

Rain-Flow Modelling Using the GR4J Model for Flood Risk Management in the Oti Watershed (Togo)

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Abstract

In recent years, West Africa has been confronted with hydro-climatic disasters causing crises in both urban and rural areas. The tragedy in the occurrence of such events lies in the recurrent aspect of high water and associated floods. The devastating floods observed in Africa's major rivers have revealed the need to understand the causes of these phenomena and to predict their behavior in order to improve the safety of exposed people and property. The aim of this study is to reproduce flood flows using the GR4J (Rural Engineering Four Daily Parameters) model to analyze flood risk in the Oti watershed in Togo. Daily data on flows (m³/s), potential evapotranspiration (mm/day) and average precipitation (mm) over the basin from 1961-2022 collected at the National Meteorological Agency of Togo (ANAMET) and the Department of Water Resources in Lome, were used with the R software package airGR. The Data from the West African Cordex program from 1961-2100 were used to analyze projected flows. The results obtained show the GR4J model's effectiveness in reproducing flood flows, indicating that observed flows are well simulated during the calibration and validation periods, with KGE values ranging from 0.73 to 0.85 at calibration and 0.62 to 0.81 at validation. These KGE values reflect the good performance of the GR4J model in simulating flood flows in the watershed. However, a deterioration in the KGE value was observed over the second validation period. Under these conditions, there may be false or missed alerts for flood prediction, and the use of this model should be treated with the utmost caution for decision-support purposes.

Keywords

Modeling, Génie Rural à 4 Paramètres Journaliers (GR4J), Floods, Kling-Gupta Efficiency (KGE), Oti Watershed, Risk

1. Introduction

In West Africa and Togo, floods have become recurrent in recent years with strong socio-economic and ecological impacts such as loss of life and material damage [1]. The recurrence of these floods is due to a frequent pluviohydrological hazard combined with an increased vulnerability of the population [2] [3]. This situation has made hydrological forecasting necessary to reduce the population's vulnerability. The key to effective hydrological modeling is a better characterization of climatic variability, including possible changes in the precipitation regime and rhythm (frequency, intensity and spatio-temporal distribution), thus directly affecting the magnitude and timing of runoff, flood intensity and flooding [4]. Hydrological modelling is a solution for reproducing flows and, above all, flood risks. It is an essential tool for understanding the dynamics of a watershed, for the rational use of water resources and for combating flood-related natural disasters.

In fact, recent studies [5]-[7] have shown that climate change has enormous consequences for the availability of water resources, in terms of an increase or decrease in the amplitude of extreme events, changes in the frequency of occurrence of these extreme events and changes in the processes that lead to these extremes. Knowing the hydrological behavior of a watershed, therefore, becomes a priority in the sustainable management of water resources and, above all, in highlighting the impact of climate variability on these water resources [8]. Similarly, anthropogenic factors such as changes in land use and water abstraction for agriculture and urbanisation further complicate river flow forecasting [9]-[12]. Thus the hydrological modelling approach appears to be a practical solution for improving streamflow simulation in data-scarce catchments, offering a glimmer of hope for regions grappling with the challenges of managing water resources under conditions of limited observational data [9] [13] [14].

Thus, the management of surface water and consequently flooding, requires a better understanding of runoff and extreme events through rain-flow modelling [15] [5]. To protect riverside populations in the Oti watershed against the recurrence of flooding, an operational and reliable forecasting tool is needed, as the issue of flood forecasting is a totally open subject of undeniable interest today. To this end, the rational control and management of surface water require a better understanding of episodic runoff and the influence of extreme climatic events, through conceptual rainfall-runoff modelling. In recent years, several approaches have been developed to improve the accuracy of streamflow modelling, which represents the fundamental hydrological processes associated with extreme events such as floods [16]-[18]. Hence, the need to use hydrological modeling with the

GR4J conceptual model to reproduce 24-hour flood flows.

In addition, the GR4J model has already proved its worth in several West African watersheds. These include the upper Oueme watershed [6] [19], the Beninese Niger River basin [20], the Mono watershed at Nangbéto in Benin and Togo [5] [7] and the developed watershed of the Sassandra River at the Soubré outlet in southwest Côte d'Ivoire [21] in a context of climate variability and environmental change. In addition, it should be noted that the use of hydrological models in basins characterised by sparse or non-existent data presents significant challenges, mainly due to the difficulty of calibrating and validating models without adequate observational datasets [22]-[25].

However, in the Oti watershed at the Mango outlet in Togo, research into hydrological modelling is little addressed, following the example of [26] who used the semi-distributed model. A rain-flow model is of particular interest in developing countries, since it can be used to estimate or represent the resource available for development, but also to predict how this resource will evolve in the coming years in the context of climate change [6] [27]. It does, however, enable us to appreciate the rainfall-flow relationship likely to generate flooding. It is in this perspective that the use of the GR4J conceptual model in the Oti watershed is justified. The slight increase in rainfall since the late 1990s in West Africa in general and in Togo in particular, in an environment increasingly marked by anthropogenic pressure, has led to an increase in runoff and flooding in rivers compared with the 1970s and 1980s [4] [28]. In addition, flood damage has become more catastrophic in this part of Africa [5] [29] [30].

For this research, the GR4J conceptual model is used to reproduce flood flows, as it can be used to transform climate series on a watershed scale (precipitation and ETP) and simulate flows. It can be used as a decision-making tool for updating hydrological norms in the study area. GR4J has been used to determine flood flows in order to analyze the risk of flooding. The aim of this study is to reproduce flood flows using the GR4J model to analyze the risk of flooding in the Oti watershed in Togo.

2. Data and Methods

2.1. Study Area

The Oti watershed is located in the Volta River basin and drains part of the trans-boundary countries (Burkina-Faso, Benin, Togo and Ghana) with a surface area of 58,670 km² at the Sabari outlet in Ghana. It is the largest of the three basins, sharing the Togolese territory. At the Mango outlet, the Oti basin in Togo covers an area of 35,652 km² and is located between 11°05' and 10°96'N and 0°12' and 0°95'E (**Figure 1**).

The Oti watershed has a relatively dense hydrographic network, controlled by the River Oti. The Oti, the main water collector (167 km long in Togo), rises in northern Benin on the eastern slopes of the Atacora chain, under the name Pendjari. It flows south-west-north-east, crosses Atacora and then reverses,

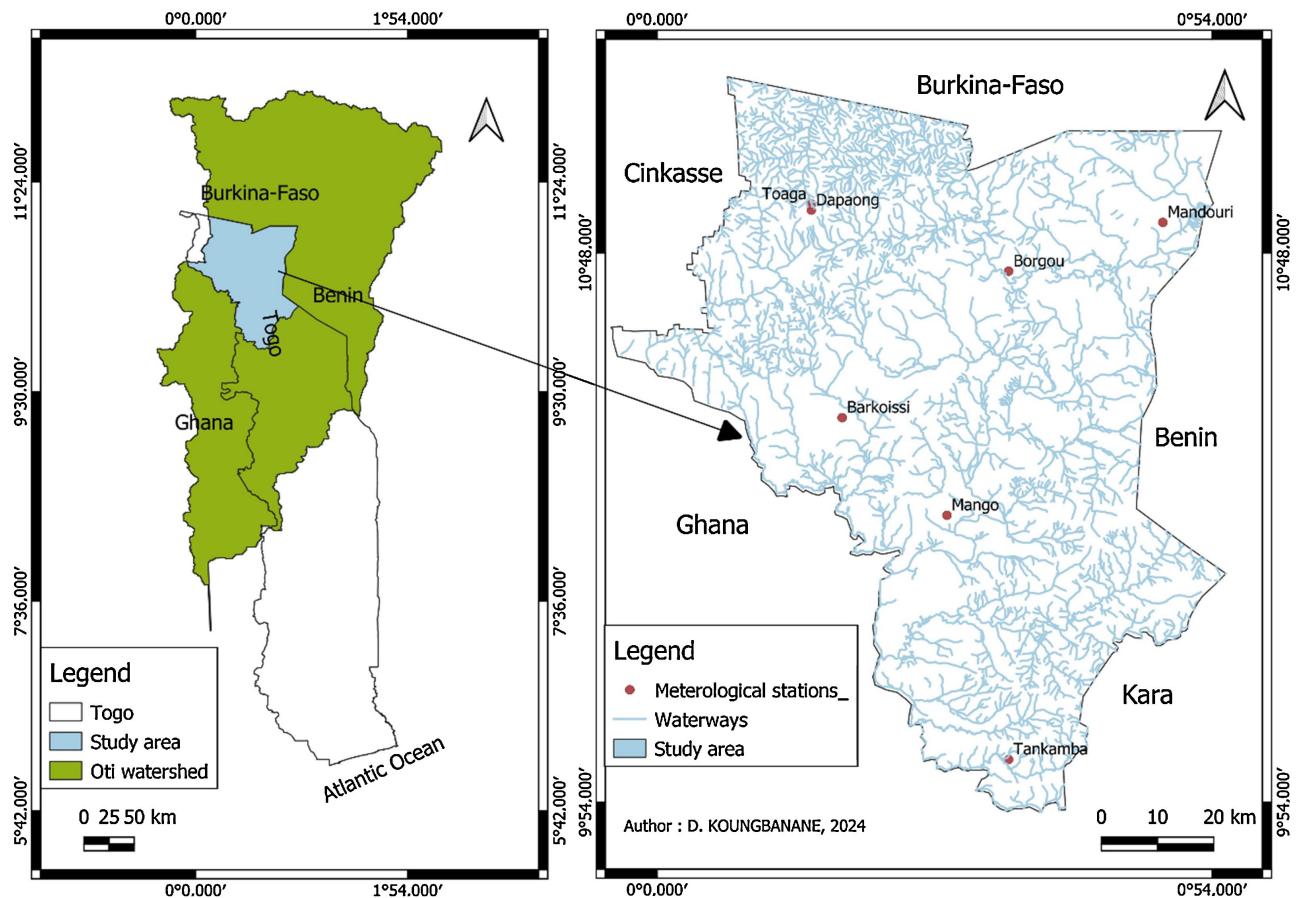


Figure 1. Geographical location of the Oti watershed.

flowing back south-west, arriving in Togo where it takes the name of the Oti [31] and flows into the White Volta in Ghana. Its tributaries are the Wabga, Namiélé and Sansargou on its right bank. Its left-bank tributaries are the Koumongou, Kéran and Kara rivers. The bed of the Oti is cut into the clay formations and bordered here and there by a forest gallery. The overflowing of the Oti during the rainy season causes catastrophic flooding in the area.

In hydrological terms, it is, on average, a gently sloping basin, dominated in its north and south-western parts by an immense plain. The Oti has an irregular tropical regime. It is controlled by the average seasonal rhythm. During the high-water period (August-September-October), the Oti rises out of its bed and joins, according to [32], the large body of stagnant water in the overflow basins, causing lateral runoff and flooding vast tracts of land. In its low-water period (March-April-May), during the dry season, the Oti has a low flow due to the absence of rainfall. It should also be noted that the middle waters correspond to the months of June-July (start of the wet season) and November and December (start of the dry season). This is the intermediate period between high and low water in the Oti. However, the construction of the Kompienga dam upstream in Burkina-Faso on the Oti tributary (Wabga) has disrupted the Oti's hydrological regime. In the rainy season, flooding is severe due to water releases from the dam. In the dry season, the medium water regime is more

regular, thanks to the operating current of the dam's turbines.

According to the fifth General Population and Housing Census (5th RGPH) in 2022, the Oti watershed had a population of 1,143,520, unevenly distributed across the entire basin. Several types of activities are practiced by these populations. These are agriculture, livestock, fishing, hunting, crafts, trade, tourism, sand and gravel extraction and transport. However, agriculture appears to be the main activity of the populations of the watershed.

2.2. Data

The hydroclimatic data used for this study relate to daily rainfall and discharge over the period 1961-2022. Rainfall data are collected at seven (07) meteorological stations of the National Meteorological Agency of Togo (ANAMET) in Lome. The stations are Dapaong, Toaga, Mango, Mandouri, Borgou, Barkoissi and Tankpamba. The data covers the period from January 1, 1961 to December 31, 2022. Flows at the Oti hydrometric station in Mango were obtained from the Department of Water Resources in Lome. The mean daily temperature at the Mango station was used to calculate the daily potential evapotranspiration (PTE) using the method of [33].

Rainfall and PTE projection data from the RCP 8.5 and RCP 4.5 scenarios of the Cordex West Africa program models were used to project future flows in the Oti watershed at Mango using GR4J, in order to obtain flood inducing flows for the 2050 horizon. Thus, the Cordex model provides high-resolution data in the form of grids of $0.44^\circ \times 0.44^\circ$, which is approximately $50 \text{ km} \times 50$ [34] [35]. The models whose data are used for this study are REMO and CCLM.

2.3. Methods

2.3.1. Calculation of Potential Evapotranspiration (PTE)

The method used to calculate PTE is that of [33], previously tested by [36] and [5]. It consists of estimating daily PTE for hydrological modelling and is derived from the Jensen-Haise and McGuinness models. These models take into account only the average daily air temperature and solar radiation, which depends on latitude and the 365 days of the year. They are presented as follows:

$$PE = \frac{R_e T_a + K_2}{\gamma_r K_1} \quad (1)$$

If $R_e T_a + K_2 > 0$, $PE = 0$,

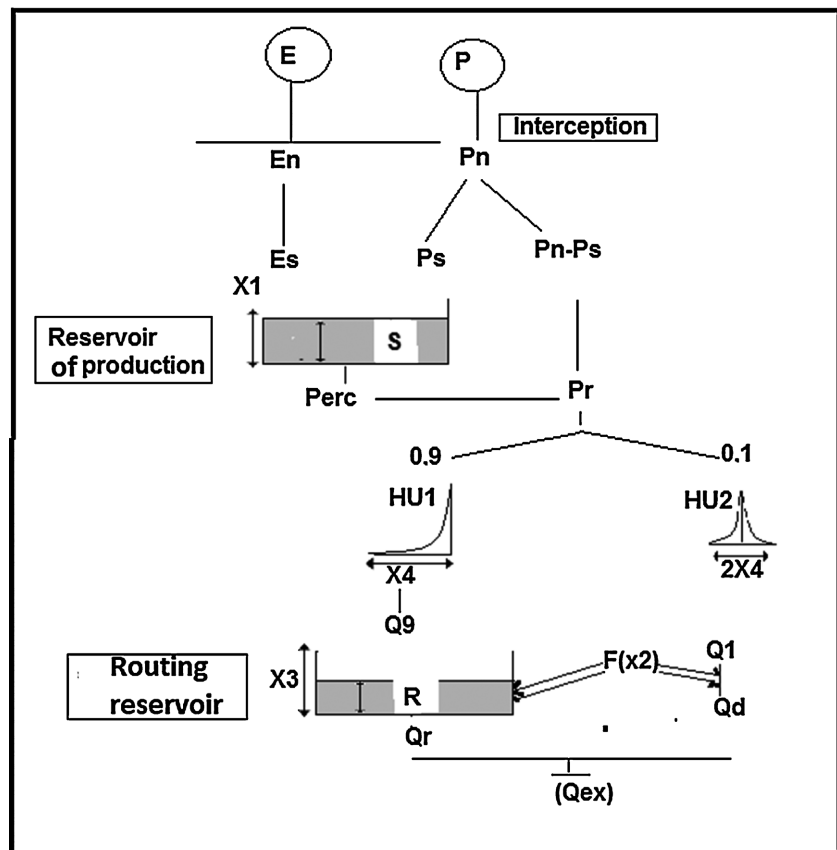
where PE : daily potential evapotranspiration ($\text{mm}\cdot\text{d}^{-1}$); R_e : solar radiation ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$); T_a : daily mean temperature ($^\circ\text{C}$); γ : latent heat of evaporation of water at 20° (taken equal to $2.45 \text{ MJ}\cdot\text{Kg}^{-1}$); r : density of water ($\text{kg}\cdot\text{m}^{-3}$).

K_1 ($^\circ\text{C}$) and K_2 ($^\circ\text{C}$) are fixed model parameters because they are adjusted during the sampling of the entire basin and are not specifically calibrated for each watershed [33] [37].

2.3.2. Structure and Operation of the GR4J Model

There are several versions of the GR4J model. The one used in the present study

is the version adapted by [38] and [39] and illustrated in **Figure 2**.



Source: [38] [39].

Figure 2. How the GR4J model works.

The GR4J model is a daily model with four optimizable parameters: $X1$ is the capacity of the production reservoir (mm); $X2$ is the underground exchange coefficient (mm); $X3$ is the one-day capacity of the routing reservoir (mm) and $X4$ is the unit hydrograph (HU1) base time in days. The first reservoir, called the production reservoir, $X1$, is used to assess the observed precipitation at watershed scale. From the net precipitation, it is possible to define the watershed discharge, taking into account evapotranspired water (precipitation and PTE). The second reservoir, the $X3$ routing reservoir, enables the quantity of water linked to the flow rate to be broken down over time using previously defined parameters.

The model uses as input the average rainfall over the watershed area P (mm) and the potential evapotranspiration PTE (mm) and provides as output the flow rate Q (m³/s).

The soil water balance is determined by gross rainfall plus potential evapotranspiration (PTE). This action is mathematically represented by:

$$\text{-If } P \geq E \text{ then } P_n = P - E \text{ and } E_n = 0$$

$$\text{-If } P < E \text{ then } E_n = E - P \text{ and } P_n = 0$$

In the production reservoir, the rainfall remaining after withdrawal by the

action of the PTE is divided between the quantity of water going into the soil reservoir P_s and that of $P_n - P_s$, which transits towards the outlet as follows:

$$P_s = \frac{P_n \left(1 - \left(\frac{S}{X1} \right)^2 \right)}{1 + P_n \left(1 + \frac{S}{X1} \right)} \quad (2)$$

$$E_s = \frac{E_n \frac{S}{X1} \left(2 - \frac{S}{X1} \right)}{1 + \frac{E_n}{X1} \left(2 - \frac{S}{X1} \right)} \quad (3)$$

The reservoir content is thus updated by: $S = S - E_s + P_s$ and the percolation of the production reservoir is written as $Perc$, which is added to $P_n - P_s$ such that:

$$Perc = S - \left(S^{-4} + \left(\frac{9}{4} X1 \right)^{-4} \right)^{\frac{1}{4}} \quad (4)$$

The reservoir content is then again identified by: $S = S - Perc$.

Rainfall is separated into two flow components in the model.

-A pseudo-direct flow is routed by a unit hydrograph ($SH1(X4)$) representing 10% of the effective rainfall, *i.e.*, each day j :

For $J = 0$, $SH1(j) = 0$

$$\text{For } 0 \leq j \leq X4, \quad SH1(j) = \left(\frac{j}{X4} \right)^{\frac{5}{2}} \left(\frac{j}{X4} \right)^{\frac{5}{2}} \quad (5)$$

For $j > X4$, $SH1(j) = 1$

-The remaining 90% of effective rainfall is routed via a unit hydrograph ($SH2(X4)$) and a routing reservoir (transfer).

For $j = 0$, $SH2(j) = 0$

$$\text{For } 0 \leq j \leq X4, \quad SH2(j) = \frac{1}{2} \left(\frac{j}{X4} \right)^{\frac{5}{2}} \quad (6)$$

$$\text{For } X4 < j \leq 2X4, \quad SH2(j) = 1 - \frac{1}{2} \left(2 - \frac{j}{X4} \right)^{\frac{5}{2}} \quad (7)$$

For $j > 2X4$, $SH2(j) = 1$

At the level of the underground reservoir, the exchange function is provided by $F(X2)$, which can be either an underground inflow or an underground outflow for the basin.

$$\text{It is presented as follows: } F = X2 \left(\frac{R}{X3} \right)^{\frac{7}{2}} \quad (8)$$

where R is the level in the routing reservoir (groundwater).

The level in the routing reservoir R is updated by adding the output $Q9$ of the hydrograph ($SH1(X4)$) and F : $R = \max(0; R + Q9 + F)$.

It then empties to an output Qr given by the following formula:

$$Qr = R - (R^4 + X3^{-2})^{\frac{1}{2}} \quad (9)$$

$$\text{The level in the reservoir then becomes } \Delta: R = R - Qr. \quad (10)$$

The output $Q1$ of the hydrograph ($SH2(X4)$) is subjected to the same exchanges to give the direct flow component (Qd) of the stream and the delayed flow (Qr), representing groundwater recharge and materialized by the following formula:

$$Q = Qr + Qd. \quad (11)$$

The usefulness of this model is to reproduce flood flows [1] [6] [21], as well as flood hazards based on rainfall and PTE, in order to alert communities [1].

It should be pointed out that the equations developed in this section are limited to watersheds with interconnected reservoirs.

2.3.3. Optimization Quality Criteria

Hydrological modelling using the GR4J model enables us to assess water availability by highlighting its performance in reproducing flood, low water and mean flows, based on Nash, R^2 and KGE criteria. Moreover, the rainfall-runoff model does not provide a solution, but rather a better understanding of the watershed's hydrological dynamics [1] [7] [40].

The best known and most widely used model optimization criteria for conceptual models are the Nash and Sutcliff criterion and the KGE (Kling-Gupta Efficiency). For this study, it is the KGE criterion that has been highlighted, as the study aims to find the criterion that best matches GR4J's ability to reproduce high water flows in the Oti watershed. Similarly, the KGE enables a goodness-of-fit measure developed to provide an interesting diagnostic decomposition of Nash-Sutcliffe efficiency (and hence MSE), which facilitates analysis of the relative importance of its different components (correlation, bias and variability) in the context of hydrological modelling [41] [42]. Based on the above, this study used the KGE criterion to analyze the performance and robustness of the GR4J model in simulating high water flows, as [35] had done in the Ouémé basin in Bonou (Benin). The KGE ranges from $-\infty$ to 1. The closer it is to 1, the closer the simulated flows are to the reference flows. It is obtained by the formula:

$$KGE = 1 - ED \text{ et } ED = \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \quad (12)$$

where, ED = Euclidean distance to the ideal point; r = Pearson correlation coefficient.

$$\alpha = \frac{\sigma_s}{\sigma_0} \quad (13)$$

α = the ratio between the standard deviation of simulated values and the standard deviation of observed values.

$$\beta = \frac{\mu_s}{\mu_0} \quad (14)$$

β = the ratio between the mean of simulated values and the mean of observed values.

Table 1 shows the performance of the GR4J model with the KGE criterion on the Oti watershed in Togo.

Table 1. GR4J model performance with the KGE criterion.

Kling-Gupta Efficiency criterion (KGE)	Model performance
$0.75 < KGE \leq 1$	Very Good
$0.65 < KGE \leq 0.75$	Good
$0.50 < KGE \leq 0.65$	Sufficient
$KGE \leq 0.50$	No Sufficient

Source: [41].

2.3.4. Model Calibration and Validation

The calibration and validation procedure involves first dividing the data time series into two independent periods of equal size (P1 and P2). The model is then calibrated on the first period (P1) and validated on the second (P2). Depending on the objectives pursued, it may be possible to recalibrate on the second period (P2) and validate on the first (P1). All selected periods must be preceded by a start-up year to allow initialization of reservoir contents.

Thus, to ensure that the model reproduces flood flows correctly during calibration and validation, *i.e.*, that the model best reproduces the hydrological behavior of the watershed, four periods were taken into account in the time series for this study and implemented in the R software package airGR. In the first step, the model is calibrated from 2016-2017 and validated from 2018-2019. In a second step, it is calibrated from 2019-2020 and validated from 2021-2022. The choice of periods for calibration and validation in the present study is explained by the fact that these periods present a less incomplete set of data.

3. Results and Discussion

3.1. Variability of Observed and Simulated Flows in the Oti Watershed at Mango

Figure 3 illustrates the variability of observed and simulated flows at calibration (2016-2017) and validation (2018-2019) with GR4J.

Analysis of **Figure 3** shows that simulated flows overestimate observed flows during low water periods from October to July with a probability of 0 - 60%, and underestimate them by 60-95% during high water periods (August to September) for the period (2016-2017). In validation (2018-2019), simulated flows overestimate observed flows from November to July with a probability of 0 - 55%, and underestimate them by 55% - 75% from August to October.

Figure 4 highlights the results of the variability of observed and simulated flows in calibration (2019-2020) and validation (2021-2022).

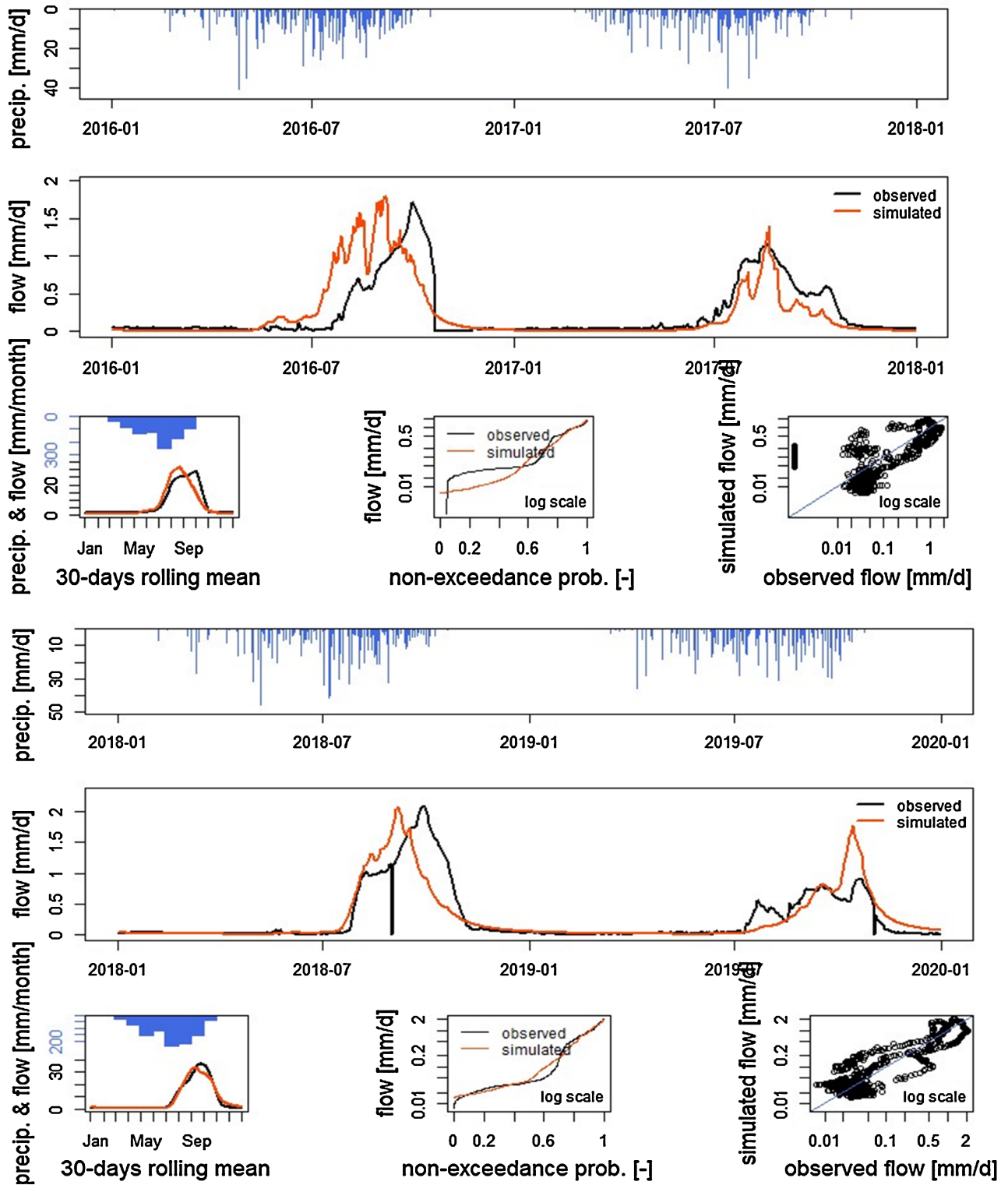


Figure 3. Variability of observed and simulated flows during calibration (2016-2017) and validation (2018-2019).

The analysis of **Figure 4** shows that simulated flows overestimate observations from October to July during low water periods with a probability of 0 - 55%, and underestimate them by 55% - 90% from August to September (floods) in the

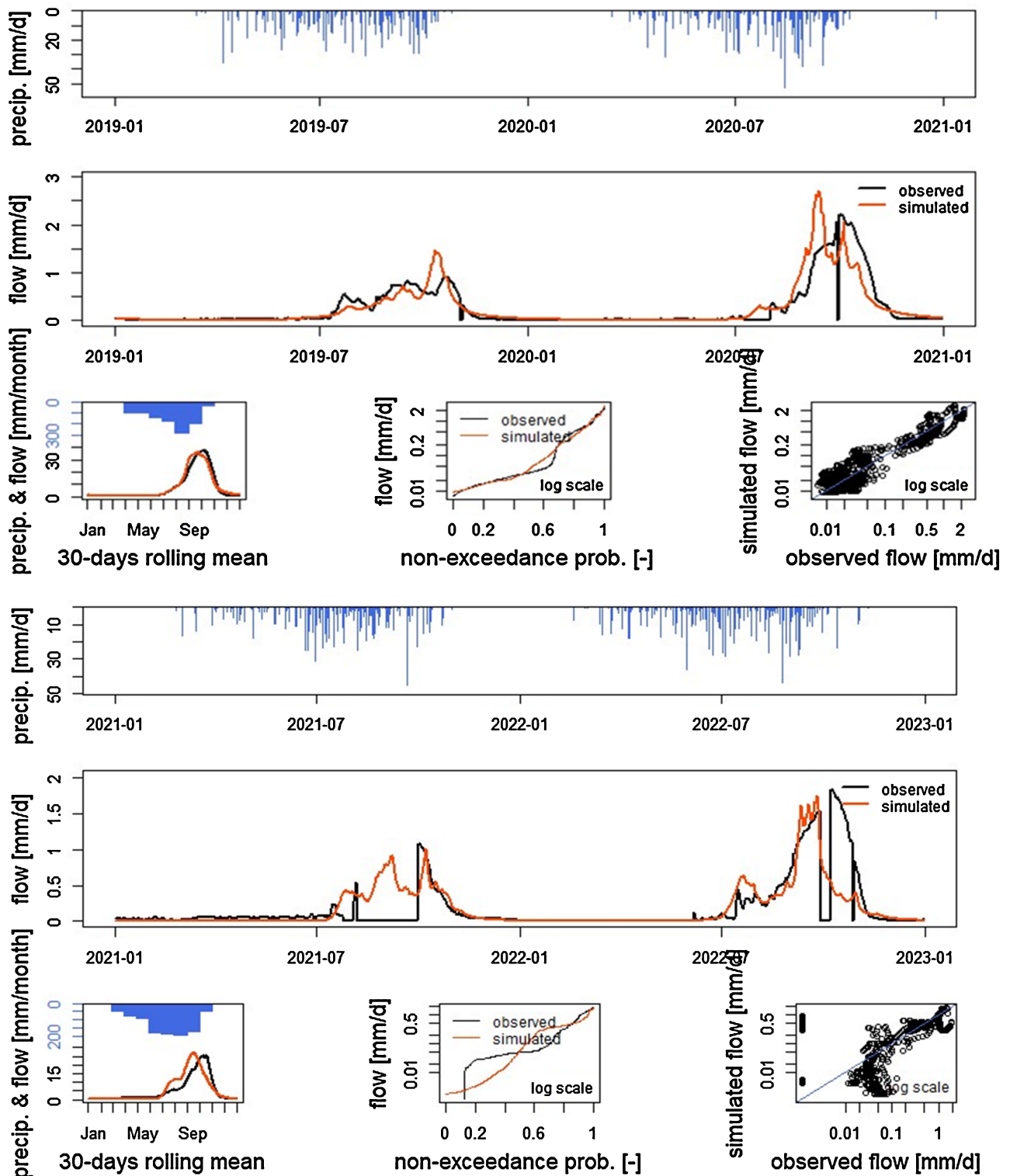


Figure 4. Variability of observed and simulated flows during calibration (2019-2020) and validation (2021-2022).

calibration period (2019-2020). At validation (2021-2022), simulated flows also overestimate observations from October to July with a probability of 0 to 55% and underestimate them from August to October by between 55% and 92%.

From the above, it should be noted that the underestimates during high water are due to the effect of cumulative rainfall in August, September and October in the watershed. Indeed, the hydroclimatic events responsible for flooding in Togo's Oti watershed occur in August and September.

This confirms the findings of [43] on the importance of cumulative rainfall in the occurrence of floods. This finding has been validated by the model in that simulated and observed flows peak in September or October, depending on the year. This corroborates the results of [35] [44] [45] in Benin. Similarly, observed and simulated flows are found to follow the same rhythm as rainfall, with occasional slight lags that are the result of the watershed's response time to rainfall events. In tropical regions, runoff is dependent on rainfall. In view of these results, GR4J is a tool that can be used to reproduce flood flows in the Oti watershed at the Mango outlet in Togo.

3.2. Model Optimization Criteria for Calibration and Validation

Table 2 shows the GR4J model's optimization criteria for reproducing flood flows in the Oti watershed at the Mango outlet in Togo.

Table 2. Values of optimization and robustness criteria for the GR4J model.

Période	KGE
Calibration: 2016-2017	0.73
Validation: 2018-2019	0.81
Calibration: 2019-2020	0.85
Validation: 2021-2022	0.62

Analysis of the results in **Table 2** shows that the KGE criterion ranging from 0.73 to 0.85 at calibration and 0.62 to 0.81 at validation. The first calibration period (2016-2017) results in a KGE value below 0.75. This KGE value (0.73) shows good model performance during this period. On the other hand, the second calibration period (2019-2020) gives a KGE value (0.85) higher than 0.75, showing very good model performance. The validation phase of the first period (2018-2019) shows a KGE value of 0.81, justifying the model's very good performance in simulating flood flows. On the other hand, a deterioration in the KGE value was observed in the second validation period (2021-2022), at 0.62, demonstrating the model's sufficient performance. The decrease in model performance from the calibration period to the validation period is significant, with a difference of 0.23. This deterioration of the KGE value in validation may be linked to the missing data recorded in the series. From this observation, it can be said that the KGE is a good criterion for better optimizing and simulating high water flows in the Oti watershed. It is for this reason that this study has used the KGE to better assess the effectiveness of the GR4J model in simulating flood flows.

This approach has already been used by [35] [41] [42] to show the performance of the GR4J model in simulating high-water flows. In all the results obtained, the

KGE criterion shows the performance and robustness of the GR4J model in reproducing flood flows and, more specifically, 24-hour high water flows.

3.3. Projected Flood Flows in the Oti Watershed at the Mango Outlet, 2006 to 2050, Averaged from Two Models (REMO and CCLM)

Rainfall and PTE projection data from the RCP 8.5 and RCP 4.5 scenarios of the Cordex West Africa program models being available over the period 2006-2050, the projection of future flows on the Oti watershed at Mango was carried out with the GR4J in order to have the flow rates causing flooding.

Thus **Figure 5** shows the evolution of projected flows from 2006 to 2050 in relation to the simulated rainfall of the RCP 4.5 and RCP 8.5 scenarios in the Oti watershed, in order to identify possible high-water events that could lead to flooding.

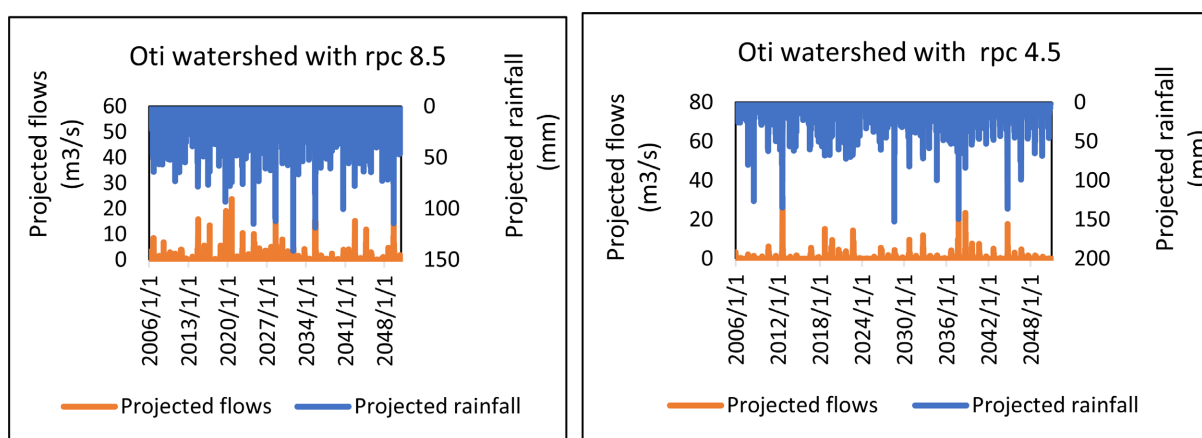


Figure 5. Daily evolution of projected flows from 2006 to 2050 in relation to simulated rainfall for the RCP 4.5 and RCP 8.5 scenarios of the Cordex West Africa program models.

Analysis of **Figure 5** shows that projected flows evolve at the same pace as rainfall under both scenarios (RCP 4.5 and RCP 8.5). Rainfall peaks coincide with flow peaks. This means that the heavier the rainfall, the greater the runoff and the greater the flooding in the watershed. The simulated flow thresholds are 48.37 m³/s for the RCP 8.5 scenario recorded on August 30, 2035 and 57.93 m³/s for the RCP 4.5 obtained on September 27, 2037. It should be noted, however, that there is a time lag in places (around one to two days) between the simulated rainfall peaks and those of projected flows from 2006 to 2050, which is the result of the watershed's response time to rainfall events. This is due to the geological characteristics and land-use dynamics of the watershed.

An analysis of the evolution of projected flows has thus enabled us to detect the occurrence of high water (flood waters) by 2050, with the consequent risk of flooding in the Oti watershed. It should therefore be said that projected flows follow the variation in climatological parameters such as precipitation and PTE. Variations in these two parameters influence the evolution of simulated flows. This corroborates the findings of [46] [47].

4. Conclusions

Hydrological modelling is a very important tool for water resource management, decision making and understanding the hydrological functioning of watersheds. The aim of this study is to reproduce flood flows from the GR4J model to analyze flood risk in the Oti watershed in Togo. The model was calibrated over two periods (2016-2017 and 2019-2020) and validated over two periods (2018-2019 and 2021-2022), and the quality of both calibration and validation was highlighted by the KGE criterion.

The results show that the KGE criterion varies from 0.73 to 0.85 at calibration and 0.62 to 0.81 at validation, indicating that the GR4J model is very efficient and effective in reproducing flood flows in the Oti watershed in Togo. On the other hand, there was a deterioration in the KGE value to 0.62 in the second validation period (2021-2022), showing the model's declining performance. In view of the results presented, the GR4J model could be used as a tool to help predict floods, but with greater caution in view of the deterioration in the KGE value, to avoid false or missed alerts. Under these conditions and given the uncertainties over the stability of the parameters over time, it would be difficult to forecast 24-hour flood flows in the watershed using GR4J for future horizons in order to assess the impact of climate change. Other approaches would be necessary to assess the hydrological impacts of climate change on 24-hour flood flows in this watershed. Analysis of the evolution of projected flows has enabled us to detect the occurrence of high water (flood water) by 2050, with the consequent risk of flooding in the Oti watershed.

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Conflicts of Interest

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

References

- [1] Amoussou, E. (2015) Analyse hydrométéorologique des crues dans le bassin versant du Mono en Afrique de l'Ouest avec un modèle conceptuel pluie-débit. Rapport à publier avec la Fondation Maison des Sciences de l'Homme (FMSH). <https://shs.hal.science/halshs-01143318v1>
- [2] Panthou, G. (2013) Analyse des extrêmes pluviométriques en Afrique de l'Ouest et de leurs évolutions au cours des 60 dernières années. Université de Grenoble.
- [3] Koumassi, D.H. (2019) Caractérisation spatiale du risque d'inondation dans le bassin versant de la Volta au Bénin. Colloque Internationale de l'AIC, 211-2016.

- [4] Amoussou, E. (2010) Variabilité pluviométrique et dynamique hydro-sédimentaire du bassin-versant du complexe fluvio-lagunaire Mono-Ahémé-Couffo (Afrique de l'Ouest). Thèse de Doctorat, Université de Bourgogne, 315 p. + annexes.
- [5] Amoussou, E., Trambly, Y., Totin, H.S.V., Mahé, G. and Camberlin, P. (2014) Dynamique et modélisation des crues dans le bassin du Mono à Nangbéto (Togo/Bénin). *Hydrological Sciences Journal*, **59**, 2060-2071. <https://doi.org/10.1080/02626667.2013.871015>
- [6] Kodja, D.J., Mahé, G., Amoussou, E., Boko, M. and Paturel, J.-E. (2018) Assessment of the Performance of Rainfall-Runoff Model GR4J to Simulate Streamflow in Ouémé Watershed at Bonou's Outlet (West Africa). <https://doi.org/10.20944/preprints201803.0090.v1>
- [7] Nonki, R.M., Amoussou, E., Tshimanga, R.M., Koubodana Houteta, D., Kodja, D.J., Kemgang Ghomsi, F.E., *et al.* (2024) Performance Assessment of Daily GR Conceptual Rainfall-Runoff Models in the Upper Benue River (cameroon) Using Airgr Packages. *Proceedings of IAHS*, **385**, 319-326. <https://doi.org/10.5194/piahs-385-319-2024>
- [8] Sambou, S., Sane, M.L., Leye, I., Ndione, D.M., Kane, S. and Badji, M.L. (2021) Calage et validation de SWAT sur le bassin versant du Bafing (Fleuve Sénégal) en amont de bafing Makana: Vers une application à la gestion du barrage de Manantali. *Proceedings of the International Association of Hydrological Sciences*, **384**, 363-366. <https://doi.org/10.5194/piahs-384-363-2021>
- [9] Tran Tuan, T. (2024) Multiple Conceptual Hydrological Models for Simulating Streamflow in Data-Sparse River Basins: An Application of the Vietnamese Cau River Basin. *Water Practice & Technology*, **19**, 2944-2958. <https://doi.org/10.2166/wpt.2024.181>
- [10] Mehta, D., Hadvani, J., Kanthariya, D. and Sonawala, P. (2023) Effect of Land Use Land Cover Change on Runoff Characteristics Using Curve Number: A GIS and Remote Sensing Approach. *International Journal of Hydrology Science and Technology*, **16**, 1-16. <https://doi.org/10.1504/ijhst.2023.131824>
- [11] Yin, Z., Ottlé, C., Ciaï, P., Zhou, F., Wang, X., Jan, P., *et al.* (2021) Irrigation, Damming, and Streamflow Fluctuations of the Yellow River. *Hydrology and Earth System Sciences*, **25**, 1133-1150. <https://doi.org/10.5194/hess-25-1133-2021>
- [12] Hundecha, Y. and Bárdossy, A. (2004) Modeling of the Effect of Land Use Changes on the Runoff Generation of a River Basin through Parameter Regionalization of a Watershed Model. *Journal of Hydrology*, **292**, 281-295. <https://doi.org/10.1016/j.jhydrol.2004.01.002>
- [13] Dutta, P. and Sarma, A.K. (2020) Hydrological Modeling as a Tool for Water Resources Management of the Data-Scarce Brahmaputra Basin. *Journal of Water and Climate Change*, **12**, 152-165. <https://doi.org/10.2166/wcc.2020.186>
- [14] Ragetti, S., Cortés, G., McPhee, J. and Pellicciotti, F. (2013) An Evaluation of Approaches for Modelling Hydrological Processes in High-Elevation, Glacierized Andean Watersheds. *Hydrological Processes*, **28**, 5674-5695. <https://doi.org/10.1002/hyp.10055>
- [15] Le Lay, M., Saulnier, G., Galle, S., Seguis, L., Métadier, M. and Peugeot, C. (2008) Model Representation of the Sudanian Hydrological Processes: Application on the Donga Catchment (Benin). *Journal of Hydrology*, **363**, 32-41. <https://doi.org/10.1016/j.jhydrol.2008.09.006>
- [16] Kapoor, A., Pathiraja, S., Marshall, L. and Chandra, R. (2023) Deepgr4j: A Deep Learning Hybridization Approach for Conceptual Rainfall-Runoff Modelling. *Environmental*

- Modelling & Software*, **169**, Article ID: 105831.
<https://doi.org/10.1016/j.envsoft.2023.105831>
- [17] Devia, G.K., Ganasri, B.P. and Dwarakish, G.S. (2015) A Review on Hydrological Models. *Aquatic Procedia*, **4**, 1001-1007. <https://doi.org/10.1016/j.aqpro.2015.02.126>
- [18] Solomatine, D.P. and Wagener, T. (2011) Hydrological Modeling. In: Wilderer, P., Ed., *Treatise on Water Science*, Elsevier, 435-457.
<https://doi.org/10.1016/b978-0-444-53199-5.00044-0>
- [19] Le Lay, M. (2006) Modélisation hydrologique dans un contexte de variabilité hydro-climatique. Une approche comparative pour l'étude du cycle hydrologique à méso-échelle au Bénin, PhD Thesis, LTHE/UJF/INPG, 251 p.
- [20] Vissin, E.W. (2007) Impact de la variabilité climatique et de la dynamique des états de surface sur les écoulements du bassin béninois du fleuve Niger. Thèse de Doctorat de l'Université de Bourgogne, 280 p.
- [21] Kouamé, K.F.C. (2024) Approche de la prévision des crues fluviales à partir d'une modélisation hydrologique: Cas du modèle GR4J appliqué au bassin versant aménagé du fleuve Sassandra à l'exutoire de Soubré (Sud-ouest de la Côte d'Ivoire). *Revue Espace Géographique et Société Marocaine*, No. 83, 127-145.
- [22] Alipour, M.H. and Kibler, K.M. (2018) A Framework for Streamflow Prediction in the World's Most Severely Data-Limited Regions: Test of Applicability and Performance in a Poorly-Gauged Region of China. *Journal of Hydrology*, **557**, 41-54.
<https://doi.org/10.1016/j.jhydrol.2017.12.019>
- [23] Sirisena, T.A.J.G., Maskey, S. and Ranasinghe, R. (2020) Hydrological Model Calibration with Streamflow and Remote Sensing Based Evapotranspiration Data in a Data Poor Basin. *Remote Sensing*, **12**, Article No. 3768.
<https://doi.org/10.3390/rs12223768>
- [24] Feng, D., Lawson, K. and Shen, C. (2021) Mitigating Prediction Error of Deep Learning Streamflow Models in Large Data-Sparse Regions with Ensemble Modeling and Soft Data. *Geophysical Research Letters*, **48**, e2021GL092999.
<https://doi.org/10.1029/2021gl092999>
- [25] Lu, D., Konapala, G., Painter, S.L., Kao, S. and Gangrade, S. (2021) Streamflow Simulation in Data-Scarce Basins Using Bayesian and Physics-Informed Machine Learning Models. *Journal of Hydrometeorology*, **22**, 1421-1438.
<https://doi.org/10.1175/jhm-d-20-0082.1>
- [26] Komi, K. (2016) Flood Risk Assessment in Poorly Gauged River Basins—A Case Study of the Oti River Basin, Togo, West Africa. Dissertation, PhD of University of Abomey-Calavi (Benin Republic), 161 p.
- [27] Mounirou, A., Laroche, C., Paturel, J.-C. and Mar, A.L. (2005) Détermination de la connaissance hydrométrique minimale nécessaire et suffisante pour une estimation raisonnable des paramètres d'un modèle de transformation pluie-débit au pas de temps mensuel. Rapport d'activités de recherche, PNRH 2003, 134 p.
- [28] Koungbanane, D., Totin Vodounon, S.H., Amoussou, E., Zahiri, P.E. and Laré, L.Y. (2019) Variabilité hydro-climatique et risques d'inondation dans le bassin versant de l'Oti au Togo. *Revue de Géographie de l'Université de Ouagadougou*, **1**, 1-17.
- [29] Koungbanane, D., Lemou, F., Djangbedja, M. and Totin, H.S.V. (2023) Impacts socio-économiques et environnementaux des risques d'inondation dans le bassin versant de l'Oti au Togo (Afrique de l'Ouest). *VertigO*
- [30] 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>
- [31] Mul, M., Obuobie, E., Appoh, R., Kankam, Y., Bekoe-Obeng, E., Amisigo, B., Logah, Y., Ghansah, B. and McCartney, M. (2015) Évaluation des ressources en eau du bassin de la Volta. Programme des Nations Unies pour l'Environnement.
- [32] Kankpéndja, L. (2002) Contribution à l'étude géomorphologique de la plaine alluviale du Kpendjal (Région des Savanes). Mémoire de maîtrise en Géographie, Université de Lomé, 136 p.
- [33] Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andréassian, V., Anctil, F., *et al.* (2005) Which Potential Evapotranspiration Input for a Lumped Rainfall-Runoff Model? Part 2—Towards a Simple and Efficient Potential Evapotranspiration Model for Rainfall-Runoff Modelling *Journal of Hydrology*, **303**, 290-306.
<https://doi.org/10.1016/j.jhydrol.2004.08.026>
- [34] Giorgi, F., Jones, C. and Asrar, G.R. (2009) L'expérience CORDEX: Répondre aux besoins d'information climatologique à l'échelle régionale. *Bulletin de l'OMM*, **58**, 175-177.
- [35] Kodja, D.J. (2018) Indicateurs des événements hydroclimatiques extrêmes dans le bassin-versant de l'Oueme à l'exutoire de Bonou en Afrique de l'ouest. Thèse de Doctorat, Université de Montpellier, 287 p.
- [36] Kay, A.L. and Davies, H.N. (2008) Calculating Potential Evaporation from Climate Model Data: A Source of Uncertainty for Hydrological Climate Change Impacts. *Journal of Hydrology*, **358**, 221-239. <https://doi.org/10.1016/j.jhydrol.2008.06.005>
- [37] Houessou, S. (2016) Les inondations et les risques prévisionnels liés aux barrages hydroélectriques dans la basse vallée du mono. Thèse de Doctorat de Géographie, Université d'Abomey-Calavi, 198 p.
- [38] Perrin, C. (2002) Vers une amélioration d'un modèle global pluie-débit au travers d'une approche comparative. Towards an Improved Version of a Lumped Rain-Fall-runoff Model through a Comparative Approach. *La Houille Blanche*, **88**, 84-91.
<https://doi.org/10.1051/lhb/2002089>
- [39] Perrin, C., Michel, C. and Andréassian, V. (2003) Improvement of a Parsimonious Model for Streamflow Simulation. *Journal of Hydrology*, **279**, 275-289.
[https://doi.org/10.1016/s0022-1694\(03\)00225-7](https://doi.org/10.1016/s0022-1694(03)00225-7)
- [40] Coron, L., Thirel, G., Delaigue, O., Perrin, C. and Andréassian, V. (2017) The Suite of Lumped GR Hydrological Models in an R Package. *Environmental Modelling & Software*, **94**, 166-171. <https://doi.org/10.1016/j.envsoft.2017.05.002>
- [41] Gupta, H.V., Kling, H., Yilmaz, K.K. and Martinez, G.F. (2009) Decomposition of the Mean Squared Error and NSE Performance Criteria: Implications for Improving Hydrological Modelling. *Journal of Hydrology*, **377**, 80-91.
<https://doi.org/10.1016/j.jhydrol.2009.08.003>
- [42] Kling, H., Fuchs, M. and Paulin, M. (2012) Runoff Conditions in the Upper Danube Basin under an Ensemble of Climate Change Scenarios. *Journal of Hydrology*, **424**, 264-277. <https://doi.org/10.1016/j.jhydrol.2012.01.011>
- [43] Issaou, L. (2014) Risques climatiques dans le Sud-Togo: Manifestations, impacts et stratégies d'adaptation. Thèse de Doctorat de Géographie de l'Université de Lomé, 264 p.
- [44] Le Barbé, L., Alé, G., Millet, B., Texier, H., Borel, Y. and Gualde, R. (1993) Les ressources en eaux superficielles de la République du Bénin. Edition ORSTOM, 540 p.
- [45] Totin, V.S.H., Amoussou, E., Odoulami, L., Boko, M. and Bliivi, B.A. (2016) Seuils

pluviométriques des niveaux de risque d'inondation dans le bassin de l'Ouémé au Bénin (Afrique de l'Ouest). *XXIXe Colloque de l'Association Internationale de Climatologie*, Lausanne, 6-9 July 2016, 369-374.

- [46] IPCC (2001) Impact of Climate Change in the Regions: Vulnerability Assessment in Africa. Report of the Intergovernmental Panel on Climate Change, 1-3.
- [47] Kodja, D.J. (2011) Prédiction des crues dans le bassin-versant du Zou à Atcherigbé avec le modèle GR2M. Mémoire de Maîtrise, DGAT/FLASH/UAC, 104 p.