

Full Length Research Paper

Assessment of satellite rainfall products for stream flow simulation in Gambia watershed

Bakary FATY^{1,5*}, Abdou ALI², Honoré DACOSTA¹, Ansoumana BODIAN³, Salif DIOP¹ and Luc DESCROIX⁴

¹Departement of Géography at University of Cheikh Anta Diop of Dakar, Sénégal.

²Centre Régional AGRHYMET, Niamey, Niger.

³Laboratoire Leïdi "Dynamique des territoires et Développement", Université Gaston Berger (UGB)/Sénégal.

⁴LUMR PALOC IRD/MNHN, LMI PATEO, IRD Hann, BP 1386, Dakar, Senegal.

⁵Direction de la Gestion et de la Planification des Ressources en Eau, Dakar, Sénégal.

Received 20 August 2018; Accepted 30 October 2018

Satellite rainfall estimates (SRE) with high spatial and temporal resolution and large areal coverage provide a potential alternative source to force hydrological models within regions where ground-based measurements are not readily available. The Gambia Basin in West Africa provides a good example of a case where the use of satellite precipitation estimates could be beneficial. This study aims to compare three SRE over a 12-year periods (1998-2010), before and after their integration into the GR4J hydrological model over the Gambia Basin. The inter-compared products are Climate Hazards Group Infrared Precipitation with Stations (CHIRPS), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record (PERSIANN-CDR) and TRMM 3B42v7 (Tropical Rainfall Measuring Mission). The calibration and validation of the GR4J model over the Gambia basin using a reference rainfall product (RRP) pointed out a very good performance. The correlation coefficient between simulated and observed daily discharge is higher than 0.8 both for calibration and validation. The inter-comparison of SRE against RRP and using them as forcing data into the calibrated GR4J hydrological model presented some coherence in the product performance. PERSIANN-CDR performs better both when comparing against RRP and when used in GR4J. The low performance of CHIRPS is surprising because it is supposed to be a product that includes ground-based station. This result may also indicate that in areas without ground stations, the CHIRPS is less accurate than other rainfall products that are based only on satellite images. Finally, a bias correction is applied to the SRE using the RRP. The bias correction had significantly improved the product performance. On average, the bias fell from 100 to 1.5% compared to the RRP, but the impact on the error is less significant. When using the corrected SRE in the hydrological model, the impact is very significant both on the bias and error. The overall performance of the different biases that corrected SRE is comparable.

Key words: Gambia, precipitation, satellite, evaluation, modeling, bias correction, Climate Hazards Group Infrared Precipitation with Stations (CHIRPS), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), Tropical Rainfall Measuring Mission (TRMM).

INTRODUCTION

Precipitation is a key variable in the hydrological cycle (Yang et al., 2017). Its quality is of paramount importance

to hydrologists, as uncertainty in precipitation estimates can give rise to biases in other hydrologic fluxes and

states because of nonlinearities in the hydrological cycle (Nijssen and Lettenmaier, 2004; Su et al., 2008; Harris and Hossain 2008, Yang and al., 2017). However, in many populated regions of the world, including developing countries, ground-based measurement networks are either sparse in both time and space or nonexistent (Hsu et al., 1999). In West Africa, the rainfall measurement network is generally very low compared to the spatial variability of rainfall (Taupin et al., 1998). In addition to the low density of *in-situ* measurements, this region faces a difficulty in acquiring daily data (Ali et al., 2004, Panthou et al., 2014, Bodian et al., 2016a). This is a major obstacle to conducting hydrological studies on certain watersheds (Bodian et al., 2016b), such as that of the Gambia, where precipitation is poorly quantified: the precipitated volume as the temporal variability of rains has been poorly studied due to the shortcomings of the traditional observation networks in this basin (44 rainfall stations for 77100 km²). In order to remedy these shortcomings, the user community most often uses the satellite-based rainfall estimate (SRE) products available at high resolution from operational and academic institutions and suitable for water resources monitoring particularly for hydrological modeling.

Despite their widespread use satellite products carry a certain level of uncertainty (e.g. estimation biases). The presence of bias in satellite rainfall estimates can lead to inaccuracies in the calculation of water balance since a significant amount of water is stored in the hydrological model. In order to have an overview of the desirability of using satellite products, two questions will be addressed here: i) what is the contribution of satellite rainfall products in hydrological modeling? ii) What is the best product for hydrological modeling? This study will evaluate three satellite rainfall products to determine their appropriateness for use in hydrological studies for the River Gambia.

There are two main evaluation approaches in the scientific literature: 1) an estimate of precipitation by satellite observations compared against the RRP constructed from measurements of the ground-based observations and 2) a hydrological assessment of these satellite products. The first is widely used in Africa (Ali et al., 2004, 2005; Roca et al., 2010; Jobard et al., 2011; Ceccherini et al., 2015; Toté et al., 2015; Dembélé and Zwart, 2016). The second is based on the hydrological assessment of satellite products, that is, the assessment of their ability to reproduce the observed flow. Despite its success in previous studies, there have been very few attempts to apply this approach in Africa, some examples including: Grimes and Diop (2003); Gosset et al. (2013), Thiemig et al. (2013) and Habib et al. (2014). However, on a global scale, it continues to gain popularity in the

scientific community (Yilmaz et al., 2005; Hong et al., 2006; Artan et al., 2007; Harris et al., 2007; Collischonn et al., 2008; Shrestha et al., 2008; Su et al., 2008; Behrangi et al., 2011; Xue et al., 2013; Ashouri et al., 2016). Although both approaches can be applied independently, they can be considered complementary (Thiemig et al., 2013), one providing a broad assessment of satellite product accuracy, while the other assesses the usefulness of products in other applications, such as hydrology.

It should be noted, however, that many of the example studies given above have either evaluated a single product on a watershed or several products on a single basin. To evaluate the hydrological performance of satellite products, most of these studies calibrated the model with the estimated rainfall by satellite rather than with the ground rainfall data. Additionally, few studies have applied the correction of the bias associated with satellite rainfall products. This contribution provides an innovative perspective on the hydrological assessment of estimated precipitation by satellite for four reasons: i) several products are evaluated and cross-compared in this study; (ii) the contribution of bias correction on the hydrological performance of satellite products; (iii) automatic calibration with a multi-objective approach (NSE and KGE); iv) quantification of the uncertainties associated with the average rainfall calculated by kriging in order to have a better quality RRP. With the results of this study, potential uncertainties on hydrological simulations in the Gambia Basin can be quantified. This study focuses on the hydrological assessment of three satellite products, CHIRPS (Funk and al., 2014), PERSIANN-CDR (PCDR) (Miao and al., 2015) and TRMM-3B42v7 (Huffman and Bovin, 2013), and a reference rainfall product (RRP) built from measurements of the ground-based observations. These products are validated on the Gambia Basin. For hydrological evaluation, the rainfall-runoff model GR4J (Perrin et al., 2003) was used and calibrated automatically over the period 1981-1996. In addition, a bias correction method was applied to correct bias in the satellite rainfall estimates (SRE) by CDFt bias correction method. By following this approach, this study will address two research objectives: i) establishing the contribution of bias correction on the hydrological performance of satellite products; (ii) The construction of a RRP by kriging to obtain an acceptable hydrological performance. The results of this study will help to elucidate the limits or weaknesses of the usefulness of SRE as input data for hydrological modeling. The overall objective of this study is to assess the contribution of SRE in hydrological modeling, as they can be the only source of precipitation for areas where ground networks are not available.

*Corresponding author. E-mail: bakaryfaty@gmail.com. Tél: +221 776647029.

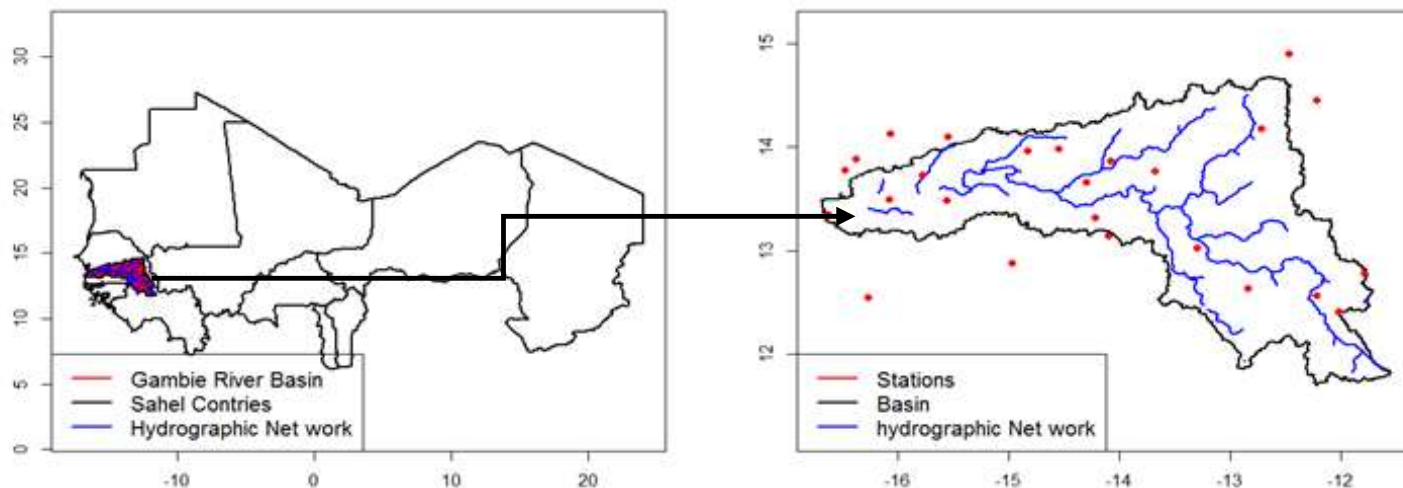


Figure 1. Network of stations gauge in the Gambia River basin.

MATERIALS AND METHODS

Study area

The study area is the basin of the Gambia which is a transboundary basin, draining an area of 77100 km², between latitudes 11° 22 ' and 14° 40 ' N and longitudes 11° 13 and 16° 42 ' W. Over a total length of 1180 km, the Gambia River has a lower course of 540 km influenced by the tide and a higher course in Guinea of only 200 km. It takes its source at about 1150 m above sea level in the Fouta-Djallon, near Labé. Its initially south-north course leads from Mako to Goulombou to the northwest and then west to the sea at the latitude of 13° 30 (Olivry, 1983). Figure 1 shows the location of the basin and the stations managed by Department of Water Resources (DWR) for the Gambia and National Agency for Civilian Aviation and Meteorology (ANACIM) for Senegal. From the climate point of view, the Gambia basin is subjected to tropical monsoon climate with a long dry season from November to May and a short rainy season from June to October. The characteristics of the rainy season and precipitation heights make it possible to classify the essential of the Gambia basin in the Sudano-Guinean zone.

Satellite products evaluated

The satellite products evaluated in this study are CHIRPS, PERSIANN-CDR (called PCDR) and TRMM 3B42. A brief description of these three products is presented below.

CHIRPS

CHIRPS data are global products of precipitation estimates by satellite. They are available at spatial resolutions of 27 and 5 km, since 1981. The CHIRP algorithm combines the estimates of infrared precipitation and calibrated with TRMM data and reanalysis model products. CHIRP merges resolution 0.25 satellite imagery with ground observation data to create monthly gridded time series for the monitoring of seasonal drought and water resource management. CHIRP incorporates Infrared (IR) estimates of historical and current precipitation in two stages for the period 1981 to the present day.

PCDR

Precipitation Estimation from remotely sensed Information using Artificial Neural Networks (PCDR) was developed by the University of California's Center for Hydrometeorology and Remote Sensing (CHRS) at Irvine and uses the technique of Classification using an artificial neural network to calibrate IR images with microwave (MW). PCDR has undergone several developments (Hsu et al., 1997, 1999). Initially, PCDR only incorporated IR satellite data but currently includes MW data from TRMM Microwave Imager (TMI). The IR data usually comes from the GOES-8, GOES-9/10, GOES-12, GMS-5, Meteosat-6, and Meteosat-7 geostationary satellite imagery and VIRS. After revision in 2014, another PCDR (Climate Data Record) product has been available since 2015 in the daily time period 1983-present, with a spatial resolution of 0.25° × 0.25°. It is a post-adjusted product that is based on the archives of IR measurements. The main input data of the PCDR algorithm come from another CDR: IR measurements of the product GridSat-B1 (International Satellite Cloud Climatological Project, ISCCP B1). GridSat-B1 products are combined data from the various geostationary satellites available over the years, from 1980 to the present. The other input data is the monthly precipitation of Global Precipitation Climatology Project (GPCP) (Huffman et al., 1997).

TRMM

The product TRMM 3B42 is based on the Tropical Rain Measurement Mission. TRMM is a joint project between the national Aeronautics and Space Administration (NASA) and the National Space Development Agency of Japan (NASDA). It was launched on 27 November 1997 on an H-II rocket from the NASDA. It is a product of near-real-time rain estimation, with a spatial resolution of 0.25° and time resolution of three hours. TRMM uses MW estimates when available, and IR estimates if not. IR estimates are calibrated with MW estimates to be consistent when simultaneously available. The calibrated MW estimates data are merged with IR data from the GOES-W, GOES-E, GMS, Meteosat-5 and Meteosat-7 and NOAA-12 satellites. Then, the IR/MO merged precipitation estimates are integrated into a grid for each observation. Finally, the measurements of the ground-based observations of the Global Precipitation Climatology Project (GPCP) (Huffman et al., 1997) are included in the procedure. Huffman et al. (2007) describe the

Table 1. Main characteristics of satellite-based precipitation estimate products used in this study.

Name	Time resolution (h)	Spatial resolution	Zonal coverage	Input data	File Format	Period covered
TRMMv7	3	0.25	50N~50S	IR/MW+Gr	Netcdf	1998-Present
PCDR	24	0.25	60N~60S	GridSatB1+ IRWIN	Netcdf	1983~Present
CHIRPS	24	0.25	50N-50S	IR+Gr.	Netcdf	1981~Present

construction of TRMM-3B42. Table 1 presents a summary of the characteristics (spatial coverage, temporal and spatial resolutions, etc.) of the three satellite products.

GR4J model and meteorological data for calibration

The GR4J model (Perrin et al., 2003) was used for the hydrological inter-comparison of CHIRPS, PCDR and TRMM satellite products in the simulation of stream flows in the Gambia River basin. GR4J is a daily lumped four-parameter rainfall-runoff model (Perrin et al., 2003). It consists of a production reservoir, two unit-hydrograph, a routing reservoir and an underground exchange function (Gosset, 2014). The GR4J has a function for compensating precipitation by evapotranspiration. The model is based on the production function that determines the effective precipitation that supplies the production reservoir (capacity $\times 1$ in mm) and on routing function based on a unit hydrograph.

A percolation from the production reservoir adds to the effective rains to reach a transfer module. Two units-hydrograph (with a base time governed by the free parameter $\times 4$ in daylight) and a routing reservoir (of capacity $\times 3$ in mm) simulate two flow components, each of which is applied a water exchange function (coefficient $\times 2$ in mm/d). This GR4J model has been used via AirGR which is a package R (Coron et al., 2016).

The calibration meteorological data for the GR4J model include daily precipitation, maximum (Tmax) and minimum (Tmin) temperatures, and Evapotranspiration (ETo) calculated from Tmax and Tmin with the methodology proposed by FAO (1998). The precipitation and temperature data were provided by the DWR for the Gambia and the ANACIM for Senegal and cover the period 1981-2010. The reference rainfall product (RRP) was calculated by ordinary kriging, from 25 rain gauges. For more details of this method, the reader can refer to Ali et al. (2005), Renard and Sarr (2009) and Vischel et al. (2011).

Hydrological calibration data for the GR4J model

With regard to the large number of Senegalese Hydrometric stations (14 stations) in the Gambia River, a sample of four stations may appear to be restricted, particularly with a goal to have generalizable results. These gauges were selected due to the relative quality and completeness of their records and by the fact that these gauges including data over a period that is common to all stations. In fact, a pre-selection was made on the 14 stations available in Senegalese territory of the basin. Only the stations with at least 20 years of availability over the period 1981 – 2010 have been selected, with an annual gap rate of less than 30%. The measured stream flows of these four stations constitute the reference data of the selected hydrological model and they are used for both parameter calibration and model validation. These daily hydrological data are from the database of the Water Resources Management and Planning Direction (DGPRE) of Senegal. The daily stream flows observed at the Wassadou station cover only the period 1981-2000, while the simulation period ranges from 1999 to 2009.

Statistical criteria for performance evaluation

The primary objective of this study is to evaluate the SRE (CHIRPS, PCDR and TRMM) products in comparison with gauge-derived estimates. Twenty years of basin-averaged precipitation from SRE and gauge estimates were compared at daily time scale. To evaluate stream flow simulation implications of the for products rainfall, the GR4J model was forced by the daily SRE and gauged precipitation at three stations of Gambia River basin. The simulated stream flow results were compared against the stream flow observations. Several statistical criteria were used to evaluate the model performance for calibration period and stream flow simulations. The choice of several criteria is explained by the fact that a single performance criterion cannot claim to be usefully considered for all aspects of a product (Ali, 2004; Ebert et al., 2007). The quantitative accuracy of satellite precipitation estimations was assessed by relative percent of bias (PBIAS), mean absolute error (MAE) and root-mean-square error (RMSE). The GR4J model performance evaluations were based on Nash-Sutcliffe efficiency (NSE), Kling Gupta Efficiency (KGE) and the Pearson correlation coefficient (r). These criteria are defined as follows:

$$NSE = \frac{(Q_{Obs} - Q_{Sim})^2}{(Q_{Sim} - \bar{Q}_{Sim})^2} \quad (1)$$

$$KGE = 1 - \sqrt{\left(\frac{\sigma_{Q_{Sim}}}{\sigma_{Q_{Obs}}}\right)^2 + \left(\frac{1}{Bias}\right)^2 + (r - 1)^2} \quad (2)$$

$$R = \frac{\sum_{i=1}^n (Q_{Simi} - \bar{Q}_{Sim})(Q_{Obsi} - \bar{Q}_{Obs})}{\sqrt{\sum_{i=1}^n (Q_{Simi} - \bar{Q}_{Sim})^2} \sqrt{\sum_{i=1}^n (Q_{Obsi} - \bar{Q}_{Obs})^2}} \quad (3)$$

$$Bias(\%) = \left| \frac{\sum_{i=1}^n (Q_{Sim} - Q_{Obs})}{\sum_{i=1}^n Q_{Obs}} \right| \times 100 \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (R_{Si} - R_{Gi})^2} \quad (5)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |R_{Si} - R_{Gi}| \quad (6)$$

With n , the number of measurements; P_{Si} , the estimated or simulated daily value; P_{Gi} , the daily reference or observed value; \bar{P}_{Gi} , the average of the reference values or observed; \bar{P}_{Si} , the average of the simulated values; and where $\sigma_{P_{Gi}}$ is the standard deviation of the observed stream flows; $\sigma_{P_{Si}}$, the standard deviation of the simulated daily stream flows; r is the Pearson correlation coefficient between observation and simulation and the Pbias represents the mean volume error.

Bias correction method used in this study

The comparison of satellite products against RRP shows that satellite data require bias correction. Indeed, several authors have demonstrated that satellite-based rainfall products need to be corrected for use in various regional applications (Islam et al., 2010; Shrestha et al., 2011; Xue et al., 2013; Khandu et al., 2015). This study uses the CDFt (Cumulative Distribution Function-Transform) bias correction method, originally developed for the downscaling of the climate model outputs, to correct the bias of SRE. Here the method is based on the assumption that the satellite and *in situ* data have similar statistical properties. It takes into account only the probability distribution instead of applying the quantile-quantile correction between satellite and RRP. It calculates a cumulative distribution function (CDF) for satellite data.

Calibration of the GR4J model

In this study, the model was calibrated and validated using the RRP and run for each precipitation forcing in a simulation mode (using rain gauge calibrated parameters). The observed discharge data were divided into two parts for calibration and validation. The model calibration was performed over the period 1981-1996. The choice of the calibration period is due to the continuity of the data observed over this period. The GR4J model does not allow for gaps in calibration periods. However, the only time series with no gap is the one used. This period was preceded by a year (1981-1982) of warm-up of the model, to initialize the contents of the reservoirs. The period 1997-2000 was used for the validation of the model. Thus, the resulting model could be considered robust and capable of simulating the mean daily stream flows satisfactorily. The Kling Gupta Efficiency (KGE) and Nash-Sutcliffe Efficiency (NSE) were adopted as the objective function. The optimization is performed by iteratively and systematically changing the values of the model parameters in order to obtain a Nash optimum criterion and a significant KGE value close to 1. The KGE, NSE and r were used to evaluate the model performance. In addition, there are also four classifications when using NSE. The KGE, r and NSE range from $-\infty$ to 1, with higher values indicate better agreement. The calibration method, applied in this study, is based on two objective functions (NSE and KGE). The optimization is performed by iteratively and systematically changing the values of the model parameters in order to obtain a Nash optimum criterion and a significant KGE value close to 1.

RESULTS

Calibration

The results of the statistical criteria of the GR4J model calibration and validation with the RRP, over the 1981-1996 period are given in Table 2. Both in calibration and validation, NSE present high values, ranging respectively from 0.77 to 0.78 and 0.58 to 0.74; r is greater than 0.8 at all stations both in calibration and validation. Furthermore, the KGE presents high values that are greater than 0.75 in all stations. According to Thiémig et al. (2013), the performance of model is deemed good when $KGE \geq 0.75$, an efficient medium if it is between 0.75 and 0.5 and mediocre if it is less than 0.5. In addition, there are also four classifications when using NSE: unsatisfactory ($NSE \leq 0.50$), satisfactory ($0.5 < NSE \leq 0.70$), good ($0.70 < NSE \leq 0.80$), and excellent ($NSE > 0.80$) (Ren et al.,

2018). According to these classifications, we can conclude that the model is well calibrated because the values of NSE are greater than 0.76 in all stations (Table 2). The calibrated model is effective in simulating high stream flow but less effective at simulating the low stream flow. This is due to the fact that it does not fully take into account the relationship between groundwater and surface water (Fabre et al., 2015) which is inadequate to represent low flows.

Globally, the model has quiet similar performance in calibration and validation. In other words, the model is capable to reproduce high or low stream flows not observed during the calibration period. In validation one notices that the values of NSE fell at all the stations while those of the KGE have increased at all stations. This result in validation can be explained by the length of the validation period. Graphical results during calibration period (Figure 2) indicated adequate calibration. This good calibration matches with the high values of correlation coefficients.

Evaluation of satellite products against RRP

Results from the statistical criteria

The results of PBIAS, MAE and, RMSE of the evaluation of SRE (CHIRPS, PCDR and TRMMv7) against RRP over Gambia River are presented in Table 3. PCDR underestimates with respect to RRP (negative PBIAS) while CHIRPS and TRMM overestimate (CHIRPS presents larger overestimation). The RMSE and MAE of PCDR are smaller than those of CHIRPS and TRMM. We can consider from these results that PCDR is more accurate than CHIRPS and TRMM. Despite these results, the CHIRPS product includes ground station data while PCDR and TRMMv7 are satellite-based products without gauge station. These results are somehow surprising, because the integration of the gauge data should have a significant impact on the SRE performance. Additional investigation is necessary to check how many stations are included in the CHIRPS product over the Gambia basin.

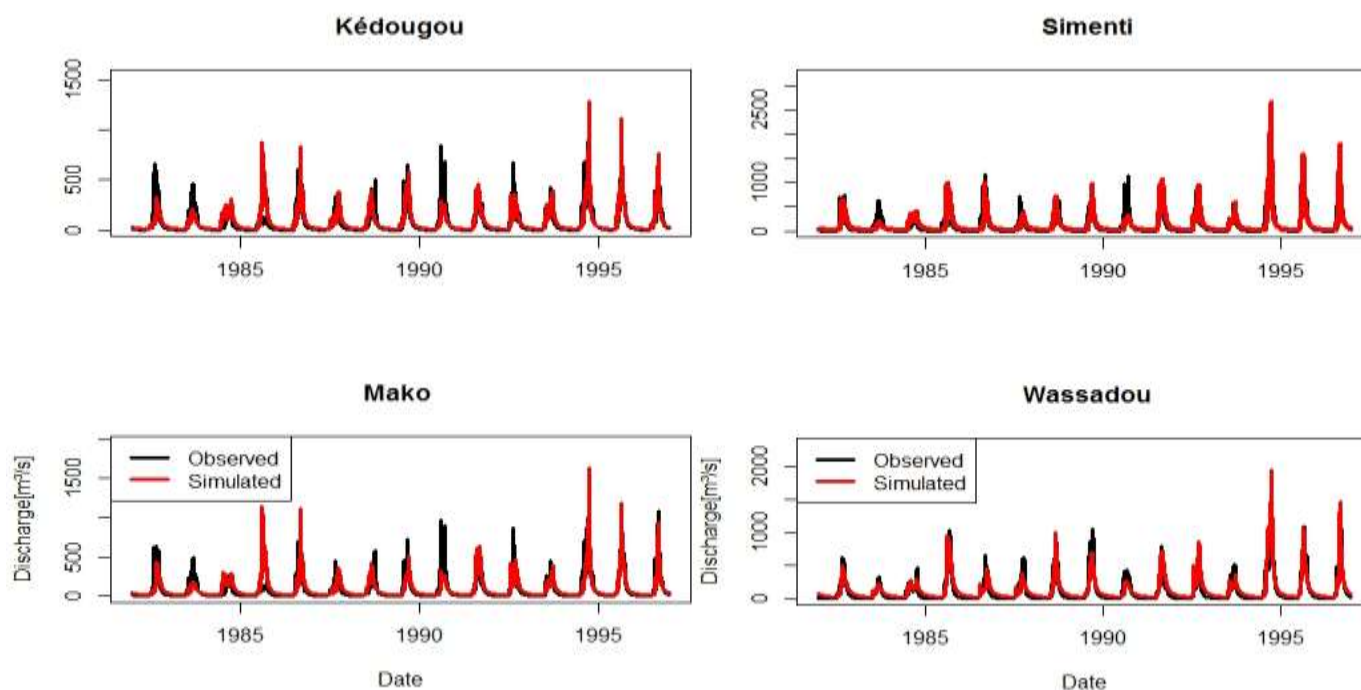
Evaluation of simulations with CHIRPS, PCDR and TRMM uncorrected

This section focuses on the performance study of CHIRPS, PCDR and TRMM satellite products in hydrological modeling. Consequently, it has been excluded from the stations on which the hydrological assessment of satellite products has been carried out.

The GR4J hydrological model calibrated with the RRP was forced by CHIRPS, PCDR and TRMM to simulate stream flows at Kédougou, Mako and Simenti stream flow gauge stations. In this analysis any bias correction of the SRE products is made. The results of the analysis (Table

Table 2. Calibration and validation of the GR4J model with the RRP.

Station	Calibration			
	Kédougou	Mako	Simenti	Wassadou
NSE	0.767	0.769	0.774	0.779
KGE	0.801	0.816	0.794	0.759
r	0.888	0.882	0.904	0.891
	Validation			
NSE	0.583	0.608	0.747	0.706
KGE	0.79	0.806	0.832	0.85
r	0.79	0.811	0.88	0.86

**Figure 2.** Daily hydrographs observed and simulated by the GR4J model at Kédougou, Mako, Siment, and upstream Wassadou, the black Hydrographs represents the observed flows.**Table 3.** Results of Evaluation criteria for the different SRE over 1998-2010 period.

Statistical criteria		Kédougou	Mako	Simenti	Wassadou
PBIAS	CHIRPS	50.2	45	27.3	4.4
	PCDR	-31.4	-31.7	-39.6	-43.2
	TRMMv7	29	28	20.9	7.7
RMSE	CHIRPS	11.46	11.13	10.08	9.26
	PCDR	9.03	8.89	8.88	8.79
	TRMMv7	12.21	12.55	12.56	12.51
MAE	CHIRPS	7.97	7.68	6.88	6.26
	PCDR	6.29	6.19	6.17	6.07
	TRMMv7	7.83	7.81	7.66	7.61

Table 4. Statistical criteria for hydrological evaluation of satellite products CHIRPS, PCDR and TRMM.

Statistical criteria		Kédougou	Mako	Simenti
PBIAS	CHIRPS	115.1	138.2	92.6
	PCDR	-52.9	-44.2	-60.9
	TRMMv7	77.2	108.8	93.4
RMSE	CHIRPS	238.6	287.1	361.6
	PCDR	142	152.7	282.5
	TRMMv7	180.9	233.2	356.9
MAE	CHIRPS	114.7	142.4	167.3
	PCDR	66.7	69.8	130.3
	TRMMv7	86.78	116.7	169.2

4) show a similar rank of performance of the stream flow simulation. Even if the bias and errors are very high for the stream flow simulation (the bias is higher than 100%), PCDR performs better than TRMM, which is better than CHIRPS. These performances of the stream flow simulation are consistent with the SRE evaluation against the RRP. This overestimation is larger for CHIRPS than for TRMM (Table 4). Therefore, CHIRPS estimation errors are more important than those of TRMM. Regarding the RMSE and the MAE, PCDR seems to show the best accuracy. However, its ability to underestimate reduces its estimation performance.

Simulated daily stream flows with uncorrected products

Figure 3 shows the simulated and observed daily hydrographs at Kédougou, Mako and Simenti stream gauge stations. The watershed of the Gambia is subject to rainfall variability which is reflected in the annual regime of its waterway. Visual evaluation of hydrographs showed that the model reproduces the observed stream flows more accurately when forced with the RRP. The daily flows simulated by the model with the RRP and the uncorrected satellite data (CHIRPS, PCDR and TRMMv7) are compared to the daily stream flows observed over the Gambia River basin (Figure 3). Although the model simulates stream flows, it tends to overestimate some of the peak stream flows at all stations with CHIRPS and TRMM products. In all the stations and with all products, the correlation coefficient is high. Indeed, it is between 0.6 and 0.67 for simulated stream flows with PCDR, 0.77 and 0.82 for simulated stream flows with CHIRPS and between 0.77 and 0.84 for TRMM stream flows. The lowest correlation values for all products are found at Kédougou.

In summary, the simulated stream flows with the SRE and the RRP correctly reproduce the inter annual variations of observed stream flows during the eleven

years of the simulation period (1999-2009). The simulated stream flows with the RRP correspond better to the observed stream flows than those simulated with the satellite-based rainfall estimated for the Gambia River basin (Figure 3). Most peak stream flows are overestimated by the forced model with satellite products (with the exception of PCDR), due to overestimation of heavy rains by CHIRPS and TRMM compared against RRP. It is in this context that the application of bias correction is necessary.

Effect of bias correction on satellite rainfall products

As shown in the previous section, satellite products, though an important asset in many applications, are subject to substantial biases. On the other hand, hydrological models, even though they are designed from physics-based equations, are generally statistical tools calibrated with meteorological data on the ground. In addition, they are often nonlinear, and they can be very sensitive to estimation biases. To limit this "weakness" and allow satellite data to be integrated into the hydrologic model more efficiently, a correction of satellite rainfall estimation biases has been applied. Although this correction of satellite estimation biases against baseline data is not a complete solution due to the shortcomings associated with soil network data for calibration and validation in Africa (Washington et al., 2006), it helps to reduce the bias of satellite precipitation estimates and gives more improved qualities (Jobard et al., 2011).

Contribution of the bias correction of the satellite rainfall products

We used the calibrated model with the RRP to simulate the stream flows using the corrected CHIRPS, PCDR, and TRMM precipitation estimates. We used the parameters of this model calibrated with RRP in all simulations with CHIRPS, PCDR, TRMM and the RRP to

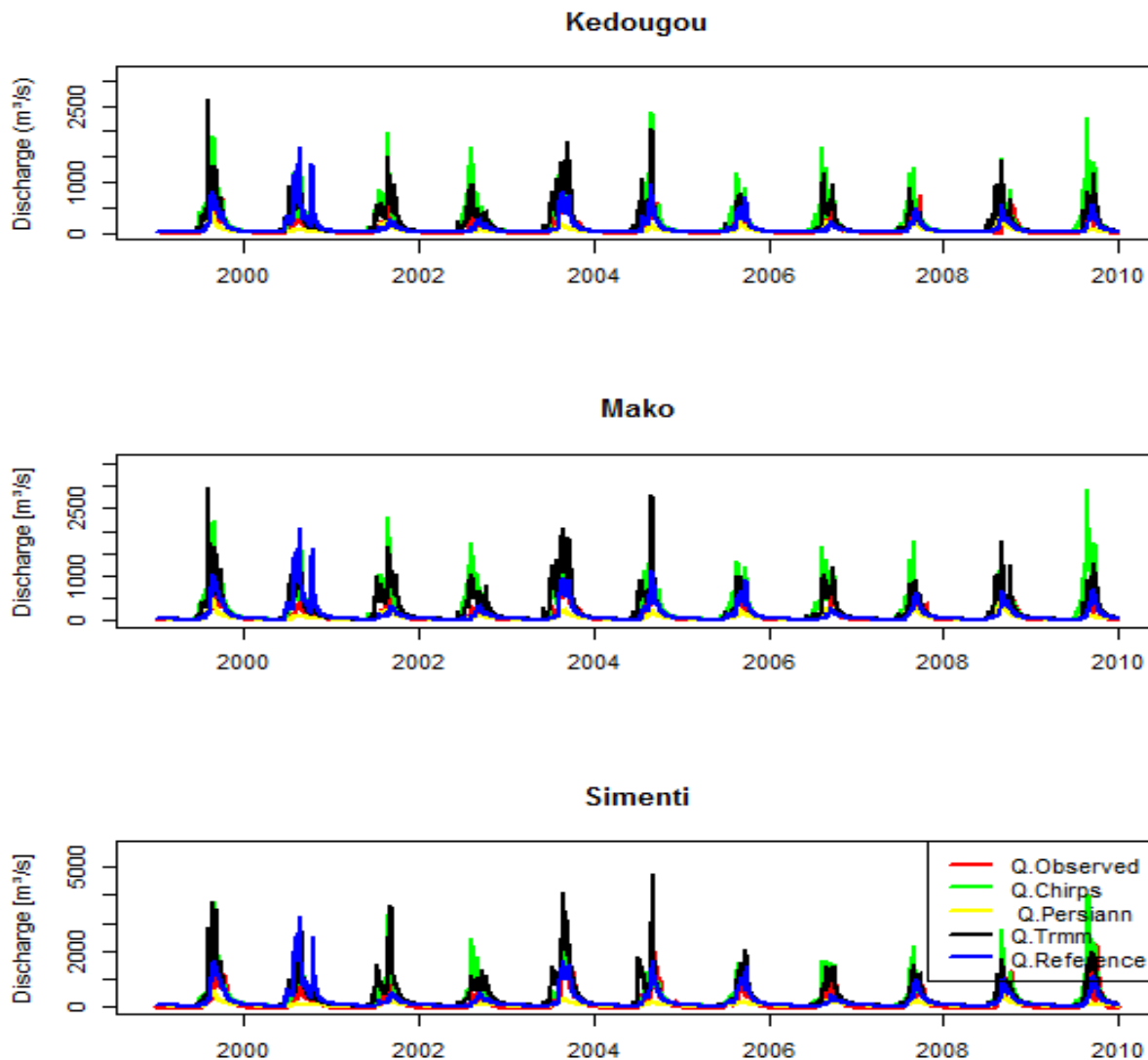


Figure 3. Hydrographs observed and simulated from RRP and uncorrected satellite rainfall products. Red represents the observed stream flow, black forced stream flow with TRMM, blue represents forced stream flow with RRP, green represents the forced stream flow with CHIRPS and the yellow represents PCDR.

minimize the impact of simulation biases from other sources of uncertainty (for example, the uncertainty related to the parameters). For the entire simulation period (1999-2009), the biases of all products are positive at all stations, except for Kedougou stream gauge station where the underestimation bias occurs. Even in periods of high water (the months of August and September), biases are always negative. This suggests that a proportion of the rains is stored in the model instead of contributing to the production of stream flow. Overall, the results indicate that the biases of CHIRPS, PCDR, and TRMM are amplified in model simulations. Bias correction impacts moisture conditions by making simulated stream flows with satellite products more realistic.

We evaluated the contribution of bias correction on the

simulations of the GR4J model, with the products CHIRPS, PCDR and TRMM. Figure 4 shows the simulated hydrographs from CHIRPS, PCDR, and TRMM data corrected by the cumulative distribution Function-Transform (CDFt) method (Michelangeli et al., 2009). CDFt is a statistical method developed to generate local cumulative distribution (CDF) functions from large-scale fields. After bias correction, the gap between the corrected daily SRE and RRP became very low. Indeed, product biases have been significantly reduced (Tables 3 and 5). Table 5 clearly shows that bias correction has added value to the corrected products. Overestimation biases have been passed through low underestimations for CHIRPS and TRMM to very strong underestimation at a very low underestimation with PCDR. The statistics are

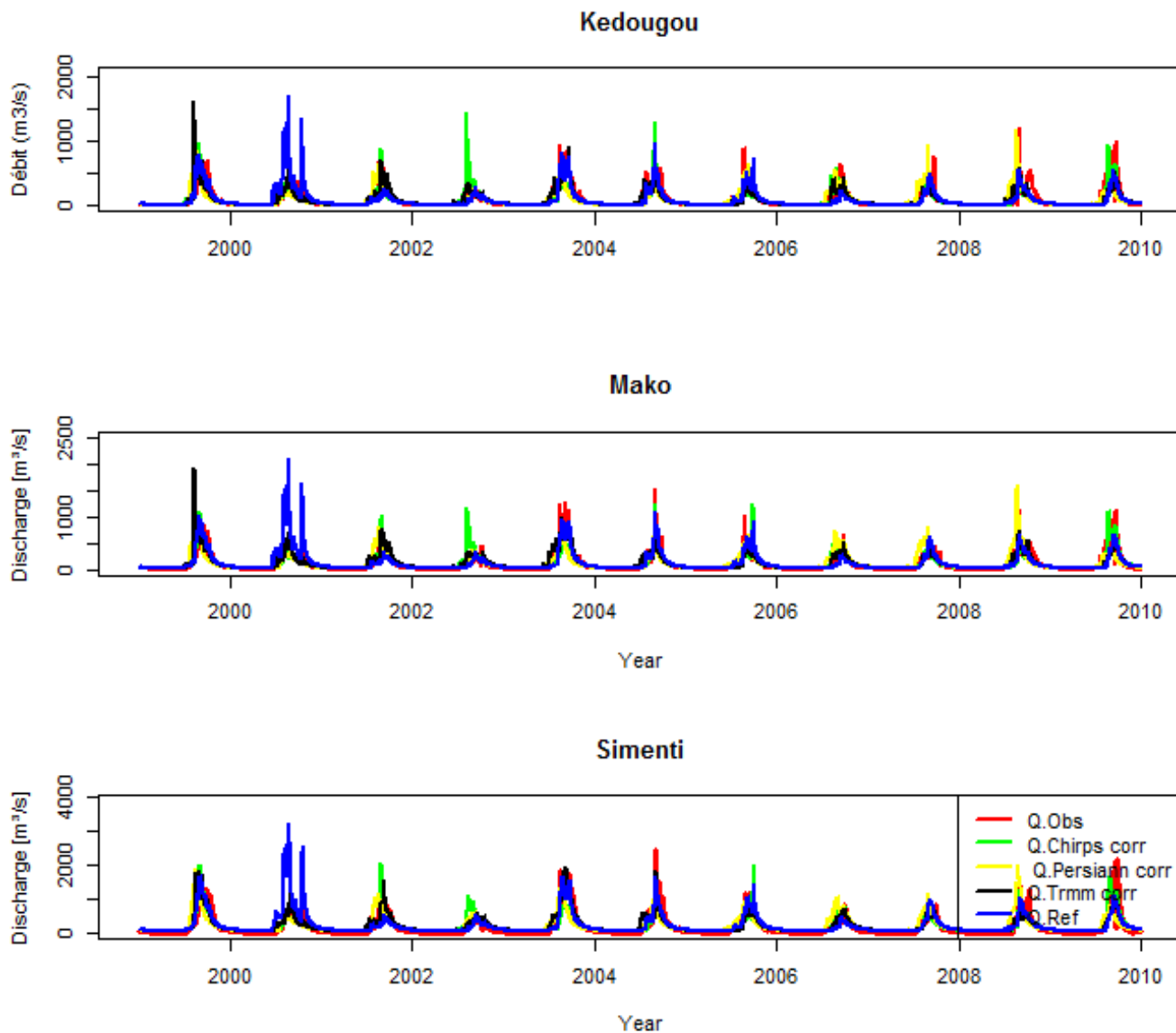


Figure 4. Hydrographs observed and simulated from the corrected satellite rainfall products (CDF-T method) and the RRP.

Table 5. Evaluation of the corrected products (CHIRPS, PCDR and TRMM) against the RRP over a period of 1998-2010.

Statistical criteria		Kédougou	Mako	Simenti	Wassadou
PBIAS	CHIRPS	-1.90	-1.4	-2	-2
	PCDR	-0.5	-0.8	-0.2	-2
	TRMMv7	-2.20	-0.9	-2	-2
RMSE	CHIRPS	8.95	8.70	8.47	8.39
	PCDR	9.75	9.49	9.51	8.39
	TRMMv7	9.53	9.51	9.47	8.39
MAE	CHIRPS	5.90	5.70	5.53	5.46
	PCDR	6.57	6.39	6.40	5.46
	TRMMv7	6.14	5.94	6.08	5.46

better for corrected products than for uncorrected products that are closer to reality.

Contributions of the satellite rainfall bias correction on the simulated flow

The analysis of Figure 4 demonstrates that the observed hydrographs are reproduced more accurately with corrected CHIRPS, PCDR and TRMM rainfall estimates compared to the uncorrected data. However, the observed hydrographs are better represented using only the RRP (Figure 4). The hydrographs simulated from the two input sources of the model (RRP and corrected satellite products) show the same variability as those of the observed hydrographs. Such agreements can be explained by the contribution of bias correction of satellite products.

The study then evaluates the propagation of errors in estimation of CHIRPS, PCDR, and TRMM rainfalls in model simulations (Table 5). To dissociate the effect of rainfall estimation errors from the effects of uncertainty resulting from model parameters on model performance, model simulations with kriged RRP were used as a RRP to compare the criteria for product performance. After bias correction, the precipitation estimates of CHIRPS, PCDR, and TRMM is lower than that of the RRP from -2 to -1.9%, respectively; -0.8 to -0.2% and from -2.2 to -0.9%. These low underestimations resulted in biases in simulated stream flows in larger satellite rainfalls (Tables 5 and 6). However, simulated flows with corrected products have lower biases than those simulated with uncorrected satellite rainfalls (Table 5). The propagation of precipitation bias at simulated stream flows persists for all products (CHIRPS, PCDR, and TRMM) both corrected and uncorrected. In addition to this propagation, it is noted that the negative biases of the precipitation at Mako and Simenti stream gauge stations have been transformed into positive biases in the simulated stream flows of these stations. This indicates non-linearity in the parameters of the hydrological process in the GR4J model. Thus, the amplification of errors in the simulated stream flows with the products is probably related to the non-linearity of the rainfall-runoff relationship and the streamflow generation relative to the model. A small bias in rainfall input can propagate to result in larger streamflow bias when the watershed is wet than when it is dry (Habib et al., 2014). Such situations may be caused by deficiencies in model structure (e.g. simplified, incomplete or incorrect description of hydrological processes), low representation of precipitation by low density of the network, or errors in the transformation of the flows observed in a water slide.

Table 6 presents biases in model-simulated stream flows using corrected and uncorrected satellite rainfall. In relation to the observed stream flows and those simulated with the RRP, the simulated stream flows with

the uncorrected and corrected satellite data (with the exception of PCDR) are consistently stronger during the rainy season (June-July-August-September) of the period 1999-2009. However, the simulated stream flows in low-flow periods with the corrected or uncorrected products do not differ from the observed stream flows (Figure 4). However, statistical analysis has shown that errors associated with the simulated flows with CHIRPS PCDR and TRMM products are more important than those associated with RRP. This may be due to the buffer effect of the model because they transform the rainfall, which is highly variable, into flow. The bias between the observed flows and the flows obtained with the corrected SRE is smaller than the bias between the observed stream flows and the stream flows resulting from the simulation of uncorrected SRE. Bias correction thus contributes to improve the quality of the stream flows obtained with SRE. Overestimation biases become weaker and more underestimates are improved. Therefore, the correction significantly reduced the bias of the simulated stream flows.

DISCUSSION

In this study, we used model calibration based on RRP and observed stream flow over 1982-1996 for all the GR4J model runs. For evaluating hydrological simulation, over the period 1998-2010, our benchmark was the observed discharges. Various studies (Yilmaz et al., 2005; Artan et al., 2007; Zeweldi et al., 2011) noted an increased performance of hydrological model when the model calibrated using SRE than RRP. Although we could calibrate with the SRE, we found four reasons for not doing so : (i) calibrating the model using the RRP gives better coefficients to simulate stream flows with all its products, (ii) the length of the RRP used for our calibration is longer than that of the SRE and provides better basis for evaluating model performance under different climate conditions, (iii) keeping same model parameters allows one to investigate how various rainfall estimates affect simulated streamflow, and (iv) as GR4J model parameters are the same for all runs, biases in the simulated streamflow (Tables 4 and 6) could be attributable to differences in input precipitation. Most peak of stream flows were overestimated in daily hydrographs. This is associated with the apparent overestimation of high rainfall in the SRE. The large overestimation of the peak flow over Gambia River basin was mostly attributable to the overestimation of high rainfall in SRE in this basin. All positive rainfall bias drove large positive bias response in simulated stream flow. This finding is in good agreement with those of Nijssen and Lettenmaier (2004) who found that unbiased and temporally uncorrelated errors in precipitation can give rise to biases and temporally correlated errors in other hydrologic fluxes and states because of nonlinearities in

Table 6. Statistical criteria for hydrological assessment of CHIRPS, PCDR and TRMM.

Statistical criteria		Kédougou	Mako	Simenti
PBIAS	CHIRPS	-2.4	10.5	6
	PCDR	-4.9	13	12
	TRMMv7	-4.1	14.2	9.6
RMSE	CHIRPS	103.1	109.1	176.9
	PCDR	126.5	148.6	235
	TRMMv7	98.66	105.6	152.9
MAE	CHIRPS	49.3	56.3	88.2
	PCDR	59.3	68.1	108.7
	TRMMv7	47.26	55.2	81.3

the hydrological cycle. We hope that this assessment will contribute to improve the accuracy of satellite precipitation estimates for hydrological modelling.

Conclusion

Somme studies, such as Habib et al. (2014) have shown that satellite-based rainfall estimates are subject to systematic and random errors. However, very few studies have shown how these products can be used in various applications by reducing their errors. In this study, we evaluated the contribution of bias correction of CHIRPS, PCDR, and TRMM on the performance of the hydrological model GR4J. The study is novel in that it evaluates the effect of bias correction of CHIRPS, PCDR, and TRMM for hydrological modeling in a poorly gauged river basin. The results contribute to efforts to improve the use of SRE products. In general, CHIRPS, PCDR and TRMM all present uncertainties and biases on the precipitation estimates over the Gambia River basin. These uncertainties and biases of SRE could come from the calibration of sensors, algorithms and sampling errors of rain fields (Delahay, 2013). The present study showed by the hydrological assessment that uncertainties are not only derived from rainfall estimates.

The correction of the estimation biases of CHIRPS, PCDR and TRMM was made with the CDFt correction method. One of the main innovations of this study is the contribution of bias correction on the three products used. It has significantly improved the quality of the products by reducing their bias. The low density of the ground measurement network in the Gambia basin could contribute to the persistence of residual biases after correction, resulting in a slight gap between the observed data and the corrected satellite data. The model reproduces better the variability of the observed hydrographs when using the corrected estimates than when using the uncorrected estimates. The study shows that the model amplifies small errors in estimating

precipitation and large errors on simulated stream flows. The values of these error amplifications have become lower for the corrected satellite data than for the uncorrected ones. In this study, mean biases of 40% of CHIRPS precipitation, -34.1% of PCDR, and 26% of TRMM resulted in mean stream flow biases of 1115.3% for CHIRPS, -52.7% for PCDR, and 93.1% for TRMM. Bias amplification is more important (for example, 45% precipitation bias at 138% flow bias for CHIRPS to Mako) when the model is forced with uncorrected data. It should be noted that this amplification of errors depends not only on the errors in the input data (precipitation), but also on the accumulation of precipitation which affects the actual humidity and the initial state of the model (water in the reservoirs of Models). Future studies could calibrate the model with the satellite products used to show how the performance of a hydrological model changes when RRP is replaced with satellite products.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

- Ali A, Amani A, Dieddhiou A, Lebel T (2005). Rainfall estimation in the sahel Part II: Evaluation of rain gauge networks in the cilss countries and objective intercomparison of rainfall products. *Journal of Applied Meteorology* 44:1707-1722.
- Ali A, Amani A, Lebel T (2004). Estimation des pluies au Sahel : utilisation d'un modèle d'erreur pour évaluer réseaux sol et produits satellitaires, *Sécheresse* 15:271-278.
- Ali A (2004). Modélisation de l'invariance d'échelle des champs de pluie sahéliens : Application aux algorithmes d'estimation et aux études de variabilité climatique. Thèse de doctorat de l'Institut National Polytechnique de Grenoble 129 p.
- Artan G, Gadain H, Smith JL, Asante K, Bandaragoda CJ, Verdin JP (2007). Adequacy of satellite derived rainfall data for stream flow modeling. *Natural Hazards* 43:167-185.
- Ashouri H, Nguyen P, Thorstensen A, Hsu KL, Sorooshian S, Braithwaite D (2016). Assessing the Efficacy of High-Resolution Satellite-Based PERSIANN-CDR Precipitation Product in Simulating

- Streamflow. *American Meteorological Society* 17:2061-2076.
- Behrangi A, Khakbaz B, Jaw TC, Agha Kouchak A, Hsu K, Sorooshian S (2011). Hydrologic evaluation of satellite precipitation products over a mid-size basin. *Journal of Hydrology* 397:225-237.
- Bodiani A, Ndiaye O, Dacosta H (2016a). Evolution des caractéristiques des pluies journalières dans le bassin versant du fleuve Sénégal : Avant et après rupture. *Hydrological Sciences Journal* pp.1-9.
- Bodiani A, Dezetter A, Deme A, Diop L (2016b). Hydrological Evaluation of TRMM Rainfall over the Upper Senegal River Basin. *Hydrology* 15:1-18.
- Ceccherini G, Ametztoy I, Hernández CP, Moreno C (2015). High-Resolution Precipitation Datasets in South America and West Africa based on Satellite-Derived Rainfall, Enhanced Vegetation Index and Digital Elevation Model. *Remote Sensing* 7:6455-6488.
- Collischonn B, Collischonn W, Tucci CEM (2008) Daily hydrological modeling in the Amazon basin using TRMM rainfall estimates. *Journal of Hydrology* 360:207-216.
- Coron L, Perrin C, Delaigue O, Andréassian V, Thirel G (2016). airGR: a suite of lumped hydrological models in an R-package, *Environmental Modelling and software*. in preparation.
- Dembélé M, Zwart SJ (2016). Evaluation and comparison of satellite-based rainfall products in Burkina Faso, West Africa. *International Journal of Remote Sensing* 37:3995-4014.
- Ebert EE, Levizzani V, Bauer P, Turk FJ (2007). Methods for verifying satellite precipitation estimates. In *Measuring Precipitation from Space: EURAINSAT and the Future*. 345-356 (Berlin: Springer).
- Fabre J, Ruelland D, Dezetter A, Grouillet B (2015). Simulating past changes in the balance between water demand and availability and assessing their main drivers at the river basin scale. *Hydrology and Earth System Sciences* 19:1263-1285.
- Funk CC, Peterson PJ, Landsfeld MF, Pedreros DH, Verdin JP, Rowland JD, Romero BE, Husak GJ, Michaelsen JC, Verdin AP (2014). A quasi-global precipitation time series for drought monitoring. *US Geological Survey Data Series* 832 :4
- Gosset C (2014). Quel apport des données satellites d'enneigement pour le calage d'un modèle hydrologique sur des bassins de montagne ? mémoire de Master Univ Paris Sud 63.
- Gosset M, Viarre J, Quantin G, Alcoba M (2013). Evaluation of several rainfall products used for hydrological applications over West Africa using two high-resolution gauge networks. *Quarterly Journal of the Royal Meteorological Society* 139: 923-940.
- Grimes D, Diop M (2003). Satellite-based rainfall estimation for river flow forecasting in Africa: rainfall estimates and hydrological forecasts. *Hydrological Sciences Journal* 4:567-584.
- Habib E, Haile AT, Sazib N, Zhang Y, Rientjes T (2014). Effect of Bias Correction of Satellite-Rainfall Estimates on Runoff Simulations at the Source of the Upper Blue Nile. *Remote Sensing* 6:6688-6708.
- Harris A, Hossain F (2008). Investigating the Optimal Configuration of Conceptual Hydrologic Models for Satellite-Rainfall-Based Flood Prediction. *IEEE Geoscience and Remote Sensing Letters* 5:532-536.
- Harris A, Rahman S, Hossain F, Yarborough L, Bagtzoglou AC, Eason G (2007). Satellite-based Flood Modeling Using TRMM-based Rainfall Products. *Sensors* 7: 3416-3427.
- Hong Y, Hsu K, Moradkhani H, Sorooshian S (2006). Uncertainty quantification of satellite precipitation estimation and Monte Carlo assessment of the error propagation into hydrologic response. *Water Resources Research* (42) W08421.
- Hsu KL, Gupta HV, Gao X, Sorooshian S (1999). Estimation of physical variables from multichannel remotely sensed imagery using neural networks: Application to rainfall estimation. *Water Resources Research* 35:1605-1618.
- Hsu KL, Gao X, Sorooshian S, Gupta HV (1997). Precipitation estimation from remotely sensed information using artificial neural networks. *Journal of Applied Meteorology* 36:1176-1190.
- Huffman GJ, Adler JRF, Philip A, Alfred C, Ferraro R, Gruber A, Janowiak J, McNab A, Rudolf B, Schneider U (1997). The Global Precipitation Climatology Project (GPCP) Combined Precipitation Dataset. *Bulletin of the American Meteorological Society* 78: 5-20.
- Huffman GJ, Bolvin DT (2013). TRMM and other data precipitation dataset documentation Technical Report, Mesoscale Atmospheric Processes Laboratory, NASA Goddard Space Flight Center and Science Systems and Applications. Inc Greenbelt MD.
- Islam MN, Das S, Uyeda H (2010). Calibration of TRMM derived rainfall over Nepal during 1998-2007. *The Open Atmospheric Science Journal* 4:12-23.
- Jobard I, Chopin F, Berges JC, Roca R (2011). An intercomparison of 10-day satellite precipitation products during West African monsoon. *International Journal of Remote Sensing* 32:2353-2376.
- Khandu, Awange JL, Forootan E (2015). An evaluation of high-resolution gridded precipitation products over Bhutan (1998-2012). *International Journal of Climatology* 21.
- Miao C, Ashouri H, Hsu KL, Sorooshian S, Duan Q (2015). Evaluation of the PERSIANN-CDR daily Rainfall Estimates in Capturing the Behavior of Extreme Precipitation Events over China. *Journal of Hydrometeorology* 16:1387-1396.
- Michelangeli PA, Vrac M, Loukos H (2009). Probabilistic downscaling approaches: Application to wind cumulative distribution functions. *Geophysical Research Letters* 36:1-6.
- Nijssen B, Lettenmaier DP (2004). Effect of precipitation sampling error on simulated hydrological fluxes and states: Anticipating the global precipitation measurement satellites. *Journal of Geophysical Research* 109:D02 103.
- Olivry JC (1983). Evaluation des données hydrologiques et météorologiques disponibles sur le bassin du fleuve Gambie. Rapport préliminaire ORSTOM 94
- Panthou G, Vschel T, Lebel T (2014). Short Communication Recent trends in the regime of extreme rainfall in the Central Sahel. *Royal Meteorological Society* p. 9.
- Perrin C, Michel C, Andréassian V (2003). Improvement of a parsimonious model for streamflow simulation. *Journal of Hydrology* 279:275-289.
- Ren P, Li J, Feng P, Guo Y, Ma Q (2018). Evaluation of Multiple Satellite Precipitation Products and Their Use in Hydrological Modelling over the Luanhe River Basin. *China Water* 10:677.
- Renard F, Sarr M (2009). Quantification spatiale de la pluie en milieu rural sahélien (Ferlo, Sénégal) et en milieu urbain tempéré (Grand Lyon, France). *Evaluation de méthodes d'interpolation spatiale. Sécheresse* 20:244-522.
- Roca R, Chambon P, Jobard I, Kirstetter PE, Gosset M, Bergès JC (2010). Comparing Satellite and Surface Rainfall Products over West Africa at Meteorologically Relevant Scales during the AMMA Campaign Using Error Estimates. *Journal of Applied Meteorology and Climatology* 49:715-731.
- Shrestha MS, Artan GA, Bajracharya SR, Sharma RR (2008). Using satellite-based rainfall estimates for streamflow modelling: Bagmati Basin. *Journal Flood Risk Management* 1:89-99.
- Shrestha M, Artan G, Bajracharya S, Gautam D, Tokar S (2011). Bias-adjusted satellite-based rainfall estimates for predicting floods: Narayani Basin. *Journal Flood Risk Management* 4:360-373.
- Su F, Hong Y, Lettenmaier DP (2008). Evaluation of TRMM Multisatellite Precipitation Analysis (TMPA) and Its Utility in Hydrologic Prediction in the La Plata Basin. *Journal of Hydrometeorology* 9:622-640.
- Taupin JD, Amani A, Lebel T (1998). En effet, au Sahel, le réseau de mesures de la pluie est en général trop lâche par rapport à la variabilité spatiale des pluies. *Water Resources Variability in Africa during the XXth Century IAHS Publ* 252:143-158.
- Thiemig V, Rojas R, Zambrano BM, Roo AD (2013). Hydrological evaluation of satellite-based rainfall estimates over the Volta and Baro-Akobo Basin. *Journal of Hydrology* 499:324-338.
- Toté C, Patricio D, Boogaard H, Wijngaart R, Tarnavsky E, Funk C (2015). Evaluation of Satellite Rainfall Estimates for Drought and Flood Monitoring in Mozambique. *Remote Sensing* 7:1758-1776.
- Washington R, Kay G, Harrison M, Conway D, Black E, Challinor A, Grimes D, Jones R, Morse A, Todd M (2006). African climate change: Taking the shorter route. *Bulletin of the American Meteorological Society* 87:1355-1366.
- Vischel T, Quantin G, Lebel T, Viarre J, Gosset M, Cazenave F, Panthou G (2011). Generation of High-Resolution Rain Fields in West Africa: Evaluation of Dynamic Interpolation Methods. *Journal of Hydrometeorology* 12:1465-1482.
- Xue X, Hong Y, Limaye AS, Gourley JJ, Huffman GJ, Khan SI, Dorji C, Chen S (2013). Statistical and hydrological evaluation of TRMM-

- based multi-satellite precipitation analysis over the Wangchu Basin of Bhutan: are the latest satellite precipitation products 3b42v7 ready for use in ungauged basins? *Journal of Hydrology* 499:91-99.
- Yang Z, Hsu K, Sorooshian S, Xu X, Braithwaite D, Verbist Koen MJ (2017). Bias adjustment of satellite-based precipitation estimation using gauge observations: A case study in Chile. *Journal of Geophysical Research* pp. 5267-5284.
- Yilmaz KK, Hogue TS, Hsu KL, Sorooshian S, Gupta HV, Wagener T (2005). Intercomparison of Rain Gauge, Radar, and Satellite-Based Precipitation Estimates with Emphasis on Hydrologic Forecasting. *Journal of Hydrometeorology* 6:497-517.
- Zeweldi DA, Gebremichael M, Downer CW (2011). On CMORPH rainfall for stream flow simulation in a small, Hortonian watershed. *Journal of Hydrometeorology* 12:456-466.