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Spatially distributed hydrological modelling of a Western Africa basin

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Abstract

Distributed hydrological simulations aid to investigate the spatio-temporal behaviour of hydrological variables. However, data to feed hydrological models are not always available mainly due to lack of gauges or high retrieval fees. In this research, two 0.25-degree daily precipitation databases from the Tropical Rainfall Measuring Mission (TRMM) were tested to simulate daily runoff in the basin of the main Upper Niger River tributary. Precipitation data are TRMM and TRMM Real Time (RT) 3B42V7. For runoff simulation, the grid-based hydrological model CEQUEAU was chosen. To estimate the evaporation in the model, temperatures were retrieved from the third-generation reanalysis ERA-Interim. From gauges and both TRMM data, monthly basin precipitation was calculated and compared to analyse the performance of TRMM to estimate rainfall. Runoff was simulated with each of these three precipitation products. In each case, the daily ERA-Interim temperatures were used. By Nash-Sutcliffe model Efficiency (NSE) and coefficient of determination (R^2), model performance was evaluated through comparison of daily discharges with simulations for both calibration and validation periods. Results show correlation of TRMM by 0.95 and TRMMRT by 0.91 with gauge data. Both TRMM products combined with ERA-Interim temperature were found suitable for daily runoff modelling with NSE >0.835 and R^2 >0.872.

1 Introduction

In order to investigate the spatio-temporal behaviour of hydrological variables, spatially distributed hydrological model simulations can be used (Karimi and Bastiaanssen, 2015; Ruelland *et al*., 2008). Nevertheless, in some regions, data to feed this type of models are not always available, mainly due to

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lack of gauges or high retrieval fees, as is the case in many parts of Africa (Bâ *et al*., 2013; Chaibou-Begou *et al*., 2016; Worqlul *et al*., 2017).

This abstract paper presents the results of the performance of two satellite precipitation products to estimate monthly rainfall and to simulate daily runoff (discharge) of the Bani River basin, which is the main Upper Niger River tributary. Daily precipitation data correspond to the Tropical Rainfall Measuring Mission (TRMM): TRMM and TRMM Real Time (RT) 3B42V7 (Huffman *et al*., 2007). Monthly basin precipitation with both TRMM and TRMMRT were compared with those calculated with gauge data over the Bani River basin. In addition, the distributed hydrological model CEQUEAU was used to simulate daily runoff. Daily temperatures of the third-generation reanalysis ERA-Interim (Dee *et al*., 2011) were considered for the modelling due to the lack of ground observations. After this section, Methodology is shown followed by Results and discussion.

2 Methodology

2.1 Study area

The Bani River is one of the most important in Africa. This basin has an area of 112 000 km^2 until Beneny Kegny discharge gauge. The river runs over three countries Mali, Côte d'Ivoire and Burkina Faso (Figure 1). Percentage of drainage area of these countries are 77, 18 and 5% respectively. Only a small percentage (<1%) of the basin is shared with Guinea. Rainfall average varies from South (Odienne) with 1300 mm/year to North (Segou) with 740 mm/year (period 1992-1999). The annual average discharge of the Bani River at Beneny Kegny is 361 m^3/s (period 1952-2008). Peak Discharge can reach 3000 m^3/s at that gauge. The river flows from southwest to northeast.

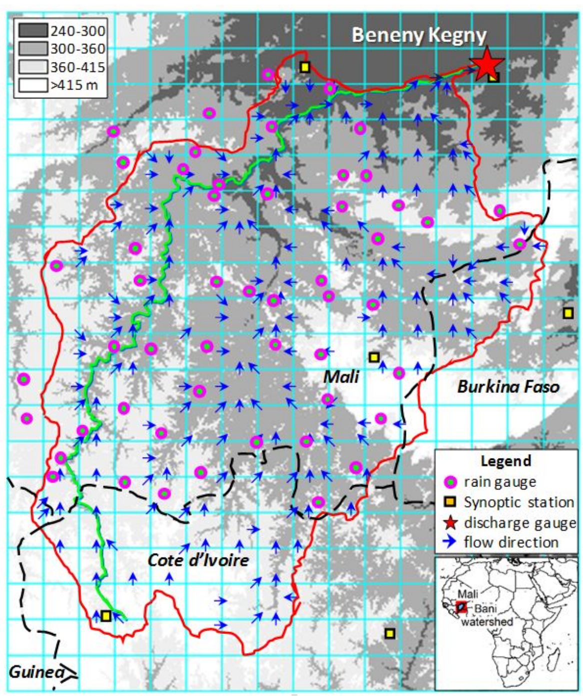

Figure 1: Bani basin at Beneny Kegny. Every square represents a 0.25-degree TRMM cell

2.2 Data

Precipitation databases are 0.25-degree TRMM and TRMM Real Time (RT) 3B42V7 (Huffman *et al*., 2007) on a daily basis. TRMM data was retrieved from 1998/01 to 2016/10, and TRMMRT from 2000/03 to 2016/12. A group of rain gauges and synoptic stations were considered for the comparison with satellite precipitation (Figure 1). This group is integrated by gauges located in Mali and six synoptic stations located in Mali (3 stations), Côte d'Ivoire (2 stations), and Burkina Faso (1 station). Data of synoptic stations was retrieved from NOAA website (https://www.ncdc.noaa.gov/). Rain gauge data was available from 1992 to 2002. To estimate evaporation in the model, due to the lack of observed temperatures, those from the third-generation reanalysis ERA-Interim were used at the same spatial resolution as TRMM and on a daily basis.

2.3 Cequeau model

The distributed hydrological model CEQUEAU (Morin *et al*., 1997; Morin, 2002; Morin and Paquet, 2007) was developed at the National Institute for Water-Scientific Research (formerly INRS-EAU, now INRS-ETE) at the University of Quebec, Canada. This model considers the physiographical characteristics of the watershed by means of a spatial division (grid). In each cell, the representation of the space-time evolution of the hydrological processes is performed by two functions: production and routing (Figure 2). In the production function, the evaporation is calculated by Thornthwaite method with the temperature data.

The model was implemented by Morin *et al.* (1997) and extensively tested on Canadian watersheds for the evaluation of hydrological resources in the framework of hydroelectric power generation. Applications in watersheds around the globe include Morin *et al*. (1997), Llanos Acebo *et al*. (1999), Bâ *et al*. (2001), Guerra-Cobián (2007), Eleuch *et al*. (2010), Bâ *et al*. (2013), and Diaz-Mercado *et al.* (2015). CEQUEAU model was compared with others well-known hydrological models in the framework of two inter-comparisons of hydrological models forested by the World Meteorological Organization (WMO), where its performance was very remarkable (WMO, 1986; 1992).

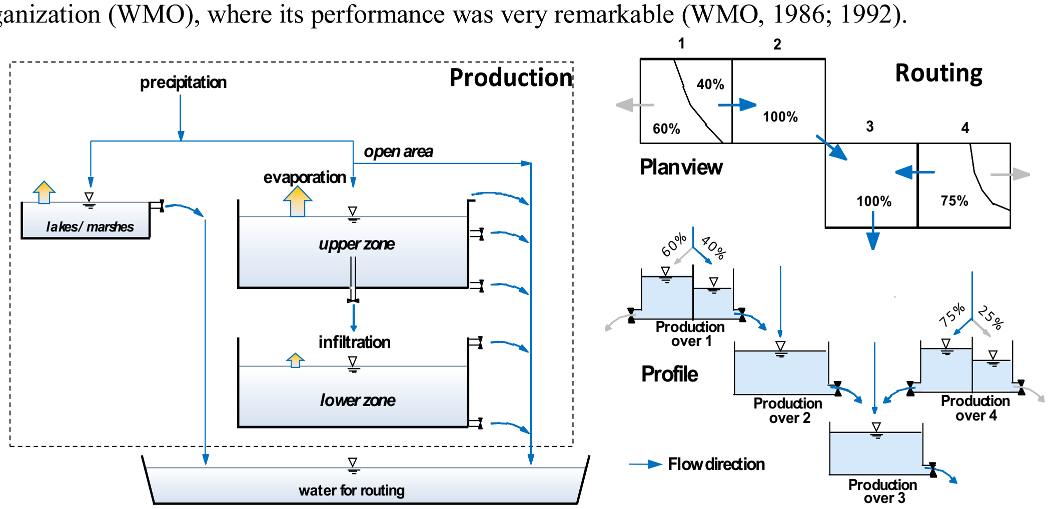

Figure 2: CEQUEAU model production (left) and routing (right) scheme

2.4 Experiment setup

From gauges and both TRMM data, monthly basin precipitation was calculated and compared to analyse the performance of TRMM to estimate rainfall. Samples of monthly rainfall were computed for both gauged and satellite rainfall between 1998 and 2002. On the other hand, because well-distributed gauged precipitation was only available from 1992 to 1999, runoff simulation with that information was carried out only for this period.

Runoff was simulated for different calibration and validation periods by the three sources of precipitation: gauges, TRMM and TRMMRT. ERA-Interim temperatures were used in all simulations to compute evaporation in the model. By Nash-Sutcliffe model Efficiency (NSE) and coefficient of determination (R^2), model performance was evaluated through comparison of daily discharges with simulations for both calibration and validation periods.

3 Results and discussion

Precipitation trends of rain gauges were confirmed by TRMM data. It was found that average rainfall varies from South with 1385 mm to North with 716 mm (period 2005-2016). Coefficients of determination between the mean monthly gauged rainfall over the basin and those of TRMM and TRMMRT were 0.95 and 0.91, respectively.

On the other hand, the annual average discharge, as well as the NSE and R^2 for each source of precipitation are presented in Table 1 for the years when data were available. Columns (O), (G), (T) and (RT) in Table 1 show the **O**bserved annual discharge, those simulated with **G**auged rainfall and those simulated with **T**RMM and TRMM**RT** respectively.

For the performance evaluation of the model, in this study, the criterion of Moriasi *et al.* (2015) is followed. According to those authors, simulations are very good when NSE is higher than 0.80, good when between 0.70 and 0.80, satisfactory when between 0.50 and 0.70 and not satisfactory when NSE is less than 0.50. Regarding R^2, simulations are very good when it is higher than 0.85, good when between 0.75 and 0.85, satisfactory when between 0.60 and 0.75 and not satisfactory when it is less than 0.60. As shown in Table 1, the lowest values of NSE and R^2 for simulations with gauged rainfall were 0.800 and 0.929, respectively. Whereas for simulations with TRMM data, the lowest values of NSE and R^2 were 0.711 and 0.912. Overall, simulations with the two products were very good. However, for TRMMRT data, over the sixteen years of simulation, there are two years (2002 and 2004) with NSE values that indicate not satisfactory simulations, but in terms of R^2, all simulations were very good. The lowest NSE obtained for TRMMRT is perhaps due to input data or to model parameter calibration.

Figure 3 shows the hydrographs of observed and calculated discharges with the three sources of information. It is observed that, in general, the three sources of precipitation reproduce the peaks well. It seems that of the two satellite products, TRMM best estimates the maximum discharges. For the three precipitation sources, Table 2 presents NSE and R^2 calculated for the respective calibration (C), validation (V), and global (GL) periods. Gauges, TRMM, and TRMMRT shown an overall NSE of 0.919 (1992-1999), 0.929 (1998-2016), and 0.866 (2001-2016), respectively. Of all the precipitation sources, modelling with TRMM rainfall shown the best performance (Table 2).

Table 1: Average discharge, NSE and R^2

	Annual discharge (m^3/s)				NSE			R^2		
Year	O	G	T	RT	G	T	RT	G	T	RT
1992	131.5	155.9			0.934			0.982		
1993	126.8	156.7			0.916			0.963		
1994	430.3	436.7			0.977			0.977		
1995	218.9	180.7			0.921			0.951		
1996	190.7	173.5			0.925			0.929		
1997	186.3	194.4			0.931			0.947		
1998	343.6	224.1	369.1		0.800	0.972		0.985	0.976	
1999	454.2	373.7	465.7		0.921	0.971		0.957	0.971	
2000	(*)									
2001	250.6		249.5	277.5		0.947	0.924		0.964	0.973
2002	144.7		145.8	215.2		0.891	0.489		0.924	0.953
2003	424.2		333.7	362.3		0.953	0.960		0.974	0.961
2004	135.5		(**)	283.4		(**)	-1.124		(**)	0.941
2005	172.8		201.6	241.3		0.853	0.699		0.941	0.952
2006	210.7		253.5	266.1		0.909	0.908		0.973	0.962
2007	351.0		350.0	309.5		0.939	0.944		0.941	0.979
2008	272.8		374.1	375.1		0.711	0.645		0.951	0.949
2009	267.3		210.9	263.2		0.877	0.936		0.922	0.952
2010	451.0		410.2	316.1		0.964	0.907		0.968	0.964
2011	194.1		192.7	201.0		0.859	0.925		0.912	0.942
2012	462.3		398.7	363.3		0.927	0.900		0.945	0.967
2013	245.7		207.8	297.4		0.921	0.875		0.932	0.940
2014	244.3		291.7	285.7		0.879	0.894		0.926	0.937
2015	301.8		277.4	408.4		0.957	0.831		0.960	0.974
2016	442.9		350.4	387.9		0.890	0.872		0.957	0.881

* Missing discharge data during wet period, ** no data available from June to October.

In this study, some limitations were related to the availability of input data, mainly. In addition to not being able to obtain all meteorological data from National Meteorological Services, there were some gaps in the daily discharges and TRMM data records. In 2000, only 48% (174 days) of observed discharge data were retrieved. As the missing data were from the wet period, this year was excluded from the performance evaluation. Moreover, TRMM data were not available in 2004 from June to October (wet period). Because it was not possible to reproduce the discharges with this source of data during these months, where peaks occur, NSE and R^2 were not calculated.

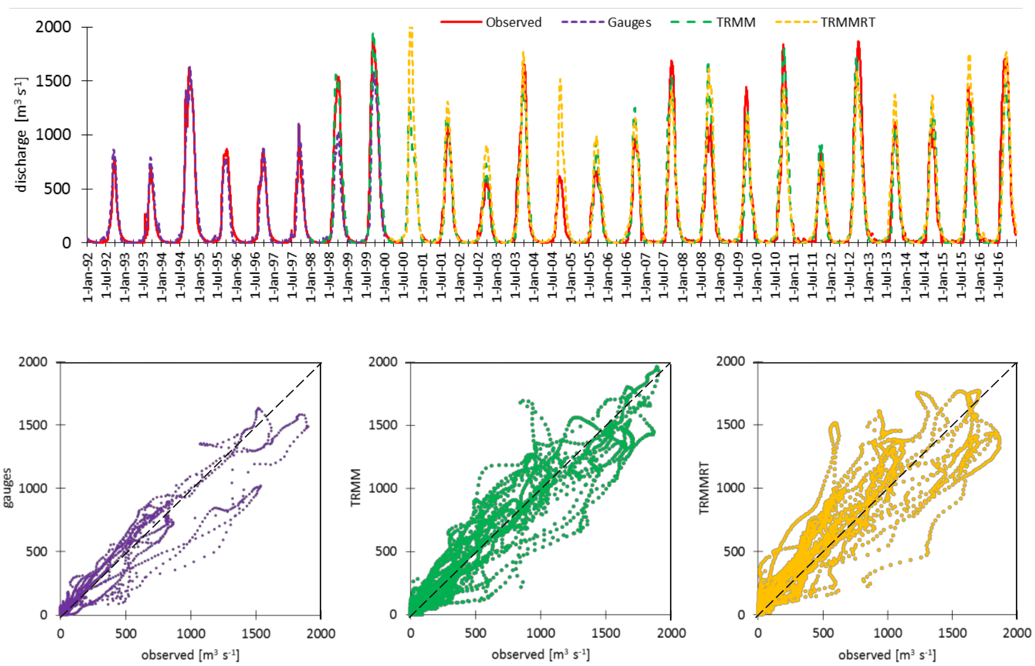

Figure 3: Daily observed and calculated discharge at Beneny Kegny from the period 1992 to 2016

Table 2: Model performance for calibration (C), validation (V), and global (GL) periods

	Gauges			TRMM			TRMMRT		
	C (1992-1996)	V (1997-1999)	GL (1992-1999)	C (2005-2016)	V (1998-2003)	GL (1998-2016*)	C (2008-2016)	V (2001-2007)	GL (2001-2016)
R^2	0.959	0.928	0.928	0.911	0.965	0.929	0.880	0.872	0.875
NSE	0.959	0.885	0.919	0.910	0.965	0.929	0.878	0.835	0.866

* No data available from June to October 2004.

4 Conclusions

The performance of two satellite precipitation estimates TRMM and TRMMRT 3B42V7 was investigated for their use in the distributed hydrological model CEQUEAU. Daily TRMM rainfall combined with ERA-Interim temperature were used to simulate the daily discharges of the Bani River (Upper Niger) basin at Beneny Kegny. Additionally, a small sample of gauged precipitation (8 years) combined with ERA-Interim temperature were used for the same purpose. Two objectives criteria were considered for modelling performance, i.e., Nash-Sutcliffe model Efficiency (NSE) and coefficient of determination (R^2). Considering all the criteria, the performance of all simulations was very acceptable (NSE >0.835, R^2 >0.872). It can be concluded that satellite precipitation and temperature estimates (in this case TRMM products and Era-Interim temperature) can help to better improve the accuracy of hydrological studies in this large western Africa basin. Also, based on the results of this study, it can be concluded that TRMMRT data are promising for near real-time hydrological forecasting in this basin, on a spatially distributed basis. This hydrological model set-up is subject to improvements to obtain better results both for calibration and for validation period, although the results so far are very satisfactory.

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