



Simulation of extreme event-based rainfall–runoff process of an urban catchment area using HEC-HMS

Surendar Natarajan¹ · Nisha Radhakrishnan¹

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Abstract

Flood is ranked as the deadliest natural disaster that has been experienced by the urban basins in the world. Its detrimental effects can be minimized by appropriate modeling, analysis and management methods. Such modeling and analysis techniques help in flood risk assessment predicting flood occurrence, aid in the emergency preparation for evacuation and reduce damage from the impact of floods. Numerous modeling techniques are available for analyzing flood events, of which HEC-HMS software is chosen for this explorative study because of its simplicity and as it is a freely available open-source software. The present study aims to develop a rainfall–runoff simulation model by generating peak flow and volume of the extreme rainfall event that occurred on 22 November 1999 in the ungauged Koraiyar basin located south of Tiruchirappalli City in South India. The hydrographs are generated for the basin by using specified hyetograph and frequency storm method to identify the best method to be adopted in the study. Digital elevation model processed with geographic information system (GIS) and HEC-Geo HMS, which is an extension of GIS, is used for the analysis. Using the terrain processing tools in ArcGIS, the basin delineation and parameters such as slope and river length are extracted from the basin. The data generated during the HEC-Geo HMS process are the hydrologic parameters of Koraiyar basin, and it is imported to HEC-HMS modeling for generating peak flow and volume. In the modeling process, HEC-HMS has three modules, namely transform, loss and base flow. SCS curve number and SCS unit hydrograph are used to determine the losses and transformation of rainfall into the runoff process in the present study. The SCS method is adopted because of its simplicity and requirement of limited data approach for modeling. The peak flow and volume prepared from the model are compared with the standard Nash–Sutcliffe values. The frequency storm method has a Nash value of 0.7, which is higher than the value obtained from the specified hyetograph process, and it is chosen as a better model for generating flood peak and volume for different return periods in the basin. It can therefore be adopted for other studies of similar basin conditions.

Keywords Flood · GIS · DEM · Land use · HEC-HMS · Specified hyetograph · Flood frequency

Introduction

Flood is distinguished as inordinately high levels of water flow, which overtops the channel or canal bank (Al-Zahrani et al. 2017). Floods not only occur in large river basins, but also in small watersheds and foothill streams. They are

ranked as the first natural disaster in the world and impacted the lives of nearly 32 million people all over the world between 1995 and 2015 Guha-Sapir et al. (2015). The damages caused by frequent floods have increased over the years due to rapid urban population growth, unplanned socio-economic development, and undesirable climate change. Thus, it is necessary to define a suitable method for mitigating the impact of floods on human life, property, and the environment Derdour et al. (2018). There are several types of floods, such as urban floods, flash floods, coastal floods, and river floods (Pil et al. 1988; Wheater et al. 1991). It is estimated that more frequent floods are likely to occur in the near future, and gauging the extent of the flood will be a challenging task. To overcome the many adverse impacts of flood, certain structural and non-structural measures can be

✉ Surendar Natarajan
surendarnatarajan86@gmail.com; 403114052@nitt.edu
http://www.nitt.edu

✉ Nisha Radhakrishnan
nisha@nitt.edu

¹ Department of Civil Engineering, National Institute of Technology Tiruchirappalli (An Institute of National Importance), Tiruchirappalli, Tamil Nadu 620015, India

adopted. However, these measures have certain limitations, the analysis and quantification of data are generally more difficult and time-consuming, Cahyono and Adidarma (2019).

Modeling techniques have gained importance as they help visualize the flood risks and the protection measures to be planned. Hydrologic modeling is used to estimate streamflow over river basins and makes a comparison between the simulated stream and observed flow for predicting the hydrologic process. There are numerous distributed flood models such as MIKE-SHE, Modular Modeling System and semi-distributed models such as SWAT, TOPMODEL and HSPF (Bedient et al. 2003; Beven and Kirkby 1979; Warach et al. 2002), CASC2D (Downer et al. 2002; Marsik and Waylen 2006), but these models are proprietary and require considerable data. Open-source software can be easily accessed and has a wide range of applications. In this study of hydrological modeling, Hydrologic Engineering Centre-Hydrologic Modeling System (HEC-HMS) is adopted due to its ease of application in short and longtime event simulation (Halwatura and Najim 2013). HEC-HMS was developed by the US Army corps of Engineers (USAC 2001). It is a simple model and establishes a relationship between rainfall and the runoff process. The model is used in the dendritic watershed and its physical properties are used as model parameters. The model selection depends on the watershed characteristics and its shape. The HEC-HMS model can be applied to extensive geographic areas for solving most hydrological problems related to floods. The output generated from HEC-HMS can be integrated with hydraulic modeling for generating flood extent and depth maps.

Oued M'zab in Algeria is an arid region which was surveyed for identifying the tools for estimating and measuring the risks related to floods and the associated uncertainties. The damage caused in the region was analyzed using hydrologic and hydraulic modeling, HEC-HMS and RAS (Kheira Yamani et al. 2016). The upper Klang–Ampang basin located in the capital of Malaysia is a flood-prone urban area. To delineate the basin and its catchment characteristics, the DEM is processed in GIS for terrain process and extended with HEC-GeoHMS to develop the hydrologic parameters of the river basin. This is then used as data for the estimation of streamflow runoff in the HEC-HMS model (Ramly and Tahir 2016). A flood modeling study in Uganda for the Sironko catchment was undertaken by Martin et al. 2012 using HEC-HMS hydrological modeling. The study developed the expected and observed runoff volumes in the catchment for various rainfall events. (Sampath et al. 2015) modeled the rainfall–runoff relations using HEC-HMS for the tropical catchment in Sri Lanka.

Ain Sefra is one of the Algerian cities that has experienced several devastating floods during the past years, and the runoff was simulated using (HEC-HMS). The methodology adopted to calculate the loss rate was the Soil

Conservation Service unit hydrograph technique, and for a meteorological model frequency storm adopted by Derdour et al. (2018) to simulate the volume and surface runoff in the city.

The curve number technique was applied to analyze the runoff in the Sebou watershed in Morocco. The use of GIS simplified the mapping and the geoprocessing of spatial and temporal data. The average curve number of the watershed was 85, which indicates a high runoff and less infiltration in the basin. The results proved that the hydrologic model could support the integrated watershed management system (Chadli et al. 2016).

The peak discharge and volume from an excess rainfall event in the upper Teesta basin in Darjeeling region were computed. The drainage pattern and delineation of the basin and sub-basin were acquired from DEM. The runoff in the basin was calculated from the NRCS curve number, a function of land use land cover and hydrologic soil group of the basin (Mandal and Chakrabarty 2016).

The SCS model calculates the direct runoff volume from the given rainfall event, and it evaluates the volume and peak rates of surface runoff in agricultural, forest, and urban watersheds (Ponce and Hawkins 1996). The SCS-CN method was used for calculating runoff volume from the land surface and streams in the Pappiredipatti watershed of the Vaniyar sub-basin, South India, and in the study the SCS-CN model was improved for Indian conditions by using GIS (Satheeshkumar et al. 2017).

In the ungauged Keseke River catchment of South Nation Nationality and People (SNNP), Ethiopia, a deterministic and empirical modeling system was adopted for generating the flood frequency curve. The satellite precipitation data were adjusted, and a single gamma distribution and Pearson correlation were adopted for extreme rainfall events and a good correlation was observed. The results obtained prove that SCS-CN and ANN approaches are suitable for predicting runoff in ungauged basins (Meresu 2019). Wadi Al-Lith is a western region in Saudi Arabia where a study was conducted to quantify and delineate the channel losses spatially by implementing Muskingum–Cunge flow routing method. The HEC-HMS model was used to simulate rainfall–runoff and to fix the losses in the channel during runoff. The slope, roughness, and channel geometry were the parameters acquired from GIS, and they had a close relation with losses. The model was calibrated and validated with actual rainfall events, and the parameters were optimized. The simulated and observed hydrograph exhibited a good correlation and showed the losses in the channel (Rahman et al. 2017).

An integrated flood modeling approach was developed for the Qinhuai watershed in Jiangsu Province of China by using HEC-HMS, Markov chain, and Cellular Automata land use change model. The model was adjusted and validated by using observed and simulated stream flow data.

The sensitive analysis test provides that flood volume and peak discharge increased with impervious surface. It was identified that the small floods were more sensitive than the more massive floods with the same imperviousness (Du et al. 2012).

In the meteorological model, the specified hyetograph method is used to derive runoff from the rainfall. The gauges are assumed to receive uniform rainfall in the basin when there are minimum gauges or absence of gauges in the sub-basins. In case of sufficient gauges, each sub-basin is provided with individual rainfall events. The other simple method is frequency storm method to derive rainfall–runoff values for different return periods of 2, 5, 10, 50 and 100 years. Most of the hydraulic structures are designed based upon the frequency storm method. The hydrologic design requires a design storm, and it is developed through statistical distribution techniques due to the absence of historical data (Ternate et al. 2017).

Identification of knowledge gap in the literature study

From the comprehensive literature study, it is noted that most of the earlier research studies have concentrated on the loss and transform method and the influence of its parameters on rainfall–runoff losses. In the current study, the extreme rainfall event of 22 November 1999 was selected for developing rainfall–runoff modeling for Koraiyar basin, Tiruchirappalli city; the meteorological model selection and its influences are noted. The extreme event in the meteorological model is analyzed by specified hyetograph and frequency storm technique for generating peak flow and volume in the basin. The output obtained from the two methods is compared with simulated and observed values. The suitable method is selected based upon the Nash–Sutcliffe efficiency which determines the certainty of model with values ranging from 1 to negative infinity. The value of 1 indicates there is not much difference between the simulated and observed hydrographs.

Study area

Tiruchirappalli City is located along the Cauvery River in Tamil Nadu, South India. Cauvery is the main river flowing across the city. The latitude and longitude of the city are 10°48′16.11″N and 78°41′59.71″E, respectively. The northern part of the river is called Coleroon (Kollidam in local parlance) and is the main flood carrier, while the southern part of the river retains the name Cauvery. The river has numerous tributaries such as Ayyar and Uppar in the north and Koraiyar in the south. The Koraiyar River basin with latitude of 10°33′11.79″N to 10°48′16.75″N and longitude of

78°32′34.70″E to 78°39′47.29″E was chosen for this study, as shown in Fig. 1. The Koraiyar River is 75 km long with dendritic drainage pattern and is structurally controlled. The basin usually receives rainfall during the north-east monsoon (October to November) with an average rainfall of 908.5–1062.18 mm. The basin usually experiences a tropical climate. It is characterized by a hot and dry summer from April to September and pleasant weather from December to February. The basin has a total area of 1470 km². The total area is divided into six land use–land cover categories which include agricultural land, built-up land, forests, open land, vegetation and water bodies.

Data acquisition and methodology adopted in the study

Data used in the study

Rainfall data

The daily rainfall data of 40 years (1976–2016) is collected from State Ground and Surface Water Resources Data Centre, WRD (Water Resources Division), Chennai. From the gathered data, it is noted that more than 100 mm of rainfall in a single day occurred 16 times over 40 years. The extreme rainfall event of 324.14 mm received in the year 1999 is used for developing a rainfall–runoff model for the basin.

Image data

Landsat data of 30 m resolution is obtained from the USGS website for preparing LULC maps. The soil map is acquired from the Food and Agriculture Organisation of United States. The digital elevation model (DEM) data is acquired from “The Global Digital Elevation Model (GDEM) of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) of Terra satellite (<http://asterweb.jpl.nasa.gov>) for watershed delineation and development of basin parameters through the HEC-Geo HMS model.

Software and model description

HEC-Geo HMS is an extension of ArcGIS 10.2.2 (ESRI) developed by the US Army Corps of Engineers, Hydrologic Engineering Center (HEC). The software used for the present study is HEC-HMS (v4.0) and was downloaded from the USACE website <http://www.hec.usace.army.mil/software/hec-hms>.

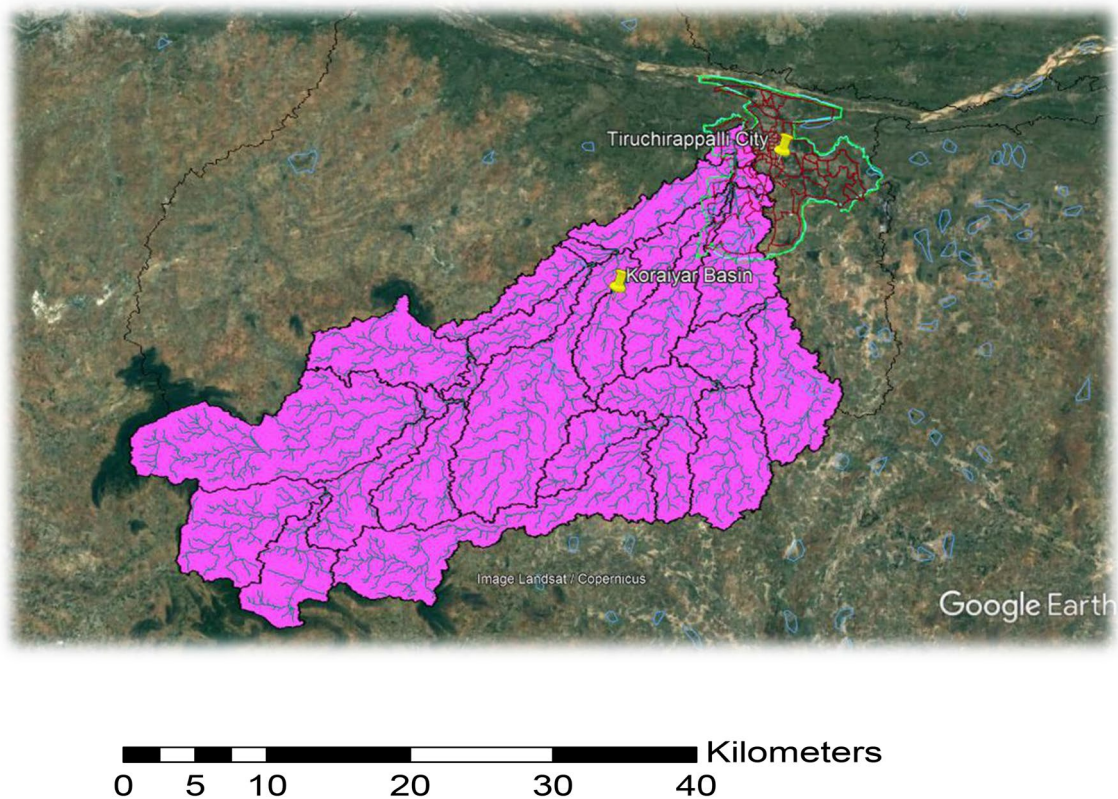


Fig. 1 Location map of the Koraiyar basin

HEC-Geo HMS

HEC-Geo HMS is an integrating tool between HEC-HMS and GIS. It is a spatial hydrology tool used in ArcGIS 10.2.2 to produce input for HEC-HMS model 4.0. The physical basin characteristics are extracted from DEM along with GIS. It creates a river network and delineates the basin and sub-basin. The drainage network is also created by analyzing digital terrain data. The hydrologic data are required for developing the rainfall–runoff model.

HEC-HMS

The Hydrologic Engineering Center-Hydrologic Modeling system was developed by the US Army Corps of Engineers. The model favors simulation in a dendritic pattern of the watershed. The output obtained from the model is peak flow in m^3/s and volume in mm, and it is also expressed in the form of a hydrograph. The output obtained from the hydrologic model is used as an input to the hydraulic model for generating flood spread area. The setup consists of four main models such as the basin model, meteorological model, control specifications, and time series data. The basin model consists of a basin and sub-basin, connectivity, and runoff factor. The meteorological model consists of precipitation,

evapotranspiration, and snowmelt. The control specifications set the time frame of the simulation with start time, end time, and time interval.

Methodology

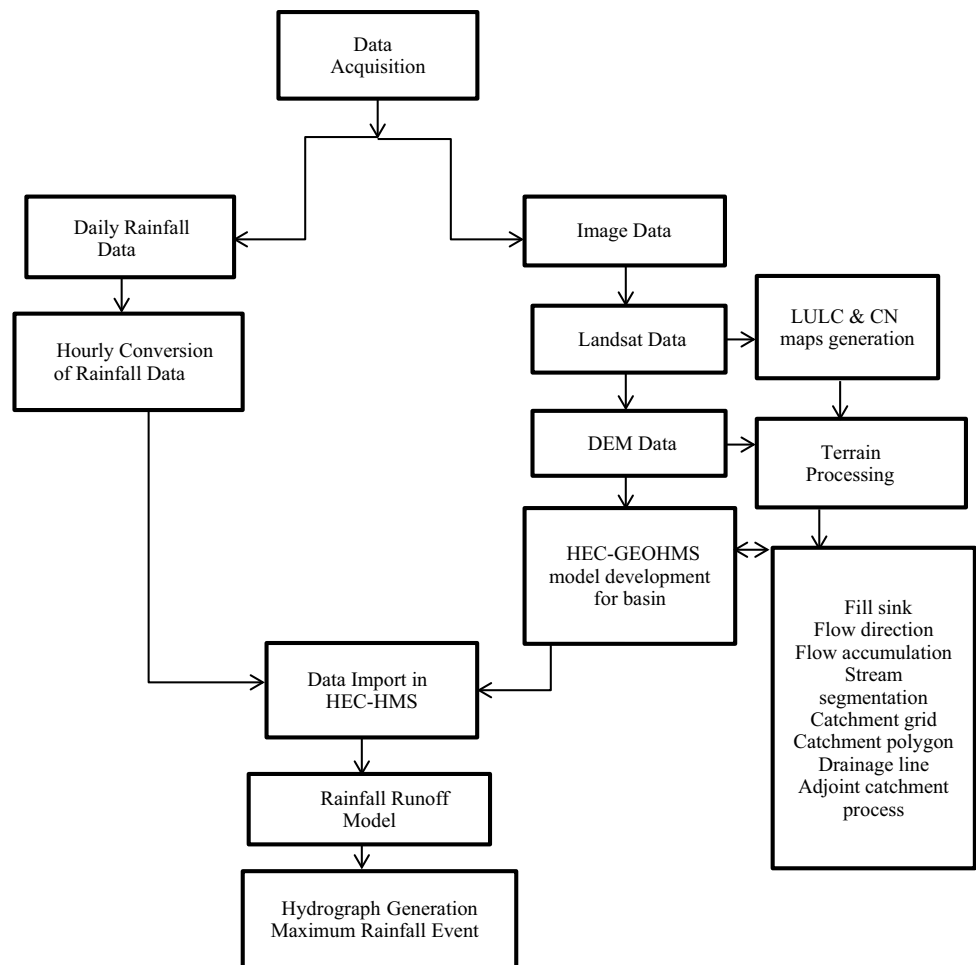
The methodology adopted for the present study is shown in Fig. 2.

The collected daily rainfall is converted into hourly rainfall by modified Kothyari and Garde's method as shown in Eq. (1) (Kothyari and Garde 1992; Zope et al. 2016):

$$I_t^T = C \frac{T^{0.20}}{t^{0.71}} (R_{24}^T)^{0.33}. \quad (1)$$

In the above equation, I_t is rainfall intensity in mm/h, return period is T in years, t is duration of rainfall in h and C is geographic constant which is taken as 7.1 since Koraiyar basin is in southern India (Kothyari and Garde 1992).

Recent remote sensing image data are obtained from Landsat 7 ETM+ with 30 m resolution of the latest year and compared with that gathered from Landsat 8 OLI for generating the land use–land cover (LULC) map. Using reclassifying techniques, the curve number map of the basin is created, which is one of the parameters for the HEC-HMS

Fig. 2 Methodology of the study

model. The DEM data of 30 m resolution are used with a spatial analyst extension tool in GIS for the terrain processing process.

The stream network and watershed are created during the terrain processing in HEC-Geo HMS. It computes the dataset to generate the hydrological parameters. The hydrologic parameters are given as input to the HEC-HMS model to develop a rainfall–runoff model for the basin.

The topography of the basin

The topographic characteristics such as aspect, hill shade, and contour line of the basin are extracted from DEM by using the spatial analyst tool in ArcGIS, as shown in Fig. 3. The contour line is generated at intervals of 10 m. The slope in the basin ranges from 5 to 30%. The basin has three types of slopes, and it is classified as a low, moderate, and very steep slope. The basin has a very steep slope of 30% in the western part, a moderate slope of 6–29% in the center part, and a low slope of 5% in the remaining parts of the basin. The slope percentage is considered due to its impact on travel time in the runoff.

Land use–land cover

The Landsat 7 ETM + image with path 3 and row 55, taken on November 11 of the year 2016, is used for producing the LULC map. The maximum likelihood algorithm with a combination of eight Landsat TM layers (band 7 through 4 and 2) is used for classification of LULC classes. The agricultural land, built-up areas, forests, open land, vegetation, and water bodies are identified, as shown in Fig. 4. The agricultural land comprises 21.91% of the whole area, and the remaining LULC classes percentages are: 10.12, 8.39, 16.51, 8.82, and 7.29.

Curve number (CN) generation

The reclassifying technique is used to generate CN from LULC classes. It is based on the hydrological soil group (HSG) given by the Natural Resources Conservation Service (NRCS 2007). B soil classes are widespread in the forests, they have a moderate runoff and a CN of 40 is given. The agricultural and open lands are categorized into D type soil which has high runoff and CN values of 79 and 88,

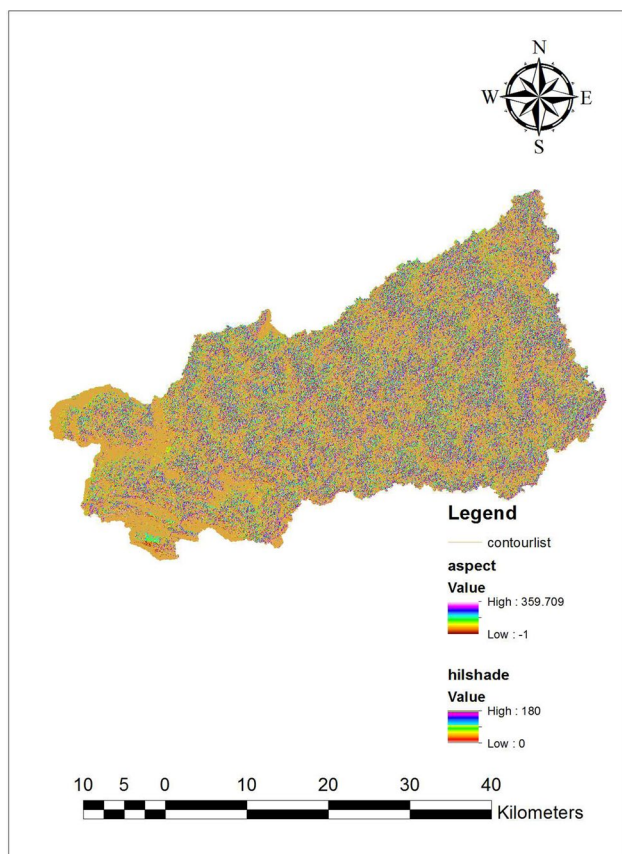


Fig. 3 Hypsometric map of Koraiyar basin

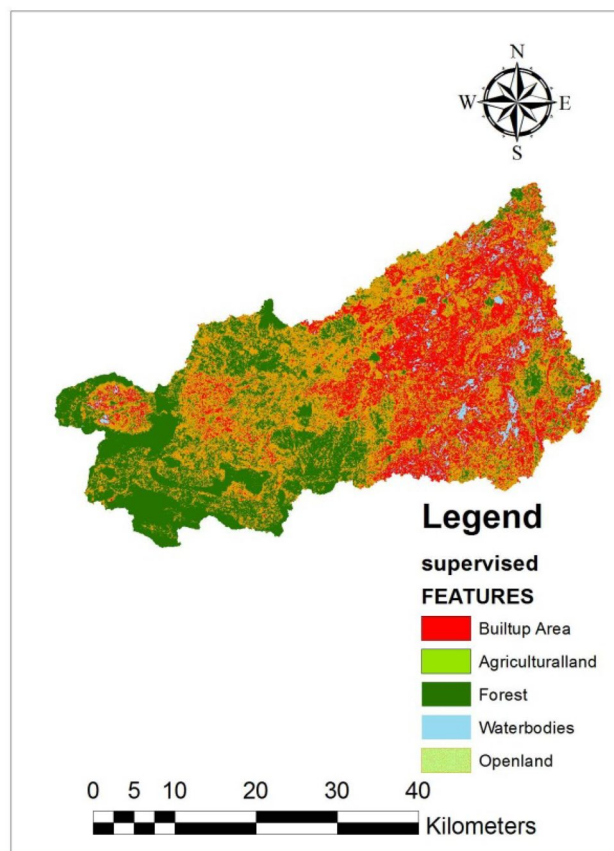


Fig. 4 Land use–land cover map of Koraiyar basin

respectively. The built-up area in the basin belongs to soil group A which has a low runoff with CN 77 and water bodies are taken as 100. The HEC-Geo HMS model generates the curve number data based upon LULC and HSG. CN is one of the parameters for the HEC-HMS model.

Development of rainfall–runoff modeling

Data processing in HEC-Geo HMS

Terrain processing is a procedure for creating hydrologic parameters as shown in Fig. 5. The hydrologic parameters are river length, slope, and the basin centroid, elevation and centroid flow, catchment area and longest flow path.

The data obtained are in raster and vector format. The raster format data include filled DEM, flow direction grid, flow accumulation grid, stream grid, stream link grid, catchment grid, and slope grid. The vector data are catchment polygons, drainage line polygons, and adjoint catchment polygons. Project pointing in the basin creates the outlet point for the basin. The created raster and vector data are

used in the HMS project set up to create a new HMS project for the basin.

Hydrologic modeling system (HEC-HMS)

The hydrologic model uses the parameters obtained from HEC-Geo HMS to develop a rainfall–runoff model for the basin. The model is developed by creating a basin model, meteorologic model, and control specification. The basin and stream data derived from HEC-Geo HMS are imported to the basin model as a background map. The different methods to simulate infiltration losses are SCS curve number, soil moisture accounting, deficit-constant and exponential.

The excess precipitation into runoff is calculated by methods such as Clark unit hydrograph, kinematic wave, Mod Clark, SCS unit hydrograph, Snyder unit hydrograph, user-specified graph, and user-specified unit hydrograph. For developing a routing model, methods such as lag routing, wave routing, modified puls routing, kinematic wave routing, Muskingum routing, and Muskingum–Cunge routing are used. In the meteorological model, methods such as gauge weights, gridded precipitation, frequency storm, inverse distance, SCS storm, specified hyetograph, and standard project

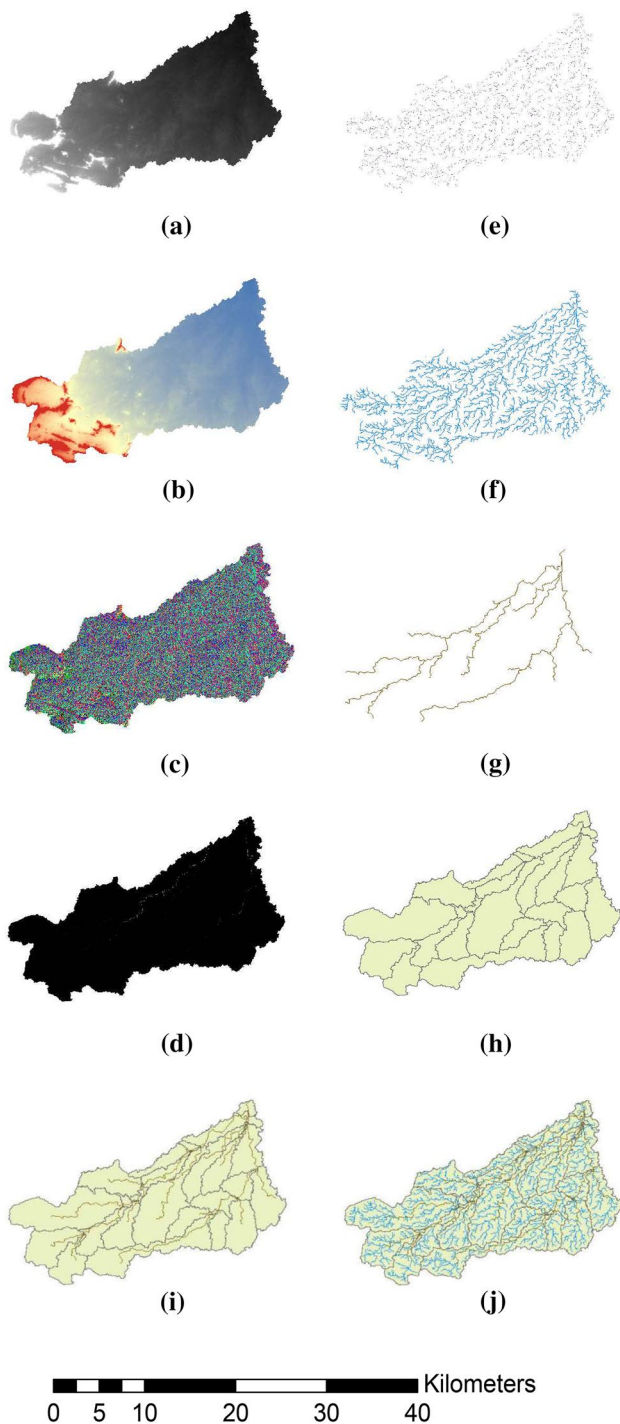


Fig. 5 Terrain preprocessing results for each step. **a** DEM reconditioning, **b** fill sink, **c** flow direction, **d** flow accumulation, **e** stream definition, **f** stream segmentation, **g** catchment grid, **h** catchment polygon processing, **i** drainage line processing, **j** adjoint catchment processing

storm are combined (Bakir and Xingnan 2008). The SCS curve number unit hydrograph method is adopted because

of its limited parameter requirements, and it is suitable for all environmental conditions.

Basin modeling process

The basin is divided into 21 sub-basins, as shown in Fig. 6. The basin model consists of sub-basins, junctions, reaches, and sink. In the model, hydrological parameters such as area, slope, and stream length are developed.

The Soil Conservation Service (SCS) curve number (CN) is used as a loss method to determine the hydrologic loss rate. The CN for a basin is valued as a sign of land use, soil type, and antecedent soil moisture condition. The CN values vary from 100 to 30. The value of 100 is assumed for water bodies and 30 for permeable soils of high infiltration rates. The SCS-CN model is given by Eq. (2) (USDA 1972).

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)}, \tag{2}$$

where Q is the runoff value (mm); P is the precipitation (mm); I_a is the initial abstraction (mm); S is the potential maximum retention.

The potential maximum retention (S) is a measurement of the capacity of a catchment to abstract and retain storm precipitation. There will be no precipitation excess until the accumulated rainfall exceeds the initial abstraction, as shown in Eq. (3).

$$I_a = 0.2 \times s. \tag{3}$$

The cumulative excess at time t is calculated with Eq. (4).

$$Q = \frac{(P - 0.2S)^2}{(P - I_a + S)}. \tag{4}$$

The maximum retention (S) and watershed characteristics are related by curve number (CN) and are adopted from the SCS Handbook of Hydrology (NEH-4), Section 4 (USDA 1972). The relationship is given in Eq. (5).

$$S = \frac{25400 - 254CN}{CN}. \tag{5}$$

In this study, the CN generated for the entire basin is based on land use–land cover and hydrological soil group (USDA-SCS 1974). The average curve number for the entire catchment is obtained from Eq. (6) (Ojha et al. 2008) and the overall generated curve number for the basin is 78.43.

$$CN_{avg} = CN_1 \left(\frac{A_1}{A} \right) + CN_2 \left[\left(\frac{A - A_1}{A} \right) \right], \tag{6}$$

where $\frac{A_1}{A} + \frac{(A-A_1)}{A}$ represents the average area-weighted curve number.

Fig. 6 HEC-HMS model of the Koraiyar basin

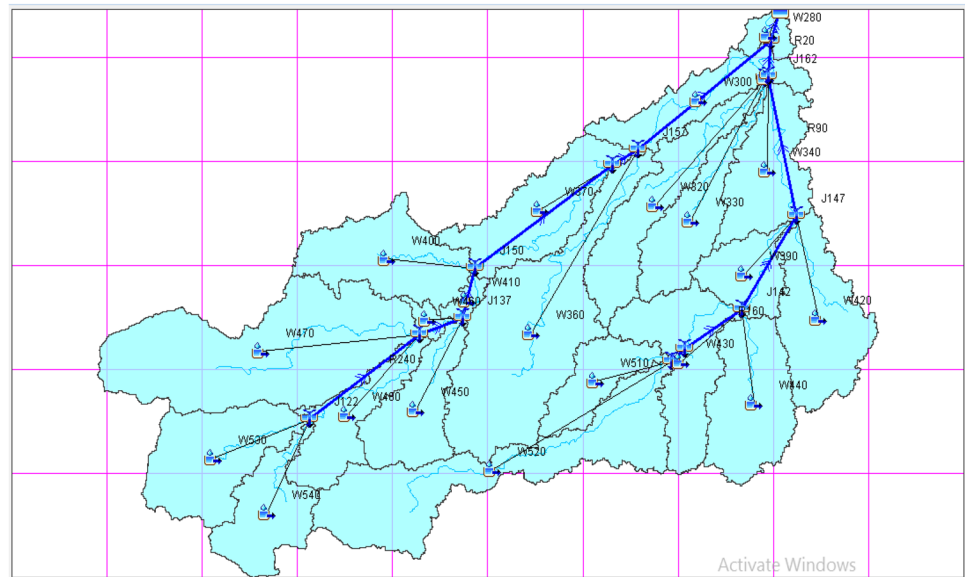


Table 1 Lag time and time of concentration for Koraiyar basin

Geomorphological parameters	Particulars	T_{lag} (h)	T_c (h)
Length (km)	75	88.65	53.19
Area (km ²)	1470		
Slope (%)	5		
Curve number	73		

The conversion of rainfall into the runoff is done by the transform method. In the transform method, an SCS unit hydrograph with standard graph type is used. The transform method is adopted since it requires only lag time as a parameter. The lag time is defined as the time of peak to time of the center mass of a hydrograph. It is calculated as 0.6 times that of the time of concentration, as shown in Eq. (7). The time of concentration is the time taken for a water droplet to travel from the upstream part of the basin to the outlet point of the basin and is generally computed using Giandotti’s empirical formula shown in Eq. (8) (Giandotti 1934). It also depends upon the geomorphological parameters of the basin. The estimated lag time and time of concentration are shown in Table 1. The lag time of the basin is taken as 0.6* times the time of concentration.

$$T_{Lag} = 0.6T_c, \tag{7}$$

$$T_c = \frac{4\sqrt{A} + 1.5L}{0.8\sqrt{H}}. \tag{8}$$

The meteorological model is created for the basin using observed precipitation and discharge data. The observed rainfall and streamflow data of Koraiyar basin are used for

Table 2 Conversion of daily rainfall data into hourly data

Date	In hours	Rainfall (mm)	Runoff mm
22 Nov 1999	1	0	0.012
	4	24.178	21.05
	8	62.808	59.44
	12	112.82	109.39
	16	72.698	69.311
	20	38.048	34.784
	24	0	0.0127
Total rainfall (mm)		310.56	307.06

model calibration and validation. The time step of 1 h is used for the simulation based on the time interval of the data available. In time series data in the precipitation and discharged gauge, the observed rainfall and discharge data were incorporated. The specified hyetograph and frequency storm method are set in the meteorological model to identify which method is suitable for metrological model development.

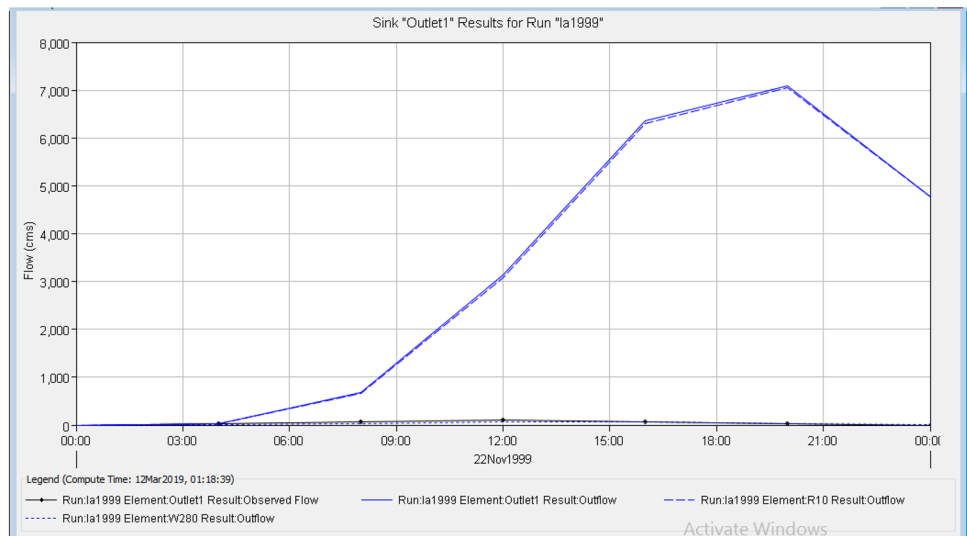
In the specified hyetograph method, a single extreme event of precipitation is taken from the basin, and it is assumed that the rainfall is distributed uniformly throughout the basin due to the ungauged nature of the basin. The extreme event of rainfall that occurred is shown in Table 2.

In the frequency storm method, the single extreme event of rainfall is converted into various return periods of rainfall by extreme value type I distribution method, as shown in Eq. (9) and Eq. (10) (Ojha et al. 2008). u refers to the location parameters and β is a scale factor. The precipitation depth for the given return period is calculated from Eq. (11) in which x_{ave} is the mean of maximum precipitation matching a particular duration, K is the frequency factor for the return period, and S is the standard deviation.

Table 3 Frequency of storm rainfall intensity for various durations

Time (h)	Return period				
	2 years	5 years	10 years	50 years	100 years
1	0.94	1.81	2.38	3.63	4.16
3	4.91	9.38	12.35	18.87	21.63
6	13.88	26.53	34.93	53.36	61.17
9	25.51	48.74	64.16	98.03	112.38
12	39.27	75.04	98.79	150.93	173.01
15	54.88	104.88	138.06	210.94	241.80
21	72.14	137.87	181.48	277.28	317.85
24	90.91	173.73	228.70	349.41	400.54

Fig. 7 The observed and simulated hydrographs for Koraiyar watershed in HEC-HMS model before calibration



$$f(x) = \frac{1}{\beta} \exp \left[-\left(\frac{x-u}{\beta} \right) \right] - \exp \left\{ -\left(\frac{x-u}{\beta} \right) \right\}, \quad (9)$$

$$F(x) = e^{-\exp \left[-\left(\frac{x-u}{\beta} \right) \right]}, \quad (10)$$

$$x_T = x_{ave} + KS. \quad (11)$$

The hyetograph is computed for each sub-basin in the basin based upon the partial or annual duration of precipitation depth given. In the Koraiyar basin, the extreme rainfall event is converted into various return periods such as 2, 5, 10, 50 and 100 years for durations like 1, 3, 6, 9, 12, 15, 21 and 24 h of different storm intervals, as shown in Table 3. In this study, it is assumed that the entire watershed will receive the same amount of design rainfall. The time step simulation is added in the control specification with start and end date time. Finally, the basin model, meteorological model, and control specification are combined before running the program.

Results and discussion

The extreme rainfall event of 310.56 mm that occurred in the basin on 22 November 1999 was recorded at the airport. The 12-h storm resulted in high intensity of rainfall of 112.82 mm in the ungauged basin in a day. The model is calibrated and validated for the specified hyetograph and frequency storm duration methods to identify a suitable meteorological method for Koraiyar basin. In the initial simulation before calibration, it is observed that there is a lot of difference between the simulated and observed values. The differences between the simulated and observed hydrographs for the event of 22 November 1999 is shown in

Fig. 7. From the figure, it is seen that there is a sharp peak with a small deviation from the simulated and the observed hydrographs. A calibration process is required to eliminate the significant differences between the observed and simulated hydrographs.

Model calibration

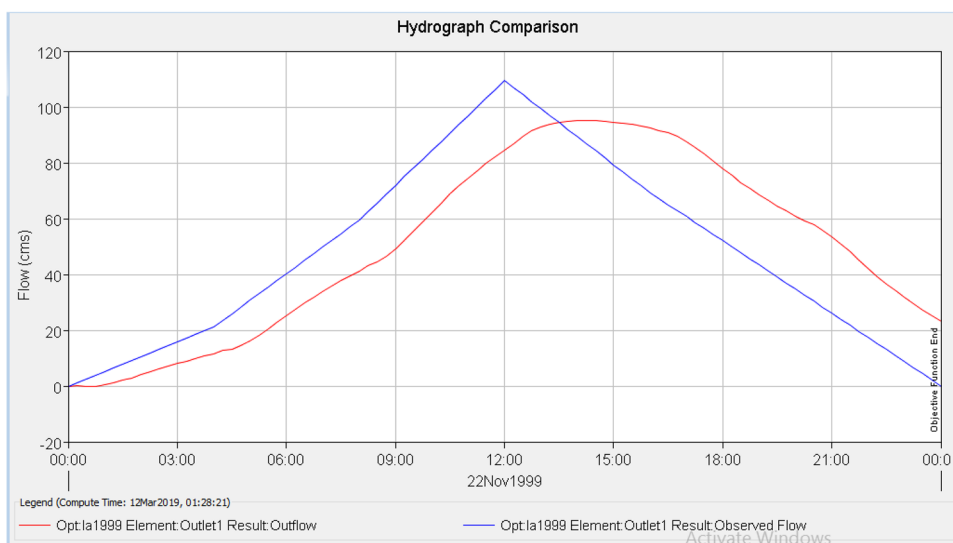
Specified hyetograph method

The simulation of an extreme event of rainfall is done with HEC-HMS with time control specification of every 1-h interval, as shown in Table 4. It shows that at every 1-h duration, the 3, 7, 13, and 14 h durations show closer values compared to other durations and it is due to travel time, imperviousness, and other physical factors in the basin.

The calibration is a method of fine-tuning the model parameter values until the model results fit with the observed data. It is tough to choose the parameter which has more

Table 4 Time series simulated and observed—1 h duration

Date	Time (h)	Outflow (m ³ /s)	Observed flow (m ³ /s)	Time (h)	Outflow (m ³ /s)	Observed flow (m ³ /s)	Time (h)	Outflow (m ³ /s)	Observed flow (m ³ /s)
22-Nov-99	0:00 a.m.	0	0	9:00 a.m.	49.1	71.9	18:00 p.m.	77.9	52
22-Nov-99	1:00 a.m.	0.5	5.3	10:00 a.m.	62.2	84.4	19:00 p.m.	68.6	43.4
22-Nov-99	2:00 a.m.	4	10.6	11:00 a.m.	74.5	96.9	20:00 p.m.	61	34.8
22-Nov-99	3:00 a.m.	8	15.8	12:00 p.m.	84.5	109.4	21:00 p.m.	53.5	26.1
22-Nov-99	4:00 a.m.	11.7	21.1	13:00 p.m.	92.9	99.4	22:00 p.m.	42.2	17.4
22-Nov-99	5:00 a.m.	16.2	30.7	14:00 p.m.	95	89.4	23:00 p.m.	31.7	8.7
22-Nov-99	6:00 a.m.	25.2	40.2	15:00 p.m.	94.7	79.3	24:00 p.m.	0	0
22-Nov-99	7:00 a.m.	33.9	49.8	16:00 p.m.	92.5	69.3			
22-Nov-99	8:00 a.m.	41.2	59.4	17:00 p.m.	87.7	60.7			

Fig. 8 The observed and simulated hydrograph of Koraiyar basin after calibration, by the specified hietograph method (x axis—time, y axis—discharge)

influence in the basin. However, the actual parameter values assumed in the modeling studies are taken over the discretized sub-basin in a certain degree of uncertainty. The calibration of model can be done manually or by auto tool optimization process. The parameters such as CN, lag time, and imperviousness are required to calibrate the model. In the present study, the imperviousness is considered and it is tuned from 0.5 to 1%.

The most suitable value of imperviousness for the basin is 0.6% in the specified hietograph method during the calibration process. In future, other parameters such as SCS-CN can also be measured. In this study, the Muskingum parameters X and K are adjusted to ensure that the observed and simulated values are closer. The trial K values are given from 0.1 to 1 within the permissible limit, and X the weighing factor between inflow and outflow is inputted from 0 to 0.3. The purpose of calibration is to identify the parameters whose variation causes significant changes in the outputs of the model. This shows that the slope, length of the stream, and

time of travel influence the basin due to imperviousness. The calibration of the model indicates the modification between simulated and observed hydrographs at the outlet of Koraiyar basin. It is seen that the simulated and observed hydrographs shown in Fig. 8 are smooth and close to each other due to the calibrated values of imperviousness by keeping other parameters constant. The peak discharge and flood value in the basin before model calibration was 109.4 m³/s and peak discharge is noted to have occurred around 12:00 p.m. After adjustment of parameters through the optimization process, it was seen that the maximum peak discharge was around 95.1 m³/s which occurred at 14:15 p.m. The comparison of observed and simulated peak flow and flood volume after calibration is shown in Table 5.

The performance and certainty of the HEC-HMS model are evaluated using the peak weighted RMS error and Nash–Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe 1970), given by Eq. (12), and the range of the permissible value is from negative infinity to 1. NSE values

Table 5 Comparison of simulated and observed peak flow and flood volume

Extreme event occurred on	Peak flow (m ³ /s)		Flood volume (mm)		Nash–Sutcliffe efficiency
	Observed	Simulated	Observed	Simulated	
22 November	109.4	95.1	2.79	2.9	0.64

of 0.5–1.0 show that there is good agreement between the observed and predicted hydrographs (Morisai et al. 2007). In calculating the NSE value, it is noted that the hydrograph obtained after simulation shows a good match with the observed hydrograph, with the Nash–Sutcliffe coefficient value of 0.64 in the specified hyetograph method. Similarly, the same range of values (0.5–0.6) were obtained during the validation period.

$$\text{NSE} = 1 - \frac{\sum_{i=1}^N (Q_i, \text{obs} - Q_i, \text{sim})^2}{\sum_{i=1}^N (Q_i, \text{obs} - Q_{\text{obs}})^2} \quad (12)$$

Frequency storm method

The extreme event of rainfall is calibrated for the frequency storm method to identify the suitable method from a selected single extreme event of rainfall. In the calibration process, the model is calibrated for the imperviousness factor by keeping other parameters such as SCS-CN constant. The imperviousness is fine-tuned around 0.7% till the observed and simulated hydrographs show very few differences, as shown in Fig. 9.

In the frequency storm method, the peak discharge and runoff volume for the ungauged basin are simulated for various return periods of 2, 5, 10, 50, and 100 years. The lag time is the time interval from the center of mass of the rainfall to the center of mass of the hydrograph. The time of peak and lag time for various return periods are listed in Table 6. The time interval between the time of peak of the hydrograph and the time from the center of mass of the excess rainfall in the basin for various return periods are listed in Table 6. The time of peak and center of mass simulated values show that the peak flow values occurred 3 h ahead of the observed values. The generated peak discharge and runoff from the frequency storm method are shown in Table 7.

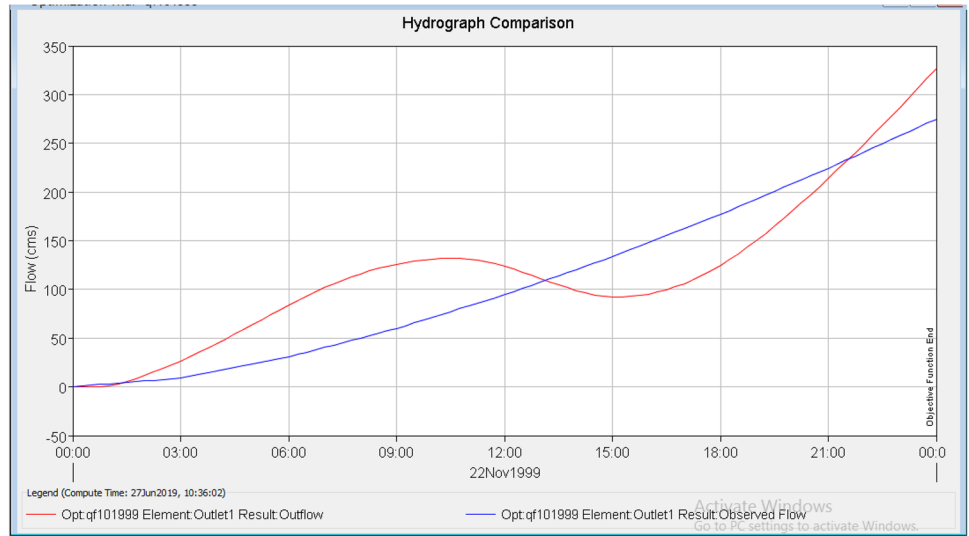
The simulated values of various return periods during the extreme rainfall event that occurred on 22 November 1999 show that the peak discharges and volumes for the Koraiyar

basin for a return period of 100 years are 576.3 m³/s and 11.84 mm, respectively, with Nash value of 0.456. Similarly, for the other return periods, the peak discharge and volume are 101.2 m³/s, 316 m³/s, 326.6 m³/s and 2.7 mm, 3.2 mm, and 6.72 mm with NSE value of 0.73–0.76, which show the goodness of fit. There is little difference between the simulated and observed value for the 50 year return period with Nash value of 0.255, which is well within the permissible limit. This difference is due to the topographic conditions, imperviousness, time of concentration, and catchment characteristics. The other reason for differences in the simulated values is during the calibration process.

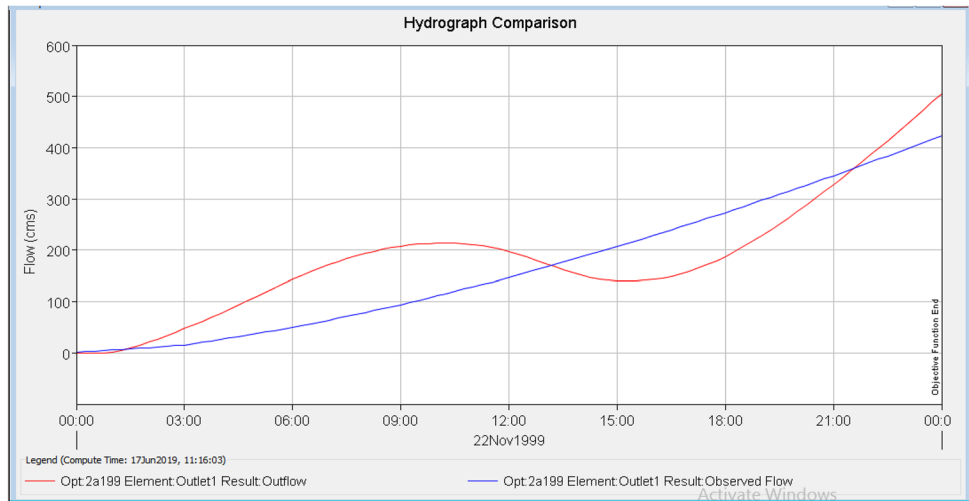
Conclusion

The calibrated HEC-HMS model is used to estimate direct runoff volume and the peak discharges for an extreme single event rainfall by two different meteorologic methods to identify a suitable method and the influencing parameters for the Koraiyar basin. The digital elevation model of 30 m resolution is used for the basin delineation and catchment characteristics by the terrain processing method. The LULC data is generated to understand the peak runoff of various land use classes. The terrain processing is done by Arc-Hydro extension in GIS and is known as HEC-Geo HMS, a data generator for HEC-HMS modeling. The hydrologic modeling is adopted to forecast the surface runoff in the basin. The SCS curve number loss method is adopted because it requires fewer parameters and it is used to determine the hydrologic losses in the basin. The SCS unit hydrograph method is used for effective rainfall transformation. The Nash–Sutcliffe efficiency is used to evaluate the goodness of fit between the observed and simulated flow; the developed hydrologic model is found to be a good fit for the basin. In this study, the model is calibrated by tuning the imperviousness of the basin in the range of 0.5–1%. It is also found that above 0.6–0.7%, there are many converging influences on the simulated and observed values. It is recommended that in future, other parameters should also be considered for model simulation. The modeling simulation was carried out by the specified hyetograph and frequency storm method. In the present study, only one extreme event was considered. In future, the simulation can be done for other maximum rainfall events, and the calibration can also be done accordingly. The simulated peak discharge and runoff volume generated by the specified hyetograph and frequency methods show a close match with observed values. It is analyzed by NSE in which the specified hyetograph shows a value of 0.64, and the frequency storm method shows values in the

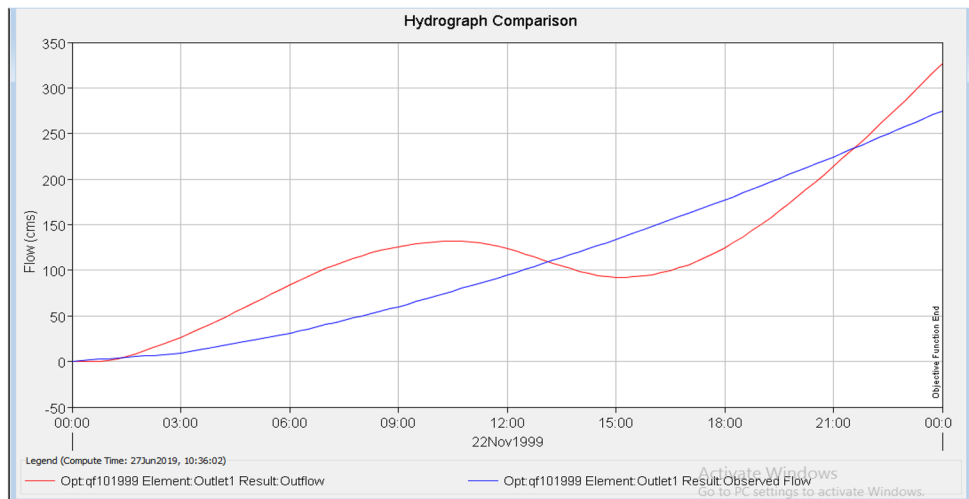
Fig. 9 Observed and simulated hydrograph of Koraiyar basin 2, 5, 10, 50, and 100-year return period–frequency storm method



(a) Hydrograph Comparison for 2years

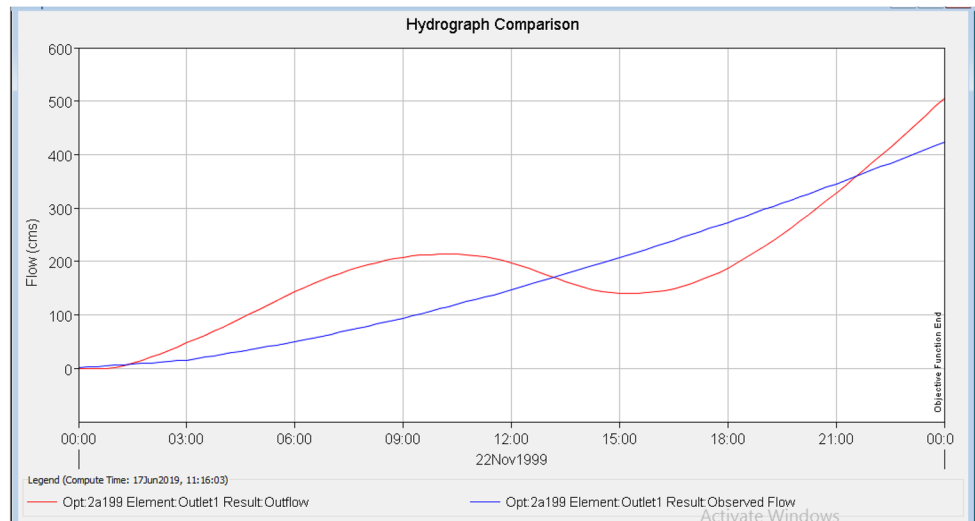


(b) Hydrograph Comparison for 5years

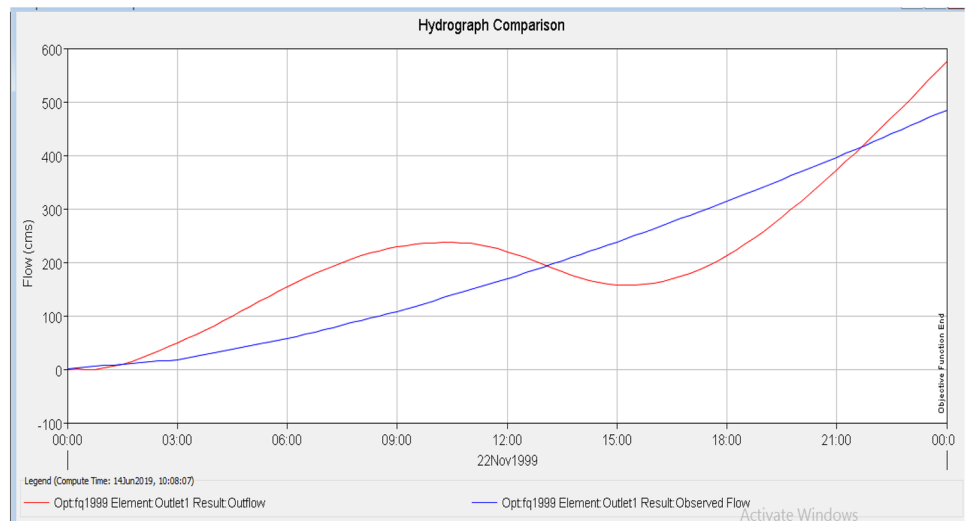


(c) Hydrograph Comparison for 10 years

Fig. 9 (continued)



(d) Hydrograph Comparison for 50 years



(e) Hydrograph Comparison for 100 years

Table 6 Comparison of simulated and observed lag time for basin during different return periods

Return period	Time of peak		Time of center mass	
	Simulated	Observed	Simulated	Observed
2	23 Nov 1999, 00:00	23 Nov 1999, 00:00	22 Nov 1999, 14:21	22 Nov 1999, 17:25
5	23 Nov 1999, 00:00	23 Nov 1999, 00:00	22 Nov 1999, 14:23	22 Nov 1999, 17:17
10	23 Nov 1999, 00:01	23 Nov 1999, 00:00	22 Nov 1999, 15:48	22 Nov 1999, 17:14
50	23 Nov 1999, 00:00	23 Nov 1999, 00:00	22 Nov 1999, 15:35	22 Nov 1999, 17:11
100	23 Nov 1999, 00:00	23 Nov 1999, 00:00	22 Nov 1999, 15:42	22 Nov 1999, 17:10

range of 0.73–0.76 for 2, 5 and 10 years return periods. For 50 and 100 year return periods, the Nash value is around 0.2–0.4, which might be due to basin characteristics. The analysis from the two methods shows that the frequency

storm method can be adopted for the Koraiyar basin. This is because, in future, the generated peak discharge and volume for various return periods by the frequency storm method can be used in any hydraulic model for generating flood plain, velocity, and hazard maps.

Table 7 Simulated and observed peak discharge for the various return periods

Return period (years)	Peak flow (m ³ /s)		Volume (mm)		Nash–Sutcliffe efficiency
	Simulated	Observed	Simulated	Observed	
2	101.2	106.7	2.7	2.33	0.733
5	316	464	3.2	2.9	0.7
10	326.6	275	6.72	6.17	0.761
50	505.4	422.5	10.58	9.54	0.255
100	576.3	484.9	11.84	10.97	0.456

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Compliance with ethical standards

Conflict of interest The author declares there is no conflict.

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