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Article

# Hydrological Evaluation of PERSIANN-CDR Rainfall over Upper Senegal River and Bani River Basins

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**Abstract:** This study highlights the advantage of satellite-derived rainfall products for hydrological modeling in regions of insufficient ground observations such as West African basins. Rainfall is the main input for hydrological models; however, gauge data are scarce or difficult to obtain. Fortunately, several precipitation products are available. In this study, Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks–Climate Data Record (PERSIANN-CDR) was analyzed. Daily discharges of three rivers of the Upper Senegal basin and one of the Upper Niger basin, as well as water levels of Manantali reservoir were simulated using PERSIANN-CDR as input to the CEQUEAU model. First, CEQUEAU was calibrated and validated using raw PERSIANN-CDR, and second, rainfalls were bias-corrected and the model was recalibrated. In both cases, ERA-Interim temperatures were used. Model performance was evaluated using Nash–Sutcliffe efficiency (NSE), mean percent bias (MPBIAS), and coefficient of determination ( $R^2$ ). With raw PERSIANN-CDR, most years show good performance with values of  $NSE > 0.8$ ,  $R^2 > 0.90$ , and  $MPBIAS < 10\%$ . However, bias-corrected PERSIANN-CDR did not improve the simulations. The findings of this study can be used to improve the design of dam projects such as the ongoing dam constructions on the three rivers of the Upper Senegal Basin.

**Keywords:** PERSIANN-CDR; ERA-Interim; discharge; Bani River; Senegal River; CEQUEAU

## 1. Introduction

In hydrological modeling, rainfall data are the main source of information [1,2]. Satellite precipitation has become an important source, especially in areas where the rainfall measurements are nonexistent, scarce, or difficult to access. Satellite products have become increasingly accurate and easy to access for hydro-meteorological applications [3]. Furthermore, meteorological and hydrological studies show that rain estimation and runoff modeling turn out to be very acceptable with this type of data [2,4–10]. However, some of these studies also emphasize that the use of satellite information must be verified for local applications. In this respect, there is a considerable number of studies on this subject, but in the western part of Africa, these studies are limited, e.g., References [5,7,8,11].

A traditional approach to evaluate and quantify the rainfall estimation performance is to compare estimated rainfall with ground measurements. Whenever discharge data are available, the reliability of rainfall estimation can be verified with the evaluation of their skill to simulate runoff, e.g., References [5,7,11,12].

Dembélé and Zwart [5] compared the performance of seven databases for the representation of daily rainfall in Burkina Faso, West Africa. The experiment included Africa Rainfall Estimate Climatology (ARC 2.0), Climate Hazards Group Infrared Precipitation with Stations (CHIRPS), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks—Climate Data Record (PERSIANN-CDR), African Rainfall Estimation (RFE 2.0), Tropical Applications of Meteorology using SATellite (TAMSAT), African Rainfall Climatology and Time series (TARCAT), and Tropical Rainfall Measuring Mission (TRMM 3B43V7) datasets. The comparison was made with gauge data for the period 2001–2014. Results showed that all products correctly captured the spatial distribution of annual rainfall; however, daily rainfall was poorly represented in all cases. Monthly rainfall showed better results than daily rainfall. Kimani et al. [12] conducted a comparison of monthly rainfall of seven satellite products and information from stations in East Africa for the period of 1998–2012. Their study included Climate Prediction Center (CPC), CPC Merged Analysis of Precipitation (CMAP), Global Precipitation Climatology Project (GPCP), CMORPH, PERSIANN-CDR, TAMSAT, and TARCAT datasets. The ground and satellite information were used at a resolution of 0.05 degrees. Results indicated that the spatial distribution of monthly rainfall was correctly captured by satellite information. The authors found that the largest disagreement between databases existed in mountainous areas. Beck et al. [2] carried out a study where they compared thirteen rainfall databases with gauge data from around the world for the period 2000–2016. They also evaluated the performance of nine satellite precipitation products corrected with ground gauges to simulate runoff with the HBV model in a lumped way for the period 2000–2012. Results showed that, in general, those products showed a better representation of rainfall patterns. Regarding hydrological modeling in West Africa, it was found that the bias-corrected products gave a better performance. They report that among the best products for runoff simulation for this area are CHIRPS, PERSIANN-CDR, TMPA 3B42V7, and CMORPH-bias corrected (CMORPH-CRT). All these databases include in their calculation a correction method with gauge information. Poméon et al. [7] evaluated ten databases for runoff simulation of six basins located in West Africa. They used the HBV hydrological model. The authors found that the calibration of the model for each precipitation source played an important role in the results of the runoff simulation.

In the context of the evaluation of precipitation databases approach through the comparison of simulated and observed runoffs, the study of basins located between two or more countries is a case that occurs frequently. In this situation, it becomes necessary to perform the analysis in a distributed or semi-distributed fashion, this is to take into account the changes in the spatial distribution of precipitation and runoff over the basin. In this way, the hydrological cycle components are better represented throughout the basin and in each country [13,14].

As a contribution to the use of satellite precipitation in hydrological modeling, this study aims to assess the performance of Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks—Climate Data Record (PERSIANN-CDR) to simulate daily discharges and water level in West African basins. For the calculation of potential evapotranspiration (PET), in the absence of ground data, ERA-Interim temperatures [15] were used instead. The hydrological model chosen was CEQUEAU [16] because it has shown good performance in distributed simulations under different types of climates and orographic conditions as shown in several applications [17–21]. In the evaluation of simulations, two experiments were conducted, one using original PERSIANN-CDR and another using PERSIANN-CDR corrected with ground data. This was done to also analyze the suitability of the use of this dataset as it is. The paper is structured as follows: Section 2 describes the materials and methods, which include the study area, input data, CEQUEAU model, bias correction procedure, and model calibration and validation methodology. Section 3 provides results and discussion, and Section 4 summarizes the main findings.

## 2. Materials and Methods

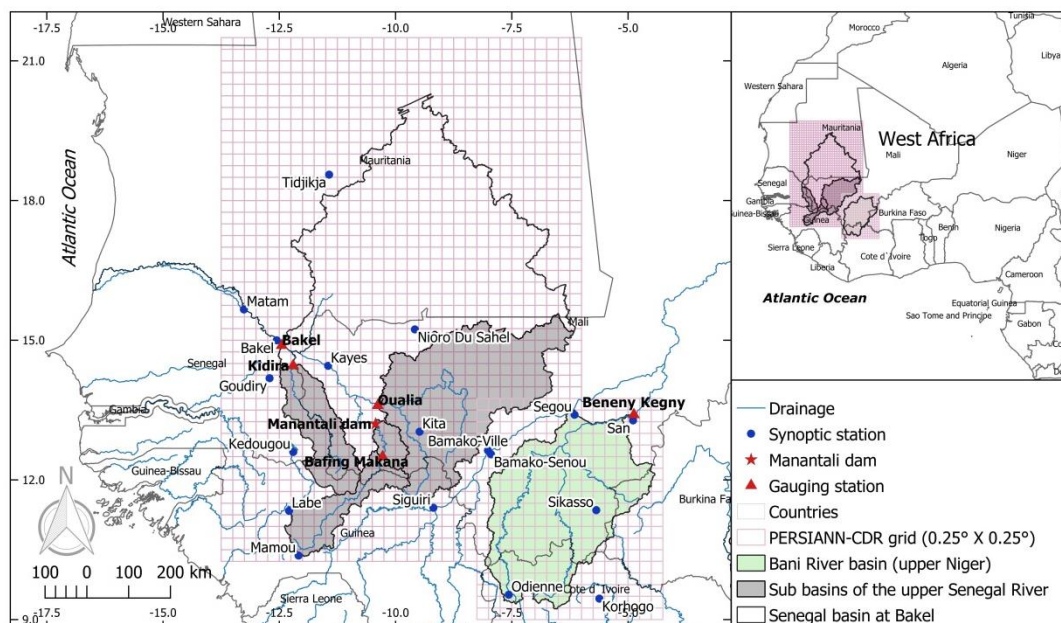
### 2.1. Study Area

Figure 1 shows the study area that covers the Bani watershed (Upper Niger River), and three watersheds of the Upper Senegal River: Bafing, Bakoye, and Faleme.

Bani River is the main tributary of the Niger River and has an area of about 112,000 km<sup>2</sup> at Beneny Kegny gauging station. Its drainage basin is mainly located in Mali but spans small parts of Cote d'Ivoire, Burkina Faso, and Guinea. Similar studies have been applied to this watershed, mainly at Douna gauging station [22,23]. In this study, the gauging station of Beneny Kegny was chosen because of the availability of data up to 2015 and the fact that the station is located only at about 100 km downstream of Douna. Therefore, it will be possible to compare the results of this study to the studies cited here.

Over Bani watershed, average rainfall varies from South (Odienne) with 1300 mm/year to North (Segou) with 740 mm/year (1992–1999). The annual average discharge of the Bani River at Beneny Kegny station is about 373 m<sup>3</sup>/s (1995–2016). Peak discharge can reach 3000 m<sup>3</sup>/s at that gauge. The river flows from southwest to northeast.

Regarding the Senegal River, it is shared by four countries: Guinea, Mali, Mauritania, and Senegal, and is managed by the Organisation pour la Mise en Valeur du fleuve *Sénégal* (OMVS). The main tributaries of this river are Bafing, Faleme, and Bokoye. The annual discharge is higher in the Bafing River, with an average of 250 m<sup>3</sup>/s (1995–2015) at the Bafing Makana gauging station, but only 124 m<sup>3</sup>/s in Faleme at Kidira and 81 m<sup>3</sup>/s in Bakoye at Oualia. This river is regulated since 1987 by the Manantali hydroelectric dam. At present, other dams are under construction or planned in each of these rivers. The precipitation regime has a large spatial variation. In the north, annual rainfall is only about 80 mm, while in the south of the basin, it can reach 2000 mm. The rainy season generally starts in June and ends in October.



**Figure 1.** Location of Upper Senegal River and Bani River basins, synoptic and hydrometric stations, and PERSIANN-CDR grids.

## 2.2. Climate and Discharge Data

### 2.2.1. Gauge Network

In this study, daily rainfalls of eighteen synoptic stations (Figure 1) were used for validation purpose of PERSIANN-CDR. Daily temperatures from seven of those eighteen stations are available and their datasets were used for the evaluation of ERA-Interim.

### 2.2.2. Discharge and Water Level Data

A number of these hydrometric stations have been in operation since the beginning of the 20th century. Discharges of four gauging stations are used, Bani at Beneny Kegny (112,000 km<sup>2</sup>), Bafing at Bafing Makana (21,900 km<sup>2</sup>), Faleme at Kidira (29,000 km<sup>2</sup>), and Bakoye at Oualia (102,000 km<sup>2</sup>); these data were available up to 2015. In addition, operation data of the Manantali reservoir were used for the simulation of its water level. The Manantali hydropower dam is located on the Bafing River (27,740 km<sup>2</sup>). The outflows consist of ecological river flows and spillway discharges. The daily water level and water volume of the reservoir are available until 2015.

### 2.2.3. PERSIANN-CDR Precipitation

Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) is a satellite-based precipitation retrieval algorithm that provides near real-time rainfall information between 60°S–60°N at 0.25° spatial resolution and at daily, monthly, and yearly time resolution. The algorithm uses infrared (IR) satellite data from global geosynchronous satellites as the primary source of precipitation information. The IR-based precipitation estimates are then calibrated using satellite microwave data available from low Earth orbit satellites (such as Tropical Rainfall Measuring Mission Microwave Imager, Special Sensor Microwave Imager, and Advanced Microwave Scanning Radiometer-Earth observing system). The rainfall estimates are bias-corrected with GPCP monthly data [24]. PERSIANN-CDR dataset is available on <http://chrsdata.eng.uci.edu/>. There are missing data in PERSIANN-CDR database and some occur during the wet period; that is why only data from 1995 to 2015 were used in this study.

### 2.2.4. ERA-Interim Temperatures

The chosen hydrological model requires daily air temperature data for evapotranspiration calculation. Temperature from the third-generation reanalysis from the European Centre for Medium Range Weather Forecast (ECMWF) was used in this study [15]. ERA-Interim provides global data of several climatological variables (e.g., surface temperature) from 1979 to the present (see Dee et al. [15] for the complete list). The original configuration of the model is set on a three-hourly basis and with a spatial resolution of 0.75 degrees. Mooney et al. [25] compared three reanalysis datasets of surface air temperature with observations at 11 synoptic stations in Ireland over the period 1989–2001. The three reanalysis datasets show good agreement with the observed data and with each other. ERA-Interim was slightly better than the two other and had higher correlation coefficients with the observations. Simmons et al. [26] found a high temporal correlation ( $R = 0.997$ ) between ERA-Interim and CRUTEM3 (gridded observations) for monthly temperature from 1989 to 2001 in Europe. Gao et al. [27] also found a good agreement ( $R = 0.992$ ) between ERA-Interim and daily observed surface air temperature in the European Alps. In the present work, daily temperature with a spatial resolution of 0.25 degree at was used to be consistent with the spatial and temporal resolution of gridded precipitation.

## 2.3. CEQUEAU Model

The distributed hydrological model CEQUEAU (Morin [28]; Morin and Paquet [16]) developed at The Institut National de la Recherche Scientifique (INRS) (formerly INRS-EAU, now INRS-ETE -Eau Terre Environnement-, University of Quebec), is a model that considers the physiographical



characteristics of the watershed by means of a spatial division. This division consists of a grid that considers the representation of the space-time evolution of the process. The grid size depends mainly on the size of the watershed, the distribution of rain gauges, the topography, etc. Each grid is divided into a maximum of four partial sub-grids based on drainage divides that are present in that grid.

The model has been implemented by Morin et al. [29] and tested on Canadian watersheds for the evaluation of hydrological resources from a hydroelectric power generation perspective.

In this study, we used CEQUEAU 4.0 [16] although a new version is available (<http://ete.inrs.ca/ete/publications/cequeau-hydrological-model>). This new version is only a translation of the original model from FORTRAN with interface in C++ to C++. The model allows flow simulations from hourly to daily time steps. However, simulations at time steps less than a day have rarely been done with this model due to the scarcity of hydrometeorological data at these time steps. The model allows also simulations of some variables of water quality; for instance, Ouellet-Proulx et al. [30] used CEQUEAU to simulate the water temperature of two Canadian rivers.

The CEQUEAU model has been applied in watersheds all over the globe [17,18,31,32] and has been tested in comparison with well-known hydrological models within the framework of two inter-comparisons of hydrological models of the World Meteorological Organization [19,20].

Moreover, the CEQUEAU model is designed to use physiographical data of the watershed to be studied from topographical maps. In the past, the pre-processing to retrieve the physiographical data was done manually, which is highly time-consuming and prone to human errors. Now, with the availability of digital elevation models (DEM), this task is much more efficient. Guerra-Cobián [33] and Dugdale et al. [34] designed tools that can process the DEM to obtain the physiographical file needed for the CEQUEAU model. A DEM image with a resolution of 3 arc-seconds downloaded from the USGS website (<http://earthexplorer.usgs.gov/>) has been used in this study. Land use data required by CEQUEAU is obtained from the U.S. Geological Survey database (<http://earthexplorer.usgs.gov/>). We set the CEQUEAU model to run at the resolution of 0.25 degree as the PERSIANN-CDR resolution.

The CEQUEAU model consists of two main modules and provides an improved description of the water flow towards the exit of the watershed. The first module, called “production function” considers the vertical flow, the main processes being: rainfall, snowmelt, evapotranspiration, infiltration, and variations of near-surface and deeper water reserves. This operation is calculated on each “whole square” and for each time step. The second function considers water flow transfer in the drainage network. The processes included in this part takes into account the influence of lakes, marshes, and artificial waterworks such as dams, deviations, canals, water intakes, etc. This module is labelled “routing function” (Figure 2).

The production function, which is evaluated on each whole square at each time step, requires the meteorological data on each whole square in addition to the physiographic data. The meteorological data, precipitation, and air temperature used by the model, on each whole square, comes from climatologic stations in or near the watershed of interest. The estimation of the meteorological data on each whole square can be computed via interpolation through algorithms implemented inside the CEQUEAU model. In this study, there is no need for interpolation because each square has its PERSIANN-CDR and ERA-Interim values.

The CEQUEAU model allows for carrying out the simulation of watersheds having one or more real or fictitious dams. The procedure for taking into account dams in CEQUEAU is explained in Morin [28]. Basically, for a real dam at the exit of a partial square, the inflow computed by the model at the exit of the partial square where the dam is located is introduced into the reservoir and outflows (flowing water plus spill) are read as an input file to the model. Outflows are added into the partial square immediately downstream. The reservoir water level is calculated by CEQUEAU using the relation level-storage. This relation is computed outside the model using historical information of the reservoir. The accuracy of the simulations is analyzed by comparing simulated and observed water levels.

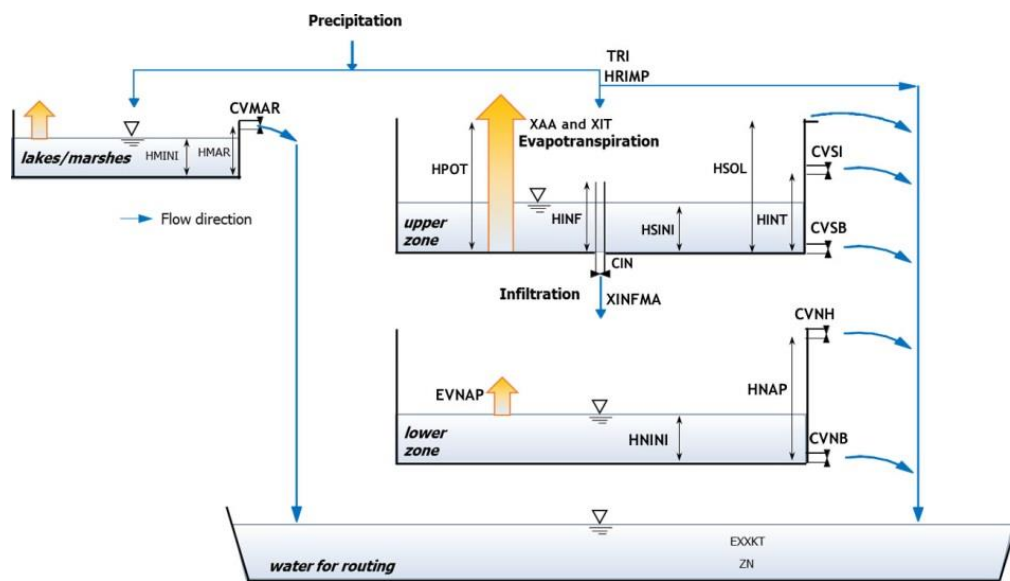


Figure 2. Scheme and parameters of CEQUEAU hydrological model.

#### 2.4. Bias Correction of PERSIANN-CDR Data

The biases on rainfall estimated via satellite are due to different factors. For instance, Valdés-Pineda et al. [35] indicated that the biases depend significantly on elevation, latitude, climate, and rainfall prediction mechanisms. On the other hand, validation studies indicate that satellite products are more accurate in flat areas with little vegetation cover than in forested areas in northern latitudes [36]. Precipitation shows great spatial variation. Rain gauge observations are point values, meanwhile satellite products, in this case PERSIANN-CDR, are averaged over an area of  $0.25^\circ \times 0.25^\circ$ . Due to this significant scale discrepancy, comparison between these two products at short time scales is less meaningful. Stisen and Sandholt [37] adjusted satellite rainfall data to local rain gauge observations by matching their annual means over a basin during the period of study. However, recent studies consider bias correction based on monthly observed and estimated rainfalls [38]. In this study, the daily bias-corrected PERSIANN-CDR rainfall is computed by applying a multiplicative correction coefficient to daily rainfall estimates, and is given in Equation (1):

$$P_{sc(d)} = P_{s(d)} \frac{\overline{P_{o(m)}}}{\overline{P_{s(m)}}} \quad (1)$$

where  $P_{sc(d)}$ : daily bias-corrected PERSIANN-CDR rainfall,  $P_{s(d)}$ : daily PERSIANN-CDR rainfall,  $\overline{P_{s(m)}}$ : monthly areal PERSIANN-CDR rainfall, and  $\overline{P_{o(m)}}$ : monthly areal gauged rainfall.

In a first stage, the hydrological model was calibrated and validated using the original PERSIANN-CDR data (Raw) as input. Then monthly correction factors were applied to rainfall data (Bias-corrected) and the model was recalibrated. In both cases, the ERA-Interim temperatures were used to compute evapotranspiration into the hydrological model.

#### 2.5. Validation of Input Data

PERSIANN-CDR was compared to gauge rainfall data. The comparison was done on monthly basis between the gauge and estimated rainfall for the satellite pixel in which a gauge is located. In addition, the areal PERSIANN-CDR monthly rainfall over each watershed was compared to the areal gauge rainfall. The goal was to determine how accurately the PERSIANN-CDR rainfall reproduces the mean gauge rainfall over each watershed.

ERA-Interim data is required to be validated in this region. Due to the nature of the phenomenon, validation was realized on a daily basis.

## 2.6. Model Calibration and Validation

In a first stage, the hydrological model was calibrated and validated using the original PERSIANN-CDR data (Raw). Then monthly correction factors were applied to rainfall data (Bias-corrected) and the model was recalibrated. In both cases, the ERA-Interim temperatures were used to compute evapotranspiration in the hydrological model.

The CEQUEAU model has 21 parameters that must be calibrated (Figure 2). However, two parameters COEP and COET, that are coefficients of correction for precipitation and temperature, respectively, can be computed as functions of altitude. Moreover, depending on the watershed, some parameters do not affect the response of the watershed, which reduces the number of parameters to be calibrated.

The chosen calibration strategy was the combination of “trials and error” and optimization methods. The process begins with the calculation of parameters related to evapotranspiration  $\lambda_{AA}$  and  $\lambda_{IT}$ , which are Thornwaite coefficients in the traditional method. Subsequently, a calibration by “trials and error” is done according to our knowledge of the phenomenon. In addition, the CEQUEAU model has an optimization tool based on the Powell method [39], which consists in maximizing or minimizing an objective function in order to reproduce the observed flows with a minimum of error.

The performance of the model was evaluated using multiple objective functions, such as the Nash–Sutcliffe Efficiency for a given year (NSE), or for a given period (NSEP), the Mean percent bias of simulated discharges for a given period (MPBIAS), and the coefficient of determination ( $R^2$ ). The Nash–Sutcliffe Efficiency is used to estimate the relative magnitude of the variance of the residual compared to the variance of observation. NSE and NSEP values range from  $-\infty$  to 1, with 1 being perfect simulation. Negative values of NSE refer to the use of average observations for predictions rather than simulated values. MPBIAS is used to determine how well the model simulates the average magnitudes of the discharges. Values of MPBIAS range from  $-\infty$  to  $+\infty$ , with 0 as an optimum value.  $R^2$  is a standard regression statistic that indicates the proportion of observation variance explained by the model.  $R^2$  ranges from 0 to 1, with 0 representing no correlation, and values close to 1 representing high variance correlation.

The equations of these objective functions are as follow:

$$NSE = 1 - \frac{\sum_{i=1}^{ND} (Q_{0i} - Q_{s_i})^2}{\sum_{i=1}^{ND} (Q_{0i} - \bar{Q}_0)^2} \quad (2)$$

$$R^2 = \frac{\left[ ND \sum_{i=1}^{ND} (Q_{0i} Q_{s_i}) - \sum_{i=1}^{ND} Q_{0i} \sum_{i=1}^{ND} Q_{s_i} \right]^2}{\left[ ND \sum_{i=1}^{ND} Q_{0i}^2 - \left( \sum_{i=1}^{ND} Q_{0i} \right)^2 \right] \left[ ND \left( \sum_{i=1}^{ND} Q_{s_i}^2 \right) - \left( \sum_{i=1}^{ND} Q_{s_i} \right)^2 \right]} \quad (3)$$

$$NSEP = 1 - \frac{\sum_{n=1}^{NY} \sum_{i=1}^{ND} (Q_{0ni} - Q_{s_{ni}})^2}{\sum_{n=1}^{NY} \sum_{i=1}^{ND} (Q_{0ni} - \bar{Q}_{0n})^2} \quad (4)$$

$$MPBIAS = \sum_{n=1}^{NY} \frac{\sum_{i=1}^{ND} (Q_{0i} - Q_{s_i})}{NY \sum_{i=1}^{ND} Q_{0i}} \times 100 \quad (5)$$

where NSE: Nash-Sutcliffe Efficiency for  $ND$  overlapping days of a given year,  $Q_{0i}$ : daily gauged discharge,  $Q_{s_i}$ : daily simulated discharge,  $\bar{Q}_0$ : mean value of daily gauged discharges,  $i$ : day  $i$ , NSEP: Nash–Sutcliffe efficiency for a period of  $NY$  years, MPBIAS: Mean percent bias of simulated discharges for a period of  $NY$  years,  $R^2$ : coefficient of determination.

Moriasi et al. [40] classified the simulation results of a hydrological model into four categories according to the values of Nash–Sutcliffe Efficiency, coefficient of determination and percent bias. This classification is shown in Table 1. The results of this study will be analyzed on the basis of this classification.



**Table 1.** Performance criteria according to Moriasi et al. [41].

Efficiency	NSE [-]	PBIAS [%]	R <sup>2</sup> [-]
Very good	NSE > 0.80	PBIAS < ±5	R <sup>2</sup> > 0.85
Good	0.70 < NSE ≤ 0.80	±5 ≤ PBIAS < ±10	0.75 < R <sup>2</sup> ≤ 0.85
Satisfactory	0.50 < NSE ≤ 0.70	±10 ≤ PBIAS < ±15	0.60 < R <sup>2</sup> ≤ 0.75
Not satisfactory	NSE ≤ 0.50	PBIAS ≥ ±15	R <sup>2</sup> ≤ 0.60

### 3. Results and Discussions

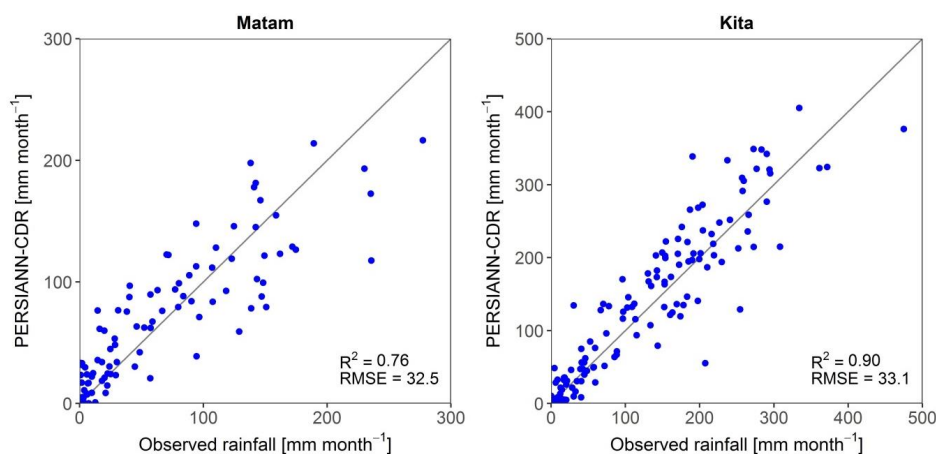
#### 3.1. PERSIANN-CDR Rainfall Estimates

Validation of PERSIANN-CDR was performed for the overlapping period between this product and gauged rainfall at eighteen synoptic stations (Figure 1). This validation was done through point-to-pixel analysis by computing the coefficient of determination (R<sup>2</sup>) and the root mean square error (RMSE) between the monthly rainfalls. Also, annual rainfalls have been compared. Although the size of the pixel is very large, PERSIANN-CDR reproduces the observed monthly rainfall well (Table 2) with coefficients of determination (R<sup>2</sup>) between 0.76 and 0.90. The root mean square error values ranged from 9 to 74 mm. As an example, we show only two scatter plots representing the lowest and highest R<sup>2</sup> (Figure 3). Moreover, at the annual time step, PERSIANN-CDR also reproduced the observed rainfall very well with only a slight overestimation (Table 2).

**Table 2.** Validation of PERSIANN-CDR rainfall.

Gauge Name	X	Y	Altitude (masl)	Statistics over Monthly Rainfall			Statistics over Yearly Rainfall			
				Om	R <sup>2</sup>	RMSE	Oy	ArG	ArP	Error (%)
Matam	-13.880	16.170	16	96	0.76	32.5	0	NA	NA	
Goudiry	-11.400	16.630	128	300	0.83	36.0	25	589	712	21
Bakel	-13.170	16.430	30	290	0.86	28.3	19	509	569	12
Mamou	-12.085	10.375	740	298	0.85	63.9	23	1713	1922	12
Kedougou	-12.200	12.600	160	300	0.84	53.2	25	1119	1190	6
Labe	-12.290	11.336	1030	273	0.86	74.7	20	1474	1845	25
Kayes	-10.300	14.720	280	213	0.85	53.2	15	578	646	12
Nioro Du Sahel	-9.584	15.233	240	225	0.80	28.7	16	417	484	16
Kita	-9.482	13.036	327	224	0.90	33.1	17	903	952	5
Siguiri	-9.186	11.402	388	293	0.85	50.0	24	1156	1283	11
Bamako-Ville	-8.013	12.633	325	210	0.85	43.5	12	938	953	2
Bamako-Senou	-7.946	12.549	390	287	0.89	33.7	23	898	963	7
Segou	-6.150	13.400	287	263	0.88	29.6	20	630	672	7
Tidjikja	-11.428	18.557	398	300	0.77	9.1	25	90	111	3
Odienne	-7.565	9.534	400	136	0.86	45.6	5	1431	1547	8
San	-4.892	13.278	290	204	0.89	28.5	6	698	751	8
Sikasso	-5.683	11.350	382	275	0.89	36.3	10	1178	1167	-1
Korhogo	-5.616	9.450	380	108	0.77	53.4	4	1168	1177	1

Om: Overlapping months; Oy: Overlapping years; ArG: Annual rainfall Gauge, ArP: Annual rainfall PERSIANN-CDR; NA: not available.

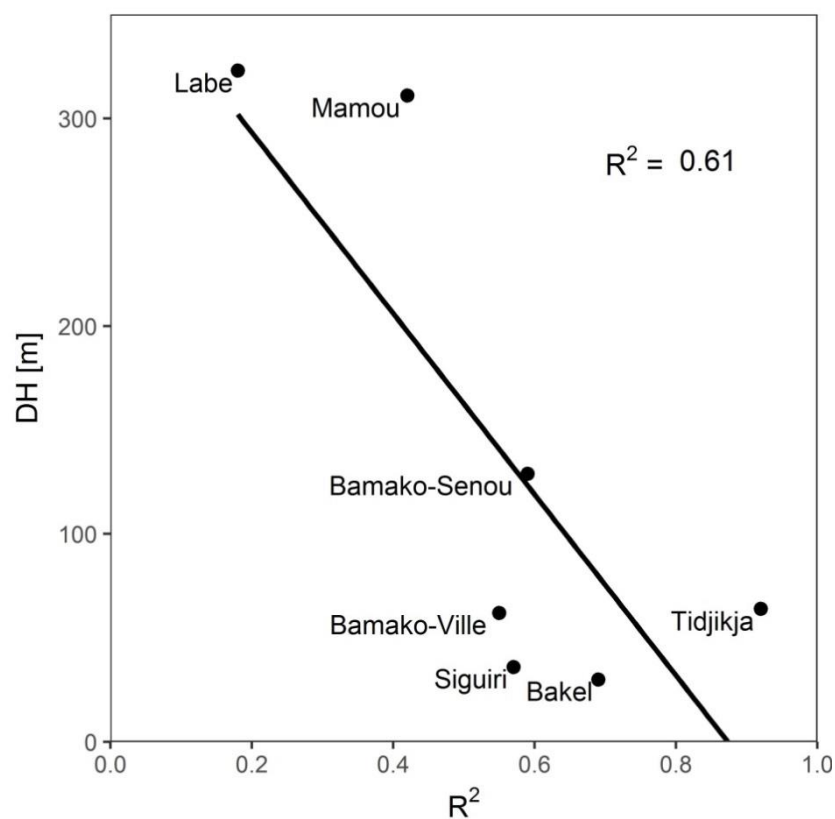
**Figure 3.** Sample of scatter-plots of monthly PERSIANN-CDR and gauged rainfalls.

### 3.2. Validation of ERA-Interim Daily Temperature Estimates

Regarding ERA-Interim daily temperatures, the coefficients of determination  $R^2$  ranged from 0.18 to 0.92 (Table 3). To explain this behavior, the topography of the land was analyzed using the Digital Elevation Model (DEM) of the Shuttle Radar Topographic Mission (SRTM) of The USGS at 3 arc-seconds of resolution [41]. Furthermore, each Era-Interim pixel ( $0.25^\circ \times 0.25^\circ$  of resolution) contained 300 pixels of the DEM. With this sample of 300 altitudes, it was possible to calculate the difference in height (DH), which is the difference between the highest and lowest altitudes. Afterwards, it was possible to make a regression between DH values and the coefficients of determination ( $R^2$ ) computed previously. Figure 4 shows that there was a strong correlation between DH and  $R^2$  with a coefficient of determination of 0.61. This relation indicates that the smaller DH was, the more ERA-Interim was similar to the observed temperature. This is the case for the pixels where Tidjikja and Bakel synoptic stations are located (Figure 1), that correspond to flatter areas. However, for stations such as Labé and Mamou (located in the mountainous area of Fouta Djallon, Guinea), the coefficients of determination were smaller. This was due to the topographic heterogeneity and temperature amplitude. Here, it should be pointed out that raster value (of  $0.25^\circ$  of resolution) was being compared to the point value and results indicate that they were similar in flat areas and different in mountainous areas. Therefore, it can be concluded that ERA-Interim data are in reasonable agreement with observed temperatures.

**Table 3.** Correlation between ERA-Interim and observed daily temperatures—topography analysis.

Name	$R^2$	Altitude DEM	Altitude Mean DEM	Altitude Min DEM	Altitude Max DEM
Tidjikja	0.92	398	442	378	520
Siguiiri	0.57	388	368	332	452
Mamou	0.42	740	748	437	1052
Labe	0.18	1030	1036	713	1282
Bamako-Senou	0.59	390	444	315	609
Bamako-Ville	0.55	325	361	299	553
Bakel	0.69	30	41	11	123



**Figure 4.** Relation between  $R^2$  (of observed temperature vs. ERA-Interim) and DH.

Given the results of the previous section showing a good performance of PERSIANN-CDR when compared to gauged rainfall and ERA-Interim when compared to observed daily temperature, we can reliably use these precipitation and temperature datasets as the forcing to the CEQUEAU hydrological model.

### 3.3. Results with Original PERSIANN Data

The model parameters were calibrated for each sub-basin using the PERSIANN-CDR and ERA-Interim data for the period 2001–2011, while the periods 1995–2000 and 2012–2015 were used for the validation of the model. The numerical criteria (NSE and  $R^2$ ) were calculated for each year (Table 4) and the NSEP and MPBIAS criteria for the calibration and validation periods.

**Table 4.** Performance criteria of daily discharge simulations using original PERSIANN-CDR.

Basin	Niger				Senegal					
River	Bani		Bakoye		Faleme		Bafing		Bafing	
Gauge	Beneny Kegny		Oualia		Kidira		Bafing Makana		Manantali Dam	
Year	NSE	$R^2$	NSE	$R^2$	NSE	$R^2$	NSE	$R^2$	NSE	$R^2$
1995	0.86	0.98	0.89	0.93	0.90	0.93	0.88	0.88	0.23	0.67
1996	0.77	0.96	0.88	0.88	0.77	0.87	0.83	0.89	0.96	0.96
1997	0.86	0.92	0.83	0.83	0.90	0.9	0.84	0.88	0.94	0.95
1998	0.97	0.98	0.71	0.81	0.70	0.76	0.91	0.93	0.93	0.98
1999	0.94	0.98	0.88	0.88	0.88	0.89	0.83	0.89	0.83	0.88
2000	0.74	0.89	0.80	0.88	0.77	0.88	0.74	0.81	0.09	0.58
2001	0.94	0.96	0.65	0.78	0.70	0.83	0.74	0.78	0.54	0.79
2002	0.85	0.91	0.73	0.74	0.74	0.81	0.87	0.89	0.81	0.92
2003	0.96	0.97	0.85	0.88	0.83	0.88	0.83	0.84	0.84	0.89
2004	-	-	0.31	0.76	0.66	0.74	0.46	0.70	0.57	0.79
2005	0.93	0.93	0.63	0.86	0.62	0.83	0.76	0.81	0.55	0.71
2006	0.90	0.96	0.63	0.84	0.46	0.73	0.64	0.91	0.57	0.84
2007	0.93	0.95	0.85	0.89	0.87	0.91	0.84	0.85	0.95	0.99
2008	0.84	0.95	0.86	0.88	0.80	0.82	0.92	0.93	0.91	0.96
2009	0.81	0.97	0.65	0.81	0.72	0.94	0.86	0.94	0.75	0.82
2010	0.81	0.93	0.86	0.87	0.65	0.83	0.61	0.78	0.69	0.81
2011	0.84	0.90	0.55	0.65	0.32	0.73	0.72	0.92	0.21	0.47
2012	0.86	0.95	0.72	0.76	0.81	0.84	0.82	0.84	0.80	0.91
2013	0.97	0.97	0.77	0.86	0.74	0.86	0.74	0.79	0.88	0.93
2014	0.96	0.97	0.49	0.87	0.91	0.92	0.83	0.86	0.81	0.94
2015	0.96	0.97	0.78	0.81	0.60	0.83	0.84	0.88	0.80	0.92

For the Bani Basin, the annual NSE coefficients of the 20 years of simulations were all greater than 0.74 (Table 4). In 90% of cases, they were greater than 0.80, and in 50% of cases, greater than 0.90. All coefficients of determination between observed and simulated daily discharges ( $R^2$ ) were greater than 0.90. According to the criteria established in Table 1, based on NSE and  $R^2$ , the simulations were very good for this basin.

Simulations of daily flows in the three watersheds of the Upper Senegal River Basin (Table 4) gave very good results in 38% to 62% of cases according to the NSE objective criterion. Moreover, according to this same criterion, the results of the simulations were satisfactory for 19 of the 21 years of simulation. Only for 1–2 years depending on considered basin, the simulations qualified as unsatisfactory. However, based on the criterion of coefficients of determination ( $R^2$ ) between observed and simulated daily flows, the simulations could be qualified as very good for more than 50% of the cases, good for more than 90% of the cases, and satisfactory for all the simulated years according to Table 1.

Also, according to Table 1, results concerning the water level of the reservoir (Table 4) showed very good simulations for 12 out of 21 years of simulation. The results were satisfactory in more

than 90% of the cases according to NSE and  $R^2$ . Based on the NSE criterion, it can be noted that the simulations were not satisfactory for 3 years and same for the  $R^2$  criterion for 2 years out of 21.

In addition, based on the NSEP criterion for calibration and validation periods, all values were greater than 0.80 (Figure 5). In this study, the simulations concerned five hydrometric stations, and for each station, a calibration period and two validation periods, for a total of fifteen periods. MPBIAS was less than 10% in 75% of cases. In all cases MPBIAS did not exceed 22.2% in absolute value. These results prove once again that the simulations were very good. Observed and simulated hydrographs and water level in the Manantali reservoir are shown in Figure 5.

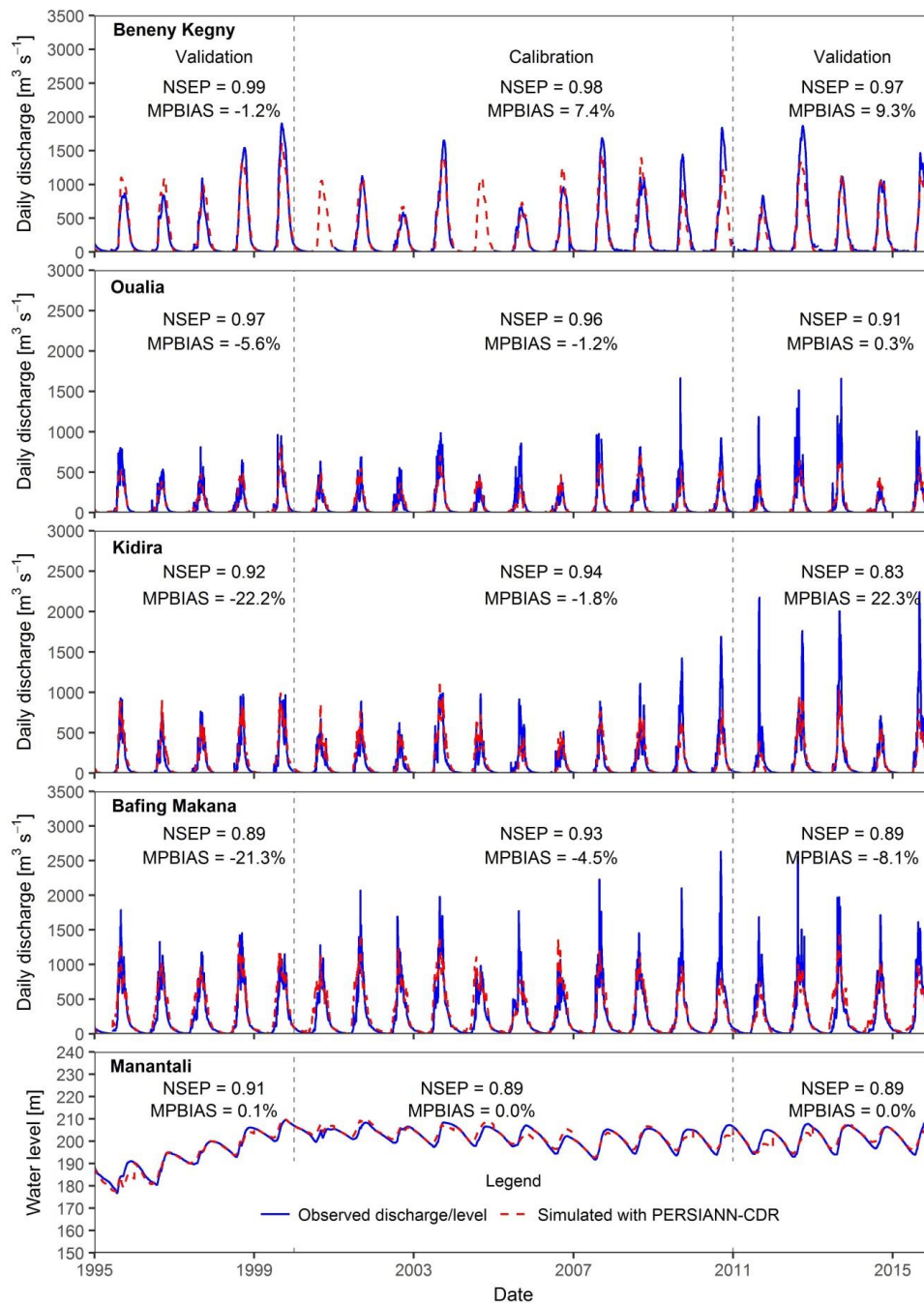


Figure 5. Observed and simulated discharges and water level using original PERSIANN-CDR data.

Usually, authors do not indicate values of NSE and  $R^2$  year by year as in this study, but values over periods of calibration and validation, this is the case in Bitew et al. [4], Bodian et al. [11], Chaibou Begou et al. [22], Ruelland et al. [42], Stisen et al. [8], etc.

3.4. Results for PERSIANN-CDR Bias-Corrected

Bâ et al. [31] and Bâ et al. [21] used the CEQUEAU model to simulate the daily runoff of Bani River and Upper Senegal River Basins. From these studies, we could obtain the average monthly gauged rainfall in each basin through a subroutine of the CEQUEAU model. In the same way, average monthly PERSIANN-CDR rainfall was obtained through the same CEQUEAU model (previous section). A correlation was made between the average monthly rainfalls of the twelve months of the overlapping years for each basin (Figure 6). The coefficients of determination were 0.98 and 0.97, respectively, for the Bani and the Upper Senegal basins. The interannual average gauged and estimated rainfalls were 1016 and 1100 mm, respectively, for the Bani basin (1995–2002), and 553 and 617 mm for the Upper Senegal basin (1995–2004).

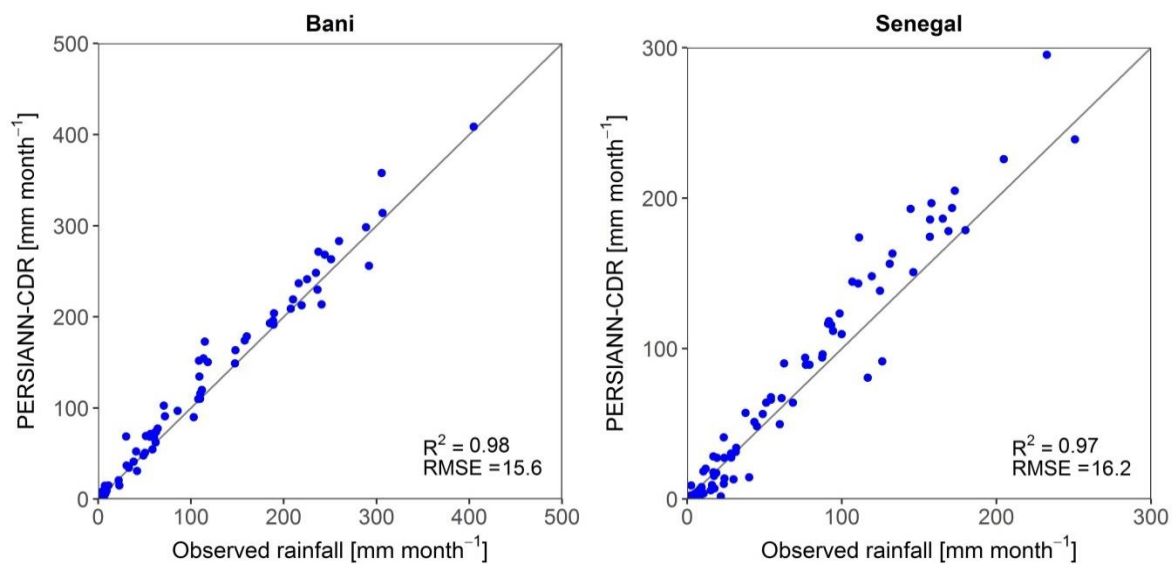


Figure 6. Correlation between mean monthly rainfall over Upper Senegal and Bani basins.

The monthly correction coefficients for each basin (Table 5) were obtained from the quotient between the interannual monthly observed and estimated rainfalls (see Equation (1)). It should be mentioned that due to the lack of sufficient rainfall gauges in Makana, Bakoye, and Faleme sub-basins, the correction coefficients of these sub-basins were considered equal to those of the whole Upper basin (Senegal basin at Bakel). For both Bani and Upper Senegal basins, the rainy season is between May and October. During this period, the correction coefficients were between 0.84 and 1.17, which means that PERSIANN-CDR estimated the monthly rainfall relatively well during the rainy season. However, during the driest months (November to April), the coefficients could be much higher than 1 for both basins, especially for the Senegal River basin. Usually, precipitations during this period are light and do not generate runoff.

Table 5. Bias coefficients correction of PERSIANN-CDR data.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Bani Basin	1.04	1.53	0.82	0.82	0.88	0.85	0.96	0.97	0.93	0.91	0.91	0.66
Senegal Basin	3.03	0.90	2.75	1.99	1.17	0.86	0.87	0.87	0.87	0.84	2.07	2.08



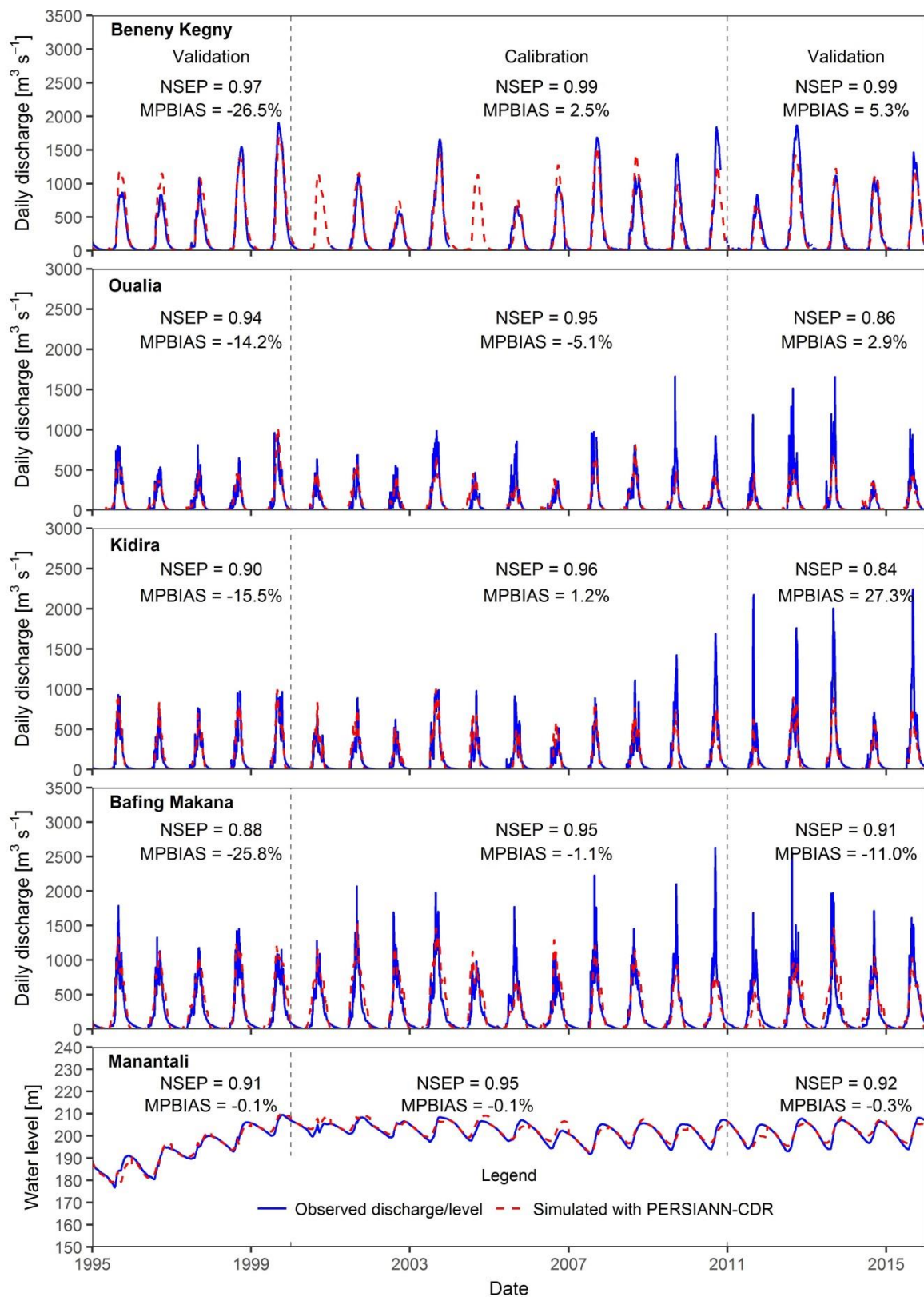
In this study, PERSIANN-CDR daily rainfalls were corrected based on the coefficients in Table 5. Simulations of daily discharges were done for each basin using the same model parameters obtained with the original PERSIANN-CDR data. Results show an underestimation of runoff between 10 to 24%, and consequently, a reduction of the values of the Nash–Sutcliffe efficiency (NSEP). Original values of NSEP (1995–2015) were 0.987, 0.978, 0.956, 0.932 and 0.903, for Beneny Kegny, Oualia, Kidira, Bafing Makana, and Manantali, respectively. These coefficients dropped to 0.962, 0.907, 0.854, 0.912, and 0.761, respectively. Because of this deterioration of results, we decided to re-calibrate the CEQUEAU model for each sub-basin. The results, according to the numerical criteria are shown in Table 6. Observed and simulated hydrographs at each gauging station and water level in the Manantali reservoir are shown in Figure 7.

Overall simulations were good to very good for each year for Bani at Beneny Kegny, except for year 2000 due to the fact that overlapping discharges data were only available during 174 days corresponding to low flows. Simulations of daily discharges for Bakoye at Oualia, Faleme at Kidira, and Bafing at Bafing Makana ranged from satisfactory to very good, except for 1 year of 21 years of simulation according to the classification of Table 1. In addition, for the simulations of water level of Manantali Dam, results for 17 of the 21 years ranged from satisfactory to very good.

The results of the two experiments using original and bias-corrected PERSIANN-CDR are summarized in Table 7, according to numerical criteria of Nash–Sutcliffe efficiency (NSEP) and percent of bias (MPBIAS) over the calibration and validation periods. Simulations with these two products were very good; however, we cannot conclude that the applied correction coefficients have improved the simulations.

**Table 6.** Performance criteria of daily discharge simulations using bias-corrected PERSIANN-CDR.

Basin	Niger		Senegal							
	Bani		Bakoye		Faleme		Bafing		Bafing	
River	Beneny Kegny		Oualia		Kidira		Bafing Makana		Manantali Dam	
Gauge	NSE	R <sup>2</sup>	NSE	R <sup>2</sup>	NSE	R <sup>2</sup>	NSE	R <sup>2</sup>	NSE	R <sup>2</sup>
1995	0.69	0.98	0.89	0.90	0.88	0.93	0.92	0.94	0.75	0.90
1996	0.57	0.95	0.76	0.79	0.75	0.92	0.81	0.92	0.92	0.95
1997	0.73	0.90	0.72	0.76	0.92	0.93	0.85	0.92	0.89	0.95
1998	0.97	0.98	0.70	0.80	0.67	0.75	0.86	0.93	0.98	0.98
1999	0.95	0.95	0.68	0.83	0.85	0.86	0.75	0.94	0.77	0.91
2000	−1.01	0.98	0.65	0.89	0.66	0.89	0.77	0.88	−0.15	0.50
2001	0.92	0.97	0.56	0.75	0.65	0.84	0.74	0.86	0.24	0.82
2002	0.77	0.93	0.72	0.75	0.72	0.85	0.80	0.84	0.85	0.95
2003	0.97	0.97	0.83	0.90	0.91	0.93	0.82	0.86	0.89	0.92
2004	-	-	0.30	0.70	0.57	0.70	0.58	0.84	0.41	0.75
2005	0.89	0.91	0.58	0.83	0.81	0.89	0.70	0.82	0.59	0.75
2006	0.87	0.97	0.81	0.83	0.01	0.71	0.33	0.82	0.39	0.78
2007	0.97	0.97	0.89	0.89	0.83	0.93	0.81	0.82	0.99	1.00
2008	0.77	0.95	0.84	0.88	0.78	0.82	0.84	0.90	0.88	0.96
2009	0.85	0.95	0.63	0.79	0.81	0.93	0.83	0.90	0.82	0.88
2010	0.87	0.94	0.81	0.84	0.72	0.86	0.59	0.78	0.74	0.85
2011	0.89	0.91	0.54	0.61	0.55	0.83	0.58	0.86	0.30	0.52
2012	0.91	0.97	0.62	0.71	0.78	0.81	0.82	0.83	0.88	0.96
2013	0.97	0.98	0.83	0.86	0.77	0.89	0.71	0.82	0.80	0.90
2014	0.93	0.95	0.68	0.86	0.90	0.92	0.91	0.91	0.87	0.96
2015	0.97	0.98	0.76	0.84	0.64	0.86	0.90	0.93	0.84	0.94



**Figure 7.** Observed and simulated discharges and water level using bias-corrected PERSIANN-CDR.

In previous studies, daily discharges of the Bani and Upper Senegal Rivers have been simulated using distributed and semi-distributed models with gauged and satellite rainfalls. In the following, the results of this study will be compared with some of these previous studies.

Bâ et al. [21] used the Tropical Rainfall Measuring Mission (TRMM) 3B42V7 data, the TRMM Real Time 3B42V7 data, and gauged rainfall to simulate the daily discharges of the Bani at Beneny Kegny. Their results in terms of NSE and  $R^2$  (which were computed for each year) were very good. In addition, Ruelland et al. [23] used the hydrological model HydroStrahler and gauged rainfall to simulate the daily discharges of the Bani River at Douna Station, which is located around 100 km upstream of the Beneny Kegny hydrometric station. They obtained values of Nash–Sutcliffe efficiency of 0.92 for the period of calibration and 0.94 and 0.89 for two periods of validation.

**Table 7.** Summary of numerical criteria over calibration and validation periods.

Gauge	Calibration (2001–2011)				Validation 1 (1995–2000)				Validation 2 (2012–2015)			
	Raw		Bias-Corrected		Raw		Bias-Corrected		Raw		Bias-Corrected	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Beneny K.	0.98	7.4	0.99	2.5	0.99	−1.2	0.97	−26.5	0.97	9.3	0.99	5.3
Oualia	0.96	−1.2	0.95	−5.1	0.97	−5.6	0.94	−14.2	0.91	0.3	0.86	2.9
Kidira	0.94	−1.8	0.96	1.2	0.92	−22.2	0.90	−15.5	0.83	22.0	0.84	27.3
Bafing M.	0.93	−4.5	0.95	−1.1	0.89	−21.3	0.88	−25.8	0.89	−8.1	0.91	−11.0
Manantali	0.89	0.0	0.95	−0.1	0.91	0.1	0.91	−0.1	0.89	0.0	0.92	−0.3

(a) = NSEP, and (b) = MPBIAS.

On the other hand, for the same purpose and for this hydrometric station, Chaibou Begou et al. [22] used the Soil and Water Assessment Tool (SWAT) model obtaining values of Nash–Sutcliffe efficiency (NSEP) of 0.76 and 0.85, respectively, for calibration and validation. Values of NSE were not given year by year in Ruelland et al. [23] and Chaibou Begou et al. [22]. The results of these previous studies are summarized in Table 8 in term of Nash–Sutcliffe coefficients (NSEP) for calibration and validation periods in comparison with those of this study. It is important to emphasize that the Douna station was not considered in this study due to a shorter overlapping period between discharges and PERSIANN-CDR data in comparison with Benegy Kegny’s dataset.

Furthermore, for the tributaries of the Upper Senegal River Basin, daily flows have been simulated in a few recent studies. Stisen and Sandholt [37] used the Mike SHE model with five satellite products and gauged rainfall to simulate daily discharges of rivers of the Upper Senegal basin object of this study. These five products were CMORPH, CPC-FEWS, CCD, PERSIANN, and TRMM. Among the criteria they used, NSEP was included. Using each of the five products, they obtained NSEP values for the period of simulation (1987–1996) between −205 and 0.66 for Oualia, and −0.06 and 0.70 for Bafing Makana. After applying bias-correction and re-calibrating the model, their results improved, with values of NSEP between 0.63 and 0.87 for Oualia and between 0.67 and 0.87 for Bafing Makana. In addition, using gauged rainfall, they obtained values of NSEP close to those of the product that gave better simulations. Bodian et al. [11] used the hydrological model GR4J to simulate the daily discharges of the Bafing River at Bafing Makana with two products: gauge and TRMM rainfalls. For gauge rainfall, their results in term of NSEP were 0.88 and 0.84 for the calibration and validation periods, respectively, while results with TRMM data gave a value of NSEP of 0.80 using model parameters obtained with the first experiment.

However, for simulations of the daily water levels of the Manantali reservoir, the only study we have encountered in the literature review is that carried out by Bâ et al. [31] who simulated this variable using the CEQUEAU model and gauged rainfall. Their results were very good in most of the thirteen years of simulation with an overall NSEP of 0.935. The results of the above-cited studies over Upper Senegal River basin are summarized in Table 9.

**Table 8.** Comparison with other studies conducted over the Bani basin.

Authors	Model	Source	Gauge	Calibration	NSEP	Validation	NSEP
This paper	CEQUEAU	PERSIANN-CDR	Beneny Kegny	2001–2011	0.98	1995–2000 2012–2015	0.99 0.97
Bà et al. [21]	CEQUEAU	Gauge	Beneny Kegny	1992–1996	0.96	1997–1999	0.88
Bà et al. [21]	CEQUEAU	TRMM	Beneny Kegny	2005–2016	0.91	1998–2003	0.96
Bà et al. [21]	CEQUEAU	TRMMRT	Beneny Kegny	2008–2016	0.88	2001–2007	0.83
Ruelland et al. [23]	Hydro-Strahler	Gauge	Douna	1961–1990	0.92	1952–1960 1991–2000	0.94 0.89
Chaibou Begou et al. [22]	SWAT	Gauge	Douna	1983–1992	0.76	1993–1997	0.85

**Table 9.** Comparison with other studies over the Senegal basins.

Authors	Model	Source	Gauge	Calibration	NSEP	Validation	NSEP
This paper	CEQUEAU	PERSIANN-CDR	Oualia	2001–2011	0.96	1995–2000 2012–2015	0.97 0.91
Stisen and Sandholt [37]	Mike SHE	Gauge	Oualia	1991–1996	0.83	1987–1990	0.76
This paper	CEQUEAU	PERSIANN-CDR	Bafing Makana	2001–2011	0.93	1995–2000 2012–2015	0.89 0.89
Stisen and Sandholt [37]	Mike SHE	Gauge	Bafing Makana	1991–1996	0.88	1987–1990	0.90
Bodian et al. [11]	GR4J	Gauge	Bafing Makana	1963–1982 1983–1997	0.88 0.79	1983–1997 1963–1982 1998–2004	0.84 0.80 0.88
Bodian et al. [11]	GR4J	TRMM	Bafing Makana			1998–2004	0.80
Stisen and Sandholt [37]	Mike SHE	Gauge	Bafing Makana	1991–1996	0.88	1987–1990	0.90
This paper	CEQUEAU	PERSIANN-CDR	Manantali Dam	2001–2011	0.89	1995–2000 2012–2015	0.91 0.89
This paper	CEQUEAU	PERSIANN-CDR bias	Manantali Dam	2001–2011	0.95	1995–2000 2012–2015	0.91 0.92
Bà et al. [31]	CEQUEAU	Gauge	Manantali Dam			1988–2000	0.94

#### 4. Summary and Conclusions

In many watersheds around the world, such as in Africa, meteorological networks are often inexistent or sparse. Data are not generally accessible and are often of questionable quality. Remote sensing data could be a suitable alternative for hydrologic applications. A given satellite product can be suitable in a specific region but not in another, therefore its quality must be assessed before its use for any specific application. In this study, we evaluated the performance of PERSIANN-CDR over the Upper Senegal and Upper Niger basins through a rainfall-runoff modeling scheme, where the CEQUEAU distributed model was chosen.

First, PERSIANN-CDR data were compared with gauge rainfall. Although the PERSIANN resolution is  $0.25^\circ$ , the point to pixel comparison of the monthly rainfalls gave coefficients of determination between 0.76 and 0.90. In addition, the coefficients of determination of areal monthly rainfalls of basins were greater than 0.90. Also, PERSIANN-CDR reproduced the annual gauged rainfall over this region very well.

In addition, due to not having enough observed temperatures, we used estimated temperatures ERA-Interim for evapotranspiration calculation in the CEQUEAU model. A comparison showed good agreement between ERA-Interim and observed temperature.

In order to evaluate PERSIANN-CDR with the hydrological model, two phases of the study were designed. First, the performance of the original PERSIANN-CDR for the simulation of daily discharges was assessed in three hydrometric stations of Upper Senegal River and one station of the Bani River (Upper Niger River), as well for the simulation of water level of the Manantali reservoir. In a second phase, we applied a bias-correction to PERSIANN-CDR data and tested the new product as this was done in first phase. The Nash–Sutcliffe efficiency and coefficient of determination were used as numerical objective criteria and were computed for each year of simulation with values greater than 0.8 and greater than 0.90 respectively for most years.

In addition, Nash–Sutcliffe efficiency and the mean percent of bias were computed for the periods of calibration and validation with values greater than 0.83 and less than 10% (in absolute value), respectively, for 12 out of 15 periods.

The hydrographs of gauge and simulated discharges were compared. Considering these criteria, PERSIANN-CDR and bias-corrected PERSIANN-CDR gave very good simulations. Results show that these two products derived simulations had close performances. This was probably due to the fact that PERSIANN-CDR is an adjusted product with GPCP monthly data. It could also be due to the fact that the applied correction coefficients were calculated using areal gauged and estimated monthly rainfall, which are similar during the rainy season (Table 5). Since the spatial distribution of rainfall over the studied basins was highly heterogeneous, the correction coefficients should be calculated on local basis by determining the pixels that are in the area of influence of each station. Subsequently, the correction coefficients of each pixel could be calculated using the rainfall of this gauge.

The numerical criteria resulting from this study were better than those from other studies realized by other authors who used gauged and satellite rainfalls.

In the CEQUEAU model, the basin is discretized in cells as in the case of satellite products; this means that there is no need to interpolate the meteorological data, and the same spatial and temporal discretization can be used. In this study, a spatial resolution of 0.25° and a daily time step were used. Although the model has many conceptual parameters, for the studied basins, the number of parameters was reduced to represent the runoff phenomenon. Calibration results indicated that for all studied watersheds, important parameters were those related to evapotranspiration (XAA, XIT, HPOT), surface runoff (HSOL, TRI, HRIMP), infiltration (HINF, CIN, XINFMA), transfer coefficient (EXXKT), and to a lesser extent, hypodermic flow (HINT, CVSI). The base flow and the flow produced by the reservoir “Lakes and Marshes” did not intervene in any of the studied watersheds. Only the above parameters were calibrated at each gauge station. The model, once calibrated well, can reproduce the runoff well.

The study shows that PERSIANN-CDR is useful for rainfall-runoff simulation in this region. This product can be particularly helpful for simulation of streamflow for example for dam construction at sites where there is no gauge data, for long-term hydrological modeling, and for water resources management. More specifically, this study can help to better design the dams under construction on the three rivers of the Upper Senegal basin.

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