

Assessment and Prediction of Rainfall-Runoff Models Using GR4J in the Klela Basin in Mali

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Abstract

The study on water resources is very important for a country like Mali Republic. This is because the climate of the Sahel is projected by many climate scenarios that contribute to a premature dry season. So, the Klela basin being one of the affected areas by the phenomenon is selected for this study. Hence, it is interesting to evaluate this vital resource for a better planning in order to facilitate the decision making from the concerned authorities. For this research, the hydrological model, GR4J, is used to evaluate the dynamics of the surface water flow. The main objective of this study is to assess and predict (using scenarios RCP4.5 and RCP8.5) the correlation between rainfall and runoff in the Klela basin. In tandem with on this objective, the water flow and climate data were used as input data into the GR4J model. The model was calibrated and evaluated using the time series data 2000-2007 and 2008-2013, respectively. The performance of the model was evaluated mainly based on the Nash-Sutcliffe efficiency. The overall outputs display that the surface water flow is declining over time and this is more significant in the worst scenario RCP8.5.

Keywords: climate, GR4J model, klela basin, rainfall-runoff, surface water flow

1. Introduction

Water resources play a significant role for agricultural development in many countries around the globe, particularly in developing countries. The study focuses on the *Klela* basin which is an agricultural zone; where rice and potatoes are farmed during the rainy and dry season respectively (Toure, 2017). The managing surface water (dams, lakes, etc.) is a big challenge. This is because of its scarcity during the dry season.

Many climate change predictions showed a reduction in the rainfall quantity in the Sahel which could considerably affect runoff patterns. Hence, better knowledge for integrated management of this important resource is the main demand for decision makers. So, this is why a scientific tool should be used to evaluate the dynamics of surface water in the selected area of this research.

The aim of this study is to use the GR4J model to assess and predict the correlation between rainfall and runoff in the Klela basin. The GR4J model has been applied in many hydrologic systems throughout the world by various researchers (Kodja et al., 2018, 2020; Kunnath-Poovakka and Eldho, 2019; Ruellandj et al., 2010; Zafari et al., 2022) to evaluate the link between rainfall-runoff. Based on the available literature, it can be said that there is few or no previous studies conducted on the selected area of interest for the present study using the earlier mentioned model. However, Mahe et al. (2009) and Mahe et al. (2000) have revealed that the Niger River dramatically decreased after the 1970s.

For this research, it is very important to briefly present the selected area of study. Located in the south of Mali, the study area is situated between 5°55'58.8" - 5°16'12" longitude and 11°40'58.8" - 10°59'45.6" latitude. The surface area of the study is approximately 3685 km². Most of the activities of the population are based on the primary sector (agriculture, livestock, fishing). The elevation of the Klela Basin increases from north to south,

from 305 m (north) to 748 m (south). Although a major part of Mali is the Sahelian zone, this area belongs to the Sudano-Sahelian zone. The rainy season is straight linked to the motion of the monsoon (categorized by lukewarm and humid maritime wind) in the Intertropical Convergence Zone (ITCZ). The dry season starts with the occurrence of the Harmattan (dominated by a dry wind from the Sahara) (USAID, 2006; Toure et al., 2016). The *Klela* basin is principally characterized by only one mode of rainfall distribution with the mean annual rainfall fluctuating from 800 to 1,300 mm. The basin is drained by several minor streams that dry out some months after the rainy season (Figure 1). The path of the principal River of the study area is estimated at 136 km. The average annual temperature of the area is 27.4°C.

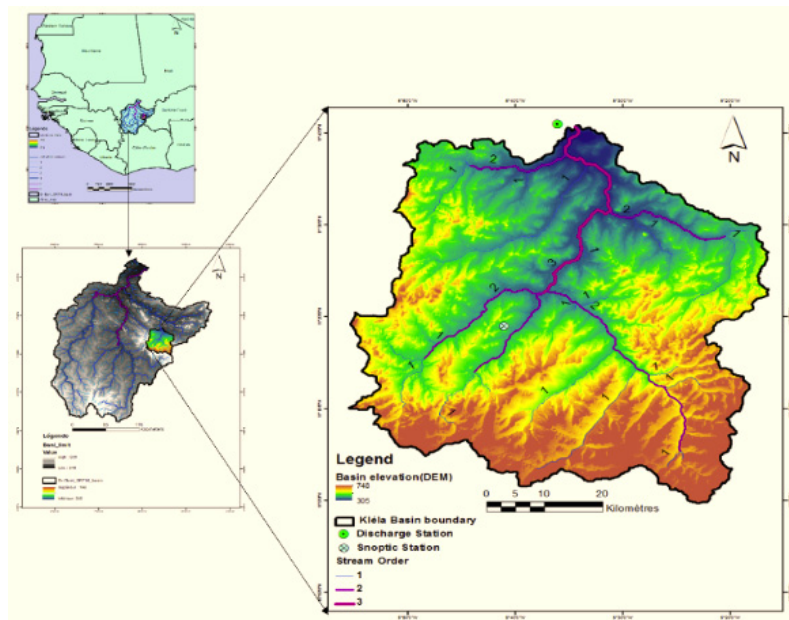


Figure 1. Presentation of the study area (Kléla Basin)

2. Materials and Method

2.1 Materials

The researchers use national directions mainly are their secondary sources of data. For instance, the climate data (daily rainfall and evapotranspiration) from 1990 to 2013 was provided by the “Mali-Meteo”; the time series data of rainfall was recorded from the installed synoptic station in Sikasso Town. Also, the standard Evapotranspiration was estimated by applying the method of Blaney - Criddle. The daily streamflow discharge was collected from 1990 to 2013, from the “Direction Nationale de l’Hydraulique (DNH)” of Mali. The downscaled regional climate models (RCM) data (daily rainfall and PET from 2026-2050) from the scenarios (RCP4.5 and RCP8.5) were used for the prediction of the basin flow. The scenario RCP4.5 is a middle pathway that is near the stabilization (approximately 4.5 W/m²) (Moss et al., 2008). So, the RCP4.5 is a stabilization scenario that assumes that all the countries accept policies for emission scenario mitigation (Thomson et al., 2011; Toure et al., 2017). RCP8.5 is considered as the worst scenario. It is also called the reference scenario and represents the utmost RCP scenario concerning GHG emissions devoid of any appropriate climate policy (Riahi et al., 2011). These climate data were provided by the CORDEX (Coordinated Regional Climate Downscaling Experiment) program.

2.2 Method

2.2.1 Hydrological Model

In this work, the GR4J hydrological model has been used to simulate the daily streamflow in Kléla Basin. This model is based on the cascade of the reservoirs and links rainfall to runoff (Anshuman et al., 2021; Zhang et al., 2021; Chiew et al., 2022). Scientifically, the model was improved by Perrin et al. (2003) and applied by many scholars such as (Ruelland et al., 2010; Kunnath-Poovakka and Eldho, 2019; Zeng et al., 2019; Kodja et al., 2020; Zafari et al., 2022) in various climate regions. The GR4J is a global conceptual model for rainfall-runoff that needs 4 parameters: X_1 , the maximum volume of the production stock (mm); X_2 , the coefficient of groundwater exchange (mm); X_3 , the maximum volume of the routing store (mm); and X_4 , the time highest ordinate of hydrograph unit UH1 (day) (Figure 2). A description of the model can be found in Perrin et al. (2003).

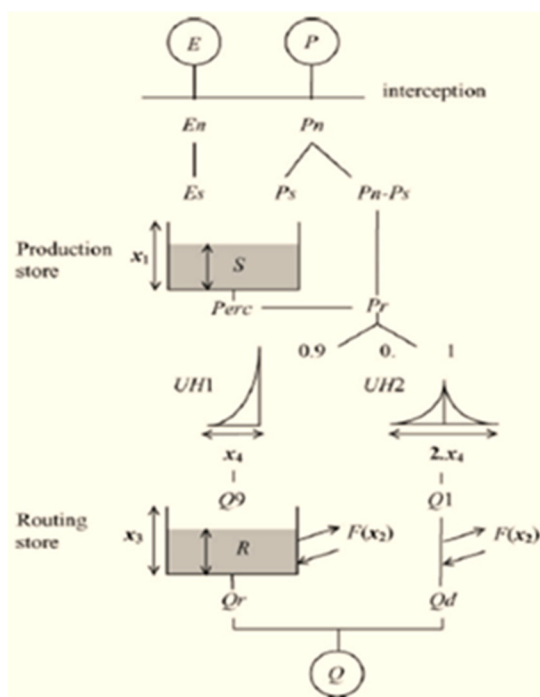


Figure 2. Diagram of the GR4J model (adapted from Perrin et al., 2003)

P: rainfall (mm); E: potential evapotranspiration; Pn: net rainfall; En: net evapotranspiration capacity; Ps: production storage; Es: actual evapotranspiration; Perc: percolation; X₁, the maximum volume of the production stock (mm); X₂, the coefficient of groundwater exchange (mm); X₃, the maximum volume of the routing store (mm); and X₄, the time highest ordinate of hydrograph unit UH1 (day).

2.2.2 Model Calibration

Model calibration is a process that changes unknown parameters of the model to fit the observed and simulated values. To calibrate the GR4J model in this study, the four parameters (X₁ to X₄) announced above were manually adjusted to obtain an accurate correlation between observed and simulated flows for the basin. The calibration sampled a period of eight years (2000 - 2007) of daily rainfall and PET.

2.2.3 Model Validation

After model calibration, model validation is used to validate the calibration. In this research, model validation.

Is based on using daily time series data from 2008 - 2013. This didn't change the parameters during this process.

3. Results and Discussion

3.1 Model Calibration and Validation

The model was calibrated using the observed climate (rainfall and PET from 2000 to 2007) data in the *Klela* basin. As described in Figure 3. The visual line chart shows that the trend between both simulated and observed flow is well significant.

However, it is interesting to note that the model globally overestimates the simulated results. Besides, the scatter chart exhibits the correlation between the simulated and the observed flow. The $R^2 = 0.63$ shows that the correlation is good because the considered time series is a daily time step, which is difficult to be calibrated.

The same comparison procedure is adopted during the validation process and the overall results are satisfactory. (Figure 4).

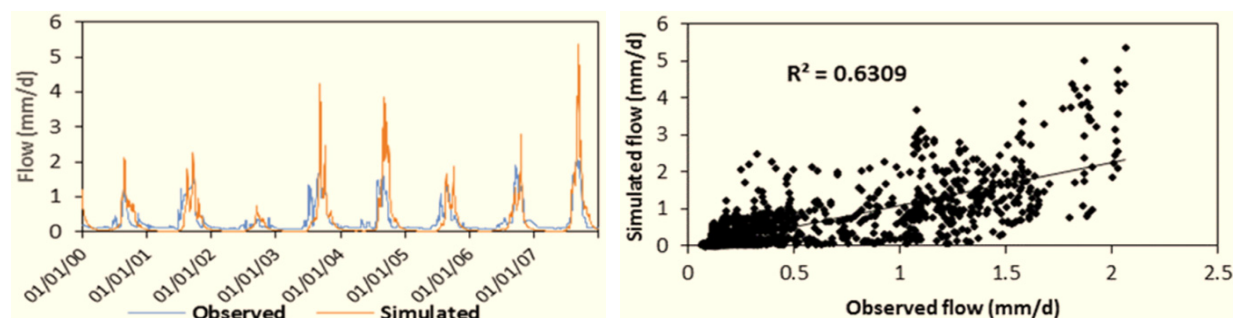


Figure 3. GR4J model calibration for the period 2000 - 2007

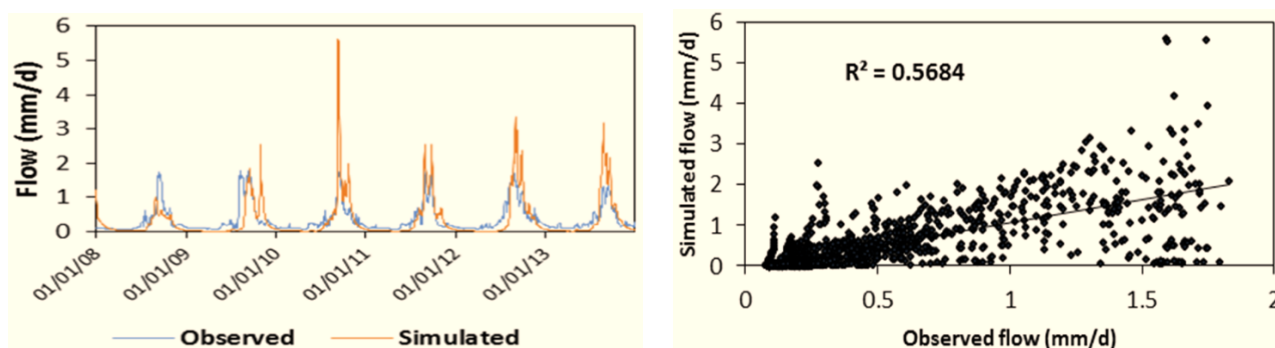


Figure 4. GR4J model validation for the period 2008 - 2013

3.2 Climate Data Projection

3.2.1 Comparison between Observed and Climate Data

It is important to note that in order to use climate data in an environmental study; it is recommended to investigate the scenarios data developed by IPCC fifth assessment report. Consequently, for this research, the climate data was collected from the ICHEC-EC-EARTH (RCM) by considering two scenarios (RCP4.5 and RCP8.5). This facilitates in comparing the observed scenarios. The historical climate (Precipitation, max. and min. temperatures) data from 1986 to 2005 was compared with the observed data of the same order to evaluate the variance between the observed and simulated data.

The findings of the study show that there is a difference between the two categories of data that are observed and simulated. The observed line charts (Figure 5) highlight the existing tendency from both lines (curbs) that are evaluated in the same direction. Although, the graphs (Figure 5) indicate the coefficient of determination (from 0.55 - 0.69) is relatively light for the minimum temperature, but it is still valid for the use of climate data without bias correction.

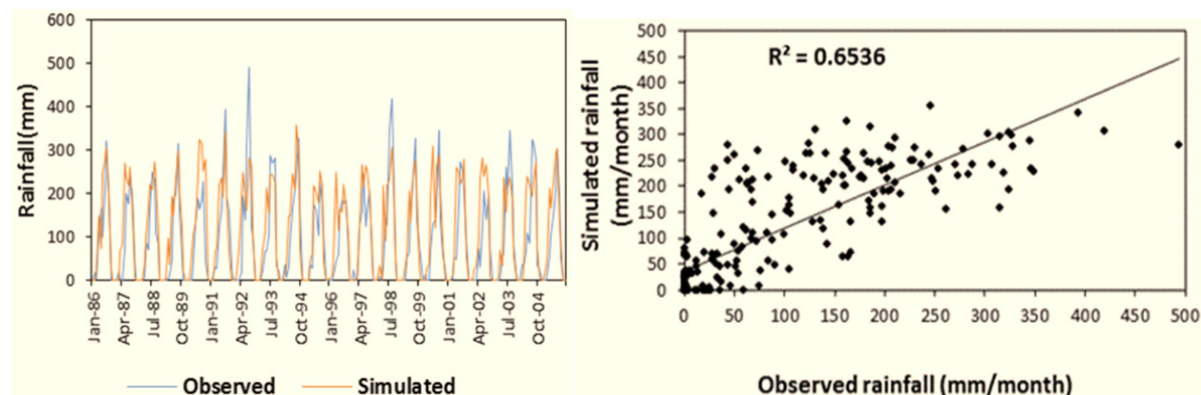


Figure 5. Comparison between observed and simulated climate data from Mali Meteo and ICHEC-EC-EARTH (RCM) respectively

3.2.2 Flow Prediction

After a detailed and clear presentation of model calibration and validation, it is possible to present the findings related to projection. The climate future data (daily precipitation and evapotranspiration) from 2026 - 2050 for the scenarios RCP4.5 and RCP8.5 was used to simulate the dynamics of the future flow. These scenarios project a decrease in the surface flow but it is more obvious in RCP8.5 than in RCP4.5.

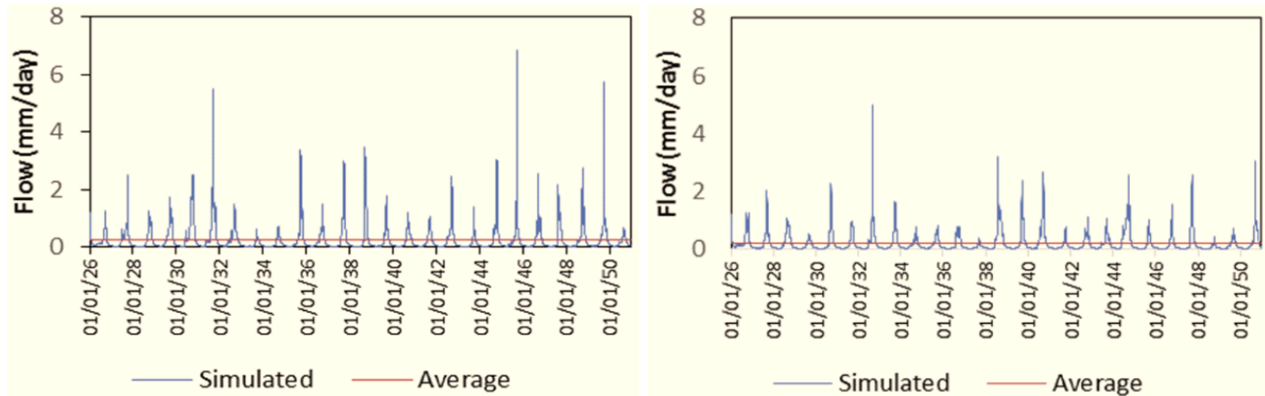


Figure 6. Flow projections of the study basin, a) RCP4.5; b) RCP8.5

This figure shows that the whole future average monthly discharge is reducing in the RCP8.5 than RCP4.5 (Figure 7). Hence, the maximum value is lesser than 1 mm/d.

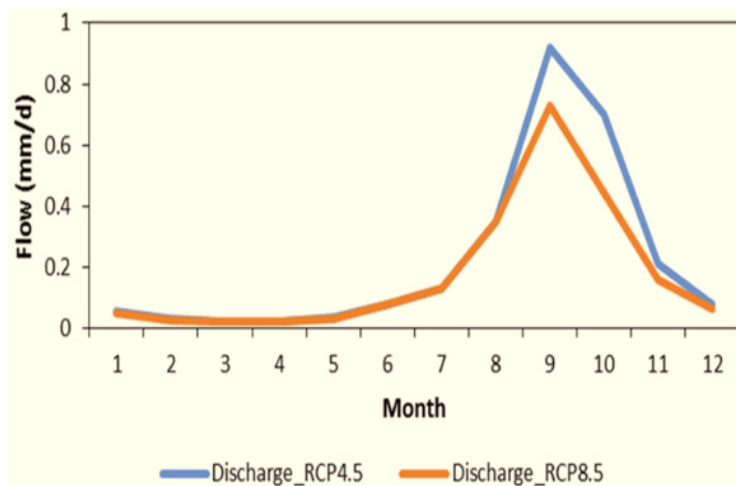


Figure 7. Mean monthly discharge flow in the Klela basin from the period 2026 to 2050

3.3 Criteria for Model Performance

The performance evaluation technique of Nash and Sutcliffe (1970) is used as criteria for model performance in this study. The technique is a normalized statistic that expresses the relative magnitude of the variation between the simulated and the observed data. It allows evaluation of the existing variance in the plot of observed versus simulated data. The Nash-Sutcliffe Efficiency (NSE) values range between $-\infty$ and 1, where $NSE = 1$ is the optimum value. The values between 0 and 1 indicate an acceptable level of performance. When the values are negative, it means that the mean observed value is a better predictor than the simulated value; otherwise, it is an unacceptable performance.

The NSE performance evaluation method was suggested by several researchers such as (Servat and Dezetter, 1991; ASCE, 1993; Legates and McCabe, 1999).

So, to evaluate the performance based on the chosen technique, three periods of flow evolution were proposed by the GR4J version, such as high water flow (equation 1), average flow (equation 2), and low flow (equation 3).

$$NSE(Q) = 1 - \frac{\sum_{i=1}^n (Q_{sim} - Q_{obs})^2}{\sum_{i=1}^n (Q_{obs} - \overline{Q_{obs}})^2} \quad (1)$$

$$NSE(\sqrt{Q}) = 1 - \frac{\sum_{i=1}^n (\sqrt{Q_{sim}} - \sqrt{Q_{obs}})^2}{\sum_{i=1}^n (\sqrt{Q_{obs}} - \sqrt{\bar{Q}_{obs}})^2} \quad (2)$$

$$NSE(\ln Q) = 1 - \frac{\sum_{i=1}^n (\ln(Q_{sim}) - \ln(Q_{obs}))^2}{\sum_{i=1}^n (\ln(Q_{obs}) - \ln(\bar{Q}_{obs}))^2} \quad (3)$$

where Q_{sim} is the simulated value, Q_{obs} is the measured value, and \bar{Q}_{obs} is the average measured value

$$R^2 = \frac{\left| \sum_{i=1}^n (Q_{obs} - \bar{Q}_{obs})(Q_{sim} - \bar{Q}_{sim}) \right|^2}{\sum_{i=1}^n (Q_{obs} - \bar{Q}_{obs})^2 \sum_{i=1}^n (Q_{sim} - \bar{Q}_{sim})^2} \quad (4)$$

The determination coefficient of linear regression measures the correlation between calculated and observed data using equation (4).

where \bar{Q}_{sim} is the average simulated value.

Gupta et al. (1999) define the PBIAS as “measures the average tendency of the simulated data to be larger or smaller than their observed counterparts”. The optimal value of PBIAS is 0, with low-magnitude values indicating accurate model simulation. IT should be noted that positive values indicate model underestimation bias, while negative values indicate overestimation bias (Gupta et al., 1999). PBIAS is calculated with equation 5 as shown in the following operation.

$$PBIAS = \left[\frac{\sum_{i=1}^n (Q_{obs} - Q_{sim})}{\sum_{i=1}^n Q_{obs}} * 100 \right] \quad (5)$$

where PBIAS expresses the margin of error of the calculated data. The PBIAS can show poor model performance (Gupta et al., 1999).

The Root Mean Square Error (RMSE) is one of the most popular uses of error index statistics (Chu and Shirmohammadi, 2004; Singh et al., 2004; Vasquez-Amabile and Engel, 2005). The smaller the RMSE, the better the model performance. The value of 0 of the RMSE indicates the perfect fit between the observed and simulated parameters.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (Q_{obs} - Q_{sim})^2}{n}} \quad (6)$$

where n is the number of the data.

The table 1 presents a summary of the findings on all the model's performances. Globally, the results show that the calibration and validation used in this study are scientifically valid.

Table 1. Model performance criteria in calibration and validation process

Model performance criteria	Calibration	Validation
Nash-Sutcliffe(Q)	0.10	0.27
Nash-Sutcliffe(VQ)	-0.04	0.26
Nash-Sutcliffe(ln(Q))	-0.33	-0.15
PBIAS	-35.19	-0.14
RMSE	0.02	0.02
R ²	0.63	0.57

Kodja et al. (2018) have used the GR4J model to evaluate the dynamics of streamflow in Ouémé Watershed at Bonou's outlet and found that it overestimates the streamflow during the low water period and underestimates them in high water. Ruelland et al. (2010) have applied the same model in the simulation of hydro-climatic variability in the Soudano-Sahelian catchment and showed that it gives a more accurate estimate of cumulated discharge.

4. Conclusion

The results of this research show that the hydrological system of the *Klela* basin can be well simulated using the GR4J model. The dynamics of the basin surface water were evaluated under climate scenarios (RCP4.5 and RCP8.5). The water flow of the basin is declining over time for all scenarios and this would be more highlighted in the years the 2030s. This is particularly due to the impact of climate change. The results of this study can be analyzed based on previous research findings on the hydrological model. This can facilitate in confirming the validity and the accuracy of the present findings. The model calibration and validation could be improved with the collection of more data in the selected area of the research. Based on the nature of the aim of the study, the researchers didn't use sensitivity analysis. However, this method of data analysis can be used for further study in this area of interest.

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Author Contributions

The authors, Adama TOURE and Souleymane KEITA are responsible for this study. They developed the methodology and wrote it together. The third author supervised the study.

Conflicts of Interest

The authors declare no conflict of interest.

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