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Automatic calibration of arid rainfall-runoff model for Wadi Thara Western Kingdom of Saudi Arabia

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ABSTRACT

Input parameter calibration to rainfall-runoff models is the most critical stage of the overall flood modeling processes, where the input parameters values are adjusted to make the simulated flood hydrographs fit the corresponding records. Wadi Thara (275 km^2) in the Western Kingdom of Saudi Arabia (KSA) is selected and hourly rainfall data are extracted from the paper charts. Five-minute observed runoffs are analysed and ASTER Digital Elevation Model (DEM) with 30-m pixel size is processed to compute automatically the morphometric parameters and to extract the geometric features of the catchment. hydrological soil group map and land cover/land use (LCLU) map are developed to estimate the excess rainfall using composite SCS curve number (SCS-CN). Clark unit hydrograph (Clark-UH) time of concentration approach is used to transform the excess rainfall to flood hydrograph. Four parameters are chosen for calibration, which are SCS-CN, initial abstraction (I_a), Clark-UH time of concentration (T_c) and Clark storage coefficient (R). Nine observed runoff events are selected for modeling; seven different events are chosen for parameter calibration and two for parameter validation. This study focuses on calibrating the peak flow only, which is one of the most critical hydrograph characteristics in rainfall-runoff modeling in arid regions. Calibration process produced exact peak flow for five out of seven events and one event with very close match (–2.6% of change). On the average parameters, calibrations for SCS-CN, I_a, T_c and R are 81.6, 11.0 mm, 3.81 h and 1.88 h, respectively, where R is the most highly variable parameter with 139% coefficient of variation. The reason behind this variation may be because of the local search algorithms usage, which produce local minimum objective function and assign optimized value to the parameter that is not in existence, also the selected hydrological methods are lumped, where the spatial rainfall variation and the other input parameters are not taken into consideration. In the validation process, the four average calibrated parameters are used to validate two events, the first event produced a peak flow with –50% change, which can be considered as relatively high, while the second event resulted in a peak flow with –6.0% change). The value of calibrated parameters is very valuable and can be used in the future for the same and similar catchments. More optimization module applications may be needed with global search algorithm and multiple objective functions to enhance the estimated parameters in future studies.

Keywords: Automatic calibration; Parameter optimization; Rainfall runoff model; Arid regions; Kingdom of Saudi Arabia; Wadi Thara

1. Introduction

The input parameters calibration to the rainfall-runoff models is the most critical stage of the overall flood modeling processes. Unfortunately, these input parameters are usually highly variable in space and difficult to estimate properly for ungauged catchments (Yang et al., 2018). For Wadi systems with runoff gauging station (gauged catchments), the calibration techniques help to optimize (enhance) the parameter estimation. The optimization process adjusts the input hydrological model parameters to produce a flood hydrograph simulation that closely matches the observations (Duan et al., 2003). Historically, parameter optimization techniques back to the start of digital revolution in the 1960s of the previous century (i.e., Rosenbrock, 1960, Nelder and Mead 1965).

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Nowadays, parameter optimization can be achieved automatically using computer capabilities (Todini and Biondi, 2017). Calibration techniques can be categorized in different approaches, by the objective function, the optimization techniques can be divided into single or multiple objective functions, and by the search algorithms into local or global search. In this paper, Hydrological Engineering Center – Hydrological Modeling system (HEC-HMS) software by Corps of engineers in US Military is used, and HEC-HMS is commonly used to simulate the surface runoff hydrograph based on basin rainfall and the physiographical characteristics.

Several methods are available in HEC-HMS to develop surface response basin simulation. In this study, soil conservation services curve number (SCS-CN) method (Soil Conservation Services, 1985) is used to compute the effective rainfall (excess rainfall), while Clark synthetic unit hydrograph (Clark-UH) method is selected and the time of concentration (T_c) equation developed by Arizona Department of Transportation (ADOT, 1993) is implemented. These two methods are categorized as lumped empirical approaches and usually used in single event rainfall-runoff modeling (Feldman, 2000).

Optimization module of HEC-HMS software has 12 different objective functions "Goodness-of-fit Index" (Scharffenberg, 2016), which all are single objective function and none of them are multi-objective function. Two search algorithms are available in HEC-HMS, which are univariate-gradient search and Nelder and Mead algorithms (Skahill, 2016). Both search algorithms are local and none of them is global. Several attempts have been made for using optimization module of HEC-HMS software in rainfall-runoff modeling in Arab arid regions (Hammouri and El-Naqa, 2007, Abushandi and Merkel, 2013, Laouacheria and Mansouri, 2015, El-Alfy, 2016, Skhakhfa and Ouerdachi, 2016, Derdour, et al. 2017, Rahman, et al. 2017).

The aim of this study is to investigate the optimization of four input parameters to rainfall-runoff models for peak flow discharges calibration in Wadi Thara Western of Kingdom of Saudi Arabia (KSA).

2. Study area

Wadi Thara is an upper sub-basin of Wadi Allith, which drains into the Red Sea, located in Tihama Escarpment Mountains of the Arabian shield on the western cost of the Kingdom of Saudi Arabia (KSA) with about 200 km south of Jeddah city, and administratively located within Makkah Province. Wadi Thara is located in the west of the main catchment with an area of about 275.5 km^2. It lies between 40°11′E and 40°25′E longitudes and 20°39′N and 20°50′N latitudes (Fig. 1).

In 1986 Ministry of Agriculture and Water (MAW) in KSA (currently Ministry of Environment, Water and Agriculture) conducted an intensive field survey and laboratory analysis to determine the soil types (Ministry of Agriculture and Water, 1986). It was found that Wadi Thara consists mainly of two soil types: rock outcrops and alluvial deposits. Rock outcrops are mainly lithic and Typic Torriorthents complex, extremely steep gravelly and loamy soils, which have in steep to extremely steep side slopes in mountainous uplands. Alluvium deposits contain mainly deep, very cobbly sandy and sandy soils.

Wadi Thara can be considered mainly as arid range land. The vegetation cover in the rock outcrops consists of about 20% shrubs and 5% grass. The vegetation cover in the alluvial deposits consists of about 25% trees and 20% shrubs. There are no farms or villages in Wadi Thara and only insignificantly very small and scattered houses are found near the main channel.

3. Methodology

3.1. Runoff computation approach

Rainfall-runoff modeling is presented to simulate the flash flood discharge (hydrograph) using the hourly rainfall data and physiographic characteristics of the catchment as input to the model. Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) software is used for flash flood simulation and parameter optimization.

Two hydrological computation processes are usually employed to develop the flood hydrograph simulation, namely, excess rainfall using loss methods and direct runoff transformation by synthetic unit hydrograph (UH) methods. In this study, SCS-CN method (Soil Conservation Service, 1986) is used to compute the effective rainfall (excess rainfall), while Clark-UH method is used to compute the direct runoff hydrograph. SCS-CN method is based on mapping of land cover/land use (LCLU) and hydrological soil groups (HSG). The other parameters of SCS-CN method such as potential maximum retention (S) can be calculated easily, which is a measure of the watershed ability to abstract and retain storm rainfall, and initial abstraction (I_a), the equations for computing storage (S) and initial abstraction (I_a) for SI units can be given as follows (Mishra and Singh, 2013)

$$S = \frac{25,400 - 254\text{CN}}{\text{CN}} \quad (1)$$

$$I_a = 0.2S \quad (2)$$

Finally, the effective rainfall (or excess rainfall) depth (R_e) can be estimated by the following expression,

$$R_e = \frac{\left(P - 0.2S\right)^2}{\left(P + 0.8S\right)} \quad (3)$$

where P is the accumulated rainfall depth at time (t).

Direct runoff hydrograph process is the method to transform excess rainfall to point runoff hydrograph. Synthetic UH (SUH) methods are usually used to compute the direct runoff. SUH uses the watershed characteristics to compute travel time parameter, which influences the shape and peak of runoff hydrograph. Usually this parameter can be expressed as lag time or time of concentration (T_c), which is indications of the response time at the outlet of the watershed for the rainfall event. In this study, Clark-UH method is selected and the T_c equation by Arizona Department of Transportation (ADOT, 2014) is adapted for mountainous terrain, which can be expressed as:

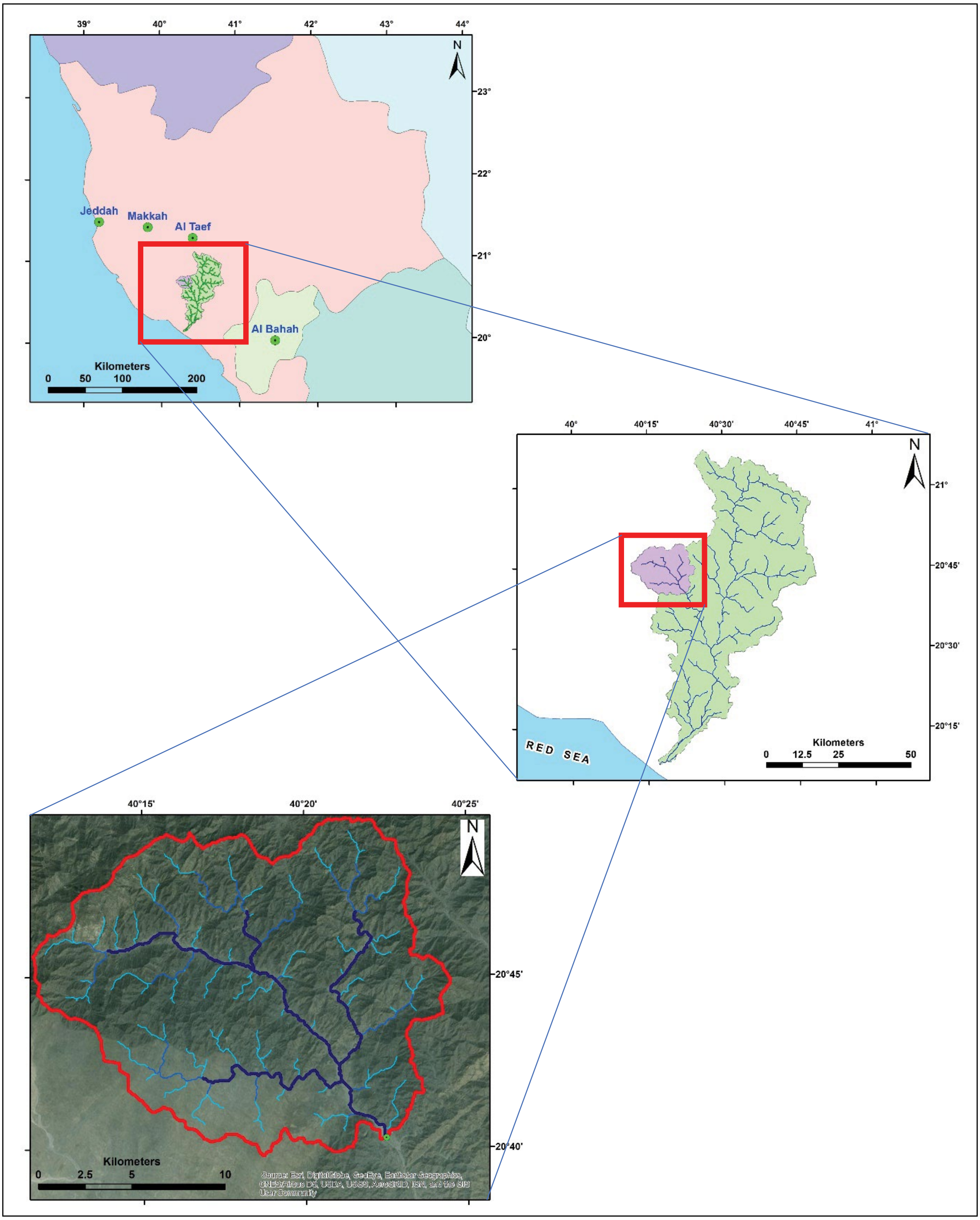

Fig. 1. General location of study area.

$$T_c = 2.4 \times A^{0.1} \times L^{0.25} \times L_{\mathrm{Ca}}^{0.25} \times S^{-0.2} \tag{4}$$

where T_c is the time of concentration in hours,

A is the catchment area in square miles,

L is the length along main channel from outlet to upstream boundary in miles,

L_{Ca} is the length along main channel from outlet to point opposite to centroid in miles.

S is the slope along main channel from outlet to upstream boundary in feet/mile.

The catchment storage coefficient, R, can be computed as;

$$R = 0.37 \times T_c^{1.11} \times L^{0.8} \times A^{-0.57} \tag{5}$$

3.2. Calibration process approach

Parameters estimation can be optimized via automatic calibration. In rainfall-runoff modeling, usually the hydrological process parameters (i.e., SCS-CN and Clark-UH) are selected for calibration and validation depending on the methods used. In this study, the goal of automatic calibration process is to specify reasonable values for the input parameters that produce the best computational fit to observed peak flow. HEC-HMS optimization module is used and four input parameters are selected for calibration, which are SCS-CN, I_a, T_c and R.

Parameter estimation optimization process starts with selection the objective function. Since the most critical value for rainfall-runoff in arid regions is the peak flow, the percentage error in the peak (PEP) objective function is selected, which is the absolute value of the difference between observation and simulation flood peak discharges in percentage. This objective function ignores the entire hydrograph ordinates except for the single peak flow value and can be expressed as follows:

$$Z = 100\left|\frac{Q_p(\text{Simulated}) - Q_p(\text{Observed})}{Q_p(\text{Observed})}\right| \tag{6}$$

where Z is the objective function that needs to be minimized, Q_p (observed) is the observed peak flow of the hydrograph event, and Q_p (simulated) is the simulated peak flow resultant from optimized parameters.

The second step in optimization process is to select the search algorithm for minimizing the objective function and finding optimal parameter values. In this study, both search algorithms are used. Two parameters are needed for the search algorithm, which are tolerance value that should be very small (i.e., 0.001) and maximum number of iterations as high as possible (i.e., 1,000). Mathematical description of these two search algorithms is out of the scope of this study.

The next step in optimization process is to specify the constraints on the search, which sets the range of feasible and acceptable parameter limits (or boundaries), where the search outside of these boundaries is not acceptable.

The last step in the optimization process is to select the initial estimates of the parameters. As with any search, the better these initial estimates (the starting point of the search), the quicker the search will yield a solution. In this study, the estimated parameter from previous sections will be used as initial value.

The observed dataset is sub-divided into two groups, the first group of events are for calibration (≈ 80% of the dataset) and the second group for validation (≈20% of the dataset), where the average calibrated (optimized) parameters are used in the validation process.

The most critical hydrograph characteristic is the peak flow discharge in most rainfall-runoff modeling in arid regions. This study focuses on calibrating the peak flow.

4. Results and discussions

4.1. Geomorphological and morphometric analysis

One of the most important steps in rainfall-runoff modeling is the extraction of geomorphological features (basin boundary, drainage network) and computation of the morphometric parameters (catchment area, channel length, channel slope) of study area, which can be achieved by automatic techniques such as the GIS software and DEM.

In this study, DEM developed by Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2) is processed at 30 m pixel size using Aquaveo Watershed Modeling System (WMS) software (Aquaveo, 2014). It is found that the catchment area of Wadi Thara is about 275.5 km^2, and it has three main tributaries (streams) flowing from north west to south east, which are Dilimah stream in the eastern part of the Wadi, main Thara stream in the middle, and Tabshu stream in the western part of the Wadi. Fig. 2 shows the DEM of Wadi Thara with the automatically delineated boundary and extracted drainage network, while Table 1 presents the automatically computed morphometric parameters.

4.2. Rainfall and runoff data analysis

Wadi Thara contains two recording rainfall stations, J-235 in the upper part of the sub-catchment, and J-237 inside the catchment near the outlet. Thiessen polygons for these rainfall stations are developed automatically by GIS capabilities of Aquaveo Watershed Modeling System package (WMS), where the inputs are the boundary of the sub-catchment and the location of two rainfall stations. It is found that the effective area ratio for station J-235 and station J-237 are 52% and 48%, respectively.

As the paper charts are not available for most of recording rainfall stations, hourly rainfall records in tabular form are used instead. For this reason, rainfall time interval is set to 1 h (60 min) for modeling, but shorter rainfall intervals could not be developed. Strom events that produced runoff flows as mentioned in the next section are selected and presented in Table 2. It can be shown that almost all the selected rainfall storms occurred in the afternoon period except for 19 December 1985 and rainfall duration is less than three hours for most of the storms.

The paper charts of Wadi Thara runoff station (J-416) at the catchment outlet are examined and the selected runoff events are analyzed and processed to produce

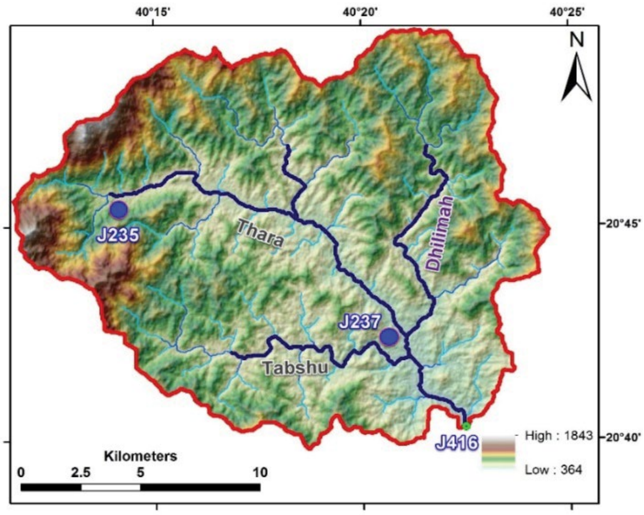

Fig. 2. ASTER DEM and automatically extracted drainage system of Wadi Thara.

Table 1
Automatically computed morphometric parameters from ASTER GDEM

Morphometric parameter	Value
Basin Area (km²)	275.5
Total stream length (m)	94,735
Basin (overland) slope (%)	35.93
Main channel length (m)	29,660
Main channel slope (%)	4.6
Shape Factor "or circularity" (mi²/mi²)	1.64
Sinuosity	1.31
Perimeter (m)	103,403
Mean elevation (m)	740
Average stream slope (m/m)	0.022
Drainage density (km/km²)	0.34

Table 2
General characteristics of selected storm events

Event No.	Date	Weighted average rainfall depth (mm)	Duration (hr)	Start time
1	25/11/1984	16.6	2	14:00
2	05/09/1985	10.6	2	14:00
3	18/09/1985	11.8	3	15:00
4	19/12/1985	9.2	2	00:00
5	02/03/1986	38.6	3	14:00
6	30/07/1986	54.9	3	15:00
7	14/01/1987	6.9	2	16:00
8	07/08/1987	17.5	5	15:00
9	09/08/1987	17.7	3	16:00

Table 3
Selected hydrograph characteristics (in historical order)

Event No.	Runoff date	Runoff peak (m³/sec)
1	25-Nov-84	73.4
2	05-Sep-85	26.0
3	18-Sep-85	26.4
4	19-Dec-85	22.3
5	2-Mar-86	49.3
6	30-Jul-86	210
7	14-Jan-87	60.0
8	8-Jul-87	63.0
9	8-Sep-87	44.0

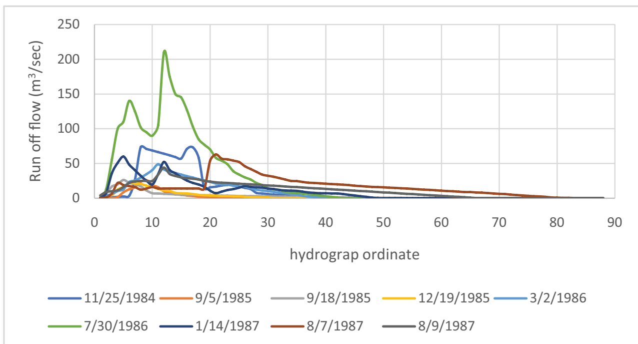

Fig. 3. Selected observed run off hydrograph of Wadi Thara.

runoff ordinates at 5-min intervals. Only 17 significant runoff events are recorded in the paper charts, from which only 9 suitable events are selected for modeling. Table 3 presents runoff peak discharges of these selected nine runoff events extracted from the paper charts. Fig. 3 shows these runoff hydrographs (with timeless ordinates). It is noticed that the peak flow of these nine floods are less than 100 m^3/s (except event in 14th July 1986) and four events appeared with peak flows more than 50 m^3/s.

4.3. Computing runoff volume and flood hydrograph

From Section 2, it was noticed that Wadi Thara has mainly one LCLU feature, which is in arid ranges with desert shrub that can take SCS-CN between 63 for HSG type A and 88 for HSG type D. There are two soil types in Wadi Thara, namely, rock outcrops (81% areal coverage), which represents hydrological soil group type D and alluvial deposits (19%), which represents hydrological soil group type A. The computed composite SCS-CN is found as 83.3.

From the composite SCS-CN, the storage of Wadi Thara is computed using Eq. (1) leading to about 51.0 mm. The initial abstraction is computed by Eq. (2), which is about 10.2 mm. These values are inputs into the rainfall-runoff model to compute the effective rainfall (runoff volumes).

For the flood hydrographs computation, the Clark time of concentration (Clark-T_c) is selected using ADOT equation for mountainous desert regions. Four input parameters are necessary for T_c, which are computed automatically from DEM using Aquaveo WMS software. It is found that the Clark-T_c for Wadi Thara is about 4.16 h, while R coefficient is about 2.23 h.

HEC-HMS software is used to compute the flood hydrographs. Table 4 presents the percentage difference between observed and uncalibrated peak flows, which range from –124% up to +142%, where 78% of values have positive difference (underestimation), the percentage change ranges from –83.2% up to 323.2%, where most of values are in decrease. These results show the importance of rainfall-runoff modeling calibration process in arid regions.

4.4. Calibration and validation

The runoff hydrograph dataset is sub-divided into two main groups, seven runoff events are selected for parameter calibration and two runoff events (the first and the last events) for parameter validation. Table 5 shows the two categories of runoff event and the selected events for calibration and validation.

Four input parameters (SCS-CN, I_a, T_c and R) are used for enhancing the simulated peak discharge flow hydrographs. Already estimated parameters in Section 4.3 are used as initial values. Running the HEC-HMS optimization module for the selected seven events using the input values as mentioned in the previous section produced the calibrated hydrographs given in Fig. 4. It can be seen from Table 6 that six (out of seven) calibrated peak flows are almost exactly the same as the observed one, while event 14th Jan. 1984 failed to produce close peak with –55.7 % difference. The reasons behind this failure may be due to using of local search algorithm.

Calibration process also shows that the average of the optimized SCS-CN, I_a, T_c and R parameters are 81.6, 11.0 mm, 3.81 h and 1.88 h, respectively, where R is the most highly variable with 139% coefficient of variation. These optimized values are used in the validation process for the two selected validation events, which are 25th Nov 1984 and 9th Aug 1987.

In the validation stage, the first and last events are chosen and then the average optimized parameters are used. Validation process results are shown in Table 7, which presents the percentage difference and percentage change between the peak flow observation and the validation. For the 25th Nov 1984 event, the percentage difference and change are 67.4% and –50.4%, respectively, which can be considered as relatively high, while for the 9th Aug 1987 event they are 6.6% and –6.6%, respectively, which are insignificant. Fig. 5 shows the observation and the computation flood hydrographs from the validation process. There are several reasons behind these variations and high errors in the validation process, including the limited number of events available for calibration, the highly variable calibrated parameters, usage of local (non-global) search methods for calibration, etc.

Table 4
Comparison between observed and uncalibrated peak hydrographs for Wadi Thara

Events	Observed	Uncalibrated	% Diff.	% Change
19,841,125	73.4	36.5	67.2	–50.3
19,850,905	26	17.1	41.3	–34.2
19,850,918	26.4	17.7	39.5	–33.0
19,851,219	22.2	14.7	40.7	–33.8
19,860,302	49.1	207.8	–123.6	323.2
19,860,730	210	388.1	–59.6	84.8
19,870,114	60	10.1	142.4	–83.2
19,870,807	63	37.6	50.5	–40.3
19,870,809	44	41.6	5.6	–5.5

Table 5
Selected observed runoff events for calibration and validation (in peak flow ascending order)

Runoff date	Runoff peak (m^3/s)	
19,841,125	73.4	Validation Calibration
19,850,905	26	Calibration
19,850,918	26.4	Calibration
19,851,219	22.2	Calibration
19,860,302	49.1	Calibration
19,860,730	210	Calibration
19,870,114	60	Calibration
19,870,807	63	Validation
19,870,809	44	Validation

5. Conclusions

The main aim of this paper is parameter optimization for the peak flow discharge calibration in Wadi Thara (275 km^2), Western KSA. Seven runoff flows observations are considered for calibration, while two for validation. In the calibration process, the average optimized parameters, SCS-CN, I_a, T_c and R are 81.6, 11.0 mm, 3.81 h and 1.88 h, respectively. Six out of seven calibrated events produced almost exactly the same peak flow as observation, while one ended at underestimation with –55% of change. The reason behind this variation may be that HEC-HMS has only local search algorithms, which produce local minimum objective function and assign optimized value to the parameter that is not in existence. The structure of the lumped hydrological model can also be another reason, where the spatial rainfall variation and the other input parameters are not taken into consideration. In the validation process, the average optimized parameters are applied for other two observed events. The first validated event produced very close peak flow with –6.4% of change, while the second validated event failed to produce a good match to peak flow observation, where the percentage of change was –50.4%. There are several reasons behind this including the limited number of events selected for calibration and the high variability in resultant optimized parameters. In the future, more optimization module applications are necessary with global search algorithm to enhance the parameters estimations. The resultant optimization estimations of Wadi Thara parameters can be used for future simulations and also for similar catchments.

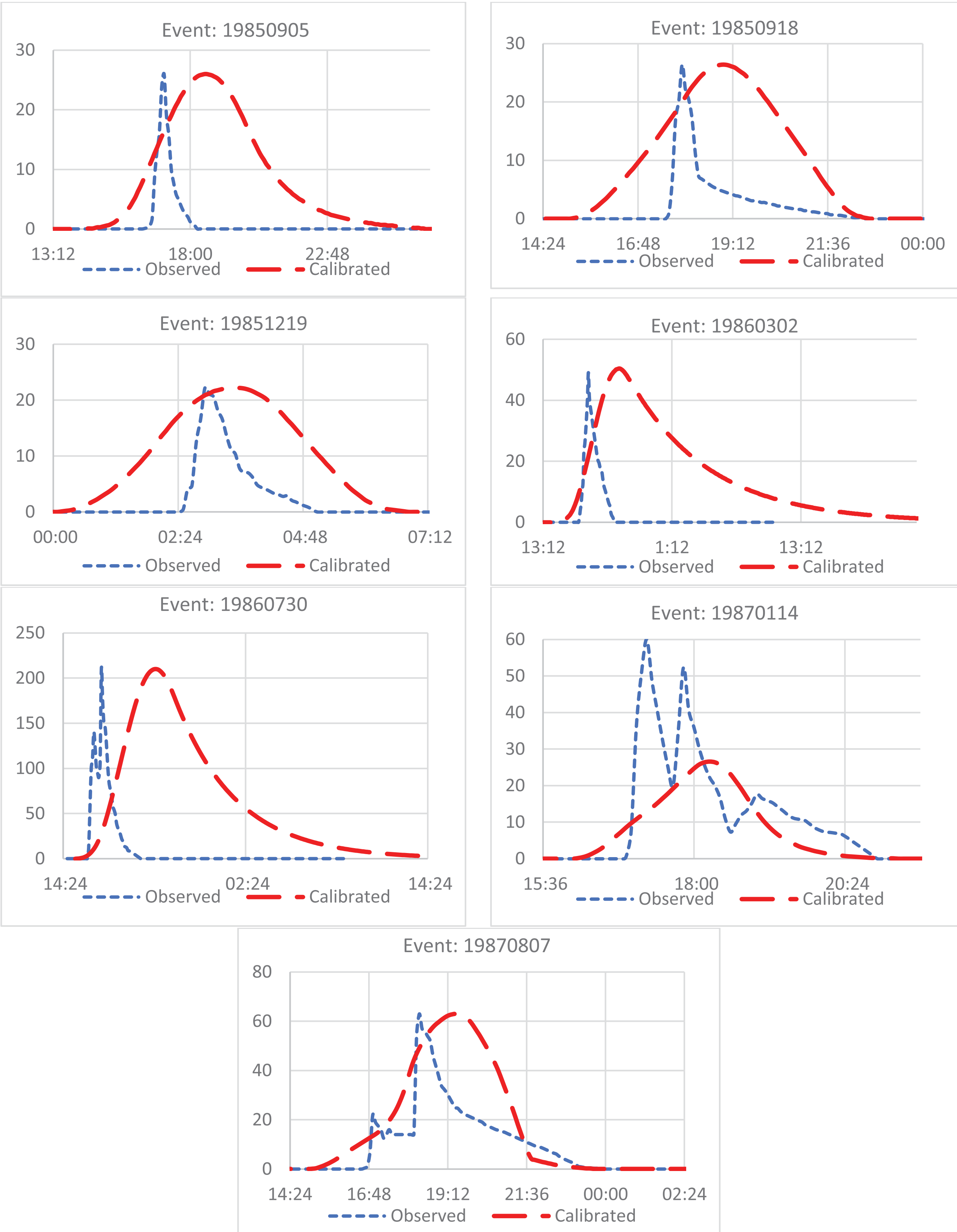

Fig. 4. Observed and calibrated hydrographs of Wadi Thara.

Table 6
Observed and calibrated peak flows of Wadi Thara

Events	Observed	Calibrated	Diff.	% Diff.	% Change
19,850,905	26	26	0	0.0	0.0
19,850,918	26.4	26.4	0	0.0	0.0
19,851,219	22.2	22.2	0	0.0	0.0
19,860,302	49.1	50.4	1.3	–2.6	2.6
19,860,730	210	209.9	–0.1	0.0	0.0
19,870,114	60	26.6	–33.4	77.1	–55.7
19,870,807	63	63	0	0.0	0.0

Table 7
Results of validation process for the two selected events

Event	Peak flow (m^3/s)		GOF tests		
	Observed	Validated	Diff.	% Diff.	% Change
19,841,125	73.4	36.4	–37	67.4	–50.4
19,870,809	44	41.2	–2.8	6.6	–6.4

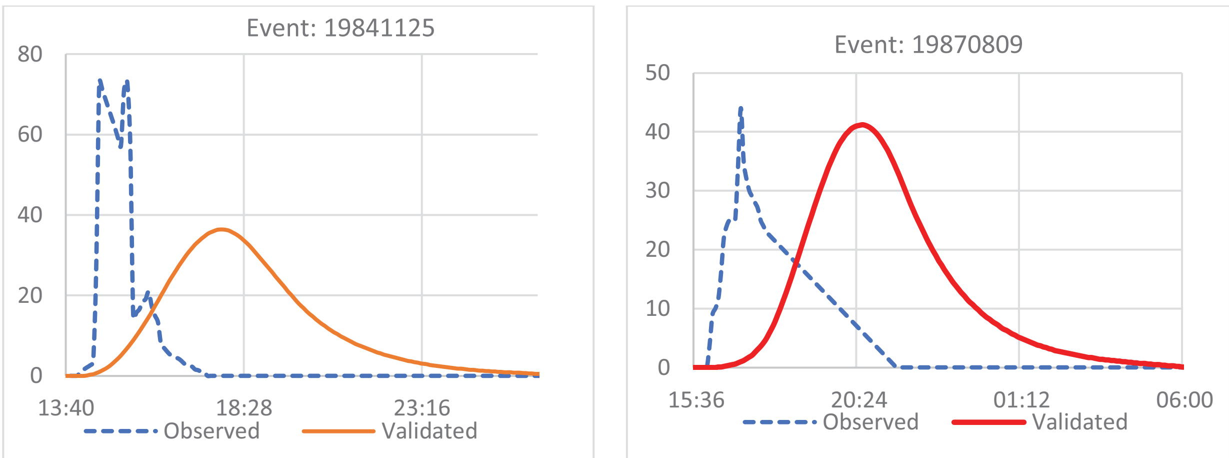

Fig. 5. Observed and the flood hydrographs computed from validation process.

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