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MODELLING AND PREDICTION OF OUÉMÉ (BENIN) RIVER FLOWS BY 2040 BASED ON GR2M APPROACH

MODELISATION ET PREVISION DES DEBITS DU FLEUVE OUÉMÉ (BÉNIN) A L'HORIZON 2040 SUIVANT L'APPROCHE GR2M

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ABSTRACT

The study described in this paper has consisted of simulating the real future behaviour of the Ouémé river basin's water flow by 2040. The approach of the Rural Engineering model, with two variables, at a monthly time step named GR2M has been adopted owing to its robustness. This model is an indispensable tool for studying the evolution of water resources in the medium and long term. For our approach, the projected data, from 2016 to 2040, were generated using the Auto-Regressive Integrated Moving Average model. Observed data were then used for the calibration and the validation of the GR2M model. The results obtained showed that the GR2M model is a very satisfactory tool for simulating the transformation of rainfall data into flows on the one hand and an impact of future climate change resulting in a decrease in annual average flows between

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11.90% and 46.37% by 2040 on the other hand. The quality parameters revealed very interesting values obtained from the model on the three representative sites of the Ouémé basin with Nash-Sutcliffe more than 70% and determination coefficient more than 0.75.

Keywords: rainfall-runoff modeling, GR2M, simulation, forecasts, Oueme river basin.

RESUME

L’étude décrite, dans le présent article, a consisté à simuler le comportement futur réel du débit d’eau du bassin du fleuve Ouémé à l’horizon 2040. L’approche du modèle du Génie Rural, à deux variables, au pas de temps mensuel (GR2M) a été empruntée, car par sa robustesse, le modèle GR2M est un outil indispensable d’étude de l’évolution des ressources en eau à moyen et long termes. Dans la démarche proposée, les données prévisionnelles, de 2016 à 2040, ont été générées en empruntant le modèle Auto-Regressive Integrated Moving Average (ARIMA). Celles observées ont ensuite été utilisées pour le calage et la validation du modèle GR2M. Les résultats obtenus montrent que le modèle GR2M est un outil très satisfaisant pour simuler la transformation des données pluviométriques en débits d’une part et un impact du changement climatique futur se traduisant par une diminution de débits moyens annuels comprise entre 11,90 % et 46,37 % à l’horizon 2040 d’autre part. Les critères de qualité ont révélé des valeurs très intéressantes obtenues du modèle sur les trois sites représentatifs du bassin de l’Ouémé avec Nash supérieur à 70 % et R^2 supérieur à 0,75.

Mots-clés : Modélisation pluie-débit, GR2M, simulation, prévision, fleuve Ouémé

INTRODUCTION

In tropical areas, the hydrological response of watersheds is largely controlled by climatic parameters, especially those related to rainfall and temperature, to which they are subjected (Bodian *et al.* 2013). Generally in West Africa, and particularly in Benin, there is an increasing trend towards extreme climatic events, such as the disruption of seasons’ alternation, rise in temperature and changes in hydrological regimes (Nicholson 2001, IPCC 2007). In order to solve problems related to the disruption of hydrological regimes and the management of watersheds, it is necessary to have a perfect knowledge of their low flows and floods (Bouanani *et al*. 2012). Hydrological models have thus become indispensable tools in understanding the dynamics of a watershed (Medane 2012). Global hydrological models can simulate the transformation of rainfall data into flows on natural basins for many practical applications in the field of water resource management (Djellouli *et al*. 2013). The objective of hydrological modelling is to provide developers with a simple tool for estimating or predicting flows for a desired development study (Bodian *et al*. 2012).

In view of the increasing demand for water, linked to population growth, the multiplication of uses (domestic consumption, industry, agriculture, recreation, etc.) and rainfall variability, hydroelectric dams and hydro-agricultural construction projects are initiated on the Ouémé river basin. The purpose of these projects is to adapt to the effects of climate change, which poses a serious threat to hydroelectric production and seasonal agriculture and, consequently, to food autonomy. However, a resource can only be well managed when it is well known (Bodian *et al*. 2012). Although much scientific work have been carried out on the Ouémé basin, it is still difficult to conclude today that it is well known for its efficient exploitation. In most cases, hydrologists possess rainfall series data more abundantly than flow data (Djellouli *et al*. 2013). The modelling of the rain-flow relationship is then one of the solutions to overcome this lack of data on the flow rate. This is why the use of models is useful or even indispensable to complete or reconstitute the flow series from rainfall data (Djellouli *et al*. 2013). Rainfall-flow modelling is very beneficial for issues involving continuous time processing, such as flow forecasting (Medane 2012). It has been proved effective by providing solutions to many water-related problems, such as sizing and management of structures, flood forecasting (Djellouli *et al*. 2013, Périn 2002). Among the many existing rainfall-flow models, the family of models developed by the Rural Engineering (GR) and the Centre for the Study of Agricultural Machinery and Rural Engineering of Waters and Forests (CEMAGREF) is recognized as reference in this field based on their simplicity of implementation, adaptability and robustness (Bouanani *et al*. 2012, Djellouli *et al*. 2013).

The objective of our study is to find or elaborate a rainfall-flow model that characterizes the Ouémé river basin and allows the simulation of the future behaviour of its flow by 2040. In this paper, the Conceptual Model of Rural Engineering, at monthly time step with two (2) parameters (GR2M), has been considered adequate and retained in the exploitation of the data of the Ouémé river basin and the simulation of the actual hydrological behaviour of its flow over the period 2016- 2040. Its robustness, for simulating flows in African context, has been proved by several research results (Bodian *et al*. 2012, Mahé *et al*. 2005, Ardoin-Bardin *et al*. 2009).

MATERIAL AND METHODS

Study Area

The Ouémé river basin (Figure 1) covers an area of about 47,000 km^2 or about 43% of that of the country (Barthel *et al*. 2008). Located between 6.8 and 10.2° North Latitude, the Ouémé basin is characterized by a transition from the Sudanien climate at the North, with an average of 900 to 1,000 mm of precipitation per year, with the 'Beninien' climate at South with 1,200 mm of rain on average per year. About 89% of the basin is located in Benin, 10% in Nigeria and 1% in Togo (Bossa 2012). The basin records an average annual temperature of 26 to 30 °C (Bossa 2012). From a hydrological point of view, this basin is characterized by low and low flows and early drying of seasonal flows (Lawin 2007). With a length of 510 km and the two largest affluents, the Ouémé river flows to Lake Nokoué (150 km^2) and flows into the sea through the coastal lagoon (Diekkrüger *et al*. 2010). Water from precipitation, which drains into the basin, is subdivided into water intercepted by plants, soil water, infiltrated water and surface water (Beven 2001). All intercepted water and some of the water retained by the soil are lost through evaporation and transpiration (Arnold *et al*. 1998). Surface water is an important part of the flow-rate at the outlet.

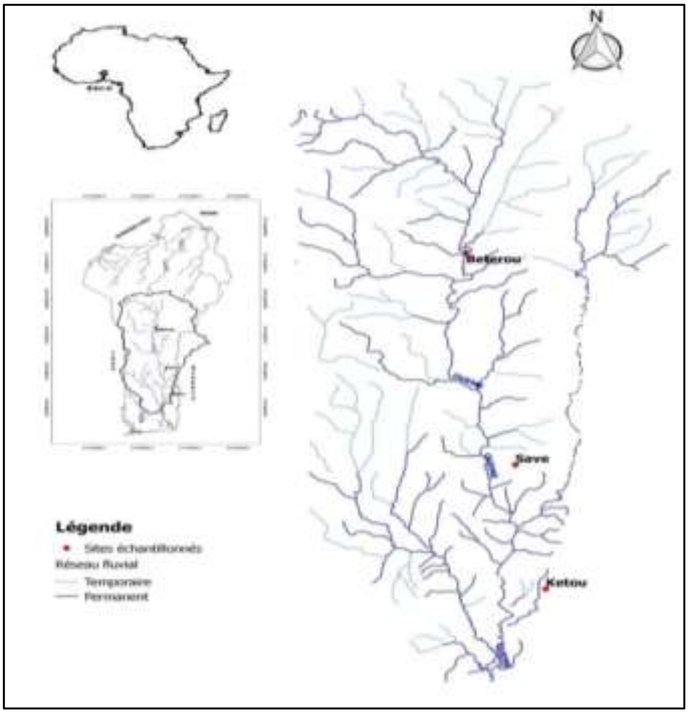

Figure 1 : Presentation of the catchment area of the Ouémé river basin in Benin

Data Collected

The observed data, exploited in the present work relative to the rainfall (P), potential evapotranspiration (PE) and flow-rate (Q), extend over the period 1989 to 2015. It was provided by the Laboratory of Climate, Water, Ecosystems and Development (LACEEDE) named Pierre Pagney of the University of Abomey-Calavi (UAC). These data are based on the daily values recorded on twenty (20) stations of which three (3) are synoptic and all located in the study area. For the latter three (3) stations, we have the rainfall and flow-rate data per day and the potential evapotranspiration data per decade. For the remaining seventeen (17) stations, data related to the potential evapotranspiration are not available. The mean missing data rates of the period 1989 to 2015, for all stations, are estimated to 5.3 % for rainfall, 7.67 % for PE and 10.03 % for flow. Rainfall data have been reconstituted by local polynomial linear regression with d=1 (Cornillon, and Løber 2007). As far as the PE is concerned, missing data have been filled by the monthly mean (Bodian 2011). For the flow, the missing data have been determined with the data from Zagnanado, Kaboua and Barérou stations using the ungauged catchment flow reconstituted method respectively for Kétou, Savè and Bétérou stations (Andréassian *et al*. 2012).

Methods

Four (4) types of data are required to apply the GR2M model. These are: the monthly rainfall, monthly potential evapotranspiration, soil water retention capacity and monthly average flows. From the hourly time step to yearly time step, there are many existing models available (Perrin *et al*. 2007). The Rural Engineering model, with a monthly time step and two (2) parameters (GR2M), was chosen for this study because it requires easily accessible data, namely rainfall, potential evapotranspiration and flow. Its development was initiated at CEMAGREF in the late 1980s, with application objectives in the field of water resources and low flows. It has known several versions of which the most recent and the best performing is that of Mouelhi *et al*. (2006). A representative diagram of the structure of the GR2M model is given in Figure 2 (Mouelhi *et al*. 2006). The GR2M model consists of a reservoir controlling the production function and characterized by its maximum capacity and a "gravity water" reservoir governing the transfer function. This model uses two (2) optimizable parameters: X_1 and X_2, where X_1 represents the maximum capacity of the production tank and X_2 the underground exchanges coefficient.

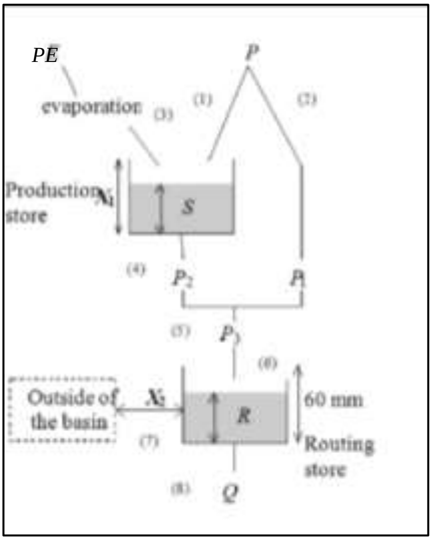

Figure 2 : Structure of the GR2M model and its functional variables (modified from Mouelhi *et al*. 2006).

GR2M Model Description

The GR2M model describes each basin as having two reservoirs, a soil reservoir denoted as S that controls the production function with a maximal capacity X1 (mm; the first free parameter of the model) and a routing reservoir denoted as R that controls the transfer function with a capacity of 60 mm. The former is intended to reproduce hydrological processes in soils and their interfaces while the second reflects transfer of water to the river, notably groundwater exchanges. At each modeling time step, precipitation is channeled either towards the soil reservoir by infiltration (Equation 1) or directly towards the routing reservoir as surface flows (P1 (mm); Equation 2).

$$S_1 = \frac{S + X_1\varphi}{1+\varphi\frac{S}{X_1}} \quad \text{with } \varphi = \tanh\left(\frac{P}{X_1}\right) \tag{1}$$

$$P_1 = P + S + S_1 \tag{2}$$

$$S_2 = \frac{S_1(1-\psi)}{1+\psi\left(1-\frac{S_1}{X_1}\right)} \quad \text{with } \psi = \tanh\left(\frac{PE}{X_1}\right) \tag{3}$$

$$S = \frac{S_2}{\left[1+\left(\frac{S_2}{X_1}\right)^3\right]^{1/3}} \quad \text{with} \quad P_2 = S_2 - S \tag{4}$$

$$P_3 = P_1 + P_2 \tag{5}$$

$$R_1 = R + P_3 \tag{6}$$

$$R_2 = X_5 R_1 \tag{7}$$

$$Q = \frac{R_2^2}{R_2 + 60} \quad \text{with } R = R_2 - Q \tag{8}$$

The soil reservoir reaches the level S_1 (mm) and then loses part of its moisture by potential evapotranspiration (Equation 3). Consequently it reaches a new level S_2 (mm). Part of soil moisture P_2 (mm) is then transferred to the routing reservoir by percolation (Equation 4). P_3 (mm), the net precipitation (sum of P_1 and P_2; Equation 5 enters the routing reservoir that reaches the level R_1 (mm; Equation 6). Part of water is then gained or lost by the routing reservoir as lateral water exchanges between the underground part of the river basin and its outside environment (Equation 7). If X_2 (without units; the second free parameter of the model) is greater than 1, there is a water supply from the outside of the basin; otherwise there is a loss. Finally, the routing reservoir provides the river water discharge Q (Equation 8). An important specificity of this new version of the GR2M model is the introduction of the parameter X_2. From a modeling point of view, this parameter corrects possible biases in climatic and discharge time series in order to correct errors in water balance (Equation 7). Mouelhi *et al*. (2006) also indicated that this parameter allows better representation of lateral water exchanges between the underground part of any topographic basin and its external environment (through permeable geologic layers). They also found that the best performances of the model are obtained when X_2 acts on the level of the routing store.

Assessment Criteria for the Hydrological Model

The measurement of the performances of a model is carried out according to the objectives that are set and, consequently, the selected criterion. However, the quantitative criterion, the most used to measure the quality of the adjustments made by this type of model, is the one proposed by Nash and Sutcliffe expressed in equation (9) (Nash and Sutcliffe 1970).

$$\mathrm{Nash(Q)} = 1 - \frac{\sum_{i=1}^{N}(Q_{sim,i}-Q_{obs,i})^2}{\sum_{i=1}^{N}(Q_{obs,i}-\overline{Q_{obs}})^2} \tag{9}$$

In this formula (1), $Q_{obs,i}$ the observed flow rate at the time step i, $Q_{sim,i}$ the simulated flow rate at the time step i, $\overline{Q_{obs}}$ the observed average flow rate, N is the total number of time steps in the simulation period. This formula reflects a certain yield of the model, comparable to the determination coefficient (R^2) of a regression. A hydrological model is generally considered to yield acceptable results if the Nash-Sutcliffe (Nash) criterion value is greater than 70% (Perrin *et al*. 2007).

Blocking and Validation of the GR2M Model

In the approach adopted for the blocking of the model, we carried out, manually, repetitive changes in the values of the parameters X_1 and X_2 until obtaining the optimal values of the coefficient of the Nash quality criterion and the R^2 of the correlation between the calculated flows and those observed. These two quantitative criteria were used in this study to measure the quality of the adjustments made by the model. If R^2 informs only the correct occurrence of the observations (the flows in our present case) without evaluating their intensities, the Nash criterion makes it possible to know whether the results of simulations are in good agreement or not with observations, both in terms of phase and intensity (Sighomnou 2004).

For the validation of the model, new precipitation and potential evapotranspiration data corresponding to the selected period and not used during the blocking were introduced. The calculations were started considering, for parameters X_1 and X_2, the optimized values obtained during the blocking. Flow values, generated from the model, were further compared to the observed values using simple linear correlation.

Simulation of the Ouémé River Flow Rates by 2040

In order to predict flows based on a hydrological model, it is essential to have information on predictions of input data, which are essential for the functioning of hydrological models (Nicolle 2010) and for prospective flow analyses (flow-rates). Therefore, the trend modelling by 2040 for the rainfall and potential evapotranspiration has been carried out with Auto-Regressive Integrated Moving Average [ARIMA (p,d,q)] model, where parameters p, d and q are non-negative integers. The parameters p is the order of the autoregressive model, d is the degree of differencing and q is the order of the moving-average model. The best model ARIMA (p,d,q) has been retained in each case using auto.arima function of the forecast package in R, version 3.2.3 (R Core Team 2016). The estimated values had 95 % confidence level. If predictions of rainfall and potential evapotranspiration can be obtained using ARIMA models, no information is available on the water retention capacity of soils. Under these conditions, and despite the fact that this is rather restrictive, we hypothesized the conservation of soil water retention capacity in a situation close to their present state. On the basis of this hypothesis and the data used as inputs for the rain-flow model GR2M adopted, predicted flows were then simulated for the Ouémé river up to 2040, using the same parameters X_1 and X_2 resulting from the blocking and the validation step. At the end, trends of rainfall, potential evapotranspiration and flow, as well as for actual and predicted values, have been drawn and analyzed.

RESULTS AND DISCUSSION

Performance of the GR2M Model during blocking and validation

It should be remembered that three (03) sites have been retained as references to represent the Ouémé river basin. These are respectively the sites of Bétérou, Savè and Kétou.

Bétérou Site

The evaluation of the GR2M model is based on the examination of the performance parameters (Nash and R²) and the examination of the trajectories of hydrographs observed and simulated during the blocking and validation phases (Kouamé *et al*. 2013). Table 1 summarizes the Nash criterion values obtained during the different blocking procedures and validation at the Bétérou site.

The observation of the values of the Nash criterion, presented in Table 1, shows that the GR2M used is powerful for the modelling of the data collected on the reference site of Bétérou. Indeed, the values of the Nash criterion obtained, in blocking (91.2%), as in validation (89.2%), are greater than 70%.

Table 1 : Blocking and validation results for Bétérou station: parameter values, Nash criterion and determination coefficient

Nash criterion parameters and determination coefficient	Units	Blocking (period: 1989-2000)	Validation (period: 2001-2015)
X_1	mm	1092.26	1092.26
X_2	-	0.53	0.53
Nash	%	91.20	89.20
R^2	-	0.93	0.91

The observed gap between the two values of the criterion for the two parameters determined (blocking and validation), over the periods 1989-2000 and 2001-2015 respectively, marks in fact a certain degeneracy: on average 2% (i.e. [100 (89.2-91.2 / 91.2) = - 2.0%)]) in absolute terms. The relative variation of the value of the Nash criterion in validation with respect to calibration, defines the criterion of robustness of a hydrological model. Indeed, the degradation thus registered by the criterion of Nash (2%), is considered quite acceptable, because its absolute value is less than 10% (Kouamé *et al*. 2013). This reflects the very good robustness of the GR2M model, Mouelhi *et al*. (2006) version on the Bétérou site. The hydrographs obtained at Bétérou site are also of good quality in general (Figures 3 and 4), the flow dynamics being well respected.

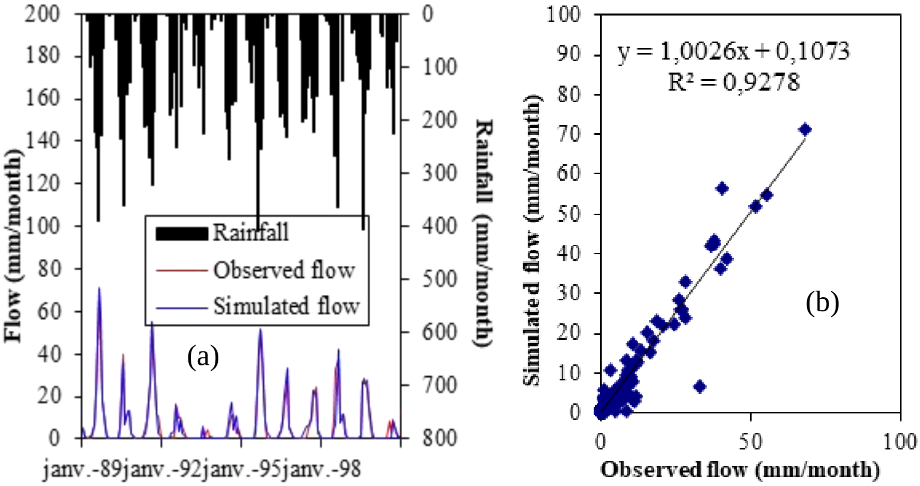

Figure 3 : Blocking of the obtained GR2M model from the Bétérou station:
(a) Rainfall-flow based on GR2M model. (b) Correlation from observed vs simulated flows.

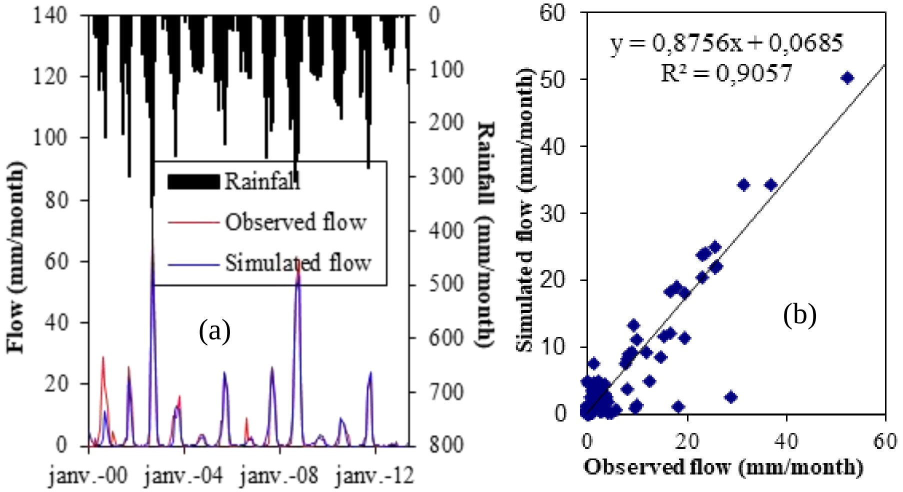

Figure 4 : Validation of the obtained GR2M model from the Bétérou station:
(a) Rainfall-flow based on GR2M model. (b) Correlation from observed vs simulated flows.

The correlation resulting from the blocking and the validation of the simulated flow rates, as a function of the observed flow rates (Figures 3 and 4), gives values of the coefficient R² very significant ($R^2>0.90$). Therefore, rainfall-flow modelling, using the GR2M model, gives satisfactory and very encouraging results for the Ouémé basin at the Bétérou reference site.

Savè's Site

The value of the Nash criterion in blocking stage is good on the site of Savè, because it is greater than 95 % (Table 2). The same applies to the Nash criterion in validation stage.

Table 2 : Blocking and validation results for the Savè station: parameter values, Nash criterion and determination coefficient

Nash criterion parameters and determination coefficient	Units	Blocking (period : 1989-2000)	Validation (period : 2001-2015)
X_1	mm	500.69	500.69
X_2	-	0.80	0.80
Nash	%	97.60	95.30
R^2	-	0.98	0.95

The hydrographs obtained at the site of Savè are also of good quality (Figures 5 and 6). The blocking correlation and the validation of the simulated flows as a function of the flow rates observed (Figures 5 and 6) gives values of the coefficient R² very significant ($R^2 \geq 0.95$). Therefore, we can say that the rain-flow modelling by using the GR2M model gives acceptable and very encouraging results for the Ouémé basin at the site of Savè.

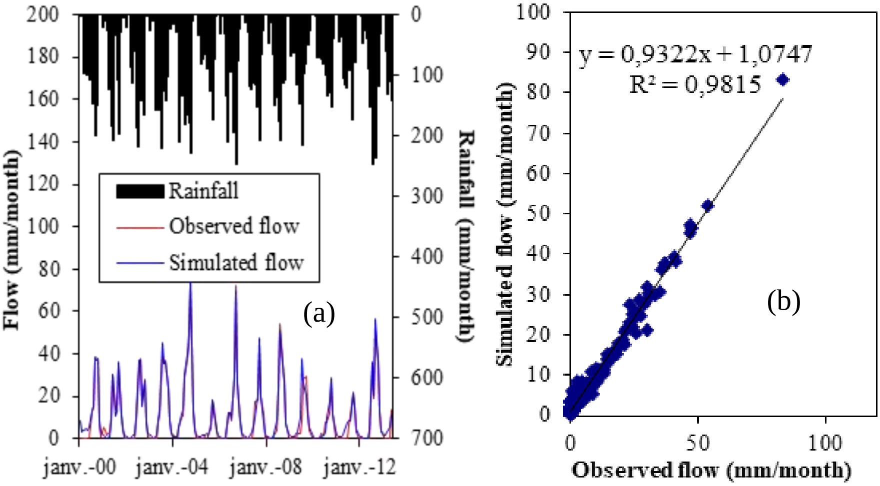

Figure 5 : Blocking of the GR2M model obtained at Savè station:
(a) Rainfall-flow based on GR2M model. (b) Correlation from observed vs simulated flows.

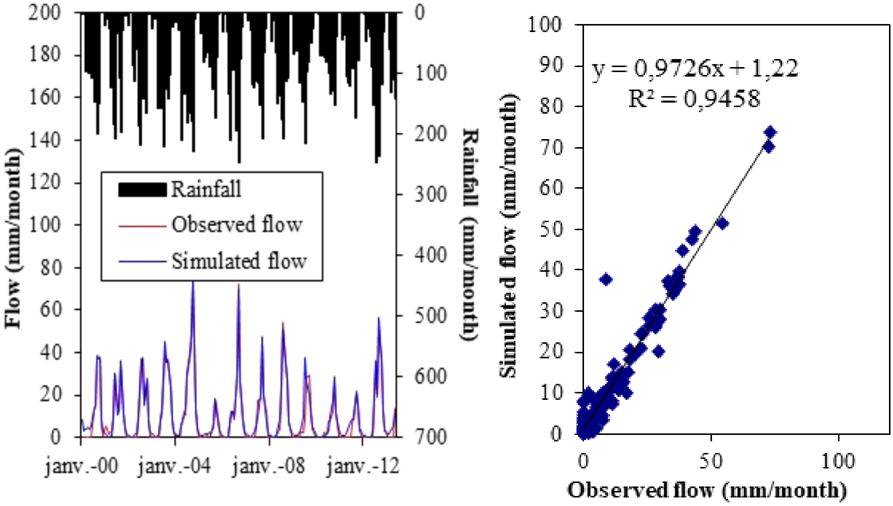

Figure 6 : Validation of the obtained GR2M model at Savè station:
(a) Rainfall-flow based on GR2M model. (b) Correlation from observed vs simulated flows.

Kétou's Site

The results obtained on the Kétou site (Table 3) and the good superimposition of the two curves, for respectively the simulated and calculated flow rates, displayed in Figures 7 and 8, make it possible to conclude that the selected model is well blocked. The values of Nash criterion in validation (Nash = 91% and R^2 = 0.92) confirm the good performance of the model.

Table 3 : Blocking and validation results for the Kétou station: parameter values, Nash criterion and determination coefficient

Nash criterion parameters and determination coefficient	Units	Blocking (period : 1989-2000)	Validation (period : 2001-2015)
X_1	mm	867.83	867.83
X_2	-	0.66	0.66
Nash	%	0.95	0.91
R^2	-	0.95	0.92

The hydrographs obtained at the Kétou site are of good quality (Figures 7 and 8). Therefore, we can say that the rain-flow modelling, using the the GR2M model, gives interesting results for the Ouémé river basin at the Kétou site.

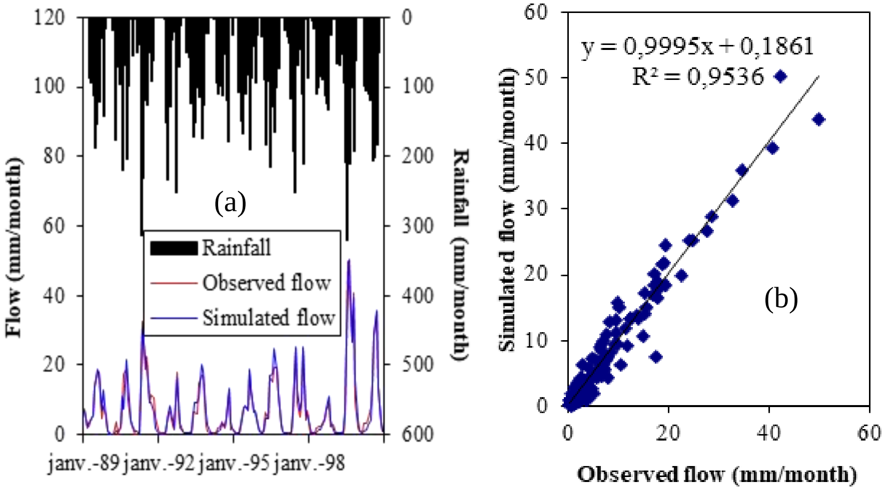

Figure 7 : Blocking of the obtained GR2M model at the Kétou station:
(a) Rainfall-flow based on the GR2M model. (b) Correlation of observed vs simulated flows.

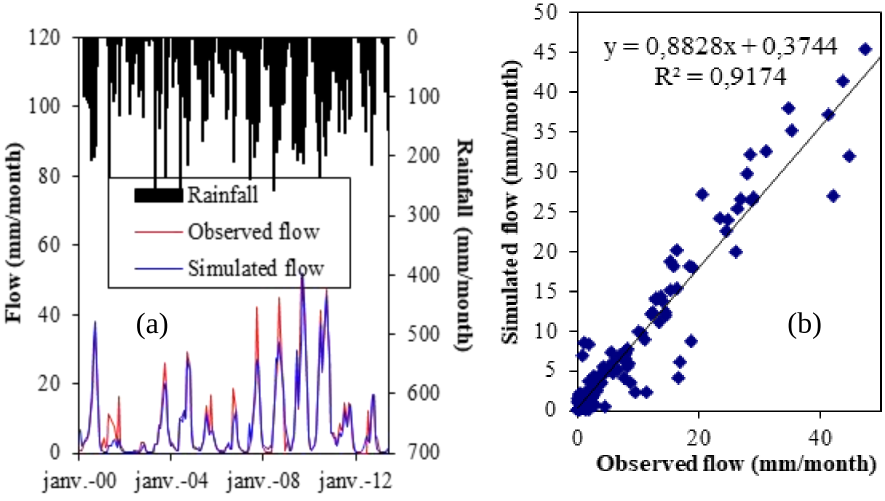

Figure 8 : Validation of the obtained GR2M model at the Kétou station:
(a) Rainfall-flow based on the GR2M model. (b) Correlation of observed vs simulated flows.

Simulation of future parameters for the Hydraulic Balance

Table 4 shows, by 2025 and 2040 respectively, the rates of change in rainfall, potential evapotranspiration and flow-rates, while Figures (from 9 to 17) show their respective evolutions in time, at the different reference sites of the Ouémé river basin.

Table 4 : Rates of change (%) in rainfall, potential evapotranspiration and predicted flows by 2025 and 2040 reported to those for the 1989–2015 period.

Studied parameters	**Bétérou station**		**Savè station**		**Kétou station**	
	Rates of change (%) over periods of:					
	2016-2025	2025-2040	2016-2025	2025-2040	2016-2025	2025-2040
Rainfall	-6.17	-7.75	-2.60	-3.43	-1.40	-5.31
PE	+3.80	+6.55	+0.51	+0.64	+7.64	+9.00
Flow-rate	-41.41	-46.37	-13.28	-15.13	-9.09	-11.90

From the results thus presented in Table 4 and illustrated in figures (from 9 to 17), it is noted that rainfall and flow-rate have a downward trend over the period 2016-2040 at the level of the three reference sites.

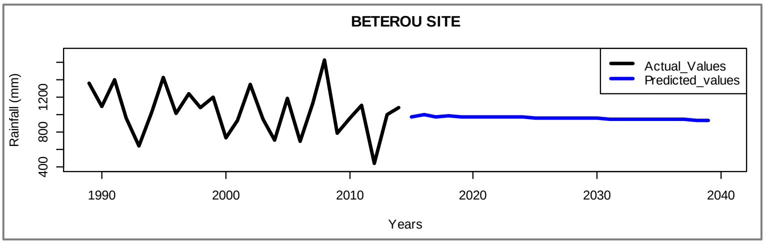

Figure 9 : Annual evolution for the rainfall at Bétérou site

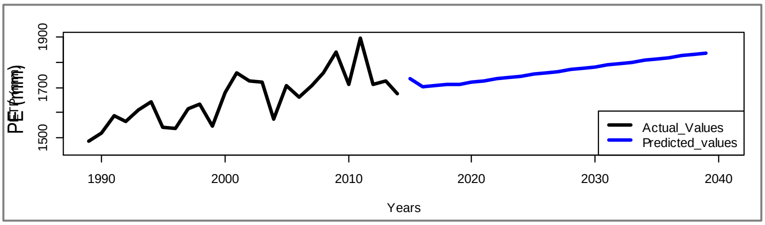

Figure 10 : Annual evolution for the potential evapotranspiration at Bétérou site

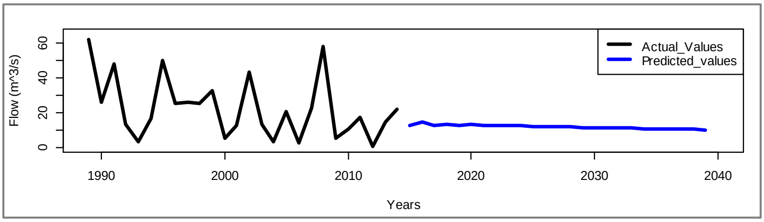

Figure 11 : Annual evolution for the flow-rate at Bétérou site

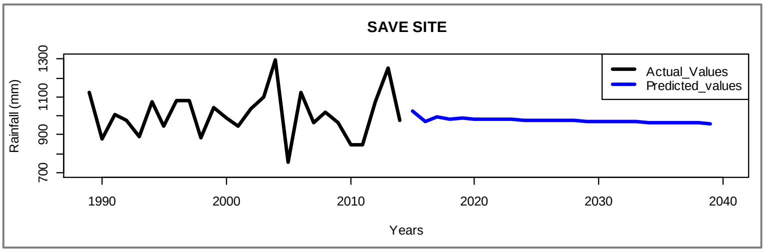

Figure 12 : Annual evolution for the rainfall at Savè site

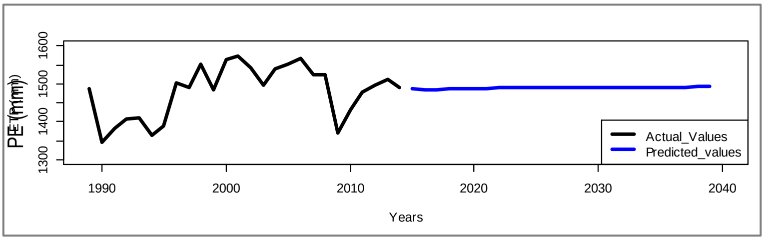

Figure 13 : Annual evolution for the potential evapotranspiration at Savè site

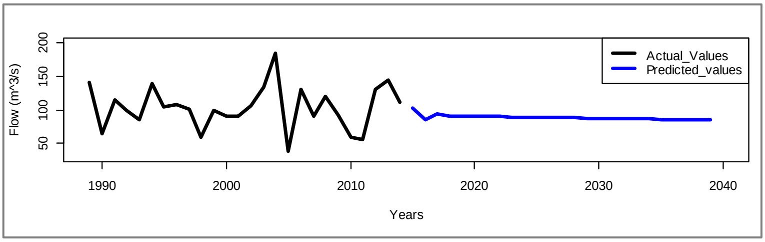

Figure 14 : Annual evolution for the flow-rate at Savè site

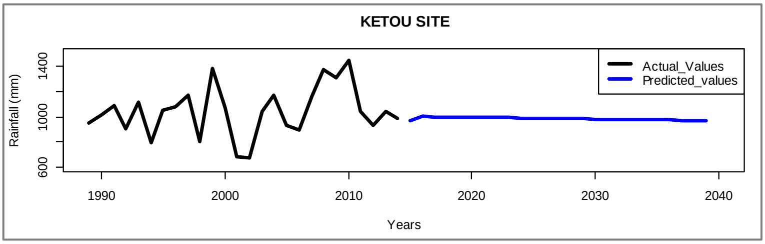

Figure 15 : Annual evolution for the rainfall at Kétou site

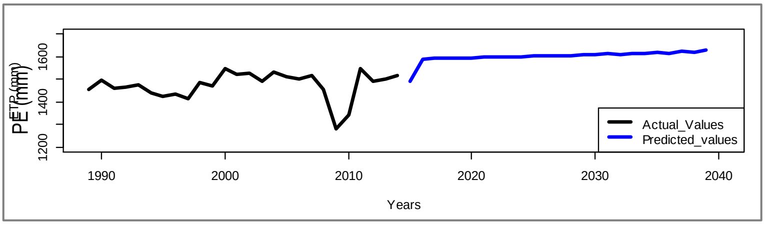

Figure 16 : Annual evolution for the potential evapotranspiration at Kétou site

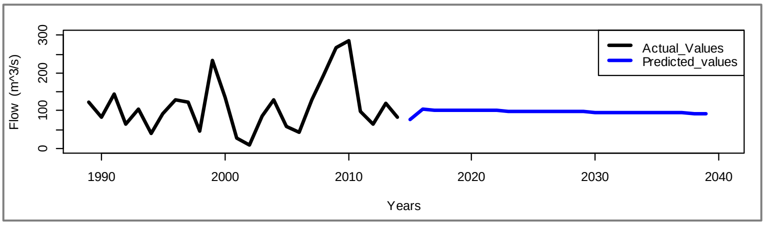

Figure 17 : Annual evolution for the flow-rate at Kétou site

This decline appears to be more pronounced over the period 2016-2025 than from 2025 to 2040. Concerning the potential evapotranspiration, there is an increasing trend, with a peak of 9.00 % in Kétou, by 2040. As for rainfall and flow, PE is experiencing a rapid increase over 2025. With a 9.00% increase by 2040, 84.88% of this rate is reached over the period 2016-2025.

Impacts on the Use of Water Resources

The forecast of water resource utilization in the Ouémé river basin over the next few years should seriously take into consideration the main results obtained from this study. Nowadays, the waters of the Ouémé river basin are mainly used for domestic and small scale agriculture purposes. The development of irrigated agriculture and hydroelectricity should particularly take into account the significant reduction in rainfall and the increase in potential evapotranspiration as demonstrated by our present results. Studies have shown that an increase in temperature of 3°C would lead to a 26% increasing need of irrigation water due to increased potential evapotranspiration (Sharma, 2003). The demand for water in the agricultural sector should therefore become much more important. This situation could then contribute to an increase in flows (flows). This should be taken into account in the hydro-agricultural and hydroelectric developments underway or planned in the Ouémé basin. The variety of processes used in climate models, in basins, and their temporal and spatial aggregation, however, is such that findings may differ substantially from one model to another and from one basin to another. However, our analyses allow us to get an idea of the mean and frequency predictions of the distribution of climatic and hydrological variables studied in the Ouémé river basin.

CONCLUSION

The aim of this study was to predict the potential impacts of climate change on the future evolution of the hydrological regime of the Ouémé river basin (by 2040). The predicted trends in rainfall and PE clearly show that the Ouémé river basin is already affected by the effects of climate change. The use of these trends, as inputs to the GR2M model previously well configured and validated, allowed the simulation of the flow over the next 25 years. The impact of future climate change, as simulated by the GR2M model and resulting in a decrease in average annual flows between 11.90% and 46.37%, could be detrimental to any hydrological project in the basin, and more particularly in Bétérou, if the projected trends are maintained. These results, in average values, should not mask the fact that model uncertainty increases for simulations of future periods compared to those of the current period. The varied simulation results obtained based on the sub-basins considered in this study, are due both to the very relative quality of the available flows and to the fact that the GR2M model is of a simple conceptual type. However, it is clear from the results obtained that the model exploited makes it possible to reveal the effects of climate change on the current hydrological regime of the studied basin and to predict its future behaviour, notably by 2040. Hence, the outcome of this paper reveal a strong warning for a careful exploitation of the Ouémé river basin which in recent years has been attracting in the Republic of Benin, all necessary stakeholders for the realization of various hydroelectric and hydro-agricultural development projects.

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