

Flood forecasting with a dam watershed event-based hydrological model in a semi-arid context: case study in Morocco

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ABSTRACT

Event-based rainfall-runoff mechanism modeling is a very useful process for flood forecasting, in particular at the level of the dam watersheds in semi-arid regions. In this regard, this paper presents a flood modeling application in the Sidi Mohammed Ben Abdellah (SMBA) dam watershed in Morocco, using the HEC-HMS model. The Soil Conservation Service (SCS) Curve Number (CN), the SCS Unit hydrograph, and the Recession were chosen as loss, transform, and baseflow methods respectively. The various frequency floods entering the SMBA dam were simulated using the elaborated model. The results show that it is possible to estimate the volumes of water generated during floods satisfactorily with errors of 6–11%, while the error in peak flow is around 20%. The median NSE, during validation, is 0.58 and the R^2 is about 0.67. Sensitivity analysis shows that the runoff volume, the peak flow, and the NSE were found to be more sensitive to lag time and CN parameters. The developed event-based model will make it possible to carry out several simulations allowing the assessment of the North to South Water Transfer Project operation, in particular, the SMBA dam reservoir management during the flood periods.

Key words: event-based model, flood management, frequency analysis, HEC-HMS model, sensitivity analysis, SMBA dam reservoir

HIGHLIGHTS

- HEC-HMS has proved its ability to simulate the floods at the SMBA dam watershed.
- T_{lag} and CN are the most influential parameters on the elaborated model outputs.
- Frequency floods entering the SMBA dam were simulated using the validated model.
- The resulted model will allow optimal SMBA dam-reservoir management.

INTRODUCTION

Under the combined effect of growing water needs and decrease of the global water resources due to climate change, integrated and sustainable water resources management has become a major priority (Luo *et al.* 2019; Şen 2021). This challenge is most felt in areas with an unequal spatio-temporal distribution of water resources. To deal with this stressful situation, dams constitute an important means to alleviate the problems linked to the temporal heterogeneity of water resources. Thus, water transfers from the surplus areas to the deficit ones make it possible to remedy the uneven spatial distribution of water (Liu *et al.* 2019; Laassilia *et al.* 2021).

Since the 1960s, Morocco has opted for a policy of building dams to secure water supply for domestic purposes and to accompany the economic development of the country. In recent years, water transfer projects between the surplus basins in the North and the deficit ones in the South are under study (Laassilia *et al.* 2019). The effectiveness of this kind of projects is linked to the understanding of the rainfall-runoff mechanism in the watersheds concerned by the water transfer. The estimation of the runoff produced within a given catchment will make it possible to optimize the sizing and the management of the water transfer whether under current or future climatic conditions.

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Hydrologic models are often used as a tool for a wide range of tasks, such as the modeling of flood events, the long-term water resources assessment, or the prediction of floods (Jia *et al.* 2009). The type of the modeling approach normally depends on the study purpose, data availability, and ease of use (Tassew *et al.* 2019). Known as a powerful tool to model the hydrologic mechanism in the various climatic context, the HEC-HMS model was selected for the concretization of the rainfall-runoff relationship at the level of the SMBA dam watershed, considered as one of the main components of the North to South Water Transfer Project (NSWTP) in Morocco. The HEC-HMS model was chosen for its adequacy with the study aims, its applicability in the semi-arid zones as Morocco, and availability of the input data.

Previous studies on HEC-HMS proved its ability to simulate and forecast streamflow based on different datasets and catchment types (Chu & Steinman 2009). In this regard, Joo *et al.* (2013) carried out a comparison of two event-based flood models (ReFH and HEC-HMS). The authors concluded that the ReFH model shows the limitations in the simulation of peak flow, while HEC-HMS shows good simulations in the studied catchments. De Silva *et al.* (2014) used the HEC-HMS for the modeling of events and continuous flow hydrographs in the Kelani River Basin (Sri Lanka). The results depict the capability of HEC-HMS to reproduce stream-flows in the basin to high accuracy with averaged computed Nash-Sutcliffe efficiencies of 0.91 for event-based simulations and 0.88 for continuous simulations. Ramly & Tahir (2016) applied HEC-HMS as rainfall-runoff model for flood simulation. The study had produced an illustrative and comprehensive representation of the sub-basin with reasonable accuracy indicated by the Nash-Sutcliffe coefficient of 0.86. Natarajan & Radhakrishnan (2019) applied HEC-HMS for the simulation of extreme event-based rainfall-runoff process in an urban catchment area. As a result, the frequency storm method has a Nash value of 0.7, which is higher than the value obtained from the specified hyetograph process, and it is chosen as a better model for generating food peak and volume for different return periods in the basin. Katwal *et al.* (2021) validated an event-based and a continuous flood modeling in Zijinguan watershed, Northern China. The authors found that the performance of SCS-CN model is more satisfactory than that of SMA model. In the semi-arid Moroccan context, many authors have validated rainfall-runoff models, using HEC-HMS, in several catchments of the country (Khaddor *et al.* 2016; Khattati *et al.* 2016; Ahbani *et al.* 2018; Elhassnaoui *et al.* 2019).

It is worth mentioning that the Bouregreg basin was the subject of several studies dealing with the various hydro-climatic aspects. However, the rainfall-runoff modeling of this catchment using the HEC-HMS model has not yet been carried out. Therefore, this paper aims to validate an event-based rainfall-runoff model to assess the magnitude of the floods in this basin and their impact on SMBA dam reservoir management. In relation with the NSWTP, this developed hydrological model will make it possible to carry out several simulations allowing the assessment of the NSWTP operation, in particular, SMBA dam reservoir management during the flood periods.

METHODS

Presentation of the SMBA dam watershed (Figure 1)

The SMBA dam, located at the north-central of Morocco, was commissioned in 1974 to ensure the domestic and industrial water supply for the coastal zone of Rabat-Casablanca, and to protect the Bouregreg Valley against floods. Its watershed area is about 9 600 km². The yearly inflow volume is estimated at 540 Mm³ (1975–2020), with a maximum of 2,600 Mm³ in 2010. The climate is semi-arid. The average annual rainfall is around 420 mm and the temperature varies between 11 and 27 °C. The main rivers are Bouregreg (125 km), Grou (260 km), and Mechra (93 km).

Data used

Available instantaneous rainfall and runoff data are presented in the Table 1. To verify certain incomplete records, the intensity-duration-frequency (IDF) curves available for the Rabat city were used. These IDF curves were developed on the basis of instant rainfall by the Directorate of National Meteorology in Morocco. The comparison between the cumulative instantaneous rainfalls and the cumulative daily rainfalls was also carried out.

As regards the selected events, we have chosen the most important events in terms of the peak flow. About 9–11 events, for each sub-basin, were used for the calibration and validation of the model. Table 2 lists the flood characteristics of samples events used in this study. The analysis of the events used for the model calibration and validation made it possible to draw certain observations. Indeed, most of the recorded events took place between October and March, which corresponds to the rainy period in Morocco. In addition, there has been

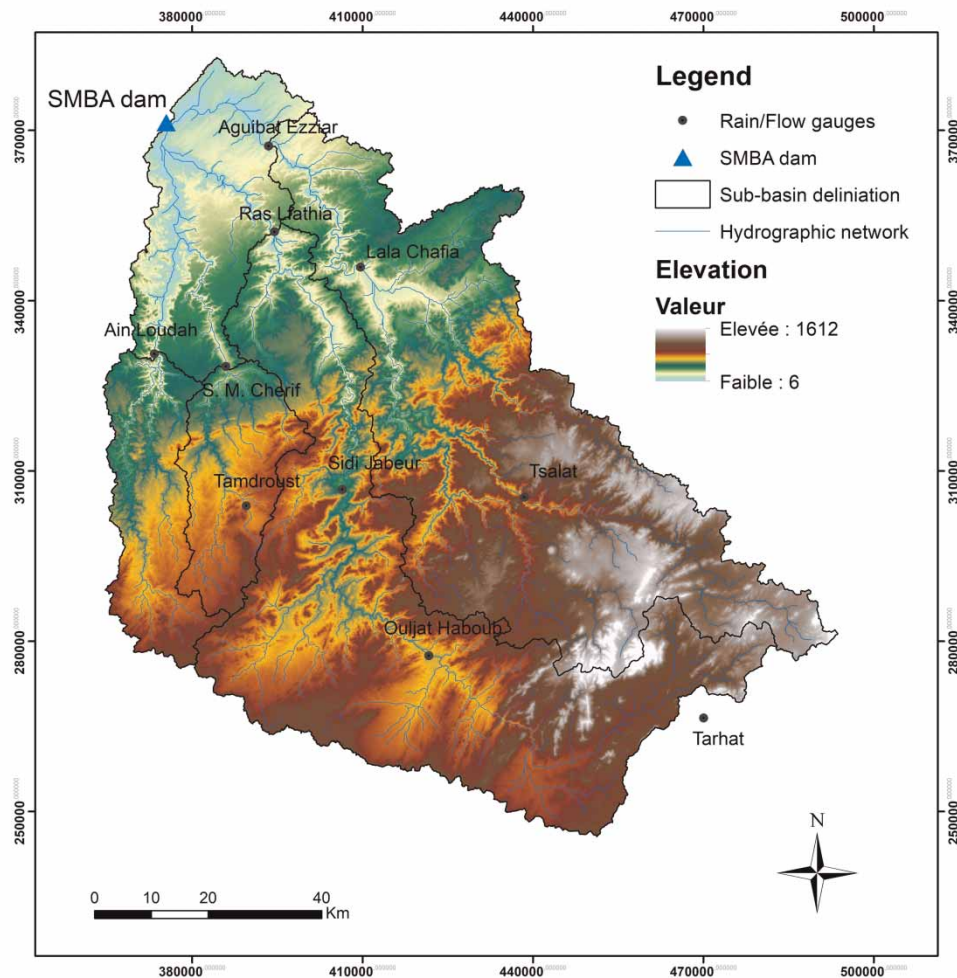


Figure 1 | Map of the Bouregreg watershed and the meteorological gauges used.

Table 1 | Rainfall and runoff data used for Bouregreg basin modeling

N°	Rain gauges	Elevation (m)	Instantaneous runoff		Instantaneous rainfall	
			Beginning	End	Beginning	End
1	Aguibat Ezziar	130	25/03/1977	31/01/2018	21/07/2009	18/07/2017
2	Ras Elfathia	161	25/03/1977	31/01/2018	04/08/2009	18/07/2017
3	S. M. Cherif	299	01/11/1972	31/01/2018	10/07/2009	18/07/2017
4	Lala Chafia	227	01/09/1980	31/01/2018	10/07/2009	18/07/2017
5	Ain Loudah	273	01/10/1972	31/01/2018	27/06/2009	18/07/2017
6	Tsalat	692	01/03/1977	31/01/2018	26/07/2009	18/07/2017
7	Sidi Jabeur	232	17/12/1971	31/01/2018	15/07/2009	18/07/2017
8	Ouljat Haboub	552	01/11/1972	31/01/2018	01/03/2012	18/07/2017
9	Tamdroust	312	01/09/1974	31/01/2018	25/06/2009	18/07/2017

a very remarkable reduction in the amount of precipitation over the past decade, which has been reflected by a decrease in the flows recorded at the various gauges. Also, the magnitude of floods varies from one sub-basin to another. Indeed, the Aguibat Ezziar basin (3,640 km²) receives significant amounts of precipitation, sometimes exceeding 80 mm/day, which has generated very immense floods whose flow exceeds 1,300 m³/s (events 1, 5, and 6). The neighboring sub-basin, Ras Ifathia (2,100 km²), is marked also by significant flows, but less

Table 2 | Sample events characteristics used for calibration and validation of the model

Sub-basins	Events	Baseflow (m ³ /s)	Date of Start	Date of end	Duration (h)	Peak flow (m ³ /s)	Peak time	Total rainfall (mm)
Aguibat Ezziar	AZ 1	84	23/12/2009 20:00	26/12/2009 14:00	66	1,347	25/12/2009 06:00	86.5
	AZ 3	142	20/02/2010 20:00	23/02/2010 02:00	54	1,187	22/02/2010 03:00	81.27
	AZ 5	123	09/03/2010 02:00	11/03/2010 05:00	51	1,574	09/03/2010 16:00	80.8
	AZ 6	32	29/11/2010 21:00	02/12/2010 12:00	63	1,771	01/12/2010 04:00	92
	AZ 7	6.7	30/10/2012 07:00	03/11/2012 12:00	97	866	01/11/2012 14:00	56
	AZ 9	26	13/03/2013 12:00	16/03/2013 08:00	68	852	14/03/2013 14:00	60.7
Ras El Fathia	RE 1	54	24/12/2009 03:00	26/12/2009 06:00	51	710	25/12/2009 02:00	51
	RE 2	70	21/02/2010 06:00	23/02/2010 20:00	62	850	22/02/2010 09:00	53
	RE 4	51	29/11/2010 20:00	02/12/2010 23:00	75	883	30/11/2010 22:00	69.9
	RE 7	59	30/10/2012 12:00	02/11/2012 23:00	83	813	01/11/2012 08:00	77.33
	RE 8	15	06/03/2013 01:00	08/03/2013 17:00	64	400	06/03/2013 22:00	42
	RE 10	9,9	27/11/2014 23:00	30/11/2014 18:00	64	697	29/11/2014 01:00	50
S. M. Cherif	SM 1	12	23/12/2009 12:00	25/12/2009 18:00	42	201	24/12/2009 09:00	54.8
	SM 2	18	07/01/2010 07:00	09/01/2010 06:00	47	105	07/01/2010 21:00	40
	SM 4	19.2	20/02/2010 18:00	22/02/2010 23:00	53	193	21/02/2010 12:00	37.4
	SM 5	7.7	08/03/2010 18:00	10/03/2010 07:00	37	216	09/03/2010 07:00	34
	SM 7	8.2	30/11/2010 01:00	01/12/2010 23:00	46	96.5	30/11/2010 20:00	26.4
	SM 9	7.5	30/11/2012 20:00	02/12/2012 21:00	49	80,8	01/12/2012 12:00	26.5
Ain Loudah	AL 1	19	23/12/2009 10:00	25/12/2009 23:00	61	128	24/12/2009 12:00	40.4
	AL 4	14.6	16/02/2010 08:00	18/02/2010 20:00	60	207	17/02/2010 23:00	37.34
	AL 5	10.4	08/03/2010 18:00	10/03/2010 12:00	42	140	09/03/2010 08:00	32
	AL 7	3.5	29/11/2010 18:00	01/12/2010 22:00	52	75	30/11/2010 21:00	24.8
	AL 8	8.1	30/10/2012 19:00	01/11/2012 12:00	41	99,8	31/10/2012 18:00	29.7
	AL 10	2.1	29/11/2014 21:00	01/12/2014 23:00	50	53,6	30/11/2014 22:00	26.1

pronounced compared to the Aguibat Ezziar sub-basin. The peak flows recorded varied from 400 to 883 m³/s. The small SM Cherif and Ain Loudah sub-basins are marked by modest events, which rarely exceed 200 m³/s with a low base flow (less than 20 m³/s at the start of the events). The variation in the flood extent recorded at the various sub-basins is mainly due to the amounts of precipitation received by these different sub-basins, which depend to the area surface and the climatic context, and its physiographical characteristics namely the land use, the soil types, the altitude, and the slopes. Furthermore, the amount of precipitation having generated event 1, in the Aguibat Ezziar sub-basin, is slightly greater than that relating to event 5. However, the peak flow of the latter is greater than that of the former (event 1). This can be explained, on the one hand, by the variation in

the soil moisture at the start of each event, and by the rain intensity corresponding to the various events, on the other hand. The same explanation can be granted to events 4 and 7 of the Ras Lfathia sub-basin.

Modeling formalism and initial values estimation

The Bouregreg watershed was divided into four sub-basins (Aguibat Ezziar, Ras Lfathia, S.M. Cherif, and Ain Loudah) following the major Bouregreg rivers or tributaries. The basin model in HEC-HMS is set up for each sub-basin using two hydrologic elements: sub-basin and junction. The sub-basin element handles the infiltration loss and rainfall-runoff transformation process. The junction element comprises the observed flow data that is essentially used to compare the observed flow hydrographs with the simulated one. In this study, we opted for a semi-distributed modeling with an hourly time step. HEC-HMS has nine different loss methods, some of which are designed primarily for simulating events, while others are intended for continuous simulation. It also has seven different transformation methods. The Soil Conservation Service Curve Number (SCS CN) has been selected as a loss method. The SCS Unit hydrograph (SCS UH) and the Recession method were chosen as transform model and baseflow respectively. These methods were chosen on the basis of applicability and limitations of each method, availability of data, suitability for the same hydrologic condition, stability, wide acceptability, and well-established researcher recommendations (Tassew *et al.* 2019).

SCS CN loss method

The CN was estimated for the sub-basins, based on the hydrologic soil group and the land cover type. After determining the required soil and land cover characteristics, the CN was estimated for each unit of the sub-basin, followed by area-weighting for the whole sub-basin. The tables used for computation are found in the Technical Release Number 55. The retained CN values are 81, 83, 78, and 77 for Aguibat Ezziar, Ras Lfathia, S.M. Cherif, and Ain Loudah sub-basins respectively.

SCS UH transform method

Once excess precipitations is known, it is converted to direct runoff. In this study, the SCS UH model was chosen to transform excess precipitation into the runoff. The lag time (T_{lag}) is the only input for this method. It is the time from the mass center of excess rainfall to the hydrograph peak, and is calculated for each sub-basin based on the time of concentration T_c , as:

$$T_{lag} = 0.6T_c \quad (1)$$

where T_{lag} and T_c are in minutes. The time of concentration was calculated by the different methods existing in the literature (Almeida *et al.* 2015; Azizian 2018). Thus, the retained value of the T_c corresponds to the average of the convergent values (Table 3).

Table 3 | Representative T_c and T_{lag} for different sub-basin of the Bouregreg watershed

Sub-basin	T_c (min)	T_{lag} (min)
Aguibat Ezziar	515	309
Ras Lfathia	506	304
S.M. Cherif	166	100
Ain Loudah	151	91

Recession

Baseflow is the flow component that returns to the stream from underground storage and aquifers. Basic flow knowledge is important for modeling the hydrograph recession after the peak flow, as well as for estimating the volume of the flood. The recession method uses an exponentially declining baseflow developed from standard baseflow separation techniques. However, given unavailability of information to assign an initial value for the recession constant (R_c) and the threshold (T_d), and their value can be calibrated, a value from literature has been used until calibration of these parameters (Tramblay 2012; Rihane *et al.* 2019). The recession constant R_c is set at 0.5 and the threshold T_d at 0.3. Only the initial baseflow at the beginning of the episode is necessary.

Calibration, validation, and performance evaluation

Before a hydrological model can be considered to have reliable outputs, it needs to be calibrated and validated using observed stream flow. The simulated stream flow must be compared to the observed stream flow to evaluate the goodness of fit and conclude whether the model is able to predict and present credible results. In this work, the model was calibrated using the identified parameters to achieve good fit between the simulated and observed data. The auto-calibration (through optimization trials) tool available in the HEC-HMS model was used for optimizing the estimates of the model parameters. We choose the weighted root mean square error as the objective function in the calibration process, which has the advantage of considering both the magnitude and temporal synchronization of the flood (Moriassi *et al.* 2007).

Validation aims to expose a calibrated model to a real phenomenon different from that used for calibration, in order to assess its response and its ability to reproduce the hydrograph shape properly, especially the peak flow. In this study, the model validation was done by simulating other events for each sub-basin.

The HEC-HMS model performance evaluation involves assessing the goodness of fit in the observed and simulated stream flow using statistical techniques such as:

1. Percentage error in volume (PEV)

$$PEV = \frac{Vol_o - Vol_s}{Vol_o} * 100 \quad (2)$$

where Vol_o and Vol_s are the observed and simulated volumes, respectively.

2. The Percentage error in peak flow (PEPF)

$$PEPF = \frac{Q_{o(peak)} - Q_{s(peak)}}{Q_{o(peak)}} * 100 \quad (3)$$

where $Q_{o(peak)}$ and $Q_{s(peak)}$ are the observed and simulated flows, respectively.

3. The coefficient of correlation (R^2)

$$R^2 = \left[\frac{\sum_{i=1}^n (O_i - \bar{O}) * (S_i - \bar{S})}{\sum_{i=1}^n (O_i - \bar{O})^2 * ((S_i - \bar{S}))^2} \right]^2 \quad (4)$$

where O_i and S_i are the observed and simulated flows at time i , respectively; and \bar{O} , \bar{S} are the average observed and simulated flows during the calibration period, respectively.

4. The index of agreement (d)

$$d = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (|S_i - \bar{S}| + |O_i - \bar{O}|)^2} \quad (5)$$

5. The Nash-Sutcliffe model efficiency (NSE)

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (6)$$

6. The root mean squared error (RMSE) - standard deviation ratio (RSR)

$$RSR = \frac{\sqrt{\sum_{i=1}^n (O_i - S_i)^2}}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2}} \quad (7)$$

Lower values of RSR indicate a lower RMSE normalized by the standard deviation of the observations, which indicates the appropriateness of the model simulation.

To interpret the results, [Tables 4](#) was used as a guide.

Table 4 | General performance ratings for recommended statistics ([Moriassi et al. 2007](#))

Performance Rating	PEV (%)	PEPF (%)	R ² /NSE	d	RSR
Very good	< ± 10	<15	0.75–1.0	0.90–1.0	0.0–0.50
Good	± 10 to ± 15	15–30	0.65–0.75	0.75–0.90	0.50–0.60
Satisfactory	± 15 to ± 25	30–40	0.50–0.65	0.50–0.75	0.60–0.70
Unsatisfactory	> ± 25	>40	<0.50	<0.50	>0.70

Frequency analysis

Frequency analysis is a statistical prediction method consisting of studying the past events to define the probabilities of future appearance ([Meylan et al. 2008](#)). Frequency analysis is used, in particular, to estimate the magnitude of the temporal event associated with a return period. To estimate the probability that a hydro-meteorological event will appear, a series of flows or rainfall over a period of observation must be available. Then, the observed series must be sampled to select the maximum values. Subsequently, this analysis consists of looking for the probability law that best fits our data series after comparing different probability laws and the estimation methods using adequacy tests.

Since the simulations will be done at an hourly time step, the creation of a synthetic hourly hyetograph from the daily rainfall is unavoidable. There are several methods that allow the disaggregation of the daily rainfall to the hourly one ([Arnaud & Lavabre 2000](#); [Mendoza-Resendiz et al. 2013](#); [Kossieris et al. 2016](#)). The approach adopted in this study has been demonstrated and validated in several basins in Morocco ([Hasnaoui et al. 2015](#); [Bennani-Baiti et al. 2017](#); [Elhassnaoui et al. 2019](#)). It consists of creating the maximum annual data over time steps of 1–10 days. Values for return periods of 2–100 years are determined by the Gumbel distribution. Then for each of the return periods, the parameters of Montana are established to obtain IDF curves that allow the calculation of the critical intensity of rainfall according to its duration and its return period using the following equation:

$$I(t, T) = a(T)t^{-b(T)} \quad \text{for } t > 24 \text{ h} \quad (8)$$

where $I(t, T)$ indicates the intensity of the rainfall over time t (min) and return period T (years), $a(T)$ and $b(T)$ the parameters of Montana, t the duration of the rainfall (min) and T the return period (years).

To apply this equation for $t < 24$ hours, it has been necessary to compare the Montana parameters calculated by the approach described above with those obtained from the short-term observed data. This comparison made it possible to calculate the error order and verify the reliability of the chosen approach. Montana parameters thus corrected were used to establish the synthetic hyetograph of the daily rainfall corresponding to each return period. Indeed, this process was established using the Chicago method (proposed by [Keifer & Chu 1957](#)), which uses IDF curves and the equations derived from them. The proposed hyetograph is adjusted from two exponential curves, one before and the other after the rainfall point (for more details, see [Lopes-da-Silveira \(2016\)](#) and [Elhassnaoui et al. \(2019\)](#)).

Sensitivity analysis

Sensitivity analysis (SA), the most important component of hydrologic modeling, helps to simplify the complexities and understand the physical processes of complex hydrologic systems in a comprehensive way. The principal aim of SA is to assess the variability of response surface with respect to significant changes in input factors and to prioritize these factors by finding the non-influential factors. This would simplify the complexity of the model either by omitting a few trivial input parameters or by assigning a constant value to them (Devak & Dhanya 2017). Various SA methods exist, which differ in terms of mathematical approaches, assumptions, availability, cost of application, and applicability. The employment of any SA approach depends on the field of application and the definition.

The selected method consists in running the model with the optimized model parameters obtained after calibration and validation. Next, one parameter at a time method was applied: the value of each parameter was varied from -30% to $+30\%$ in increments of 10% , keeping all other parameters constant. The output values (simulated volume, peaks, and NSE) were analyzed to determine variation with respect to the initial estimates of the parameters. The elasticity ratio (e) (Walega *et al.* 2014) was used to rank the parameters in descending order from most to the least sensitive. Also called the relative sensitivity, e expresses the relative change in the dependent variable with respect to the independent variable. The elasticity ratio is invariant to the dimensions of the variables and is given by the following formula as proposed by (McCuen 2003):

$$e = \frac{\Delta O/O}{\Delta I/I} = \frac{\% \text{change}_{\text{output}}}{\% \text{change}_{\text{input}}}$$

where O and I are the output and the input variables, respectively. A greater elasticity ratio indicates a more highly sensitive variable.

RESULTS AND DISCUSSION

The elaborated hydrological model results showed a reasonable fit between the simulated and observed flow after optimization; the hydrograph shape and timing of peaks matched well, although the model tended to underestimate the peak flow and slightly overestimate the volumes in the majority of events for the overall sub-basins (Figure 2).

During calibration, four parameters have been optimized: T_{lag} , CN , R_c , and T_d . For the overall sub-basins, the T_{lag} mean value was increased while the other parameters mean values were decreased. We note that the R_c values for the Ain Loudah sub-basin were slightly increased after the optimization process (Table 5).

Figure 2 show that the selected events, for the calibration, are marked by an acute peak, materialized by a sub-vertical rising limb corresponding to a very short rising time and generally a short falling time as well. This can be explained by the significant slope characterizing the studied basin as well as the intensity of the rains that generated these floods. We also note the existence of some events with two peaks (RE 3 & SM1), which can be reflected by the occurrence of two successive rainfall episodes. In addition, the importance of the flood's events in term of peak and volume depends on the extent of each sub-basin, as indicated previously.

Model performance evaluation was conducted for each event. The time series of simulated and observed flows from the results of the simulation run in the HEC-HMS model were analyzed in Microsoft Excel to compute the statistics used for performance evaluation. Table 6 and Figure 3 show the performance evaluation results during the calibration for the different studied sub-basins. According to the simulation's results for the Aguiat Ezziar sub-basin, and based on the mean values of PEV, PEPF, R^2 , d , NSE, and RSR calculated, the model performance is evaluated as good to very good. Indeed, the PEV ranges from -15.96 to -11.89 , the PEPF ranges from 9.03 to 28.39 depending on the different events, the NSE and the R^2 ranges from 0.71 to 0.87 , which indicate a good model performance. As for the Ras El Fathia sub-basin, the performance rating of the PEV and PEPF criteria was improved. However, the NSE and R^2 criteria, for which the mean values are 0.71 and 0.74 , respectively, are slightly decreased compared with the first sub-basin. Nevertheless, the performance evaluation is still good. As for the S. M. Cherif and Ain Loudah sub-basins, we can judge that the simulated hydrologic response is similar for those sub-basins. This is justified by the common physiographic characteristics and the climatic context, as well as the chosen modeling formalism, which is almost identical for the two basins. the mean values of PEV, PEPF, R^2 , d , NSE, and RSR were found to be -1.32% , 11.21% , 0.67 , 0.89 , 0.64 and 0.61 , respectively for S. M. Cherif, and -2.55% , 12.68% , 0.80 , 0.93 , 0.72 , and 0.49 , respectively, for Ain Loudah. The model

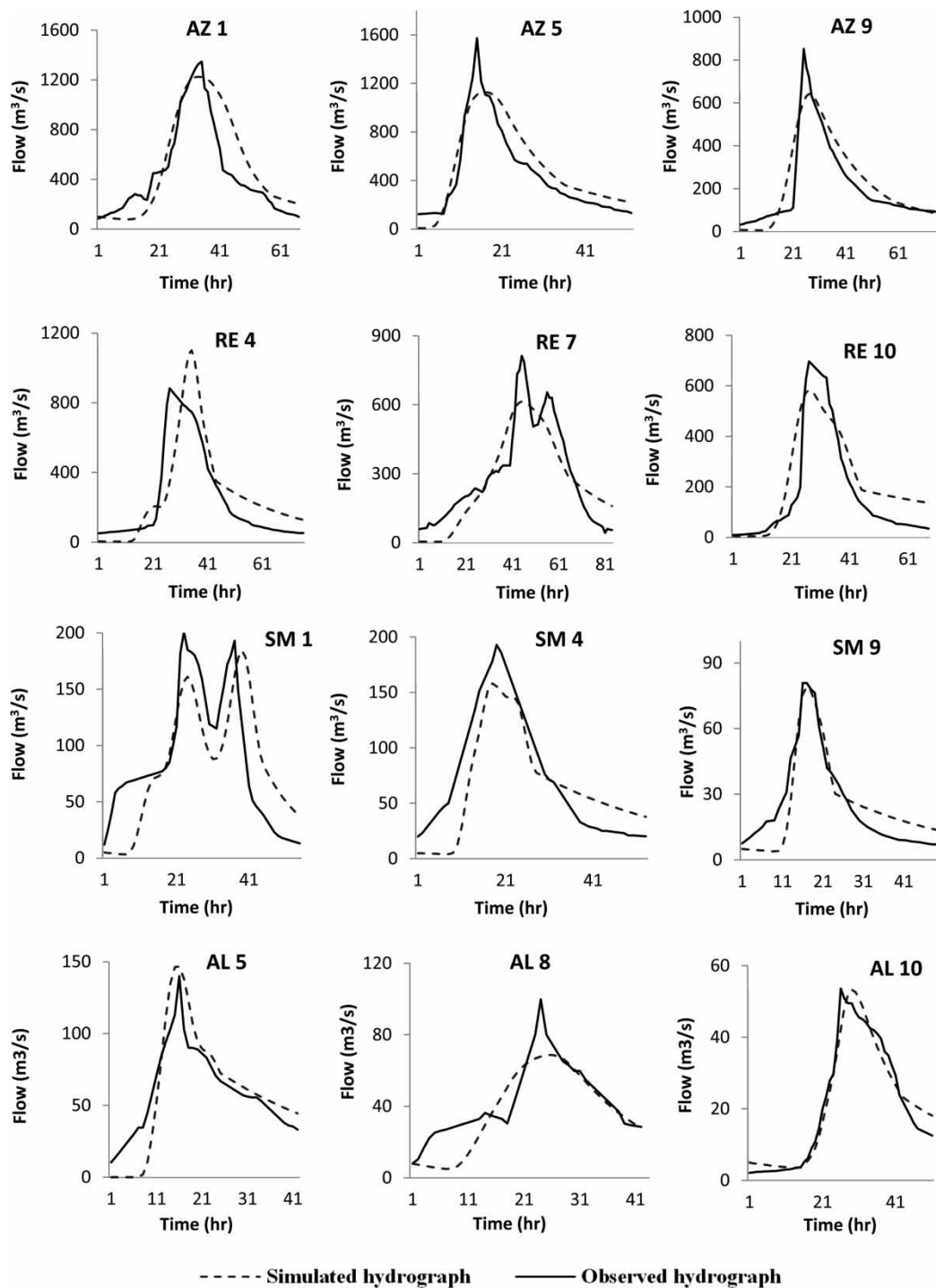


Figure 2 | Samples of the simulated and observed hydrographs for the Bouregreg basin during calibration.

performances are also good to very good. We note that the NSE and R^2 for the event SM 1 was unsatisfactory. This was due to the limited capability of the model to simulate an event with two peaks. Nevertheless, the mean values reflect a good fit between the simulated and observed flow.

After having successfully calibrated the model, four or five different events were selected to validate the model, considering the mean of the optimized parameters as shown in Table 5. In general, the performance of the model in validation is slightly degraded compared to the calibration performance. The results nevertheless remain satisfactory. Figures 4 and 5 showed the simulated and observed hydrographs and their correlation respectively.

The result showed that the simulated values are close to the observed ones for all the events. This was confirmed by the performance criteria evaluation as shown in Table 7. Indeed, the mean values, for the Aguibat

Table 5 | Optimized model parameters for the various events used in calibration

Sub-basins	Events	T _{lag}	CN	R _c	Td
Aguibat Ezziar	AZ 1	467.74	70.80	0.47	0.28
	AZ 2	382.20	80.36	0.40	0.21
	AZ 5	313.34	75.35	0.41	0.27
	AZ 9	440.00	64.80	0.45	0.28
	Mean	400.8	72.8	0.43	0.26
	Median	411.1	73.1	0.43	0.28
Ras El Fathia	RE 3	512	78	0.31	0.18
	RE 4	354	75.8	0.47	0.28
	RE 6	420	79.5	0.42	0.18
	RE 7	356	82	0.52	0.33
	RE 10	301	83	0.46	0.25
	Mean	388.6	79.7	0.44	0.24
S. M. Cherif	SM 1	120.32	71.12	0.38	0.32
	SM 3	145.26	66.98	0.44	0.35
	SM 4	109.36	72.39	0.5	0.32
	SM 8	132.8	77.31	0.52	0.37
	SM 9	92.3	75.9	0.43	0.25
	Mean	120.0	72.7	0.45	0.32
Ain Loudah	AL 2	93.36	72.3	0.63	0.21
	AL 5	123.2	78.64	0.51	0.36
	AL 6	85.69	79.35	0.62	0.29
	AL 8	106.25	75.7	0.52	0.3
	AL 10	134.3	78.6	0.59	0.31
	Mean	108.6	76.9	0.57	0.29
	Median	106.3	78.6	0.59	0.30

Table 6 | Performance evaluation of the developed event-based model during calibration

Sub-basins	Events	PEV	PEPF	R ²	d	NSE	RSR
Aguibat Ezziar	AZ 1	-15.96	9.03	0.81	0.93	0.78	0.54
	AZ 2	-12.7	16.82	0.71	0.88	0.68	0.58
	AZ 5	-14.3	28.39	0.87	0.96	0.84	0.4
	AZ 9	-11.89	24.58	0.85	0.96	0.83	0.41
	Mean	-13.71	19.71	0.81	0.93	0.78	0.48
	Median	-13.5	20.7	0.83	0.95	0.805	0.48
Ras El Fathia	RE 3	-10.58	15.42	0.69	0.91	0.65	0.6
	RE 4	-14.89	-24.7	0.68	0.9	0.62	0.62
	RE 6	-8.56	18.36	0.71	0.91	0.72	0.52
	RE 7	6.41	24.42	0.8	0.94	0.79	0.46
	RE 10	-25.8	16.33	0.82	0.93	0.77	0.48
	Mean	-10.68	9.97	0.74	0.92	0.71	0.54
S. M. Cherif	SM 1	4.93	8.31	0.49	0.83	0.42	0.76
	SM 3	-12.52	15.39	0.61	0.86	0.58	0.7
	SM 4	10.87	18.03	0.75	0.92	0.73	0.52
	SM 8	-8.36	12.33	0.69	0.89	0.67	0.62
	SM 9	-1.52	1.98	0.82	0.95	0.82	0.43
	Mean	-1.32	11.21	0.67	0.89	0.64	0.61
Ain Loudah	AL 2	-4.92	24.22	0.71	0.91	0.7	0.5
	AL 5	-2.37	-4.79	0.88	0.93	0.61	0.62
	AL 6	-14.62	12.35	0.72	0.91	0.71	0.5
	AL 8	11.55	31.06	0.76	0.92	0.64	0.6
	AL 10	-2.41	0.56	0.95	0.99	0.96	0.21
	Mean	-2.55	12.68	0.80	0.93	0.72	0.49
	Median	-2.41	12.35	0.76	0.92	0.7	0.5
Mean		-7.07	13.39	0.76	0.92	0.72	0.53
Median		-6.50	14.34	0.74	0.92	0.71	0.51

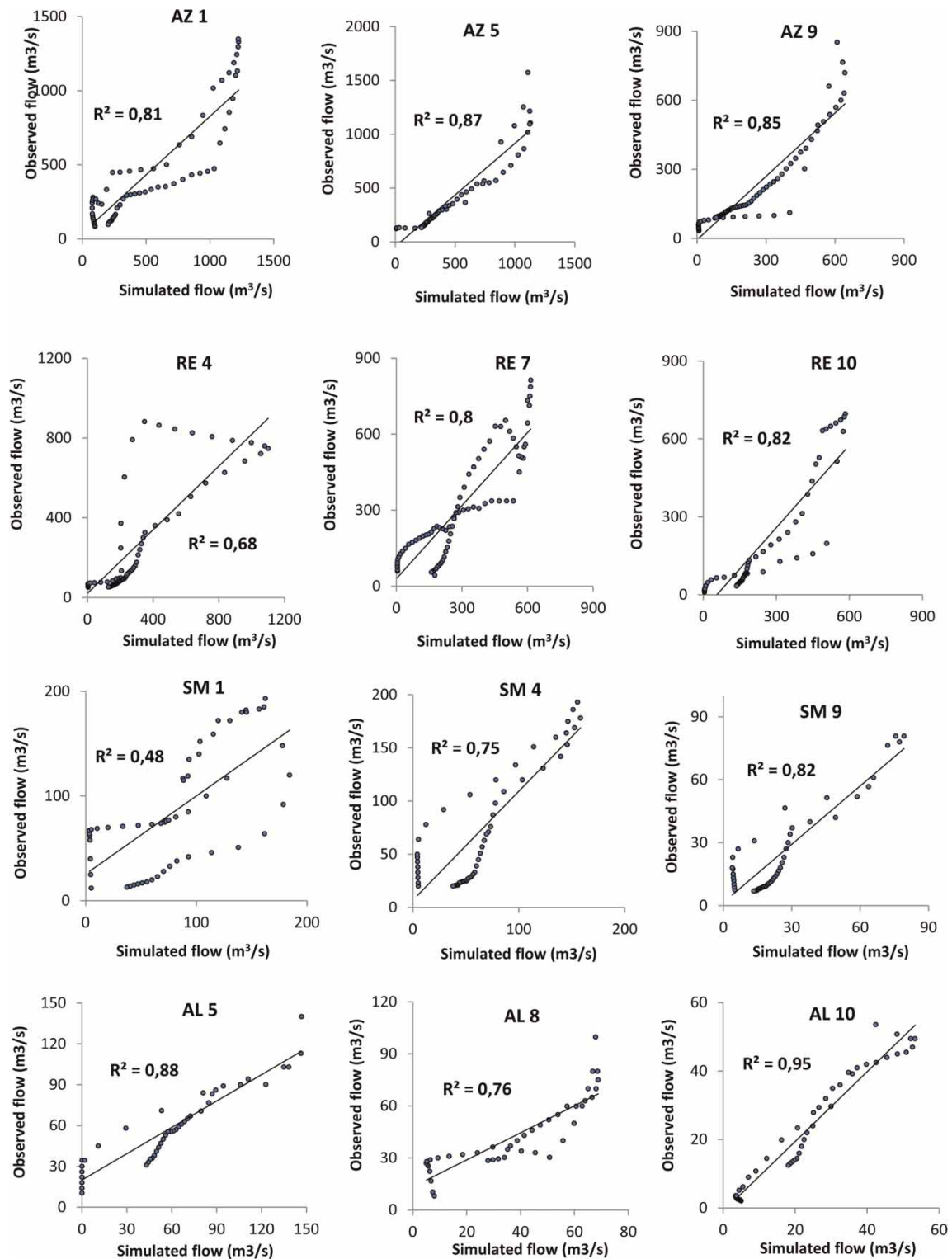


Figure 3 | Correlation between observed and simulated flow during calibration.

Ezziaz sub-basin, of PEV, PEPF, R^2 , d, NSE, and RSR were found to be -15.36% , 30.46% , 0.64 , 0.86 , 0.61 , and 0.62 , respectively. The performance rating is generally satisfactory to good. Similarly for the Ras El Fathia sub-basin, the performance evaluation results are also satisfactory to good, except the events RE2 and RE9, for which the PEV and NSE evaluation is unsatisfactory. Concerning the S. M. Cherif and Ain Loudah sub-basins, the PEV is evaluated as very good and the performance rating of the other criteria is good in general.

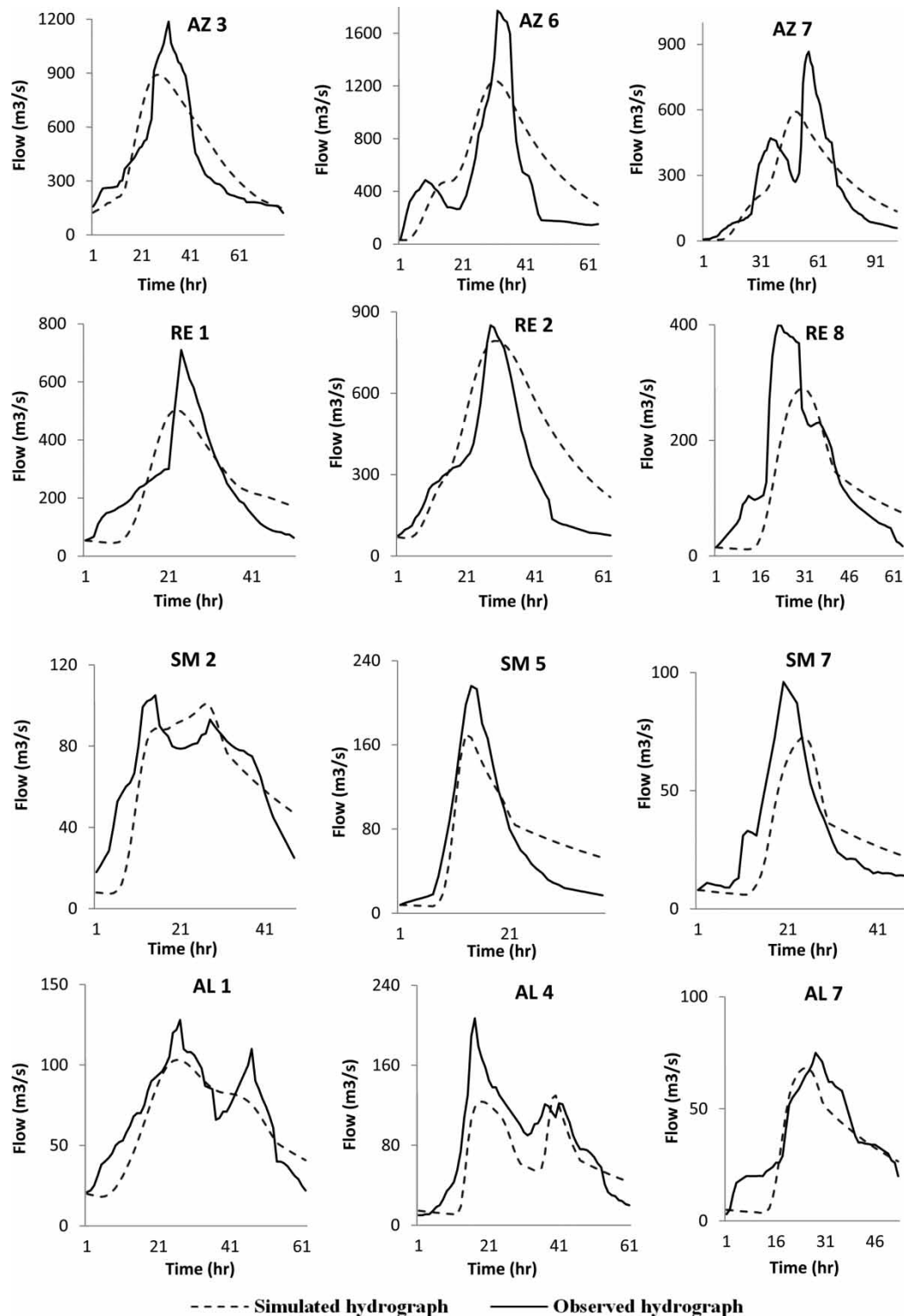


Figure 4 | Samples of the simulated and observed hydrographs for the Bouregreg basin during validation.

This can be explained by the small area surface of those sub-basins comparing to the Aguiat Ezziar and Ras El Fathia sub-basins.

Frequency analysis of the daily maximum rainfall annual series was carried out using the data from the rainfall stations inside the studied basin. Statistical adjustment of the data was made by applying the five laws, usually used in frequency analysis of maximum daily rainfall, namely the generalized extreme value (GEV), Gumbel, normal law, lognormal with three parameters, and the Pearson Type III (according to [Habibi et al. 2013](#)).

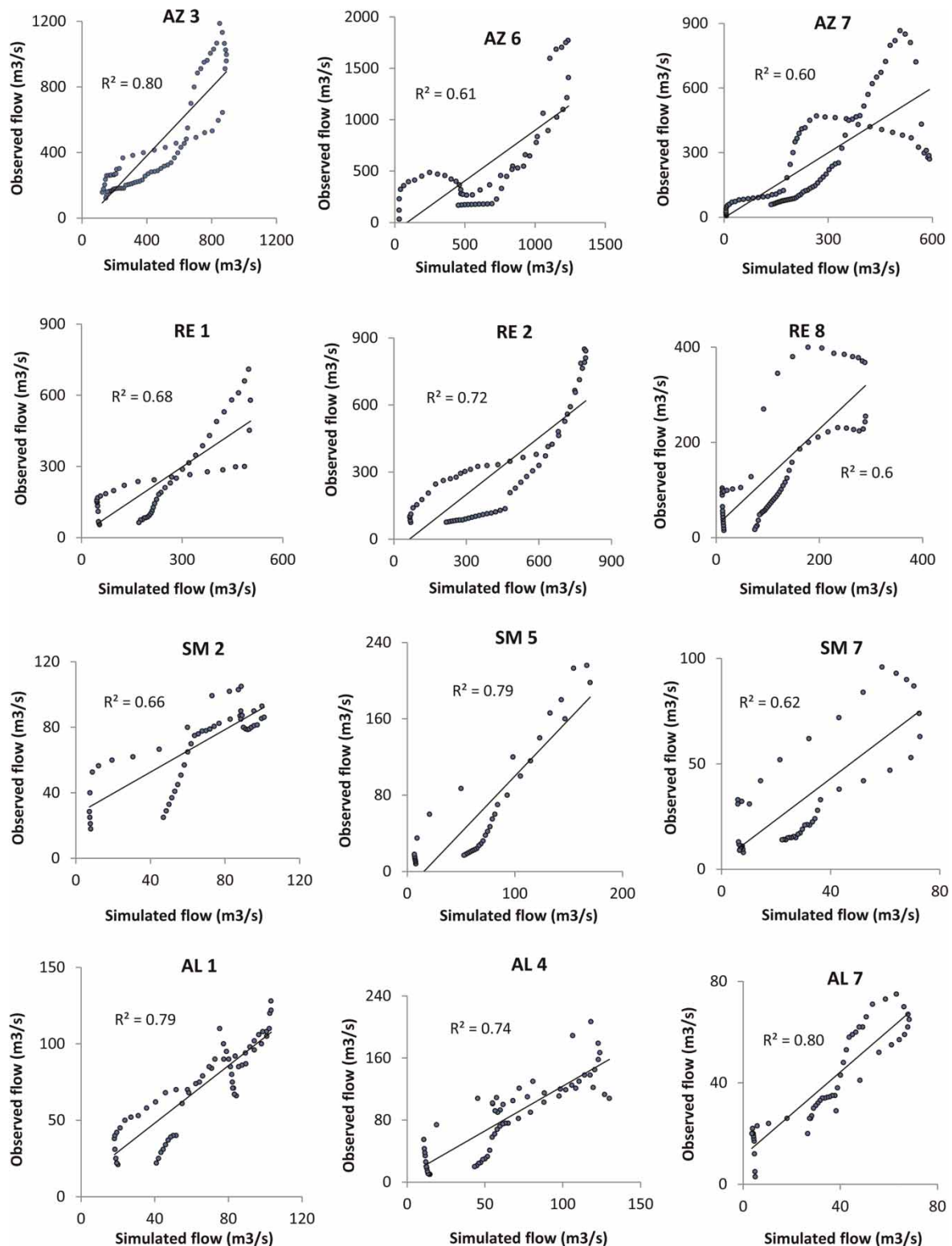


Figure 5 | Correlation between observed and simulated flow during validation.

Applying the homogeneity, stationarity, and independence tests, Gumbel's law showed a good adjustment to the maximum daily rainfall series of the SMBA dam watershed.

After having computing the frequency rainfall from the various stations for the studied basin (Table 8), we have established the representative synthetic hourly hyetograph of each sub-basin for different return period. The rainfall-runoff simulations have been carried out on the basis of the already elaborated event-based hydrological

models. The results show the extent of the floods received by the SMBA dam (Table 9 and Figure 6). Indeed, the peak flow rises from 1,092 m³/s for the return period T2 to 6,097 m³/s for T100. The volumes are also important, they vary between 80 and 438.5 Mm³, according to the return periods.

Table 7 | Performance evaluation of the developed event-based model during validation

Sub-basins	Events	PEV	PEPF	R ²	d	NSE	RSR
Aguibat Ezziar	AZ 3	-4.21	24.89	0.79	0.94	0.79	0.46
	AZ 4	-25.63	28.3	0.58	0.81	0.52	0.7
	AZ 6	-22.26	30.09	0.61	0.84	0.56	0.67
	AZ 7	-0.38	31.66	0.60	0.86	0.60	0.63
	AZ 8	-24.32	37.36	0.61	0.84	0.57	0.67
	Mean	-15.36	30.46	0.64	0.86	0.61	0.62
	Median	-22.26	30.09	0.61	0.84	0.57	0.67
Ras El Fathia	RE 1	0.27	29.06	0.68	0.90	0.68	0.57
	RE 2	-38.76	6.68	0.72	0.85	0.43	0.75
	RE 5	-26.32	18.71	0.63	0.87	0.6	0.62
	RE 8	17.83	27.68	0.60	0.84	0.55	0.67
	RE 9	-30.68	15.32	0.54	0.82	0.52	0.71
	Mean	-15.53	19.49	0.63	0.85	0.55	0.67
	Median	-26.32	18.71	0.63	0.85	0.55	0.67
S. M. Cherif	SM 2	6.33	3.81	0.66	0.88	0.44	0.75
	SM 5	-7.74	21.34	0.79	0.92	0.77	0.48
	SM 6	-12.65	28.52	0.58	0.85	0.57	0.67
	SM7	9.81	24.27	0.62	0.87	0.61	0.63
	Mean	-1.06	19.49	0.66	0.88	0.59	0.63
	Median	-0.71	22.81	0.64	0.87	0.59	0.65
Ain Loudah	AL 1	9.48	19.38	0.79	0.93	0.73	0.52
	AL 3	-11.63	17.38	0.71	0.83	0.68	0.55
	AL 4	22.04	37.25	0.74	0.86	0.59	0.64
	AL 7	14.12	8.80	0.84	0.94	0.72	0.53
	AL 9	-5.63	28.32	0.68	0.82	0.65	0.56
	Mean	5.67	22.22	0.75	0.87	0.68	0.56
	Median	9.48	19.38	0.74	0.86	0.68	0.55
Mean		-6.57	22.91	0.67	0.87	0.61	0.62
Median		-11.49	21.09	0.64	0.85	0.58	0.66

Table 8 | Rainfall depth corresponding to different return periods

Sub-basins	Return periods (T)					
	100	50	20	10	5	2
Aguibat Ezziar	73.3	67.7	60	53.8	47	36
Ras Elfathia	64.2	58.5	50.9	45	38.8	29.3
S. M. Cherif	68.3	62.1	53.9	47.4	40.7	30.4
Ain Loudah	66.4	60.8	53.3	47.4	41.1	31.2
Intermediate	59.8	55.2	48.9	43.9	38.4	29.7

Table 9 | Peak flow and total volume of the frequency floods in the studied basin

Studied basins	T100		T50		T20		T10		T5		T2	
	P	V	P	V	P	V	P	V	P	V	P	V
SMBA dam	6.097	438.5	5.053	364.6	3.871	277.6	3.056	219.5	2.233	161	1.092	80

P. Peak flow. V. Total volume.

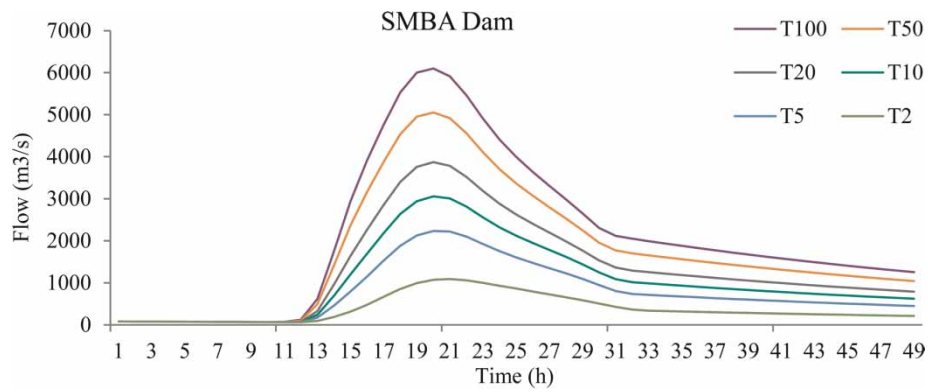


Figure 6 | Frequency flood hydrographs of the SMBA dam watershed.

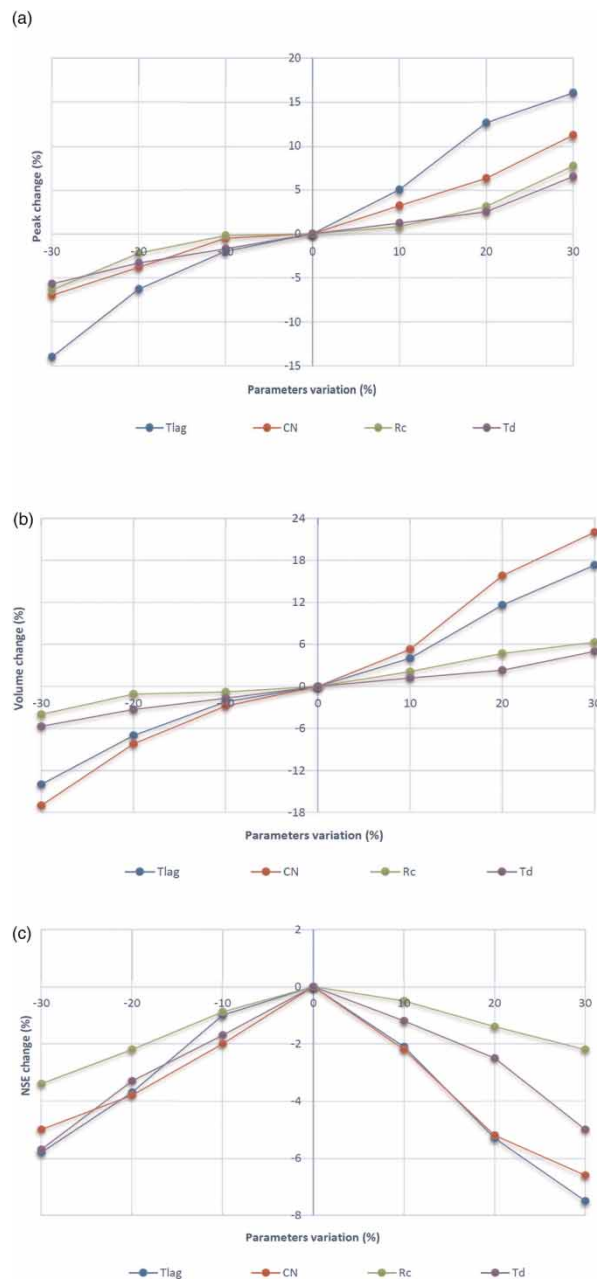


Figure 7 | Percentage changes in simulated peak (a), volume (b), and NSE (c) plotted against the percentage variation of each parameter.

Sensitivity analysis was carried out in order to determine the sensitivity of the error in volume, the computed peak, and the NSE criterion to the model parameters, namely T_{lag} , CN, R_c , and the T_d (Figure 7). The runoff volume was found to be more sensitive to and CN, respectively. While the peak flow was found to be more sensitive to CN and T_{lag} , respectively. At the same time, the NSE was found to be more sensitive to T_{lag} and CN. (Table 10). R_c and T_d were found to be the least sensitive parameters.

Table 10 | The model parameters sensitivity ranking for volume, peak, and NSE

Parameters	Volume	Peak	NSE
T_{lag}	0.43	0.44	0.17
CN	0.55	0.25	0.17
R_c	0.15	0.14	0.14
T_d	0.15	0.16	0.16

CONCLUSION

Flood forecasting has become a priority task, especially in a global context influenced by climate change. Knowledge of the extent of the floods is very needed for dam management. Understanding the rainfall-runoff mechanism in a given dam watershed allows improving the management of this reservoir and protecting the downstream against floods.

This paper presents a flood modeling application in the SMBA dam watershed, using the HEC-HMS modeling platform. The event-based models that have been developed make it possible to reproduce, with a reduced number of parameters, the floods in the four main Bouregreg sub-basins and the hydrographs of the frequency of floods entering the SMBA dam. The results show that it is possible to estimate the volumes of water generated during floods satisfactorily with errors of the order of 6–11%, while the error in peak flow is around 20%. The median NSE during validation is 0.58% and the R^2 is about 0.67. Sensitivity analysis shows that the runoff volume, the peak flow, and the NSE were found to be more sensitive to T_{lag} and CN parameters, while the R_c and T_d were found to be the least sensitive parameters.

The model could thus operate in real time, fed by data from the stations transmitted to the concentrator station. Such a tool would make it possible to anticipate the hydrological response of the basin during precipitation, with an anticipation time of the order of 10–12 hours, after a rainy episode. Thus, the management of the dam would be improved, making it possible both to maximize the filling of the reservoir and to minimize the risks of spills and flooding downstream.

This hydrological modeling could also be supplemented by hydraulic modeling downstream of the dam to develop floodplain scenarios for different volumes of releases at the SMBA dam.

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DECLARATION OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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