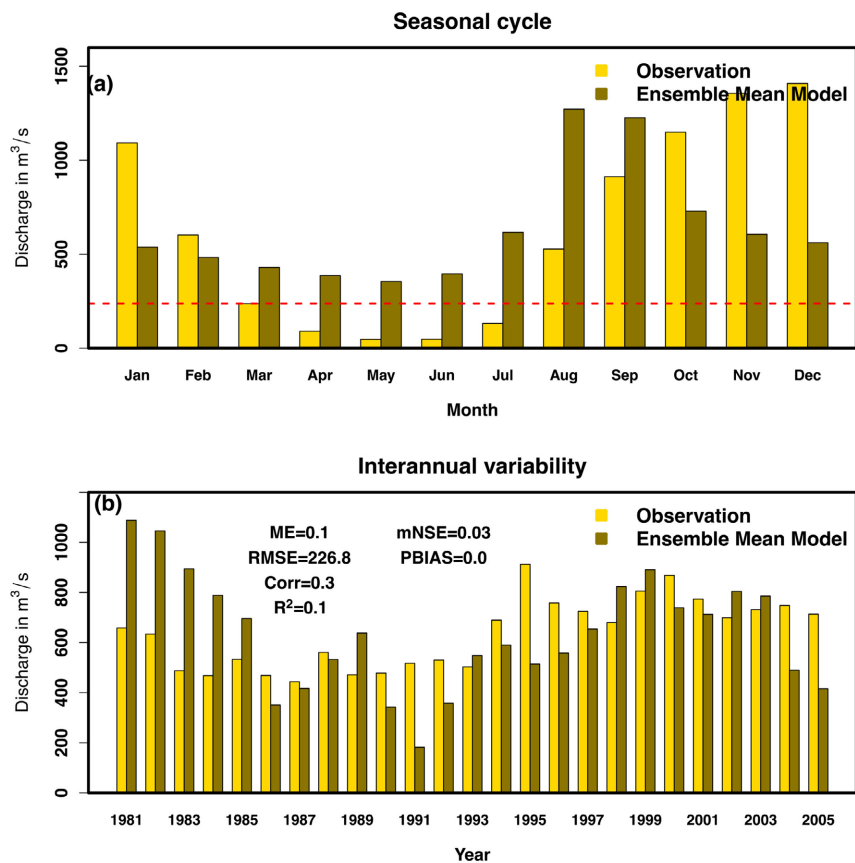


Figure 4. The mean ensemble models (CWatM_GFDL, CWatM_IPSL, CWatM_HadGem) discharge compared to the observation at Kandadji station for (a) the seasonal cycle and (b) inter-annual variability.

Furthermore, the low correlation ($\text{Corr} = 0.30$) and determination ($R^2 = 0.10$) coefficients and the little modified Nash-Sutcliffe Efficiency ($\text{mNSE} = 0.03$) indicate a limited capacity of the model to reproduce daily streamflow and its variability at Kandadji station. Several factors account for these hydrological limitations. First, CWatM is a global hydrological model driven by three global climate models (GFDL, IPSL, HadGem). Each model has its own strengths and limitations, and their relatively coarse spatial resolution may limit the representation of some subgrid-scale processes and local hydro-climatic features. Second, the meteorological forcing data are derived from the global climate models and therefore represent an additional source of uncertainty that may propagate through the hydrological simulations. In this regard, [27] concluded that the quality of meteorological forcing data driving the hydrological models represents an external limitation and a source of uncertainty. Finally, the hydrological model outputs used in this study were obtained from ISIMIP, an international modelling initiative that may not fully capture local-scale processes and subgrid-scale variability due to the coarse spatial resolution of the underlying model inputs and simulations [24].

3.3. Future Changes in the Hydroclimate Parameters

Table 2 summarizes the projected future changes in hydroclimatic parameters used in this study. Significant increases in maximum and minimum temperatures are expected, ranging from 1.1°C to 4.4°C depending on the periods (2025-2049 and 2075-2099) and the scenarios (SSP126 and SSP370). Furthermore, the increase in the minimum temperature appears to be more pronounced than that of maximum temperature. While the temperature increase is unequivocal [30], the thresholds reached by these changes could have significant impacts on natural (water, biodiversity, etc.) and human systems (health, dams, electricity transmission systems, etc.). Under these warming conditions, significant increases in rainfall are also projected, ranging from 12% to 42%. This aligns with the results of recent studies that have shown an increase in rainfall and intense rainfall over the Sahel region [19] [45]. Potential evapotranspiration exhibits an increasing pattern, but a less pronounced relative increase compared to rainfall. Indeed, it is projected to vary from less than 1% over the period 2025-2049 (SSP126) to more than 5% over the period 2075-2099 (SSP370). Naturally, increased evapotranspiration would result from rising temperatures and enhanced atmospheric moisture content could feedback into rainfall intensification [19] [46]. Regarding the flow rates, a slight increase ranging from 0.13% to 2.55% could be recorded. This increase appears to coincide with the increase in rainfall, but to a much lesser extent. However, the consensus positive change in the future discharges found in our study seems divergent to some previous studies, which reported mixed trends [14] [44]. Unlike our case, which considered the ensemble mean models, these authors performed analyses on individual models. This may favor mixed trends in one case and smoothing in the other. Otherwise, the increase in the maximum number of wet hydrological days (HCWD) and the decrease in maximum number of dry hy-

drological days (HCDD) contribute to this streamflow increase (**Table 2**). However, the smallest increase in flow (0.13%) recorded for the RCP8.5 scenario and over the period 2075-2099, despite the significant increase in rainfall, could stem from the drastic reduction in HCWD (−18.75%), which is largely offset by a smaller decrease in HCDD (−14%).

Table 2. Future changes in the selected Hydroclimate parameters at Kandadji hydroelectricity power plant. Significant changes in bold and italics.

Climate Variables	SSP126		SSP370	
	2025-2049	2075-2099	2025-2049	2075-2099
Rainfall (%)	<i>19.3</i>	<i>12.12</i>	<i>19.2</i>	<i>42.76</i>
Maximum temperature (°C)	<i>1.1</i>	<i>1.3</i>	<i>1.3</i>	<i>3.7</i>
Minimum temperature (°C)	<i>1.3</i>	<i>1.5</i>	<i>1.7</i>	<i>4.4</i>
Potential Evapotranspiration (%)	<i>0.68</i>	<i>1.58</i>	<i>0.67</i>	<i>5.43</i>
Hydrological Variables	RCP2.6		RCP8.5	
	2025-2049	2075-2099	2025-2049	2075-2099
Discharge (%)	2.06	1.37	2.55	0.13
Maximum number of hydrological consecutive wet days (HCWD, in %)	39.8	9.06	21.09	−18.75
Maximum number of hydrological consecutive dry days (HCDD in %)	0.78	−9.2	−13.75	−14.06

3.4. Changes in the Electricity Power Generation

To analyze the impact of climate change on potential electricity production at Kandadji, we calculated the difference between the energy projected in the future periods (2025-2049 & 2075-2099) under two RCP scenarios (RCP2.6 and RCP8.5) and that produced during the baseline reference period (1981-2005). The results obtained from the CWatM ensemble mean are presented in **Figure 5**. It appears that the ensemble mean of the model simulates a very slight increase in the average potential electricity production (<3%) over the two periods, regardless of the scenario (**Figure 5(a)**). During the period 2075-2099 under the scenario RCP8.5, the largest increase is projected, although it remains marginal (~0.13%). The small increase recorded in energy production seems to be correlated with the change in the flow rates. Similar results were found in previous studies [15] [47] which showed that the energy produced is highly sensitive to reservoir inflows. Conversely, our findings diverge from those of [20] who reported hydropower decreases of −9.1% and −8.4% for 2020-2049 and 2070-2099 periods. While these authors projected increases in mean discharge, the discrepancy likely stems from the differences in the defined discharge thresholds used power generation formulas.

On the seasonal scale (**Figure 5(b)**, **Figure 5(c)**), changes are characterized by more pronounced variations. Indeed, energy production varies from −24% to

+26%. During the dry and the Guinean flood seasons (October to June), there is a predominance of positive changes, thus an increase in energy production. Meanwhile, most of the dry seasons (October–November, March–May) are characterized by the highest temperatures and electrical energy demands [48] [49]. Thus, the increasing trends in energy production can help to fill the gap of the energy demand. The months of July and August appear to be the most affected by the negative changes, with decreases ranging between -10% and -24% . This pattern of monthly energy change distribution is comparable to that of monthly discharge changes obtained by [14]. These authors showed that changes in monthly discharge ranged from an increase of up to 50% to a decrease of up to 50%.

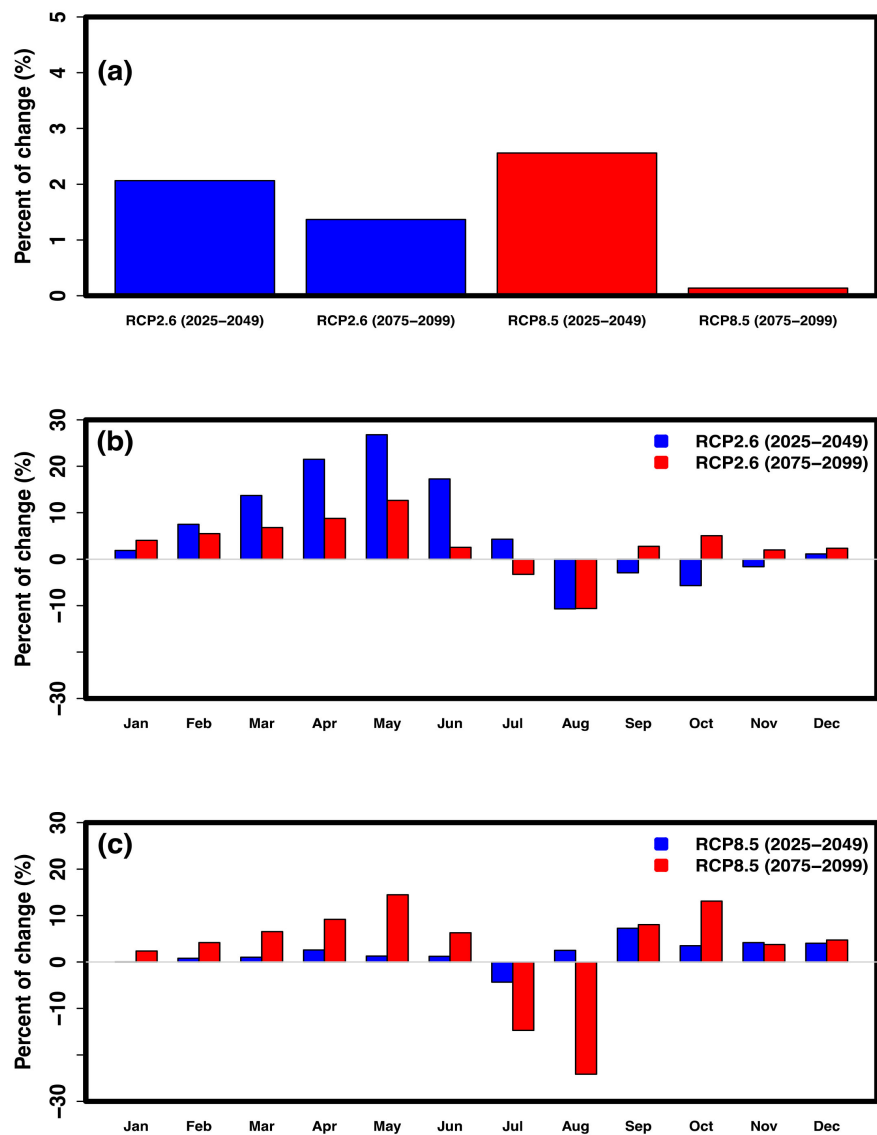


Figure 5. Future changes in the electricity power generation (in %) at Kandadji hydroelectricity power plant under RCP2.6 and RCP8.5 (a) for near (2025–2049) and far (2075–2099) futures (b) and (c) seasonal changes for RCP2.6 and RCP8.5 respectively.

4. Concluding Remarks

The observed historical rainfall and streamflow reveal an intensification of the hydrological cycle at the Kandadji station over the Niger river. Indeed, the hydroclimatic parameters are characterized by significant increases in annual rainfall amount, the frequency of rainy days (RR1) and heavy rain events. Over the future periods, significant positive changes are projected in all hydroclimatic parameters across the study area under climate change scenarios. This has led to a strengthening of streamflow, particularly an increase in the frequency of high flow rates (except for RCP8.5 during 2075-2099). As concluded by [13] the strengthening of the hydrological cycle is particularly exacerbated by climate change across West Africa. The average flow rate at Kandadji is projected to increase moderately (<3%). Consequently, small positive changes (<3%) in hydroelectric power generation could be recorded over future periods, regardless of the scenarios. This confirms the strong link between flow rate and hydroelectric power generation. However, the general trend masks significant seasonal disparities. Indeed, seasonal changes exhibited high variability in the hydroelectric power generation varying from -24% to up to +26%.

In summary, while the insights gained in this study are constrained by the limitations of the global-scale CWatM model within the ISIMIP framework, these directional findings provide a reliable baseline for strategic planning in Niger. The results offer promising prospects for future grid stabilization, energy service delivery, and national socio-economic development. However, the intensification of the hydrological regime may also increase flood risks, posing significant threats to both human and natural systems. Consequently, future investigations using fine-scale regional hydrological models and considering localized subgrid processes are essential to confirm these findings and better quantify the modeling uncertainties and confidence levels.

Acknowledgements

The data used in this study were obtained through the Scientific Research and Technological Innovation Support Fund (FARSIT) of the Ministry of Higher Education, Research and Technological Innovation (MESR/IT) of the Republic of Niger.

Author Contributions

Conceptualization, I.A.S. and A.L.D.; methodology, I.A.S. and A.L.D.; software, I.A.S., A.L.D., B.A.B., H.S.D.N., M.R.I.O., A.A.S.C.; validation, I.A.S., A.L.D., B.A.B., H.S.D.N., M.R.I.O., A.A.S.C.; formal analysis, I.A.S., A.L.D., B.A.B., H.S.D.N., M.R.I.O., A.A.S.C.; investigation, I.A.S. and A.L.D.; resources, I.A.S. and A.A.S.C.; data curation, I.A.S. and A.L.D.; writing—original draft preparation, I.A.S., A.L.D., B.A.B., H.S.D.N., M.R.I.O., A.A.S.C.; writing—review and editing, I.A.S., A.L.D., B.A.B., H.S.D.N., M.R.I.O., A.A.S.C.; visualization, I.A.S., A.L.D., B.A.B., H.S.D.N., M.R.I.O., A.A.S.C.; supervision, I.A.S.; funding acquisi-

tion, I.A.S. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Ember (2025) Global Electricity Review 2025. Ember.
<https://ember-climate.org/insights/research/global-electricity-review-2025/>
- [2] International Energy Agency (2025) Global Energy Review 2025. International Energy Agency. <https://www.iea.org/reports/global-energy-review-2025>
- [3] Ember (2026) Global Electricity Review 2026. Ember.
<https://ember-climate.org/insights/research/global-electricity-review-2026/>
- [4] International Hydropower Association (2025) 2025 World Hydropower Outlook: Opportunities to Advance Net Zero. International Hydropower Association.
<https://www.hydropower.org/publications/2025-world-hydropower-outlook>
- [5] Clarke, L., Wei, Y.-M., De La Vega Navarro, A., Garg, A., Hahmann, A.N., Khennas, S., *et al.* (2022) Energy Systems. In: Shukla, P.R., Skea, J., Slade, R., *et al.*, Eds., *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 613-746. <https://doi.org/10.1017/9781009157926.008>
- [6] Kumar, A., Schei, T., Ahenkorah, A., Caceres Rodriguez, R., Devernay, J.-M., Freitas, M., *et al.* (2011) Hydropower (Chapter 5). In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., *et al.*, Eds., *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, Cambridge University Press, 437-496.
<https://doi.org/10.1017/CBO9781139151153.009>
- [7] International Renewable Energy Agency (2021) Renewable Power Generation Costs in 2020. International Renewable Energy Agency.
- [8] Brown, A., Müller, S. and Dobrotková, Z. (2011) Renewable Energy Markets and Prospects by Technology. IEA/OECD.
- [9] International Hydropower Association (2019) Hydropower Sector Climate Resilience Guide. International Hydropower Association.
<https://www.hdropower.org/publications/hydropower-sector-climate-resilience-guide>
- [10] Christensen, N.S., Wood, A.W., Voisin, N., Lettenmaier, D.P. and Palmer, R.N. (2004) The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. *Climatic Change*, **62**, 337-363.
<https://doi.org/10.1023/b:clim.0000013684.13621.1f>
- [11] Graham, L.P., Andréasson, J. and Carlsson, B. (2007) Assessing Climate Change Impacts on Hydrology from an Ensemble of Regional Climate Models, Model Scales and Linking Methods—A Case Study on the Lule River Basin. *Climatic Change*, **81**, 293-307. <https://doi.org/10.1007/s10584-006-9215-2>
- [12] Minville, M., Brissette, F. and Leconte, R. (2010) Impacts and Uncertainty of Climate Change on Water Resource Management of the Peribonka River System (Canada). *Journal of Water Resources Planning and Management*, **136**, 376-385.
[https://doi.org/10.1061/\(asce\)wr.1943-5452.0000041](https://doi.org/10.1061/(asce)wr.1943-5452.0000041)
- [13] Todzo, S., Bichet, A. and Diedhiou, A. (2020) Intensification of the Hydrological Cy-

- cle Expected in West Africa over the 21st Century. *Earth System Dynamics*, **11**, 319-328. <https://doi.org/10.5194/esd-11-319-2020>
- [14] Aich, V., Liersch, S., Vetter, T., Huang, S., Tecklenburg, J., Hoffmann, P., *et al.* (2014) Comparing Impacts of Climate Change on Streamflow in Four Large African River Basins. *Hydrology and Earth System Sciences*, **18**, 1305-1321. <https://doi.org/10.5194/hess-18-1305-2014>
- [15] Obahoundje, S., Diedhiou, A., Dubus, L., Adéchina Alamou, E., Amoussou, E., Akpoti, K., *et al.* (2022) Modeling Climate Change Impact on Inflow and Hydropower Generation of Nangbeto Dam in West Africa Using Multi-Model CORDEX Ensemble and Ensemble Machine Learning. *Applied Energy*, **325**, Article 119795. <https://doi.org/10.1016/j.apenergy.2022.119795>
- [16] Sylla, M.B., Nikiema, P.M., Bambara, L., Dosio, A. and Giorgi, F. (2016) Climate Change Features over West Africa in CORDEX Regional Climate Models. *Climatic Change*, **137**, 629-643.
- [17] Monerie, P., Mohino, E., Moine, M., Biasutti, M., Pohl, B. and Mignot, J. (2025) Exploring Uncertainty in Dynamical Future Changes in Sahel Precipitation: The Extratropical Influence. *Climate Dynamics*, **63**, Article No. 353. <https://doi.org/10.1007/s00382-025-07835-0>
- [18] Salack, S., Saley, I.A., Lawson, N.Z., Zabré, I. and Daku, E.K. (2018) Scales for Rating Heavy Rainfall Events in the West African Sahel. *Weather and Climate Extremes*, **21**, 36-42. <https://doi.org/10.1016/j.wace.2018.05.004>
- [19] Saley, I.A. and Salack, S. (2023) Present and Future of Heavy Rain Events in the Sahel and West Africa. *Atmosphere*, **14**, Article 965. <https://doi.org/10.3390/atmos14060965>
- [20] Mutsindikwa, T.C., Yira, Y., Bossa, A.Y., Hounkpè, J., Salack, S., Saley, I.A., *et al.* (2021) Modeling Climate Change Impact on the Hydropower Potential of the Bamboi Catchment. *Modeling Earth Systems and Environment*, **7**, 2709-2717. <https://doi.org/10.1007/s40808-020-01052-w>
- [21] Descroix, L., Bouzou Moussa, I., Genthon, P., Sighomnou, D., Mahé, G., Mamadou, I., *et al.* (2009) Impact of Land Use Change in the Sahel: How Deforestation Increases Catchment Runoff. *Journal of Hydrology*, **370**, 138-152.
- [22] Descroix, L., Genthon, P., Amogu, O., Rajot, J., Sighomnou, D. and Vauclin, M. (2012) Change in Sahelian Rivers Hydrograph: The Case of Recent Red Floods of the Niger River in the Niamey Region. *Global and Planetary Change*, **98**, 18-30. <https://doi.org/10.1016/j.gloplacha.2012.07.009>
- [23] Boko, B.A., Konaté, M., Yalo, N., Berg, S.J., Erler, A.R., Bazié, P., *et al.* (2020) High-resolution, Integrated Hydrological Modeling of Climate Change Impacts on a Semi-Arid Urban Watershed in Niamey, Niger. *Water*, **12**, Article 364. <https://doi.org/10.3390/w12020364>
- [24] Souley Tangam, I., Yonaba, R., Niang, D., Adamou, M.M., Keïta, A. and Karambiri, H. (2024) Daily Simulation of the Rainfall-Runoff Relationship in the Sirba River Basin in West Africa: Insights from the HEC-HMS Model. *Hydrology*, **11**, Article 34. <https://doi.org/10.3390/hydrology11030034>
- [25] Autorité du Bassin du Niger (2012) Projet de développement des ressources en eau et gestion durable des écosystèmes dans le bassin du Niger (PDRE/GDE-BN): Cadre de gestion environnementale et sociale (CGES). Rapport Institutionnel.
- [26] Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., *et al.* (2015) The Climate Hazards Infrared Precipitation with Stations—A New Environmental Record for Monitoring Extremes. *Scientific Data*, **2**, Article No. 150066.

- <https://doi.org/10.1038/sdata.2015.66>
- [27] Burek, P., Satoh, Y., Kahil, T., *et al.* (2020) Développement du modèle communautaire de l'eau (CWatM v1.04)-un modèle hydrologique à haute résolution pour l'évaluation mondiale et régionale de la gestion intégrée des ressources en eau. *Geoscientific Model Development*, **13**, 3267-3298.
 - [28] Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., *et al.* (2010) The Next Generation of Scenarios for Climate Change Research and Assessment. *Nature*, **463**, 747-756. <https://doi.org/10.1038/nature08823>
 - [29] Meinshausen, M., Nicholls, Z.R.J., Lewis, J., Gidden, M.J., Vogel, E., Freund, M., *et al.* (2020) The Shared Socio-Economic Pathway (SSP) Greenhouse Gas Concentrations and Their Extensions to 2500. *Geoscientific Model Development*, **13**, 3571-3605. <https://doi.org/10.5194/gmd-13-3571-2020>
 - [30] IPCC (2021) Climate Change 2021: The Physical Science Basis. Cambridge University Press, 2391 p.
 - [31] Thiessen, A.H. (1911) Precipitation Averages for Large Areas. *Monthly Weather Review*, **39**, 1082-1089. [https://doi.org/10.1175/1520-0493\(1911\)39<1082b:pafla>2.0.co;2](https://doi.org/10.1175/1520-0493(1911)39<1082b:pafla>2.0.co;2)
 - [32] Parker, J.A., Kenyon, R.V. and Troxel, D.E. (1983) Comparison of Interpolating Methods for Image Resampling. *IEEE Transactions on Medical Imaging*, **2**, 31-39. <https://doi.org/10.1109/tmi.1983.4307610>
 - [33] Meijering, E. (2002) A Chronology of Interpolation: From Ancient Astronomy to Modern Signal and Image Processing. *Proceedings of the IEEE*, **90**, 319-342. <https://doi.org/10.1109/5.993400>
 - [34] Burrough, P.A., McDonnell, R.A. and Lloyd, C.D. (2015) Principles of Geographical Information Systems. Oxford University Press.
 - [35] Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56.
 - [36] Mohawesh, O.E. and Talazi, S.A. (2011) Comparison of Hargreaves and FAO56 Equations for Estimating Monthly Evapotranspiration for Semi-Arid and Arid Environments. *Archives of Agronomy and Soil Science*, **58**, 321-334. <https://doi.org/10.1080/03650340.2010.516253>
 - [37] Tong, Y., Gao, X., Han, Z., Xu, Y., Xu, Y. and Giorgi, F. (2020) Bias Correction of Temperature and Precipitation over China for RCM Simulations Using the QM and QDM Methods. *Climate Dynamics*, **57**, 1425-1443. <https://doi.org/10.1007/s00382-020-05447-4>
 - [38] Amengual, A., Homar, V., Romero, R., Alonso, S. and Ramis, C. (2012) A Statistical Adjustment of Regional Climate Model Outputs to Local Scales: Application to Platja De Palma, Spain. *Journal of Climate*, **25**, 939-957. <https://doi.org/10.1175/jcli-d-10-05024.1>
 - [39] Gareyane, M. (2017) Détermination des débits environnementaux: Développement d'une approche méthodologique technique et participative pour le Niger supérieur et le Delta Intérieur du Niger. Présenté à La répartition de l'eau dans les bassins transfrontières: Un atelier mondial sur l'état actuel et les bonnes pratiques, UNECE. https://unece.org/fileadmin/DAM/env/documents/2017/WAT/10Oct_16-17_WS_on_Water_Allocation/Session_1_Gareyane_eflow_Presentation_vf.pdf
 - [40] Snedecor, G.W. and Cochran, W.G. (1989) Statistical Methods. 8th Edition, Iowa State University Press.

- [41] Kendall, M.G. (1975) Rank Correlation Methods. 4th Edition, Charles Griffin.
- [42] Krause, P., Boyle, D.P. and Bäse, F. (2005) Comparison of Different Efficiency Criteria for Hydrological Model Assessment. *Advances in Geosciences*, **5**, 89-97. <https://doi.org/10.5194/adgeo-5-89-2005>
- [43] Taylor, C.M., Belušić, D., Guichard, F., Parker, D.J., Vischel, T., Bock, O., *et al.* (2017) Frequency of Extreme Sahelian Storms Tripled since 1982 in Satellite Observations. *Nature*, **544**, 475-478. <https://doi.org/10.1038/nature22069>
- [44] Yira, Y., Diekkrüger, B., Steup, G. and Bossa, A.Y. (2017) Impact of Climate Change on Hydrological Conditions in a Tropical West African Catchment Using an Ensemble of Climate Simulations. *Hydrology and Earth System Sciences*, **21**, 2143-2161. <https://doi.org/10.5194/hess-21-2143-2017>
- [45] Yang, K., Wang, G., Cai, W., Mohino, E., Rodriguez-Fonseca, B., Ng, B., *et al.* (2025) Increased Interannual Variability of Sahel Rainfall under Greenhouse Warming. *Nature Communications*, **17**, Article No. 1125. <https://doi.org/10.1038/s41467-025-67885-0>
- [46] Douville, H., Raghavan, K., Renwick, J., Allan, R.P., Arias, P.A., Barlow, M., *et al.* (2021) Water Cycle Changes. In: Mas-son-Delmotte, V., Zhai, P., Pirani, A., *et al.*, Eds., *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 1055-1210.
- [47] Obahoundje, S., Ofosu, E., Akpoti, K. and Kabo-bah, A. (2017) Land Use and Land Cover Changes under Climate Uncertainty: Modelling the Impacts on Hydropower Production in Western Africa. *Hydrology*, **4**, Article 2. <https://doi.org/10.3390/hydrology4010002>
- [48] Saley, I.A., Salack, S., Sanda, I.S., Moussa, M.S., Bonkaney, A.L., Ly, M., *et al.* (2019) The Possible Role of the Sahel Greenbelt on the Occurrence of Climate Extremes over the West African Sahel. *Atmospheric Science Letters*, **20**, e927. <https://doi.org/10.1002/asl.927>
- [49] Aissatou, N., Rabani, A., Moussa, G. and Arona, D. (2017) Global Warming and Heat Waves in West-Africa: Impacts on Electricity Consumption in Dakar (Senegal) and Niamey (Niger). *International Journal of Energy and Environmental Science*, **2**, 16-26.