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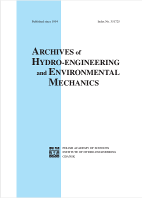

Extreme Rainfall-Runoff Events Modeling Using HEC-HMS Model for Oued El Hachem Watershed, Northern Algeria

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Abstract. Flood forecasting has become necessary for dam management during extreme hydrological events. The lack of streamflow data in ungauged watersheds of arid and semi-arid regions makes the assessment of water resources difficult. In this paper, the Hydrologic Modeling System developed by the Hydrologic Engineering Center (HEC-HMS) was applied to the Oued El Hachem watershed. Calibration and validation of the model have been performed, taking into account the lag time and the curve number CN that is expressed as a function of soil group, land use and antecedent runoff condition. The model was evaluated on the basis of the coefficient of determination, the Nash Sutcliffe Efficiency (NSE), and the percentage differences between peak and volume. Performance indices of calibration showed a good agreements between observed and computed flows. The validation of the model has given satisfactory results. The calibrated model can be used to manage the dam of Boukerdane during extreme rainfall events by forecasting the induced hydrographs from which adequate procedures will be operated in order to ensure the safety of the dam against possible overtopping.

Key words: Dam safety; HEC-HMS model; hydrologic modeling; model calibration; rainfall-runoff; arid region

1. Introduction

The flow regime of watersheds located in arid and semi-arid regions has been strongly disturbed because of climate change, which has recorded a non-regularity of precipitation and a remarkable increase in extreme events over the years. Flood risk management in the gauged watersheds requires the use of hydrological models to forecast the flood hydrographs that are characterized by the peak flow, time to peak and decreasing time. Calibration and validation of the model consists of minimizing the fit between computed and observed hydrographs. Flow control stations, when they exist in the gauging watershed, give data about streamflow during the same time of precipitation event. The rating curve could be useful for model calibration and validation.

However, the ungauged watershed does not contain stations for flow control, which made the calibration of the models difficult. To fill the gap in data, several methods were developed throughout the world in order to explain the particular relationship between loss and excess of precipitation. During special warnings of extreme storms, deciders do not have the tools to use in order to make a decision and prepare the dam for the forecasted flood volume. Then it would be a crucial decision to make about the opening of the bottom gates in order to avoid the overtopping of the dam.

The HEC-HMS model is a computer program developed by the hydrologic engineering center (HEC) of the US Army Corps of Engineers. It includes several methods for simulating the behavior of watersheds, channels, and water control. It permits the forecasting of flow, stage, and timing for natural and controlled rainfall-runoff and routing processes (HEC 2000).

Modeling of the rainfall-runoff process using the HEC-HMS program is generally performed throughout models that compute runoff volume, direct runoff, and channel flow. Runoff volume models consider, as input data, the volume of precipitation falling on the watershed and the infiltration rate. Then, the computed results will be the resultant runoff volume and time of runoff beginning. The direct runoff models give information about the excess of water that has not infiltrated or been stored in the watershed. They are based, in the first step, on the curve number loss method to estimate the excess of precipitation as a function of cumulative precipitation, soil group, land use, and antecedent moisture. In the second step, the transformation of precipitation excess into direct runoff is performed using a parametric unit hydrograph model (HEC 2000). The propagation of the flood along the mainstreams is calculated using flow channel models, such as the Muskingum-Cunge model (Miller and Cunge 1975). This model employs the basic channel flow equations, which require initial and boundary conditions to compute the resulting hydrograph (HEC 2013).

Several case studies have been documented throughout the world using the HEC-HMS program to model and simulate the watershed behavior towards precipitation events (Halwatura and Najim 2013). The integrated tools of lumped and distributed models make them useful for modeling the hydrologic processes of dendritic watershed systems. Its simplicity and capability of using common methods make it widely used to simulate the rainfall-runoff process over large watersheds (Hamdan et al 2021). Demlie et al (2018) and Hussain et al (2021) used the HEC-HMS model for flow simulation in ungauged watersheds where the performance of the model to reproduce the observed hydrographs was evaluated using the coefficient of determination and the Nash Sutcliffe Efficiency (NSE). The applicability of HEC-HMS for flash floods was positively tested by Zhuohang et al (2019) for intense rainfalls in fourteen typical small catchments in hilly areas across China. Gopi and Rema (2021) used the percentage error in peak, percentage error in volume, and net difference of observed and simulated time to peak for evaluating the HEC-HMS performances in the Chalakduy river basin that is situated in India.

The purpose of this paper is to apply the HEC-HMS model to the Oued El Hachem watershed using its components of the loss and transform methods for computing, in the first step, the direct runoff over the watershed. The flow channel components were used to calculate the flood propagation along the mainstreams. The model was calibrated and validated over the entire watershed in order to calculate the resultant hydrographs of possible extreme rainfall events.

2. Material and Method

2.1. Study Area

The Oued El Hachem watershed is located in Tipaza province in the northern part of Algeria (Fig. 1). It extends over 160 km^2 of surface and 63 km of perimeter. It is drained by two mainstreams of lengths 24 and 12 km. The watershed elevations oscillate from 78 to 1417 m. It is limited by UTM geographical coordinates (X1 = 421889, Y1 = 4029996; X2 = 440 814, Y2 = 4045196).

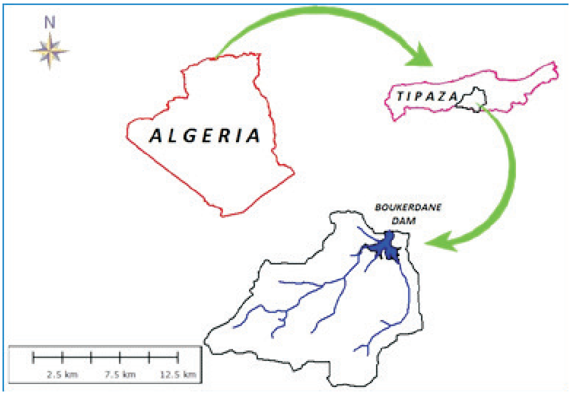

Fig. 1. Situation of Oued El Hachem watershed

2.2. Characteristics of Boukerdane Dam

Boukerdane dam is an embankment dam. It was built at the downstream of Oued El Hachem watershed. With 74.5 m of height, its storage capacity is about 123 million m^3. Fig. 2 shows an aerial view of the dam.

2.3. Land Use

Clear forest represents 58% of the global surface of the Oued El Hachem watershed (Fig. 3). Cereal cultivation, which is not irrigated, is about 15% and 5% for irrigated cultivation.

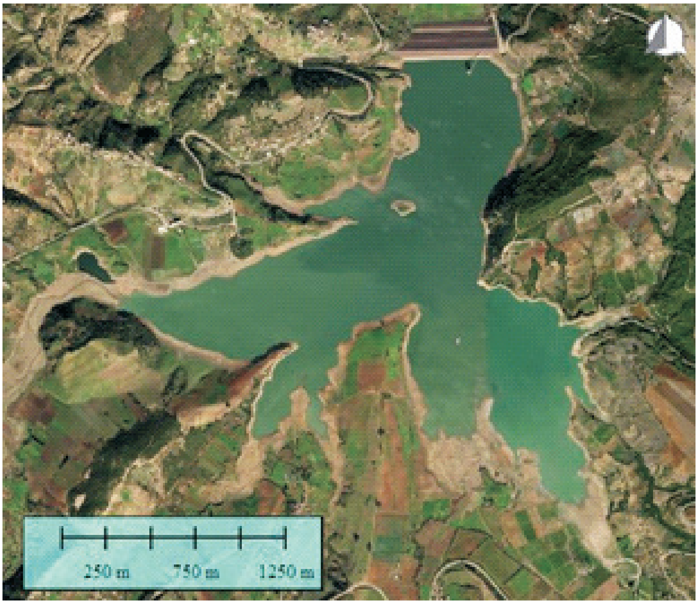

Fig. 2. Boukerdane Dam (Google Earth by author)

2.4. Basin Model for Oued El Hachem Watershed

In order to describe physically the watershed properties and the topology of the stream network (HEC 2013), I have created the basin model for the Oued El Hachem wa-

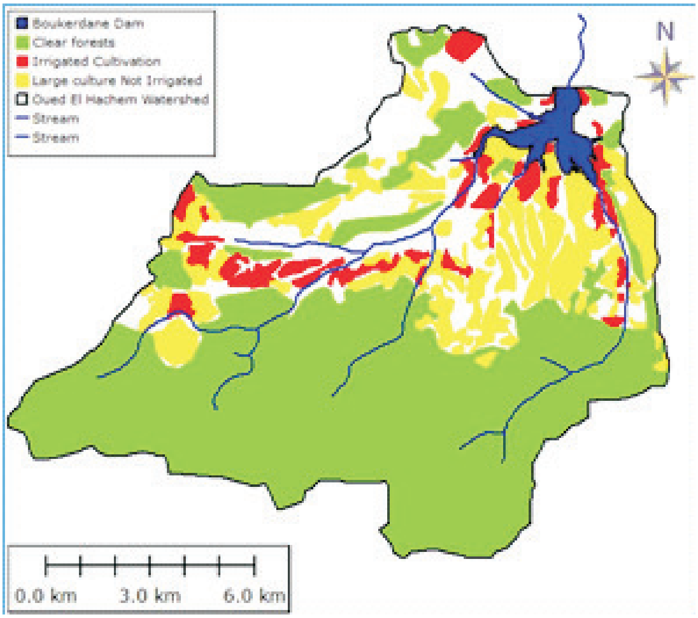

Fig. 3. Land use of Oued El Hachem watershed. Adapted by the author from Bneder (2011)

tershed (Fig. 4). It contains the modeling components, such as subbasins, junctions, and reaches. In fact, the watershed was sub-divided into 18 subbasins to effectively represent the rainfall-runoff process.

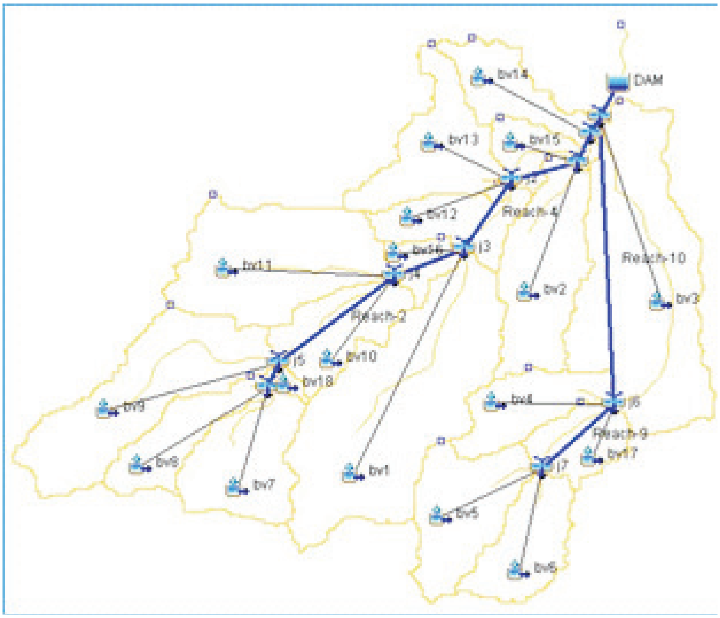

Fig. 4. Basin model for Oued El Hachem watershed

2.5. HEC-HMS Model Parameters

The precipitation loss was estimated by using the curve number CN, which is a function of land use, soil type, and antecedent watershed moisture. Values of CN that consider the soil type and land use for semi-arid rangelands were published by the soil conservation service SCS (HEC 2000). The transformation of excess rainfall into direct runoff was calculated by using the SCS parametric unit hydrograph (HEC 2013). The SCS expresses the lag time t_{lag} as a function of concentration time t_c for ungauged watersheds as follows (HEC 2013):

$$t_{lag} = 0.6 t_c. \tag{1}$$

Time of concentration was calculated by the Giandotti formula, which is expressed as (Giandotti 1934):

$$t_c = \frac{4\sqrt{A} + 1.5L}{0.8\sqrt{H_{med} - H_{\min}}}, \tag{2}$$

where t_c represents the time of concentration [min], A represents the subbasin surface [km^2], L represents the mainstream length [km], H_{med} represents the medium elevation [m], and $H_{\min}$ represents the minimum elevation [m]. Table 1 shows the concentration and lag times for all subbasins.

Table 1. Times of concentration and lag times

Nr Subbasin	Surface [km^2]	Time of concentration [min]	Lag time [min]
1	24.36	167.4	101
2	10.8	314.4	189
3	23.56	296.4	178
4	5.75	254.4	153
5	8.7	147.6	88
6	6.26	112.2	67
7	8.31	103.8	62
8	5.31	141.6	85
9	14.38	158.4	95
10	6.43	169.2	102
11	14.44	226.8	136
12	5.55	243	144
13	8.26	316.2	190
14	5.77	163.2	60
15	2.79	79.2	47
16	2.23	163.2	98
17	4.23	132	79
18	0.63	68.4	41

The Muskingum-Cunge routing model (HEC 2000, Miller and Cunge 1975) was used to calculate the channel flow along the mainstreams, considering as assumptions a trapezoidal natural channel and a constant Manning's roughness coefficient with an average value for the whole reach equal to 0.035.

2.6. Initial and Boundary Conditions

Direct runoff models require precipitation data as boundary conditions for each subbasin. The resultant runoff at the upstream of the channel will be used as a boundary condition for routing models. It is assumed that there is no initial flow along the mainstreams before beginning the simulation.

2.7. Meteorological Model

Precipitation and flow data over the period of 1995 to 2018 (ANBT 2021) were used to apply the HEC-HMS model to the Oued El Hachem watershed. Ten floods (Fig. 5) that are considered the largest were selected to calibrate and validate the model. Table 2 shows the characteristics of these meteorological events.

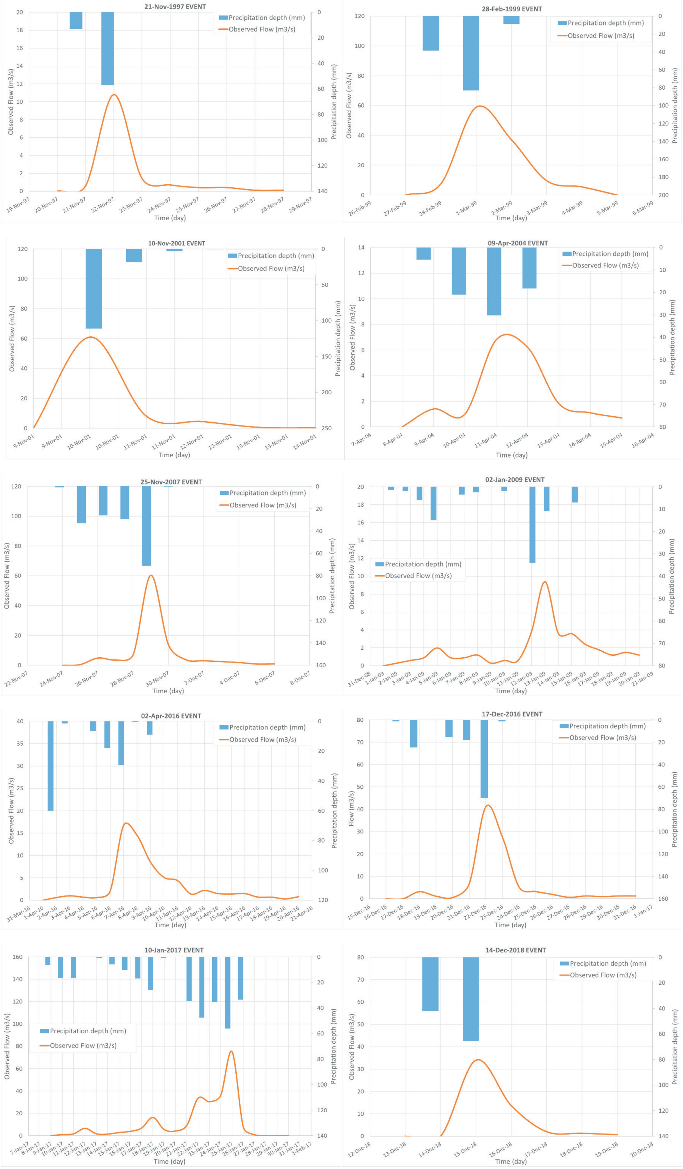

Fig. 5. Hydrological events for model calibration and validation

Table 2. Data of main storms

Time of event	Precipitation depth [mm]	Observed Volume [m^3]	Observed Peak Flow [m^3/s]
21-Nov-97	70	1 239	10.8
28-Feb-99	130	12 326	58.9
10-Nov-01	133	6 442	61
09-Apr-04	75	2 139	6.8
25-Nov-07	160	9 376	60.3
02-Jan-09	84.5	3 149	9.4
02-Apr-16	125	5 551	16.7
17-Dec-16	132	8 280	41.19
10-Jan-17	308	21 750	75.3
14-Dec-18	108	4 654	34

3. Results and Discussion

3.1. Calibration

In order to calibrate the model on the Oued El Hachem watershed, the precipitation depths of the events: 17-Dec-2016, 25-Nov-2007, 21-Nov-1997 and 14-Dec-2018 were used as input data for the model.

The event combinations for the calibration step require the following criteria: There was almost no rainfall activity before these events; the base flow level was at its minimum. The classical shape of the observed hydrographs makes these events excellent for calibration. The peak flows of these events are noticeable; they range from 10.8 m^3/s to 60.30 m^3/s. The size of the selected events for calibration agrees approximately with the size of the events that the calibrated model will be intended to analyze. The values of performance indices such as the percentage differences between volume and peak flow, coefficient of determination R^2, and Nash-Sutcliffe efficiency NSE. Finally, the volume of the runoff hydrograph is approximately equal to the volume of the rainfall hyetograph.

In fact, several attempts were made in order to find the best combination that provides a good accordance between observed and simulated hydrographs with unique parameters of calibration (Tab. 3), the curve number CN for the loss method, and lag time for the transform method. These parameters were varied and adjusted manually until satisfying the match between observed and computed hydrographs (Fig. 6). The ability of the model to reproduce the observed flow was evaluated by using the performance indices of calibration (Tab. 4). The percentage difference of volume (Eq. 3) and peak flow (Eq. 4) ranges respectively from ±4.26% to ±21.35% and from ±2.06% to ±16.29%. According to Najim et al (2006) and Cheng et al (2002), percentage differences of less than 20% considered a good performance for calibration. Statistical performance indices, Nash-Sutcliffe efficiency NSE (eq. 5) (Nash and Sutcliffe 1970) and coefficient of determination R^2 (eq. 6) values were above 0.90. Moriasi et al (2007) consider that a NSE close to 1 means a good accordance between observed and computed flows.

Table 3. Parameters of calibration

Nr of Subbasin	Parameters	
	Loss method	Transform method
	Curve Number [–]	Lag time [min]
1	65	101
2	62	189
3	62	178
4	62	153
5	62	88
6	62	67
7	65	62
8	65	85
9	65	95
10	65	102
11	65	136
12	62	144
13	62	190
14	62	60
15	62	47
16	62	98
17	62	79
18	65	41

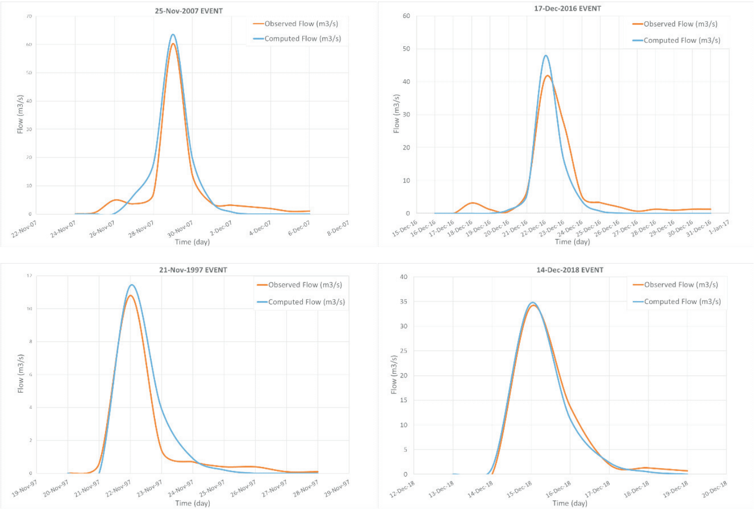

Fig. 6. Model calibration

Table 4. Performance indices of calibration

Event	Precipitation	Volume [1000 m^3]		Peak Flow [m^3/s]		Percentage Difference		NSE	R^2
	depth [mm]	Observed	Simulated	Observed	Simulated	Volume	Peak Flow		
21-nov-97	70	1239	1407	10.8	11.4	13.56	5.56	0.93	0.95
25-nov-07	160.1	9376	9775	60.30	63.60	4.26	5.47	0.94	0.95
17-dec-16	131.5	8280	6512	41.19	47.90	–21.35	16.29	0.90	0.90
14-dec-18	107.5	4654	4331	34.00	34.70	–6.94	2.06	0.99	0.99

$$PVD = \frac{(Vol_{obs} - Vol_{sim})}{Vol_{obs}} \cdot 100, \tag{3}$$

$$PPD = \frac{\left(Q_{p,obs} - Q_{p,sim}\right)}{Q_{p,obs}} \cdot 100, \tag{4}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N} (Q_{i,obs} - Q_{i,sim})^2}{\sum_{i=1}^{N} \left(Q_{i,obs} - \overline{Q_{obs}}\right)^2}, \tag{5}$$

$$R^2 = \left[\frac{\sum_{i=1}^{N} \left(Q_{i,obs} - \overline{Q_{obs}}\right)\left(Q_{i,sim} - \overline{Q_{sim}}\right)}{\sqrt{\sum_{i=1}^{N} \left(Q_{i,obs} - \overline{Q_{obs}}\right)^2 \sum_{i=1}^{N} \left(Q_{i,sim} - \overline{Q_{sim}}\right)^2}} \right]^2, \tag{6}$$

where:

PVD – Percentage Volume Difference,
PPD – Percentage Peak Difference,
NSE – Nash-Sutcliffe efficiency,
R^2 – Coefficient of determination,
Vol_{sim} – Simulated Volume,
Vol_{obs} – Observed Volume,
$Q_{p,sim}$ – Simulated Peak,
$Q_{p,obs}$ – Observed Peak,
$Q_{i,sim}$ – the simulated flow at time $t = i$,
$Q_{i,obs}$ – the observed flow at time $t = i$,
Q_{obs} – the average observed flow,
N – number of observations,
$\overline{Q_{sim}}$ – Mean simulated flow,
$\overline{Q_{obs}}$ – Mean observed flow.

3.2. Validation

The model was validated by using six meteorological events where the precipitation depth and observed peak flow varied respectively from 75 to 308 mm and from 6.8 to 75 m^3/s (Tab. 2). The duration of the resultant floods was about 7 to 22 days. The computed hydrographs are nearly similar to the observed hydrographs (Fig. 7). The performance indices for model validation are presented in (Tab. 5). The Nash-Sutcliffe efficiency (NSE) ranges from 0.33 to 0.89 and the coefficient of determination (R^2) varies from 0.53 to 0.96. According to Motovilov et al (1999), during the validation step, the values of NSE that range between 0.36 and 0.75 are considered satisfactory. There was a difference between observed and simulated peak flows (±1.20% to ±50%) and a volume difference (±5.6% to ±47.26%), which are considered acceptable results. However, the values of NSE and R^2 in the weather events of 2 Jan 2009 and 2 Apr 2016 are so small because of the flood duration, which was more than 21 days. This large timing, combined with spatial variation of the rainfall event in the watershed and time of precipitation gauging, induced the differences between observed and simulated hydrographs.

Table 5. Performance indices for validation

Event	Precipitation	Volume [1000 m^3]		Peak Flow [m^3/s]		Percentage Difference			
	depth [mm]	Observed	Simulated	Observed	Simulated	Volume	Peak Flow	NSE	R^2
28-Feb-99	129.9	12326	6501	58.90	46.10	−47.26	−21.73	0.84	0.96
10-Nov-01	132.9	6442	6803	61.00	38.30	5.60	−37.21	0.69	0.63
09-Apr-04	75	2139	1718	6.8	10.2	−19.68	50.00	0.45	0.72
02-Jan-09	84.5	3149	2405	9.4	9.6	−23.63	2.13	0.33	0.53
02-Apr-16	124.8	5551	5972	16.70	24.30	7.58	45.51	0.35	0.58
10-Jan-17	307.8	21750	28823	75.30	76.20	32.52	1.20	0.56	0.76

4. Conclusion

In this paper, the HEC-HMS model was applied to the Oued El Hachem watershed in order to model and simulate its behavior during extreme precipitation events. The loss and transform methods were used to calculate the direct runoff over the watershed. The propagation of floods along the mainstreams was calculated using the Muskingum-Cunge method for flow channels. Precipitation and streamflow data collected from 1995 to 2018 were used as input data for the HEC-HMS model. The largest extreme floods were adopted for calibration and validation purposes. The performance indices of calibration, such as the percentage differences of volume and peak flow, the coefficient of determination, and the Nash-Sutcliffe efficiency, all were in good accordance with the observed and computed hydrographs. The calibrated model was validated by six meteorological events for which the computed hydrographs were nearly

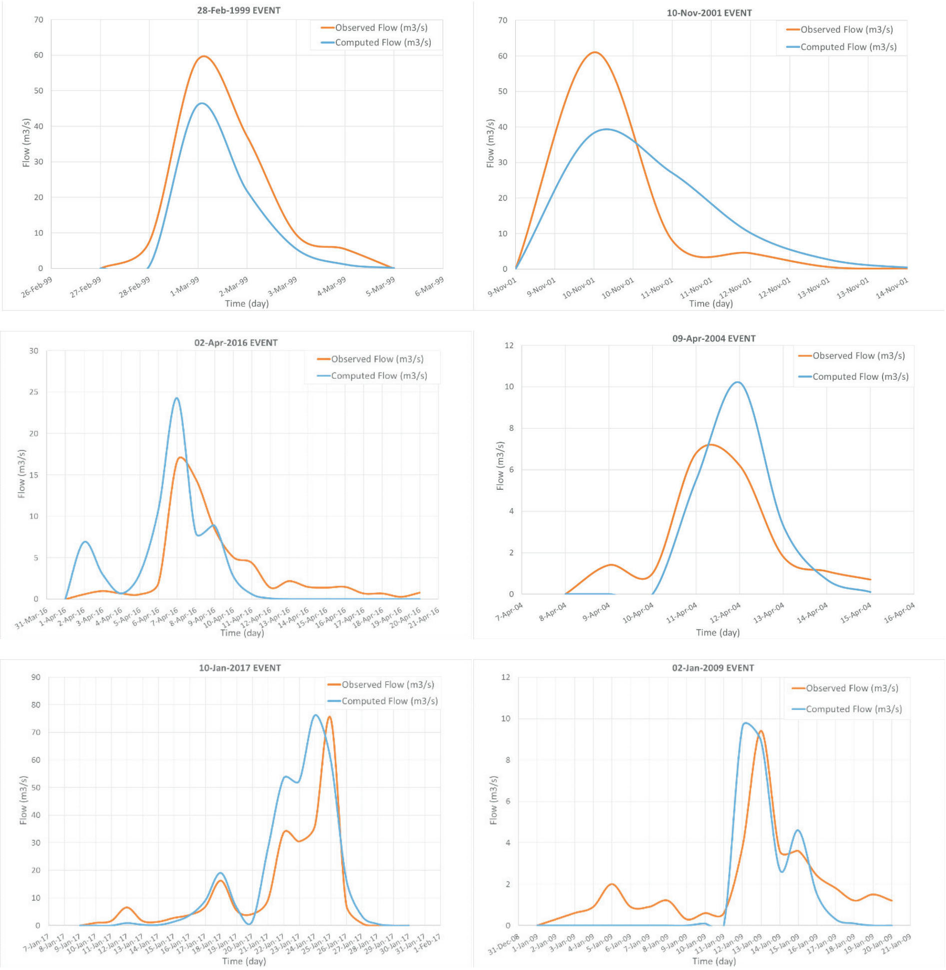

Fig. 7. Model validation

similar to the observed ones. The performance indices for validation were considered satisfactory according to the Nash-Sutcliffe efficiency and the coefficient of determination. Meanwhile, acceptable differences between the observed and simulated values of peak flow and volume were reported, which can be caused by the spatial variation of rainfall over the watershed and the time of precipitation gauging. The calibrated model can be used to compute the resultant hydrographs of possible extreme rainfall events that may occur over the watershed. Also, adequate procedures will be operated in order to ensure the safety of Boukerdane dam against the overtopping risks.

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