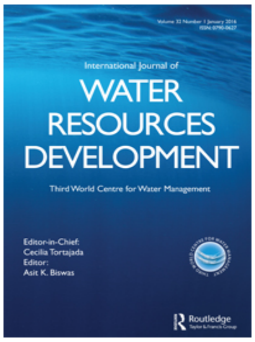

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Rainfall-runoff modelling of water resources in the upper Senegal River basin

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The streamflow series for the upstream basin of the Senegal River is marked by considerable gaps. The objective of this article is to simulate and extend hydrological data, using the GR2M rainfall-runoff model. A sensitivity analysis of the model to rainfall and water holding capacity input data was performed. This analysis was performed after calculating catchment rainfall, mean potential evapotranspiration, and maximum, minimum and mean water holding capacity. The best combination of input data was chosen by catchment based on the Nash-Sutcliffe criterion. Then cross calibration-validation tests were performed, using the selected input data to choose model parameter sets.

Keywords: upper Senegal River basin; rainfall-runoff modelling; water resources; GR2M; streamflow

Introduction

At all spatial scales, good management of water resources is a necessity. This general observation takes on even greater meaning in sub-Saharan regions, where water shortage and flooding hazards due to poor water management have dramatic consequences for the local population and for socio-economic activity. However, one cannot manage a resource when its extent is unknown. In recent decades, the countries which share the Senegal River basin (Guinea-Conakry, Mali, Senegal and Mauritania) have had difficulty providing suitable hydrological monitoring of the river and its tributaries. The number of gauging stations has fallen, partly due to a lack of human and financial resources. On the Guinean side, especially, knowledge of water resources and their seasonal variation has been limited by truncated hydrological data. The flow chronicles that are currently available, for example at the National Water Direction (DNH) of Guinea, are often incomplete, discontinuous and short. Consequently, the flow chronicles are difficult to use for reliable hydrological analysis. This lack of knowledge in the upper basin, which is the main source of Senegal River water (Varis, Rahaman, & Stucki, 2008), is an obstacle to its development, especially as the monitoring of the hydrological regime of the Senegal River in the Guinean part is not ensured (Kane & Diallo, 2005). In addition, the lack of quantitative knowledge of inputs (uncontrolled tributaries, episodic monitoring) presents an objective limitation to ensuring the optimal management of water resources for both the river and the Manantali Dam (OMVS, 2006), located on the Bafing River in Mali.

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To fulfil its mission, the Organization for the Development of the Senegal River (OMVS) requires data and information that will enable it to monitor and forecast the evolution of the resources, also taking into account the importance of climate variability in the region – a region characterized by recurrent drought, the potential impacts of climate change, and the pressures of an increasing population on water resources. Thus, a significant research effort has been made to improve understanding of the hydrological functioning of the upper basin. To this end, studies have been carried out by Bamba and Baldé (2005), Coly, Ould Soufi, Camara, Diallo, and Lakh (2005), CSE (2006), and Nonguierma and Niang (2006). However, it is not always possible to have the continuous and long time series on the same site in the top upstream part of the basin which would allow the determination of water resources and thus the knowledge and prediction of extreme flood situations or low flows and their risk of occurrence.

The rainfall data are more numerous and less incomplete than the hydrological data. Thus, modelling the rainfall–runoff relationship may help overcome this lack of data. From the many existing rainfall-runoff models, the family of GR (Rural Engineering) models of IRSTEA (formerly Cemagref GR1A, GR2M and GR4J) are preferred in this area for their simplicity, scalability and robustness. This article uses the GR2M conceptual model on a monthly time step using two parameters. The robustness of that model in simulating flows in the African context has been shown in several studies (Paturel, Servat, & Vassiliadis, 1995; Ouédraogo, Servat, Paturel, Lubès-Niel, & Masson, 1998; Mahé, Paturel, Servat, Conway, & Dezetter, 2005). This study aims to develop a methodology to simulate and extend hydrometric data using the stations that have the minimum number of hydrometric data required for calibration and validation of the model. This methodology will provide a sufficiently long time series of flows for a better estimate of water resources and their temporal fluctuations.

Study area

The study area is the upper basin of the Senegal River and involves seven hydrometric stations (Table 1). This watershed extends over Guinea Conakry and Mali with an area of 21,290 km^2 at the gauging station Bafing Makana (Figure 1). In general, the value of the slope indices calculated from the Shuttle Radar Topography Mission 90 m NASA (Wermer, 2001), decreases from upstream to downstream, reflecting the importance of the mountainous region of Fouta Djalon and strong relief incision. It is also worth noticing that all the sub-basins in the Senegal basin have a relatively high average altitude for the region (Table 1). From a climatic point of view, the upper basin of the Senegal River belongs to the Soudano-Guinean zone characterized by a single rainy season in the year from April to October (Dione, 1996; Lahtela, 2003; Bodian, 2011).

Data and hydrological model

Four types of data are needed for GR2M model: monthly precipitation, monthly Potential EvapoTranspiration (PET), Water Holding Capacity of soil (WHC) and the monthly average flows.

Precipitation

Precipitation data, from the origin of stations to 2005, have been obtained from the National Meteorology Directorates (DMN) in Guinea and Mali. Their duration and quality

Table 1. Physiographic parameters of basins (K_c = Gravelius compacity index; L = length of equivalent rectangle; l = width of equivalent rectangle; I_p = Roche slope index; I_G = global slope index; D_s = specific vertical drop).

Station	River	Area (km^2)	Length (km)	K_c	L (km)	I (km)	I_p	I_G (m/km)	Elevation max. (m)	Elevation min. (m)	D_s (m)
Bafing Makana	Bafing	21290	1092	2.1	468	46	1.7	2	1389	215	336
Daka Saidou	Bafing	15660	868	1.9	219	72	2.5	5	1389	306	619
Balabori	Bafing	10910	479	1.3	158	69	2.7	6	1358	463	593
Bébélé	Téné	3509	268	1.3	87	41	3.2	8	1300	578	493
Sokotoro	Bafing	1639	194	1.3	67	25	3.7	11	1358	608	454
Téliko	Kioma	332	72	1.1	19	17	5	20	1030	643	365
Trokoto	Kioma	970	162	1.5	59	16	2.9	7	1030	641	204

vary depending on the country and the shorter chronicle is 30 years long. The inventory of rainfall data is shown in Table 2 and the spatial distribution of stations in Figure 1. A reference period of 1960 to 2000 was determined from the data in Table 2. This period has the characteristic of presenting data common to almost all the stations selected for the study.

Potential evapotranspiration data

PET data, calculated according to the formula of Penman (1948), come from the National Direction of Meteorology (DMN) of Guinea. They cover 1953–1995 for Labe, south of the basin, and 1957–1996 for Siguiri, northeast of the basin (see Figure 1). To cover the same period as the rainfall data (1960–2000), missing values were filled with monthly averages of the series in view of the low inter-annual variation of this variable.

The characteristic data of soil

The data for the WHC of soil was provided by HydroSciences Montpellier in a gridding way with the resolution of half a degree square. There are three sets of monthly data grids of WHC of soil built from the soil map distributed by FAO (FAO-UNESCO, 1974–1981). Based on the particle size distribution of the soil, the vegetation, the values of root depth and limitations of suction values, FAO has identified seven classes (A to F) of water capacity, with the last class corresponding to Wetlands. Each class includes minimum and maximum WHC values. Diello (2007) states that there is no information available on the value assigned to the W class, which corresponds to wetland soils. However, in previous studies (Ouedraogo, 2001; Ardoin-Bardin, 2004; Diello, 2007), an arbitrary value of 1000 mm was assigned to this class, and this value is used in the current study.

Hydrology

The hydrological data originated from the database of the OMVS. The series are often incomplete and have significant gaps. Figure A1 in the online supplemental data (at http://dx.doi.org/10.1080/07900627.2015.1026435) shows a timing diagram for the data,

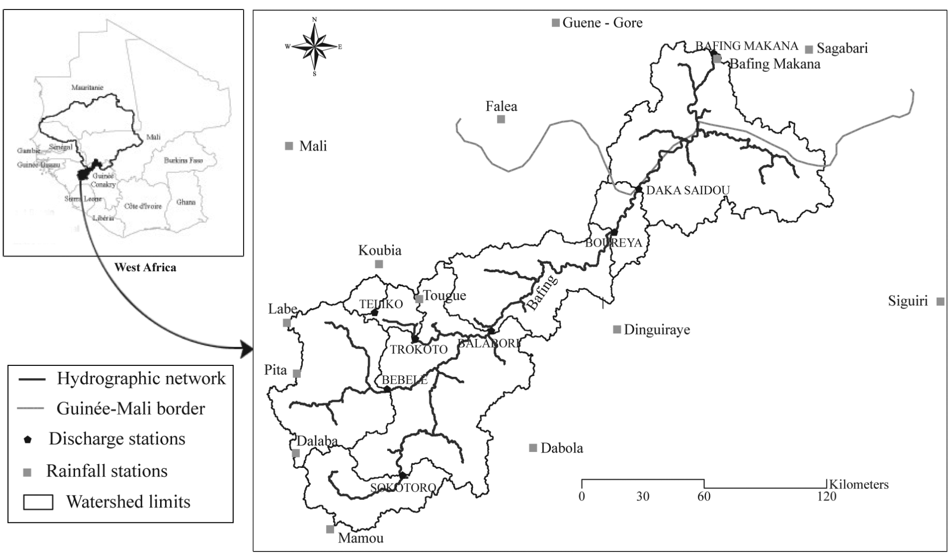

Figure 1. Location of rainfall and discharge stations in the Upper basin of the Senegal River.

Table 2. List of selected rainfall stations (P. an. Moy. = mean yearly rainfall from observed values; end of the record; start of the record; % gap = percentage of days without measurement).

Station	Elevation (m)	Start of record	End of record	Percentage of days without measurement	Mean annual rainfall from observed values (mm)
Bafing Makana	239	1/1/1963	1/9/1997	37.5	1190
Dabola	438	1/1/1933	1/10/2001	14.6	1514
Dalaba	1202	2/1/1934	31/12/2003	7.0	1977
Dinguiraye	490	16/1/1922	16/12/2005	43.7	1375
Faléa	455	1/03/1956	31/12/2003	30.4	1433
Labé	1025	16/1/1923	16/12/2006	0.7	1626
Mali	1464	16/1/1931	16/12/2005	26.2	1625
Mamou	782	2/1/1921	31/12/2008	1.9	1881
Siguiri	362	2/1/1922	30/6/2007	1.7	1272
Tougué	86	16/1/1923	16/8/2004	22.3	1559
Pita	841	16/1/1925	16/12/2004	18.6	1609
Koubia	574	2/1/1969	1/11/1999	39.3	1397
Guene – Gore	240	1/5/1956	31/12/2002	26.8	1246
Sagabari	332	01/07/1959	1/09/1997	18.8	1151

illustrating the incomplete nature of the data from selected hydrometric stations (Balabori, Bébélé, Teliko and Trokoto). These could not be used for further study. Indeed, the GR2M model needs a minimum number of flow data for its calibration and validation. We chose to work with stations that had at least 5 full years of data. However, these incomplete stations were rehabilitated under the GEF/BFS project of the OMVS in 2007; after five years of hydrological monitoring, this will provide additional data for use in the model to simulate and extend the flow series based on the methodology developed here. Finally, only the Bafing Makana, Dakka Saidou and Sokotoro stations are used here for flow modelling.

The GR2M hydrological model

This article uses a semi-global version of the GR2M model (Makhlouf & Michel, 1994). It is a comprehensive conceptual hydrological model that works on a monthly time step. It contains two free parameters to be calibrated, X_1 and X_2. X_1 is involved in the production function, while X_2 is involved in the transfer function. The production function reflects the actual transformation of the rainfall into water available for runoff; the transfer function allows this water to be delayed before reaching the catchment outlet. These two parameters are determined for the entire watershed. Figure 2 shows a conceptual diagram of the model; see Makhlouf and Michel (1994) and Paturel et al. (1995) for a detailed description.

Hydrological modelling challenges regarding policy implications

In a context of climatic deterioration and shrinking water resources, information systems for planning activities within large hydro-systems such as the Senegal River basin becomes a need at all levels: for local communities, industrial partners, farmers, dam operators and policy makers. However, over the last few years, hydrological services have found it difficult to ensure water-level monitoring, resulting in significant gaps in streamflow series. The reasons for the discontinuity of data are part and parcel of the

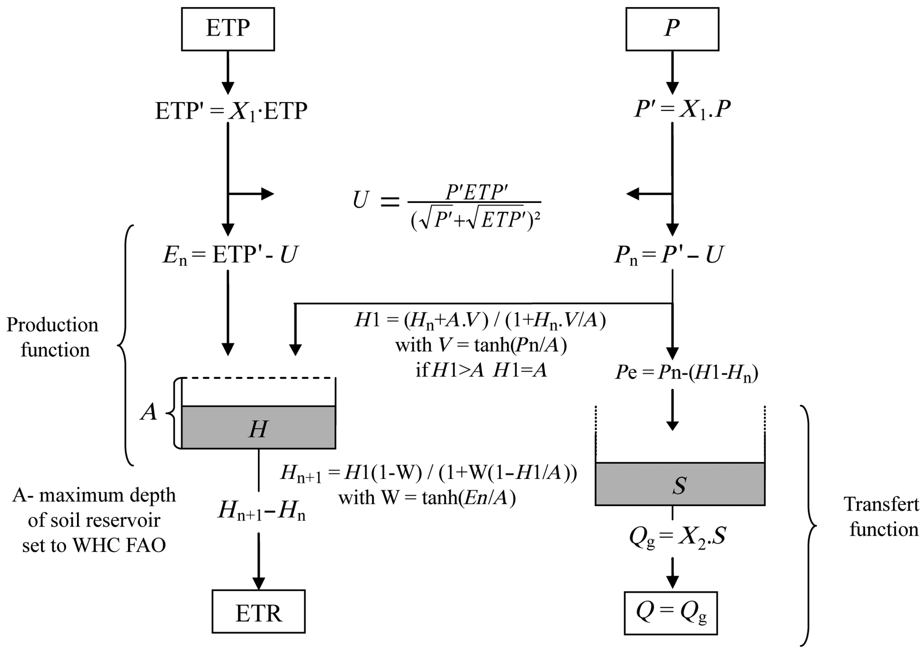

Figure 2. Conceptual scheme of the GR2M model.

imponderables of politics and geopolitics, budgetary austerity measures imposed by international financial institutions, which greatly contributed to harming sectors that are not directly essential for local communities. The gaps in the hydrologic data-sets not only make it difficult to know the status of water resources for better management of them, but also affect sizing assessments for the installation of hydraulic structures for the benefit of communities (dams, anti-salt dams, retention ponds, road structures and retaining dams).

In the absence of actual observed data, hydrological models are now giving us the opportunity to generate hydrological information from rainfall data and from PET (though they need a minimum amount of hydrometric information for their calibration and validation). Thus, one of the major issues of this study is to use the models to fill gaps in time series and at the same time to extend flows as far as possible. This will allow a better characterization of the hydrological regime of the different sub-basins of the upper basin and therefore better knowledge of the water resources and of their temporal variability. This knowledge is the first requirement for management and can be a source of improved practices and risk management tools for water resources. Finally, a good model cross-validation and therefore the knowledge of its parameters can be beneficial beyond the stakes of the upper basin. Indeed, the findings could subsequently be transposed to neighbouring ungauged catchments with similar hydrological environments, giving order-of-magnitude estimates of water resources there.

Methods

The method adopted in this work involves four steps: (1) calculation of watershed rainfall, average PET and WHC of basins; (2) analysis of the sensitivity of the model and the choice of input data-sets of the model; (3) calibration and cross-validation of the model with the input data selected in the previous step; and (4) flow simulation of basins using the validated parameter set.

Calculation of watershed rainfall

Three grids of average monthly rainfall for the period 1960–2000 were built from the rainfall data of the 14 reference stations using three interpolation methods in Surfer software: Kriging, spline function and squared inverse distance weighted.

Calculation of average PET

The average monthly PET was calculated from data from the Labe and Siguiri stations in 1960–1996 by a simple arithmetic average. The spatial variability of monthly PET is low in this region, and the GR2M model used is not very sensitive to this variable (Paturel et al., 1995; Ardoin-Bardin, Dezetter, Servat, & Bocquillon, 2001). Then, for the same period of observation of rainfall data, missing PET values (1997–2000) were extended by the average monthly interannual series.

Estimated soil WHC

To determine the WHC of basins used in this study, Dieulin (2005) developed a method, the main steps of which are recalled here. The FAO soil map divides this study area into irregular polygons with associated WHC values. For the purposes of our modelling, this information is crossed with the boundary of the basins and a regular grid (with a mesh unit of half a degree square) to extract the WHC value for each unit cell (Diello, 2007). Each soil type and associated WHC holds three values (Figure 3): a minimum, corresponding to the lower limit of the concerned class; a maximum, equal to its upper limit; and an average, equal to the arithmetic average of the lower and upper class limits.

Model optimization

The automatic calibration of the model parameters requires the definition of a function quantifying the model error (the distance between the observed and simulated flows). The quantitative criterion used to measure the quality of adjustments made by the model is that proposed by Nash and Sutcliffe (1970), commonly called Nash in hydrology, and defined as:

$$Nash(Q) = 1 - \frac{\Sigma_{i=1}^{n} (Q_{obs,i} - Q_{cal,i})^2}{\Sigma_{i=1}^{n} \left(Q_{obs,i} - \overline{Q_{obs}}\right)^2}$$

where:

$Q_{obs,i}$ is the observed flow at time step i,
$Q_{calc,i}$ is the simulated flow at time step i,
$\overline{Q_{obs}}$ is the average flow rate observed, and
$\overline{Q_{obs}}$ n is the total number of time steps of the simulation period.

The Nash criterion makes it possible to evaluate the quality of the simulation, compared with observations, in terms of both phase and intensity (Nash & Sutcliffe, 1970). It ranges from $-\infty$ to 1. The adjusted model is much better when this function is close

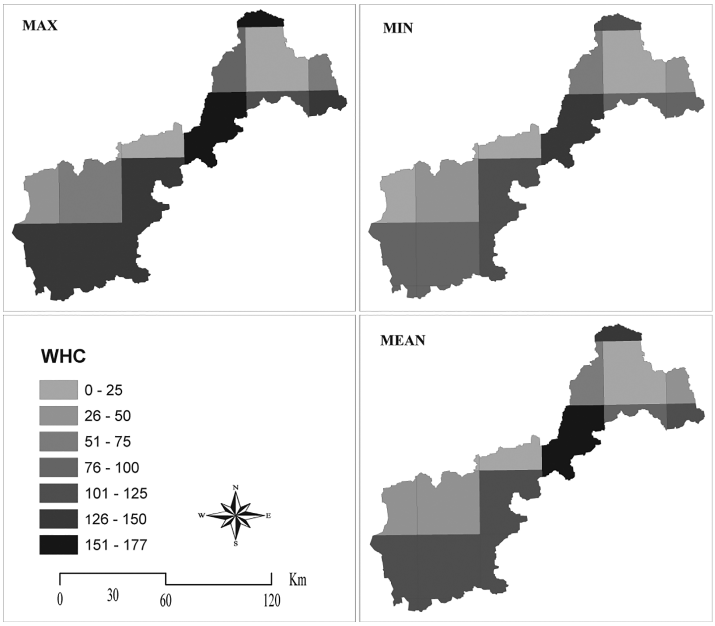

Figure 3. Maximum, minimum and mean values of soil water holding capacity in the basin of Bafing Makana, from FAO data.

to 1. A Nash below 0.6 is an indication of a failed model of the studied watershed (Ardoin-Bardin, 2004).

Test procedure in calibration and validation

Climate disruption, observed between 1960 and 1970 at 80% of the rainfall stations of the upper basin of Senegal (Bodian, Dacosta, & Dezetter, 2011), introduced heterogeneity into the climate data-sets and therefore a potential change in the hydrological functioning of watersheds (Kouassi et al., 2012; Ruelland, Ardoin-Bardin, Collet, & Roucou, 2012). The choice of calibration periods becomes crucial for the specification of the model parameters. We defined periods of 5 years and 10 years (Kouassi et al., 2012; Dezetter et al., 2010; Diello, 2007; Andréassian, Parent, & Michel, 2003) in the series of flows for Bafing Makana and Dakka Saidou. For the Sokotoro basin, this division could not be applied due to lack of data, but it is done according to the periods covered by the data. The adjustment of the two parameters (X_1 and X_2) of the model is performed successively for each period by automatic calibration (successive use of Rosenbrock and Simplex optimization procedures; Servat & Dezetter, 1988), after which the model is validated for all other periods. This cross-validation allows us to select parameter sets with good Nash values (over 0.6) in calibration which better validate for other periods (better representation of the rainfall–runoff relationship). These parameter sets are then applied to all of the rainfall series for the flow simulation.

Sensitivity of the model to the input data

The data available for the application of the model, in addition to the PET and flows, are formed by the three rainfall grids obtained by the three different interpolation methods (Krigging, spline function and squared inverse distance weighted) and the three WHC grids (max, min and mean). To determine the best combination of inputs leading to better efficiencies of model data, we tested all nine combinations (three WHC grids × 3 rainfall grids).

Results

Analysis of the sensitivity of the model to the input data

Figures A2 and A3 in the online supplemental data show the results obtained with the methodology described above over 10-year periods. For the Bafing Makana and Dakka Saidou basins, with regard to the WHC data, the best performance of the model calibration and validation is obtained for the Max WHC grid. This is also valid for 5-year periods. Dezetter et al. (2008) reported similar results for 49 basins in Ivory Coast, Guinea, Mali, Burkina Faso and Niger. For the Sokotoro River basin, even if there is an advantage for the Min WHC in terms of performance, a comparison of Nash obtained depending on the type of WHC shows that the average Nash varies very little with the WHC grid used.

For precipitation, the best model performance is obtained with the rainfall grid generated by the squared inverse distance weighted method for all divisions (Figure A4 in the online supplemental data). The rainfall grid produced by the spline function obtains the highest score for the Dakka Saidou basin in validation. However, Tabios and Salas (1985) showed that Krigging is preferable to other methods of interpolation for precipitation, at least when a monthly time step is used. On the other hand, Chang, Lo, and Yu (2005) indicate that when the network density gauge is low, as it is in our study area, estimation errors can be significant with Krigging. They stress that inverse square distance interpolation can significantly reduce the errors that occur when the number of stations is limited.

Choosing a WHC – rainfall combination

Given the need to have the same method of interpolation of rainfall and the same WHC grid, we used the combination of Max WHC and rainfall calculated by squared inverse distance weighted for all three watersheds, even though the rainfall grid produced by the spline function gives a slightly higher validation score for the Dakka Saidou basin.

Performance of the model based on time slicing

In calibration, time slicing over a 5-year period gives the best criteria for Nash because of the homogeneity of the series (Figure A5 in the online supplemental data). Nevertheless, in validation, slicing by decade gives the best Nash criteria. Indeed, it is easier to capture the average behaviorof watersheds by time slicing over a 10-year period than over a 5-year period. According to Ardoin-Bardin (2004), longer periods include greater variability of hydrological events and are representative of the range of conditions that may occur in the basins. However, the shorter periods may be significantly influenced by the most extreme conditions encountered during the period considered. Dezetter et al. (2010) note that in the basin of the Koulikoro (Niger River), the calibration periods that give the best parameter sets are the periods for which both deficit and excess years are more or less balanced but not exceptional years in terms of flows. These same considerations prevail for the basins studied here. Thus, the sets of parameters used for the simulation of flows are those obtained with time slicing by decade.

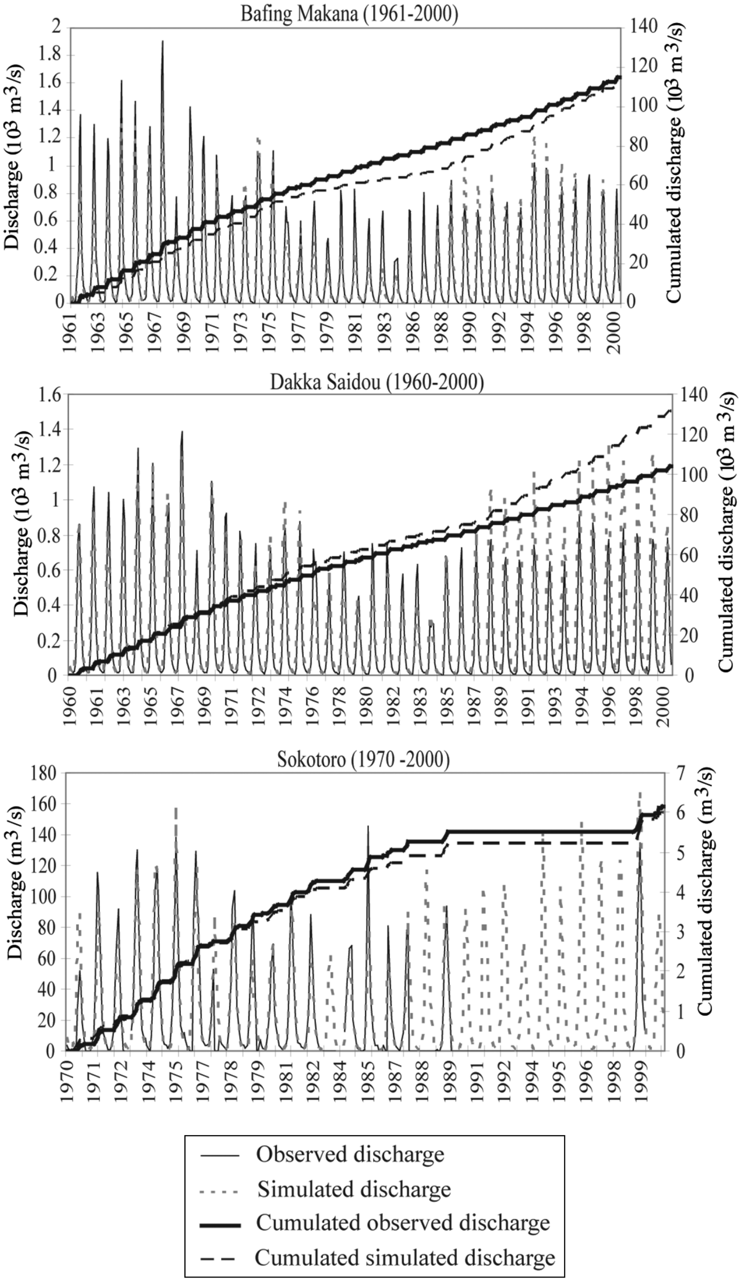

Figure 4. Comparison of simulated and observed discharges at three gauging stations.

Performance of the model in calibration and validation

The values of the Nash criterion in calibration are generally good (above 0.60) for all three basins (Figure A6 in the online supplemental data). The same observation is possible for the Nash criterion in validation, with a few exceptions. These exceptions concern

1981–1990 for Bafing Makana and 1990–1999 for Dakka Saidou. The period of 1981–1990 has the distinction of containing unusually dry years (1983 and 1984) that are difficult to reproduce by parameter sets close to the average behaviour model. Similar results were obtained by Dezetter et al. (2010) on the Niger Basin in Koulikoro. Validation of the model (last column of A6) allows choosing the parameter set that best represents the functioning of the watershed, particularly when used for the simulation of flow series from rainfall data entry. Thus, calibrated parameters for 1971–1980 and 1960–1969 for Bafing Makana and Dakka Saidou, respectively, best represent other periods, with Nash criterion validation that varies between 0.83 and 0.86. Regarding the Sokotoro Basin, the parameters of 2000–2002 better reproduce the other periods, with Nash criterion validation of 0.93. The parameters X_1 and X_2 of these periods were the ones selected for extrapolation over the entire study period.

Application of the GR2M model and monthly runoff

We applied the GR2M model with the previously selected parameters to the entire series to simulate flows from the average monthly rainfall grid obtained by the squared inverse distance weighted parameters, the average monthly PETs and Max WHC. These three input data extend the series of monthly flows for the Bafing Makana, Dakka Saidou and Sokotoro basins from 1960 to 2000. Figure 4 shows the observed and simulated hydrographs of the three basins. The maximum monthly flows calculated are well located in time but sometimes with amplitude errors, which may be due to hysteresis. For low flows, nevertheless, there is a good superposition of observed and calculated flow hydrographs. The results in Figure 4 also indicate that some uncertainties remain important in the simulations. These uncertainties are inherent in the modelling approach used here, which is a simplified view of the complex functioning of the watershed (Le Lay, 2006). In this regard, for the Bafing Makana and Sokotoro basins, the model exceeds the observed runoff by 9% and 1.24%, respectively, while at Dakka Saidou it underestimates the runoff by 15.7%.

Conclusion

This study allowed complementing and extending the series of monthly flows for the Bafing Makana, Dakka Saidou and Sokotoro basins from 1960 to 2000. But it is clear that the data from the Balabori, Bébélé, Trokoto and Teliko basins could not be extended due to insufficient hydrometric data.

Thus, following this study, the modelling of the watersheds not integrated due to insufficient hydrometric data (especially in the case of the Balabori Basin, which controls the whole Guinean contribution) will be privileged on the basis of the developed methodology. Indeed, under the GEF/BFS project, all hydrometric stations of the upper basin were renovated. This should allow, within the next 5 years, collecting the additional hydrometric data required for calibration and validation of the GR2M model to extend the series of flows. In addition, it will provide a database to study the hydrological regimes in terms of frequency analysis and main flow parameters (modules, floods, low flows, seasonality, flow coefficients, etc.) and provide developers with useful statistics for the establishment of so-called second-generation structures, namely dams, to increase the potential hydroelectric basin and regulate tributaries.

Disclosure statement

No potential conflict of interest was reported by the authors.

Supplemental data

Supplemental data for this article can be accessed at http://dx.doi.org/10.1080/07900627.2015.1026435

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