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Utilizing hydrograph transform methods and a hydrologic modeling system in rainfall-runoff simulation of a semi-arid watershed in Algeria in north-west Africa

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ABSTRACT

Hydrological modeling of rainfall and surface runoff are crucial elements for simulating flood events in watershed and water resources management. In this paper, the Soil Conservation Services Unit Hydrograph (SCS UH) and CLARK Unit Hydrograph (CLARK UH) transform methods were employed in rainfall-runoff simulation of a case study semi-arid watershed, the Wadi Ouahrane basin in Algeria in north-west Africa, by employing the Hydrologic Engineering Center's-Hydrologic Modeling System. The results obtained showed that the CLARK UH method had the higher performance compared to the SCS UH method with *R*-Squared (R^2), Nash–Sutcliffe (NSE) and root mean square error values of 0.9, 0.83, 3.5 and 0.77, 0.75, and 3.7, respectively. While both methods gave acceptable results for the Wadi Ouahrane watershed, the CLARK UH was the most suitable for flood events simulation.

Keywords: Hydrological modelling; Simulating flood events; Hydrologic Engineering Center's-Hydrologic Modeling System; Soil Conservation Services Unit Hydrograph; CLARK Unit Hydrograph; Wadi Ouahrane basin; Rainfall-runoff; Watershed; Water resources management

1. Introduction

In watershed and water resources management, hydrological modeling has become a vital tool in predicting flood events [1,2]. Furthermore, adequate knowledge of rainfall-runoff processes is essential in assessing peak flow rates, as well as the volume of runoff produced in a watershed during the transformation of rainfall hyetographs into runoff hydrographs. In semi-arid regions, it is very critical to be able to assess surface runoff mechanisms, which usually occurs when the rate of precipitation exceeds infiltration capacity [1,2]. Recently many hydrological models with diverse degrees of complexity and accuracy have been developed to simulate flood events [1,3].

Rainfall-runoff models can be divided into three categories: lumped, semi-distributed, and distributed [4,5]. The selection of a hydrological model depends on the purpose, data availability and ease of use and can therefore influence the quality of the results. Several hydrological models are available for rainfall-runoff simulations, although not all

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models are appropriate for all issues [6,7]. Likewise, several studies have utilized the semi distributed hydrological model Hydrologic Engineering Center's-Hydrologic Modeling System (HEC-HMS) to simulate hydrological processes and have attained satisfactory results in various countries and under different climate conditions [8–11]. The HEC-HMS model for example considers environmental conditions and can be adapted to watershed characteristics of each area, including semi-arid regions such as Algeria in north western Africa [7]. Furthermore, studies done by others [12–14] used the HEC-HMS for flood estimation in the semi-arid regions from Algeria. This model has also been employed for watershed control and assessing the rainfall-runoff process globally [15–22]. Steinmetz et al. [23], for example, employed HEC-HMS software of semi-distributed and conceptual modeling in the application of Soil Conservation Services Unit Hydrograph (SCS UH) and CLARK Unit Hydrograph (CLARK UH) for calculating runoff hydrographs in Brazil. The SCS UH is a dimensionless method commonly utilized due to its ease of application, to predict peak discharge and to create hydrographs. Similarly, CLARK UH is a functional, analytical approach for flooding hydrology because the hydrograph's shape and peak water flow are connected to watershed parameters [24–26]. Currently, there is a shortage of research comparing the CLARK's and SCS's Unit Hydrograph transform methods. Based chiefly on watershed's features, better insights related to these problems can be a valuable addition to engineers and decision makers in improving watershed management [23].

The aim of the present study was to employ the Soil Conservation Services Unit Hydrograph (SCS UH) and CLARK Unit Hydrograph (CLARK UH) transform methods in rainfall-runoff simulation of a semi-arid case study watershed, the Wadi Ouahrane basin in Algeria in north-west Africa, by employing the Hydrologic Engineering Center's-Hydrologic Modeling System (HEC-HMS). An analysis and comparison were made of the findings of the SCS UH and CLARK UH approaches in estimated peak discharge and surface runoff. In addition, calibration, validation, sensitivity analysis of the HEC-HMS program, and model performance were performed using statistical metrics.

2. Materials and methods

2.1. Case study region and data sets

The Ouahrane wadi basin which covers an area of 270 km^2 is part of the town of Chlef in the north-west of Algeria (Fig. 1). The elevation of the area varied from 117 to 958 m above sea level. The climate in the region is semi-arid Mediterranean type, with average precipitation of up to 400 mm y^{-1}. The watershed of the Ouahrane wadi is marked by marly soil, a carbonate-rich mud, occupying 80% of the area of the basin. In terms of land use, polyculture and cereals are the essential agricultural activities in the study region [27].

The spatial distribution of precipitation shows two rainfall levels in two different sectors; the Ouled Fares sector gets less than 400 mm of rain, below 200 m elevations.

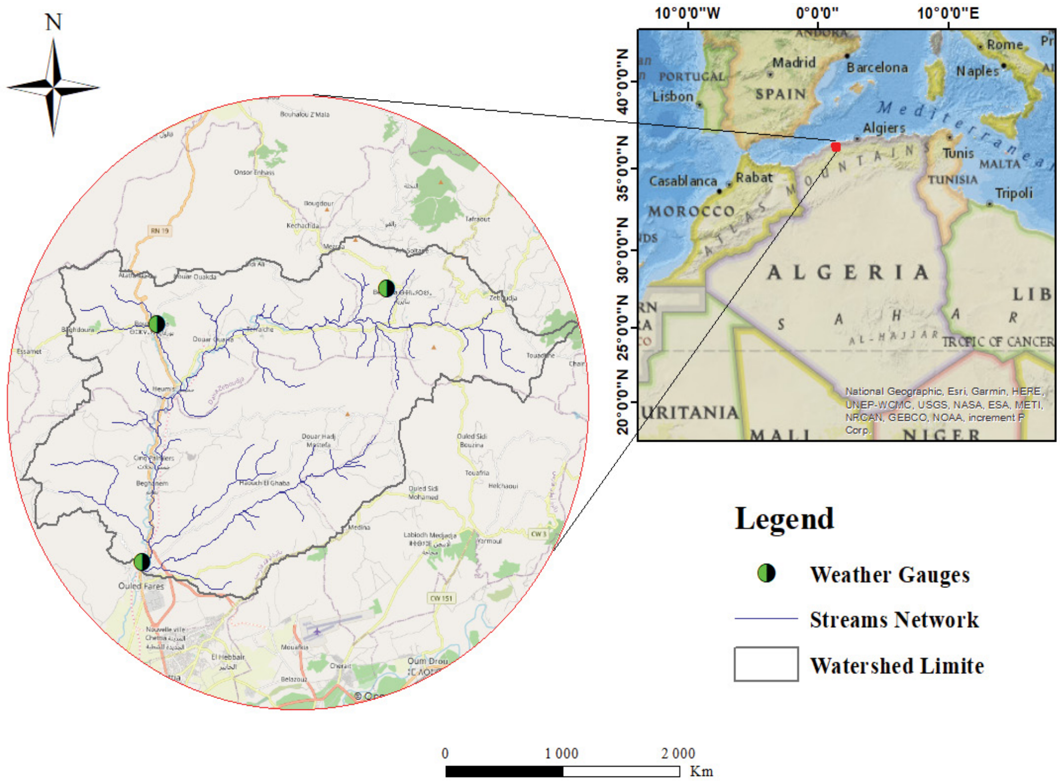

Fig. 1. Wadi Ouahrane basin location.

This sector covers about 40% of the basin. The Benairia sector on the other hand is situated at more than 380 m altitude, where the average annual rainfall is slightly higher at 480 mm; this sector covers 60% of the watershed [27,28]. The annual precipitation of the Ouled Fares and Benairia stations are shown in Fig. 2.

Land use of the Wadi Ouahrane watershed was digitalizing using Landsat8 images and then classified into six groups: 36.4% grain cultivate, 27.38% barren land, 15.6% polyculture, 11.2% forest, 9.11% built-up and urban area, and 0.32% water bodies (Fig. 3). Soil hydrological groups (HSG) in the basin were categorized as A, B, C, and D from the soil data map, and then the curve number (CN) map was generated for Fig. 3.

2.2. Basin processing and model construction

The digital elevation model (DEM) map with 30 m × 30 m resolution was inserted into ArcGIS software. The terrain concept was developed with ArcHydro tools, and the model basin was constructed with HEC-GeoHMS Extention [29,30]. Essentially, terrain processing is the first prerequisite for the construction of a basin model utilizing this method. This phase involved the reconditioning of the DEM, spatial calculation of direction and accumulation of flow, and the boundary of the grid catchment. Besides establishing the characteristics of the bowl and the process parameters, the basin was segregated into six sub-sinks (Fig. 4). Elements of the sub-basins, such as slope, length, and longest flow path of the waterways, are critical data for running the model and for ensuring the accuracy in the data collected. The possible model errors were then assessed, fixed if necessary, and imported into the HEC-HMS program [29,30].

2.3. Hydrologic modeling and HEC-HMS definition

The HEC-HMS model created by the United State Army Corps for Engineers (USACE), was employed to simulate the hydrological processes for the Wadi Ouahrane watershed. The basin model, control specifications, meteorological model, and time-series data input details were used. The watershed model, as illustrated in Fig. 5 describes the spatial basin with hydrological components. The basin model comprised six sub-basins, three reaches, and one outlet. The Soil Conservation Service-Curve Number (SCS-CN) loss method, SCS and CLARK Unit Hydrograph transform model, and Muskingum routing channel were utilized in the study. The SCS-CN loss method for the basin is represented by Eq. (1):

$$P_e = \frac{\left(P - I_a\right)^2}{P - I_a + S} \tag{1}$$

where P_e denotes accumulated excess precipitation (mm), P signifies cumulative rainfall (mm), I_a indicates original abstraction (mm) and can be set to (0.2 S), and S represents the maximum possible retention (mm) [31].

The SCS UH transform model is a non-dimensional unit hydrograph, and the Lag time (T_{lag}) of each sub-basins was measured by using the SCS formula shown in Eq. (2):

$$T_{\text{lag}} = 0.6 \times \left[\frac{L^{0.8}\left(S+1\right)^{0.7}}{1{,}900\sqrt{Y}}\right] \tag{2}$$

where T_{lag} denotes the latency period in hours; L depicts the watershed length (km), S indicates the longest potential retention (mm), and Y represents the mean watershed slope (%) [32].

The CLARK UH is a synthetic unit hydrograph method. It needs the values of two parameters: T_c (concentration-time) and S_t (storage coefficient). They are represented by Eqs. (3) and (4) and are the first steps in the model [33,34].

$$\frac{dS}{dt} = I_t - O_t \tag{3}$$

$$S_t = R_{\text{coef}} \times T_C \tag{4}$$

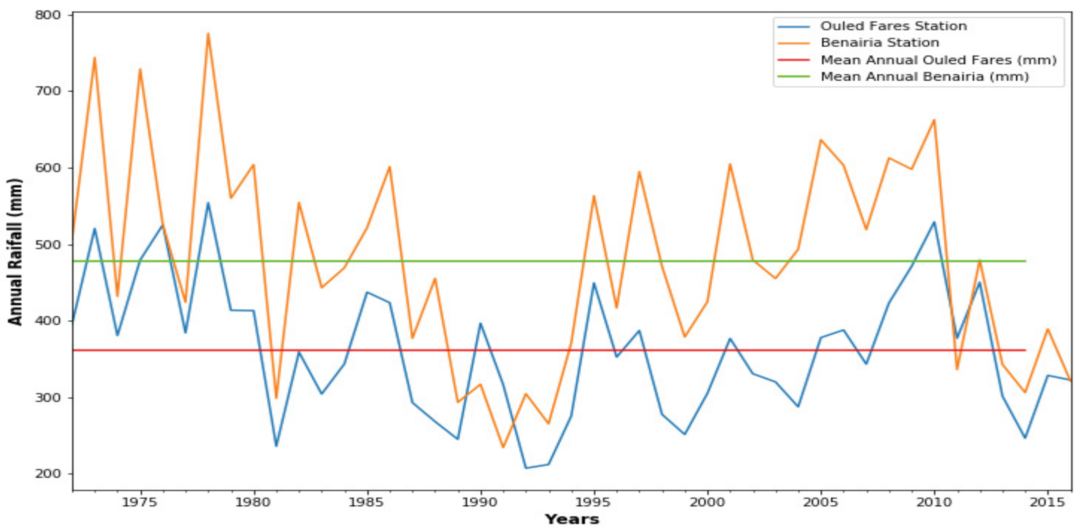

Fig. 2. The total annual rainfall at the rain gauges of Ouled Fares and Benairia.

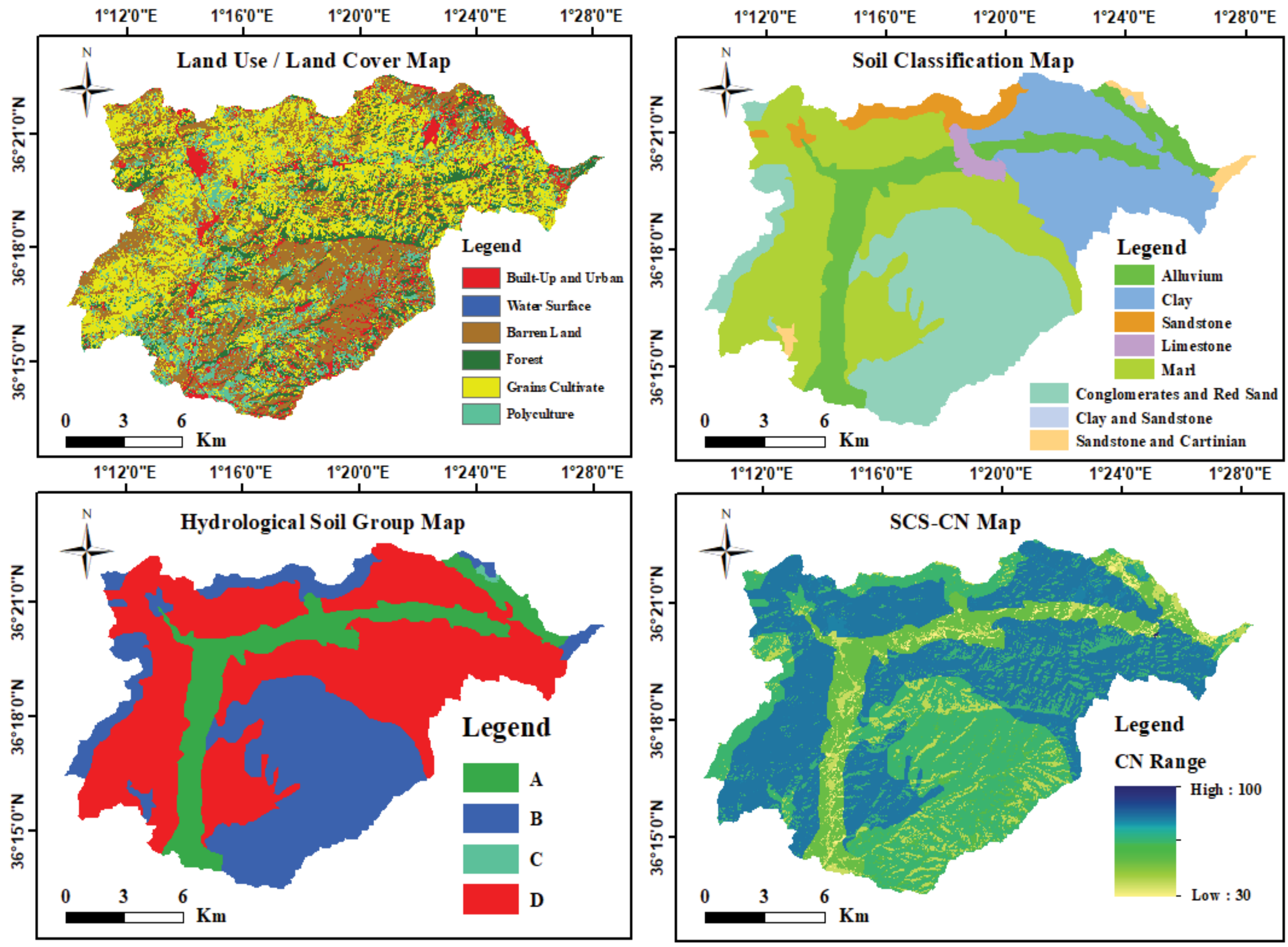

Fig. 3. LU/LC map, soil classification map, hydrological soil group (HSG) map and curve number (CN) map of Wadi Ouahrane watershed.

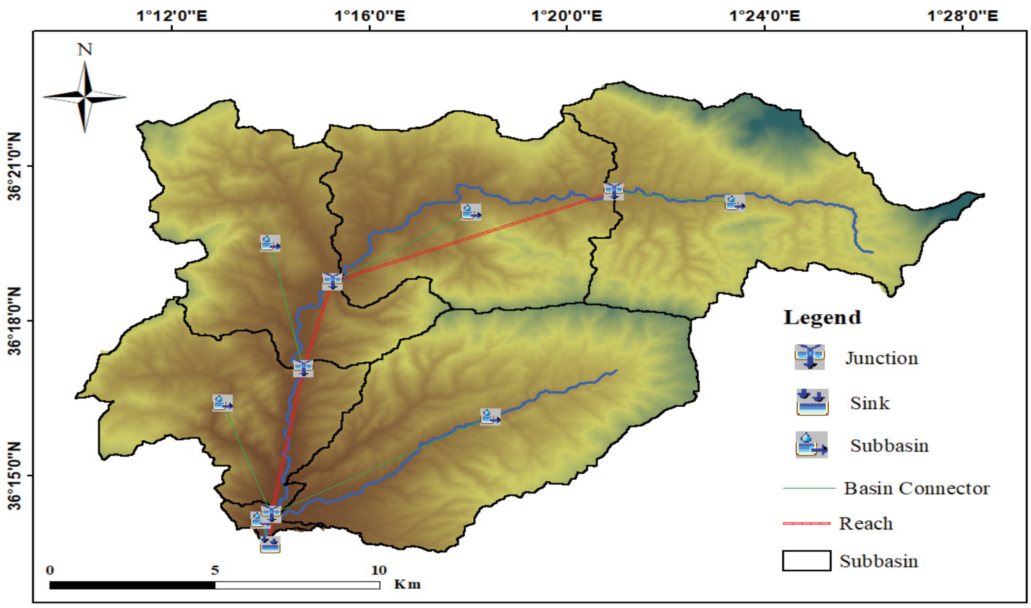

Fig. 4. Form of Wadi Ouahrane and sub-basins input to HEC-HMS.

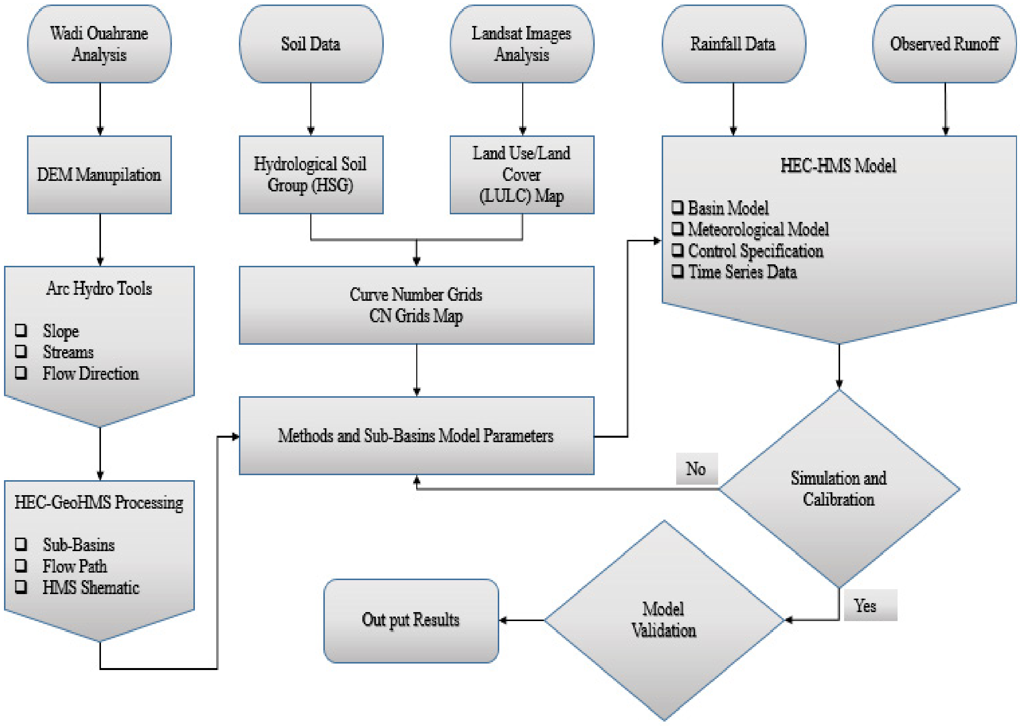

Fig. 5. Flow chart of hydrological modelling method utilizing GIS and HEC-HMS.

where dS/dt represents the rate of shift of water in storage over time. I_t stands for average inflow (m^3 s^{-1}), and O_t stands for outflow storage (m^3 s^{-1}). R_{coef} is the CLARK coefficient (1.632).

The Nash–Sutcliffe (NSE) coefficient [35] represented by Eq. (5), the root mean square error (RMSE) in Eq. (6), and the linear regression (R^2) shown in Eq. (7) were used to measure the efficiency of the models.

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} \left(Q_{iobs} - Q_{isim} \right)^2}{\sum_{i=1}^{n} \left(Q_{iobs} - \bar{Q}_{obs} \right)^2} \right] \quad (5)$$

$$\text{RMSE} = \left[\frac{\sum_{i=1}^{n} \left(Q_{iobs} - Q_{isim} \right)^2}{N} \right]^{1/2} \quad (6)$$

$$R^2 = \left[\frac{\sum_{i=1}^{n} \left(Q_{iobs} - \bar{Q}_{obs} \right) \times \left(Q_{isim} - \bar{Q}_{sim} \right)}{\sqrt{\sum_{i=1}^{n} \left(Q_{iobs} - \bar{Q}_{obs} \right)^2} \times \sqrt{\sum_{i=1}^{n} \left(Q_{isim} - \bar{Q}_{sim} \right)^2}} \right]^2 \quad (7)$$

The observed and simulated discharges at $t = I$ are Q_{iobs} and Q_{isim} (m^3 s^{-1}), respectively, and $\bar{Q}_{sim}$, $\bar{Q}_{obs}$ are the mean simulated and observed flows (m^3 s^{-1}). N is the number of data points that have been observed [36].

3. Results and discussion

3.1. Comparison of the SCS and CLARK Unit Hydrographs

The performance of the hydrological basin model depends on the quality of its calibration, which depends on the technological capabilities of the hydrological model and the quality of the input data [12]. The basin was divided into six sub-basins based on the river network, runoff hydrographs are computed based on two rainfall–flow events (05 Feb 1987 and 11 Nov 2001), using the parameter values shown in Table 1. The calibration goal of the watershed model (HEC-HMS) was to align measured and optimized runoff volumes and discharge peaks [37]. The CN, lag time, and Muskingum's parameters were adjusted through the optimization process. The initial CN values range from 64.27 to 80.50 for each sub-basin, while the optimized CN estimates values from 53.67 to 78.22 (Table 2). The same CN value was used for CLARK's UH and SCS UH. The T_{lag} values obtained by the SCS UH ranging from 73.63 to 49.68 min for one sub-basin, however, in the other sub-basins the results obtained are close to each other. Compared to CLARK's UH parameters (T_c and S_t), their values adjusted to some sub-basins showed notable variation, for example, T_c ranged from 2.04 h to 1.36 h, and S_t showed a large spread with values ranging from 3.91 to 5.90 h (Table 1). Also the results are similar for Muskingum-K (h) 1.42 to 3.19 (h).

The peak flow is the most significant feature of any hydrograph since it correlates to the highest downstream flooding. In this study, calibration was carried out using simulation of initial conditions, manual and automated calibration. After calibration, it was observed that the HEC-HMS

Table 1
Initial and calibrated parameters for HEC-HMS model

Sub-basin ID	Loss model		Transform method						Channel ID	Routing method	
	SCS-CN		SCS UH		CLARK UH					Muskingum	
	CN		T_{lag} (min)		T_c (h)		S_t (h)			Muskingum-K (h)	
	Org	Cal	Org	Cal	Org	Cal	Org	Cal		Org	Cal
W1060	78.68	76.41	86.38	78.12	2.39	2.41	3.91	5.90	R360	2.89	2.92
W1270	80.50	53.67	51.12	51.19	1.42	0.94	2.31	3.49	R430	2.39	3.61
W1290	64.27	62.99	21.66	22.00	0.60	0.60	0.98	0.65	R620	1.42	3.19
W1300	75.77	74.25	73.63	49.08	2.04	1.36	3.33	4.90	R650	0.60	0.88
W920	79.81	78.22	105.8	106.40	2.94	2.94	4.79	4.72			
W970	78.48	76.91	104.3	104.85	2.89	2.91	4.73	4.77			

Table 2
Model simulation and performance for the calibration period

	Event 5th Feb, 1987 (calibration)		Event 11th Nov, 2001 (calibration)	
	SCS UH	CLARK UH	SCS UH	CLARK UH
Observed peak discharge ($m^3 s^{-1}$)	71.80		87.60	
Simulated peak discharge ($m^3 s^{-1}$)	71.80	71.74	87.52	87.71
Observed volume (mm)	18.95	18.98		
Simulated volume (mm)	22.47	17.53	20.38	25.74
NSE	0.83	0.80	0.76	0.78
RMSE	6.80	7.30	14.40	13.90
R^2	0.91	0.86	0.86	0.88

model obtained satisfactory results for both methods (SCS and CLARK Unit Hydrographs) and events (1987 and 2001).

Fig. 6 show that the observed and simulated streamflow hydrographs for calibration, for each rainfall event (1987 and 2001), have similar shapes for the SCS and the CLARK's method, but this shape is dissimilar from the estimated hydrograph. The observed and simulated peak flow values change from 58.4, 51.30 $m^3 s^{-1}$ in the 05 Feb 1987 event to 71.8 $m^3 s^{-1}$ and 100.1 and 118.4 $m^3 s^{-1}$ in 11 Nov 2001 to 87.60 $m^3 s^{-1}$ before and after calibration, respectively.

At this stage, it was found that the results were close. The statistical assessment of calibrated phases, the modeling results for peak flow, and total volume are shown in Table 2.

The comparison of the simulated unit hydrograph of the both methods shows that the simulated volume obtained using the SCS-CN method is 22.47 and 20.38 mm while the simulated volume obtained from the CLARK UH method is 17.53 and 25.74 mm for the event of 5 February 1987 and 11 November 2001 respectively.

For the observed and optimized discharge, no differences were seen in peak discharges during the 1987 event in the SCS UH whose value is about 71.80 $m^3 s^{-1}$. A slight change of 0.08% was detected in the CLARK UH and has an estimated value of the order of 71.74 $m^3 s^{-1}$. This was also expressed in the 2001 event, where it was calculated at 0.09% and 0.11% differences for SCS UH and CLARK UH, respectively.

In terms of the model efficiency, the NSE ranges from 0.76 to 0.83 for two studied events for the both methods which the greater value of the NSE (0.83 and 0.78) was obtained by the SCS-CN method for 05 February 1987 event and the CLARK UH method for 11 November 2001 event consecutive. Likewise, the RMSE criterion varies between 6.80 to 14.40, with the highest and the weak value obtained by the SCS-CN method. The correlation coefficients (R^2) ranging from 0.86 and 0.91, reflecting the HEC-HMS model's calibration accuracy.

3.2. Model validation

The 1st February 2011 event was used in the validation phase, as this event was distinct from the events used for calibration and was chosen to confirm the efficiency of the optimization phase. The observed and simulated hydrographs are almost identical except for the peak discharge, which is higher for the simulated graph, overestimated by the CLARK UH, and underestimated using the SCS UH. The validated peak flow values for SCS UH and CLARK UH were 30.5 and 36.1 $m^3 s^{-1}$, respectively, as seen in Table 3 and Fig. 7. The average volume of the SCS UH was predicted to be 4.61 (mm), while the CLARK UH was estimated to be 6.59 mm.

The findings comparing runoffs show that the CLARK UH model in the validation process simulated the floods hydrograph with NSE, RMSE, and the R^2 values of 0.83, 3.50, and 0.9, respectively. The CLARK UH model thus had the better fitness between the observed and optimized

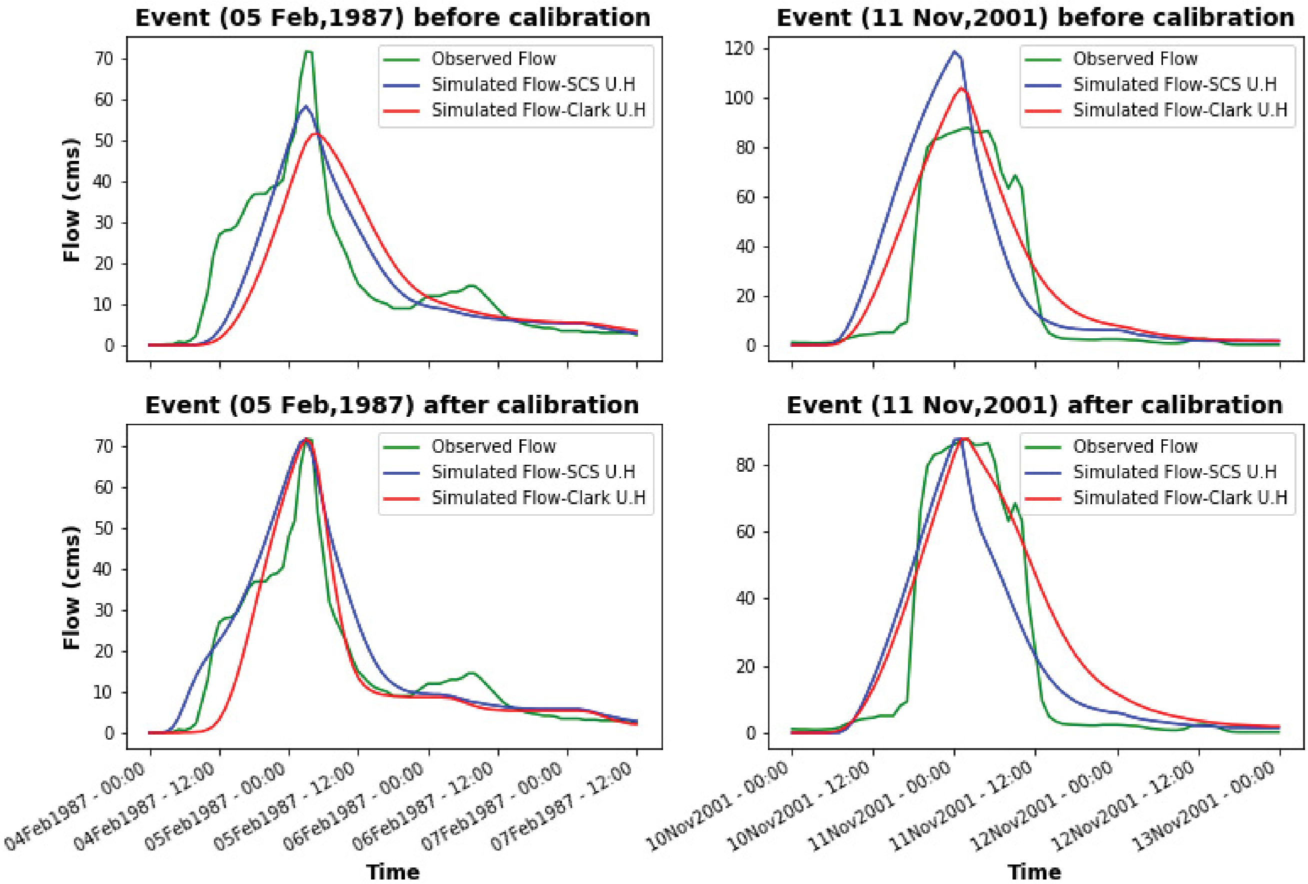

Fig. 6. Floods hydrographs of events 5th Feb 1987 and 11th Nov 2001 before and after calibration.

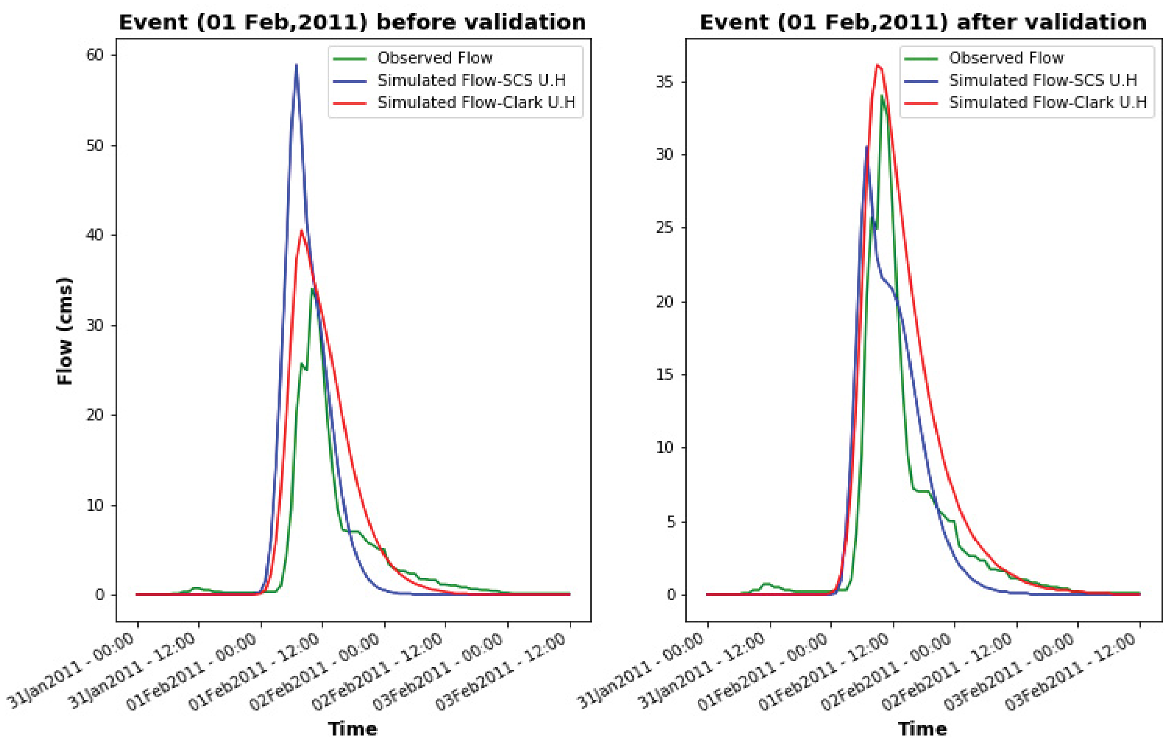

Fig. 7. The SCS and CLARK hydrographs comparison of 1st Feb 2011 event before and after validation.

Table 3
Model validation results

	Event 1st Feb, 2011 (validation)	
	SCS UH	CLARK UH
Observed peak discharge ($m^3 s^{-1}$)	34.00	
Simulated peak discharge ($m^3 s^{-1}$)	30.50	36.10
Observed volume (mm)	4.37	
Simulated volume (mm)	4.61	6.59
NSE	0.75	0.83
RMSE	3.70	3.50
R^2	0.77	0.90

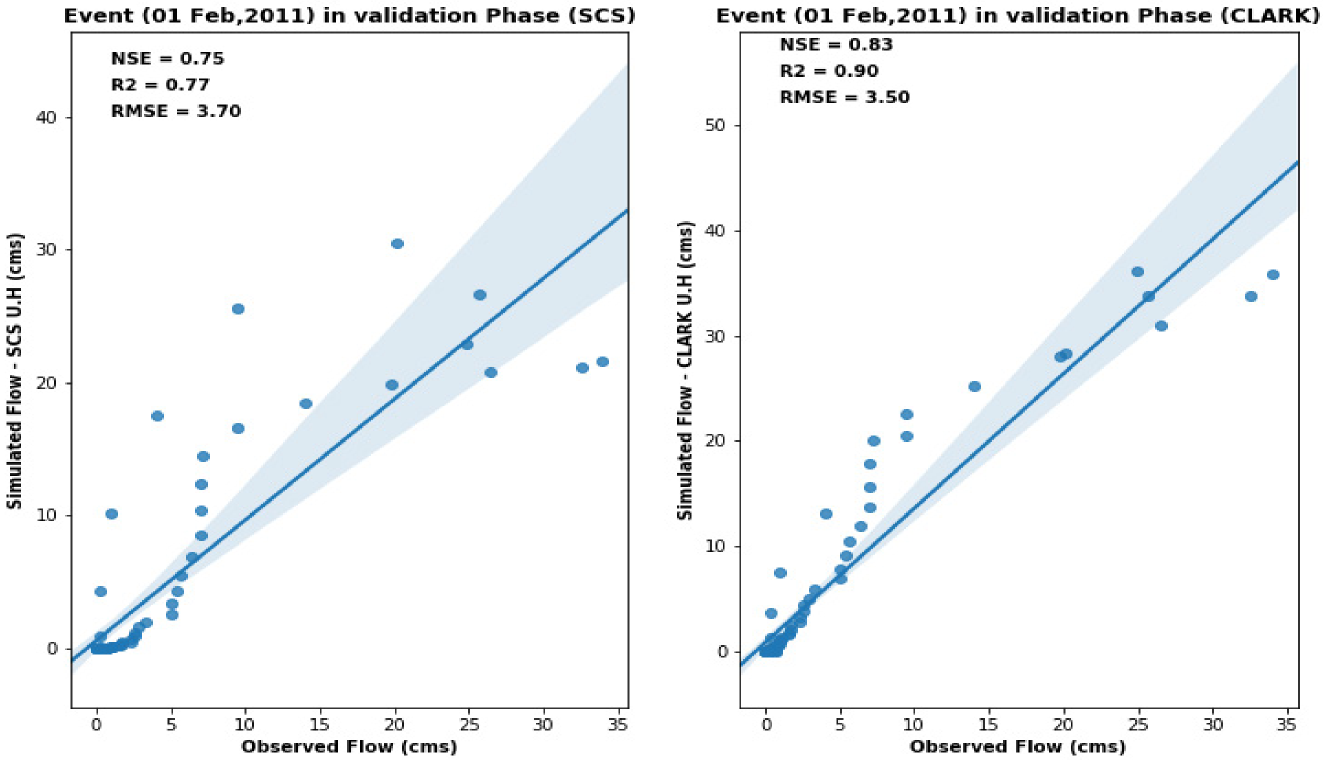

Fig. 8. Comparison of optimized and observed runoff on SCS and CLARK Unit Hydrographs during validation.

data relative to the SCS UH method which was valued at NSE = 0.75, RMSE = 3.70 and R^2 = 0.77 (Fig. 8). This meant that the CLARK UH process did well when simulating flood hydrographs [23,38]. Through comparison of the statistical evaluation parameters of NSE, RMSE, and R^2, both for optimization and validation phases, CLARK UH had a lower root mean square error and a much more accurate R^2 and NSE than the SCS UH process.

This suggests that the model is suitable for hydrological simulations for the CLARK UH method. The cause for this is based on the linear reservoir model concept and considering the Muskingum-K coefficient parameter. The SCS method is highly dependent on the calibration because of the dependence on empirical relationships. Therefore, the error is great.

4. Concluding remarks

The Hydrologic Engineering Center's-Hydrologic Modeling System (HEC-HMS) was very suitable in terms of accuracy for rainfall-runoff simulation thus supporting reports by others. The current study illustrated the importance of the Soil Conservation Services Unit Hydrograph (SCS UH) and CLARK Unit Hydrograph (CLARK UH) transform methods in runoff prediction in a watershed under various climatic conditions. The validation phase demonstrated a difference between the observed and predicted peak discharge, which ranged from 11.5% to 5.81% for both SCS UH and CLARK UH, respectively. The results obtained showed that the CLARK UH method had the higher performance compared to the SCS UH method with *R*-Squared (R^2), Nash–Sutcliffe (NSE) and root mean squared error (RMSE) values of 0.9, 0.83, 3.5 and 0.77, 0.75, and 3.7, respectively. While both methods gave acceptable results for the Wadi Ouahrane watershed, the CLARK UH was the most suitable for flood events simulation using the HEC-HMS model.

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