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RAINFALL-RUNOFF MODELING AT MONTHLY AND DAILY SCALES USING CONCEPTUAL MODELS AND NEURO-FUZZY INFERENCE SYSTEM

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Abstract
Simulating the transformation of rainfall into runoff at the catchment scale using mathematical models has known a considerable improvement since their development. This study comes down to the rainfall-runoff relationship modeling at monthly and daily time scales by the application of conceptual models deemed as the most efficient, and the Neural Fuzzy Inference System which performance has been proved in different fields. Comparing the two concepts aims to select the most efficient in simulating the extreme events of runoffs, by picking up their strengths and weaknesses. For this purpose, both statistical and graphical techniques were applied by comparing the most used criteria in the hydrological field. A choice based on the most sensitive criterion to the extreme events lead to pick: Nash-Sutclieffe (NSE), Modified NSE, RSR and PBIAS. The conceptual models used are GR2M and GR4J at monthly and daily scale respectively. They operate by application of a Production Function defining the part of rainfall filling the soil (SMA store), and a Routing store function defining the final runoff value. Application of the Neural Fuzzy Inference System aims to develop a forecast system able to reproduce the information about maximal events. It takes advantage from the learning ability and connectionist structure of artificial neural networks, and the ability to solicit interpretable rules from the inference fuzzy system. Two input partitioning modes are applied using several combinations of input data including: rainfall, evaporation, SMA and Routing store levels issued from the conceptual models. Application made on the Isser catchment (Algeria) defined that a combination between conceptual models data and neural fuzzy inference system is a conclusive concept for general detection of hydrological series trends, as well as flood forecasting by simulating the extreme runoff events.

Keywords: Conceptual modeling, Neural Fuzzy System, Forecast, catchment, extreme events.

1 INTRODUCTION

Understanding the way the water travels through waterways has become indispensable for water management, which consists on the estimation and control of water evolution over time (flood and low water forecasting, flood protection, decision support tool for managing water resources, extrapolation of hydrologic data sets, and sizing of hydraulic structures). The objective of this study is to improve the runoff simulation to get a system able to forecast the extreme events of monthly and daily runoffs.

2 METHODS OF HYDROLOGIC MODELING

Both deterministic and stochastic approaches were used to achieve the desired results and will be applied on the monthly and daily time scales.

2.1 Conceptual modeling

Conceptual models are based on the concept of water balance. They are represented by empirical formulas which aim to determine the way the water travels through watershed over time. The watershed is considered as an assembly of interconnected tanks, representing storage levels. Models used in this category are GR2M at monthly scale and GR4J at daily scale.

2.1.1 Description of GR2M model

The used version is the version of Mouelhi et al. (2006b). This model follows the watershed soil moisture to take into consideration the previous states of the basin using two functions:

- Production Function which is based on the soil moisture accounting (SMA) using the rainfall, the potential evapotranspiration and the X1 model parameter. It calculates the fraction of rainfall reaching the routing store and the initial SMA store level of the next month.

- Routing function and groundwater exchange which calculate the amount of water running in the waterway and giving the monthly runoff.

Table 1. Calibrated parameters of GR2M model obtained from a large sample of watersheds (Perrin et al., 2007)

Parameters	Median	Confidence interval at 90%
X1 (mm): Capacity of the SMA store	380	140-2640
X2 (-): Groundwater exchange coefficient	0.92	0.21-1.31

2.1.2 Description of GR4J model

The used version is the version of Perrin et al. (2003). This model follows the watershed soil moisture and associates it with unit hydrographs (UH1 and UH2) to take into consideration the previous state of the basin. It is described as follows:

- Production Function: It has the same principle as the GR2M production function.
- Routing function and groundwater exchange: Use unit hydrographs to follow how the water travels over time.

Table 2. Calibrated parameters of GR4J model obtained from a large sample of watersheds (Perrin et al., 2007)

Parameters	Median	Confidence interval at 80%
X_1 (mm): capacity of the production store (mm)	350	100 à 1200
X_2 (mm): groundwater exchange coefficient	0	-5 à 3
X_3 (mm): one day ahead capacity of the routing store (mm)	90	20 à 300
X_4 (days): base time of unit hydrograph *HU*1	1,7	1,1 à 2,9

2.2 Neuro-fuzzy inference system

The neuro-fuzzy inference system is a combination of the artificial neural networks and the fuzzy logic. It takes advantages from the learning ability and connectionist structure of the artificial neural networks, and the human-like reasoning of the fuzzy logic.

The architecture used is: The Adaptive Neuro-Fuzzy Inference System (ANFIS). There are three input data partitioning modes: Grid partitioning takes each input separately and the number of rules and choice of the membership function are made manually, tree partitioning, and scatter partitioning which interconnects the inputs and varies the model parameters automatically. Only scatter and grid partitioning were used. The variables used as inputs for this model are: the rainfall (P), evapotranspiration (E), SMA store level (noted S) and the routing store level (noted R), issued from the best simulation made by the conceptual models: GR2M and GR4J.

2.3 Application and validation criteria of the models

Application of a model follows three steps: The calibration which consists on the adjustment of input data and model parameters to reproduce observed output data, the validation step ensures that the model is able to work properly with different input data and check its reliability, and finally application of results.

Table 3. Validation criteria used for rating the general performance of the models(Moriasi et al., 2007)

Nash-Sutclieffe (NSE)	NSE= $1-\frac{\sum_{i=1}^{n}(Qo-Qs)^2}{\sum_{i=1}^{n}(Qo-Qo.m)^2}$	Gives a greater weight for the average runoff values
Modified NSE	NSEm=$1-\frac{\sum_{i=1}^{n}\lvert Qo-Qs\rvert}{\sum_{i=1}^{n}\lvert Qo-Qo.m\rvert}$	Gives a greater weight for the extreme runoff values (height and low values)
PBIAS	PBIAS= $\frac{\sum_{i=1}^{n}(Qo-Qs)}{\sum_{i=1}^{n}Qo}$	More sensitive with the extreme events especially low values
RSR	RSR=$\frac{RMSE}{STDEVobs}=\frac{\sqrt{\sum_{i=1}^{n}(Qo-Qs)^2}}{\sqrt{\sum_{i=1}^{n}(Qo-Qo.m)^2}}$	Gives the same weight for all the runoff values

Where Qo is the observed runoff, Qs is the simulated runoff, Qo.m is the mean value of observed runoffs.

Table 4. General performance ratings for the used validation criteria (Moriasi et al.,, 2007)

Performance rating	RSR	NSE	PBIAS for stream flow [%]
Very good	0.00 < RSR < 0.50	0.75 < NSE < 1.00	PBIAS < ±10
Good	0.50 < RSR < 0.60	0.65 < NSE < 0.75	±10 < PBIAS < ±15
Satisfactory	0.60 < RSR < 0.70	0.50 < NSE < 0.65	±15 < PBIAS < ±25
unsatisfactory	RSR > 0.70	NSE < 0.50	PBIAS > ±25

3 RESULTS AND DISCUSSIONS

Application was made on the Isser watershed (Algeria), characterized by a Mediterranean climate. The hydrometric station used is Lakhdaria situated at the watershed downstream. The used rainfall stations are situated at the upstream of Lakhdaria. Runoff data used are from 1982 to 2002 for monthly time scale and from 1990 to 1998 at daily time scale. Rainfall data cover all the existing runoff periods.

3.1. Conceptual modeling

Simulation was done according to the importance of the calibration period.

- Modeling at monthly time step with GR2M model:

Table 5. Performance rating for GR2M according to calibration periods

	Calibration			
Period	NSE %	NSE m %	PBIAS%	RSR
May1982-Aug 1996	75.00	54.90	-1.60	0.50
May1982-Aug 1997	75.10	56.70	2.44	0.50
May1982-Aug 1998	73.20	54.01	0.01	0.52
May1982-Aug 1999	**72.80**	**54.90**	**-2.10**	**0.52**
May1982-Aug 2000	73.40	54.90	-1.50	0.51

Table 6. Performance rating for GR2M according to validation periods

	Validation			
Period	NSE %	NSE m %	PBIAS%	RSR
Sept 1996-Aug 2002	84.60	59.90	-12.30	0.39
Sept 1997-Aug 2002	64.20	50.70	-34.34	0.60
Sept 1998-Aug 2002	75.60	58.90	-23.70	0.49
Sept 1999-Aug 2002	**87.10**	**64.90**	**-8.80**	**0.36**
Sept 2000-Aug 2002	83.10	56.90	-3.90	0.41

The calibration and validation periods taken for the monthly modeling are:

- Calibration period: Mai 1983 to August 1999 (16 years)
- Validation period: September 1999 to August 2002
- Calibrated parameters given by those periods are: X1=180 mm and X2=0.75.

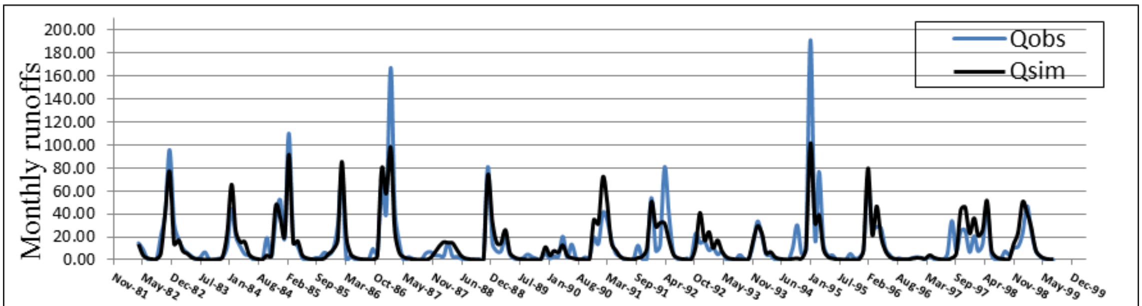

Figure 1. Graphical evaluation of the model GR2M during the calibration period

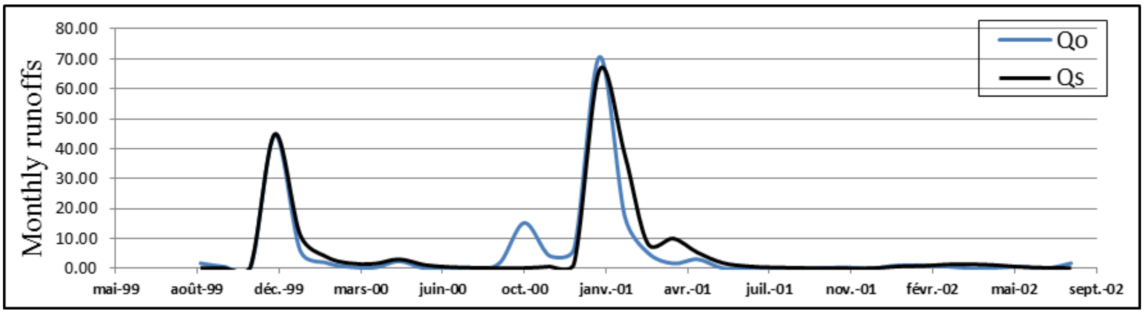

Figure 2. Graphical evaluation of the model GR2M during the validation period

Comparing the graphical and statistical results, we conclude that the NSEm is more sensitive to the underestimations of simulated runoffs and it will be used to evaluate the extreme runoff events. The PBIAS will be used to evaluate the general trend of the simulation, and RSR to quantify the error amount.

The graphical evaluation shows clearly that the highest values are underestimated. We notice that we get a simulated runoff of 98 mm instead of 167mm in February 1987 and a simulated runoff of 102 mm instead of 191 mm in January 1995. Since there's an existing other data set of monthly runoffs from September 2004 to July 2010, the validation was also made on it, and it confirms that height values aren't simulated (Qsim=133 mm, Qobs=229 mm):

Table 7. Performance rating parameters during the second validation period

Performance criteria	Validation with the second data set
Nash-Sutcliffe (NSE) (%)	71.10
PBIAS (%)	18.87
RSR	53.65

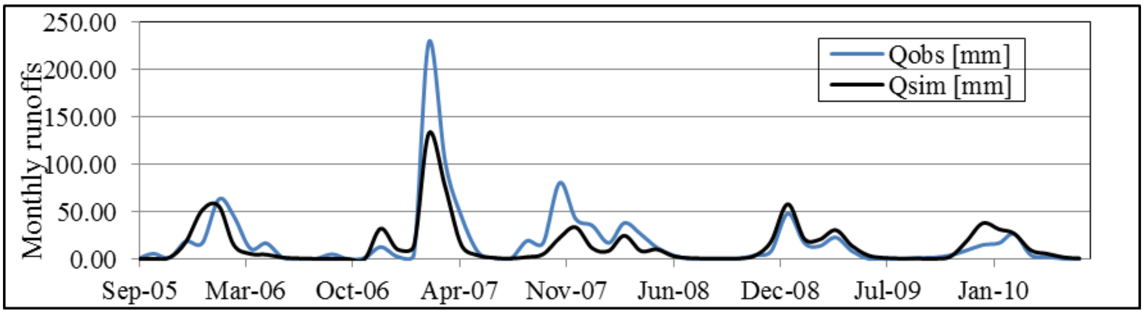

Figure 3. Graphical evaluation of the model GR2M during the second validation period

Since there were no measures of runoff between September 2002 and August 2004, we proceed to the extension of the runoff set and get the following result that we will compare with ANFIS results:

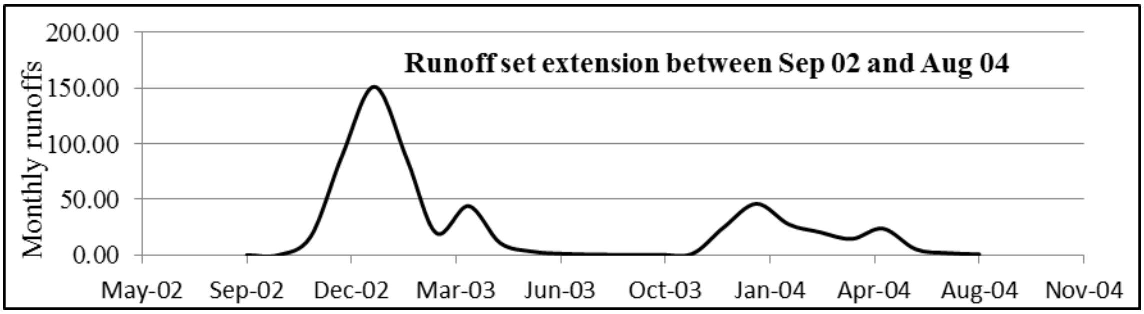

Figure 4. Runoffs given by extension of the data set by GR2M model

- Modeling at daily time step with GR4J model:

Table 8. Performance rating and parameters for GR4J according to calibration periods

	Calibration							
Period	NSE %	NSEm %	RSR	PBIAS %	X1	X2	X3	X4
1991-1995	77,30	53,90	0,48	12,90	135,00	-1,30	27,00	1,98
1991-1996	77,40	54,56	47,53	10,81	145,00	-1,20	25,00	2,00
1991-1997	**70,80**	**53,95**	**0,54**	**24,32**	**186,00**	**-1,50**	**21,00**	**1,98**

Table 9. Performance rating and parameters for GR4J according to validation periods

	Validation							
Period	NSE %	NSEm %	RSR	PBIAS %	X1	X2	X3	X4
1996-1998	41,40	28,51	0,76	-39,21	135,00	-1,30	27,00	1,98
1997-1998	32,10	28,03	0.66	-43,66	145,00	-1,20	25,00	2,00
1998	**64.10**	**41.54**	**0.59**	**-24.28**	**186,00**	**-1,50**	**21,00**	**1,98**

The calibration and validation periods taken for the daily modeling are:

- Calibration period: 1 January 1991 to 31 December 1997 (7 years),
- Validation period: 1 January 1998 to 31 December 1998 (1 year),

Calibrated parameters given by those periods are: X1=186 mm and X2= -1.5, X3=21 and X4=1.98.

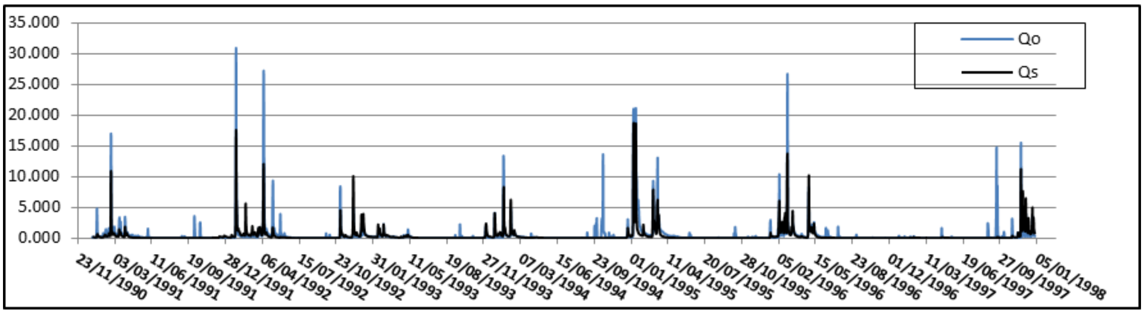

Figure 5. Graphical evaluation of the model GR4J during the calibration period

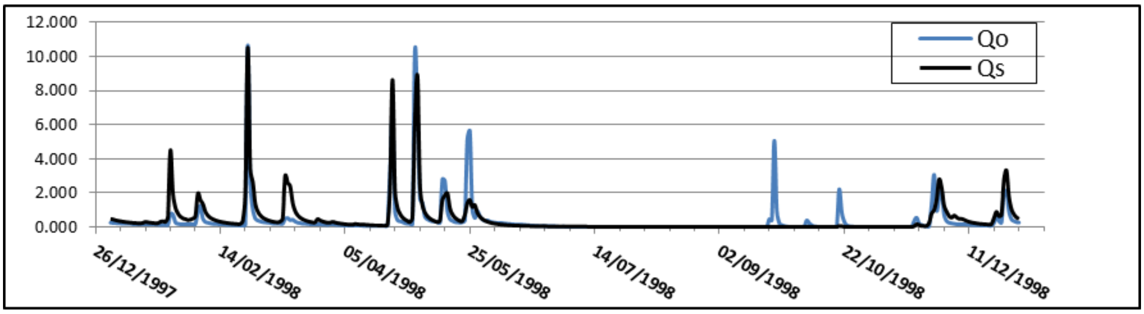

Figure 6. Graphical evaluation of the model GR4J during the validation period

The performance rating got for calibration period is good to satisfactory and satisfactory in validation period. We notice with graphical evaluation that highest runoffs are not very underestimated but there are some events not simulated. A satisfactory PBIAS shows that the general trend of simulated runoffs and observed ones are similar. A good rating of the RSR shows that the errors are not important so that we neglect the performance of the model.

3.2. Neuro-fuzzy inference system modeling

Results given by scatter partitioning were not satisfactory for both monthly and daily time scales. Only conclusive results are presented, so all results presented are given by the grid partitioning mode.

- Modeling at monthly time step:

The inputs combinations tested are: Q[mm]=f[P(t)], Q[mm]=f[P(t), E(t)], Q[mm]=f[P(t), S(t-1)], Q[mm]=f[P(t), E(t), S(t-1)]. Q[mm] is the monthly simulated runoff.

The combination that gives the best simulation for the same periods as GR2M model is: Q[mm]=f[P(t),E(t),S(t-1)], and its results are given below:

Table 10. Performance rating at monthly time step according to number of rules of the model

	Calibration	Validation	Calibration	Validation
Number of rules	**2^3**		3^3	
NSE	**86,31**	**85,61**	97,36	-24,31
NSEm	**66,03**	**55,04**	83,08	5,13
RSR	**0,37**	**0,38**	0,16	1,11
PBIAS	**-0,45**	**-38,49**	-0,36	15,77

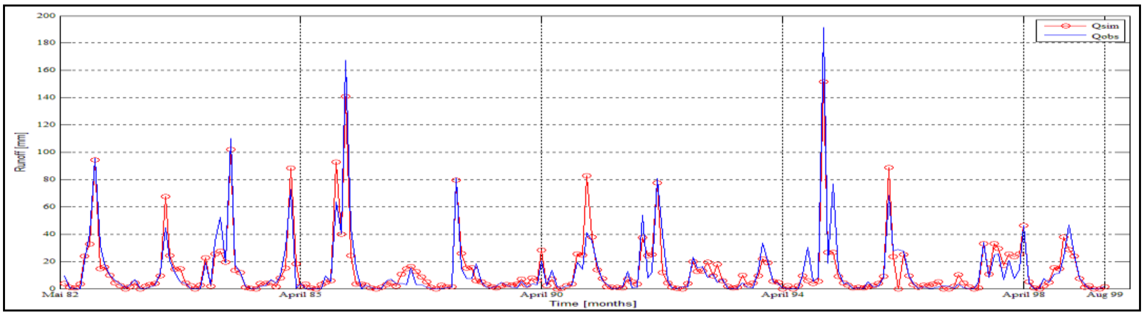

Figure 7. Graphical evaluation of the model at monthly time step during the calibration period

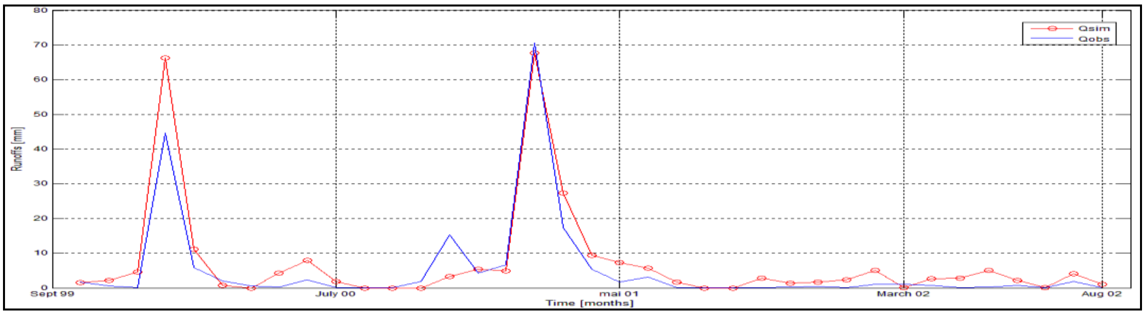

Figure 8. Graphical evaluation of the model at monthly time step during the validation period

The NSE, modified NSE, RSR, PBIAS and the graphical evaluation present very good simulated runoffs. The two height events of the calibration period are simulated with 152 mm instead of 191 mm in January 1995, and 142 mm instead of 167 mm in February 1987. All the other runoffs are in general either reproduced or overestimated. In the validation period, one height event is reproduced and the other one is overestimated. A second validation is made on the set of September 2004-July 2010, and the runoff of March 2007 is 168 mm instead of 229 mm. Then, an extension of the runoff data set is made on the period: September 2002-August 2004. This last one is compared with the result given by the model GR2M, and we got 247 mm instead of 151 mm in January 2003.

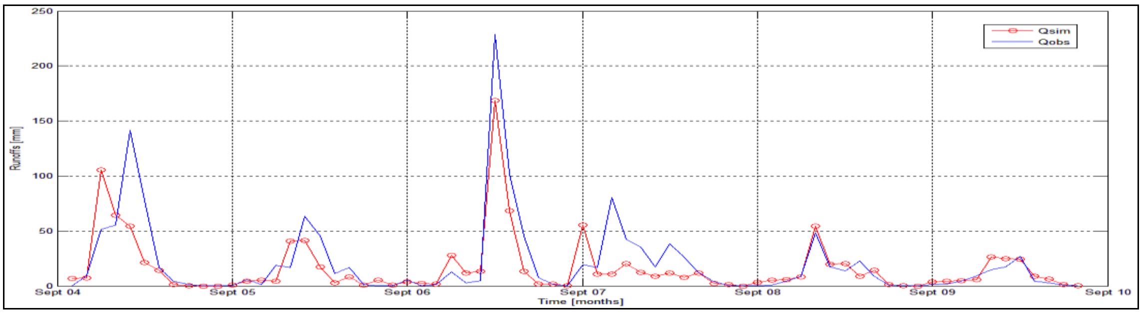

Figure 9. Graphical evaluation of the model at monthly time step during the second validation period

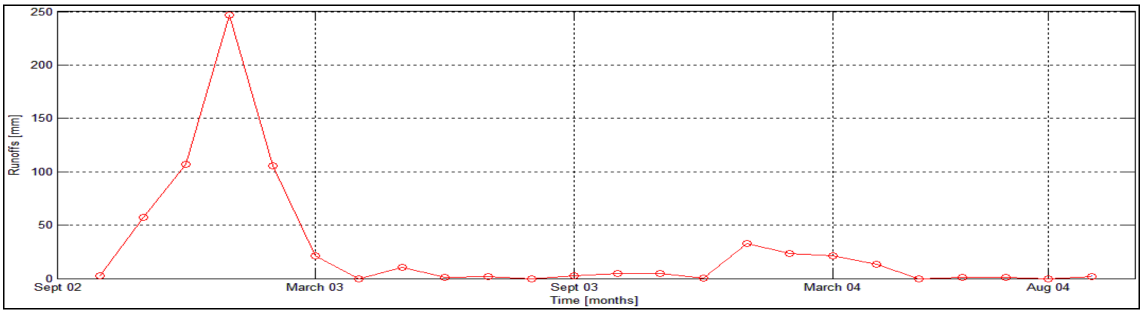

Figure 10. Runoffs given by extension of the data set by Neuro-fuzzy inference system

- Modeling at daily time step:

The inputs combinations tested are: Q[mm]=f[P(t)], Q[mm]=f[P(t), E(t)], Q[mm]=f[P(t), S(t-1)], Q[mm]=f[P(t),E(t),S(t-1)] . Q[mm] is the daily simulated runoff.
Those combinations didn't give good results. This is mainly due to the concentration time of the watershed which is equal to one day at least according the following table:

Table 11. Concentration time of the watershed calculated with different formulas

Formula	**Concentration time [days]**
Algerian formula, USTHB (1992)	2,46
Giandotti formula	1.10
Kirpich formula	2,18
X4 (base time of unit hydrograph *HU*1) of GR4J	1,98

This result lead us to introduce the routing store level (R) issued from the model GR4J to take into consideration the concentration time. The combinations tested with this input are: Q[mm]=f[P(t),R(t)], Q[mm]=f[P(t), S(t-1), R(t)], Q[mm]=f[P(t),E(t),S(t-1), R(t)].
The combination that gives the best simulation for the same periods as GR4J model is: Q[mm]=f[P(t),R(t)]:

Table 12. Performance rating at daily time step according to number of rules of the model

	Calibration	Validation	Calibration	Validation	Calibration	Validation
Rules number	2^2		3^2		4^2	
NSE	47,31	32,01	**64,49**	**42,66**	71,27	6,00
NSEm	24,59	3,96	**39,72**	**6,83**	46,68	17,76
RSR	0,72	0,82	**0,59**	**0,76**	0,54	0,97
PBIAS	-6,07	-52,5	**-0,51**	**-54,13**	-0,01	-46,81

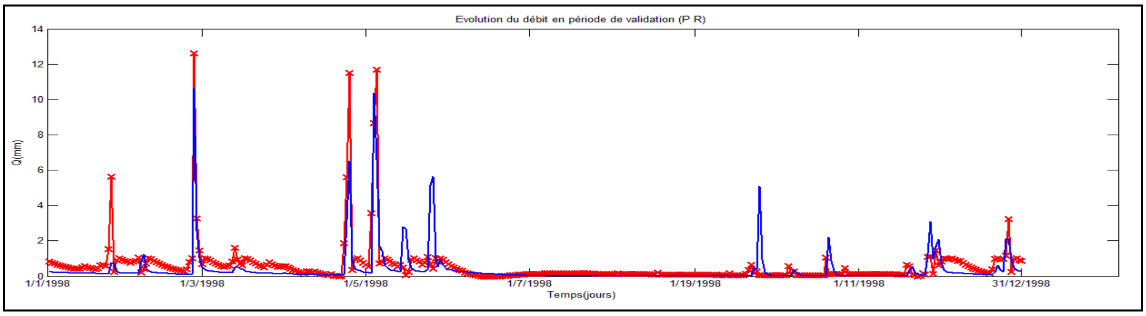

Figure 11. Graphical evaluation of the model at daily time step during the validation period

We notice that there's no great difference in the general trend of the simulation between this one and the one made by the GR4J. The only difference is that this model overestimates the flood periods, but there are also events that are not simulated.

The previous states of the soil in the daily simulation are more important than in the monthly simulation, in which we have an accumulation in the soil state, but this is not the case in daily state, in which each day is taken separately.

A simulation made on the combination: Qsim[mm]=f[P(t),R(t)], where Qsim[mm] is the simulated runoff given by the GR4J model. This simulation is made to verify if the routing store level calculated by GR4J to have the runoff simulated by this last one is reproduced.

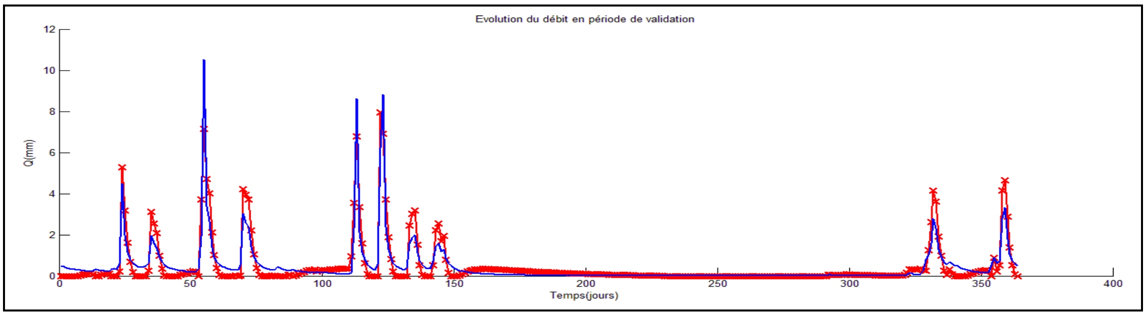

Figure 12. Graphical evaluation of the combination Qsim[mm]=f[P(t),R(t)]

We conclude from this essay, that having good information on anterior state of the soil can give a good simulation with this model, since the routing store data used here can only give the runoffs simulated by GR4J (The data set R(t) are already underestimated by GR4J in some events).

4 CONCLUSION

The monthly modeling by the conceptual model GR2M gives a good general trend simulation, but presents the drawback of not simulating the highest runoffs in their entirety. The application of neuro-fuzzy inference system covers this drawback, using as inputs: the rainfall, the evapotranspiration and the soil moisture accounting store level issued from the model GR2M. This combination gives good results concerning the highest values of runoffs. The daily modeling by the conceptual model GR4J gives a good general trend of simulated runoffs. However, some events aren't simulated. The combination of the GR4J data and the neuro-fuzzy inference system leads us to conclude that having good information on anterior state of the basin will improve the simulation at daily scale, such as measured soil moisture data which will represent the observed runoff and not an underestimated one, especially during flood periods which occurs after a drought period.

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