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Research Article

Comparison of Rainfall-Runoff Models Using HEC-HMS Software in the Kardeh Dam Watershed

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Abstract

In the present study, the HEC-HMS model was employed to examine and simulate runoff within the Kardeh Dam watershed. WMS and ArcGIS software were utilized to extract the physiographic information of the basin, and the necessary parameters for rainfall-runoff modeling were determined. To evaluate the accuracy and performance of the model in simulating runoff, the SCS + Muskingum (SCSM) and CLARK + Kinematic wave (CLARKK) approaches were applied. The modeling results indicated that the peak discharge at the outlet of the Kardeh Dam basin using the SCSM approach (81.6 m³/s) is lower than that obtained from the CLARKK approach (96 m³/s). The computed runoff volume using the SCSM approach at the basin outlet was estimated to be 1190.9 m³. In the CLARKK approach, the runoff volume was approximately similar; however, the peak discharge differed, being approximately 14 m³/s higher than that of the SCSM approach. The peak inflow to the reservoir was 160 m³/s using the SCSM approach method and 140 m³/s using the CLARKK approach. In both methods, comparison of the observed and simulated hydrographs indicated that the SCSM approach provided greater accuracy in predicting the timing of peak occurrence. For the SCSM approach, the Nash–Sutcliffe efficiency coefficients were computed as 0.9 for sub-basin 3B, 0.4 for sub-basin 4B, and 0.6 for sub-basin 5B, demonstrating the appropriate accuracy of this method. The results revealed a reasonable agreement between the observed and simulated peak runoff discharges, although differences were observed in both the magnitude and timing of peak flows between the models.

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Introduction

Flooding is one of the natural disasters with the most significant economic and social impacts in various regions of the world, and these effects have intensified over time Barati, 2010; Akbari et al., 2012; Ghandehary and Barati, 2018; Sarminingsih and Rezagama, 2019; Shakarneh et al., 2022; Sarvestan et al., 2024; Badfar et al., 2025; Kavosizadeh et al., 2025; Barati et al., 2025). Runoff modeling plays a crucial role in water resources management and the adoption of appropriate measures to mitigate the adverse effects of floods. Due to the considerable complexity of simulating hydrological systems, a comprehensive understanding of the governing processes under current and future conditions is attainable only through modeling. In the United States, major flood events between 2004 and 2014 caused an average of 4 billion USD in direct damages annually and claimed 71 lives per year. However, due to the lack of necessary infrastructure in developing countries, these nations exhibit greater vulnerability to natural disasters. In Iran as well, the geographical location, precipitation patterns, and physical conditions of watersheds give rise to severe flows, with the resulting damages progressively increasing. Therefore, the prediction and management of natural hazards, particularly floods, are of paramount importance (Barati 2011; Barati 2014; Badfar et al., 2021; Atashi et al., 2023a, b, c). Understanding and predicting runoff generation processes and their transmission to watershed outlets constitute a fundamental topic in hydrology. Numerous indirect methods have been developed to simulate the behavior of hydrological systems in order to achieve accurate and comprehensive estimations through complex computations (Rouhani & Farahi Moghaddam, 2013). Rainfall-runoff simulation is a key subject in hydrology, and various rainfall-runoff models are commonly employed to investigate it. Hydrological models are simplified representations of real hydrological systems that assist in analyzing basin performance in response to different inputs and provide a better understanding of hydrological processes. Given the successful results obtained in recent years, these models have attracted the attention of water resources managers. Hydrological models are recognized as one of the primary tools for estimating runoff resulting from precipitation. By simulating the rainfall-runoff process, these models can estimate rainfall-generated runoff in watersheds with minimal time and cost. Despite the diversity of available models, selecting an appropriate model for a given basin is essential for the efficient utilization and optimal management of water resources. In this study, the HEC-HMS model was used to model the rainfall-runoff process in the Kardeh River Basin.

Recent studies have extensively utilized the HEC-HMS model for rainfall-runoff simulation and flood prediction across diverse climatic and geographical settings, including arid environments in Dubai (Khan et al., 2024) and the Safaga Valley in Egypt (2025), tropical and data-scarce basins in Ethiopia (Tassew et al., 2019; Tikur Wuha, 2024; Baro watershed, 2024), as well as semi-arid regions of Iran (Talesh catchment, 2024; infiltration mechanism, 2025). Furthermore, recent methodological advancements have coupled HEC-HMS with hydrodynamic models for dam-breach analysis and flood inundation mapping (Dire Dam, 2024; Radiša catchment, 2025), integrated land-use/land-cover change and climate-change scenarios using CMIP6 data (2025), and benchmarked its performance against machine-learning approaches (Baro watershed, 2024), confirming the model's continued relevance for flood risk assessment and sustainable water resources planning.

This model has been employed in numerous studies worldwide and has generally yielded satisfactory results. In the following section, a review of past research utilizing this model, both domestically and internationally, is presented. Dehghani Firoozabadi et al. (2014) investigated the impact of watershed management practices on flood reduction in the Tarzjan watershed in Yazd, Iran, using the HEC-HMS model. They employed the model to compare discharge variations and the effects of check dams before and after the implementation of watershed management measures. The results indicated that a combination of biological and mechanical measures had the greatest effect on reducing peak flood discharge in this watershed. Rahimzadeh and Habibi (2018) simulated flood hydrographs using the HEC-HMS hydrological model and predicted return periods in the Ravansar watershed in Kermanshah, Iran, concluding that the model possesses a high capability in simulating the hydrological behaviors of the Ravansar basin. Hosseinzadeh and Imeni (2015) conducted hydrological modeling in the

Ghoochak watershed using the HEC-HMS model. For model validation, they extracted five rainfall-runoff events from the Roodak hydrometric station. The model results did not deem the efficiency of the HEC-HMS model in estimating runoff and peak flood discharge acceptable due to differences exceeding 20% between observed and computed peak discharges, and they introduced the model as suitable for hydrological studies only if rational parameters are considered for calibration. Azizi et al. (2021) investigated the effects of land-use change on flood hydrographs using the HEC-HMS hydrological model in the Ekbatan Dam watershed. After model calibration and validation, the simulation results showed an increase in peak discharge volumes of 3.64, 3.67, and 5.70 m^3/s during the years 1985, 2000, and 2015, respectively, which also led to an increase in runoff depth during those years. Shokraneh et al. (2022) modeled rainfall-runoff events using the HEC-HMS model in the southern watersheds of Beit al-Maqdis in the desert region of Palestine. They considered the coefficient of determination and the Nash–Sutcliffe efficiency as indicators of model performance and concluded that the HEC-HMS model can effectively evaluate predicted flow at short time steps under climate scenarios in similar environments. Vakili et al. (2022), in their research, compared the HEC-HMS rainfall-runoff model with various empirical flood estimation methods in the Shah Bahram River basin, utilizing data from the Nazmakan hydrometric station (located in Kohgiluyeh and Boyer-Ahmad Province, Iran). Their results demonstrated that the HEC-HMS hydrological model provided more accurate results with a lower error percentage compared to empirical and analytical methods. International studies have also addressed this model. For instance, NeuPEN et al. (2018) used the HEC-HMS modeling system to predict peak discharge conditions in the Irwin Creek basin located in Charlotte, North Carolina (USA). The results indicated that climate change leads to alterations in precipitation patterns, which will result in the occurrence of intense rainfall events in the future. Sarmainingsih et al. (2019) studied the rainfall-runoff relationship using the HEC-HMS model in the Garang watershed, Semarang, Indonesia. The results showed that this model provides satisfactory outcomes in estimating watershed runoff. Tsew et al. (2019) employed HEC-HMS hydrological modeling to predict peak discharge conditions in the North Nile River basin, Ethiopia. The results indicated that the HEC-HMS model performed well in simulating runoff volume and peak discharge using transformation methods. However, to enhance the model's performance in runoff simulation, it is advisable to use local curve numbers (CN) of the basin instead of standard CN values. Barbosa et al. (2019) studied the effects of spatial discretization on the performance of the HEC-HMS model by simulating the rainfall-runoff process in the upstream basin of the Garing hydrometric station in Brazil. The results demonstrated good agreement between the discharge computed by the model and observed discharge. Furthermore, spatial discretization of the basin's physical characteristics, including slope, land use, and soil type, did not have a significant impact on the performance of the HEC-HMS model. Laxmi et al. (2022) evaluated flood events in the Upper Santer watershed, Indonesia, using the HEC-HMS model. The results indicated that peak discharge for each return period can be effectively assessed. This evaluation analysis can be utilized and further improved for early warning system analysis and better design as a solution.

Numerous hydrological studies and rainfall-runoff modeling efforts have been conducted within the Kardeh Dam watershed. For instance, Sabour Kazaran et al. (2021) carried out a comparative evaluation of the IHACRES and AWBM rainfall-runoff models in the upstream basin of the Kardeh Dam and identified the AWBM model as having superior performance in runoff simulation compared to IHACRES. Furthermore, Salimi Rad et al. (2020), in their study, identified and analyzed the uncertainty of sensitive parameters of the SWAT model for runoff estimation in the Kardeh basin, emphasizing the importance of analyzing distributed hydrological cycle phenomena and comprehensive sensitivity analysis. Their results indicated that the operational capability of the calibrated SWAT model is ensured under various uncertainty conditions within the study basin. Additionally, Salajegheh et al. (2019) focused their research on rainfall-runoff modeling based on a system dynamics approach in the Kardeh Dam basin. By employing six reservoirs to simulate different components of the hydrological cycle and utilizing daily data, they confirmed the high capability of these methods in rainfall-runoff modeling of the basin. In a related context, Garmeh'i et al. (2015)

compared automatic calibration methods (PSO and Nelder-Mead algorithms) applied to the HEC-HMS hydrological model in the Kardeh Dam watershed. They demonstrated that optimization algorithms can effectively improve the fitting of HEC-HMS model parameters and enhance its efficiency in estimating and determining optimal parameter sets.

Despite these valuable studies, each of which has addressed specific aspects of hydrological modeling in the Kardeh Dam basin, the comprehensive calibration and validation of the HEC-HMS model using precise hourly data for rare flood events (such as the flood event of July 20, 2002), as well as a comparative evaluation of the model's performance against empirical flood estimation methods utilizing updated data, have not been systematically and comprehensively examined. The present study addresses this gap by aiming to comprehensively calibrate and validate the HEC-HMS rainfall-runoff model using hourly precipitation and discharge data for the significant flood event of July 20, 2002, in this basin, and by conducting a comparative assessment of the model's performance against common empirical flood estimation methods, along with a detailed analysis of hydrograph components. Accordingly, the Kardeh Dam watershed, located in Razavi Khorasan Province, Iran, was selected as the study area due to the presence of stable and storage rain gauge stations with appropriate spatial distribution across the basin, as well as the existence of a hydrometric station at the Kardeh Dam outlet.

Materials and methods

Study domain

The Kardeh Dam watershed is located in Razavi Khorasan Province, 47 kilometers north of Mashhad County, situated between latitudes 36°40'10" N and 36°56'05" N, and longitudes 59°28'48" E and 59°44'48" E. The watershed area is approximately 457 km². The Kardeh Dam watershed is a mountainous region with a relatively steep slope. This area is located in the southern foothills of the Hezar-Masjed and Kopet-Dagh mountain ranges. Most of the watershed surface is covered by rangelands, the overall condition of which ranges from moderate to poor, with rangelands in good condition observable only at higher elevations. Based on the Amberjeh classification method, the climate of this region is classified as cold semi-arid. Figure 1 shows the location of the Kardeh Dam watershed within Razavi Khorasan Province and Mashhad County. Table 2 presents the physiographic characteristics of the Kardeh Dam watershed.

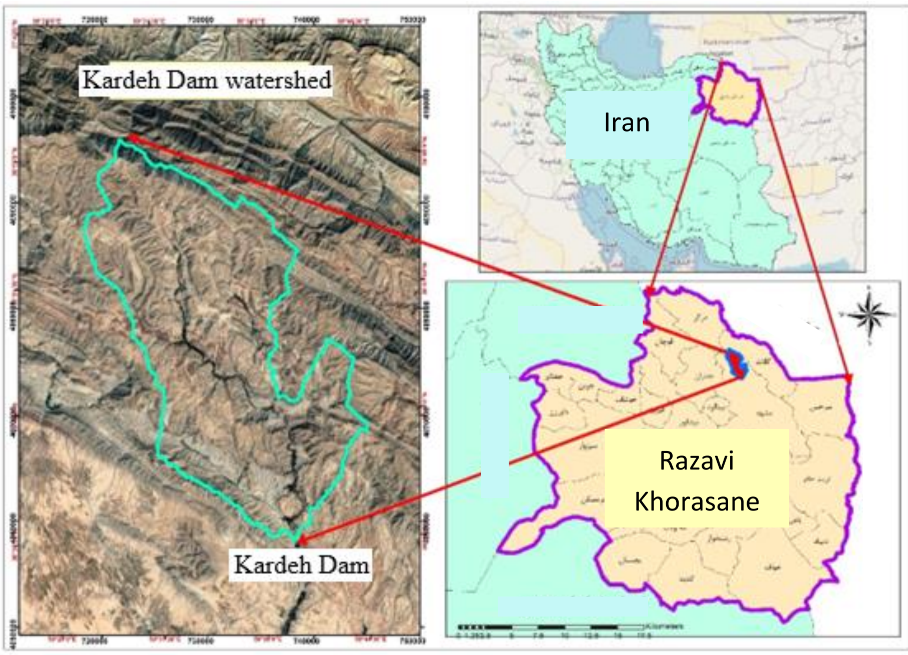

Fig 1. Location of the Kardeh Dam watershed in Iran, Razavi Khorasan Province, and Mashhad County.

Methods

The input information and data for the model used in the simulation are related to the physical characteristics of the watershed. Therefore, the model input data are first prepared. The input information includes the parameters of the basin model and the meteorological model. In this study, ArcGIS 10.8 and WMS software were employed to extract and compute this information. To this end, a Digital Elevation Model (DEM) of the study area with a spatial resolution of 10 meters was first generated from the topographic maps of the National Cartographic Center of Iran using the Topo to Raster method, which employs elevation interpolation functions. Subsequently, by importing the DEM into the WMS software environment, the basin boundary, sub-basins, and stream networks were delineated using watershed delineation methods. The physiographic characteristics of the sub-basins and waterways were then extracted, and the model output was prepared for import into HEC-HMS. To introduce precipitation data, there are seven methods available in HEC-HMS; in this study, the station weighting method was used as the appropriate meteorological model. Control specifications, including the date and time for the start and end of the simulation as well as the time step for performing calculations, are entered into the software. After introducing the type of meteorological model and control specifications for the basin, the desired precipitation can be simulated. Precipitation across the basin is measured in a pointwise manner through the existing network of stations operated by the Ministry of Energy and the Meteorological Organization.

After data collection and computations, a consistency check between the amount and temporal distribution of precipitation and the shape and volume of the flood hydrograph was performed, leading to the selection of the rainfall event and its corresponding flood event for the date of July 20, 2002. The input data for the hydrological model include the rainfall event at the Sabut Al and Marshak rain gauge stations and the flood event at the Kardeh Dam hydrometric station for the aforementioned date. Following the selection of the target flood event, daily precipitation data were extracted from the rain gauge stations at Al, Marshak, Bolghour, and Jang (interior), as well as Goush Bala and Kardeh Dam (near the Kardeh Dam watershed) for the day of the flood occurrence. The precipitation data from the aforementioned stations are presented in Table 1. The spatial distribution of these stations is also presented in terms of UTM.

Table 1. The daily precipitation amounts recorded at the rain gauge stations of the Kardeh Dam watershed

Station Name	**Al**	**Marshak**	**Jang**	**Kardeh Dam**	**Goush Bala**	**Bolghour**
Geographic Coordinates (UTM)						
X	738162	727059	731133	740695	728919	727732
Y	4066787	4077157	4073498	4056093	4066633	4086525
Precipitation Amount (mm)	4.10	3.27	0.20	0.50	3.11	3.16

2.3 Physiographic Characteristics of the Kardeh Dam Watershed

To obtain the physiographic characteristics of the Kardeh Dam watershed, after preparing a Digital Elevation Model (DEM) with a spatial resolution of 10 meters using topographic maps from the National Cartographic Center of Iran within the ArcGIS 10.8 software environment, the prepared DEM was imported into the WMS software. Using the tools of the Drainage module, the watershed was delineated by defining the outlet at the Kardeh Dam location. Subsequently, based on the main river branches leading to the Kardeh Dam, the watershed was divided into three sub-basins. It should be noted that the Kardeh Dam watershed is located within UTM Zone 40, and the relevant coordinate system settings were applied in the software used.

Among the most important physiographic characteristics of the watershed are the area of the sub-basins, slope value, storage coefficient, channel length, lag time, and time of concentration. These parameters are extracted from the Digital Elevation Model (DEM) and the formulas and functions embedded in the WMS software. For computation based on the embedded formulas, it is necessary to introduce the Curve Number (CN) values. This parameter is prepared for the watershed by integrating hydrological soil groups and land use. Given that land use changes play a major role in precipitation losses and runoff reduction, and influence the flood hydrograph, these two parameters must correspond to the same year. Therefore, the land use layer of the watershed was prepared with high accuracy using the 1:25,000 cover maps of the National Cartographic Center of Iran for the year 2002 (1381 Persian calendar). Furthermore, the hydrological soil groups layer was downloaded and extracted from the HYSOGs250m dataset, which comprises soil hydrological groups (HSGs) developed based on USDA standards at a regional scale, with a publication date of 2018. Using the HEC-HMS model embedded in the Hydrologic module of the WMS software, the Curve Number (CN) parameter of the watershed is input, and the lag time is calculated based on the SCS method, while the time of concentration is computed using the Kirpich formula. These selections were made to leverage the advantages of each method in estimating distinct aspects of these two parameters. The SCS method was deemed appropriate for estimating the overall lag time of the watershed's response to precipitation due to its comprehensiveness in incorporating soil properties and vegetation cover. In contrast, the Kirpich formula was selected as a suitable option for determining the travel time of surface flow in the study basin due to its focus on the physical characteristics of the flow path and its simplicity.

Subsequently, the index of the 1:25,000 topographic maps (Figure 2), the Digital Elevation Model (DEM) (Figure 3a), the map of the watershed and sub-basins (Figure 3b), the selected rain gauge stations within the watershed (Figure 3d), the Curve Number (CN) map (Figure 3c), the tables related to the physiographic characteristics of the Kardeh Dam watershed (Table 2), as well as the formulas for calculating lag time and time of concentration, are presented.

Lag Time Formula Using the SCS Method:

$$T_L = \frac{L^{0.8}(S+1)^{0.7}}{1900Y^{0.5}} \qquad (1)$$

where T_L is the lag time in hours, L is the length of the longest flow path in feet, S is the maximum retention capacity in inches, and Y is the average slope in percentage.

Formula for calculating the maximum retention capacity:

$$S = \frac{1000}{CN} - 10 \qquad (2)$$

Kirpich method formula for time of concentration

$$T_c = 0.949\left(\frac{L^3}{H}\right)^{0.385} \qquad (3)$$

where tc is the time of concentration in hours, L is the length of the main channel in kilometers, and H is the elevation difference of the watershed in meters.

Calculation of routing parameters:

In this study, two models, namely the kinematic wave model and the Muskingum model, were employed for routing the river flow leading to the Kardeh Dam. The parameters relevant to each model are presented below for input into each respective model.

Kinematic wave model:

To implement kinematic wave modeling, spatial and hydraulic information pertaining to the main channel's longest flow path, longitudinal slope, Manning's roughness coefficient, and the geometric characteristics of the trapezoidal channel cross-section (including bottom width and side slopes) were extracted using GIS spatial analysis tools within the WMS software and standard tables for determining roughness coefficients. These values, after processing, were transferred to the HEC-HMS model as corresponding inputs. The extracted values for the study basin are presented in Table 3. Characteristics of the trapezoidal channel section was depicted in Figure 4.

Muskingum model:

To calculate the K and X parameters, the information and values obtained from WMS, which were computed at the basin outlet, were utilized. In this study, the value of K was considered to be slightly greater than the lag time (2 hours), while X, which typically ranges between 0 and 0.5, was taken as an average of 0.25.

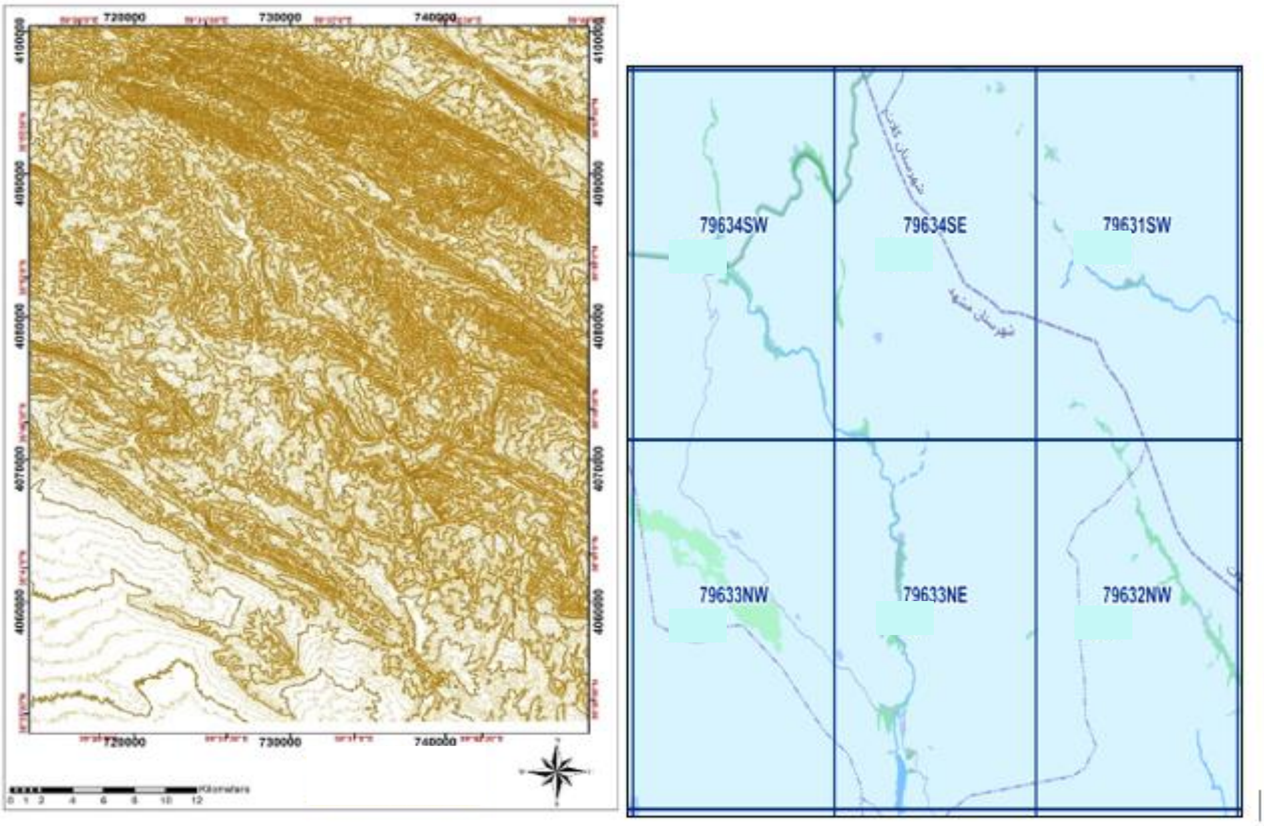

Fig 2. Index number of the 1:25,000 cover map for extracting information in the study basin, Topographic contours of the 1:25,000 maps for DEM extraction in the study basin

Table 2. Extracted physiographic information of the Kardeh Dam watershed

Sub-basin Name	Area (km²)	Longest Channel (km)	Slope (%)	CN	Lag Time (hr)	Time of Concentration (hr)	Maximum Retention Capacity
3B	223	35.09	28.23	86	2.18	3.53	1.63
4B	92	21.67	31.30	84.5	1.48	2.18	1.83
5B	190	21.19	26.72	88.5	1.36	2.02	1.30
Watershed	505	56.28	28.7	86.3	3.12	5.74	1.59

Table 3. Extracted information for the kinematic wave model

Longest Channel (m)	Channel Slope	Manning's Coefficient	Trapezoidal Bottom Width (m)	Side Slope
56,280	0.02	0.035	30	3

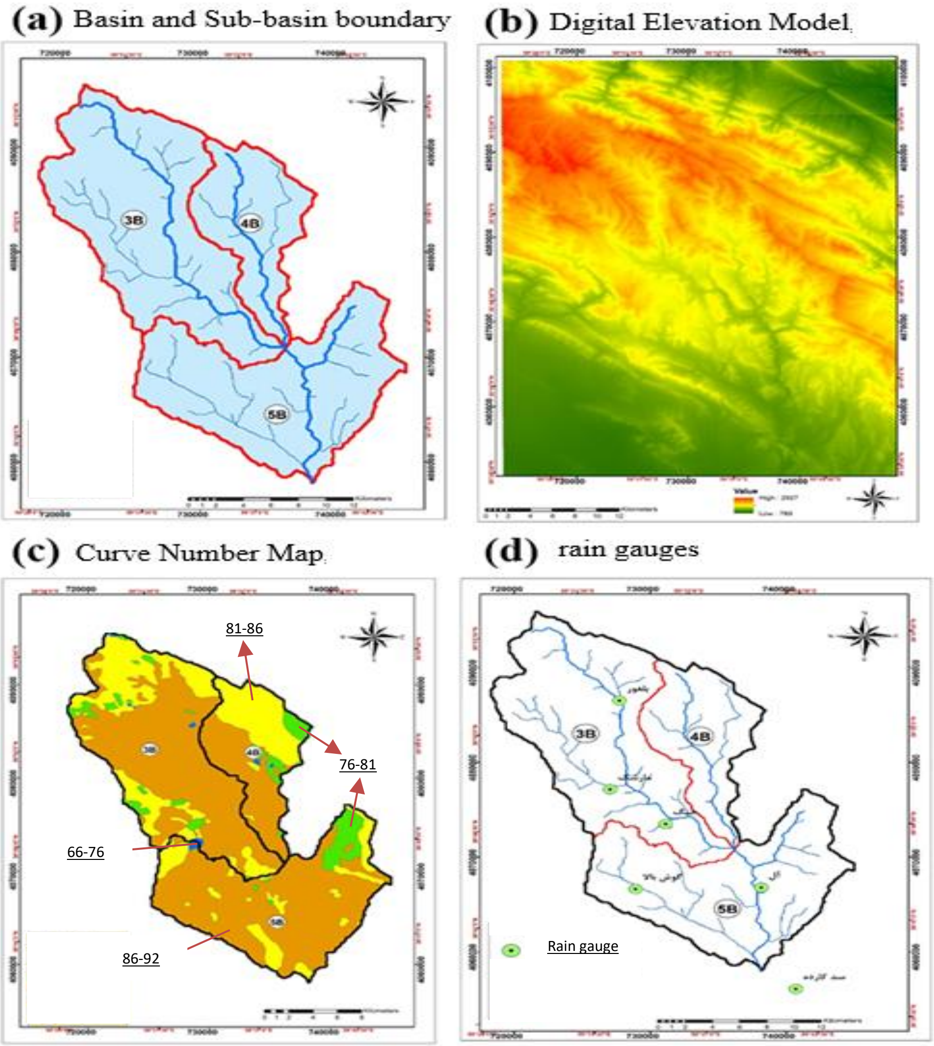

Fig 3. (a): Basin and Sub-basin boundary, (b): Digital Elevation Model, (c): Curve Number, and (d): rain gauges

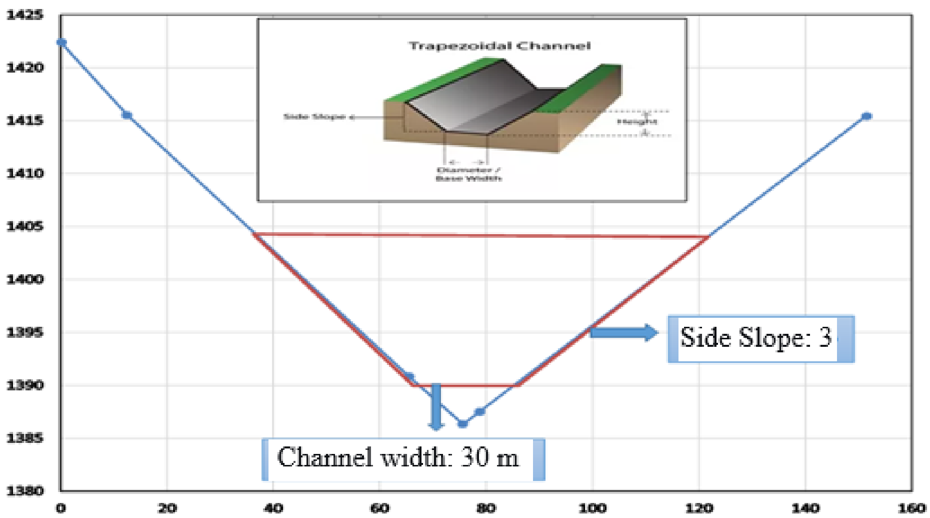

Fig 4. Characteristics of the trapezoidal channel section

2.4 Modeling Method in HEC-HMS

Since the HEC-HMS software has the capability to perform network-based rainfall-runoff modeling, this software was utilized in the present study. Simulating and calculating the hydrograph in a watershed requires the introduction of four models. After drawing the schematic topology of the watershed and the stream network in the basin model, the models for loss calculation, baseflow, rainfall-runoff transformation, and routing are determined. Dynamic information pertaining to precipitation from rain gauge stations and hydrometric stations is entered into the basin's time series data management model, and is then assigned to the relevant sub-basins in the meteorological model. In the control model, the simulation time window and time step are determined. Input information in the basin model is related to the physical characteristics of the watershed. After introducing the sub-basins, their characteristics, including area, loss model, baseflow determination model, and rainfall-runoff transformation model, must be specified. Figure (5) shows the basin model within the HEC-HMS software environment.

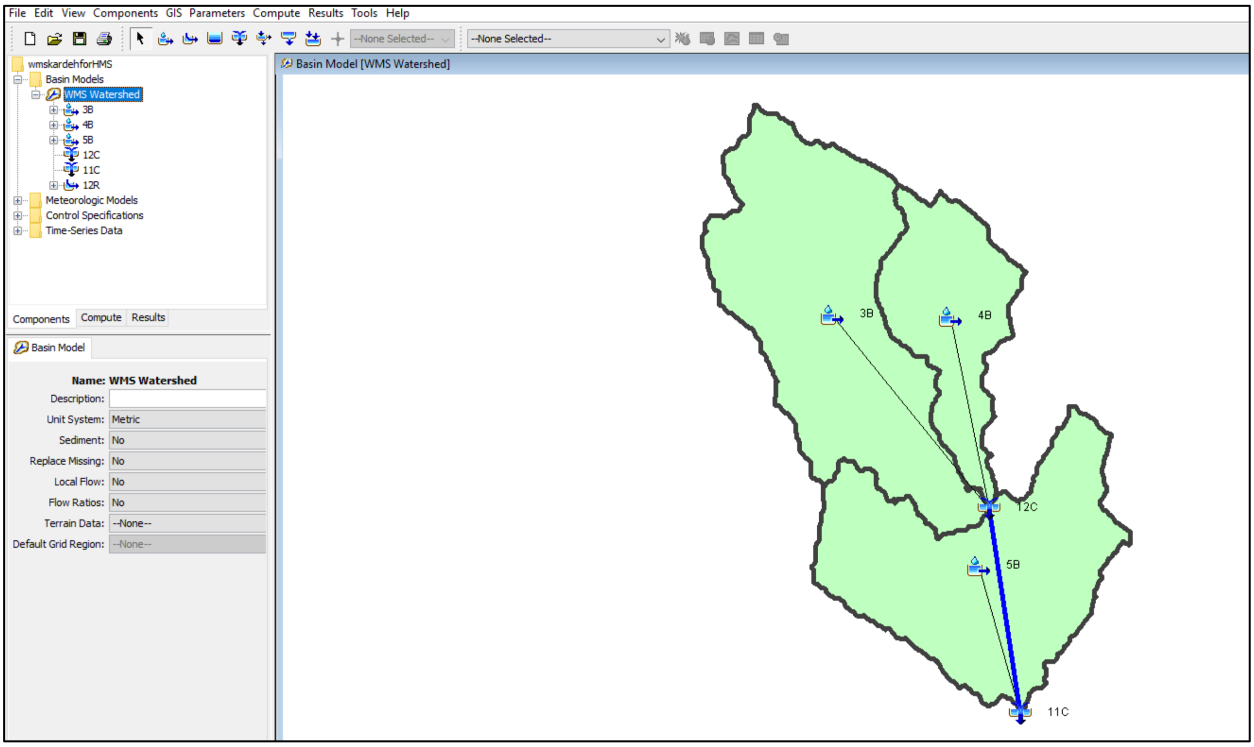

Fig 5. The basin model in the HEC-HMS software environment

Results and Discussion

After inputting the data and completing the basin model, the simulation process was executed for observed rainfall events according to the available information, and the model's simulated hydrographs were obtained. Rainfall data for the storm event dated 29 April 2002 were collected from meteorological stations within the Kardeh Dam basin, including the Al and Marshak meteorological stations. To estimate the rainfall amount in each sub-basin (3B, 4B, and 5B), the Thiessen Polygon weighting method was employed to allocate areal rainfall from the station data to each sub-basin. The estimated values for sub-basins 3B, 4B, and 5B were 27.3 mm, 35.0 mm, and 24.5 mm, respectively. The 6-hour temporal distribution for this storm event was determined based on the analysis of the rainfall hyetograph and the hourly data recorded by the recording rain gauges corresponding to the observed event dated 29 April 2002. This 6-hour duration reflected the actual and effective rainfall length, encompassing the greatest volume of effective precipitation and generating significant runoff. This approach enhances the accuracy of simulating the basin's dynamic response to precipitation and aligns with the actual conditions of the event. These rainfall values and the temporal distribution were introduced into the model. Furthermore, the observed discharge for the aforementioned storm event was also configured for model calibration and validation on the same day of the event. The results of the model run are presented below in the form of observed and computed hydrographs.

For rainfall-runoff simulation, the Soil Conservation Service (SCS) curve number method was employed to compute rainfall losses, the SCS unit hydrograph and the Clark unit hydrograph were used to calculate the surface runoff hydrograph, and the Muskingum and kinematic wave methods were applied for river flow routing. Additionally, in this study, the routing of the Kardeh Dam was simulated as a reservoir. In this manner, the inflow hydrograph to the dam reservoir undergoes deformation due to the storage conversion process and, subsequently, the conversion of storage to outflow from the dam. This deformation of the inflow hydrograph was analyzed under the heading of reservoir flow routing. First, the reservoir storage volume was extracted based on the dam height using WMS software. The height of the Kardeh Dam from its foundation was considered to be 68 meters, located at an elevation of 1,288 meters above sea level in terms of topography. Subsequently, the spillway discharge, with a spillway length of 144 meters, was calculated according to Equation (4) and input into the reservoir storage model within HEC-HMS.

$$Q = C \times L \times H^{1.5} \quad (4)$$

where: Q = Flow discharge (m³/s), C = Spillway coefficient (here taken as 2.225), L = Effective crest length of the spillway (m), here 144 m, and H = Water head above the spillway crest (m).

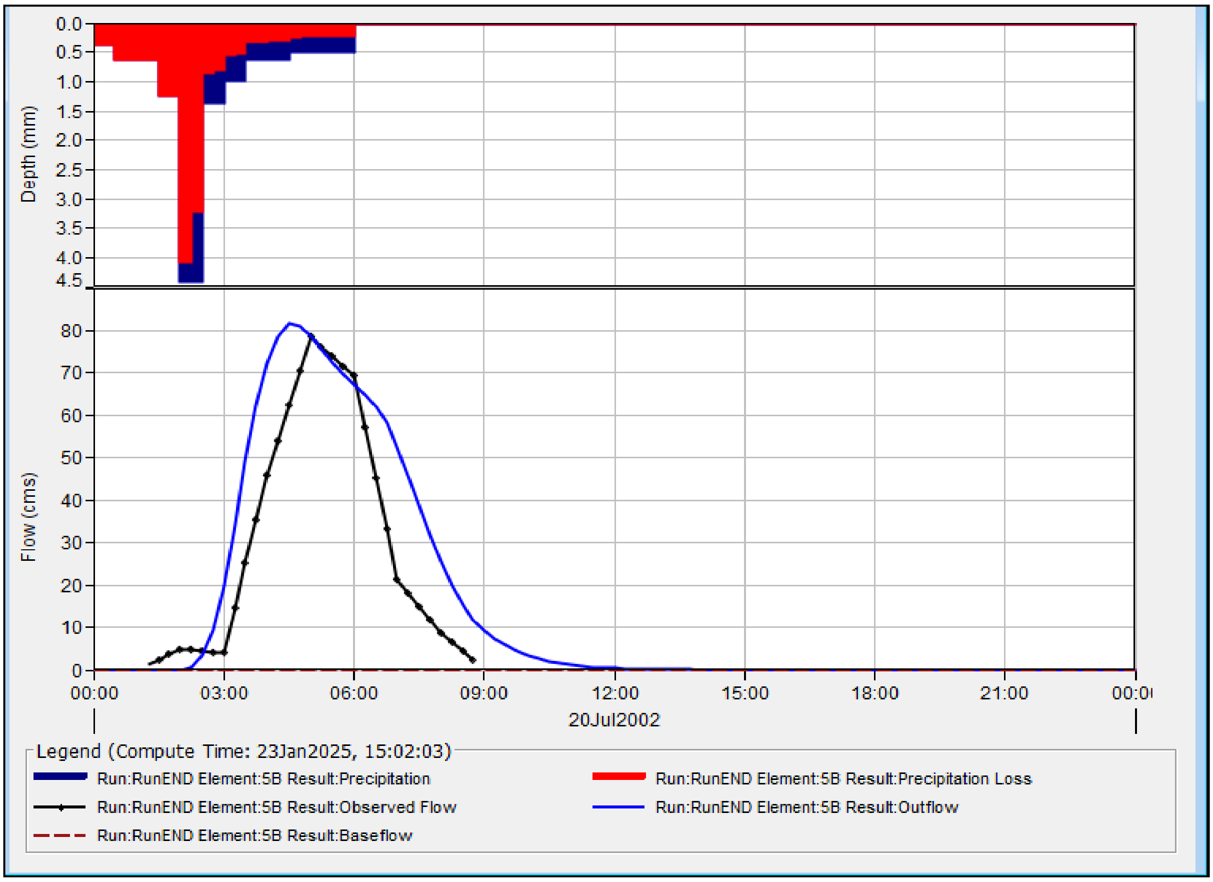

Fig 6. Rainfall-Runoff Hydrograph (SCS + Muskingum) at the Outlet of the Kardeh Dam Catchment

Figure (6) presented Rainfall-Runoff Hydrograph (at the Outlet of the Kardeh Dam Catchment The simulated hydrograph exhibits generally good agreement with the shape and trend of the observed hydrograph. However, the peak discharge time of the simulated hydrograph (blue line) occurs slightly earlier, and its peak magnitude is estimated to be somewhat higher than the observed discharge (black line). These discrepancies may be attributed to factors such as the temporal resolution of the input rainfall distribution (6-hour intervals) and the calibration approach for parameters influencing flow routing and rainfall-runoff conversion, including time of concentration (Tc) and the storage coefficient within the HEC-HMS model. Furthermore, the contribution of baseflow to the total outflow is negligible, indicating the dominance of surface runoff resulting from the intense rainfall event in this catchment.

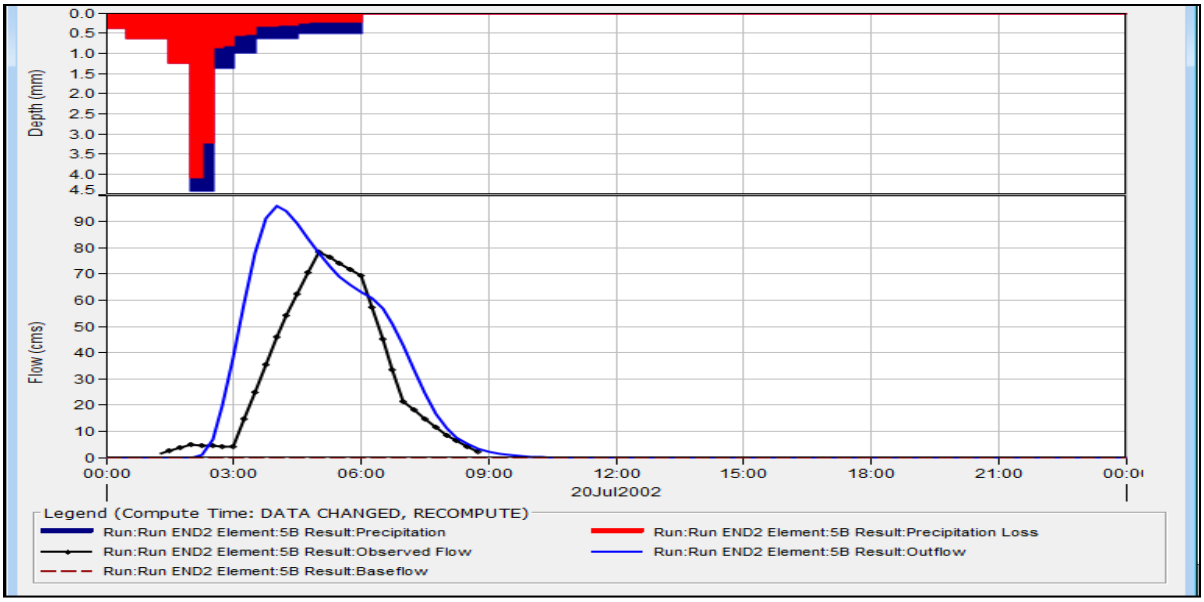

Fig 7. Rainfall-Runoff Hydrograph (Clark + Kinematic Wave) at the Outlet of the Kardeh Dam Catchment

The simulated rainfall-runoff hydrograph obtained using the Clark + Kinematic Wave method (see Figure 7) does not exhibit significant changes in loss calculations compared to the SCS + Muskingum method. Consequently, the volume computations are approximately equivalent in both methods, and the only difference between the results lies in the peak discharge values.

The implementation of the simulation model for reservoir routing of the Kardeh Dam is presented below in Figures (8) and (9).

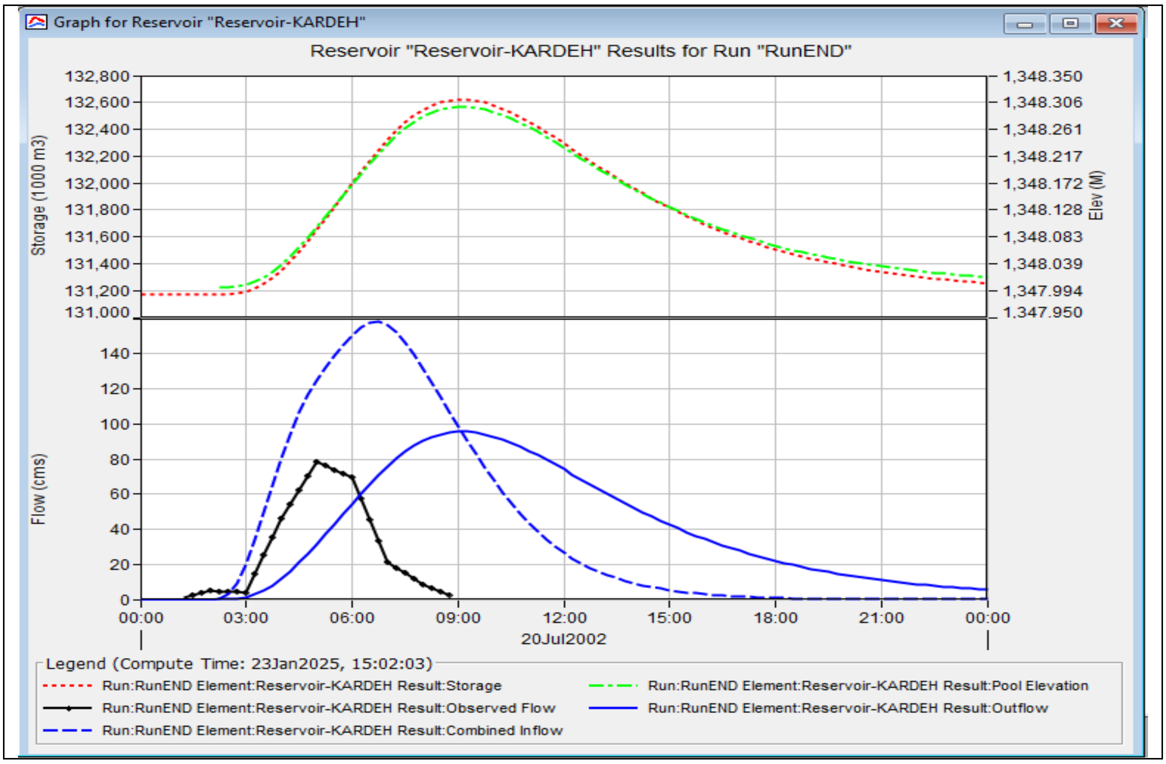

Fig 8. Reservoir Routing at Kardeh Dam Using the (SCS + Muskingum) Method

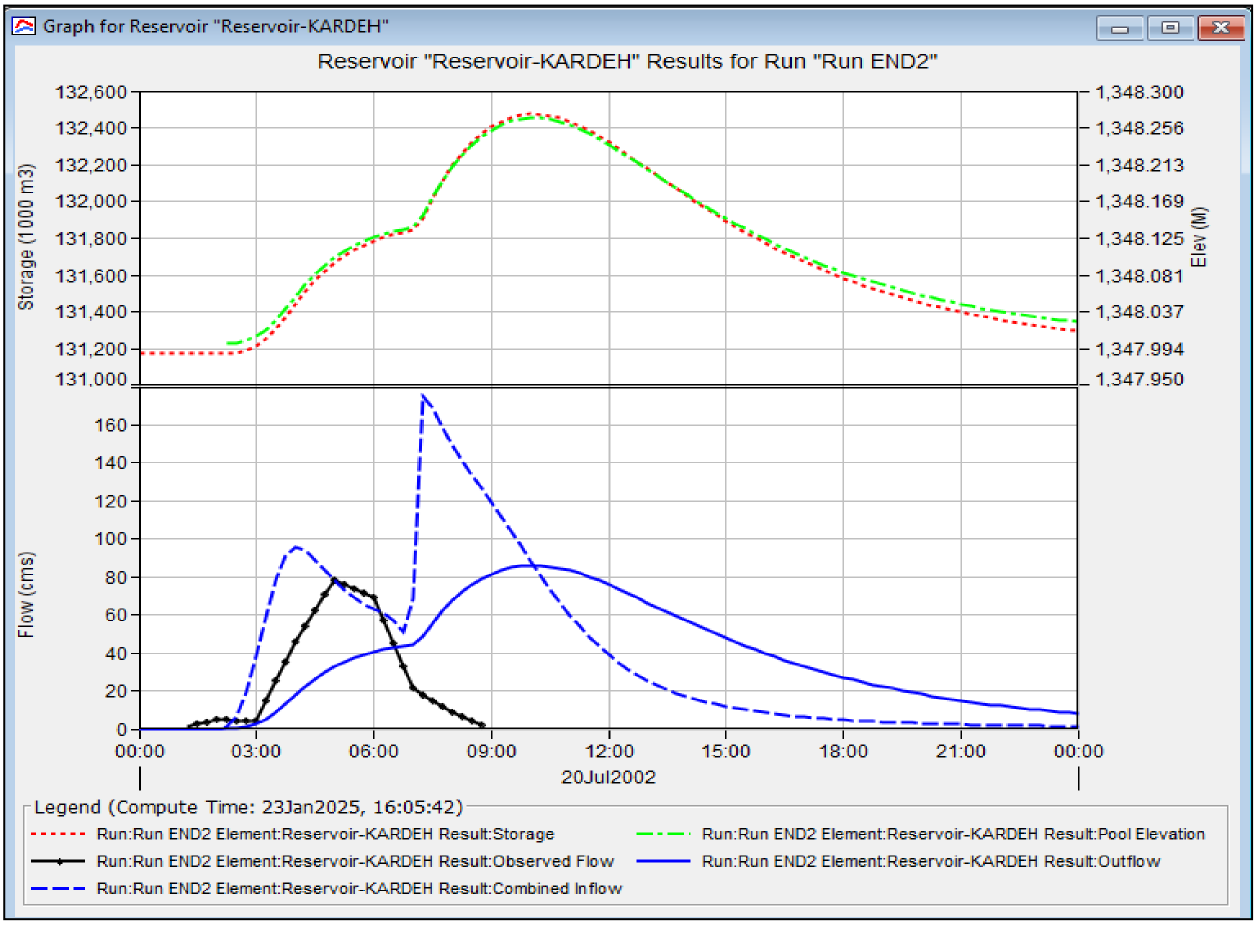

Fig 9. Reservoir Routing at Kardeh Dam Using the (Clark + Kinematic Wave) Method

The analysis of the reservoir routing graphs for the two modeling methods is described below.

Differences:

Observational modeling and inputs:

In the second method, the observed flow values deviate markedly from the modeled outflow values. In contrast, the graph of the first method shows greater concordance between these two lines. The combined inflow in the first method's graph appears to have higher precision and better represents the main peak flow.

Peak flow magnitude:

In the second method's graph, the peak inflow and outflow reach a maximum of approximately 160 cms, whereas in the first method's graph, this value is approximately 140 cms. The timing of the peak also differs slightly between the two graphs; however, in the first method's graph, the inflow and outflow peaks are closer to reality.

Reservoir storage behavior:

In the storage section, the graph of the first method (red line) exhibits a more uniform reduction, whereas the second method's graph shows more abrupt fluctuations.

Similarities:

Both graphs display the overall trend of changes in reservoir storage and outflow. The onset timing and recession of inflow and outflow are approximately similar in both methods.

Simulation Validation

To assess the accuracy of the simulation performed by the software, it is necessary to introduce and define objective functions. An appropriate objective function is one that can bring the observed and simulated hydrographs as close as possible. In this study, the performance of two functions—the root mean square error (RMSE) and the Nash–Sutcliffe efficiency (NSE)—has been evaluated.

Root Mean Square Error (RMSE) function:

This function represents the difference between the value predicted by the model or statistical estimator and the actual value, and it is used to compare prediction errors across a dataset. It is calculated according to Equation (5).

$$RMSE = \frac{\sqrt{\sum(Q_O - Q_S)^2}}{N} \qquad (5)$$

In this relationship, Q_O represents the observed data and Q_S represents the simulated data. This function is among the most widely used functions in the field of hydrological model simulation.

Nash–Sutcliffe efficiency (NSE) function:

Among the functions employed in this study is the Nash–Sutcliffe efficiency criterion. If the value of this function equals 1, there is perfect agreement between the observed and simulated data. A value of zero indicates that the model performs no better—and no worse—than using the mean of the observed data. If the NSE value exceeds 0.75, the simulation results are described as good, whereas values between 0.36 and 0.75 indicate that the model results are satisfactory. This function is expressed according to Equation (6).

$$NSE = \frac{\sqrt{\sum(Q_O - Q_S)^2}}{N} \qquad (6)$$

In this relationship, Q_O represents the observed data, Q_S the simulated data, and $\bar{Q}_O$ the mean of the observed values. Subsequently, the results obtained from the rainfall-runoff modeling using the HEC-HMS model, based on the objective functions and other computational parameters such as flood volume, peak discharge, and time to peak, are presented in Table (4).

Table 4. Flood volume, peak discharge, and time to peak

Method	Sub-basin	Peak Discharge (m³/s)	Computed Volume (thousand m³)	Time to Peak	RMSE	NSE
SCS + Muskingum	3B	76.0	1335.4	06:00	0.9	0.158
SCS + Muskingum	4B	55.2	839.7	04:45	0.4	0.799
SCS + Muskingum	5B	81.6	1190.9	04:30	0.6	0.647
Clark + Kinematic Wave	3B	90.8	1335.4	05:30	0.8	0.338
Clark + Kinematic Wave	4B	61.2	839.7	04:30	0.4	0.829
Clark + Kinematic Wave	5B	96.0	1190.9	04:00	0.8	0.325

Simulation Calibration:

Calibration is defined as the process of adjusting model parameters until an acceptable agreement is achieved between the model results and measured observations. In this procedure, initial values are assumed for the parameters, and the objective function is calculated. Subsequently, in successive iterations, the parameter values are modified by the user within their permissible ranges until the objective function reaches its minimum value. Parameters such as the curve number and lag time are among the critical factors in predicting the runoff model for the basin in the present study. Accordingly, initial values were calculated for each of the aforementioned parameters. Then, based on the input data, the rainfall-runoff model was simulated for the various sub-basins. Subsequently, to achieve a more thorough and precise analysis of the observed and simulated results, calibration was performed on parameters including the curve number, lag time, and the X coefficient. It is noteworthy that, based on the results, the (SCS + Muskingum) method model was subjected to calibration. The results obtained are presented in Figure (10).

With reference to Figure 5, no substantial change in the shape of the hydrograph has occurred, and calibration has only succeeded in bringing the peak discharge slightly closer to the observed peak discharge. According to Table 5, it can be seen that no significant change has occurred in the simulation error rate or in the other modeling parameters, which indicates the high power and accuracy of the HEC-HMS software model in rainfall-runoff modeling for this basin.

Conclusion

Given the development and advancement of hydrological models in simulating runoff flow, selecting an appropriate model for the study area is of particular importance. In this study, the HEC-HMS model was used to investigate and simulate runoff in the Kardeh Dam watershed, while WMS and ArcGIS software were employed to extract the physiographic information of the basin, and the necessary parameters for rainfall-runoff modeling were determined. Subsequently, by running the model under two different scenarios, namely (SCS+Muskingum) and (Clark+kinematic wave), the accuracy and performance of the model in simulating surface runoff and flow routing were evaluated.

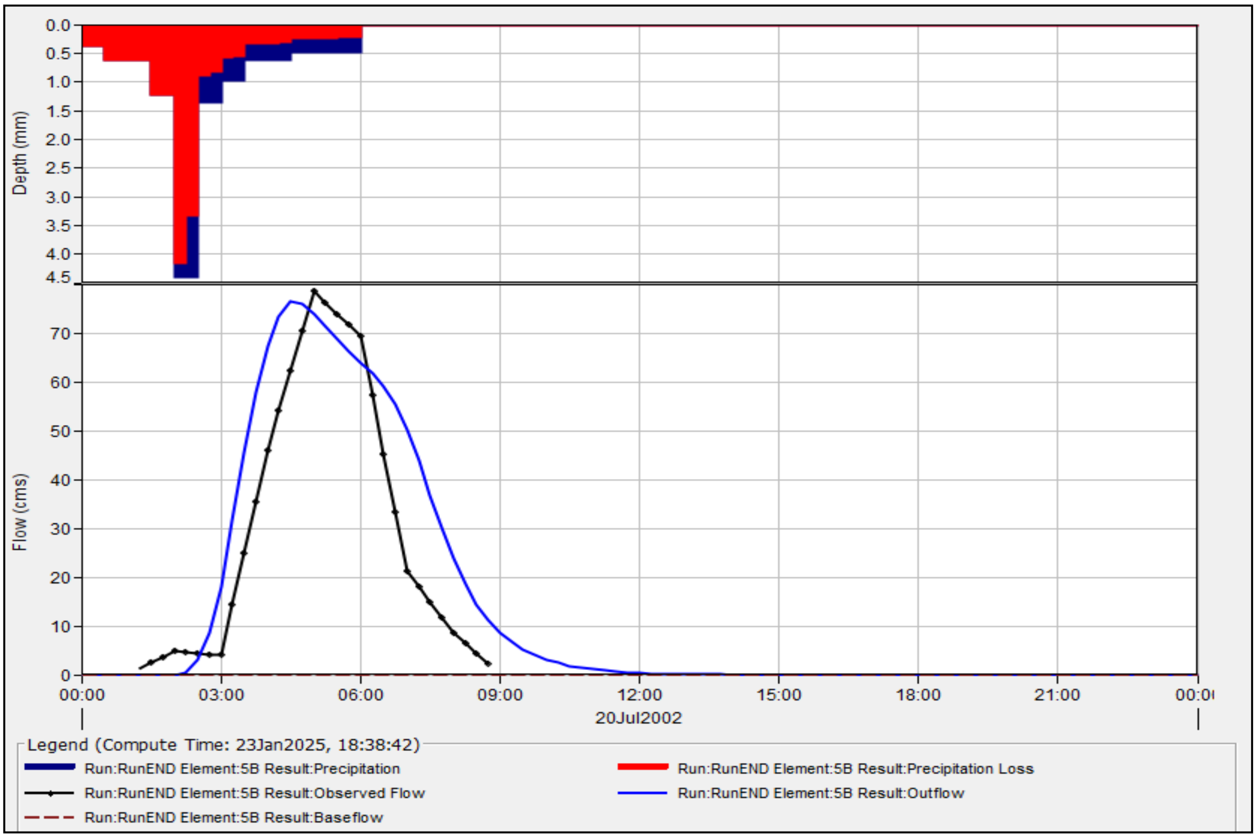

Fig 10. Observed and Computed Hydrographs Resulting from Model Calibration Using the (SCS + Muskingum)

Method

The curve number, lag time, and the X coefficient. It is noteworthy that, based on the results, the (SCS + Muskingum) model was calibrated. The results obtained are presented in Table (5).

Table 5. Calibration results for the (SCS + Muskingum) method

Sub-basin	Peak Discharge (m^3/s)	Computed Volume (thousand m^3)	Time to Peak	RMSE	NSE
SCS + Muskingum					
5B	76.4	1119.3	4:30	0.5	0.731

The results indicated a reasonable agreement between the observed and simulated peak runoff discharges, although differences were observed in both the magnitude and timing of peak flows between the models. In the modeling performed, it was found that the SCS+Muskingum method performed better in estimating peak discharge and runoff volume and provided greater accuracy across different time intervals. Furthermore, in the flow routing analysis, the Clark+kinematic wave method exhibited differences in peak discharge values, indicating the greater sensitivity of this method to initial conditions and input parameters. Additionally, the comparison of results showed that the baseflow magnitude in both models was negligible and had little influence on the outflow discharge.

The reservoir routing of the Kardeh Dam was also examined in this study, and the results demonstrated that in both modeling methods, the trend of reservoir water level changes showed relative agreement with observed data. Nevertheless, differences were observed in the outflow discharge and peak flow between the models, indicating the sensitivity of the model to input parameters and the necessity for more precise calibration. The modeling results showed that the peak discharge values in the different sub-basins are as follows: In the SCS+Muskingum method, the highest peak discharge of 81.6 m^3/s was recorded in sub-basin 5B. In the Clark+kinematic wave method, the highest peak discharge of 96 m^3/s was observed in sub-basin 5B. The computed runoff volume also varied across different methods: In the SCS+Muskingum method, the runoff volume in sub-basin 3B was estimated at 1335.4×10^3 m^3, in sub-basin 4B at 839.7×10^3 m^3, and in sub-basin 5B (outlet leading to Kardeh Dam) at 1190.9×10^3 m^3. In the Clark+kinematic wave method, these values were approximately similar, but with a difference in peak discharge of approximately 14 m^3/s higher than the SCS+Muskingum method.

Data analysis revealed that the peak flow timing in the SCS+Muskingum method for sub-basin 3B was 6:00 AM, for sub-basin 4B was 4:45 AM, and for sub-basin 5B was 4:30 AM. Meanwhile, in the Clark+kinematic wave method, these values shifted to 5:30 AM, 4:30 AM, and 4:00 AM, respectively. This difference indicates the sensitivity of the models to the hydrological parameters of the basin. In the routing process of the Kardeh Dam reservoir, the results showed that the peak inflow to the reservoir was 160 m^3/s using the SCS+Muskingum method and 140 m^3/s using the Clark+kinematic wave method. In both methods, a comparison of the observed and simulated hydrographs indicated that the SCS+Muskingum method provided greater accuracy in predicting the timing of peak occurrence. The Nash–Sutcliffe efficiency coefficients for the SCS+Muskingum method were computed as 0.9 for sub-basin 3B, 0.4 for sub-basin 4B, and 0.6 for sub-basin 5B, demonstrating the appropriate accuracy of this method.

The results of this study are inconsistent with those of Hassanzadeh (2021), who compared the RRL rainfall-runoff models in the Kardeh Dam watershed, indicating that the RRL software model cannot simulate peak values in some cases and often does not adequately estimate minimum values either. In periods with no precipitation, the discharge was zero, which is attributed to the model's neglect of surface water and groundwater flow. In the study by Hosseini Fakhr (2021), who evaluated rainfall-runoff models in the Kardeh Dam watershed using the IHACRES and AWBM models, the results showed that the AWBM model provided more satisfactory outcomes. One of the reasons for this is the use of a greater number of effective parameters in flow routing, which enabled the model to bring the flow simulation closer to the real conditions prevailing in the region. According to the findings of Hosseini Fakhr's research, it is concluded that in both models, one cannot utilize more than one meteorological and hydrometric station or other regional information; although this simplifies the modeling process for the researcher, it weakens the simulation accuracy, representing a drawback of these two models. Therefore, the results indicate that the HEC-HMS model will yield better modeling outcomes.

Based on the research findings, the following recommendations are proposed to improve the accuracy of runoff modeling and hydrological analyses in future studies: It is recommended that precipitation and discharge data with higher resolution and longer time periods be utilized to enhance the accuracy of model calibration and validation. Parameters such as land use, soil type, and riverbed roughness coefficient can significantly influence model accuracy; therefore, it is advised that these parameters be examined more rigorously in future investigations. The use of long-term precipitation and discharge data from adjacent hydrometric stations could increase the accuracy of the results. In this study, the influence of groundwater on runoff was neglected; incorporating a subsurface model could lead to a considerable improvement in the accuracy of the results. The integration of different models, such as SWAT or MIKE SHE, with HEC-HMS could provide a more comprehensive analysis of hydrological processes. It is also recommended that in future analyses, the return period of precipitation events, the duration of rainfall events, and the actual reservoir capacity under different conditions (e.g., drought or wet periods) be taken into account to further enhance the accuracy of the results.

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Declaration of Competing Interest

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Author's contribution statement

Ghaem Masoumi carried out modeling in this study. Reza Barati evaluated the modeling and its results. Both authors discussed the results and contributed to the final manuscript.

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