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Evaluation of the WRF-Hydro model output based on different rainfall input data over the upper basin of the Senegal River

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ABSTRACT

This study examines the performance of the uncoupled WRF-Hydro model under different precipitation inputs, highlighting its importance for water management in data-scarce West African regions. This study primarily uses IMERG precipitation data to calibrate and validate the WRF-Hydro model, aiming to fine-tune parameters for the accurate simulation of observed hydrological processes. ERA5-LAND and WRF precipitation datasets were also analyzed for comparison. A comparison was conducted to identify the dataset delivering the most accurate results in the uncoupled WRF-Hydro model. The 2011–2020 analysis shows the uncoupled WRF-Hydro model performs well in the upper Senegal River Basin, achieving strong KGE scores (KGE = 0.78) during calibration and validation. Both IMERG (KGE = 0.78; PBIAS = −18%) and WRF (KGE = 0.73; PBIAS = −4%) datasets show strong agreement with observed streamflows, while using ERA5-LAND as inputs results in a significant underestimation of streamflows (PBIAS = −56%). WRF precipitation proves more reliable, especially during rainy seasons.

Key words: calibration and validation, Senegal River Basin, uncoupled, upper basin, WRF-Hydro

HIGHLIGHTS

- A recent study using the high-resolution WRF-Hydro model to improve hydrological modeling in the Senegal River Basin highlighted limitations related to the integration of precipitation data.
- Our study addresses this by introducing the decoupled WRF-Hydro model. This approach enables a more flexible and independent assessment of different precipitation datasets, thereby enhancing simulation accuracy.

ABBREVIATIONS

GR2M	Two Parameter Monthly Genie Rural Model
GR4J	Four Parameter Daily Genie Rural Model
NSE	Nash–Sutcliffe efficiency
OMVS	Organisation pour la mise en valeur du fleuve Sénégal
SWAT	Soil and Water Assessment Tool
WRF-Hydro	Weather Research and Forecasting Modeling System

1. INTRODUCTION

Hydrological modeling plays a fundamental role in understanding water resource dynamics and supporting decision-making in water management. Globally, a wide range of hydrological models, from conceptual to fully distributed, have been developed and applied to simulate surface and subsurface processes. In Africa, where rapid population growth, accelerated urbanization, and climate variability intensify pressure on water resources, hydrological modeling has become essential for forecasting water availability, mitigating extreme events, and supporting sustainable planning. However, a critical limitation in hydrological modeling across African basins is the scarcity and uneven distribution of ground-based precipitation measurements, which are the most influential driver of model performance. Precipitation governs infiltration, surface runoff, and basin hydrological response, and inaccuracies in its spatial and temporal representation propagate through the modeling chain, leading to substantial uncertainties. This challenge is particularly acute in the Senegal River Basin, a transboundary basin characterized by strong hydroclimatic variability, complex land–atmosphere interactions, and limited *in-situ* observations. Therefore, selecting an appropriate precipitation dataset is a prerequisite for improving hydrological simulations in this region.

Several studies have applied hydrological models in the Senegal River Basin, including conceptual models, such as GR4J and GR2M (Sambou *et al.* 2003; Bodian *et al.* 2012), and semi-distributed or distributed physical models, such as SWAT (Sambou *et al.* 2021) and WRF-Hydro (Ndiaye *et al.* 2024). While these studies demonstrated the usefulness of hydrological modeling for climate impact assessment and flood forecasting, they also highlighted significant limitations related to input data quality, particularly precipitation. Most previous research relied on sparse rain gauge networks or used a single precipitation forcing without conducting a comparative analysis of multiple gridded precipitation products. As a result, the sensitivity of hydrological model performance to different precipitation datasets remains poorly understood in the Senegal River Basin. This represents a clear gap in the literature and limits the ability to make informed decisions regarding the most reliable data source for hydrological modeling in data-scarce regions.

To address this gap, the present study introduces, for the first time, the use of the uncoupled version of the WRF-Hydro model to perform a comparative evaluation of three widely used precipitation datasets, IMERG, ERA5-LAND, and WRF model output over the upper Senegal River Basin. Each dataset represents a distinct class of precipitation products with unique advantages and limitations. IMERG, a satellite-based product, offers high spatiotemporal resolution (0.1°, 30-min intervals) and has demonstrated strong capability in capturing convective rainfall typical of the Sahelian climate, thereby overcoming the limitations of sparse rain gauge networks. ERA5-LAND, derived from atmospheric reanalysis, provides physically consistent land surface variables with hourly temporal resolution that meets the input requirements of WRF-Hydro. WRF model precipitation, produced through dynamic downscaling, explicitly simulates regional atmospheric processes and land–atmosphere interactions, offering a process-based alternative to observation-based datasets and showing promising results in previous studies in West Africa. Despite their increasing use, a systematic comparison of these three datasets as hydrological forcing products has not yet been undertaken in the Senegal River Basin.

Therefore, the key research gap addressed in this study is the lack of a comprehensive assessment of how different precipitation datasets influence hydrological model performance in a data-scarce African basin. We hypothesize that the choice of precipitation input significantly affects the accuracy of streamflow simulations in the upper Senegal River Basin and that satellite-based and reanalysis datasets will exhibit varying performance depending on their ability to capture the spatial and temporal dynamics of rainfall. This study aims to identify which precipitation dataset (IMERG, ERA5-LAND, or WRF) provides the most accurate streamflow simulation using the uncoupled WRF-Hydro model in the upper Senegal River Basin.

2. MATERIALS AND METHODS

2.1. Study area and data

The upper basin of the Senegal River, illustrated in Figure 1, covers an area of 218,000 km^2 in the southern part of the river. It spans a geographical zone between 12°30′ and 9°30′ West longitude and between 10°30′ and 12°30′ North latitude (Faty *et al.* 2017). Due to its elongated geographical configuration, the basin encompasses a variety of climates found in Guinea, Mali, and part of Senegal. Rainfall in the basin varies significantly: in the southern part, average annual precipitation ranges from 1,400 to 2,000 mm, whereas in the northern part, it varies between 500 and 1,400 mm (Faty *et al.* 2017). The Bakel hydrometric station, located within this basin, is the most monitored site for research on the Senegal River (Faye 2015).

In this study, we use several datasets from multiple observations, accounting for the uncertainty. The observed river discharges at the outlet of the upper basin, measured at the Bakel hydrometric station, were provided by the Directorate General of Water Resources Planning (DGPRE). These data, covering the period from 2011 to 2020, serve as a crucial reference for validating our hydrological simulations. They allowed for a comparison between the simulated discharges from our model and the field observations, thereby contributing to evaluating the model's performance in replicating real hydrological flows.

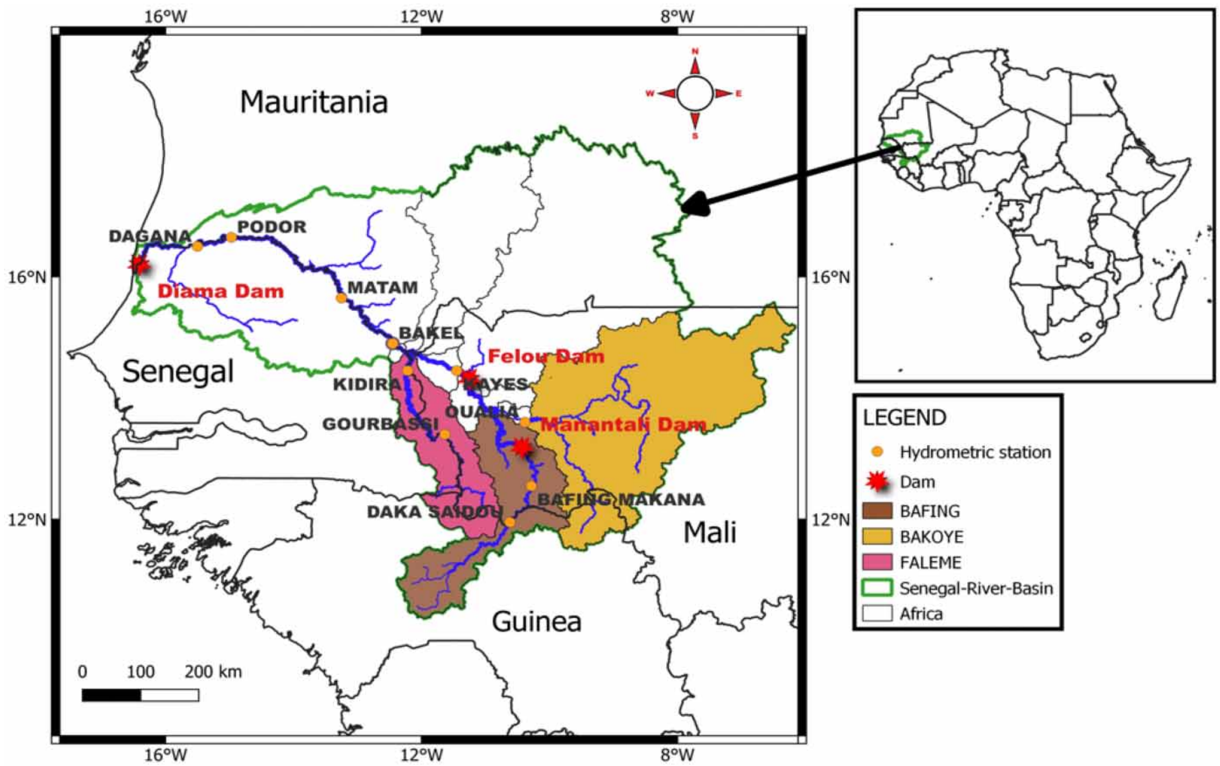

Figure 1 | Location of the Senegal River Basin.

For precipitation, we primarily use satellite estimates from the IMERG product, which have been integrated as input data into the WRF-Hydro model during the calibration and validation phases. The goal is to adjust the model parameters to improve its ability to simulate observed hydrological processes. Additionally, other precipitation datasets, such as those from ERA5-LAND (it is a high-resolution global land surface reanalysis dataset produced by ECMWF. It provides detailed hourly data on land variables, making it valuable for hydrological and environmental studies) and WRF model simulations, are also utilized. A thorough comparative analysis is conducted in Section 2.4 to identify the product that performs best when used as input precipitation in the uncoupled version of the WRF-Hydro model. This analysis aims to determine which dataset most accurately represents the spatiotemporal variability of precipitation in the Senegal River Basin.

Finally, all other input parameters required for the operation of the uncoupled version of the WRF-Hydro model are extracted from the WRF model simulations, specifically configured to replicate the atmospheric and climatic conditions of the Senegal River Basin.

2.2. WRF-Hydro model setup in uncoupled mode

In this study, we use the overbank flow version of the WRF-Hydro model developed by Arnault *et al.* (2023). This distributed model is based on physical processes and incorporates various parameterizations. It combines runoff mechanisms due to infiltration and saturation excess while leveraging high-resolution routing modules for different types of flows: surface, subsurface, baseflow, channel, and reservoir flows. WRF-Hydro supports multi-scale grids, ranging from several kilometers to a few hundred meters. In this study, we employed the Noah-MP module, specialized in land surface analysis, which is included in the WRF-Hydro configuration. This module allows the analysis of vegetation cover variations and soil moisture up to a depth of 2 m, divided into four distinct layers. The core WRF-Hydro modules are activated for the area shown in Figure 1, with a spatial resolution of 1 km. This area is defined using WRF-Hydro pre-processing tools and elevation data provided by the HydroSHEDS database (Lehner *et al.* 2008), which includes hydrological and topographical information. Data disaggregation was performed using a specific disaggregation factor (10). The baseflow model (GWBASESWCRT) is not activated. According to Arnault *et al.* (2016), for a Sahelian watershed in West Africa, the use of the groundwater reservoir option

Table 1 | Model configurations

WRF-Hydro physics	Option		References
Land surface model	Noah-MP		Niu *et al.* (2011)
Subsurface routing (SUBRTSWCRT)	1	Yes	Gochis *et al.* (2021)
Overland flow routing (OVRTSWCRT)	1	Yes	
Channel routing (CHANRTSWCRT)	1	Yes	
Baseflow bucket model (GWBASESWCRT)	0	No	
Overbankflow (OVERBANKFLOWSWCRT)	1	Yes	Arnault *et al.* (2023)

would generate baseflow that leads to river water contributions exceeding observed values, which is not desirable. Table 1 summarizes the physical parameters used during this modeling process.

2.3. Calibration and validation of WRF-Hydro uncoupled

The WRF-Hydro model, configured in uncoupled mode, is employed for a meticulous calibration for the 2011–2015 period, followed by validation for 2016–2020 within the Senegal River Basin. The primary goal is to enhance its ability to simulate river discharge with greater accuracy. Key parameters are targeted during this calibration, including the infiltration fraction (REFKFT), surface retention depth (RETDEPRT), deep drainage coefficient (SLOPE), surface runoff roughness (OVROUGHRTFAC), channel roughness (ManNFAC), and overflow threshold (HThres). The calibration methodology draws upon established approaches from studies, such as Givati *et al.* (2016), Fersch *et al.* (2020), Arnault *et al.* (2016), and Quenum *et al.* (2022). The process is systematic, beginning with the adjustment of parameters governing the overall water balance, followed by fine-tuning of deep drainage and surface roughness, and culminating in the calibration of the overflow threshold. Parameter adjustments are carried out iteratively, with each variation assessed against observed discharge records to determine the best-performing configuration. Details of the parameter ranges and their final optimized values are provided in Table 2. This approach ensures a robust model configuration, capable of reproducing observed hydrological dynamics while accounting for the complexities of the basin's hydrology.

The model's performance is thoroughly assessed through the application of key evaluation metrics outlined in Equations (1)–(5). These metrics provide a robust framework for validating the reliability and accuracy of the simulations.

$$\mathrm{BIAS} = \frac{\sum_{i=1}^{n} (Y_i^{\mathrm{siml}} - Y_i^{\mathrm{obs}})}{\sum_{i=1}^{n} Y_i^{\mathrm{obs}}} \times 100 \tag{1}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (Y_i^{\mathrm{obs}} - Y_i^{\mathrm{siml}})^2}{\sum_{i=1}^{n} (Y_i^{\mathrm{obs}} - Y_i^{\mathrm{mean}})^2} \tag{2}$$

Table 2 | Range of values used during parameter calibration

Parameters	Units	Range of values							
REFKDT	Dimensionless (–)	0.1	0.5	1.0	1.5	2.0	2.5	3.0	3.5
RETDEPRTFAC	Dimensionless (–)	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0
SLOPE	Dimensionless (m/m)	0.06	0.08	0.1	0.2	0.3	0.4	0.5	0.6
OVROUGHRTFAC	Dimensionless (–)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
ManNFac	Dimensionless (–)	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6
HThres	**m** (meters)	04	05	06	07	08	10	12	

$$\text{KGE} = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{\text{siml}}}{\sigma_{\text{obs}}} - 1\right)^2 + \left(\frac{\mu_{\text{siml}}}{\mu_{\text{obs}}} - 1\right)^2} \quad (3)$$

$$R^2 = 1 - \frac{\sum (y_{\text{obs}} - y_{\text{siml}})^2}{\sum y_{\text{obs}} - \text{mean}(y_{\text{obs}})^2} \quad (4)$$

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2} \cdot \sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}} \quad (5)$$

where Y_i^{obs} represents the observational data, and Y_i^{siml} corresponds to the simulated data from WRF-Hydro. Regarding the KGE score, r denotes the linear correlation between observations and simulations, and σ_{obs} and σ_{siml} are the standard deviations of the observations and simulations, respectively. Additionally, μ_{siml} and μ_{obs} represent the means of the simulations and observations, respectively.

2.4. Evaluation of WRF, IMERG, and ERA5-LAND precipitation

In this section, we analyzed precipitation variability in the upper basin of the Senegal River using different data sources (WRF, IMERG, and ERA5-LAND). Figure 2 highlights a good representation of the seasonal variation of precipitation in the study area. A precipitation peak is consistently observed in August across all data sources, which accurately reflects the region's climatic regime, characterized by a rainy season concentrated during this period. However, significant discrepancies emerge between the different datasets. Notably, a substantial underestimation is observed in ERA5-LAND compared with WRF and IMERG, raising questions about the suitability of this product for hydrological studies in this specific region.

Figure 3 clearly highlights the interannual variability of seasonal precipitation over the period 2011–2020. The WRF and IMERG datasets exhibit strong coherence, with very similar amplitudes and interannual trends, indicating a better ability to capture regional climate variability. In contrast, ERA5-LAND shows larger discrepancies, reflecting a less accurate representation of interannual fluctuations in the upper river basin.

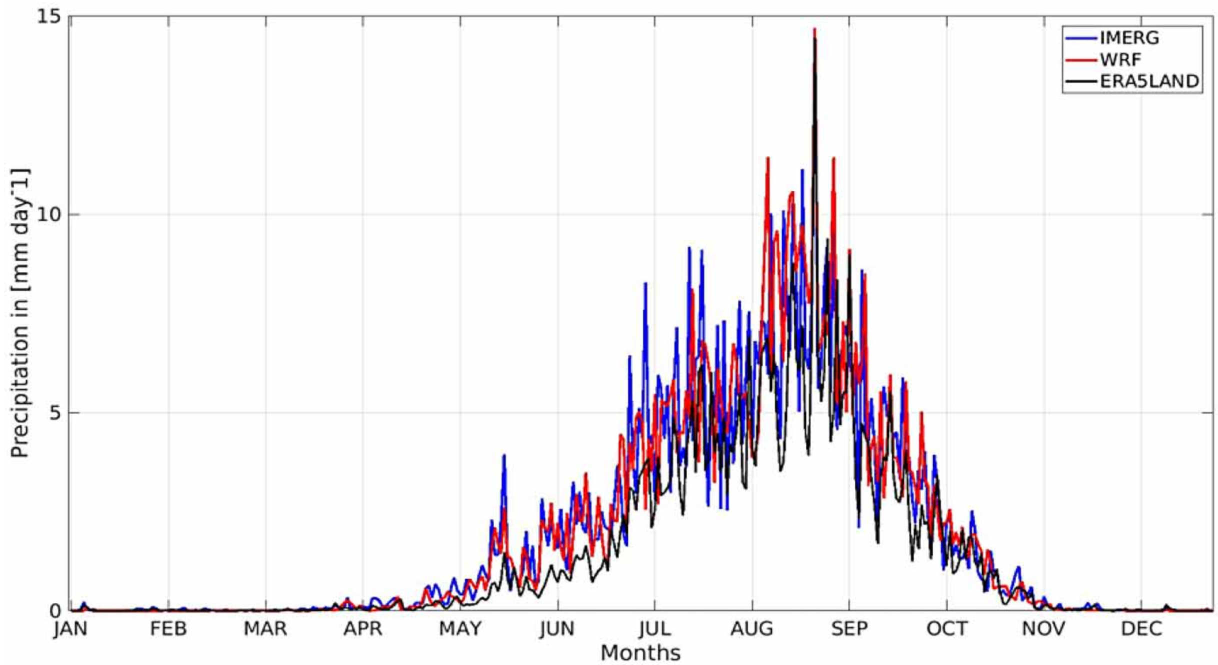

Figure 2 | Seasonal mean variation of precipitation during the period 2011–2020 in the upper river basin.

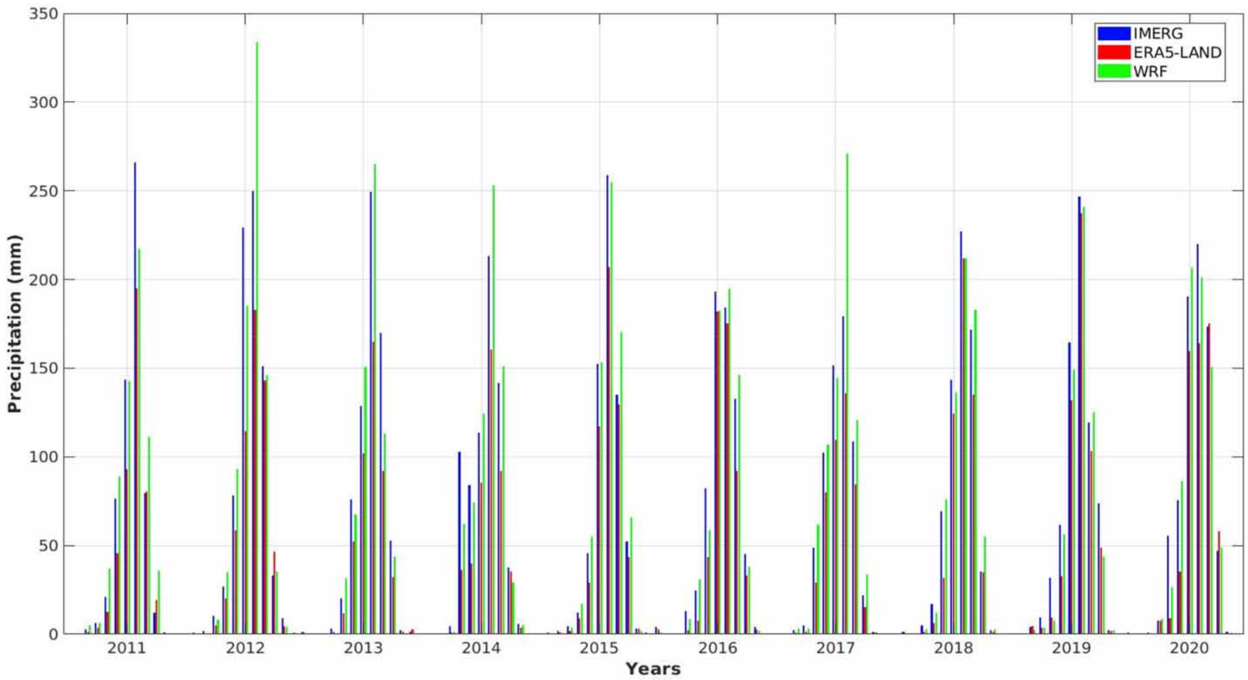

Figure 3 | Seasonal variation of the precipitation from IMERG, WRF, and ERA5-LAND during the period 2011–2020 in the upper river basin.

3. RESULTS

3.1. Calibration of WRF-Hydro uncoupled

In this section, we present the calibration results of the uncoupled hydrometeorological model WRF-Hydro applied to the upper Senegal River Basin. The findings demonstrate satisfactory model performance, supported by robust statistical indicators: NSE = 0.78, KGE = 0.78, PBIAS = −19%, $R^2 = 0.78$, and $r = 0.9$. These results, summarized in Table 3, highlight a strong agreement between simulated and observed data, effectively capturing the hydrological characteristics of the river basin.

Figure 4 demonstrates that the uncoupled WRF-Hydro model effectively captures the seasonality of discharges in the Senegal River Basin, accurately reflecting the region's typical hydrological cycles. These findings align with those of Cerbelaud *et al.* (2022), who evaluated the uncoupled WRF-Hydro model on flashier watersheds in Grande Terre, a tropical island in New Caledonia located in the Southwest Pacific. That study also reported strong performance, with Nash–Sutcliffe efficiency values exceeding 0.6 across all watersheds, underscoring the robustness of the uncoupled WRF-Hydro model in diverse hydrological and climatic contexts. For the Senegal River Basin, the results further confirm the model's ability to simulate discharges and hydrological processes effectively, reinforcing its reliability for hydrological applications and water resource management in this region.

3.2. Validation of WRF-Hydro uncoupled

Figure 5 presents the validation of the WRF-Hydro model for the Senegal River Basin over the 2016–2020 period, following calibration conducted for 2011–2015. The validation results indicate that the model maintains satisfactory performance, with statistical indicators showing KGE = 0.78, NSE = 0.72, and a PBIAS of −17%. These metrics confirm the model's ability to accurately reproduce the hydrological characteristics and discharge variations of the basin, despite a slight underestimation of discharges. Overall, the decoupled WRF-Hydro model is validated as a reliable tool for hydrological modeling of the Senegal River Basin.

3.3. Discharge variation based on multiple input precipitation datasets (IMERG, WRF, and ERA5-LAND)

The variation in discharge observed over the period 2011–2020 in the upper Senegal River Basin reflects an irregular temporal evolution, highlighting the complex dynamics of the region's hydrological regime. This irregularity can be attributed

Table 3 | Calibration of WRF-Hydro uncoupled over the Senegal River Basin

Parameter (Unit)	Value	KGE	NSE	PBIAS (%)	R^2	*r*
REFKDT (–)	0.1	−0.44	−1.47	75	−1.47	0.87
	0.5	**0.76**	**0.73**	**−20**	**0.72**	**0.88**
	1.0	0.49	0.64	−43	0.64	0.89
	1.5	0.36	0.54	−52	0.54	0.89
	2.0	0.28	0.47	−57	0.47	0.89
	2.5	0.23	0.41	−61	0.41	0.89
	3.0	0.20	0.38	−63	0.38	0.89
	3.5	0.17	0.35	−65	0.35	0.89
RETDEPRTFAC (–)	0.0	0.76	0.72	−20	0.72	0.87
	1.0	**0.76**	**0.73**	**−20**	**0.72**	**0.88**
	2.0	0.76	0.73	−21	0.73	0.88
	3.0	0.75	0.73	−21	0.73	0.88
	4.0	0.75	0.73	−21	0.73	0.88
	5.0	0.75	0.73	−21	0.73	0.88
	6.0	0.75	0.73	−21	0.73	0.88
	7.0	0.75	0.73	−22	0.73	0.88
SLOPE (m/m)	0.06	0.76	0.73	−8	0.73	0.90
	0.08	**0.79**	**0.74**	**−15**	**0.74**	**0.80**
	0.10	0.76	0.73	−20	0.72	0.88
	0.20	0.62	0.64	−32	0.64	0.85
	0.30	0.55	0.59	−37	0.59	0.83
	0.40	0.51	0.55	−40	0.55	0.82
	0.50	0.49	0.53	−42	0.53	0.81
	0.60	0.47	0.51	−43	0.51	0.80
OVROUGHRTFAC (–)	0.1	0.54	0.44	14	0.44	0.86
	0.2	0.69	0.61	1	0.61	0.87
	0.3	0.76	0.68	−6	0.68	0.88
	0.4	0.79	0.72	−11	0.72	0.89
	0.5	**0.79**	**0.74**	**−15**	**0.74**	**0.89**
	0.6	0.77	0.75	−18	0.75	0.89
	0.7	0.38	0.46	−49	0.46	0.81
	0.8	0.47	0.51	−43	0.51	0.80
ManNFac (–)	0.2	0.12	−0.80	4	−0.80	0.68
	0.4	0.41	0.02	1	0.02	0.77
	0.6	0.63	0.46	−6	0.46	0.83
	0.8	0.74	0.65	−11	0.65	0.87
	1.0	0.79	0.74	−15	0.74	0.89
	1.2	**0.78**	**0.78**	**−19**	**0.78**	**0.90**
	1.4	0.76	0.80	−21	0.80	0.91
	1.6	0.72	0.72	−24	0.80	0.92
HThres (m)	0.4	0.43	0.62	−43	0.62	0.91
	0.5	0.64	0.65	−30	0.75	0.90
	0.6	**0.78**	**0.78**	**−19**	**0.78**	**0.90**
	0.7	0.76	0.79	−9	0.71	0.90
	0.8	0.63	0.60	−1	0.59	0.89
	1.0	0.37	0.23	11.68	0.23	0.87
	1.2	0.16	−0.13	20	−0.13	0.86

The values in bold represent the best-fit values obtained after calibrating each parameter.

to the spatiotemporal fluctuations in precipitation. The results illustrated in Figure 6 and Table 4 demonstrate a robust correlation between the discharges simulated using IMERG and WRF precipitation and the observed discharges. This strong agreement is evidenced by the Kling–Gupta efficiency (KGE) values of 0.73 for WRF and 0.78 for IMERG, indicating good model performance. Additionally, the BIAS percentages of −4% for WRF and −18% for IMERG reveal that while both simulations are close to the observed values, IMERG precipitation slightly underestimates discharge more than WRF.

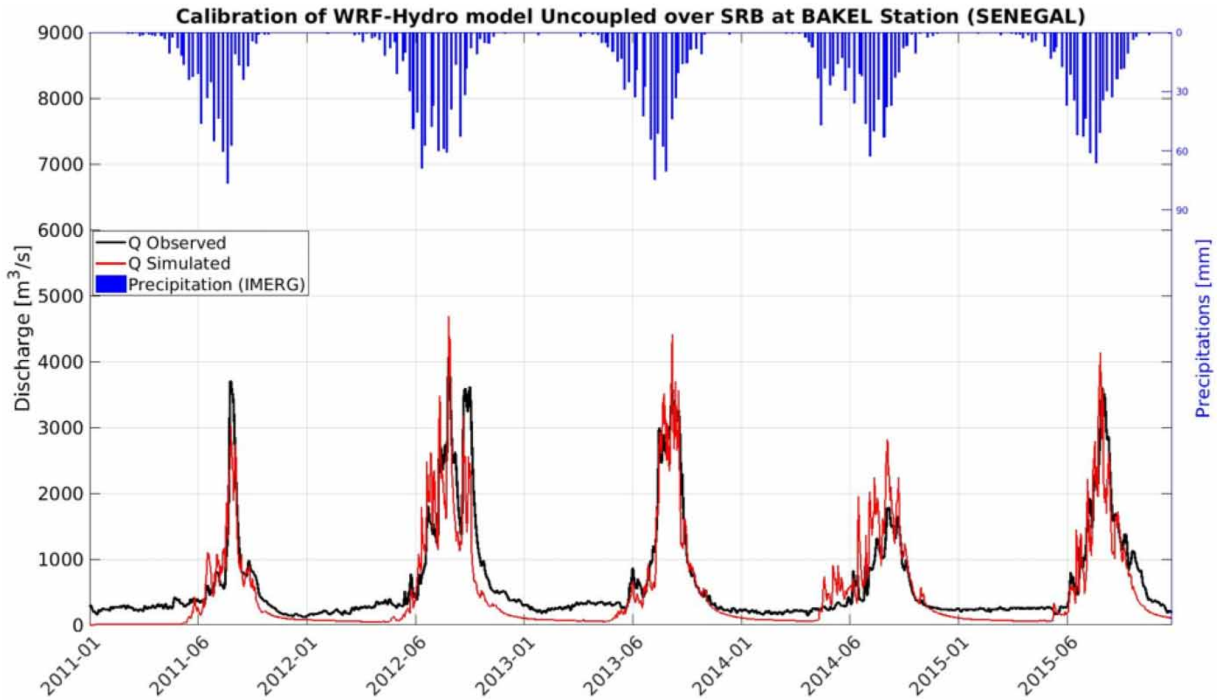

Figure 4 | Calibration of discharge with WRF-Hydro uncoupled.

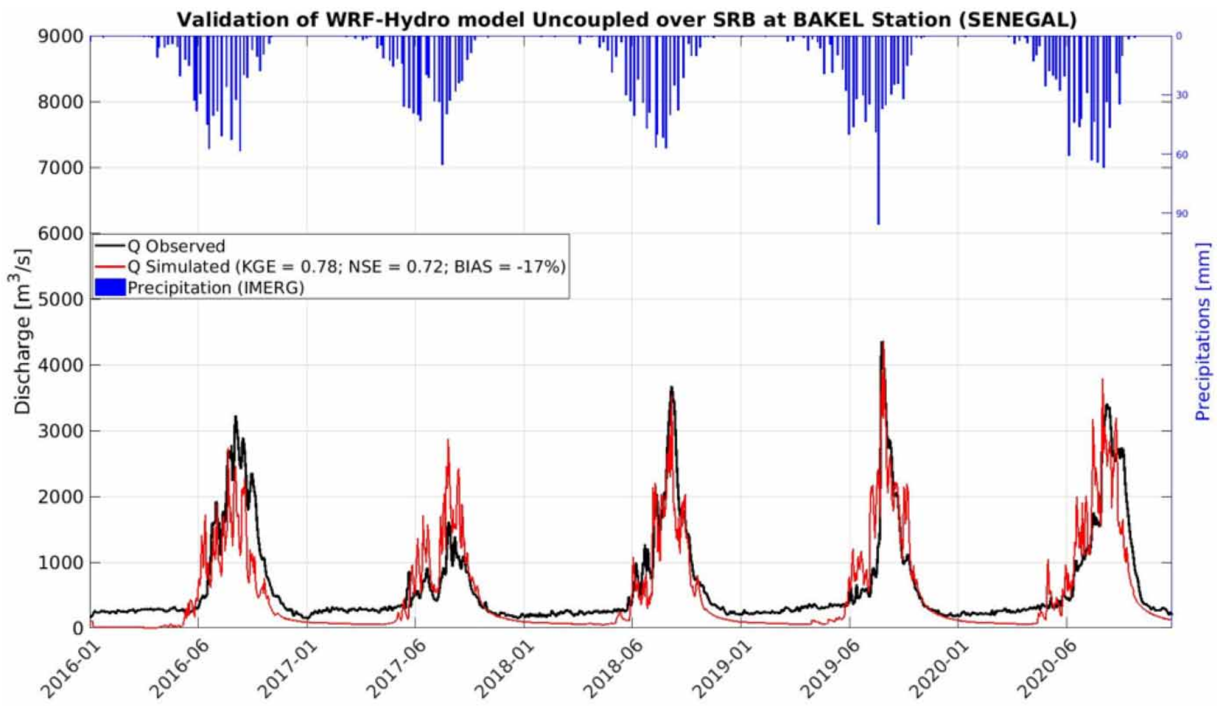

Figure 5 | Validation of discharge with WRF-Hydro uncoupled.

These results underline the reliability of both datasets in reproducing hydrological patterns, with IMERG showing a marginally higher overall efficiency but requiring attention to its tendency for greater bias. This highlights the ability of the IMERG and WRF products to satisfactorily capture the hydrological dynamics of the basin. Their performance can be explained by a

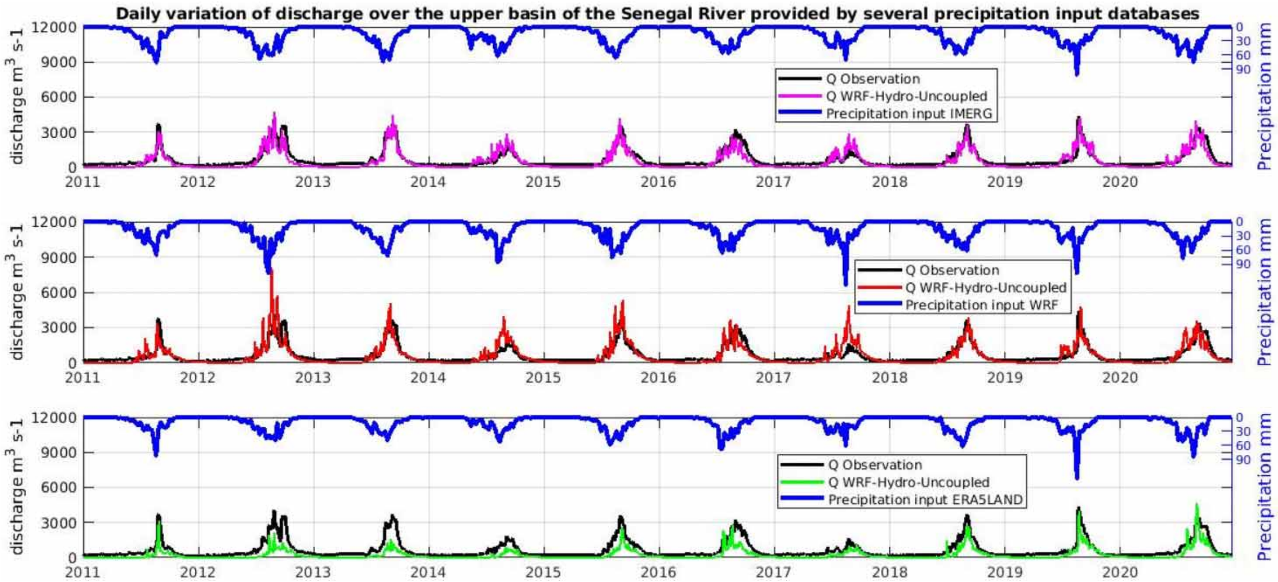

Figure 6 | Daily variation of discharge over the period 2011–2020 in the upper basin of the Senegal River.

Table 4 | Comparative statistical analysis between discharge observed and discharge from WRF, IMERG, and ERA5-LAND precipitation input

	OBS/WRF Input	OBS/IMERG Input	OBS/ERA5-LAND Input
KGE	0.73	0.78	0.28
NSE	0.52	0.74	0.40
PBIAS (%)	−4	−18	−56

better spatiotemporal resolution and improved accuracy in detecting precipitation, which allows for a more realistic simulation of flows in the upper basin. In contrast, the slight underestimation of the discharges simulated using ERA5-LAND precipitation (BIAS = −56%) highlights the limitations of this product. This underestimation could result from its spatial resolution, which may lead to a poor representation of intense and localized precipitation, characteristic of the region's climate.

The results obtained using the WRF model precipitation as input data have been confirmed by the study of Ndiaye *et al.* (2024) in the Senegal River basin, Quenum *et al.* (2022) in the Ouémé basin (West Africa), and Naabil *et al.* (2017) in the Tono reservoir, also in West Africa. In these studies, the WRF-Hydro model was coupled with the WRF atmospheric model.

The comparison of streamflow simulated using WRF and IMERG precipitation inputs reveals complementary strengths. While WRF precipitation results in a lower overall bias (PBIAS = −4%), indicating a better representation of the long-term water balance, IMERG precipitation achieves higher KGE (0.78) and NSE (0.74), reflecting a superior ability to reproduce the temporal variability and dynamics of observed streamflow, particularly during high-flow periods (JASO). These results suggest that WRF is more suitable for water balance studies, whereas IMERG performs better for capturing daily discharge variability.

4. DISCUSSION

This study provides a comprehensive assessment of the performance of the uncoupled WRF-Hydro hydrometeorological model applied to the upper Senegal River Basin, a region characterized by pronounced rainfall seasonality, sparse hydrometeorological observation networks, and high sensitivity to climate variability.

During the calibration period (2011–2015), the use of IMERG precipitation for model adjustment was chosen for its high spatial and temporal resolution and its ability to capture the convective rainfall typical of the Sahel, enabling the model to robustly reproduce observed streamflows. Key performance metrics confirm this agreement: NSE = 0.78, KGE = 0.78, PBIAS = –19%, $R^2 = 0.78$, and $r = 0.90$. These results demonstrate strong correspondence between simulated and observed flows, highlighting the model's effectiveness in capturing the seasonal dynamics of the hydrological cycle, which is critical in semi-arid Sahelian environments. Figure 4 illustrates this capability, validating the choice of parameterizations and input datasets.

The model results are consistent with those of Cerbelaud *et al.* (2022), who applied the uncoupled WRF-Hydro model to highly responsive tropical catchments in New Caledonia, achieving NSE values above 0.6 across all basins. This consistency demonstrates the model's robustness, flexibility, and transferability across diverse hydrological and climatic settings, reinforcing confidence in its structure and representation of physical processes even in uncoupled mode.

Validation for the 2016–2020 period, using parameters derived from the calibration phase, confirmed the model's stability over independent periods, with comparable performance statistics (KGE = 0.78, NSE = 0.72, PBIAS = –17%, $R^2 = 0.72$, $r = 0.88$). A slight underestimation of streamflow was observed, likely reflecting residual uncertainties in precipitation inputs or simplifications inherent in the uncoupled approach. Nevertheless, the temporal consistency between calibration and validation demonstrates the model's robustness and suitability for operational applications, including flood forecasting and water resource management.

Beyond statistical performance, differences among precipitation datasets can be explained by their underlying physical characteristics. IMERG outperforms in reproducing extreme flows due to its multi-satellite retrieval algorithm, which captures convective rainfall and localized high-intensity events, key drivers of runoff in the Sahel. WRF precipitation, although physically based, tends to smooth sub-grid convective processes, leading to underestimation of extreme events. ERA5-LAND, despite coarser spatial resolution, benefits from data assimilation that integrates land–atmosphere interactions, providing improved basin-wide precipitation representation. These physical factors explain why IMERG delivers the most accurate streamflow simulations during intense rainfall events, while ERA5-LAND performs well for moderate flows.

As highlighted by Bohn *et al.* (2019), the reliability of precipitation inputs often has a greater influence on hydrological model accuracy than parameterization itself, emphasizing the critical role of high-quality rainfall products in reducing uncertainty. In this context, our study shows that the uncoupled WRF-Hydro model, calibrated with a reliable precipitation dataset such as IMERG, provides a scientifically robust tool for hydrological modeling in data-scarce regions of West Africa. Its consistent performance across multiple periods and flow conditions supports practical applications in water resource planning, flood prediction, and climate change impact assessment, enabling more informed and resilient decision-making under uncertainty.

5. CONCLUSION

This study evaluated the performance of the uncoupled WRF-Hydro model in the upper Senegal River Basin, with a focus on the influence of different precipitation datasets. IMERG precipitation was used for calibration and validation, while WRF model outputs and ERA5-LAND were tested to assess their suitability as hydrological forcing. The model showed robust performance over the 2011–2020 period, with strong agreement between simulated and observed streamflows (KGE = 0.78 for IMERG; KGE = 0.73 for WRF), whereas ERA5-LAND resulted in a notable underestimation (PBIAS = –56%). WRF precipitation proved particularly effective in capturing streamflow variations during flood events, reflecting its ability to represent the localized and intense rainfall typical of the Sahel.

Differences in performance among datasets can be explained by their physical characteristics: IMERG accurately captures convective rainfall through multi-satellite retrievals, WRF dynamically simulates atmospheric processes but tends to smooth sub-grid convection, and ERA5-LAND integrates land–atmosphere feedbacks through reanalysis. These factors highlight the critical importance of precipitation dataset selection for reliable hydrological modeling in data-scarce regions.

Overall, the study demonstrates that the uncoupled WRF-Hydro model, calibrated with high-quality precipitation inputs, is a scientifically robust tool for streamflow simulation, flood forecasting, and water resource management in the Senegal River Basin. Its consistent performance across different periods and flow conditions supports informed decision-making under climatic uncertainty in West Africa.

Despite these promising results, several limitations should be noted. Uncertainties remain in rainfall estimation, model structural assumptions, parameter sensitivity, and scale mismatches between precipitation products and catchment characteristics. Acknowledging these limitations provides context for interpreting the results and identifies avenues for future improvements in regional hydrological modeling.

This study confirms that the quality and type of precipitation data are decisive for the accuracy of hydrological simulations in semi-arid regions. It also demonstrates that the uncoupled WRF-Hydro model can serve as a solid basis for regional hydrological studies and water management planning, while highlighting the need for future improvements to better integrate local processes and climatic extremes.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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