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Applicability of the Lumped GR4J Model for Modeling the Hydrology of the Inland Valleys of the Sudanian Zones of Benin

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Abstract

Achieving sustainable agricultural intensification in inland valleys while limiting the adverse environmental impacts and uncertainties related to water availability requires an analysis of the long-term hydrological behavior of the catchment. Such a task is particularly challenging in West Africa and Benin due to the limited availability of climate and hydrological data. This study evaluates the applicability of the lumped GR4J model for simulating streamflow in three inland valleys of the Sudanian zone of Benin (Lower-Sowé, Bahounkpo and Nalohou). Additionally, we test the reliability of satellite-based rainfall data (GPM-IMERG, CHIRPS or GSMAP) in modeling hydrological dynamics in these small catchments. The results demonstrate that the GR4J model is effective in simulating daily discharge in the three inland valleys (KGE > 0.5 during both calibration and validation periods), with particularly interesting performance in mean-flow conditions. The modeling using GPM-IMERG and GSMAP rainfall data shows mitigated results with acceptable performance at Nalohou and less accurate results at Bahounkpo and Lower-Sowé. CHIRPS emerged as the most consistent among the evaluated products, providing a sound basis for reconstructing general trends and seasonal variations in historical streamflow time series. The approach of combining historical CHIRPS data and the GR4J model provides insights and can support decision-making related to water resource management in terms of resource capacity and volume in the study area. Except for Nalohou (KGE = 0.19 with GPM-IMERG data), we observe limitations in predicting high flows with satellite-based climatic data at Bahounkpo (KGE = 0.02 with GPM-IR) and Lower-Sowé (KGE = −0.01 with CHIRPS), where the near-zero KGE scores indicate marginal improvement over a mean-flow benchmark. Future work should explore how hybrid or flexible modeling approaches can improve the accuracy of runoff simulations in inland valleys, particularly for extreme (low- and high-) flow conditions. Additionally, the analysis of the trends of indicators of hydrological alteration (IHA) must be deepened in these important ecosystems, especially under climate and land-use change scenarios.

Keywords: GR4J model; satellite-based rainfall data; discharge occurrence; water management scheme; inland valley

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1. Introduction

In Sub-Saharan Africa, inland valleys are an important asset of local agriculture due to favorable water availability and soil conditions in their bottom valleys [1,2]. Water

resource management is a challenge in these areas, where agricultural productivity and ecological stability are heavily dependent on the adequate management of water [3,4]. The pressures of climate variability, land use change, increasing population, and economic activities further constrain water resources in inland valley ecosystems, making sustainable management more challenging, yet imperative [5,6].

Streamflow dynamics are particularly important in water management schemes in the inland valleys due to their impact on flood and drought risks, agricultural productivity and water supply reliability [3,7]. Understanding streamflow patterns in inland valley ecosystems is essential for appropriate water management in Sub-Saharan Africa. Hydrological modeling emerges as an indispensable tool in this context, providing insights into the behavior of various water flow components and helping in decisions related to their sustainable use [8]. Consequently, numerous studies have employed a range of modeling approaches to simulate streamflow in inland valley hydrological systems [9–18].

Previous streamflow modeling studies of inland valleys are mainly targeted to two objectives: (1) to assess the effectiveness of models to reproduce the system's functioning, and (2) to predict the impact of global changes on water availability and water-related ecosystem services. Concerning the first objective, the analysis of the rainfall–runoff modeling studies in the inland valleys of Benin reveals a mismatch between the model types applied in the literature and the practical needs of operational stakeholders. The models used are mainly distributed models (Table 1), which are often complex and require numerous input parameters at fine temporal and spatial resolutions [19]. Most of the input parameters required by this type of model are not easily available at sites of interest in Benin [20], creating a gap in their operational use as a decision-support tool. Selecting an appropriate modeling approach that captures the essential dynamics of the hydrological system, while considering data availability and computational resources, has always been a major topic of discussion in the hydrologic community [21–25]. In regions with limited data availability, there is a practical need for models that can produce satisfactory simulation results and offer user-friendly platforms for stakeholders [9,26]. In the context of hydrological modeling of inland valleys of Benin, the reliability of lumped hydrological models, which can represent interesting alternatives to deal with limited hydrological information, has been underexplored. The challenges related to the complexity of water flow dynamics in these ecosystems and operational needs for their sustainable management underscore the importance of evaluating the predictive capability of this type of model in inland valleys.

Regarding the objective to predict the impact of global changes on water availability and water-related ecosystem services, inland valleys have received limited attention in comparison to large fluvial catchments in Benin due to the high costs associated with hydrological experimentation and the scarce resources allocated by public services to this sector. The water resource monitoring system in the country is characterized by a lack of continuous monitoring infrastructure for inland valleys. Examining data published in peer-reviewed journals and focusing on runoff at the outlets of basins with an area of less than 200 km^2, thirteen (13) inland valleys have been subject to documented monitoring in the country. Sites studied in the literature, include the inland valleys of Upper Niaou, Upper Aguima, Lower Aguima [9,10,27], Bamé [28], Nalohou, Ara, Kolokondé [11,15,29–34], Bokpérou [35], Tossahou, Kounga, Kpandouga [36,37], Koupendri [38] and Ouriyori [16,39]. There remains an important need for research to understand long-term climate dynamics, how it impacts each component of water flows and what the implications are for flood and drought prediction processes in inland valleys.

In the Sudanian zone of Benin, research is expected to adapt engineering applications in water resources management. The applicability of emergent satellite-based rainfall products in modeling studies appears in this context as an important aspect that needs attention in the field of inland valley hydrology. Similar observations have been made in the literature for numerous

tropical catchments [40]. GPM-IMERG, CHIRPS or GSMAP, which emerge as interesting alternative rainfall data in West Africa [41–45], have not been tested to determine their effectiveness in modeling hydrological dynamics in inland valleys. As a result, there is currently a lack of comprehensive understanding regarding the applicability of these products for supporting hydrological modeling and, finally, decision-making, particularly in the Sudanian zones of Benin.

As part of this study, we explored the possibilities of using the GR4J model [46] for the reconstruction of long-term discharge at the outlet of three inland valleys with the aim of better understanding the occurrence of extreme hydrological events in these catchments. We seek to bridge the gap between theoretical hydrology and practical application by adapting a lumped hydrological model to the needs of water management purposes in the inland valleys of the Sudanian zones of Benin. The outcomes are expected to inform better water resource management practices, support decision-making processes in agricultural management and aid in the development of strategies to mitigate the impacts of climate variability and change on local and regional scales.

Table 1. Overview of models applied to simulate discharge in inland valleys of Sudanian zones of Benin: model type, spatial and temporal resolution.

Model	Model Characterization			Site	References
	Type of Model	Temporal Scale	Spatial Scale		
SIMULAT-H	Distributed	1 day	30 m	Aguima: Upper Niaou, Upper Aguima, Lower Aguima	[9,10,29,47,48]
SWAT	Distributed	1 day	30 m	Ouriyori	[16]
	Distributed	1 day	30 m	Kounga, Tossahou, Kpandouga	[36]
WaSiM	Distributed	1 day	30 m	Ouriyori	[16]
ParFlow-CLM	Distributed	30 min	5 m	Nalohou	[15]
TOPLATS	Distributed	1 day	30 m	Aguima, Upper Aguima, Lower Aguima	[9]
UHP	Lumped	1 day	-	Aguima, Upper Aguima, Lower Aguima	[9,31]
REW-v4.0 model	Distributed	1 day	30 m	Ara, Bokpérou, Kolokondé	[11]

2. Methodology

2.1. Study Sites

The experimental sites used in this study are the inland valleys of Lower-Sowé, Bahounkpo and Nalohou. According to the Köppen classification [49], the climate of the 3 study sites is tropical savanna. Vegetation cover is composed of a mosaic of woody savannah, forest and grasslands with scattered trees. The inland valley of Lower-Sowé (15.22 km^2) belongs to the Sowé watershed (49 km^2) and is located West of the city of Glazoué in the center of Benin. The Bahounkpo inland valley (5.38 km^2) is located approximately 10 km from N'dali in the North East of Benin. The Nalohou inland valley (0.16 km^2) is located near the town of Djougou in the North West of Benin.

The inland valleys of Lower-Sowé and Bahounkpo are monitored as part of the technical and scientific support project for the valorization and sustainable integrated management of water resources in the inland valleys in Benin, the BAFONBE project. The Nalohou inland valley, which has been the focus of previous studies [15,32], is monitored in the framework of the AMMA-CATCH program [33]. Figure 1 provides an overview of Beninese inland valley sites that have been documented on the subject of outlet runoff and displays site locations in this study.

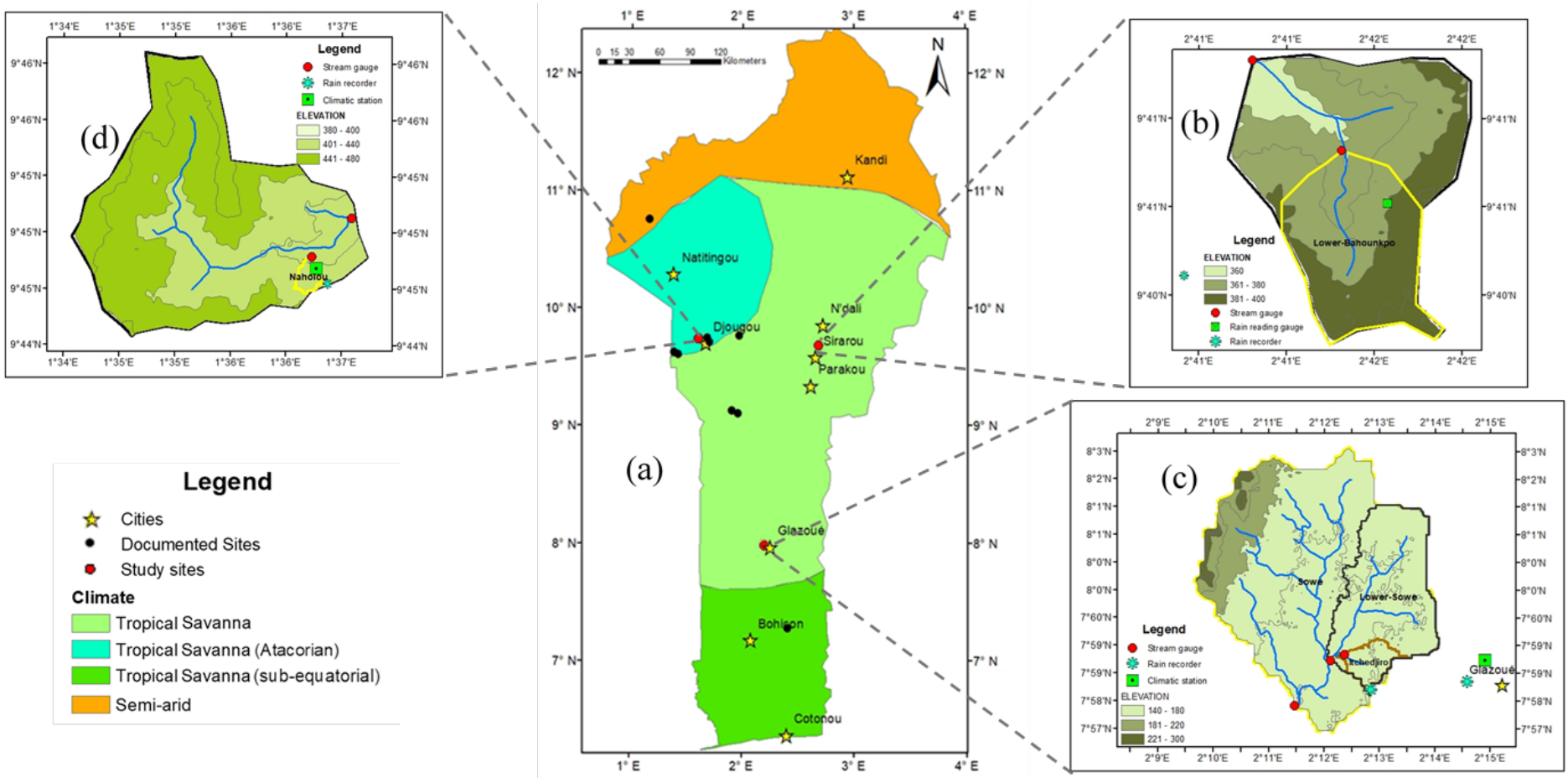

Figure 1. Documented hydrological monitoring of inland valleys in Benin (**a**) and study sites: Bahounkpo (**b**), Itchedjiro—Lower-Sowé (**c**), and Nalohou—Ara (**d**). The climatic zone categorization in this study is based on information from the World Bank Climate Knowledge Portal for Benin (https://climateknowledgeportal.worldbank.org/country/benin (accessed on 31 July 2025)). Additionally, the classification of tropical savanna climate types follows [50] for the Atacorian type and [51] for the sub-equatorial type.

2.2. GR4J Model Overview and Input Data Used

GR4J is a four-parameter, daily lumped rainfall–runoff model. It was chosen here due to its performance across numerous studies as well as its parsimony and concise model structure [24,46,52–55]. The GR4J model adopts two nonlinear reservoirs for rainfall–runoff modeling, of which the first reservoir represents the production process, and the second reservoir is employed to conceptualize the confluent process. Figure 2 provides a schematic diagram of the GR4J catchment conceptualization and model process.

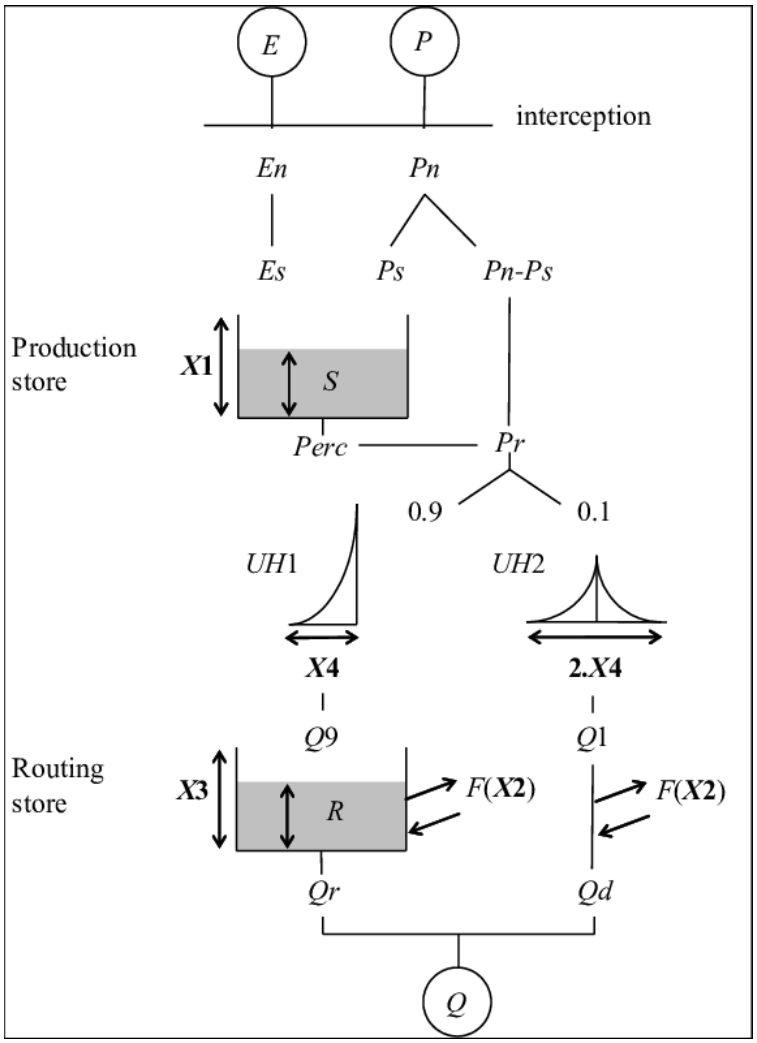

Figure 2. Structural diagram of the GR4J model [46]. Terms mean the following: P: precipitation input (mm/day), E: evapotranspiration (mm/day), S: water in the production (soil) store (mm/day), X1: maximum capacity of the production store (mm), Pn: net rainfall reaching soil (mm/day), En: net evapotranspiration demand applied to the store (mm/day), Ps: infiltrated part of Pn into the store (mm/day), Es: actual evaporation from the store (mm/day), Perc: percolation from production to routing (mm/day), Pr: effective rainfall to routing (mm/day), UH1, UH2: unit hydrographs distributing Pr in time (1/day), X4: time base of UH1 (day); R: water in the routing store (mm), X3: maximum capacity of the routing store (mm), F(X2) denotes the groundwater exchange flux computed from the parameter X2 (groundwater exchange coefficient, mm/day), Qr: routed flow from the routing store (mm/day), Qd: direct flow from UH2 branch (mm/day), and Q: total discharge at outlet (mm/day).

Input data used include rain and reference evapotranspiration for the study period of each site, corresponding, respectively, to the periods 2021–2022 for Lower-Sowé, 2021–2023 for Bahounkpo and 2015–2019 for Nalohou. Data for the Lower-Sowé and Bahounkpo

inland valleys originate from experimental monitoring carried out as part of the BAFONBE project. Data for Nalohou originates from the AMMA CATCH database.

GPM-IMERG, CHIRPS and GSMAP data were chosen for evaluation based on previous analyses demonstrating their local accuracy when compared to in situ rainfall used as a reference. Reference evapotranspiration was estimated using the Hargreaves method with ERA5 temperature data, which also provides reliable estimates in the study region [56].

2.3. Data Analysis

The objectives of this study were twofold. Firstly, we evaluated the performance of the GR4J model in simulating rainfall–runoff processes in the study sites. Secondly, the research interest has been extended to include the reconstruction of hydroclimatic conditions to provide a historical context for trend and extreme hydrological signature analysis. Runoff simulations were performed using the GR4J parameterization from the HydroGR package for hydrological modeling, which is inspired by the Irstea R language package airGR [52].

2.3.1. Performance of the GR4J Model

The first specific objective of this study involves calibration and validation of the model with different sets of rainfall data (in situ measured, GPM-IMERG, CHIRPS and GSMAP). We evaluated the performance of the GR4J model in simulating rainfall–runoff processes in the study sites using in situ measured data (Approach 0). Additionally, the study evaluates the applicability of satellite-derived precipitation datasets for streamflow modeling. Two methodological approaches were used to assess the effectiveness of satellite-derived precipitation data in streamflow modeling: (1) calibration and validation of the GR4J hydrological model using each satellite precipitation dataset independently, and (2) calibration of the GR4J hydrological model using in situ precipitation data followed by validation using each of the satellite precipitation datasets. The employment of these two distinct methodological approaches is designed to provide a robust and comprehensive assessment of the strengths and limitations of using satellite precipitation data in hydrological modeling under different scenarios of data availability and model parameterization. Calibrating and validating the model with each satellite precipitation product (Approach 1) allows for a direct assessment of the standalone capability of these products to drive hydrological simulations, particularly relevant in data-scarce regions where in situ hydro-climatic data for calibration may be limited or unavailable. This approach helps to identify the inherent biases and uncertainties associated with using satellite precipitation as the primary input for hydrological models. It allows for exploring the dependence of the results on reference data. Conversely, calibrating the model with in situ precipitation data and then validating with each satellite precipitation product (Approach 2) assesses the ability of these satellite products to accurately simulate streamflow when the model parameters have been optimized using potentially more reliable ground observations [57]. This approach explores whether satellite data can effectively capture the precipitation patterns needed for reliable streamflow simulation when the model's internal processes are reasonably well represented. The split-sample validation technique was used to split each discharge time series into two equal periods to ensure robust calibration and reliable evaluation of the hydrological model. Table 2 presents data used in the calibration and validation step according to each approach.

Table 2. Data used in the calibration and validation step according to the explored approach.

Approach	Step	Watershed	Period	Rainfall	Evapotranspiration	Streamflow
Approach 0: Calibration and Validation with in situ data	Calibration	Lower-Sowé	January 2021–December 2021	Measured (BAFONBE)	Hargreaves (ERA5)	Measured (BAFONBE)
		Bahounkpo	January 2021–July 2022	Measured (BAFONBE)	Hargreaves (ERA5)	Measured (BAFONBE)
		Nalohou	January 2015–July 2017	Measured (AMMA-CATCH)	Hargreaves (ERA5)	Measured (AMMA-CATCH)
	Validation	Lower-Sowé	January 2022–December 2022	Measured (BAFONBE)	Hargreaves (ERA5)	Measured (BAFONBE)
		Bahounkpo	July 2022–December 2023	Measured (BAFONBE)	Hargreaves (ERA5)	Measured (BAFONBE)
		Nalohou	July 2017–December 2019	Measured (AMMA-CATCH)	Hargreaves (ERA5)	Measured (AMMA-CATCH)
Approach 1: Calibration with Satellite Data	Calibration	Lower-Sowé	January 2021–December 2021	Selected satellite data (GPM-IMERG, GSMAP, CHIRPS)	Hargreaves (ERA5)	Measured (BAFONBE)
		Bahounkpo	January 2021–July 2022	Selected satellite data (GPM-IMERG, GSMAP, CHIRPS)	Hargreaves (ERA5)	Measured (BAFONBE)
		Nalohou	January 2015–July 2017	Selected satellite data (GPM-IMERG, GSMAP, CHIRPS)	Hargreaves (ERA5)	Measured (AMMA-CATCH)
	Validation	Lower-Sowé	January 2022–December 2022	Selected satellite data (GPM-IMERG, GSMAP, CHIRPS)	Hargreaves (ERA5)	Measured (BAFONBE)
		Bahounkpo	July 2022–December 2023	Selected satellite data (GPM-IMERG, GSMAP, CHIRPS)	Hargreaves (ERA5)	Measured (BAFONBE)
		Nalohou	July 2017–December 2019	Selected satellite data (GPM-IMERG, GSMAP, CHIRPS)	Hargreaves (ERA5)	Measured (AMMA-CATCH)
Approach 2: Calibration with in situ Data	Calibration	Lower-Sowé	January 2021–December 2021	Measured (BAFONBE)	Hargreaves (ERA5)	Measured (BAFONBE)
		Bahounkpo	January 2021–July 2022	Measured (BAFONBE)	Hargreaves (ERA5)	Measured (BAFONBE)
		Nalohou	January 2015–July 2017	Measured (AMMA-CATCH)	Hargreaves (ERA5)	Measured (AMMA-CATCH)
	Validation	Lower-Sowé	January 2022–December 2022	Selected satellite data (GPM-IMERG, GSMAP, CHIRPS)	Hargreaves (ERA5)	Measured (BAFONBE)
		Bahounkpo	July 2022–December 2023	Selected satellite data (GPM-IMERG, GSMAP, CHIRPS)	Hargreaves (ERA5)	Measured (BAFONBE)
		Nalohou	July 2017–December 2019	Selected satellite data (GPM-IMERG, GSMAP, CHIRPS)	Hargreaves (ERA5)	Measured (AMMA-CATCH)

The best parameter set obtained from each inland valley (according to the explored approaches) was applied to analyze the capacity of the model to simulate streamflow outside the calibration period, thereby demonstrating its validity. The model performance was evaluated on different goodness-of-fit indicators, including visual and comparative time series metrics-based analysis. We also incorporated the analysis of hydrological signature indicators, specifically considering high flows (Q10), low flows (Q90), and the runoff coefficient. The Q10 and Q90 have been computed only for discharge values above 0.1 mm to avoid biasing the detection of high and low flows, since intermittent rivers frequently have zero flow values. A similar approach has been applied by [58]. The corresponding subsets of the hydrograph (all values $\geq$ Q10 and all values $\leq$ Q90) were retained for analysis. The metrics used include the coefficient of correlation of Pearson, the Root Mean Square Error (RMSE), the Nash–Sutcliffe Efficiency (NSE) and the Kling–Gupta Efficiency (KGE). The Pearson correlation coefficient indicates the linear relationship between observed and simulated discharge values. The RMSE quantifies the average magnitude of errors, emphasizing larger errors and providing insight into the model's accuracy. The NSE assesses model predictive power by comparing the observed variance against the variance of the residuals. The KGE assesses both the correlation, bias and variability between observed and simulated data, offering a comprehensive assessment of model performance. KGE was used as the main evaluation criterion due to its balanced consideration of various aspects of model performance, making it more robust for hydrological applications. Other metrics were used to gain a deeper understanding of specific discrepancies between observed and simulated discharge, helping to identify potential areas for model improvement. For results interpretation purposes, we adopted a threshold of model performance in the range $-0.41 < \mathrm{KGE} \leq 1$ as reasonable, following [59], -0.41 being the KGE value corresponding to a mean-flow benchmark. We considered that a KGE value greater than or equal to 0.75 indicates a very good similarity between the 2-time series, and values between 0.75 and 0.5 represent satisfactory similarity as commonly used in hydrology [60]. Sensitivity analysis of the parameters of the model was performed using the variance-based sensitivity analysis of Sobol [61], whose usefulness was demonstrated in numerous studies [62,63].

2.3.2. Long-Term Climatic and Hydrological Analysis

For the second specific objective, the model that demonstrated the highest performance for each inland valley was applied to simulate historical runoff time series. Subsequently, climatic and hydrological trend analyses were conducted, along with an assessment of hydrological extremes.

Climatic and Hydrological Trend Analysis

Climatic and hydrological signatures were analyzed using the Mann–Kendall and Pettit test on multi-annual daily time series of rain, reference evapotranspiration, aridity index, total runoff, high flow and runoff coefficient. These characteristics are particularly interesting either because they can be used for decision-making in terms of water management or because they provide practical information about the state of alteration of hydrological regimes. In addition, to explore the interannual relationship between rainfall and discharge, daily rainfall and discharge data were aggregated to obtain annual totals. The year-to-year variability was assessed by calculating the percentage change in annual rainfall and discharge using the following formula:

$$Change\ (\%) = \frac{(X_i - X_{i-1}) * 100}{X_{i-1}} \quad (1)$$

where X_i and X_{i-1} represent the annual total values of rainfall or discharge for years i and $i - 1$, respectively. The computed changes were then used to assess the sensitivity of discharge to variations in rainfall on an annual scale.

Hydrological Extreme Analysis

Extreme value analysis was performed on reconstructed historical daily discharge data by fitting the Generalized Extreme Value (GEV) distribution to the high-flow events and by generating return value plots. High-flow event identification was based on the above-threshold method. This method offers the advantage of using a rational selection of events. It results in a high number of observations and a more homogeneous sample [64]. The 99-th percentile of the daily discharge time series was used as the threshold to identify extreme high-flow events in this study. A 95% confidence interval was applied to the estimates, providing a robust statistical framework for predicting the likelihood and magnitude of extreme flow events over various return periods.

3. Results

3.1. Model Performance Assessment

3.1.1. Model Performance with Measured Rainfall

The model performed well in simulating discharge in the three inland valleys. Visual comparisons clearly illustrate a good fit between observed and simulated discharge (Figures 3–5). The performance of the model in simulating discharge is supported by the statistical metrics, which indicate an overall satisfactory accuracy (KGE > 0.57). We observed consistent accuracy in the validation phase, suggesting that the model is robust. The agreement between observed and simulated discharge highlights the model's effectiveness in capturing the study area's hydrological processes.

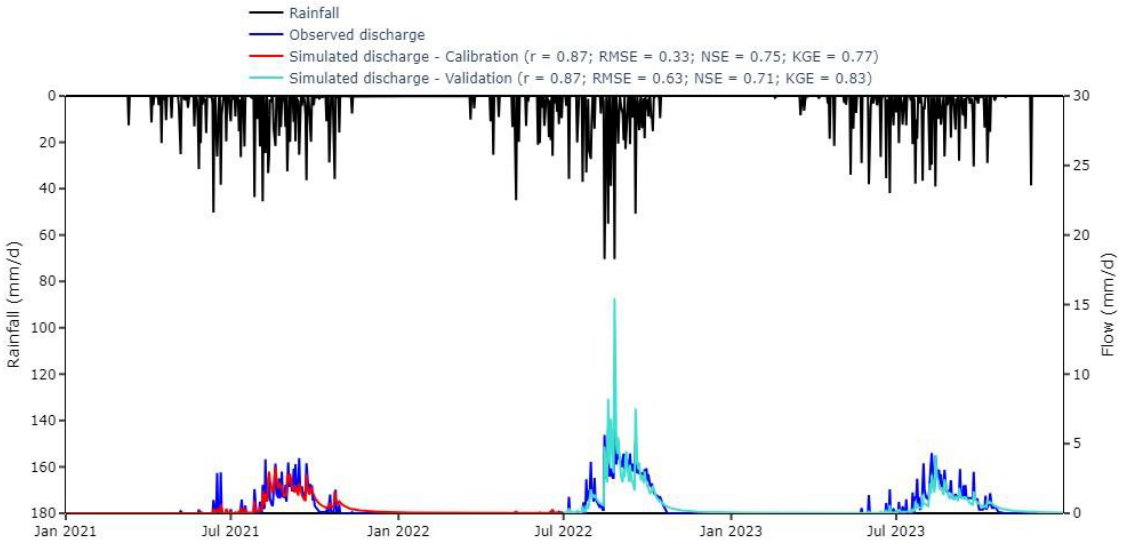

Figure 3. Results of discharge simulation with in situ rainfall data at Bahounkpo.

Despite overall satisfying simulation results, the comparative analysis of observed and simulated hydrological signatures shows some weaknesses. While the model performs acceptably in high flow and runoff coefficient simulations, there are consistent challenges in accurately capturing low and peak flow conditions across all sites (Figures 6–8). Specific simulation biases are observed at the beginning of the rainy season and in reproducing flood peaks during high-flow events.

The sensitivity analysis performed during simulations with in situ rainfall data indicates that parameter X2 (Groundwater exchange coefficient) is consistently critical across all

catchments, while parameters X3 and X4 exhibit varying degrees of sensitivity depending on the catchment (Figure 9). These parameters provide insights into the hydrological behavior of the basin, highlighting that surface–groundwater exchange and catchment response time are crucial areas where refinement may be needed to enhance model performance.

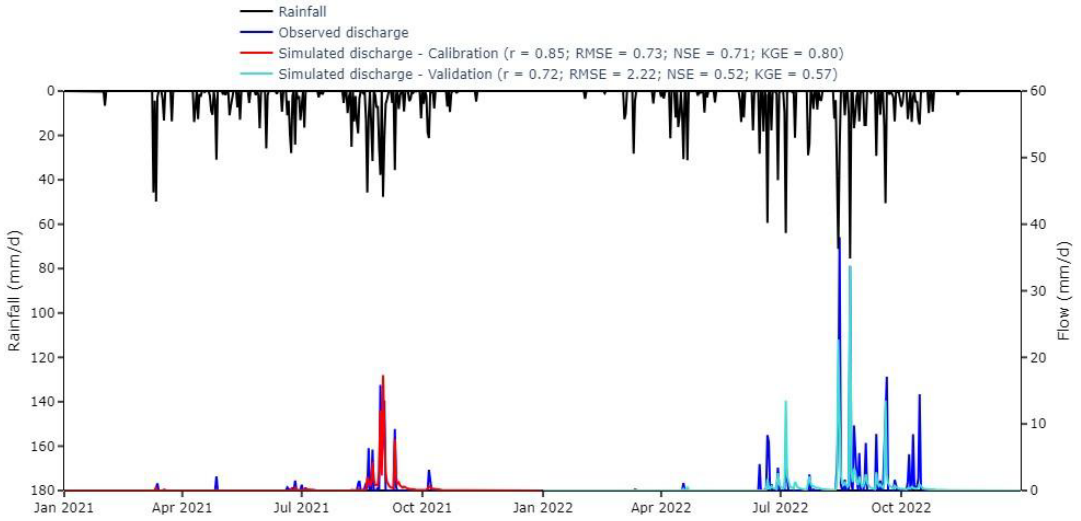

Figure 4. Results of discharge simulation with in situ rainfall data at Lower-Sowé.

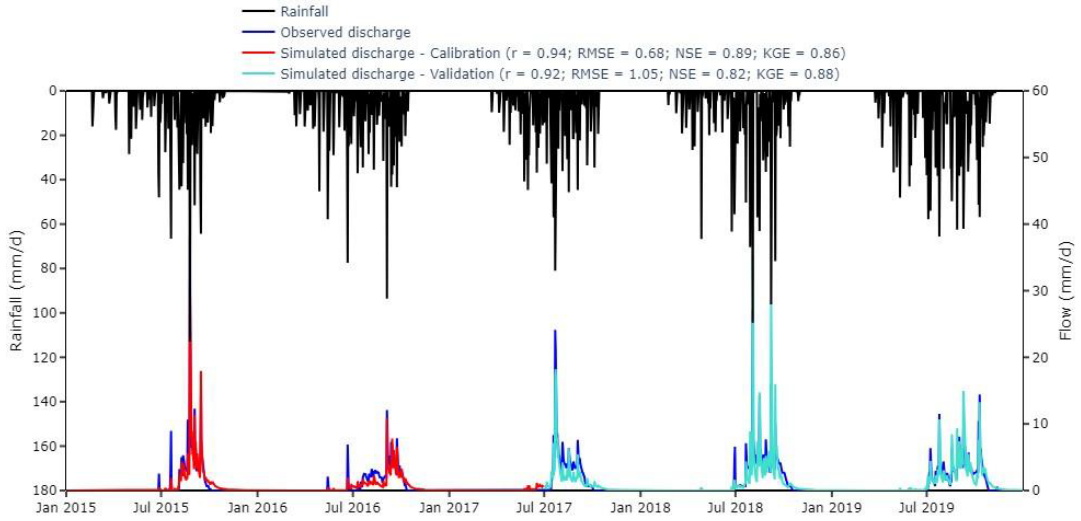

Figure 5. Results of discharge simulation with in situ rainfall data at Nalohou.

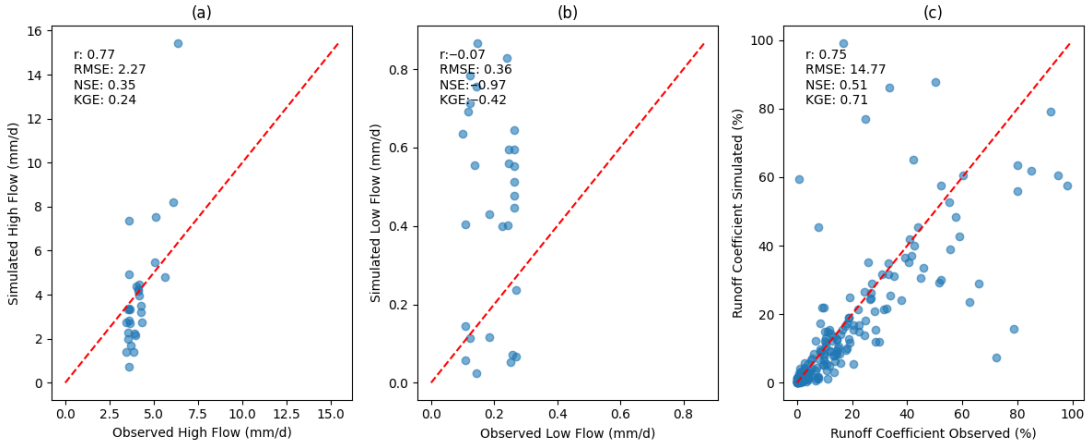

Figure 6. Observed and simulated hydrological signatures with in situ rainfall data in the inland valley of Bahounkpo: (**a**) high flows, (**b**) low flows, and (**c**) runoff coefficient.

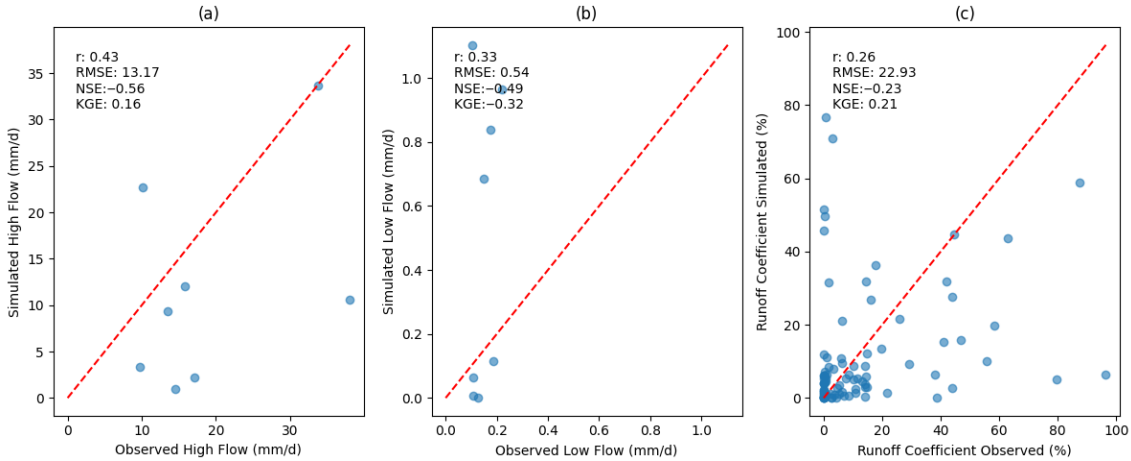

Figure 7. Observed and simulated hydrological signatures with in situ rainfall data in the inland valley of Lower-Sowé: (**a**) high flows, (**b**) low flows, (**c**) runoff coefficient.

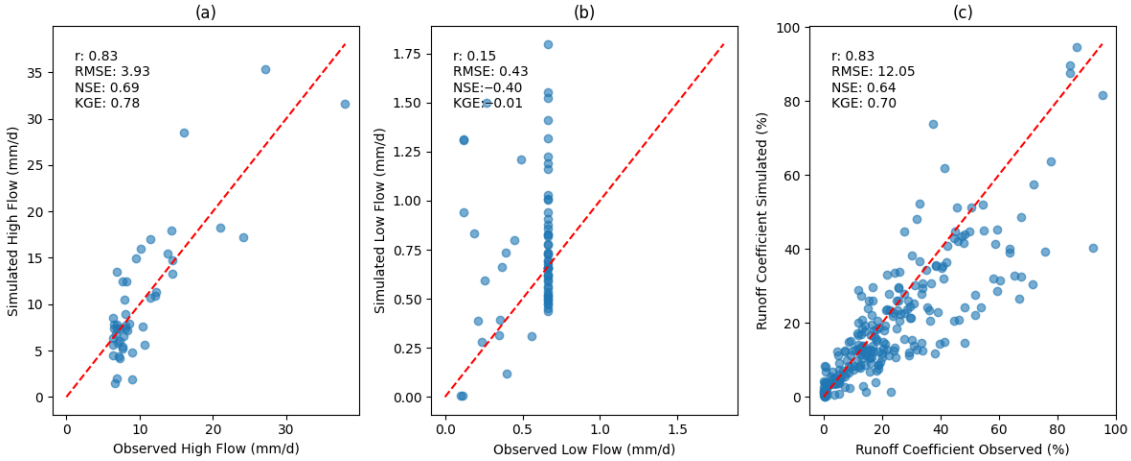

Figure 8. Observed and simulated hydrological signatures with in situ rainfall data in the inland valley of Nalohou: (**a**) high flows, (**b**) low flows, (**c**) runoff coefficient.

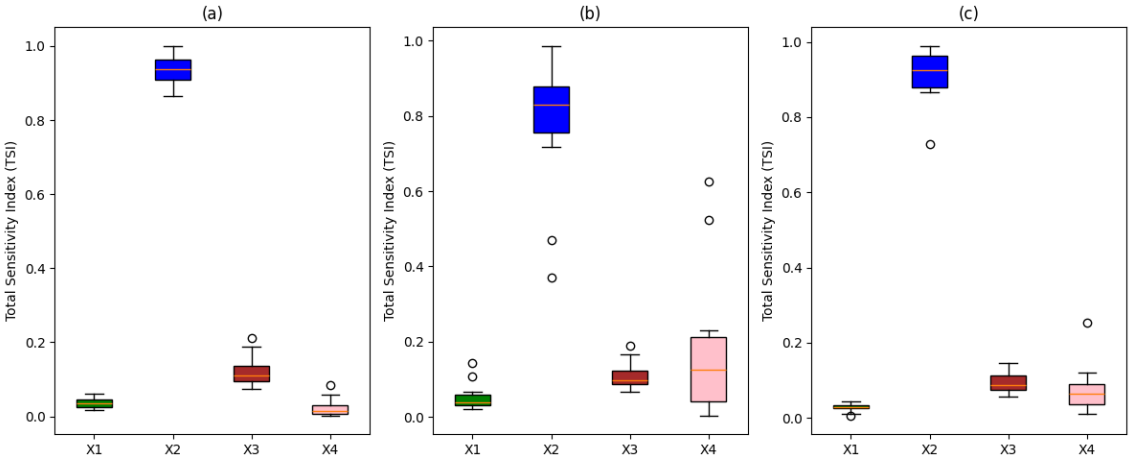

Figure 9. Sensitivity analysis of the parameters of the model in the study sites (**a**) Bahounkpo, (**b**) Lower-Sowé, and (**c**) Nalohou.

3.1.2. Model Performance with Satellite-Based Rainfall Data

Table 3 summarizes the results of the model performance using satellite-based rainfall data at calibration and validation across the three catchments. The modeling using GPM-IMERG rainfall data shows mixed results, with acceptable performance at Nalohou and

Bahounkpo (KGE > 0.44) and less accurate results at Lower-Sowé. GSMAP yields poor performance at Bahounkpo and Lower-Sowé but provides acceptable results at Nalohou. During the validation period, the decreased performance in terms of KGE is particularly marked for GSMAP at Bahounkpo and Lower-Sowé. Among the evaluated products, CHIRPS emerges as the most consistent, providing a good capture of general trends and seasonal variations in discharge prediction (KGE > 0.47). It is interesting to note the acceptable estimation of hydrological signatures like runoff coefficient and median flows observed with CHIRPS data, making the modeling approach with this satellite rainfall data useful for operational water management and planning in data-scarce inland valleys of the region. Except for Nalohou (KGE = 0.19 with GPM-IMERG data), we observe limitations in predicting high flows when using the satellite-based rainfall approach for both calibration and validation.

Table 3. Results of daily streamflow simulations at three sites using satellite-based rainfall data at calibration and validation.

		Calibration				Validation			
		r	**RMSE (mm/d)**	**NSE**	**KGE**	**r**	**RMSE (mm/d)**	**NSE**	**KGE**
GPM-IMERG	Bahounkpo	0.55	0.69	0.07	0.54	0.47	1.41	−0.24	0.44
	Lower-Sowé	0.66	1.27	0.15	0.53	0.35	3.09	0.07	0.04
	Nalohou	0.66	1.55	0.41	0.62	0.72	1.77	0.50	0.58
CHIRPS	Bahounkpo	0.67	0.59	0.31	0.66	0.64	0.99	0.39	0.47
	Lower-Sowé	0.64	1.14	0.32	0.58	0.59	2.70	0.29	0.50
	Nalohou	0.71	1.43	0.50	0.58	0.71	1.79	0.49	0.66
GSMAP	Bahounkpo	0.52	0.82	−0.32	0.35	0.52	1.20	0.11	−0.07
	Lower-Sowé	0.55	1.21	0.22	0.51	0.37	3.15	0.03	−0.38
	Nalohou	0.40	2.04	−0.01	0.38	0.69	1.86	0.46	0.49

Calibration with in situ rainfall data performs better than with satellite data. During validation of the hybrid approach (rainfall data at calibration, combined with satellite rainfall for validation), model performance varied depending on the site and the satellite product used (Table 4). Validation metrics indicated less satisfactory performance at the Nalohou inland valley across all simulation runs, particularly concerning the reproduction of temporal flow dynamics. Conversely, at the Bahounkpo and Lower-Sowé inland valleys, an inverse pattern was observed, with interesting model performance achieved when in situ rainfall data were used for calibration and satellite-based rainfall data for validation. Regardless of the calibration data source, the CHIRPS product consistently demonstrated the highest performance in simulating temporal flow dynamics within the studied inland valley systems. Furthermore, CHIRPS provided the most interesting estimations of high flow events at the Lower-Sowé station, while GPM-IMERG exhibited the best performance for this specific variable at the Bahounkpo and Nalohou sites. While it is above the 0.41 threshold, the near-zero KGE scores recorded for the performing high-flow simulations at Bahounkpo and Lower-Sowé (based on satellite-derived rainfall) indicate marginal improvement over a mean-flow benchmark, necessitating cautious interpretation. Despite limitations related to the prediction of high flows, the approach of combining historical CHIRPS data and the GR4J model provides insights and can support decision-making related to water resource management in the study area, particularly in estimating mean water balance, resource capacity and volume.

Table 4. Results of daily streamflow simulations at three sites using in situ rainfall data at calibration and satellite-based rainfall data at validation.

		Calibration				Validation			
		r	RMSE (mm/d)	NSE	KGE	r	RMSE (mm/d)	NSE	KGE
GPM-IMERG	Bahounkpo	0.87	0.33	0.75	0.77	0.61	1.85	−1.51	−0.20
	Lower-Sowé	0.85	0.73	0.71	0.80	0.25	3.77	−0.39	0.2
	Nalohou	0.94	0.68	0.89	0.86	0.69	2.07	0.32	0.14
CHIRPS	Bahounkpo	0.87	0.33	0.75	0.77	0.77	0.75	0.59	0.74
	Lower-Sowé	0.85	0.73	0.71	0.80	0.6	2.57	0.36	0.42
	Nalohou	0.94	0.68	0.89	0.86	0.68	2.09	0.31	0.12
GSMAP	Bahounkpo	0.87	0.33	0.75	0.77	0.68	0.94	0.36	0.25
	Lower-Sowé	0.85	0.73	0.71	0.80	0.28	3.11	0.05	−0.28
	Nalohou	0.94	0.68	0.89	0.86	0.73	2.32	0.15	−0.08

3.2. Long-Term Discharge Occurrence Analysis

Following the results obtained in high flow simulation with satellite rainfall data (approaches 1 and 2), long-term climatic and hydrological analysis was performed with the following:

- CHIRPS data historical simulation (1981–2023) following approach 1 at Lower-Sowé;
- GPM-IMERG data historical simulation (2000–2023) following approach 2 at Bahounkpo;
- GPM-IMERG data historical simulation (2000–2023) following approach 1 at Nalohou.

The combination of GR4J and each rainfall satellite data for high-flow simulation on the studied sites enables an analysis of parameters important for defining sustainable water management schemes, such as discharge occurrence thresholds and trends. The trend analysis was made on annual aggregated data. Lower-Sowé and Nalohou are experiencing a scenario of increased annual rainfall and reference evapotranspiration for the analyzed period. Analysis of the long-term variability of hydrological signatures revealed a distinct increase in runoff in all three sites, probably as a consequence of more water availability, resulting from the balance between rainfall and evapotranspiration (Figures 10–12). Seasonal and inter-annual variations in discharge are linked to rainfall patterns. We observe a slight increase in high discharge events, which follow high rainfall events, suggesting a risk of flooding and the need for enhanced, accurate management strategies. Pettit's tests show a change point in reference evapotranspiration trends at Lower-Sowé, but no break is depicted in rainfall and discharge trends.

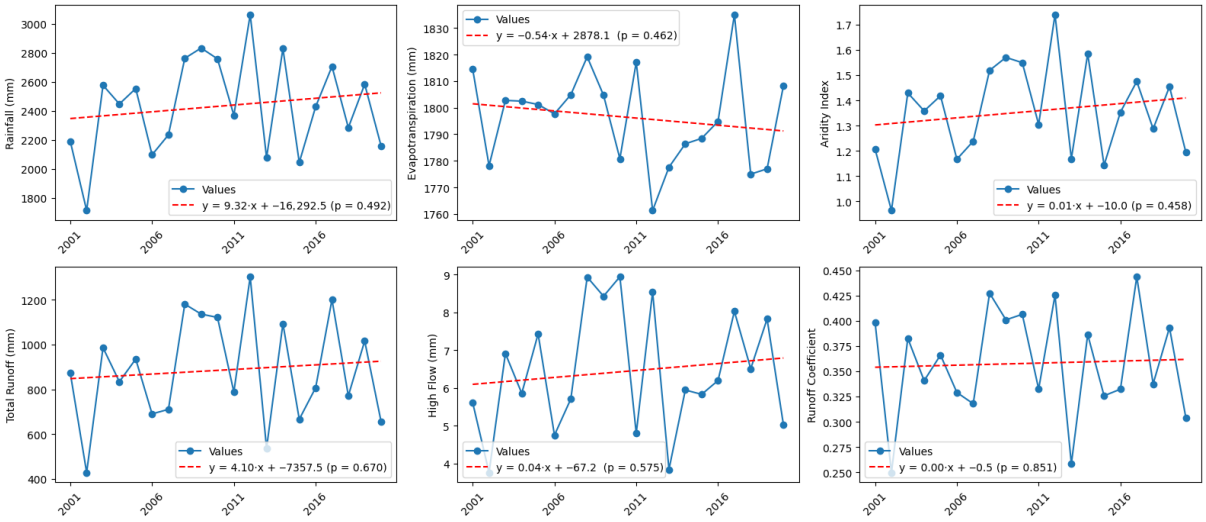

Figure 10. Trend analysis of historical climatic (rainfall, reference evapotranspiration, and aridity index) and hydrological parameters (total runoff, high flow, and runoff coefficients) in the Bahounkpo inland valley. Blue markers represent annual estimated values, and red dashed lines indicate linear regression trends.

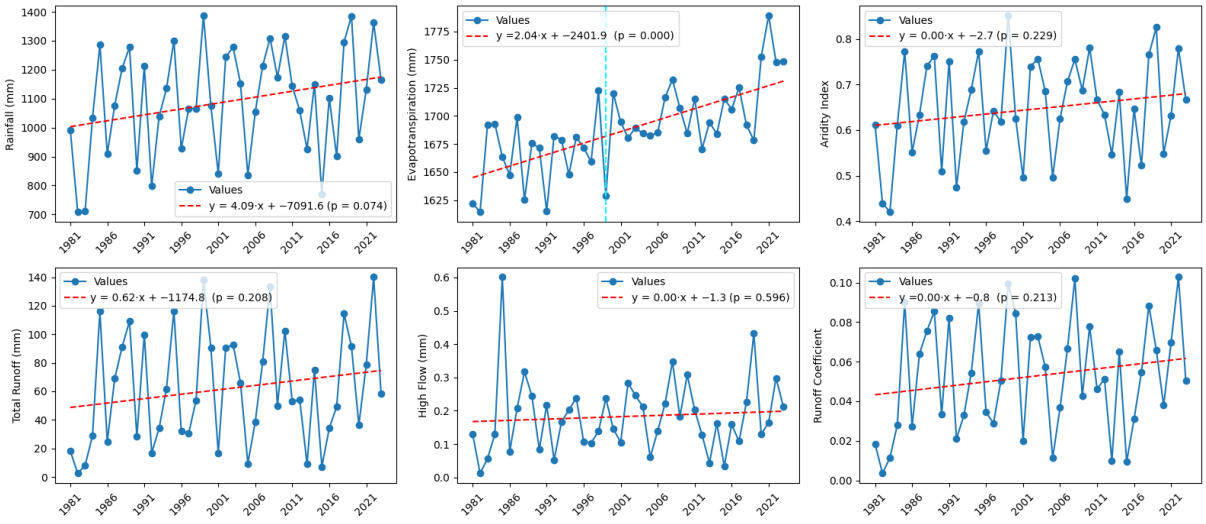

Figure 11. Trend analysis of historical climatic (rainfall, reference evapotranspiration, aridity index) and hydrological parameters (total runoff, high flow, runoff coefficients) in the Lower-Sowé inland valley. Blue markers represent annual estimated values, and red dashed lines indicate linear regression trends.

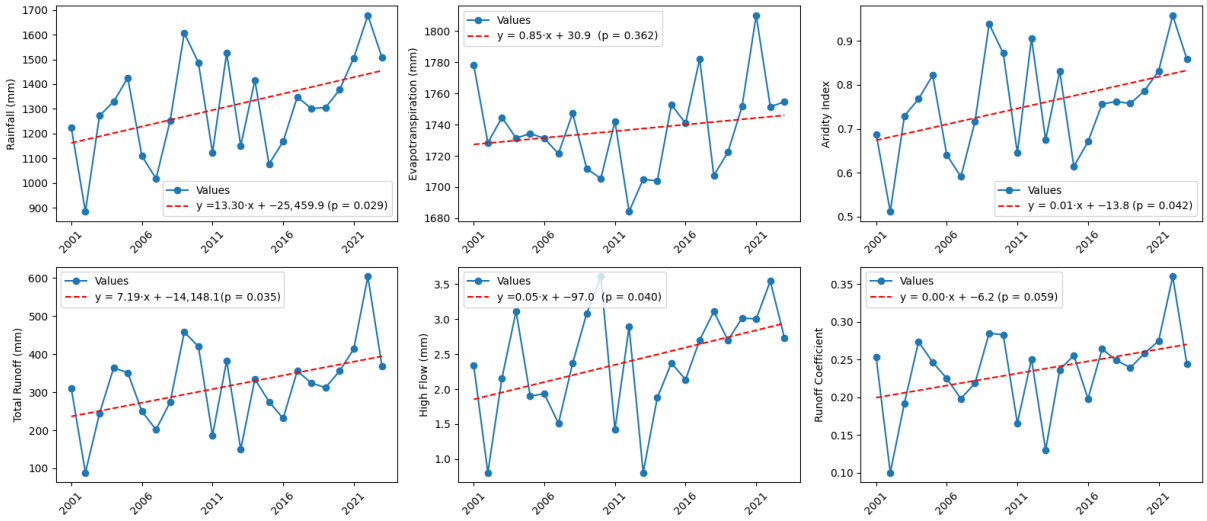

Figure 12. Trend analysis of historical climatic (rainfall, reference evapotranspiration, and aridity index) and hydrological parameters (total runoff, high flow, and runoff coefficients) in the Nalohou inland valley. Blue markers represent annual estimated values, and red dashed lines indicate linear regression trends.

3.3. Analysis of Extreme Discharge

Figures 13a, 14a and 15a quantify the probability and uncertainty of extreme discharge events, while Figures 13b, 14b and 15b explores the meteorological drivers behind these events. The fitted probability distribution closely follows the observed values, indicating a reliable representation of extreme flow behavior, while the widening confidence interval at higher return periods reflects increased uncertainty in estimating rare, high-magnitude discharge events. This suggests the need for cautious extrapolation when predicting extreme hydrological conditions for the studied inland valley, as variability increases with less frequent occurrences. A positive correlation between changes in precipitation and corresponding changes in streamflow is observed. The scatter points in Figures 13b, 14b and 15b suggest that although rainfall is a dominant driver of discharge variations, additional factors (such as land cover, soil conditions and antecedent moisture) likely modulate the hydrological response. The presence of outliers at high discharge changes illustrates the influence of nonlinear or threshold-driven processes on

the runoff events. The findings emphasize the need for integrated hydrological assessments that account for both statistical and process-based uncertainties in extreme discharge predictions.

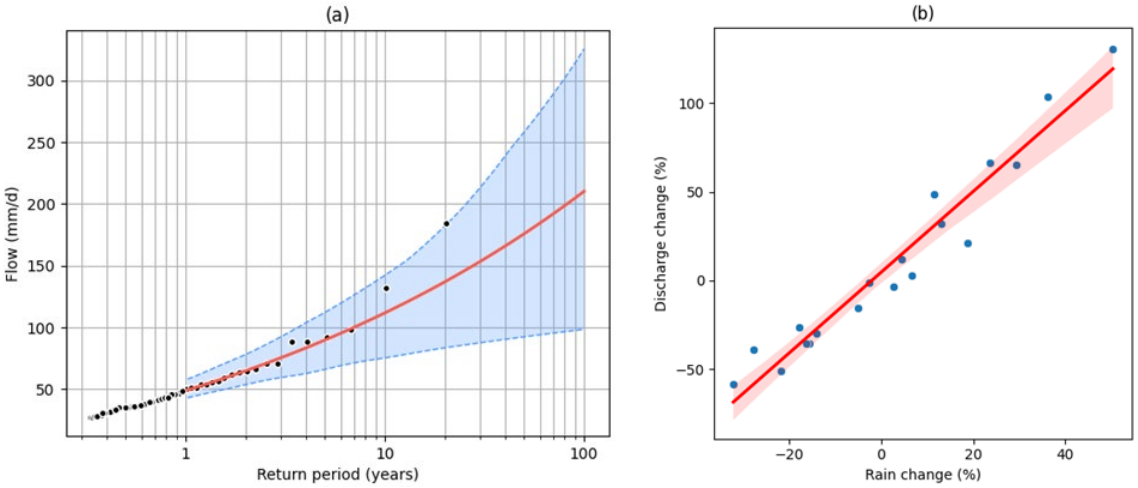

Figure 13. Discharge analysis for water management scheme definition: (**a**) high-flow return period using the GEV model, and (**b**) cross impacts of rainfall and runoff dynamics in the site of Bahounkpo.

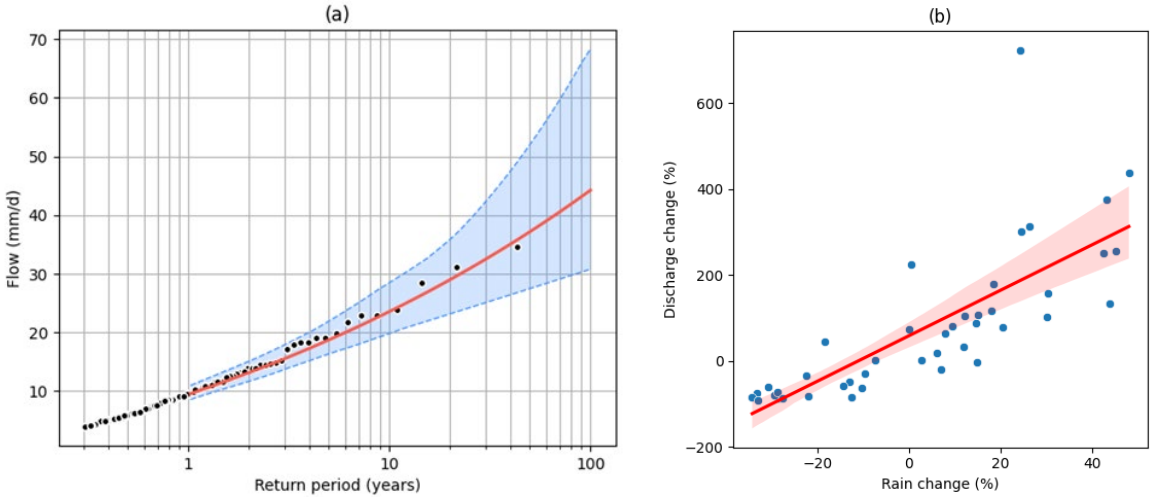

Figure 14. Discharge analysis for water management scheme definition: (**a**) high-flow return period, and (**b**) cross impacts of rainfall and runoff dynamics in the site of Lower-Sowé.

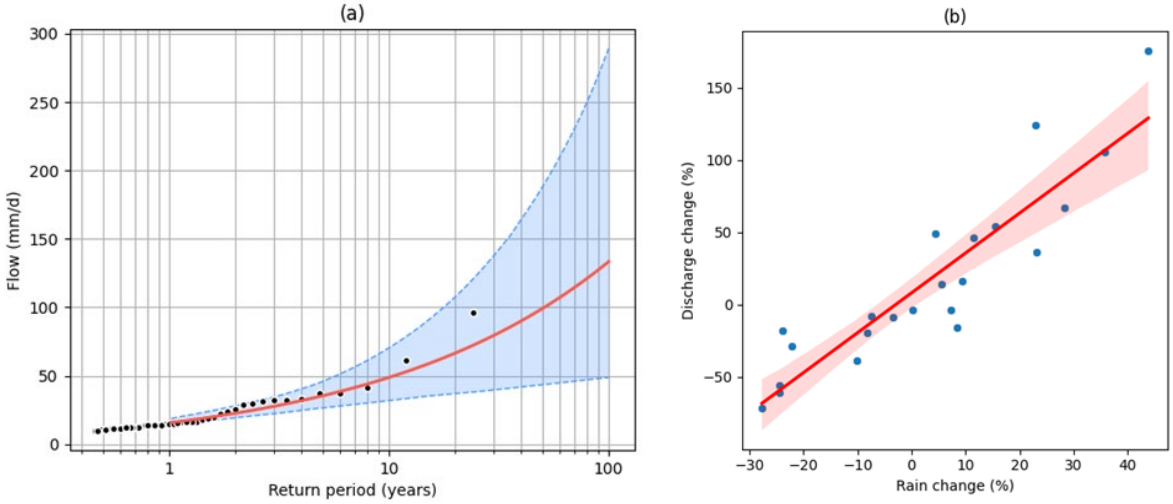

Figure 15. Discharge analysis for water management scheme definition: (**a**) high-flow return period, and (**b**) cross impacts of rainfall and runoff dynamics in the site of Nalohou.

4. Discussion

4.1. Model Performance

Although the model GR4J has been used for modeling studies in large watersheds across West Africa [13,20,65–69], its applicability to the context of inland valleys, characterized by small catchment areas (<200 km^2) with highly complex and varied hydrological dynamics, has been scarcely studied. The results illustrate the effectiveness of the model in simulating daily discharge in inland valleys in Benin. This effectiveness should be compared to the performance obtained in modeling studies of inland valleys with other models [7,10,11,15,16,36]. For instance, for the Nalohou site and compared to the study of [15], our results show that the lumped GR4J model is effective, which underscores the observations of [9]. In such conditions, a model like GR4J can be used as a decision-support tool for water management in the inland valley. It is, however, important to note that the lumped structure of GR4J, with a single production store and fixed flow partitioning, seems to limit its ability to accurately simulate high and low flows, particularly in catchments with intermittent regimes such as inland valleys, where groundwater fluctuations influence runoff generation.

Sensitivity analysis underscores the role of surface–groundwater exchange processes in the hydrological behavior of the inland valleys. Groundwater exchange coefficient appears as a key driver of runoff response in inland valleys. It highlights the importance of collecting groundwater data to improve the modeling of the hydrologic signature of inland valleys. This result indicates areas where further refinement or additional measures might be needed to improve model performance. For example, collecting data on groundwater loss or soil moisture retention could enhance the model's accuracy and reliability. Soil moisture assimilation seems to be an interesting way to improve the performance of the model. Future work should explore how hybrid or flexible modeling approaches can improve the accuracy of runoff simulations in inland valleys, particularly for extreme (low- and high-) flow conditions.

In the context of the unavailability of accurate in situ rainfall data, satellite-based rainfall products such as CHIRPS can give a good alternative for the estimation of discharge trends and seasonal variations in the three sites. These results are in accordance with those obtained by [41], who found that CHIRPS has the best overall performance over West Africa and northern Central Africa for hydrological modeling at a monthly step. Ref. [70] also demonstrated that the CHIRPS dataset enables accurate streamflow simulation in the Kaboua and Aval Sani catchments, which are located within the same geographical zone as the present study area. GSMAP and GPM-IMERG show mitigated results on the study sites. Given their accuracy against CHIRPS when compared to overall in situ rainfall time series, the low performance of GSMAP and GPM-IMERG in modeling discharge dynamics suggests that overall temporal dynamics do not fully encapsulate all hydrological characteristics. The good performance in modeling the temporal dynamics of discharge when using CHIRPS might be due to its relatively consistent quality across different seasonal conditions. GPM-IMERG demonstrates an interesting ability to simulate high discharge at Nalohou, consistent with its capability to capture extreme rainfall events (>50 mm) at the study sites. GSMAP dataset, while accurate in replicating measured rainfall, seems to be more susceptible to errors such as light precipitation events, which play an important role in hydrological processes. This highlights the importance of considering not only the accuracy of rainfall estimates but also how well each dataset aligns with the hydrological response of the basin.

Since the calibration process of hydrological models can itself introduce biases affecting runoff simulations, it is likely that the model calibration may favor rainfall datasets that better reproduce realistic runoff dynamics, rather than those that solely provide accurate

rainfall estimates. In this regard, Ref. [70] emphasizes the importance of calibrating the model individually for each rainfall product, as biases introduced during initial calibration can influence simulation outcomes. The primary objective of model calibration is to adjust parameters to align simulated runoff with observed data, which may inherently advantage datasets that more effectively capture the basin's hydrological response. Approaches to correcting biases in the presence of satellite-based rainfall data represent an option that can be tested to improve streamflow simulations in inland valleys for operational purposes, mainly for the analysis of extreme flows.

When comparing the two approaches using satellite-based rainfall data explored in this study, one notable advantage of the method involving calibration with in situ rainfall data and validation with satellite rainfall data is that in situ measurements allow optimal parameter adjustment during calibration. However, validating the model using satellite data complicates the assessment of model robustness, as it becomes challenging to discern whether poor performance results from biases inherent in satellite rainfall data or from limited model generalizability. Furthermore, this approach restricts the operational use of the model in contexts relying solely on satellite data. Conversely, calibrating and validating entirely with satellite rainfall data directly tests the applicability of satellite products for hydrological modeling, especially in regions like Benin, where rainfall stations are scarce or nonexistent. The primary difficulty of this approach lies in propagating inherent satellite rainfall biases into the runoff simulations during calibration. Without in situ reference input data, the resulting model exhibits increased versatility and requires recalibration at the same site for different datasets. Additionally, distinguishing whether observed discrepancies between simulations and observations arise from model parameterization issues or biases in the satellite input data becomes challenging. Operationally, the choice between these two approaches will depend on data availability and the specific application context.

4.2. Use of Hydrological Modeling as an Operational Decision Support Tool for Inland Valley Water Management

To control water-related risks, it is important to better understand the hazard and its impact [41]. Lumped models are among the tools for operational water management applications (including training and education) because they propose simplified catchment-scale representations of the transformation of precipitation into river discharge. However, the potential of the GR4J model for operational water management has not been evaluated often enough for inland valleys. The approach used here takes advantage of advances in alternative climate data [71] and efficient user-friendly models to provide an analytic frame for decision-making in inland valley systems. The most important practical advantage of this approach is that it gives a complete flow time series from which various flow characteristics can be extracted. Additionally, various scenarios of water use development can be easily evaluated [72]. In operational terms, for example, the reconstruction of historical flow time series offers a sound basis for defining design parameters such as extreme flow indices or indicators related to favorable periods for agricultural activities. A similar approach has been used to make a hydrological diagnosis of the Bankandi valley in Burkina Faso [3]. One direct application of such an approach in the context of inland valleys water management is related to the trends of high-flow occurrence. Historically, water management schemes in the inland valleys of Benin are based on guidelines derived from data collected in the 70s–90s by CIRAD in cooperation with CIEH and national agricultural research institutions. This research led to the conception of a tool, the "Diagnostic Rapide de Pré-Aménagement (DIARPA)", or Rapid Appraisal for Inland Valley Development, which defines the type of management scheme for a given inland valley mainly based on five parameters: decennial discharge, longitudinal slope, soil permeability, depth of the impermeable layer and depth of the interflow water table of the

study site. Decennial discharge, which is a component of extreme flows in the catchment, is among the most important and difficult-to-estimate parameters used in DIARPA. It can be easily and accurately estimated using historical time series of discharge. Figure 13 presents, as an example, the extreme flow return period analysis based on the simulated historical time series of Bahounkpo, which provides the extreme flow values that must be taken into consideration for water management infrastructure design. Another example of application is related to understanding trends in periods of high-water availability. These periods could be targeted for planting water-intensive crops like rice, while periods of low mean flow might indicate the need for drought-resistant varieties or supplemental irrigation measures. Changes in these periods can also be seen if they exist, and the indices related to favorable periods of agricultural activities in the wet season can be adjusted accordingly. In this context, the consistency of the trend information provided by the model can be reinforced by social surveys related to extreme events.

An additional operational advantage of the approach used here is the possibility to infer groundwater dynamics in the modeled catchments from the GR4J routing-store relative storage (R/X3). Comparing R/X3 with observed piezometric heads at Bahounkpo shows coherent seasonal rises and recessions (Figure 16). Spearman's rank correlations (rs) are high for most wells. Normalized cross-correlation functions ($\rho_{xy}(\tau)$) peak at positive lags ($\tau \approx +2$ to +60 days) with coefficients typically varying between 0.82 and 0.93, indicating that, once lagged, R/X3 reproduces most of the temporal variability in groundwater levels with potential predictive implications at Bahounkpo. Consequently, for this site, R/X3 can be used as an operational proxy for groundwater state to support rule-based management, with site-specific lead times informed by the observed lag range.

4.3. Limitations of the Research

Despite the interesting results observed in this study, it is important to note that there are some limitations. The limitations are related to the inherent uncertainties in environmental science data and the model, which can affect the results. For certain sites (Bahounkpo and Lower-Sowé), for high flow simulation based on satellite-derived rainfall, the near-zero KGE values show limited improvement compared to the mean-flow benchmark and should therefore be interpreted with caution. Furthermore, extremes estimated using the GEV distribution on simulated data may misrepresent uncertainty in extreme flow analysis, reinforcing the need for careful interpretation.

Another limitation of the approach used here is its direct inapplicability to ungauged sites, as at least one year of calibration/validation is required to ensure the model's operationality. It would also have been interesting to conduct the present analyses on a larger number of study sites and with tests extended to a wider range of satellite products. Additionally, this study did not explore the potential of employing bias correction techniques to further enhance the performance of satellite rainfall-driven streamflow simulations. The study also did not analyze how rainfall features and inland valley responses contribute to observed differences in the hydrological performance of satellite rainfall data. Investigating such approaches and questions could be beneficial for operational applications, especially for improving the analysis of extreme flow events. These observations, which can be integrated into future studies, do not undermine the results obtained here.

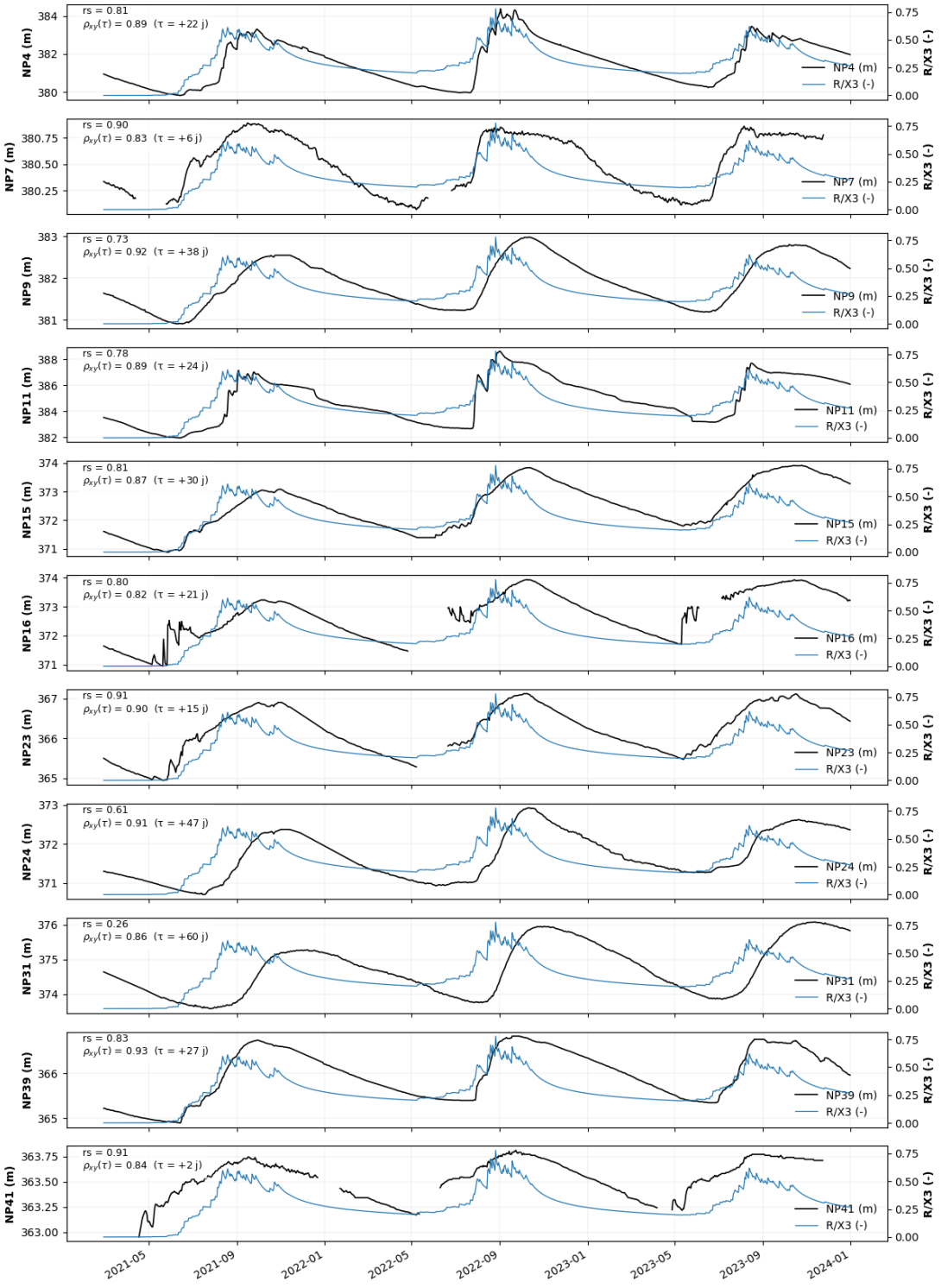

Figure 16. Time-series comparison and lagged-correlation analysis of groundwater levels and GR4J routing-store relative storage in the Bahounkpo inland valley (2021–2023).

5. Conclusions

This study demonstrates the effective application of the GR4J hydrological model to understand and predict discharge occurrences in the inland valleys of the Sudanian zones of Benin. The model has shown robust performance in simulating discharge events with high seasonal and inter-annual variations. Based on KGE values, CHIRPS stands out as the most reliable and consistent product for water management, while GPM-IMERG and GSMAP show variability and site-specific efficiency, requiring further improvements

to be considered dependable. The integration of CHIRPS rainfall data has enabled reasonable runoff simulation, enhancing our ability to understand streamflow trends and seasonal variations based on the reconstruction of historical hydrodynamic conditions. This proactive approach is a precious tool to support informed decision-making by providing a reliable estimation of streamflow thresholds and then building resilience against actual and possible future changes in sustainable water management in the region. The insights gained from this research contribute to a better understanding of the hydrological dynamics in the inland valleys of Sudanian zones of Benin and provide a foundation for developing resilient and sustainable water management practices. The effective implementation and continuous improvement of the model will ensure its long-term utility in sustainable water resource management. Additionally, training and capacity-building efforts are essential to ensure that local authorities and stakeholders effectively adopt and utilize this approach.

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Data Availability Statement: The original data presented in this study are openly available in Bafonbe at https://sites.google.com/view/projetbafonbe (accessed on 1 July 2025).

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

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