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Hydrological Modelling of the Casamance River in Its Upstream Section (Basin at Kolda Level) to Predict Its Future States as a Function of Different Stresses

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Abstract

Flow records for stations in the Casamance basin are incomplete. Several gaps were noted over the 1980-2021 study period, making this study tedious. The aim of this study is to assess the potential impact of climate change on the flow of the Casamance watershed at Kolda. To this end, hydrological series are simulated and then extended using the GR2M rainfall-runoff model, with a monthly time step. Projected climate data are derived from a multi-model ensemble under scenarios SSP2-4.5 (scenario with additional radiative forcing of 4.5 W/m^2 by 2099) and SSP5-8.5 (scenario with additional radiative forcing of 8.5 W/m^2 by 2099). An analysis of the homogeneity of the rainfall data series from the Kolda station was carried out using KhronoStat software. The Casamance watershed was then delimited using ArcGIS to determine the morphometric parameters of the basin, which will be decisive for the rest of the work. Next, monthly evapotranspiration was calculated using the formula proposed by Oudin *et al.* This, together with rainfall and runoff, forms the input data for the model. The GR2M model was then calibrated and cross-validated using various simulations to assess its performance and robustness in the Casamance watershed. The version of the model with the calibrated parameters will make it possible to extend Casamance river flows to 2099. This simulation of future flows with GR2M shows a decrease in the flow of the Casamance at Kolda with the two scenarios SSP2-4.5 and SSP5-8.5 during the rainy period, and almost zero flows during the dry season from the period 2040-2059.

Keywords

Casamance Watershed, Climate Change, GR2M, Climate Models

1. Introduction

For over a century, the combined effects of industrial development, economic growth and population growth have profoundly transformed our environment. It is now clear that industrial emissions have significantly altered the overall composition of the atmosphere, which is changing at an unprecedented rate [1].

In Africa, climate change threatens to wipe out much of the progress made in development. It threatens food and water security, political and economic stability, livelihoods and landscapes [2].

To manage water resources properly, it is therefore necessary to know the hydrological behavior of a watershed and, above all, to highlight the impact of climate variability on water resources.

Around the 1950s, the concept of the "model" appeared in hydrological science. It is a simplified mathematical representation of all or part of the hydrological cycle's processes, using a set of hydrological concepts expressed in mathematical language and linked together in temporal and spatial sequences corresponding to those observed in nature. Today, there are a very large number of models, classified in different categories, *i.e.* deterministic or stochastic, global or distributed, kinematic or dynamic, and finally empirical or physical. This is due in particular to the nature of the variables or parameters involved [3].

Although not a natural region, the Casamance basin, located in the southernmost and wettest part of Senegal, harbors the greatest diversity of natural resources thanks to the presence of the monsoon flow for more than 5 months a year [4].

Topographically, the Casamance watershed is characterized by its low relief. In fact, all the watercourses have their source on the terminal continental plateau. This low gradient explains the deep invasion of the sea into the Casamance basin, resulting in the salinization of farmland.

The sea flows up the main course of the Casamance as far as Dianamalari, 152 km from the mouth. On the Soungrougrou, it reaches Diaroumé, 130 km from the ocean; on the Baïla, it reaches Djibidione, 154 km from Diogué at the mouth [5].

The aim of this publication is to assess the long-term water resources of Casamance under different climate change scenarios using the two-parameter monthly empirical Rural Engineering model (GR2M) developed by CEMAGREF [6] [7]. The robustness of the GR2M model in simulating runoff in an African context has been demonstrated by several authors, including BODIAN *et al.* [8].

2. Materials and Methods

2.1. Geographical Location

The Casamance River, 320 km long, rises in eastern Casamance, around Fafacourou, 50 km northeast of Kolda, and crosses it from east to west, flowing into the Atlantic Ocean. It is a small coastal river whose watershed is almost entirely within the territory of Senegal [5]. The Casamance River watershed is located in the southern part of Senegal, between latitudes 12˚20' and 13˚21' North and longitudes 14˚17' and 16˚47' West (**Figure 1**). This area has a tropical Sudano-Guinean climate, hot and humid with an average annual temperature of 27˚C [9]. Only a small southern part of the basin extends as far as Guinea Bissau.

The region's climate is Sudano-Guinean, with rainfall from June to October, peaking in August and September, and a dry season from November to May [10]. Average rainfall ranges from 700 to 1300 mm. The lowest average monthly temperatures are recorded between December and January, ranging from 25˚C to 30˚C, while the highest temperatures are recorded between March and September, with variations of 30˚C to 40˚C.

2.2. Data

Rainfall and evapotranspiration data (determined using the formula proposed by OUDIN *et al.* [11] for rainfall-runoff models), which reflect the climatological phenomena of the model, and flow measurements, which reveal the hydrological functioning of the catchment, are used in this study.

- **Rainfall data**

Before studying a long series of rainfall data, it is necessary to check whether it corresponds to a homogeneous whole. For example, it is important to check whether there is any heterogeneity due to the use of faulty equipment over one or more periods of time: a rain gauge with a non-compliant ring surface and test tube, a rain gauge with buckets that tilt before or after the correct volume, etc. Last but not least, there is the possibility of human error: forgotten observations, operating errors, poor data entry, etc. [12].

Rainfall data vary in quality and duration from station to station. This makes it necessary to select reference stations. The selection criteria are based on three fundamental factors: the size of the sample, their proximity to the study area (*i.e.* their geographical position) and the quality of the data (weakness of gaps in the different series actually observed) [13].

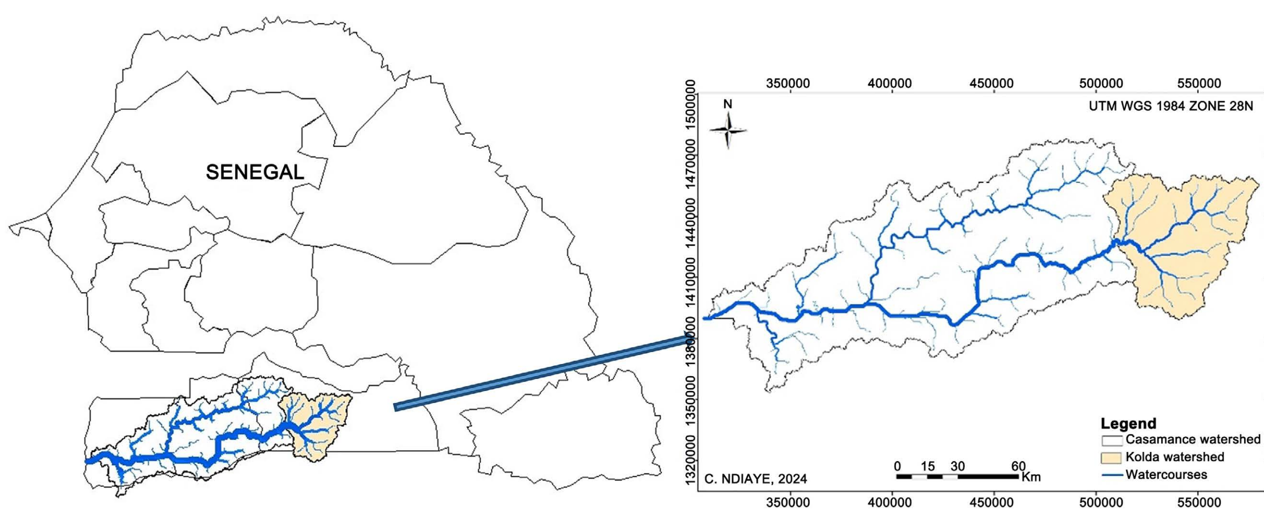


Figure 1. The Casamance River watershed.

For our study, we have rainfall data from the ANACIM (French National Civil Aviation and Meteorology Agency) stations in Ziguinchor, Sedhiou and Kolda. Of these three stations, the Kolda station was selected on the basis of its location in the upstream Casamance basin and its spatial and temporal representativeness.

The homogeneity of station data is checked using KhronoStat software. KhronoStat includes various homogeneity tests (homogeneity being understood here in the sense of the absence of breaks in the series): MANN WHITNEY test modified by AN PETTITT, TA BUISHAND U statistic, AFS LEE and SA HEGHINIAN procedure, P. BOIS control ellipse and HUBERT segmentation method. For all these tests, the null hypothesis H0 corresponds to the absence of a break at the 1% threshold. These tests are particularly sensitive to a change in mean, and if the null hypothesis of series homogeneity is rejected, they provide an estimate of the break date [14]. In this study, homogeneity is verified using the BUISHAND test, the PETTITT test, the Bayesian method of Lee and HEGHINIAN and the HUBERT segmentation method.

- **Potential evapotranspiration**

Potential evapotranspiration (PTE), an essential input to the model, expresses climatic demand and is used in the model's production function. PTE values were estimated using the formula proposed by Oudin *et al.* based on temperature data from the Kolda station. These values were calculated on a daily time step and then scaled monthly.

- **Flow rates**

Flows are used to assess the quality of the GR2M model for the Casamance watershed. The observed flows come from the Kolda station and are provided by the DGPRE (Water Resources Management and Planning Department).

2.3. Presentation of the GR2M Model

The GR2M (Génie Rural à 2paramètres Mensuel) model is a two-parameter global rainfall-runoff model. Its development was initiated at Cemagref in the late 1980s, with a view to applications in the field of water resources and low-water levels [15].

Its structure, although empirical, resembles conceptual reservoir models, with a procedure for monitoring the state of humidity in the reservoir, which seems to be the best way of taking account of past conditions and ensuring continuous operation of the model. Its structure (**Figure 2**) combines a production reservoir and a routing reservoir, as well as an opening to the outside world other than the atmospheric environment. These three functions simulate the hydrological behavior of the basin.

The model has two optimizable parameters:

X1: production reservoir capacity (mm)

X2: groundwater exchange coefficient (-)

As input data to the model, we have monthly rainfall (mm), ETP in mm and observed flows in (mm/month). As output, the model provides flows that need

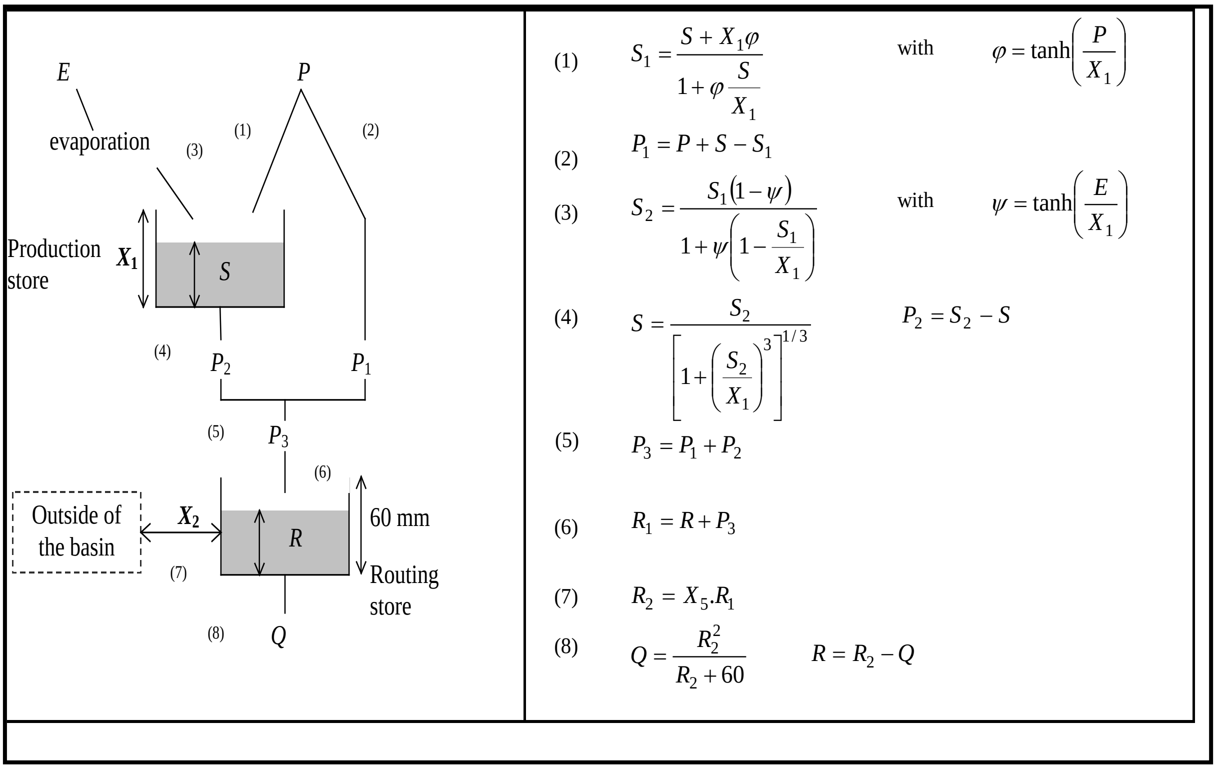


Figure 2. Schematic diagram of the GR2M model structure.

to be compared with observed flows in order to judge the model's robustness for the basin under study.

Model validation is verified by comparing calculated and observed flows using a quality criterion. The best-known and most widely used criterion for conceptual models is the Nash and Sutcliff (1970) criterion, expressed by equation (1) below.

$$\text{Nash}(Q) = 100\left[1 - \frac{\sum_i \left(Q_{i,obs} - Q_{i,cal}\right)^2}{\sum_i \left(Q_{i,obs} - \overline{Q_{obs}}\right)^2}\right] \tag{1}$$

The simulation is bad if the Nash criterion < 60%, good if it is >70% and perfect if it and equal to 100%.

2.4. Climate Models

Climate projection data are modeled data from the global climate model compilations of the Coupled Model Intercomparison Projects (CMIP), overseen by the World Climate Research Program [16].

The data presented are derived from the sixth phase of the CMIPs. The CMIPs form the database for the IPCC assessment reports. For our study, the approach applied is to represent interannual and monthly variations in temperature, precipitation and ETP under the two scenarios SSP2-4.5 and SSP5-8.5 defined as follows:

The SSP2-4.5 scenario: As an update of the RCP4.5 scenario, SSP2-4.5, with an additional radiative forcing of 4.5 W/m^2 by 2099, represents the average trajectory of future greenhouse gas emissions. This scenario assumes that climate protection measures are taken.

The SSP5-8.5 scenario: With an additional radiative forcing of 8.5 W/m^2 by 2100, this scenario represents the upper limit of the range of scenarios described in the literature. It can be understood as an update of the CMIP5 RCP8.5 scenario, now combined with socio-economic trajectories.

3. Results and Discussion

3.1. Verification of Rainfall Data Homogeneity with KhronoStat Software

The rainfall data series from the Kolda station, studied using KhronoStat software, reveals a random time series for the BUISHAND test that is accepted at the 99% confidence level and rejected at the 95% and 90% confidence levels (Figure 3). The PETTITT test, on the other hand, shows no break in the series studied at the various confidence levels. The Bayesian method defines the breakpoint at 1991, as does the HUBERT segmentation. This breakpoint corresponds in fact to a decrease in rainfall during that year. This observation confirms the earlier study by BODIAN [14], who placed the breakpoint for the Kolda station between 1990-1997.

3.2. Watershed Delimitation

The Casamance watershed at Kolda was delineated with ARCGIS as shown in Figure 4. An area of 3448.38 km^2 was obtained after delimitation. This will be used for flow conversions and also for the GR2M software.

3.3. Calibration and validation of the GR2M Model

- **Model parameters and efficiency criteria**

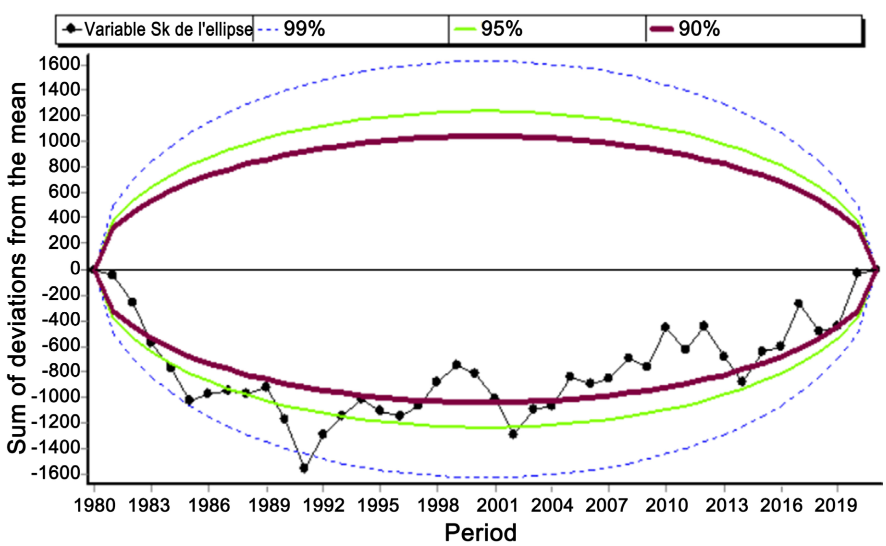


Figure 3. BUISHAND test; wood ellipse on annual rainfall at 99%, 95% and 90%.

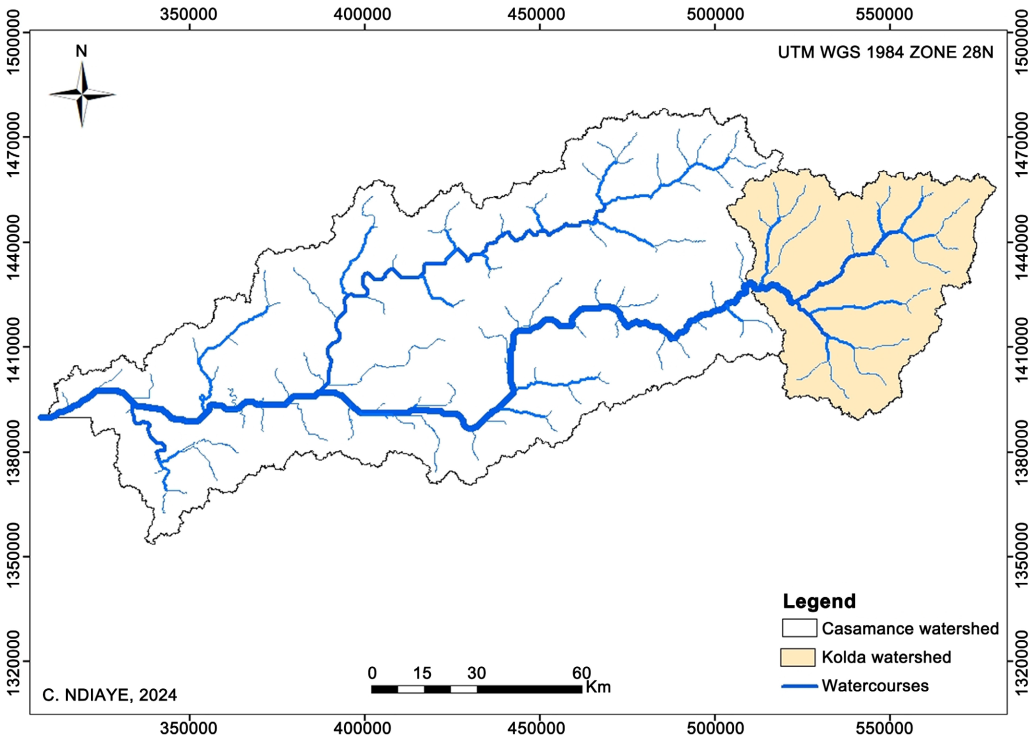


Figure 4. Casamance watershed at Kolda.

To calibrate and validate the GR2M model, a series of simulations was carried out to determine the optimal model parameters X1 and X2, which will be used to simulate flows for the 2099 horizon.

The calibration and validation results shown in **Table 1** below are considered to be good, since the NASH criteria obtained are greater than 60%.

- **Hyetogram and hydrograph obtained during calibration and validation**

Figure 5 below shows the hyetogram of monthly rainfall and the monthly hydrographs simulated and observed during the calibration period (1981-1986) and the validation period (1987-1993).

A similarity between observed and simulated flows for the calibration and validation periods has been observed, so the GR2M model applies perfectly to the Casamance watershed and can be used for future simulations.

3.4. Climate Forcing Trends to 2099

- **Temperatures**

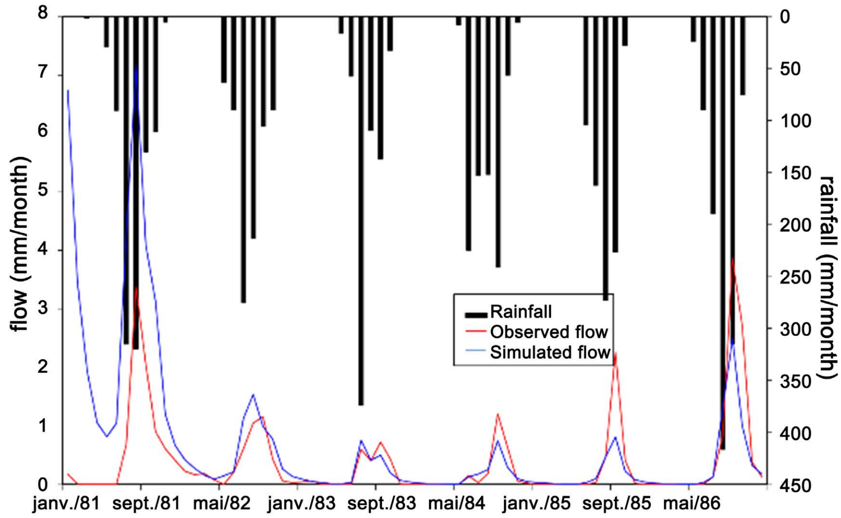
The evolution of climate forcings to 2099 in the multi-model ensemble predicts a temperature increase of 2.5˚C compared with the SSP2-4.5 scenario, and an increase of 5˚C for the SSP5-8.5 scenario, as shown in **Figure 6**. These temperatures will be used to calculate ETP for 2099.

- **Rainfall**

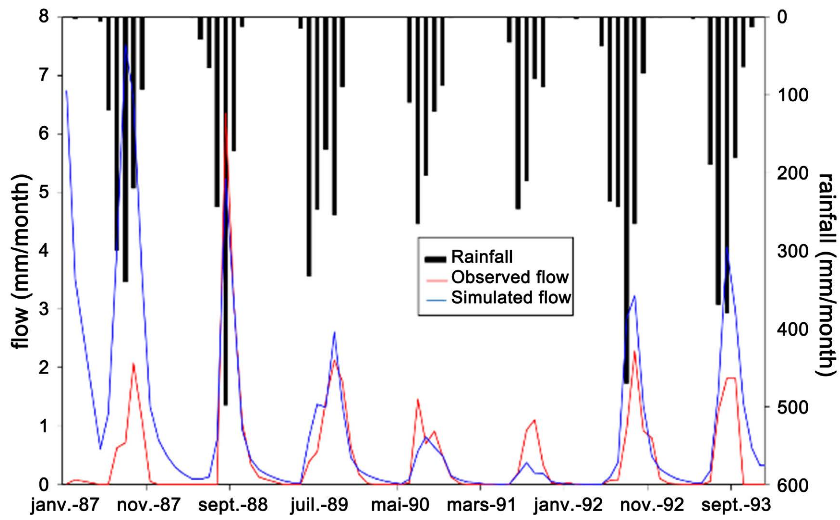
The evolution of climate forcings by 2099 in the multi-model ensemble predicts an increase in precipitation until 2039, followed by a gradual decrease of up to −18 mm by 2099, compared with the SSP2-4.5 scenario. This decrease intensifies

Table 1. GR2M model parameterization.

Designation	Efficiency criteria		Parameters	
	NASH	Balance sheet	X1	X2
Wedging (1981-1986)	70.0	87.2	8.34	0.24
Validation (1987-1993)	71.0	129.0		



(a)



(b)

Figure 5. Hyetogram and hydrograph for the calibration (a) and validation (b) period with GR2M. (a) calibration period, (b) validation period.

with the SSP5-8.5 scenario, with a drop of −65 mm in August by 2099 (see Figure 7).

- **Evapotranspiration (ETP)**

Using temperature data, we were able to project ETP to 2099. The results obtained according to the different scenarios are shown in Figure 8 and Figure 9 below.

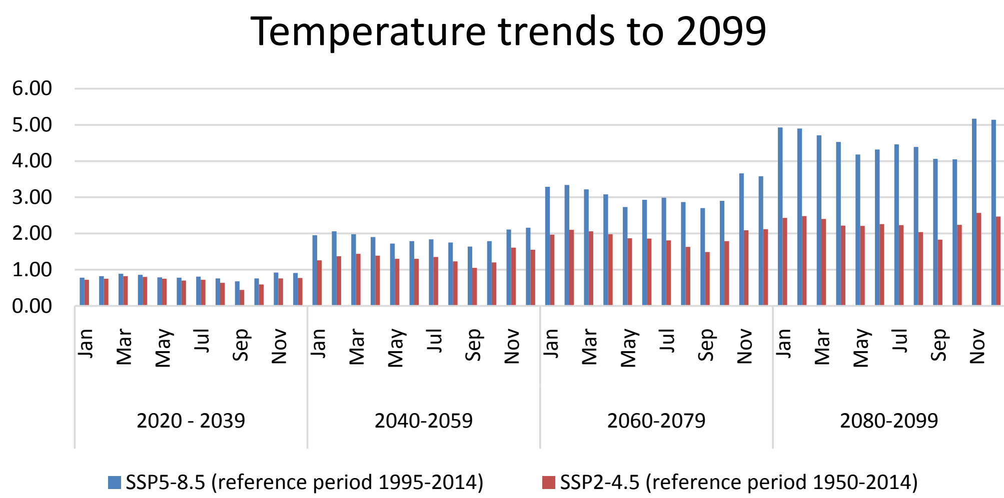


Figure 6. Temperature trends in relation to the SSP2-4.5 and SSP5-8.5 scenarios for the 2099 horizon.

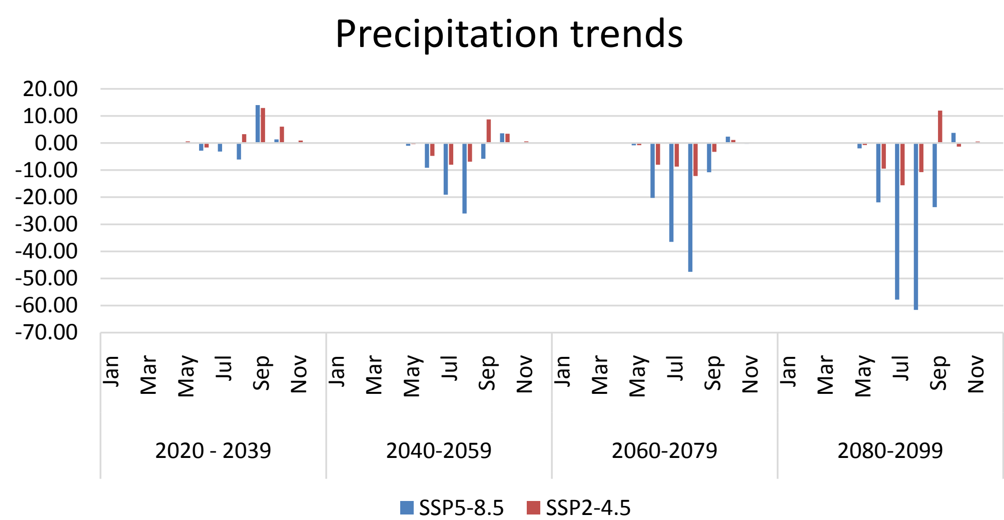


Figure 7. Precipitation trends compared with the SSP2-4.5 and SSP5-8.5 scenarios to 2099.

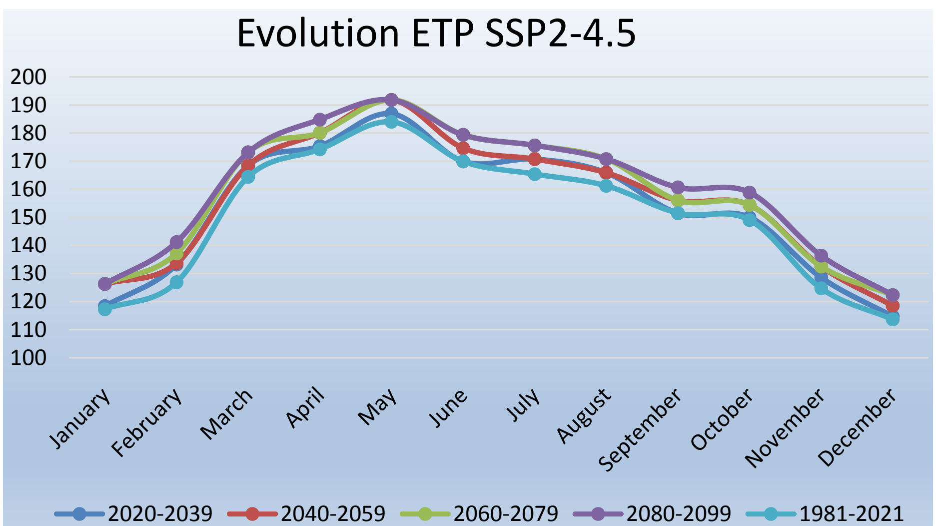


Figure 8. Change in ETP compared with the SSP2-4.5 scenario by 2099.

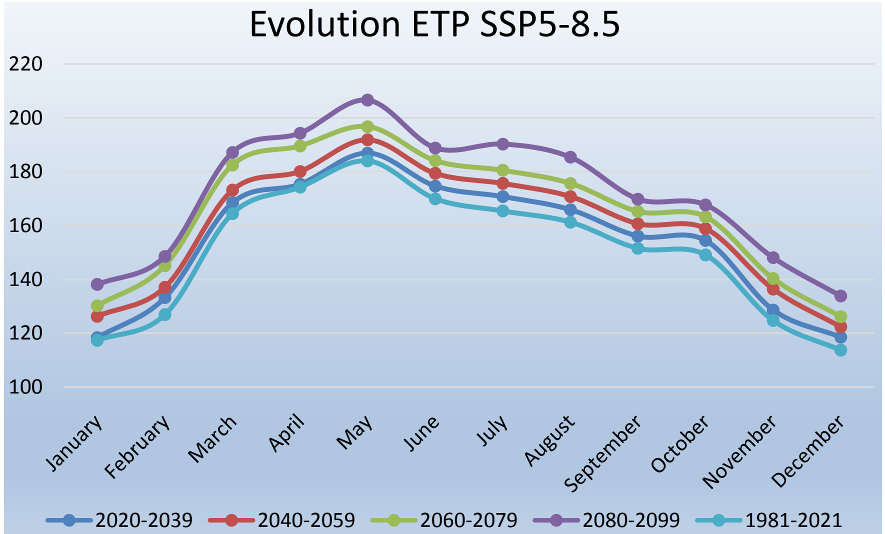


Figure 9. Change in ETP compared with the SSP5-8.5 scenario by 2099.

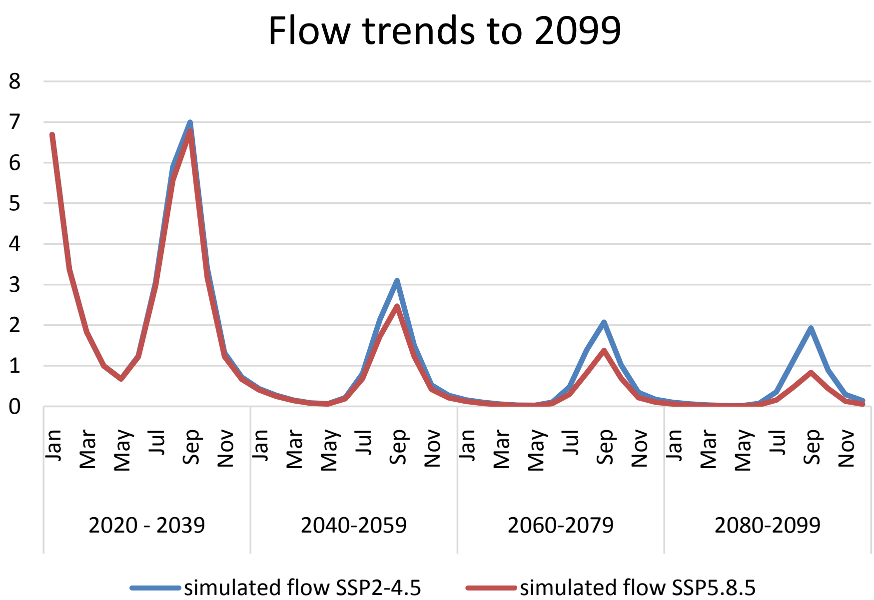


Figure 10. Runoff trends to 2099 for SSP2-4.5 and SSP5-8.5 scenarios.

With the rise in temperatures forecast by the two scenarios, evapotranspiration increases by up to 206 mm by 2099 in the most pessimistic scenario, SSP5-8.5. These ETPs exceed those of the 1981-2021 reference period, whose maximum value is 193 mm.

- **Runoff trends to 2099**

Using the parameters previously calculated by the GR2M software, we projected the evolution of runoff at Kolda for the 2099 horizon (see Figure 10 above).

Runoff on the Casamance River at Kolda will fall sharply with the SSP2-4.5 and SSP5-8.5 scenarios. From 2040 onwards, there will be no flow on the Casamance River at Kolda during non-rainy periods. In the rainy period to 2099, maximum flows will not exceed 2.5 m^3/s for the SSP2-4.5 scenario and 1 m^3/s for the SSP5-8.5 scenario.

4. Conclusions

This study involves making climate projections for an assessment of possible states of the Casamance water resource at Kolda level. The multimodel ensemble predicts, for the SSP2-4.5 scenario considered the most likely (as the emission level corresponds to that of the contributions determined at national level and is not subject to major sudden variations), a significant decrease in runoff, which can be explained by the increase in ETP due to the rise in temperatures, but also to the decrease in precipitation.

And for the SSP5-8.5 scenario, which is considered unlikely as it reflects the failure of mitigation policies, the multimodel ensemble predicts a greater decrease in runoff than the SSP2-4.5 scenario, as flow will not exceed 1 m^3/s during the rainy season.

Thus, despite the uncertainties noted in the climate projections, it remains necessary to take this study into account in order to avoid the disappearance of this water resource in Kolda, since this area is sensitive to climatic hazards and, at present, the flow rates recorded in Kolda are very low in non-rainy periods.

Conflicts of Interest

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

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