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Flood Modeling using SWAT and GR4J Models in the Oti River Basin in Togo (West Africa)

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Abstract

The Earth's climate evolution over the past few decades has been marked by global warming, leading to hydroclimatic variability and impacting water resource availability. Hydrological modeling has become a solution for reproducing river flows and is an essential tool for understanding watershed dynamics and mitigating natural disasters related to floods. The objective of this study is to reproduce flood flows in the management of floods in the Oti River Basin in Togo. To achieve this objective, the semi-distributed physically-based SWAT (Soil and Water Assessment Tool) and conceptual GR4J (Génie Rurale Quatre paramètres Journaliers) hydrological models were chosen as the base model to calculate flood hydrographs. The data used for this study consisted of a DEM, land use map, soil map, rainfall, temperature, flow, and PET observation data. Sensitivity analysis revealed the most significant parameters of the SWAT and GR4J models. The values of these parameters were determined during the calibration and validation phases. The Nash criterion value for the SWAT model is 0.83 and 0.78 for calibration and 0.72 and 0.81 for validation. Additionally, the KGE values of GR4J range from 0.73 to 0.85 during calibration and 0.62 to 0.81 during validation. These results show excellent performance of the SWAT and GR4J models in simulating flood flows in the watershed. However, the analysis of the results shows that the SWAT model is more efficient than GR4J in simulating high flows and could be used for flood management in the Oti River Basin.

Keywords: Modeling; Rainfall-Runoff; Soil and Water Assessment Tool; Floods; Oti

1. Introduction

In West Africa and Togo, floods have become recurrent in recent years, with significant socio-economic and ecological impacts, including loss of human life and material damage [1]. These floods have highlighted the need for hydrological forecasting to reduce the vulnerability of populations. In Togo, very few studies have addressed flood-related issues due to a lack of data caused by the limited number of stations and the frequent destruction of limnigraphs by high waters. Hydrological modeling is a solution for reproducing river flows, particularly in the context of flood risk. It is an essential tool for understanding watershed dynamics, rational water resource management, and mitigating natural disasters related to floods [2, 3].

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To protect the riparian populations of the Oti River Basin from recurrent floods caused by high waters, it is essential to have a reliable and operational forecasting tool, as flood forecasting is a pressing issue with undeniable importance today. To this end, mastering and rationally managing surface water requires a better understanding of episodic flows and the influence of extreme climatic events, all through conceptual rainfall-runoff modeling. With climate change and variability, as well as population growth, it has become increasingly necessary to use water resources as rationally as possible [4]. This constraint requires an in-depth understanding of watershed physics and a thorough comprehension of how hydrological processes related to water flow in the watershed occur. The hydrological model, which allows calculating fluxes (flows, sediments, nutrients, chemicals, etc.) within the watershed, has become indispensable today, both for fundamental hydrological research and for water resource planning and management.

The Oti River Basin in Togo, having experienced significant land use changes, is prone to recurrent floods. Therefore, hydrological modeling using SWAT and GR4J allows evaluating the performance of these models in simulating flows in the watershed under changing surface conditions. Considering this aspect is currently a major challenge in modeling tropical river flows, given the significant anthropization recently observed in their watersheds, with well-known hydrological impacts. The SWAT and GR4J models have already proven their effectiveness in several West African watersheds. In the Oti River Basin at the Mango outlet in Togo, research on hydrological modeling is scarce, with [5] being one of the few studies that used a semi-distributed model. A rainfall-runoff model is particularly interesting in developing countries, as it can estimate or represent available resources for development purposes and predict the evolution of these resources in the coming years in the context of climate change [6, 7]. It also allows appreciating the rainfall-runoff relationship that can generate floods.

From a spatial perspective, there are global and distributed models. Global models are one-dimensional and do not account for spatial heterogeneity or variations in hydrological variables and processes. Distributed models, on the other hand, have a spatial structure, dividing the watershed into smaller grid cells that can capture the spatial variability of hydrological processes and watershed characteristics. From a process description perspective, hydrological models can be conceptual or physically-based. Conceptual models represent different hydrological cycle processes using storage elements, with transfers between these reservoirs represented by mathematical functions. Physically-based models typically represent different hydrological cycle processes using non-linear partial differential equations derived from fluid mechanics conservation laws. Spatially distributed and physically-based models provide detailed information on watershed functioning and are used to deepen the understanding of hydrological process dynamics and simulate the hydrological response of a watershed at a spatial scale. This justifies the use of the semi-distributed physically-based SWAT model and the conceptual GR4J model in the Oti River Basin. In terms of performance, comparing global and semi-distributed approaches in rainfall-runoff modeling is a long-standing issue [8]. Scientific research on this topic presents a complex picture, with some studies clearly affirming the benefits of using semi-distributed approaches [9], while others present opposing conclusions [10]. This study aims to reproduce flood flows for sustainable flood management in the Oti River Basin, Togo.

2. Material and methods

2.1. Study area

The Oti River basin in Togo is located in the north of the country, in the Volta River basin, and drains part of the watershed areas of the countries bordering Togo, namely Burkina Faso, Benin and Ghana. At the Mango outlet, the Oti basin covers an area of 3.652 square kilometres and is located between 11°05' and 10°96' N and 0°12' and 0°95' E (Figure 1).

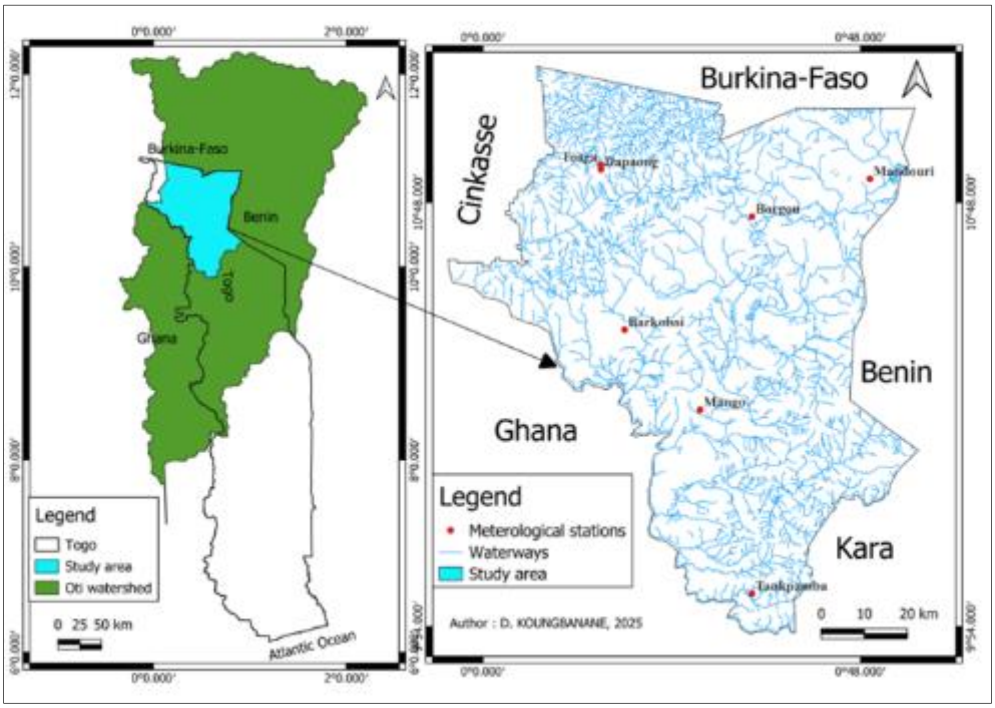


Figure 1 Location of the Oti watershed in Togo

The topography of the watershed is based on a morphology that includes the Gourma peneplain, the Dapaong-Bombouaka plateaus and the Oti plain. The total elevation ranges from 106 to 506 meters. Its relatively dense hydro-graphic network is controlled by the Oti River. The Oti river, the main water collector (167 kilometers long in Togo), rises in northern Benin on the eastern slopes of the Atacora chain, under the name of Pendjari. He follows a south-west-north-east orientation, crosses the Atacora region, and then re-verses and returns south-west, arriving in Togo, where it takes the name of the Oti [11]. The Oti river forms the natural border between Togo and Benin from its confluence with the Koumongou River, south of the Ga-langachi classified forest, to the Ghanaian commune of Sabari, south of which the Oti river flows into Lake Volta. Its tributaries are the Wabga, Namiélé and Sansargou on its right bank. Its left bank tributaries are the Koumongou, Kéran and Kara. The riverbed of the Oti is cut into the clay formations and here and there bordered by a forest gallery. When the Oti overflows its banks during the rainy season, it causes major flooding with serious consequences for the people living along its banks.

According to the 5th General Census of Population and Housing (5thRGPH) in 2022, the Oti watershed had a population of 1.143.520. Several activities are practiced by these populations. These include agriculture, livestock, fish-ing, hunting, handicrafts, commerce, tourism, sand and gravel extraction, and transportation. However, agriculture seems to be the main activity of the peo-ple living in the watershed.

2.2. Data used

Several types of data were used for this study. These include DTM, land use data, soil data and hydroclimatic data.

2.2.1. DTM (Digital Terrain Model)

HydroSHEDS data were used to delineate watersheds. HydroSHEDS is derived from SRTM (Shuttle Radar Topography Mission) elevation data at a resolution of 3 arc seconds (WWF, 2018). The original SRTM data were hydrologically conditioned using a sequence of automated procedures. Existing data enhancement methods and newly developed algorithms were applied, including gap filling, filtering, flow engraving and upscaling techniques. Manual corrections were also made. Preliminary quality assessments indicate that the accuracy of HydroSHEDS far exceeds that of existing global hydrographic and river maps.

2.2.2. Land cover data

This data comes from the ESA's Globcover database. It was produced between 2004 and 2006 and was derived by automatic and regional classification of a full-resolution MERIS surface reflectance time series. It has a resolution of 300 m.

2.2.3. Soil data

The Harmonised World Soil Database (HWSD) version 1.2 produced by the Food and Agriculture Organisation of the United Nations (FAO), the International Institute for Applied Systems Analysis, the Institute of Soil Science of the Chinese Academy of Sciences and the Joint Research Centre (JRC) of the European Commission, was used to generate the soil data required in SWAT.

2.2.4. Hydroclimatic data

For this study, the data used are hydrometric and climatic data. The hydrometric data come from the database of the Water Resources Directorate in Lomé. These are the average daily flows observed at the Mango station over the period 1961–2022. The rainfall data observed covers the period 1961–2022 and was collected at seven (07) meteorological stations of the National Meteorological Agency of Togo (ANAMET) in Lomé. These are the stations of Dapaong, Toaga, Mango, Mandouri, Borgou, Barkoissi and Tankpamba. The data covers the period from 1 January 1961 to 31 December 2022. Similarly, maximum and minimum temperature data and ETP data were used.

2.3. Methods

2.3.1. Presentation of the SWAT hydrological model

SWAT is a continuous, spatially semi-distributed, semi-physical, daily-timetable hydrological model that can be downloaded free of charge from https://swat.tamu.edu/software. The SWAT model can simulate a large number of physical processes in a catchment area with high spatial resolution. To do this, the watershed is divided into sub-basins, which are themselves subdivided into Hydrologic Response Units (HRUs). HRUs are homogeneous spatial units characterised by the same soil, vegetation cover, and slope. The water balances calculated for the HRUs are used to determine the flows at the outlets of the sub-watersheds. These different outlets are connected to each other by the hydrographic network. The water balance simulated by SWAT uses the equation below [12, 13]

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right)$$

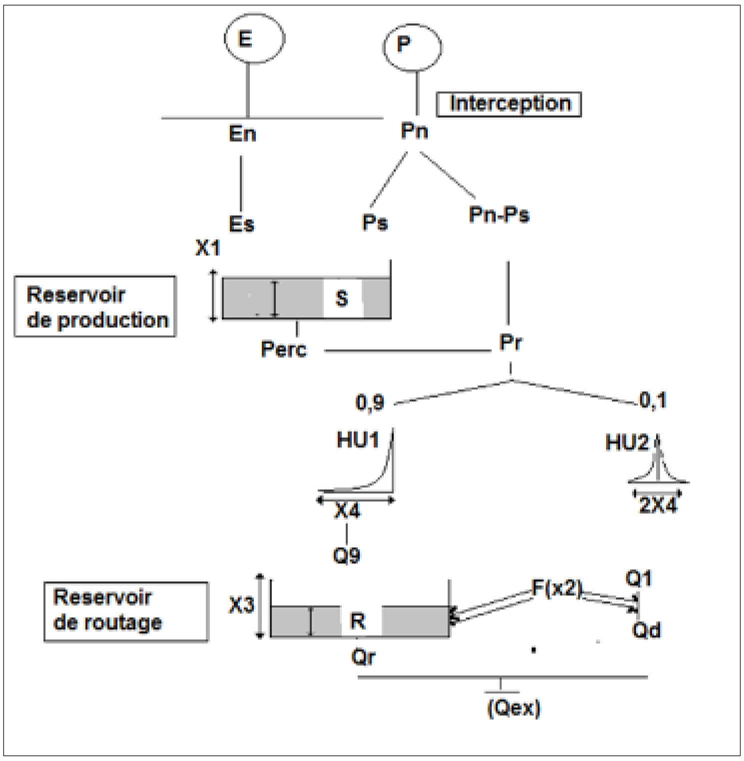
Where: t: time in days, SWt (mm) and SW0 (mm) represent the moisture content in the soil at time t and at the initial time, respectively, Rday (mm) is the rainfall at time i, Wseep (mm) is the rainfall infiltrated into the soil from the surface at time i, Qsurf (mm) is the rainfall available for runoff at time i, Qgw (mm) is the base flow from the water table at time i, and Ea (mm) is the evapotranspiration at time i.

In this study, the Penmann-Monteith method is used because it is the most widely used.

The water depth available for runoff is determined using the Curve Number method developed by the Soil Conservation Service (SCS). The flow from the watershed surface to the hydrographic network is simulated using the kinematic wave equation. River flow is calculated using the Muskingum method [12, 13].

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 [14] and [15] and illustrated in Figure 2.



Source: [14, 15]

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 po-tential 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:

-If P ≥ E then Pn = P-E and En = 0

-If P < E then En = E - P and Pn = 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 Ps and that of Pn - Ps

which transits towards the outlet as follows:

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

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

The reservoir content is thus updated by: S = S - Es + Ps and the percolation of the production reservoir is written as Perc, which is added to Pn - Ps such that

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

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

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

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

For 0 ≤ j ≤ X4, SH2(j)

For x4 < j ≤ 2X4, SH2(j) $= \frac{1}{2}\left(\frac{j}{X4}\right)^{\frac{5}{2}}$

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. Il se It is presented as follows

$$F = X2\left(\frac{R}{X3}\right)^{\frac{7}{2}}$$

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:

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

The level in the reservoir then becomes Δ: R= R – Qr

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.

The utility of this model is to reproduce flood flows [16, 17, 18], as well as flood hazards from rainfall and PET to alert communities [17].

2.3.3. Calculation of potential evapotranspiration (PTE)

The method used to calculate PTE is that of [19] Oudin et al. (2005), previously tested by [20, 21]. 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

$$PE = \frac{R_e T_\alpha + K_2}{\gamma_\rho K_1}$$

$$Si\ ReT\alpha + K2 > 0,\ PE = 0$$

$$\text{If } ReT\alpha + K2 > 0, PE = 0$$

Where PE: daily potential evapotranspiration (mm.d-1); Re: solar radiation (MJ.m-2.d-1) ; Ta: daily mean temperature (°C); γ: latent heat of evaporation of water at 20° (taken equal to 2.45 MJ. Kg-1); r : density of water (kg.m-3). K1 (°C) and K2 (°C) are fixed model parameters because they are adjusted during the sampling of the entire basin and are not specifically calibrated for each watershed [19, 22].

2.3.4. Optimization quality criteria

Hydrological modeling using SWAT and GR4J models allows evaluating water availability by highlighting their performance in reproducing flood flows, low flows, and average flows, based on Nash, R2, and KGE criteria.

The most well-known and widely used model optimization criteria are Nash-Sutcliffe Efficiency (NSE) and Kling-Gupta Efficiency (KGE). The Nash criterion is used for the SWAT model, which is one of the most commonly used statistical indicators by hydrologists. Additionally, the KGE criterion was used for GR4J because the study aims to find the criterion that best corresponds to GR4J in reproducing high-water flows in the Oti watershed. Therefore, this study is based on both Nash and KGE criteria to analyze the performance and robustness of SWAT and GR4J models in simulating flood flows. The Nash and KGE values range from -∞ to 1. The closer they are to 1, the closer the simulated flows are to the observed flows.

Table 1 Presents the performance of SWAT and GR4J models using Nash and KGE criteria in the Oti watershed, Togo

Criteria Nash/KGE	Model performance
0.75 < Nash/KGE ≤ 1	Very Goog
0.65 < Nash/KGE ≤ 0.75	Good
0.50 < Nash/KGE ≤ 0.65	Sufficient
Nash/KGE ≤ 0.50	No Sufficient

Source: [23]

2.3.5. Model calibration and validation

The calibration and validation procedure involves first dividing the time series data into two independent periods of equal size (P1 and P2). Then, the model is calibrated on the first period (P1) and validated on the second (P2). Alternatively, it can be recalibrated on the second period (P2) and validated on the first (P1) depending on the objectives. All chosen periods should be preceded by a one-year warm-up period to allow for the initialization of reservoir contents.

To ensure that the model accurately reproduces flood flows during calibration and validation, four periods were considered in the time series. Initially, the models were calibrated from 2016-2017 and validated from 2018-2019. Subsequently, they were calibrated from 2019-2020 and validated from 2021-2022. The choice of periods for calibration and validation in this study is justified by the fact that these periods have fewer missing data.

2.3.6. Model calibration and sensitivity analysis of SWAT

Calibration is the process of estimating the values of the most significant model parameters by comparing the calculated quantities with observed quantities for a fixed set of parameters. It involves testing the model with known inputs and outputs to adjust the model parameters.

The SWAT model has a large number of parameters with a wide spatial and temporal variation spectrum. Its calibration is complex and computationally intensive. Therefore, it is necessary to eliminate insensitive parameters to simplify the calibration process. This exercise is called sensitivity analysis. Sensitivity analysis provides a final list of parameters ranked in decreasing order of sensitivity. These parameters are used for calibration. Both calibration and sensitivity analysis can be performed manually or automatically using the SUFI-2 algorithm in SWAT-CUP [24, 25].

2.3.7. Validation of SWAT and GR4J models

The evaluation of the calibrated model allows verifying the ability of the estimated model parameters to realistically reproduce the watershed response using performance indicators that are either graphical or statistical. Thus, the model results after calibration are compared with direct observation and measurement results. Graphical indicators mainly involve comparing the hydrographs calculated by the models with observed hydrographs. Among the existing statistical indicators, the Nash and KGE criteria, which are widely used by hydrologists, were chosen for this study.

2.3.8. Determination of flood thresholds

Flood thresholds in the Oti watershed concern discharge rates, and for this research, the Standardized Flow Index (SFI) is used for floods. Thus, from daily discharge rates at multiple time scales, the SFI indices were calculated. The standardized index is based on the equiprobability transformation of discharge values, aggregated over k-months into standard normal values, with k typically fixed according to the analysis objectives, such as k = 1, 3, 6, 9, 12, 24, 36 months [26].

The classical standardized index (denoted Z) was used but with a change in time step to a daily scale. Discharge data are used to calculate these indices using the following formula:

where y is the unit value of the considered parameter, μ and σ denote the mean and standard deviation of the variable, respectively.

The SFI categories (Table 2) allowed classifying the maximum daily flow values in terms of flood hazards for different risk levels (limited, moderate, significant, and critical) in the Oti watershed. This categorization was made possible by transposing the classification of [27] to the daily data used.

Table 2 Classification of SFI values, flood categories, and risk levels

SFI threshold values	Flood category	Risk levels
2.00 and more	Catastrophic	Critical
1.5 to 1.99	Severe	Significant
1 to 1.49	Negligible	Moderate
0 to 0.99	No impact	Limited

Source: Adapted of [28, 27]

3. Results

3.1. Analysis of the results of the calibration and validation of the SWAT and GR4J models

Figure 3 illustrates the variability of observed and simulated flows during calibration (2016–2017 and 2019–2020) and validation (2018–2019 and 2021–2022) with SWAT and GR4J.

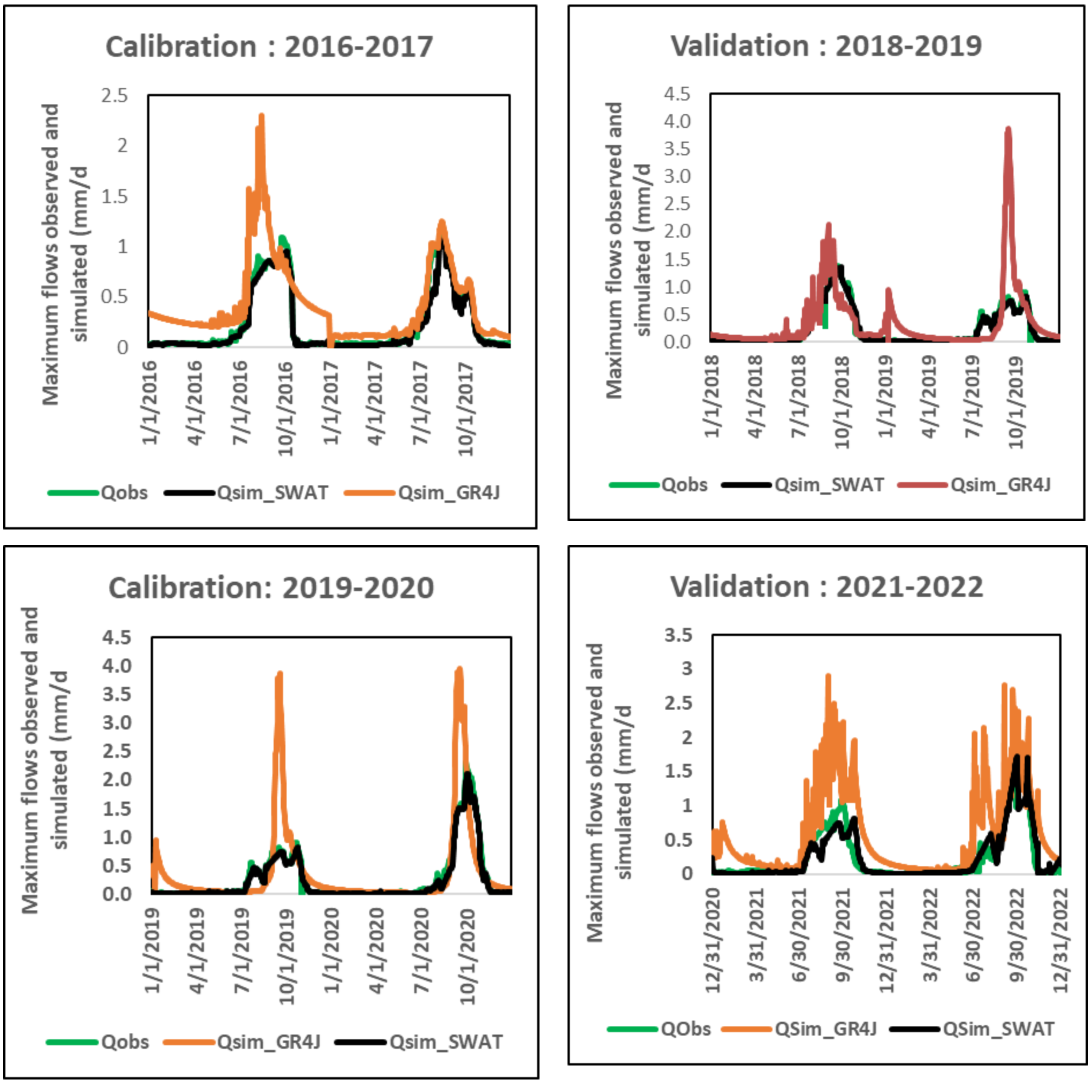


Figure 3 Variability of observed and simulated flows during calibration and validation with SWAT and GR4J

From a hydrological point of view, it is worth noting the flow variability in the Oti watershed in Togo, marked by a succession of low and high water. Surface runoff evolution shows that in some years, daily flow rates are lower than in others, resulting in daily flow variability.

With the model GR4J, the variability of observed and simulated flows in calibration and validation gives very good KGE values (ranging from 0.73 to 0.85 in calibration and 0.62 to 0.81 in validation), demonstrating the GR4J's strong performance in simulating flood flows. The observed flow rates are consistently lower than the simulated flow rates during the calibration and validation phases, which can be explained by their position below the simulated flow rate curve. Simulated flows overestimate observed flows during low water periods and underestimate them during high water periods (August to September).

Similarly, SWAT modeling results showed very good performance in simulating flood flows. Sensitivity analysis revealed the most significant model parameters. The values of these parameters were determined during calibration and validation. The value of the Nash criterion is 0.83 and 0.78 for the calibration phase and 0.72 and 0.81 for the validation phase. The Nash validation results show that the values taken by the criterion fall within the range of satisfactory values retained. The similarity between the simulated flow curve and the observed flows in Figure 3 justifies the model's excellent performance in simulating flood flows in the study area. This means that the simulated flows are close to the observed flows. Analysis of all the results obtained shows that the SWAT hydrological model can be used for flood management in the Oti watershed in Togo.

3.2. Performance assessment of SWAT and GR4J models

Table 3 shows the values of the criteria (Nash and KGE) for optimising the SWAT and GR4J models in the Oti catchment in Togo.

Table 3 Values of optimization and robustness criteria for the SWAT and GR4J model

Period	Nash of SWAT	KGE of GR4J
Calibration: 2016-2017	0.83	0.73
Validation: 2018-2019	0.72	0.81
Calibration: 2019-2020	0.78	0.85
Validation: 2021-2022	0.81	0.62

Analysis of Table 3 shows that the Nash and KGE values for SWAT and GR4J respectively indicate that these two models perform very well in simulating flood flows in the Oti river basin in Togo.

For the SWAT model, the Nash criterion value is 0.83 for the first calibration period and 0.78 for the second period. This reflects the model's very strong performance in simulating flood flows. During validation, the Nash criterion value is 0.72 for the first validation period and 0.81 for the second period. This also shows that the SWAT model is effective and robust in reproducing high water flows in the Oti watershed in Togo.

Analysis of the results for GR4J shows that the KGE criterion raiging from 0.73 to 0.85 at calibration and 0.62 to 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 robustness can be attributed to its simple and parsimonious structure (two reservoirs and only four parameters), which limits overparameterization and minimizes the impact of input data bias. Furthermore, the calibration of conceptual models such as GR4J can deform the parameters to produce good results even with data without bias correction.

From the above, it should be noted that both models (SWAT and GR4J) are effective in simulating flood flows in the Oti River basin in Togo.

3.3. Maximum daily flows observed and simulated in the Oti watershed in Mango

Figure 4 shows the observed and simulated maximum daily flows from hydrological modelling using the SWAT and GR4J models during calibration and validation in the Oti catchment in Togo.

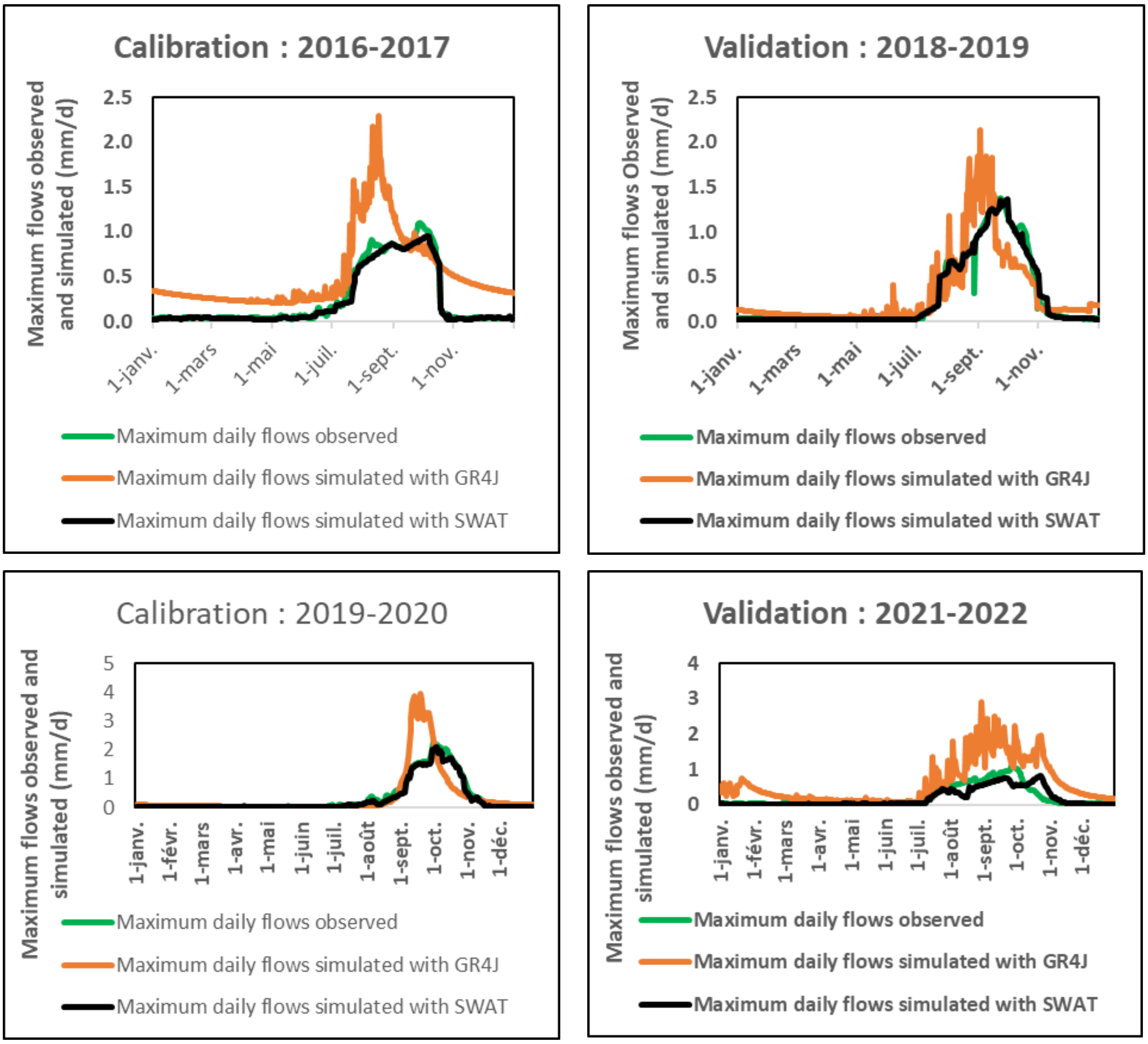


Figure 4 Trends in observed and simulated maximum daily flows with GR4J and SWAT

The results of hydrological modelling with the GR4J conceptual model show that the GR4J reproduces 24-hour flood flows in the Oti watershed in Togo with some variability. For both calibration and validation, the observed flood flows underestimate the maximum daily flows simulated during the low-water period. Underestimations are reflected in negative differences between observed flows and simulated flows during calibration and validation. These differences represent -0.26 for the first calibration period (2016-2017) and -0.04 for the second (2019-2020), -0.026 for the first validation period (2018-2019) and -0.37 for the second validation period (2021-2022).

Similarly, analysis of the hydrological modelling results with SWAT shows the model's ability to reproduce 24-hour high-water flows in the Oti watershed in Togo at the Mango outlet during both the calibration and validation periods. The observed flows slightly overestimate the simulated maximum daily flows, with an average deviation of 0.022 during the first calibration period (2016–2017) and 0.033 for the second calibration period (2019–2020). The same slight overestimations are recorded during the validation periods (2018-2019 and 2021-2022) with respective deviations of 0.007 and 0.039.

Analysis of the evolution of simulated and observed maximum daily flows using the GR4J conceptual model and the SWAT semi-distributed model gives a better reproduction of 24-hour flood flows in the Oti watershed in Togo. Compared with GR4J, the SWAT model better reproduces maximum daily flows because it takes into account several variables such as land use dynamics, slopes, soil types, etc. The underestimates reported by GR4J model during low-water periods were not reported by SWAT model.

3.4. Monitoring and Alerting of Water Level in the Oti River at the Mango Outlet

Table 4 presents the flow thresholds and corresponding flood risk classes. This classification was made possible by the Standardized Flow Indices (SFI) ranging from 0 to +2.

Table 4 Threshold flows for flood risk levels in the Oti watershed

Flood risk threshold flows	Flood risk levels
857.73 m8^3/s	Critical
788 m^3/s	Significant
757.5 m^3/s	Moderate
705 m^3/s	Limited

Analysis of Table 4 reveals that the daily threshold flows are 705 m3/s for limited risk and 757.5 m3/s for moderate risk. They correspond to the 90th and 95th percentiles and have a return period of 10 and 20 years, respectively. These two thresholds are considered acceptable risks in the basin. The flood hazard threshold flows are 788 m3/s for significant risk and 857.73 m3/s for critical risk. These risks represent the 99th percentile and have a return period of more than 50 years, and are considered hydrologically extreme events. These last two thresholds are considered unacceptable risks.

The issuance of alerts enables the mobilization of the riparian population to avoid socio-economic, human, and material damage in the Oti River Basin. This study proposes a four-level alert system corresponding to the hydrometric hazard thresholds defined in the Oti River Basin, as shown in Figure 5.

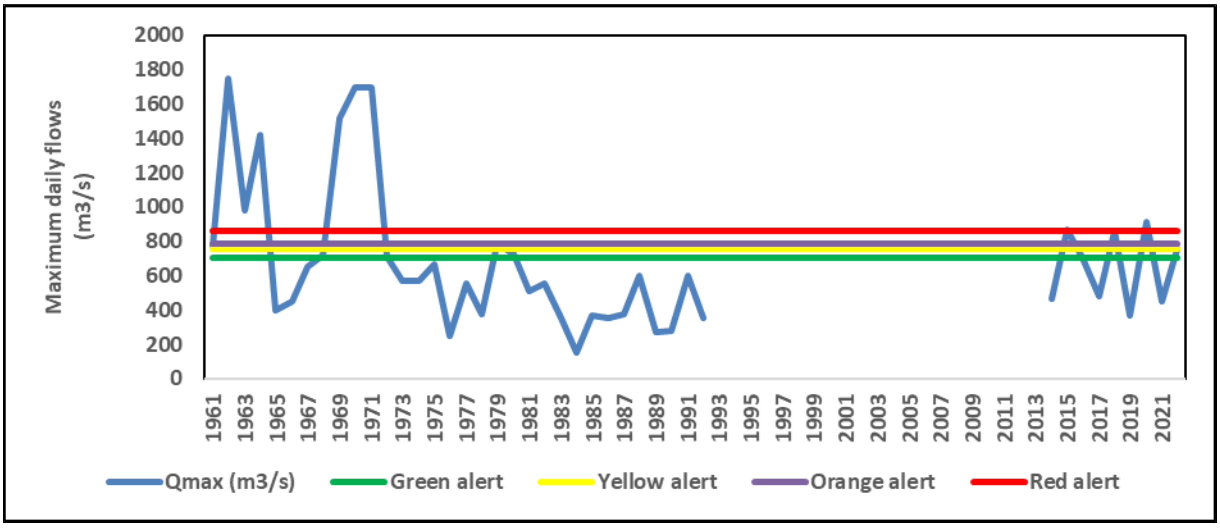


Figure 5 Profile of Maximum Water Level and Flood Risk Alert Thresholds in the Oti River Basin

Analysis of Figure 5 reveals that the proposed early warning system is based on a four-level alert or vigilance system. The first level of alert is the green vigilance, corresponding to a limited risk. The hydrometric threshold at this level is 705 m3/s, indicating that the river is already in flood. At this stage, the alert is not triggered.

The second level of alert concerns yellow vigilance and corresponds to a moderate risk threshold in the Oti River Basin. When the water level in the Oti River reaches 757.5 m3/s, the hydrology service must inform the designated authorities of this situation. These authorities are empowered to take measures to trigger the alert plan and inform prefects, mayors, who in turn share the information with canton, village, and neighborhood leaders, as well as village and neighborhood development committees, to exercise increased vigilance due to the rising waters of the Oti River at Mango.

The significant risk threshold is the third level of vigilance, indicated by orange color, showing the presence of an extreme hydrological event in the basin. The water level at this vigilance level is 788 m3/s. At this water level, the alert is total, and the population in flood-prone areas must begin to evacuate these areas to non-flooded localities. It should be noted that at this stage, the regional analysis cell of the platform must be able to make this information available in real-time to the populations of the Oti River Basin in different local languages and to the relevant services. To this end, the Minister of Security and Civil Protection, under whose authority the ANPC operates, or their representative, may take the initiative to trigger the ORSEC plan in the Oti River Basin.

The risk level becomes critical with red vigilance when exceptional hydrological events are observed in the study area, and the water level of the Oti River is at 857.73 m3/s at Mango. At this level, vigilance becomes absolute, as it constitutes a high risk of disaster.

This research proposes, for the sustainability of this EWS, increased awareness, information, education, and communication work at the community level and among stakeholders for its appropriation.

4. Discussion

This study aims to reproduce flood flows for sustainable flood management in the Oti River basin, Togo. A comparison between the semi-distributed model (SWAT) and the conceptual lumped model (GR4J) was conducted to identify the most robust model for simulating flood flows in the Oti watershed in Togo. The models were fed with different data sources according to their availability and quality and simulated over a 30-year period from 1992 to 2022. This allowed for sensitivity analysis and evaluation of the models' performance using two statistical criteria (Nash and KGE).

The input data for the SWAT model and the discharge data used to evaluate its performance had gaps and missing data. According to [29], the fewer and more unevenly distributed the input data are throughout the year, the poorer the calibration and validation results. However, the statistical analysis of the calibration and validation values yielded performance criteria above 0.65, meeting the performance standards established by [30, 31, 32, 33]. This indicates that both SWAT and GR4J models are effective in reproducing flood flows in the Oti watershed in Togo. These results are similar to those obtained by [34, 35] in the Bandama watershed and [36] for West Africa.

With GR4J, the simulated flows overestimate observed flows during low-water periods and underestimate them during high-water periods (August to September), corroborating the findings of [37, 38, 39, 7]. Both models reproduce daily maximum flows well in the Oti watershed.

Compared to GR4J, a rainfall-runoff model that does not account for landscape heterogeneity, SWAT reproduces daily maximum flows better, as it considers multiple variables such as climate, land use dynamics, slopes, soil types, etc. The underestimations reported by GR4J during low-water periods were not observed with SWAT. However, a decrease in the KGE value during validation was noted for SWAT, confirming the research findings of [3] on the Mono watershed in Togo and Benin.

The daily threshold flows are 705 m3/s for limited risk, 757.5 m3/s for moderate risk, 788 m3/s for significant risk, and 857.73 m3/s for critical risk, similar to the results of [22, 39]. Based on the threshold flows determined in the Oti basin in Togo, the proposed early warning system relies on a four-level alert system, including green, yellow, orange, and red vigilance levels.

5. Conclusion

Hydrological modeling is a real challenge in West Africa, as in many regions of the world, due to limited data access and a high percentage of data gaps. Consequently, the impacts of climate change on water resources and their management, as well as flood forecasting, become difficult. The objective of this study is to reproduce flood flows using the SWAT and GR4J models to analyze the flood risk in the Oti River Basin in Togo. The models were successfully calibrated and validated over two sub-periods using Nash and KGE criteria. The results obtained show that the Nash criterion ranges from 0.78 to 0.83 during calibration and from 0.72 to 0.81 during validation for the SWAT model. The results of the GR4J model show that the KGE criterion ranges from 0.73 to 0.85 during calibration and from 0.62 to 0.81 during validation. These results demonstrate that the SWAT and GR4J models are effective and robust in reproducing flood flows in the Oti River Basin in Togo. Compared to GR4J, the SWAT model better reproduces maximum daily flows. Given the results presented, the SWAT model could serve as a tool to predict floods and manage flooding in the Oti River Basin. This study provides valuable insights to researchers and practitioners working on hydrological modeling in contexts where data are limited. However, its findings are primarily applicable to basins with similar morphological characteristics and climatic conditions.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflicts of interest.

Statement of informed consent

Informed consent was obtained from all individual participants included in the study.

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