

Article

Climate Change and Its Impacts on Water Resources in the Bandama Basin, Côte D'ivoire

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Abstract: This study aims to assess future trends in monthly rainfall and temperature and its impacts on surface and groundwater resources in the Bandama basin. The Bandama river is one of the four major rivers of Côte d'Ivoire. Historical data from 14 meteorological and three hydrological stations were used. Simulation results for future climate from HadGEM2-ES model under representative concentration pathway (RCP) 4.5 and RCP 8.5 scenarios indicate that the annual temperature may increase from 1.2 °C to 3 °C. These increases will be greater in the north than in the south of the basin. The monthly rainfall may decrease from December to April in the future. During this period, it is projected to decrease by 3% to 42% at all horizons under RCP 4.5 and by 5% to 47% under RCP 8.5. These variations will have caused an increase in surface and groundwater resources during the three periods (2006–2035; 2041–2060; 2066–2085) under the RCP 4.5 scenario. On the other side, these water resources may decrease for all horizons under RCP 8.5 in the Bandama basin.

Keywords: rainfall; temperature; runoff; groundwater recharge; Bandama river

1. Introduction

Climate change is inevitably resulting in changes in climate variability and in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events [1]. The works of [2,3] showed that 46% of cultivated areas in the world are not suitable for rainfed agriculture because of climate changes and other meteorological conditions. Many studies have concluded that the impacts of climate change will not be equally shared among the population of the world [4–7]. The distribution of impacts will vary as both the ability to respond to impacts and the availability of resources with which to do so vary across nations [8]. There is high confidence that developing countries will be more vulnerable to climate change than developed countries, and there is medium confidence that climate change would exacerbate income inequalities between and within countries [7]. Sub-Saharan Africa is considered the most vulnerable to the impacts of climate change because of its high dependence on agriculture and natural resources, warmer baseline climates, low precipitation, and limited ability to adapt [9]. Several studies have shown that surface water and groundwater evolutions over the past decades in Sub-Saharan Africa have been strongly affected by rainfall variations. Climate models project important climate changes for the 21st century in West Africa as well as in the rest of the world, with potential impacts on the hydrological cycle [10]. This vulnerability is also due to the fact that the current climate is already severe, present information is not sufficient, and technological change has been slowest in Sub-Saharan Africa [11].

Côte d'Ivoire, located in West Africa is no exception to this situation because its economy is based on rain-fed agriculture and it has a strong dependence on river flow for the power generation and fisheries. In this country, the impacts of climate change have led to recurrent droughts, changes in rain amount distribution, reduction of arable land, coastal erosion, and flooding [12]. Many studies on the impacts of climate variability were carried out in Côte d'Ivoire [13–18]. Few studies have been conducted to investigate the impact of climate change on the water resources in the Bandama basin, despite the increase in water requirements for water supply of populations, agriculture, livestock, mining, and hydroelectric dams. Moreover, the few previous studies have used the Special Report on Emissions Scenarios (SRES) that explicitly consider the effects of prescribed levels of emissions into the atmosphere. However, there was enormous uncertainty regarding contributing factors such as population growth, economic development, and technological advances, hence, the move towards representative concentration pathways (RCPs) in this study. The better understanding of potential future changes on water resources is fundamental to inform populations in order to increase awareness and to support the development of adaptation strategies on the Bandama basin. This study examined how projected changes in temperature and precipitation regimes impact simulated runoff and groundwater recharge in the Bandama catchment using statistical downscaled climatological data.

2. Data and Methods

2.1. Study Area

Figure 1 shows the Bandama basin located in Côte d'Ivoire. The Bandama river is one of the four major rivers of the country. Its source is located north of Côte d'Ivoire between Korhogo and Boundiali. There are three major tributaries: White Bandama (22,293 km²), N'zi (3500 km²), and Marahoue (19,800 km²). The Bandama basin spreads over three different climatic and hydrographic regions because its regime follows the rainy season. Its northern part is characterized by dry sub-tropical climate (between 1000 mm and 1700 mm). This area has a unimodal rainfall distribution or pattern with distinct wet (rainy) and dry seasons. The central (equatorial climate) and southern (humid equatorial climate) parts of the basin are characterized by two rainy seasons. In the equatorial climate, the annual rainfall is greater than 1500 mm. The amount of rainfall is higher in the humid equatorial climate, with a yearly mean of 1800 mm. As described in previous studies [19,20], the lithology is characterized by the Birimian formations (volcanic, volcanogenic, and sedimentary formations) and granitoid Eburnean comprised of granitic solid masses in which several generations of granites are distinguished. Alterites and fracture aquifers provide a year groundwater supply linked to the underground grid of fractures [21]. Previous studies [22,23] have shown that groundwater recharge is highly dependent on rainfall and varies between 50 mm and 354 mm in the Bandama basin. Vegetation cover in the Bandama catchment varies from north (savannah) to south (forest). Topography of the Bandama catchment is gentle, with a maximum elevation of 809 m above sea level.

2.2. Dataset

2.2.1. Historical Time Series Data

Historical meteorological and hydrological data were collected from the Department of meteorology and hydraulic infrastructures division, Government of Côte d'Ivoire. In this study, the climate data include details of rainfall, temperature, and the potential evapotranspiration. The hydrological data includes mean monthly flow of the Bandama river and its tributaries (Marahoue and N'zi). The stations were selected to provide a good spatial coverage of the different climatic areas across in the Bandama basin (Figure 2). The meteorological stations outside the watershed were used because the climatic parameters measured at these stations influence the flows on the basin. The list of historical data used is presented in Table 1.

Table 1. Characteristics of the selected stations.

Code	Station	Data	Longitude (Decimal Degree)	Latitude (Decimal Degree)	Data Availability
1090012000	Korhogo	Meteorological	−5.61	9.41	1971–2005
1090006400	Boundiali		−6.46	9.51	1922–2005
1090005600	Bouaké		−5.06	7.73	1966–2005
1090018700	Tafiré		−5.15	9.06	1950–2005
1090007300	Dabakala		−4.43	8.38	1945–2005
1090015100	M'Bahiakro		−4.33	7.45	1944–2005
1090022200	Zuénoula		−6.05	7.41	1953–2005
1090009100	Dimbokro		−4.70	6.65	1921–2005
1090016900	Oumé		−5.41	6.36	1944–2005
1090005200	Bouaflé		−5.75	6.98	1924–2005
1090010300	Gagnoa		−5.95	6.13	1922–2005
1090019600	Tiassalé		−4.83	5.88	1959–2005
1090000100	Abidjan		−3.93	5.25	1961–2005
1090010000	Ferkessédougou	Hydrological	−5.20	9.60	1961–2005
1090101006	Marahoué		−5.75	6.97	1954–2005
1090102515	N'Zi		−4.81	6.00	1953–2005
1090100154	Tiassalé		−4.82	5.89	1954–2005

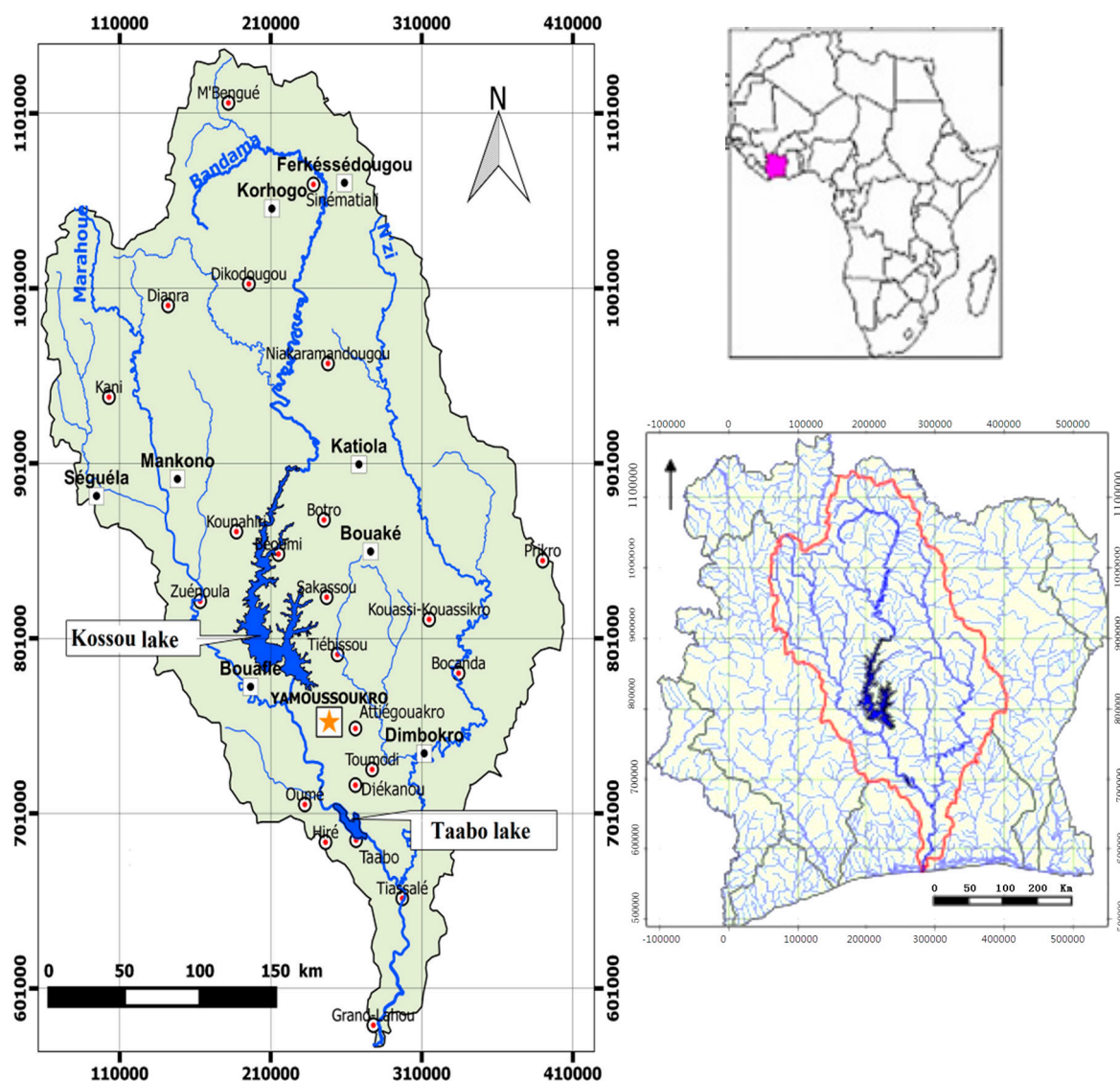


Figure 1. Geographical location of the study area.

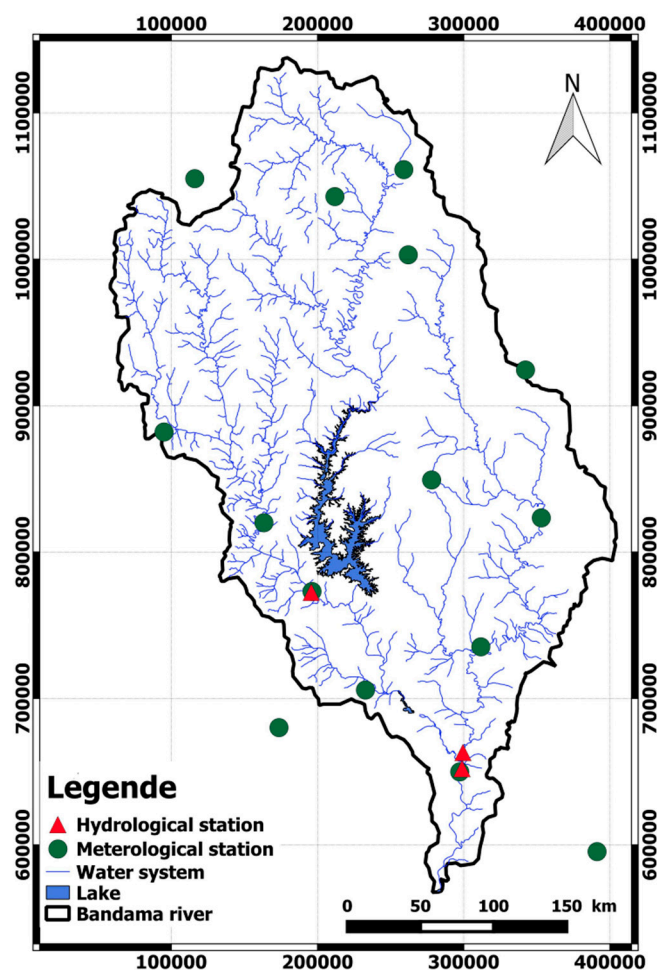


Figure 2. Network of meteorological and hydrological stations used in this study.

2.2.2. Projected Future Climate Data

Simulation results (monthly rainfall and temperature) for future climate from the HadGEM2-ES model were used. It is an Earth system model based on the HadGEM2 atmosphere-ocean general circulation model with additional representation of global-scale processes of biology and chemistry [24]. The simulations described here were driven by prescribed CO₂ concentrations from the representative concentration pathways (RCPs) as part of the 5th Coupled Model Intercomparison Project [25]. The model used the RCP scenarios of changes in other anthropogenic greenhouse gases such as methane, nitrous oxide, and halocarbons, and anthropogenic aerosols such as sulfate and black carbon [26]. For this study, the RCP 4.5 and RCP 8.5 were used. RCP 4.5 is a scenario that stabilizes radiative forcing at 4.5 Watts per meter squared in the year 2100 without ever exceeding that value. This scenario is consistent with a future with relatively ambitious emission reductions. It is similar to SRES B1 [27]. Contrariwise, RCP 8.5 corresponds to a high greenhouse gas emissions pathway compared to the scenario literature. This RCP is consistent with a future with no policy changes to reduce emissions. It is comparable to the SRES A1F1 Emission Scenario [28].

The data used in this work are available from 1900–2100. The simulations were performed to monitor the climate in the short, medium, and long term on the following periods: 2006–2035, 2041–2060, and 2066–2085. The baseline period is 1986–2005. The choice of baseline period is due to the availability of the historical meteorological and hydrological data. Indeed, since 2006, the data transmission has been interrupted in a few stations. The data transmission was re-established in 2015.

2.3. Methodology

2.3.1. Climate Change Simulations

The differences between the climate (rainfall and temperature) of the baseline period and the future climate are calculated for each cell of the general circulation model (GCM) and for each time step (month i , year j over the baseline period 1986–2005, and year k over the 2006–2085 period). They are then expressed in change ratios (Horizons scenario) based on a mean climatology drawn from the HadGEM2-ES model simulations over the same baseline period. The change ratios of monthly rainfall and temperature between the baseline period and the three horizons, 2025 (2006–2035), 2050 (2036–2065), and 2075 (2066–2085), are calculated as:

$$\Delta_{horiz,i} = 100 \times (\bar{X}_{horiz,i} - \bar{X}_{ref,i}) / \bar{X}_{ref,i} \quad (1)$$

where \bar{X}_{horiz} is the mean value of the simulated series calculated over a given time horizon and \bar{X}_{ref} is the mean value of the simulated series calculated over the baseline period.

2.3.2. Evaluation of Potential Climate Change Impacts on Water Resources

Climate Change Scenarios

General circulation model (GCMs) often show bias in their simulation of the present climate. Various studies have shown that these models overestimate or underestimate the climatic parameters [29–33]. To reduce the estimation errors, it is recommended to build climate change scenarios. In this study, the deltas method proposed in [34] was used. The delta method used allows the implementation of two types of disturbances:

- (1) Disturbances “additive” to the temperature:

$$X_{add(t,m,y)} = X_{act(t,m,y)} + M_{cc(m)} - M_{ref(m)} \quad (2)$$

- (2) Disturbances “multiplicative” to the rainfall:

$$X_{mult(t,m,y)} = X_{act(t,m,y)} \times \frac{M_{cc(m)}}{M_{ref(m)}} \quad (3)$$

where $X_{add(t,m,y)}$ and $X_{mult(t,m,y)}$ are disturbed variables, $X_{act(t,m,y)}$ is a baseline variable, and $M_{cc(m)}$ and $M_{ref(m)}$ are the monthly averages of the variable calculated from HadGEM2-ES simulations on the time horizons and baseline period. The disturbance of month m is imputed to the current variable (i.e., observed) X_{act} , at all-time steps t of the month, for all years.

Hydrological Modeling

The climate change scenarios are evaluated by means of the GR2M model to observe the impacts of rainfall and temperature changes on water resources in the Bandama river basin. The GR2M model is widely used for hydrological modeling of river basins in Sub-Saharan Africa [29–33,35]. The GR2M model is a spatially lumped and a monthly time-step model developed by IRSTEA [36]. The hydrological functioning of the model is based on two reservoirs: the production reservoir with capacity $X1$ and the routing reservoir with a capacity of 60 mm controlled by parameter $X2$. The hydrological balance of the model is defined by the five terms as:

$$P = R + I + ET + \Delta S \quad (4)$$

where P is the rainfall, R is the runoff at the outlet, I is the infiltration, ET is the evapotranspiration (transpiration and direct evaporation), and ΔS is variation in the water in the basin.

The model is run with monthly data of two climate parameters (the rainfall and the potential evapotranspiration) and the monthly discharge data of the watershed outlet. The implementation of the model consists of the determination of the two parameters X_1 and X_2 during a calibration period and then a validation where the representativeness of the two parameters is evaluated (different with the calibration period) [35]. GR2M is calibrated and validated through the Nash efficiency criterion [37]. For both periods (calibration and validation), the Nash efficiency should be higher than 60% for simulations with the optimum parameters. The efficiency criterion evaluates the representativeness of the simulated monthly discharges by the model from:

$$Nash = 100 \times \left[1 - \frac{\sum_{i=1}^n (Q_{obs,i} - Q_{cal,i})^2}{\sum_{i=1}^n (Q_{obs,i} - \overline{Q_{cal,i}})^2} \right] \quad (5)$$

where $Q_{obs,i}$ is the observed discharge for month i , $Q_{cal,i}$ is the simulated discharge for month i , and $\overline{Q_{cal,i}}$ is the mean observed discharge over the given period. A full description of the GR2M model is presented in [30].

3. Results and Discussion

3.1. Assessment of the Changes in Climate Parameters

3.1.1. Changes in Temperatures

The results showed that the temperatures from the Bandama basin will increase in the future (Figure 3). The findings are in accordance with the latest Intergovernmental Panel on Climate Change (IPCC) report. In this study, the temperature in all the months might increase in both the scenarios, but it will be higher in the RCP 8.5 than that in the RCP 4.5. The works of [38] identify tropical West Africa as a hotspot of climate change for both RCP 4.5 and RCP 8.5 pathways, and unprecedented climates are projected to occur earlier (late 2030s to early 2040s) in these regions. It shows that in RCP 8.5, the Bandama basin will experience a temperature rise of 1.5 °C with the minimum temperature rise of about 1.2 °C and a maximum of about 1.7 °C by 2025. The monthly temperatures may vary from 2.2 °C to 3 °C by 2050. A more pronounced increase in temperature is expected in 2066–2085, with annual temperature predictions approximately 20% higher than the baseline temperature. Under RCP 4.5, changes in monthly temperatures may vary from by 0.9 °C in July to 2 °C in January with an average annual of 2.5 °C by 2025. The temperature increases will be greater in the north (Ferkessedougou station) than in the south (Abidjan station) by the 2050's and 2075. Several works in West Africa show a warming range of 3 and 6 °C above the late 20th Century baseline [39–42]. As in the Bandama watershed, the work [43] has shown that the magnitude of temperature is higher for the higher emission scenarios of RCP 8.5 than for the medium–low emission scenarios of RCP 4.5.

3.1.2. Changes in Rainfall

The per cent changes in monthly rainfall based on ground-based observations and projected simulation from the HadGEM2-ES model are presented in the Figure 4. The rates of increase or decrease in rainfall are relatively more in RCP 8.5 than RCP 4.5 over the basin. Under RCP 8.5 and RCP 4.5, the rainfall may decrease from December to April in future periods. This period corresponds to the long dry season in the basin. It is projected to decrease by 3% to 42% at all horizons under RCP 4.5 and by 5% to 47% under RCP 8.5.

During the wet months (June–July and September–November) in all future periods, the rainfall may increase with respect to the reference period (1986–2005). The works of [44] show that the dry-season decrease ranges from 4% to 25% and the wet-season increase ranges from 5% to 23%. However, the increase in the wet months' rainfall may be higher in the far future (2041–2060 or 2066–2085) than in the near future (2006–2035). In West Africa, the rainfall season is predicted to be wetter and delayed by the end of the 21st Century [45]. Otherwise, the work in West Africa [33] showed that

although the GCMs manage to reproduce these seasonal dynamics (except for HadCM3), they have real difficulty in accurately simulating the volume of rainfall.

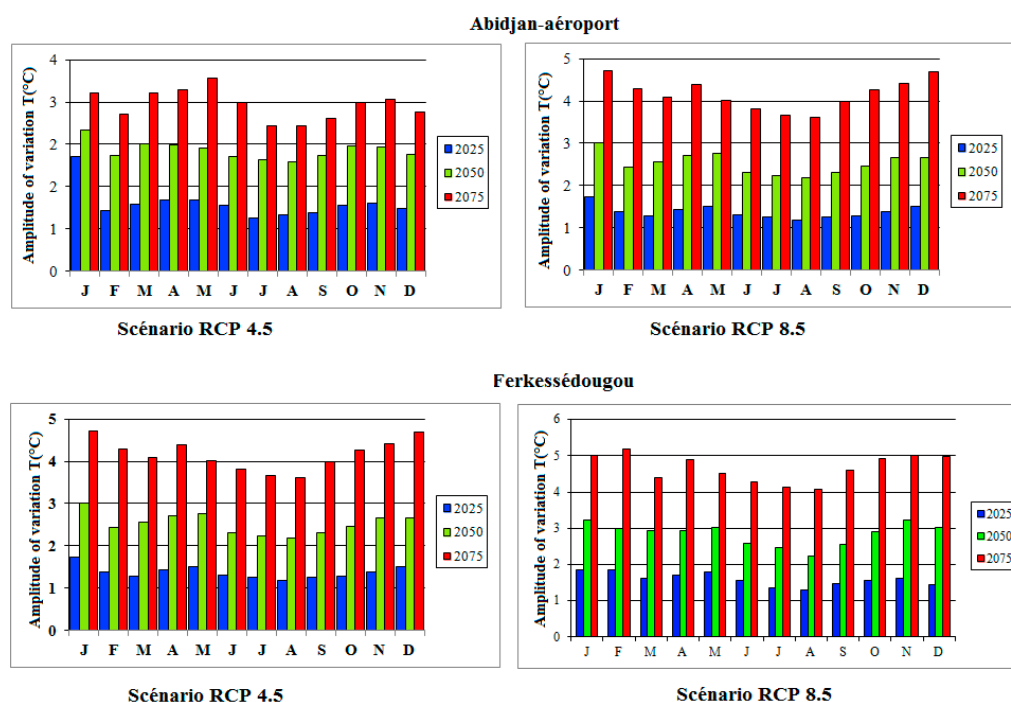


Figure 3. Amplitude of variations in monthly temperatures at different horizons according to the HadGEM2-ES model in the Bandama basin.

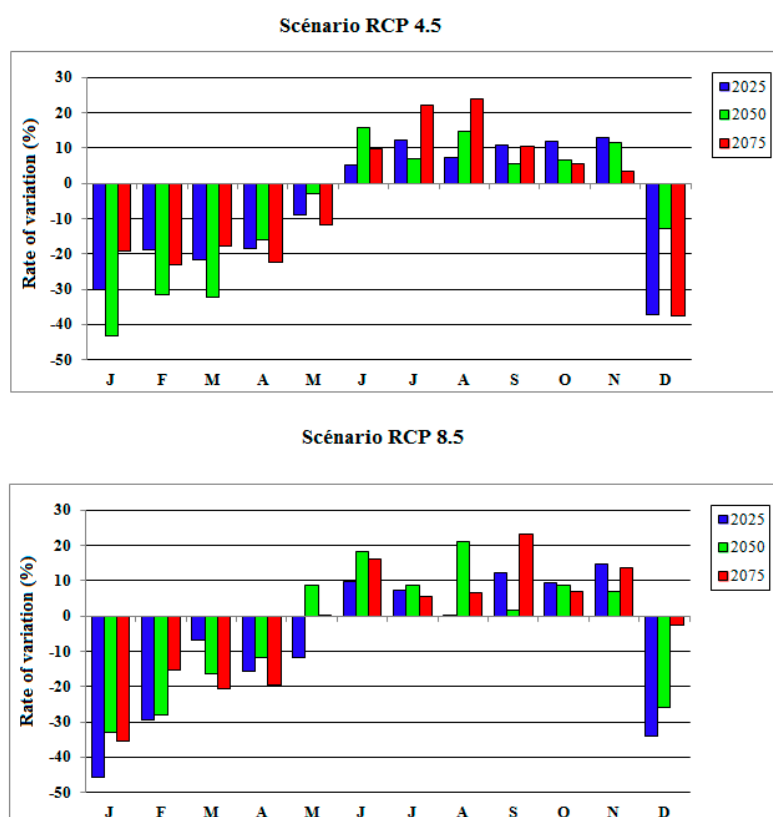


Figure 4. Percentage change in the monthly rainfall for the period 1978–2004 versus 1951–1977 in the Climate Research Unit (CRU) and University of Delaware (UD) observations (top left panels) and in each selected Coupled Model Intercomparison Project Phase 5 (CMIP5) model simulation in the Bandama basin.

3.2. Hydrological Model Calibration

Impacts of climate on water resources were assessed using a hydrological model. The hydrological model GR2M calibration was performed for the periods 1980–1989 (N'zi river), 1980–1987 (Marahoué river), and 1969–1975 (Bandama river). Calibration is the process of choosing the best sets of model parameters, by automatically adjusting their numerical values to better mimic the response observed at the outlet. For these different periods, the Nash performance coefficients are 72.3%, 77.3%, and 76.7% respectively (Table 2). Validating a model means to check the reproducibility of the results by the calibrated parameters. The model validation was done using one period by selected river: 1990–1998 (N'zi river), 1967–1977 (Marahoué river), and 1969–1975 (Bandama river). The results show that the simulated and observed monthly runoffs are very similar with the Nash coefficients greater than 70% (Figure 5).

Table 2. Calibration and validation periods with Nash criteria value from the GR2M model.

River (Station)	Calibration		Validation	
	Period	Nash Criteria Value (%)	Period	Nash Criteria Value (%)
Marahoué (Bouaflé)	1980–1987	72.3	1967–1977	74.5
N'Zi (Zianouan)	1980–1989	77.3	1990–1998	72.5
Bandama (Tiassalé)	1969–1975	76.7	1981–1989	78.4

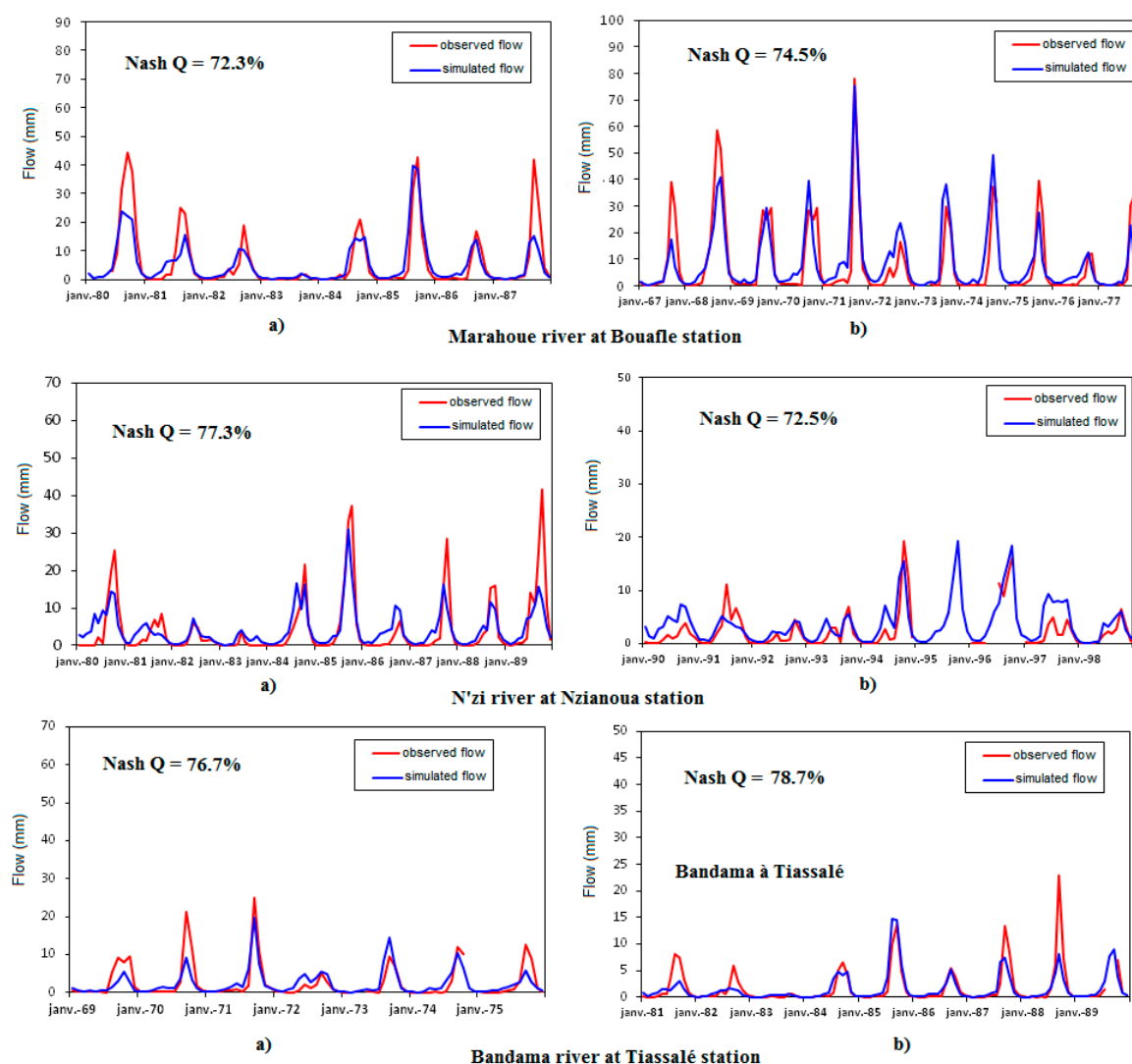


Figure 5. Monthly flow from the observations and the simulations with GR2M with (a) representing the period of calibration and (b) the validation period.

3.3. Impacts of Climate Change on Surface Water

Comparison of the mean monthly hydrographs for the three time horizons with that of the baseline period shows that the annual hydrological pattern for the Bandama, N'zi, and the Marahoué catchments remains unchanged (Figure 6a,b). The changes caused by climate change affect runoff volume in the watershed. However, the trends in river discharge are different for each scenario. Under RCP 4.5, mean monthly runoff increases for all horizons. For the Marahoué and Bandama river, the changes are important from July to October. For the N'zi river, mean monthly runoff increases gradually from March to November. The findings are in accordance with the works of [31] on the Sassandra basin in Côte d'Ivoire under several scenario (A1, A2, B1, B2, A1B). Under RCP 8.5, runoff is projected to slightly decrease up to the horizon 2025, then to decrease at the horizons 2050 and 2075. Runoff is projected to vary mainly in tributary rivers. The works in the Comoé basin of [33] with the ReGcm model and A1 scenario, revealed a decrease in runoff of 18.8% to 34% in 2031–2040 and 40% to 73% in the 2091–2100 horizon.

These results show that there is considerable uncertainty about the impacts of climate change on runoff. According to [45], overall projections of impacts of climate change on water resources in Sub-Saharan Africa are associated with large uncertainties. Apart from addressing the lack of observational data, key challenges for assessing climatic risks to water availability relate to their responses to heat waves, seasonal rainfall variability, as well as the relationship between land use changes, evapotranspiration, and soil moisture at different levels of global warming [43].

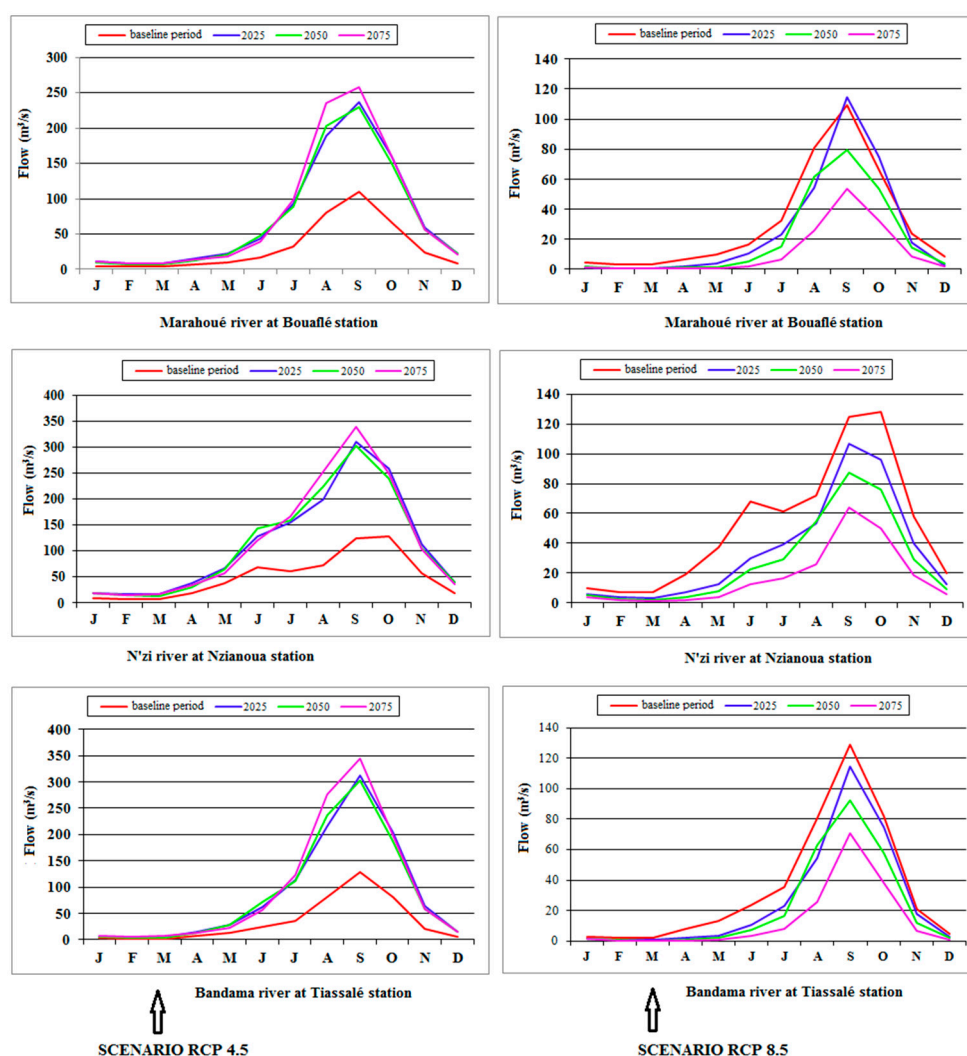


Figure 6. Monthly flows from the periods 1986–2005 (baseline period), 2016–2035, 2041–2060, and 2066–2085 of the hydrological stations in the Bandama basin.

3.4. Impacts of Climate Change on Groundwater

Under RCP 8.4 and RCP 4.5, the climate change is likely to affect groundwater due to changes in precipitation and temperature. The sensitivity of groundwater recharge to climate change is shown in Figure 7. The scenarios under RCP 8.5 show that a trend towards increasing greenhouse gases may significantly decrease in groundwater recharge. The groundwater recharge may decrease from 136.6 mm to 73.8 mm by 2025. By 2075, groundwater may decrease from 60.2% to 55.4% compared to the baseline period. In the far future (2066–2095), the groundwater recharge may decrease in the Bandama aquifers. In the Comoé basin, infiltration could decrease by 7% to 13% in the 2031–2040 horizon and 49.3% to 70% from 2091 to 2100 [26]. Contrary to RCP 8.5, RCP 4.5 indicates climate change should induce an increase in groundwater recharge of the coming decades (Figure 7).

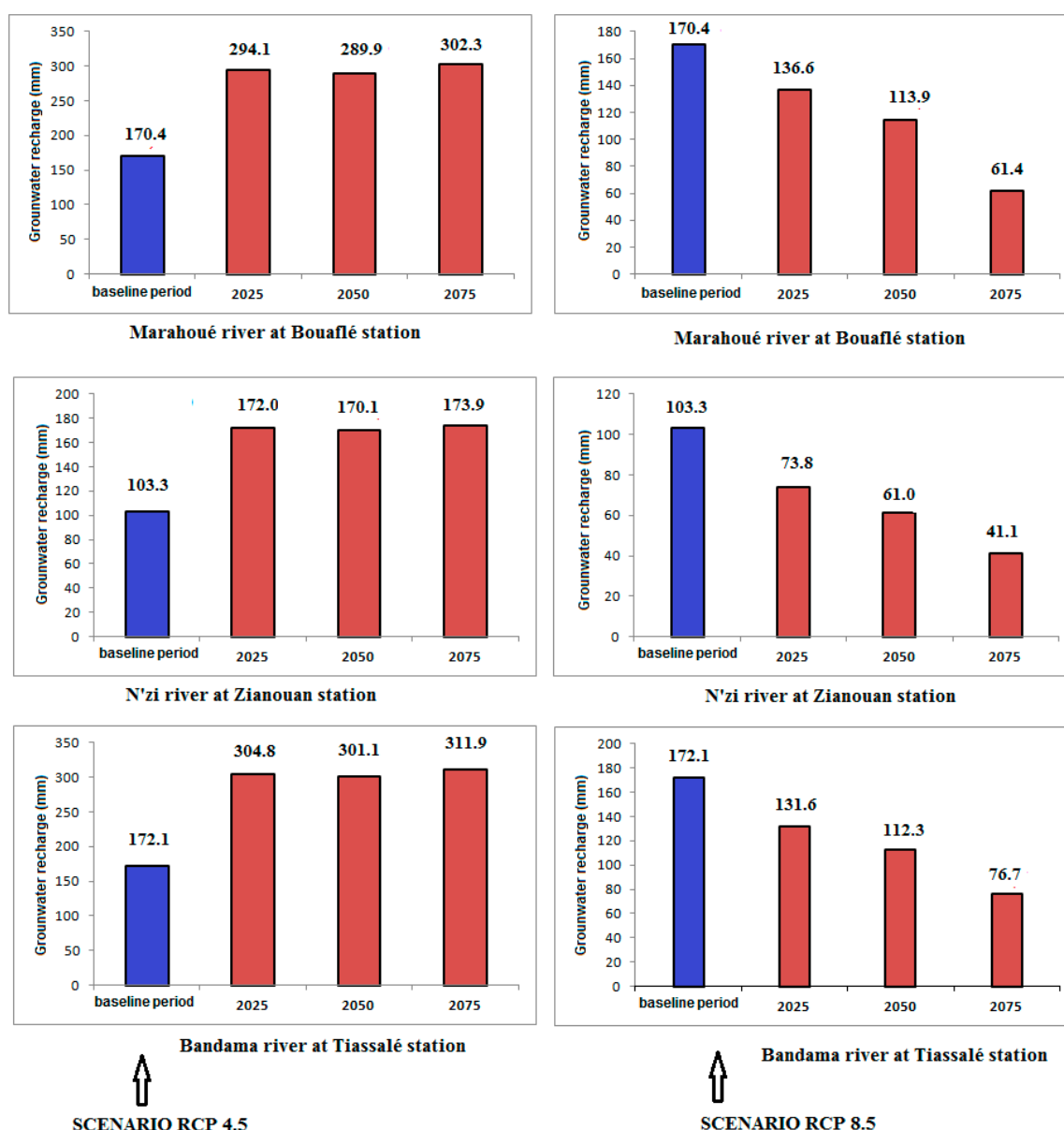


Figure 7. Evolution of annual average groundwater recharge in the Bandama basin.

4. Conclusions

This paper showed that the Bandama basin is highly vulnerable to climate change. Indeed, analyses from this work showed that the temperature may increase and monthly rainfall may

decrease from December to April in the future. In addition, the climate change analysis shows that the impacts are very different from RCP 4.5 to RCP 8.5. Under RCP 4.5, mean monthly runoff and groundwater recharge may increase for all horizons. Changes of runoffs and groundwater recharge are mainly dominated by the variations in projected precipitation. Especially in the long-term, increasing precipitation in the wet-season would make it wetter, resulting in higher runoff and aquifer recharge in the watershed. This phenomenon is due to the strong aquifer-river relationship on the basin. Indeed, the increase in aquifer levels would lead to an increase in the flow of watercourses supplied by the aquifers. On the other side, these two parameters may decrease for all horizons. These results highlight the large uncertainties associated with the impacts of climate change on water resources through global models (climatic and hydrological).

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Conflicts of Interest: The authors declare no conflict of interest.

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