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Calibrating the rainfall-runoff model GR4J and GR2M on the Koulountou river basin, a tributary of the Gambia river

Vieux Boukhaly TRAORE[1], Soussou SAMBOU[1], Séni TAMBA[2], Sidy FALL[3], Amadou Tahirou DIAW[4], Mohamed Talla CISSE[5]

[1]Laboratoire d'Hydraulique et de Mécanique des Fluides (LHMF), Université Cheikh Anta Diop de Dakar (UCAD), Sénégal. BP 5005 Dakar-Fann
[2]Ecole Polytechnique de Thiès (EPT), BP 10 Thiès, Sénégal
[3]Office du Lac de Guiers, Société d'Aménagement et d'Exploitation des Terres du Delta du fleuve Sénégal et des Vallées du fleuve Sénégal et de la Falémé (SAED)
[4]Laboratoire d'Enseignement et de Recherche en Géomatique (LERG); Campus Universitaire de l'Ecole Supérieure Polytechnique-Dakar , Sénégal. BP 5005 Dakar-Fann
[5]Université de Thiès. Thiès SENEGAL

Email address:
vieuxboukhalytraore@yahoo.fr (V. B. Traore)

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Abstract: Rainfall runoff modelling is the first step in water resources management. It is the only way to simulate the hydrological behavior of the basin for a good evaluation of the potentiality of this in term of water production. Many approaches are actually in use. In physically distributed models, deterministic relations issued from conservation laws of physics (mass conservation, moment momentum conservation) are solved to describe the hydrological processes generating flow and their interaction. A DEM that should be as complete as possible is associed. Complexity of the equations to be solved and the huge amount of required data, uncertainty in these data make these models of limited use. Conceptual rainfall-runoff models are often preferred by hydrologists. These models are based on equations relating in a realistic manner the different terms of the hydrological cycle. They are simpler than determistic models and more flexible, Conceptual models are generally global. According to the way hydrological cycle terms are taken into account, conceptual model can be classified as empirical or not. The aim of this paper is to evaluate the availability of water in the Koulountou river basin, a tributary of Gambia River. This river basin should reinforce the water resource in a neighboring Kayanga river basin. Two empirical models at daily and monthly scale, the GR4J and GR2M have been used to describe the hydrological behavior of this basin. These models have been realized by the CEMAGREF, a French research Office. They use as inputs daily or monthly rainfall and potential evapotranspiration and river basin area, and give as output daily or monthly runoff. The first step before applying a hydrological model is to calibrate it that is to estimate the best parameters that fit the outputs in a given period. The Nash criterion has been used as goodness-of-fit criterion. Model performs satisfactory when this criterion is greater than 0.70 according to available data. A period from 1971 to 1994 has been selected. This period have been divided into three parts: one for calibration (1971-1978), one for validation (1978-1986), and the last for application (1987-1994). The results we obtain shows that GR4J and GR2M performs well in the Koulountou river basin since the Nash criterion is greater than 0.8.

Keywords: Rainfall-Runoff Models, GR4J, GR2M, Validation, Calibration, Nash criterion, Koulountou River Subbasin, Gambia River basin

1. Introduction

Assessment and effective management of water resources in a watershed requires a thorough understanding of hydrological processes involved and their time scales and specific space [1]. The use of numerical models as decision support has become essential to analyze the constraints that relate to the optimization of water [1]. Many scientific disciplines use models to describe systems in simpler terms and to predict systems response [2]. The choice must be made by identifying a parsimonious model structure which capture the dominant hydrological processes and provides good predictive power [3].In recent decades, many hydrological models have been developed [4] to represent a simple manner the natural systems [5].These models allow to estimate the part of rain that leaves the watershed knowing the rain it receives [6]. Rainfall-runoff models are important tools used in operational hydrology; they enable users to forecast or predict runoff of a catchment from the amount of precipitation received by this catchment [2].This runoff in river catchment depends on how topography-geomorphology, soils and vegetation, land use and land cover and climate changes interact [7]. From the spatial point of view, hydrological models are classified as lumped, semi-distributed, and distributed [8]. According to the relationships used to describe the physical processes, rainfall-runoff models are empirical, conceptual and physically based [9]. In lumped models, catchment is taken as a whole: spatial variability of vegetation, soil, and topography are ignored [9]. Runoff is estimated only at the catchment outlet [10]. Lumped models have a simple structure and empirical parameters. They require minimum data and are easy to use because of their fast setup and calibration [6]. Distributed models account for the heterogeneity and spatial variability of the catchment [1]. Such models give the closest representation of the real system; they incorporate as many components of actual physical processes as possible. Their calibration is highly time consuming because these models require huge data and model parameters identification [11, 12]. Though these parameters have a physical meaning, they are difficult to calculate; this may limit their strength and their adequacy for operational purposes [10, 13]. Semi-distributed models are a compromise between distributed process models and lumped models [10].They are less demanding on data than distributed models, present the advantage of simulating the values of different hydrologic variables at many points of the basin [14].Conceptual models use simplified mathematical relationships to represent the hydrological processes in the catchment. These models have a simple structure, and their data requirements are lower. They need fewer parameters, although these parameters have little physical sense. These models are of easy application, what make them important for flood forecasting, water resources planning, and water resources management ([9,14]. Conceptual models represent the component processes of the hydrological cycle by interconnected storage volumes [14]. Physically based models are based on governing equations such as conservation of mass and momentum equations in the description of hydrological processes. They require input of initial and boundary conditions since flow processes are described by differential equations [5]. Parameters and state variables of these models have a physical signification and may either be directly measured in the field or reasonably assumed based on site characteristics. In these models, predictions are calculated where they are needed. These models are usually very complex; require an enormous data requirement and large computational demands, what is their main inconvenient [14]. Empiric models have no theoretical basis. They are mathematically simpler than the conceptual and physical models: they use statistical or similar technics to link observed inputs (rainfall) and output (discharges), their formulation needs little or no consideration of hydrologic cycle [15].

In this paper, we look for the feasibility of transferring water from Koulountou basin to the Kayanga basin. An understanding of the hydrologic behavior of these two basins is required. A first step is to select and run a rainfall-runoff model able to generate runoff at the outlet of each basin knowing rainfall and physical features. Distributed physically based are the best tool in such case, but as we pointed it earlier, they need to solve numerically the physical laws of conservation, are huge data demanding and time consuming and difficult to calibrate. Accounting for the available information, empiric global models are more suitable for us. These models are very little demanding in data, are very easy to calibrate. An example of such models is the “Génie Rural” models, developed by the French Research Center CEMAGREF. These models use as inputs the area of the basin, the potential evapotranspiration (E), and mean rainfall observations (P) over the whole basin. They give as outputs runoff at the outlet of the basin. These models run at monthly (GR2M) and daily (GR4J) time scale. We present the calibration and validation of the GR2M and GR4J in the Koulountou river basin. Results we obtain are satisfactory according to the Nash criterion.

2. Materials and Methods

2.1. Study Area

The Koulountou river basin (figure 1) is 6200km² at the stream gauge of Missirah Gounass. It is located between latitude 12°19 '00 N and longitude 13°5'60W. The Koulountou river is a one of the left side tributaries of the Gambia River. Its source is located in the northern foothills of the Fouta Djallon mountains, in the Republic of Guinea Conakry, 800 m above sea level. From the source to the confluence with the Gambia river (NE of the town of Missirah Gonass), the Koulountou is 245 km long. The climate is Sudano Guinean in the southern part of the catchment and Sudano Sahelian in the northern part. There are two seasons, a rainy one from May to October and a dry one from November to April. Rainfall increases from North (1100mm) to South (1300 mm), and August is the most rainy month .The rainfall varies from 1100 mm to 1300 mm. The temperature is minimum in December (11.5°) and maximum in April (43.2 °). Its estimated average is 27.9°C.

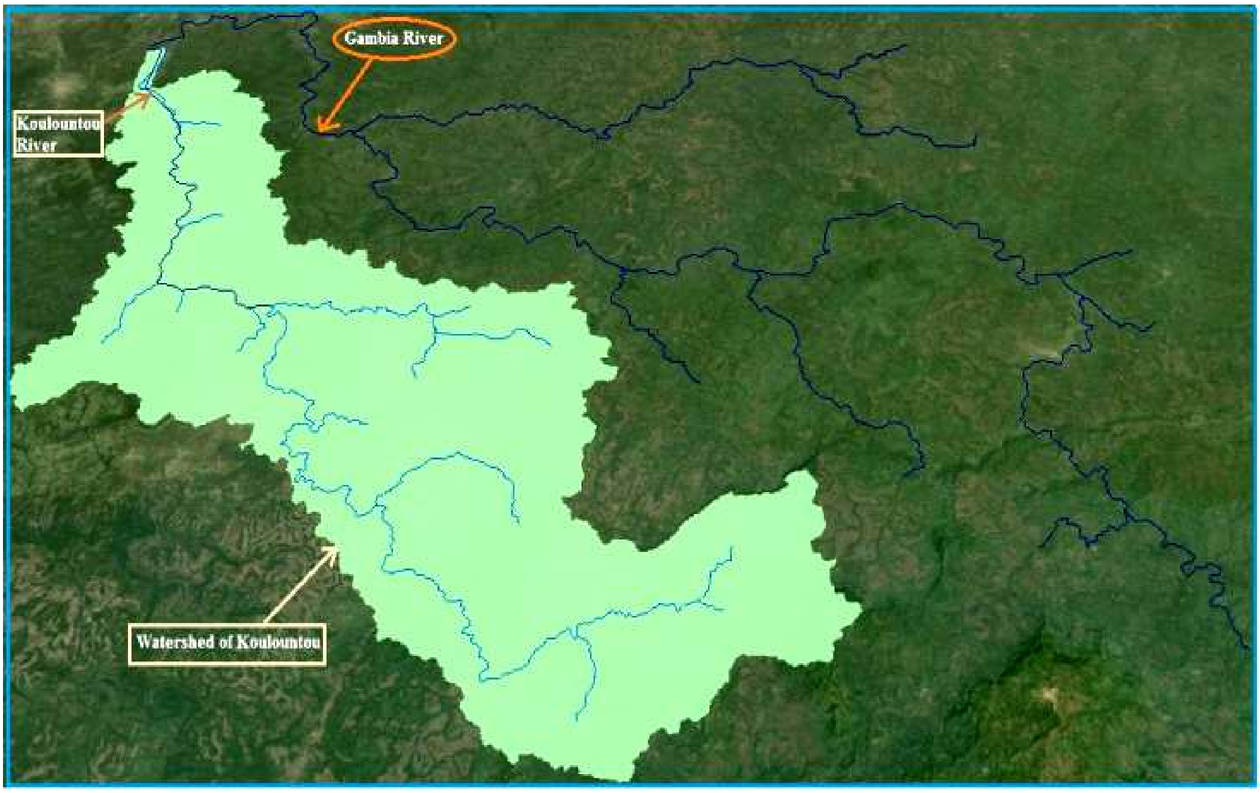


Figure 1. *Koulountou River basin*

2.2. Description of the Models: GR4J and GR2M

The choice of a hydrological model for hydrologic applications in a given basin is a challenge. The available information is of great importance. In this study, the only information we have is the area of the basin and times series of rainfall and runoff. This oriented us towards lumped empiric hydrologic model that acts as input-outputs models. Two of these are the GR4J and GR2M developed at the French CEMAGREF [16, 17].These models work at daily and monthly scale, are parsimonious in data and of easy calibration and validation what make them very popular among hydrologist [18, 19]**.**We present the main features of these models in the following.

2.2.1. Description of GR4J

GR4J is divided into two stores: a production store and a routing store (Figure 2a). Computational details are given in Figure 2b. Inputs of the model for a given day are rainfall P (mm) and potential evapotranspiration E (mm).

If P > E, then net rainfall Pn is given by (1) and net evaporation En by (2). A part Ps (3) of Pn is directed towards the production store, whose the maximum water content is the parameter X1 (mm) and actual content is S (mm).

$$\mathrm{Pn} = \mathrm{P} - \mathrm{E} \tag{1}$$

$$\mathrm{En} = 0 \tag{2}$$

$$\mathrm{Ps} = \frac{\mathrm{X1}.\left\{1-\left(\frac{\mathrm{S}}{\mathrm{X1}}\right)^2\right\}.\tanh\left(\frac{\mathrm{Pn}}{\mathrm{X1}}\right)}{1+\frac{\mathrm{S}}{\mathrm{X1}}.\tanh\left(\frac{\mathrm{Pn}}{\mathrm{X1}}\right)} \tag{3}$$

The remaining part Pn-Ps is reserved to calculate runoff.

If P< E, the net evaporation is equal to (4) and net rainfall to (5).

$$\mathrm{En} = \mathrm{E} - \mathrm{P} \tag{4}$$

$$\mathrm{Pn} = 0 \tag{5}$$

A part Es (6) of En is extracted from the production store whose actual content is updated by (7). Percolation Perc (8) is taken from this updated content of the production store and added to the direct runoff part of rainfall to give Pr (9) which is the total water available for the routing.

$$\mathrm{Es} = \frac{\mathrm{S}.\left(2-\frac{\mathrm{S}}{\mathrm{X1}}\right).\tanh\left(\frac{\mathrm{En}}{\mathrm{X1}}\right)}{1+(1-\frac{\mathrm{S}}{\mathrm{X1}}).\tanh\left(\frac{\mathrm{En}}{\mathrm{X1}}\right)} \tag{6}$$

$$\mathrm{S} = \mathrm{S} + \mathrm{Ps} - \mathrm{Es} \tag{7}$$

$$\mathrm{Perc} = \mathrm{S}.\left\{1 - \left[1 + \left(\frac{4\,\mathrm{S}}{9\,\mathrm{X1}}\right)^4\right]^{\frac{-1}{4}}\right\} \tag{8}$$

$$\mathrm{Pr} = \mathrm{Pn} - \mathrm{Ps} + \mathrm{Perc} \tag{9}$$

Pr is then divided into two parts, one part (10%) for direct runoff Q1 (10) through unit hydrograph HU2 with base time equal to 2X4; the other part, (90%) for delayed runoff Q9 (11), which reaches the routing store through unit hydrograph HU1 with base time X4. The maximum content of the routing store is X3. Its actual content R is updated using Q9 and the value of the function F(X2) (12, 13), where

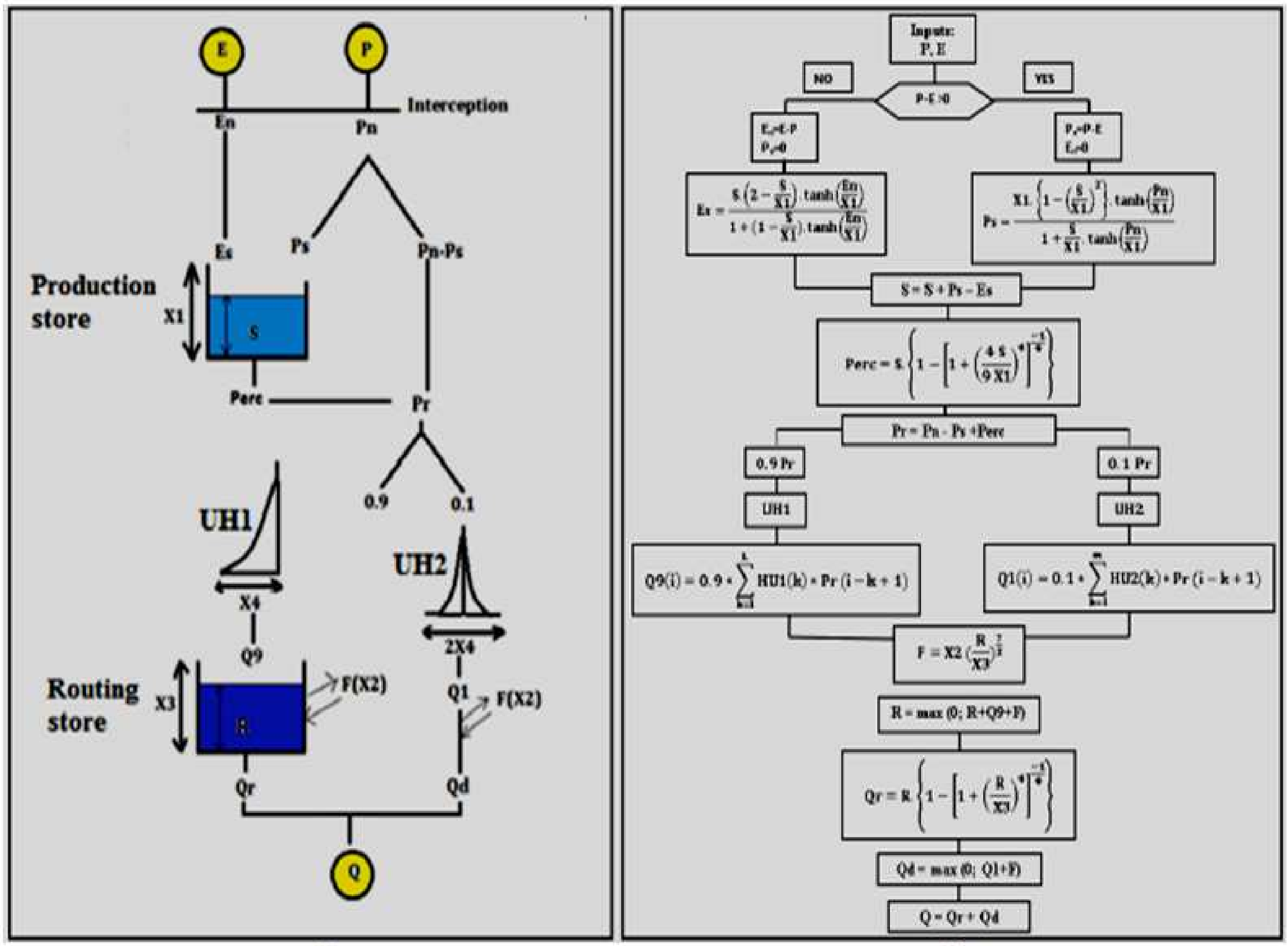
X2 is a coefficient accounting for groundwater effects.

$$Q1(i) = 0.1 * \sum_{k=1}^{m} HU2(k) * Pr(i-k+1) \ (1) \qquad (10)$$

$$Q9(i) = 0.9 * \sum_{k=1}^{L} HU1(k) * Pr(i-k+1) \qquad (11)$$

$$F(X2) = X2 \left(\frac{R}{X3}\right)^{\frac{7}{2}} \qquad (12)$$

$$R = \max(0, R + Q9 + F) \qquad (13)$$



(a) (b)

***Figure 2.** GR4J Model Structure (a); Computation organization (b)*

Then this updated content of routing store is used to calculate the final delayed output Qr (14) of the routing store. Q1 and F(X2) are combinated to calculate the direct runoff Qd (15). Total runoff for the given day at the outlet of the basin, is then estimated by summing Qr and Qd (16). Since the works of Perrin [16, 19, 20], many authors have brought contributions to that model [21, 22, 23].

$$Qr = R.\left\{1 - \left[1 + \left(\frac{R}{X3}\right)^4\right]^{\frac{-1}{4}}\right\} \qquad (14)$$

$$Qd = \max(0, Q1 + F) \qquad (15)$$

$$Q = Q + Qd \qquad (16)$$

2.2.2. Description of GR2M

GR2M is an empirical lumped monthly hydrologic model working with two stores (Figure 3a): a production store whose capacity is the parameter X1 and actual contents is S; and a routing store whose capacity is set to 60 mm and actual contents is R [17].Inputs of the model are monthly rainfall (P) and potential evapotranspiration (E) for a given month and output is monthly runoff at the outlet of the basin Q. A part Ps (17) of rainfall P is directed to production store, whose content becomes S' given by (18). The excess part P1 (19) is directed to the routing store.

$$Ps = \frac{X1.\left\{1-\left(\frac{S}{X1}\right)^2\right\}.\tanh\left(\frac{P}{X1}\right)}{1+\frac{S}{X1}.\tanh\left(\frac{P}{X1}\right)} \qquad (17)$$

$$P_1 = P - P_S \qquad (18)$$

$$S' = S + P_S \qquad (19)$$

To take account of the evapotranspiration in the production store, a part Es (20) of E is extracted from this store, whose content is updated as (21) .This new content of production store loses a quantity P2 of water through

Percolation given by (22).

$$Es = \frac{S.\left(2-\frac{S'}{X1}\right).\tanh\left(\frac{E}{X1}\right)}{1+\left(1-\frac{S'}{X1}\right).\tanh\left(\frac{E}{X1}\right)} \quad (20)$$

$$S'' = S' - E_S \quad (21)$$

$$P_2 = S''.\left\{1-\left[1+\left(\frac{S''}{X1}\right)^3\right]^{\frac{-1}{3}}\right\} \quad (22)$$

P_2 is added to the routing store. Total water P3 input of the routing store is then given by (23), and its content pass to R' given by (24).

At this step, a fraction X_2R' of R' is reserved for the routing store, and the difference F (25) is taken away from the basin as groundwater exchange.

$$P_3 = P_1 + P_2 \quad (23)$$

$$R' = R + P3 \quad (24)$$

$$F = (X2-1)\ R' \quad (25)$$

The level in the routing store becomes R'' (26). Then the output runoff Q is estimated by (27): [24, 25]. Computation organization is presented in (figure3b).

$$R'' = R' + F \quad (26)$$

$$Q = \frac{(R'')^2}{R''+60} \quad (27)$$

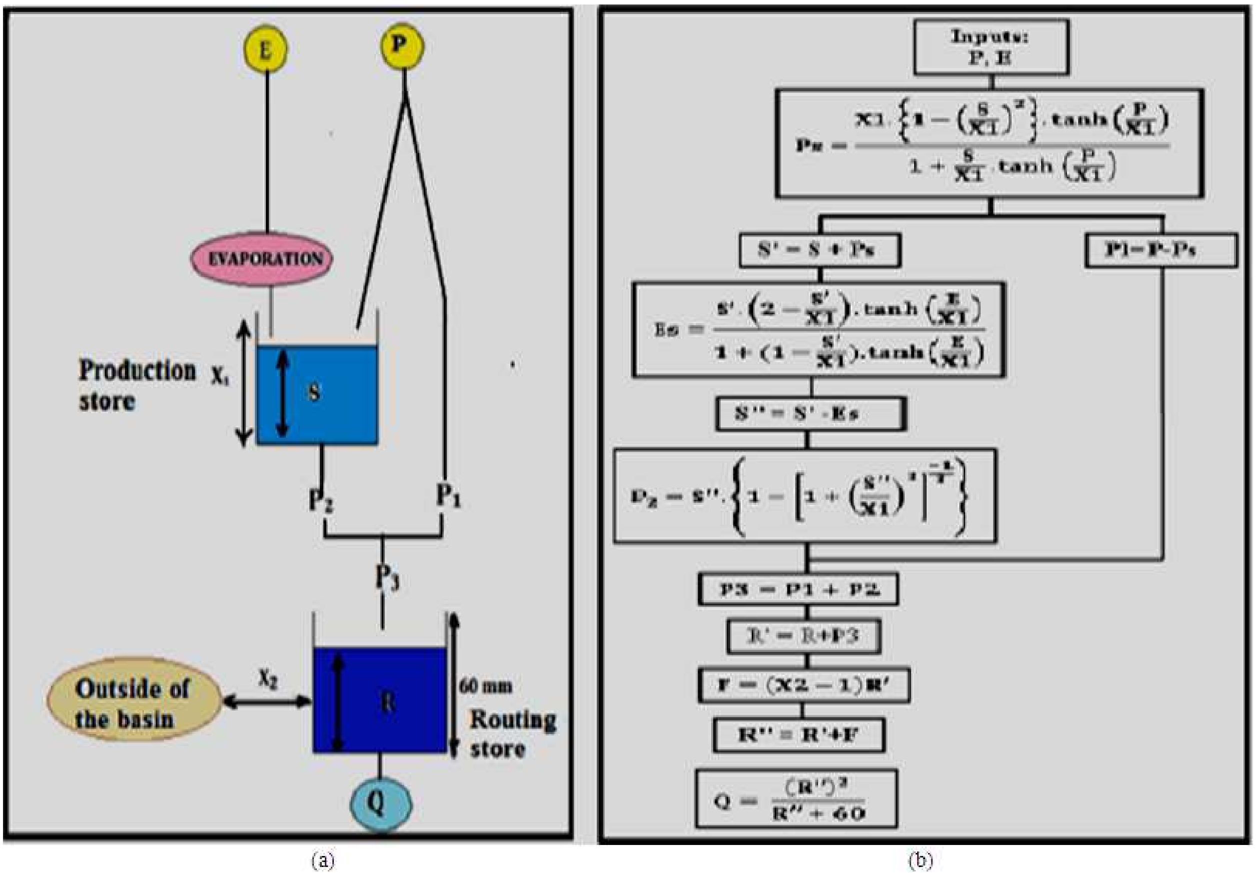


Figure 3. *GR2M model Structure (a); Computation organization (b)*

2.4. Models Calibration and Validation

Parameters of empirical models have a meaning that is not connected a priori to measurable quantities of the watershed [7]. So, their calibration is required. Calibration is the process of choosing best sets of model parameters, by adjusting manually or automatically their numerical values to better mimic the response observed at the outlet [26]. The successful application of a hydrologic watershed model depends on how well the model is calibrated [5]. The calibrated models parameters should necessarily be validated. Validating a model is to the check the reproducibility of the results by the calibrated parameters. A new data set different from that in the phase of the calibration is used. The validation of the calibration of rainfall runoff models are traditionally based on some statistical indicators [27].The Nash-Sutcliffe is a criterion of reference for the hydrologists [28, 29]. This criterion may be calculated from the natural flow (28), square root of natural flows (29) and logarithm of natural flows (30). Theses equations verify the ability of the model to reproduce maximum flows, low flows and average flows.

$$\text{NashQ} = 100\left[1 - \frac{\Sigma\left(Q_i^{obs} - Q_i^{cal}\right)^2}{\Sigma\left(\overline{Q_i^{obs}} - Q_i^{cal}\right)^2}\right] \quad (28)$$

$$\text{Nash}\sqrt{Q} = 100\left[1 - \frac{\Sigma\left(\sqrt{Q_i^{obs}} - \sqrt{Q_i^{cal}}\right)^2}{\Sigma\left(\sqrt{\overline{Q_i^{obs}}} - \sqrt{Q_i^{cal}}\right)^2}\right] \quad (29)$$

$$\text{NashlogQ} = 100\left[1 - \frac{\Sigma\left(\log Q_i^{obs} - \log Q_i^{cal}\right)^2}{\Sigma\left(\overline{\log Q_i^{obs}} - \log Q_i^{cal}\right)^2}\right] \quad (30)$$

Q_i^{obs} daily flow observed on day i; Q_i^{cal} : daily rate calculated on day i; $\overline{Q_i^{obs}}$: average rate observed during the simulation period. A value of Nash equal to 0 or less than 0 indicates a very bad correlation: it shows that observed mean is better than simulated mean; a value of Nash equal to 1 corresponds to a perfect model, which reproduces reality: it shows complete adaptation is between observed mean and simulated mean. In practice the value of 0.70 is taken as the threshold: below this value, simulation is bad and beyond, it is good [30].

3. Application

3.1. Data

Data used in this application are daily rainfall and daily flow at the stream gauge station of Missirah Gounass, outlet of the catchment, and potential evapotranspiration at the station of Kédougou on the Gambia River. These data are issued from the database of OMVG (Organization for the development of the Gambia River) shared by the countries of Guinea, Gambia and Senegal. The period extending from 1971 to 1994 has been selected. This period has been divided into three parts for calibration (1971-1978), validation (1978-1986), and application (1987-1994).

3.2. Calibration, Validation and Application of the GR2M and GR4J Models

We first generate a set of parameters of each of these models for each year of the calibration periods (1971-1978) using the Excel version. Each of these set of parameters is applied to the whole period of calibration using the FORTRAN executable version of these models, and the different Nash criteria (1), (2), (3) are calculated. Set of parameters corresponding to the best Nash values are then considered as models parameters. These parameters are then applied to the validation period (1979-1987) to verify if they are well suited, and then on the application period (1988-1994) to confirm the results.

Table 1. *Parameters generated in the period 1971-1978 with GR4J*

	Initial parameters				Parameters generated			
Calibration	X1	X2	X3	X4	X1	X2	X3	X4
1971-1972	5.90	0.00	4.50	0.20	414.237	-38.20	344.171	2.210
1972-1973	5.90	0.00	4.50	0.20	2767.290	0.820	17.700	5.600
1973-1974	5.90	0.00	4.50	0.20	350.840	-78.290	437.500	0.500
1974-1975	5.90	0.00	4.50	0.20	1515.400	2.670	76.210	2.480
1975-1976	5.90	0.00	4.50	0.20	64.130	-36.170	853.040	4.230
1976-1977	5.90	0.00	4.50	0.20	1722.900	-12.110	233.910	0.520
1977-1978	5.90	0.00	4.50	0.20	471.190	-20.310	143.020	9.400

3.3. Results and Discussion

3.3.1. Calibration and Validation of the GR4J and GR2M

In Tables 1 and 2 we have presented set of parameters on the calibration period (1971-1978) generated from the Excel version. The data of first year (for example 1971) are used to generate the set parameters corresponding to the second year (for example 1972). In tables 3 and 4, we present the criteria obtained when each set of parameters is applied to the whole validation period. Examination of the Nash criterion outlines the best set of parameters for each of the model. These parameters will be considered a priori for both models as optimal parameters for basin Koulountou Missirah Gounass which is the most downstream station.

Table 2. *Parameters generated in the period 1971-1978 with GR2M*

	Initial parameters		Parameters generated	
Calibration	X1	X2	X1	X2
1971-1972	6	1	168.30	0.79
1972-1973	6	1	3.48	0.77
1973-1974	6	1	5.33	0.71
1974-1975	6	1	2.37	0.86
1975-1976	6	1	2.09	0.85
1976-1977	6	1	22.09	0.76
1977-1978	6	1	173.86	0.73

Table 3. *Research of best set parameters with GR4J*

	Generated parameters				**Nash criteria**		
Validation	X1	X2	X3	X4	NashQ	Nash√Q	**NashlogQ**
	414.237	-38.20	344.171	2.210	0.0248	0.5285	**0.6752**
	2767.29	0.820	17.700	5.600	-1.5313	-0.8466	**-0.8193**
	350.840	-78.290	437.500	0.500	0.8355	0.9072	**0.8993**
1978-1986	1515.400	2.670	76.210	2.480	-4.0200	-1.3222	**-0.8502**
	64.130	-36.170	853.040	4.230	-1.9776	-0.3585	**-0.1485**
	1722.900	-12.110	233.910	0.520	0.3038	0.4359	**0.3531**
	471.190	-20.310	143.020	9.400	-0.0971	0.5035	**0.7633**

Table 4. *Research of best set parameters with GR2M*

	Generated parameters		**Nash criteria**		
Validation	X1	X2	NashQ	Nash√Q	NashlogQ
	168.30	0.79	0.190	0.382	0.209
	3.48	0.77	0.586	0.549	0.345
	5.33	0.71	0.866	0.864	0.760
1978-1986	2.37	0.86	-2.447	-0.883	-0.672
	2.09	0.85	-2.470	-0.861	-0.629
	22.09	0.76	0.656	0.794	0.735
	173.86	**0.73**	**0.056**	**0.356**	**0.442**

3.3.2. Application Period

The best set parameters obtained for each model on the validation period are applied to the application period for verification. As 1991 is missing, this period was divided into two sub-periods: 1987-1990 and 1992-1994. We show the whole results for the two models in Tables 5 and 6. According to these tables, Nash criteria are all greater than 0.70 so that the set of parameters can be considered as representative for the Koulountou basin and significant for each of the models. They can be used to simulate flow in the Koulountou river basin at the stream gauge of Missirah Gounass at daily (for GR4J) and monthly (for GR2M). Simulated and observed flows for the application period are compared in Figure 4 and 5. There is a generally good fitness.

Table 5. *Optimal parameters for the period 1987-1994 with GR4J*

	Optimal parameters				**Nash criteria**		
Application Phase1:(1987-1990)	X1	X2	X3	X4	NashQ	Nash√Q	NashlogQ
	350.840	-78.290	437.500	0.500	0.7976	0.8988	0.8706
Phase2 :(1987-1990)							
	350.840	-78.290	437.500	0.500	0.8473	0.8803	0.8520

Table 6. *Optimal parameters for the period 1987-1994 with GR2M*

	Optimal parameters		**Nash criteria**		
Application Phase1:(1987-1990)	X1	X2	NashQ	Nash√Q	**NashlogQ**
	5.33	0.71	0.929	0.924	**0.849**
Phase2:(1992-1994)					
	5.33	0.71	0.806	0.887	**0.849**

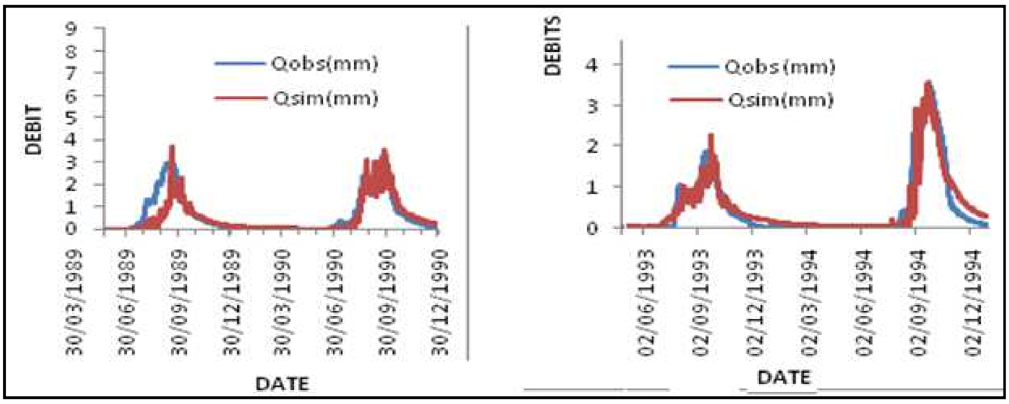


Figure 4. *Validation of GR4J on the phase 1(a) and phase 2(b)*

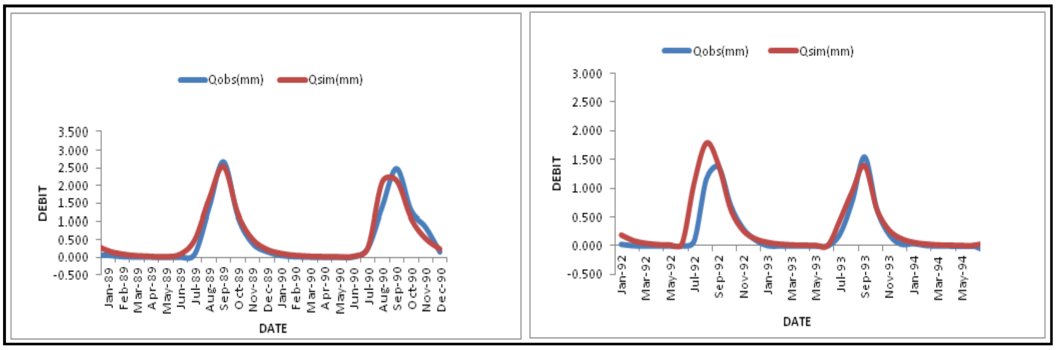


Figure 5. *Validation of GR2M on phase 1(a) and phase 2(b)*

4. Conclusion

Water resources management requires well calibrated and validated rainfall runoff models. Physical based models are well suited, but they have they present the inconvenient to be very difficult to implement: they are highly data demanding and very difficult to calibrate. Empirical global models are of easy calibration and application. In this paper, we aim at evaluating water resource of the Koulountou river Basin, a left side tributary of the Gambia River to reinforce the water resource in a neighboring river basin, the Kayanga river basin. According to the available data, we have used lumped empirical daily and monthly models, the GR4J and GR2M models developed by the French CEMAGREF. Calibration have been made by first generated in the calibration period, then applied in each year of this calibration period. Nash criteria have then been used to choose the best set of parameters for each model. Application of these best sets in the validation period gave a good adequation between calculated and observed according to the Nash criteria for the two models. To confirm these results, we have used the same parameters to simulate flows in an application period different of the calibration and validation periods. Once again, Nash criteria and plots show a good agreement between the values of simulated and observed flows. The work made in this paper has allowed us to determine the best set of parameters for the application of GR4J and GR2M models in the Koulountou river basin. These parameters can be used to restore missing flows from rainfall, and particularly to assess the water resources trends in the future horizons.

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