Calibration and Validation of HEC-HMS Model for Chalakudy River Basin

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Authors' contributions

This work was carried out in collaboration between both authors. Author GG designed the study, run the model, performed the statistical analysis, managed the literature searcher, wrote the protocol and wrote the first draft of the manuscript. Author KPR given the guidelines to complete HEC-HMS modelling, corrected the manuscript. Both authors read and approved the final manuscript.

Original Research Article

ABSTRACT

Prediction of flood prone areas in a basin and evolution of the impact of climate change on water resources needs a correct estimation of the availability of water which will solely be achieved by hydrological modelling of the basin. However, modelling the hydrology of a basin is a complex task and models should be well calibrated to increase user confidence in its predictive ability which in turn makes the application of the model effective. In this study rainfall-runoff simulation model *viz.*, Hydrologic Modelling System, developed by the Hydrologic Engineering Centre USA (HEC-HMS) has been calibrated and validated for Chalakduy river basin in Kerala, in Sothern India for prediction of its hydrologic response. The result shows Curve Number (CN), Lag time and initial abstraction (I_a) to be the sensitive parameters for the simulated stream flow. The statistical analysis of Nash-Sutcliffe model efficiency criteria, the percentage error in peak, percentage error in volume, and net difference of observed and simulated time to peak, which were used for performance evaluation, have been found to range from (0.70 to 0.87), (4.39 to 19.47%), (1.9 to 19%) and (0 to 1day) respectively, indicating a very good performance of the model for simulation of stream flow.

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1. INTRODUCTION

Globally floods are increasingly among the most devastating natural disasters affecting human life than any other natural disasters. According to Abhas, Jha, and Jessica (2012), in 2010 alone, 178 million people were affected by floods. It is also reported that one sixth of the global population (one billion people); the majority of them among the world's being low income earners live in the potential path of a 1 in 100 year flood according to Department for International Development (DFID). Extreme precipitation and floods are the hydro climatic events that draw considerable attention every year during the monsoon season in India. Millions of people are affected by extreme precipitation and flood events that often cause damage to infrastructure and agriculture in India. Extreme precipitation events have increased during the last few decades, which are likely to increase further under the warming climate (Goswami et al., 2006; Mukherjee et al., 2018; Roxy et al., 2017). India witnessed some of the most severe extreme precipitation and flood events during the recent decades. For instance, the extreme precipitation event in Mumbai in 2005 affected more than 20 million people and caused more than 1000 deaths (Gupta and Nair, 2011). The 2013 extreme rainfall and flood event in Uttarakhand resulted in the death of more than 6000 people and caused an economic loss of more than \$3.8 billion (Kumar, 2013). Furthermore, extreme precipitation in Chennai in November 2015 resulted in the economic loss of over \$3 billion (Boyaj et al., 2018; Van Oldenborgh et al., 2016).

Kerala with a total area of 38,863 km^2 is a state in south India. Southwest and Northeast monsoons control the rainfall in Kerala. Kerala experiences 90% of rainfall during monsoon season. Chalakudy river basin chosen for the study was one among the worst affected basins in Kerala 2018 and 2019 flood events causing great loss to human beings and also resulted in damage of ground-works.

In this study, the modeling of flood flows by calibration and validation of the basin simulation model, Hydrologic Modeling System, developed by the Hydrologic Engineering Center, USA (HEC-HMS) has been carried out for the Chalakudy river basin in Southern India for proper assessment and management of water resources in the basin.
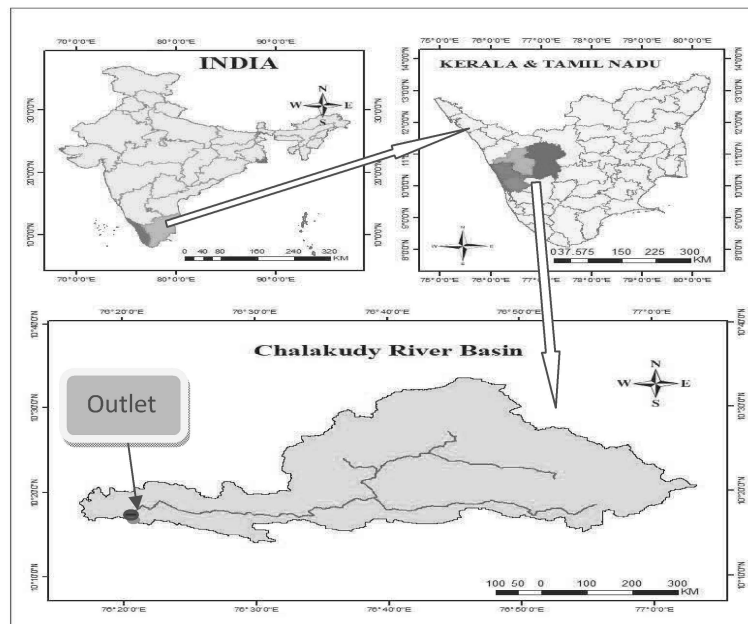
Fig. 1. Location map of Chalakduy river basin

1.1 Study Area

Chalakudy river is the fifth longest river in Kerala and drains through Palakkad, Thrissur and Ernakulam districts. The Chalakudy River Basin (CRB) lies between 10°05' to 10°35' North Lattitude and 76°15' to 76°55' East Longitude. The river originates from Anamalai hills of the Western Ghat mountain ranges and flows through the northern part of Periyar river after draining through varied physiographic and geologic terrains of Tamil Nadu and Kerala States. The basin receives an average rainfall of about 3000 mm. The total length of river is about 130 km and the catchment area is about 1370 km². Out of the total catchment area, about 300 km² lies in Tamil Nadu and the remaining in Kerala.

2. METHODOLOGY

The hydrological simulation modelling was performed using HEC-HMS, which is a semi-distributed hydrologic model with the ability to perform continuous as well as event based simulation in dendritic watershed systems [1]. HEC-HMS is an advanced version of the HEC-1 model which was developed in 1968 by the US Army Corps of Engineers. Since then, HEC-HMS has been widely applied in hydrology to model the rainfall-runoff process, flood forecasting system planning and assessing impact of land-use changes and runoff simulations in ungauged basins [2] In HEC-HMS, the catchment is constructed by disintegrating the components of a hydrological cycle into manageable, elements *viz*. precipitation, initial abstraction, evapotranspiration, infiltration, surface runoff and base flow. In this model, the physical description of the watershed is described using elements, *viz*. sub-basin, reach, junction, reservoir, diversion, source and sink. Computation proceeds from upstream to downstream direction and calculation of runoff is carried out in a sequential manner starting from canopy storage through surface or depression storage, infiltration and transform into base flow/surface flow hydrograph. Rainfall is the major input to this model along with other spatially distributed watershed characteristics, such as land use/land cover and soil, and the output from the model is the flow hydrograph.

Different components included in the HEC-HMS are listed below.

- Basin Models: The physical basin area with hydrologic elements (sub basins, junctions, reach, reservoirs) and drainage network of the catchment are included in basin models.
- Meteorological Models: Information regarding meteorological components such as temperature, precipitation evapotranspiration, sunshine, humidity and snowmelt is defined in meteorological model. HEC-HMS provides variety of options to define each meteorological element.
- Control Specification: Starting date and time, ending date and time and computational time step for the simulation are defined in control specification.
- Time series Data: Real time series data for all the meteorological elements defined in meteorological model are fed in this part. Apart from above mentioned meteorological elements, discharge data can also be supplied for calibration and simulation of the developed model. It can be supplied to the software manually or in the form of HEC-DSS, the Hydrologic Engineering Center Data Storage System.

The data required for hydrologic modelling using (HEC-HMS) includes: i. Digital Elevation Model (DEM).ii. Land use iii. Soil map iv. Meteorological data v. Flow data.

2.1 Data Collection and Analysis

a) Digital Elevation Model (DEM)

For the present study, DEM of 30 m resolution downloaded from USGS earth explorer was used for delineating the basin and to decide basin characteristics such as elevation, slope, slope length, flow direction and drainage characteristics.

b) Land use Land cover map

The land use land cover map was prepared by using ERDAS Imagine 2014 software, which is available in the Geo Spatial lab of KCAET, Tavanur,Malappuram district,Kerala. Cloud Free Sentinel satellite data (geo coded with UTM projection, spheroid and datum WGS 1984, Zone 43 North) of 30m spatial resolution of the year (2020) has been downloaded from USGS Earth Explorer website (http://earthexplorer.usgs.gov/).

The method used in this study was unsupervised classification. In this study, the land use classes taken were eight *viz* water body, forest, urban area, barren land, tea, paddy, oil palm and Coffee/Cardamom. Before classifying the different classes within the study area, ground truthing and data collection was done. Cross checking of the basin area was also done using the 'Google Earth Pro' for identifying the different classes. After the classification of each pixel was completed, every class ought to be inspected and a name assigned to it.

c) Soil map

Soils of Chalakudy river basin falls within 6 broad categories. They are: 1) lateritic soil 2) hydromorphic saline soil 3) brown hydromorphic soil 4) riverine alluvium 5) coastal alluvium and 6) forest loam. Of these, lateritic soils are the predominant soil type of the midland region. The brown hydromorphic soil is mostly confined to valley bottom of undulating topography of the midland. They are formed as a result of the deposition of material derived from the adjoining hills and slopes. A major portion of the upland is covered by forest loam having the surface layer rich in organic matter.

d) CN Grid Map

This function calculated lag time for transform method based on CN grid. CN grid was generated in Arc-GIS using land use and soil cover layers. Further, the CN value was optimized in later stages in HEC-HMS during calibration.The steps to obtain a Curve Number grid for the catchment area involved the following procedure:
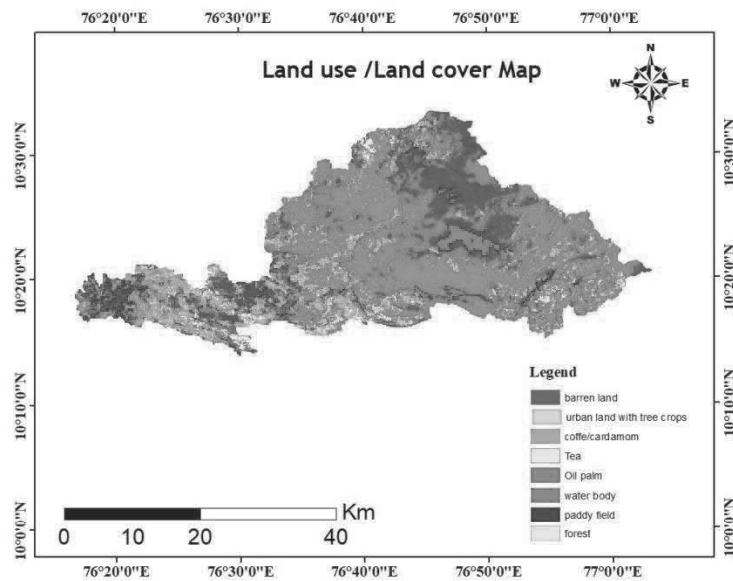
Fig. 2. Land use land cover map of Chalakduy river basin

Table 1. Areal Distribution of different Land use/land cover classes of the Chalakdudy river basin

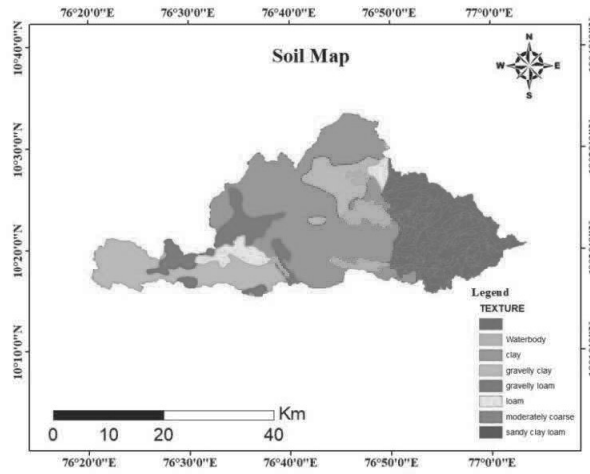| Land use class	Area(km^2)
Waterbody	30
Forest	760
Barren land	147
Paddy	120
Tea and oil palm	90
Urban land with mixed trees	182
Coffee/cardamom	41
Total	1370

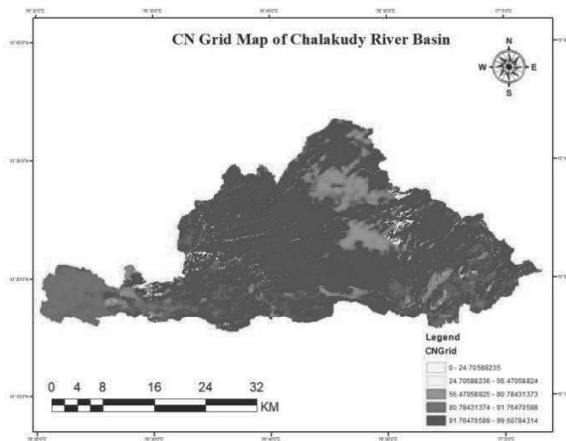**Fig. 3. Soil map of Chalakudy river basin**

Fig. 4. CN grid map of Chalakudy river basin

- Vectorization of LULC and HSG maps.
- Table or vector union operation performed to develop polygons through unique combination of both the maps in Arc-GIS software.
- CN value generation from unique polygons by query operation in Arc-GIS and thereby, creation of a CN grid map.
- CN value determination for each sub-basin from the attribute table.

e) Climate data

The study area is characterized by a tropical humid climate with summer season from March to May, and rainy season from June to September. Wet type of climate prevails in the higher hilly ranges. The area receives an average annual rainfall of 3000 mm. The rainfall increases from West to East. Nearly 68.2% of the total rainfall occurs from June to August (southwest monsoon) period. The period September –November (North-East monsoon) contributes about 17.5 % of the total rainfall. A total of 13% of rainfall is received during March to May and the balance is obtained during January to February. Out of the total 133 rainy days 83 days are during southwest monsoon. The relative humidity is higher during monsoon months. Wind speed records the highest mark during May (10.9 km/h). The area experiences almost uniform temperature throughout the year. However, the maximum temperature is in the month of March and minimum in December. Daily rainfall data from five stations along with other meteorological data like maximum and

minimum temperature, relative humidity, sunshine hours, wind speed etc., have been collected from ARS, Chalakudy and IMD, Pune.

f) Determination of average precipitation by Thiessen polygon method

Thiessen Polygon approach is the most sophisticated method in area-based weighting method, used in hydrometeorology for determining average rainfall when there is more than one observation station over a catchment area. Thiessen polygon map for calculating areal mean precipitation was prepared using the rainfall data from five rain gauge stations as shown in Fig.5. The weighted area of five gauging stations and their respective weightage of received rainfall over the basin is shown in Table 2.

2.2 HEC-HMS Hydrological Modelling

HEC-HMS uses separate models to represent each component of the runoff process, including models that compute runoff volume, models of direct runoff, and models of base flow. Each model run combines a basin model, meteorological model and control specifications with run options to obtain results [3].

Following methods were selected for each component of runoff process such as runoff depth, direct runoff, base-flow and channel routing in event based hydrological modelling. These methods were selected on the basis of applicability and limitations of each method, availability of data, suitability for same hydrologic condition, well established, stable, widely acceptable, researcher recommendation etc.

I. SCS Curve Number (CN) method

In SCS-CN method, accumulated precipitation excess is estimated as a function of cumulative precipitation, soil cover, land use, and antecedent moisture and is:

$$P_e = \frac{(P-Ia)2}{(P-Ia+S)}$$

Table 2. Weighted area and weightage of different stations

SI. No.	Gauging station	Area (km^2)	Weights
1	Thunacadavu	137	0.107
2	Chalakudy	144	0.113
3	Peruvaripallam	230	0.18
4	Parambikulam	380	0.298
5	KSD	385	0.302
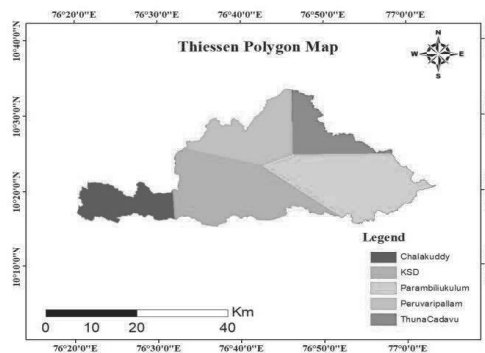
Fig. 5. Thiessen Polygon map for estimating areal mean precipitation

Table 3. Selected methods for HMS

HMS Processes	Method
Loss	SCS Curve Number Method
Transform	SCS Unit Hydrograph
Base-flow	Recession
Routing	Muskingum

Where, P_e = Accumulated precipitation excess at time t; P = Accumulated rainfall depth at time t; Ia = Initial abstraction and S = Potential maximum retention. I_a and S are calculated from following equations:

$$I_a = 0.2S$$
$$S = \frac{(25400 - 254CN)}{CN}$$

For a watershed that consists of several soil types and land uses, a composite CN is calculated as suggested by Panigrahi (2013).

II. SCS unit hydrograph method

SCS unit hydrograph method is applied for estimating direct runoff. The basin lag time (T_{lag}) is the parameter of SCS UH model which is 0.6 times the time of concentration (Tc), Value of T_c is computed as suggested by Panigrahi (2013).

III. Recession method

It is used to represent watershed base flow. It is given by:

$$Q_t = Q_o{}^{Rt}$$

Where, Q_0 = Initial base flow at time t = 0, Q_t = Threshold flow at time t, and R = Exponential decay constant.

Initial base flow (Q_o) is estimated by field inspection. The recession constant (R) is estimated from observed flow hydrograph which depends upon the source of base flow. The threshold flow (Qt) is estimated from observed flows hydrograph, wherein the flow at which recession limb is approximated well by a straight line (USACE –HEC, 2008) [4]

IV. Muskingum method

Muskingum method for channel routing was chosen. In this method X and K parameters must be evaluated. Theoretically, parameter K is the time of passing of a wave in reach length and parameter X is a constant coefficient whose value varies between 0 - 0.5. Therefore parameters can be estimated with the help of observed inflow and outflow hydrographs. Parameter K is estimated as the interval between similar points on the inflow and outflow hydrographs. Once K is estimated, X can be estimated by trial and error [4].

2.3 Calibration and Validation of Model Parameters

In the calibration procedure all the parameters involved were balanced in order to reduce the error between the observed values and the simulated values obtained for the basin [5]. It was mainly done to minimize the deviation between the observed and obtained values from the model and to get the best set of parameters in calibrating and validating the model [6]. The process was completed either by repeated manual adjustment of the parameters, computation and inspecting goodness of fit between the computed and observed hydrographs or automatically by using the iterative calibration procedure called optimization [7]. Daily available rainfall and discharge data from the year 2005 to 2007 were used for model calibration whereas the data from 2009 to 2010 were used for validation. The same parameters, obtained after calibration, were used for validation and thus the flood hydrographs of the catchment were generated.

2.4 Optimization of model parameters

HEC-HMS itself provides a tool for optimization of the model parameters with user-defined numbers of iteration which is termed as the automatic calibration system. Different statistical evaluation parameters are also available in the model, in order to ensure the variation of calibrated results [8]

3. RESULTS AND DISCUSSION

3.1 Delineation of Chalakudy river basin

The initial phase in building up HEC-GeoHMS project is terrain pre processing. Before starting the hydrologic modelling in the HEC-HMS software, the pre processing tool was used to derive eight datasets for stream and sub basin delineation. For carrying out the delineation procedure the HEC-GeoHMS extension tool in the Arc-Map was used [9].

The steps involved under pre processing menu are
a) Flow direction, b) Flow accumulation, c) Stream definition, d) Stream segmentation, e) Catchment grid delineation, f) Catchment polygon processing, g) Drainage line processing.
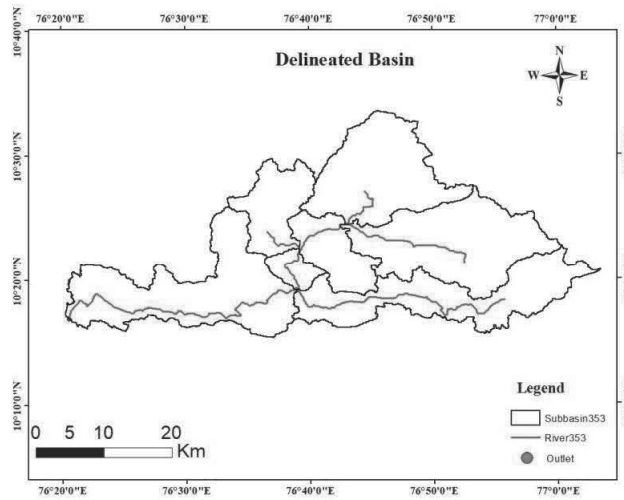
Fig. 6. Delineated Chalakudy river basin

3.2 HEC-HMS Model Application

The basin model includes hydrologic elements, their connectivity and the related geographic information that can be loaded into an HEC-HMS project. Basin model represents the physical characteristics of Chalakudy river basin and it is as shown in Fig. 4. The drainage area of sub basins are shown in the Table 4.

3.3 Results of Optimization Parameters

The model parameters were optimized using the optimization tools available in HEC-HMS. Parameters included sub basin and reach elements such as initial abstraction (I_a), curve number (CN) and lag time (LT) etc. They were estimated automatically using optimization trials. The optimization was done in such a way that resultant output hydrograph computed at the outlet, closely matches with the recorded/observed hydrograph. Objective goal of optimization was set as minimization of the function, i.e., minimisation of the difference between computed and observed discharge. 'First lag auto correlation statistics' was used to maintain this minimisation function for the analysis [9]. Using the optimised parameters, there was a desired increase in the NSE values as shown in the Table 6. These results indicated the better accuracy of the model for the simulation of rainfall-runoff for the sub basin.
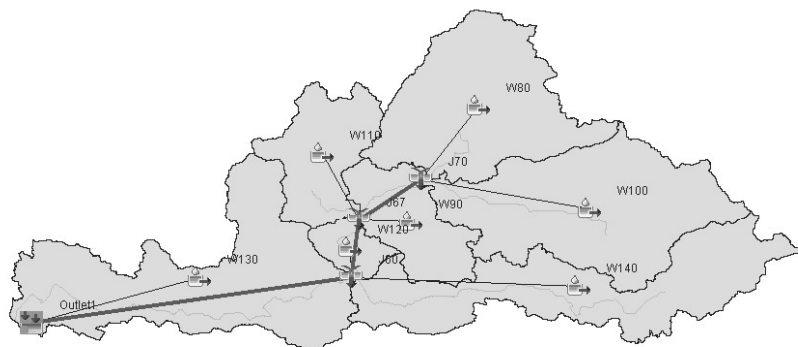

Fig. 7. Basin model of Chalakudy river basin in HEC-HMS

Table 4. Initial and optimised parameter values for different sub-watersheds

Sub basin	Basin Area(km^2)	Initial abstractions (I$_a$)		Basin CN		Lag time(min)	
		I	O	I	O	I	O
W140	237.21	15	7.71	90.95	98.16	1500	2617.40
W130	299.69	15	7.62	98.32	84.57	1500	2666.60
W120	31.43	15	8.63	92.23	73.47	1500	2912.70
W110	104.57	15	9.77	96.61	57.73	1500	3019.90
W100	277.14	15	10.60	94.23	44.42	1500	2943.70
W90	93.49	15	11.09	89.02	35.66	1500	3104.40
W80	230.99	15	11.46	92.78	33.27	1500	2695.60

Table 5. Initial and optimised parameter values for Muskingum equation

River	X		K	
	I	O	I	O
R70	0.2	0.15	0.5	0.50
R50	0.4	0.16	0.5	0.50
R30	0.2	0.17	0.5	0.50

3.4 Results of Calibration

Daily rainfall and other hydro-meteorological data, from 2005 to 2007 were selected for calibration. The calculated initial parameters, as shown in Table 4, were initially used as input to the model for calibration. Different elements like peak runoff, total volume, time to peak and discharge hydrograph were simulated. When model simulated discharge value was matched with observed discharge value, it was found that there was a definite difference between observed and predicted value in all sub basins. In order to get satisfactory results, the initial parameters were optimized using automatic optimization tool provided in the model. Using optimized parameters (Table 7), model was again calibrated to secure peak discharge, total volume and time to peak. It was found that the optimized value gave close agreement of simulated hydrograph comparable with that of the observed one. Hence, optimized values of parameters were used for model calibration and accurate simulation.

Figs. 8-10, represents the plot of hydrograph of simulated outflow and observed flow during the calibration. The graph showed that there is a close similarity of trend between the simulated and observed hydrograph in all the years including the calibration period. It was also seen that the peak of the hydrographs for calibration was not matching with the peak of observed hydrographs. This might be due to the fact that watershed physical characteristics change both spatially and temporarily.

The results were in acceptable range according to Najim et al. [10] and Sabzevari et al. [11] who recommended that the relative percent errors between the observed and simulated values should be below ±20%. The study by Cheng et al. [12] also suggested that the runoff model is considered good if the percent error of the runoff volume is less than 20%. The positive values of percent error indicated model underestimation bias while the negative values indicated model overestimation bias as per the statistical evaluation criterion.

3.5 Results of Model Validation

The comparison of simulated and observed hydrograph during the validation period is presented in Figs 12 and 13. A similarity in the trend of simulated and observed hydrographs for relatively longer duration of storms was visualized. It was also found that simulated values were near to observed values. However, there was minor difference in recorded and observed hydrograph for small duration of storms. This was because of variation of rainfall events in individual sub basins that was not been denoted by the gauge record at that particular time.
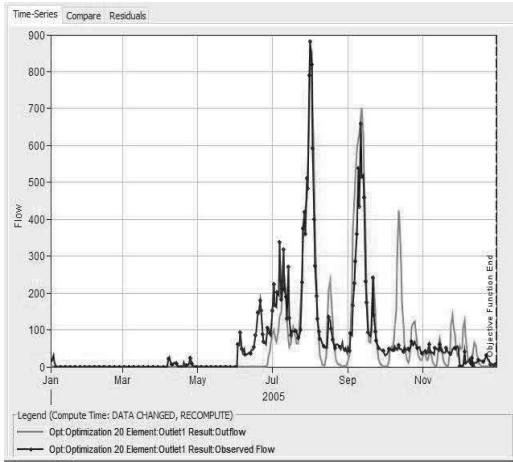
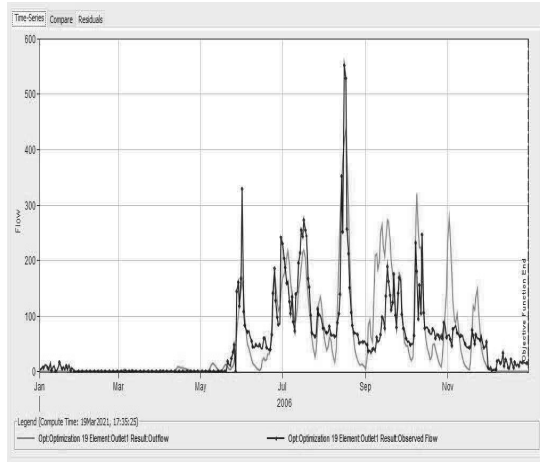**Fig. 8. Simulated and observed hydrograph for the year 2005**
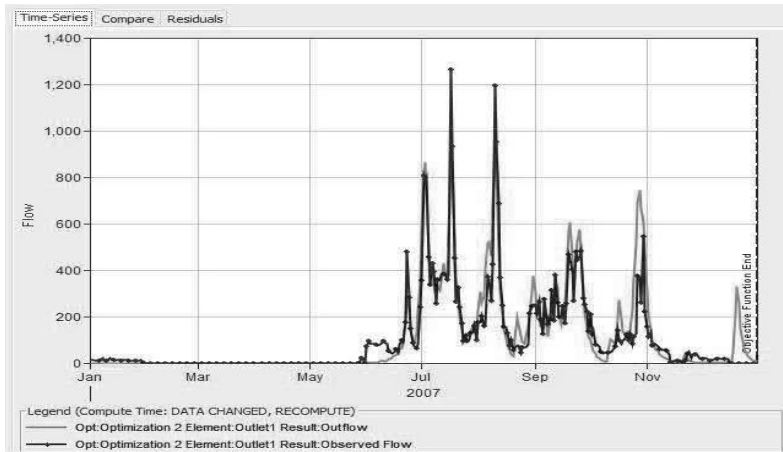

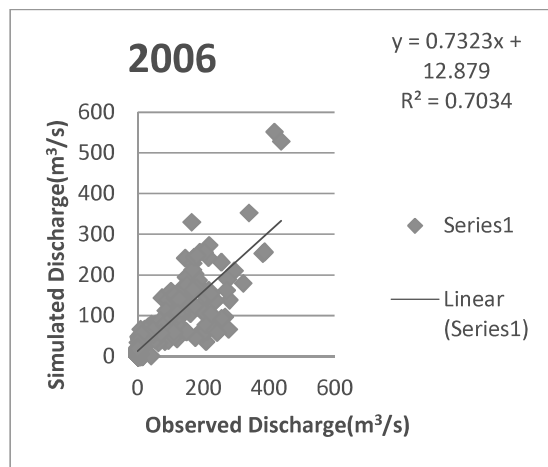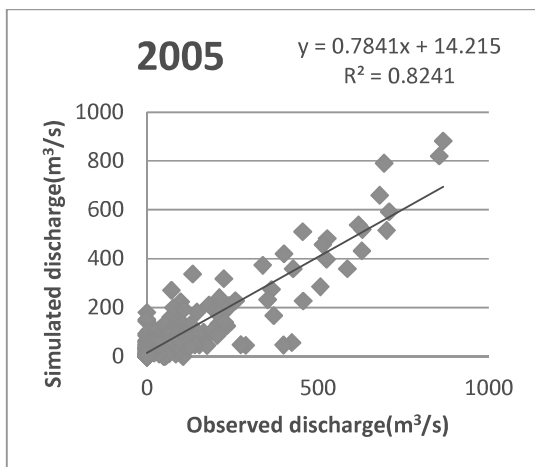**Fig. 9. Simulated and observed hydrograph for the year 2006**
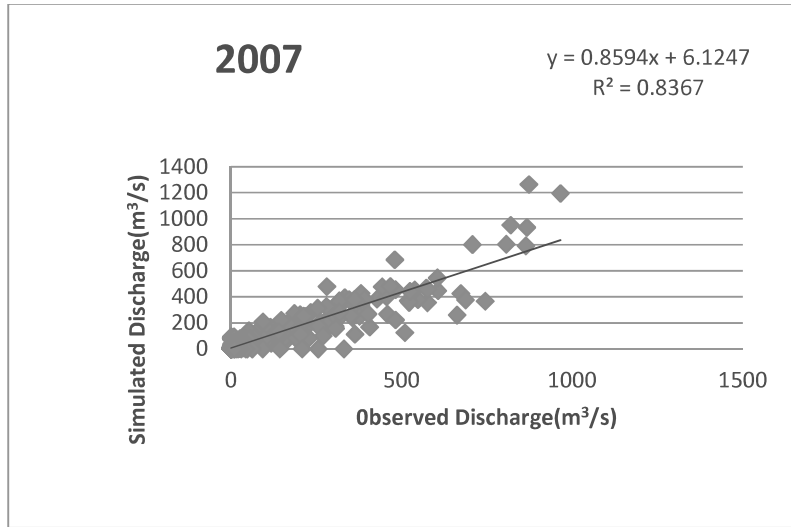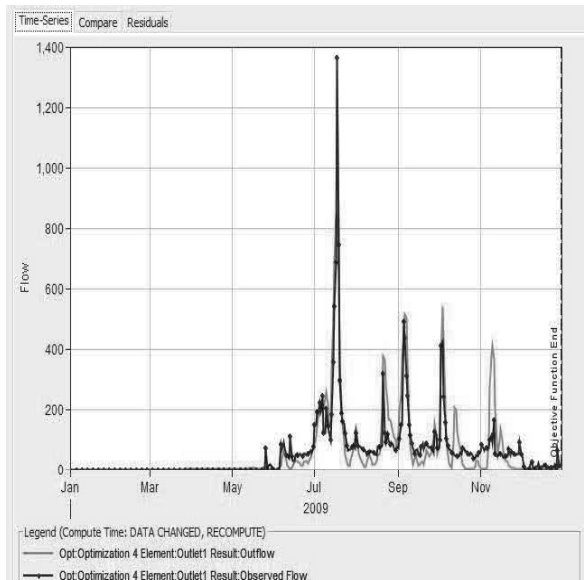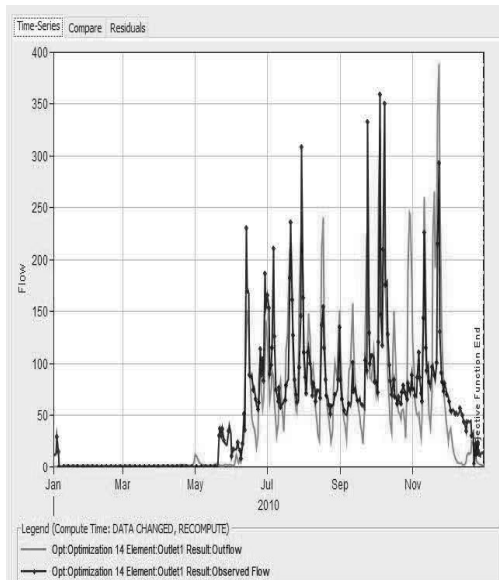

Fig. 10. Simulated and observed hydrograph for the year 2007

Fig.11. Scatter plot of observed versus simulated flow during calibration

Table 6. Performance indices of the model during calibration

Year	Nash Sutcliffe Efficiency (NSE)	Error in Peak Flow (%)	Error in Volume (%)	Coefficient of correlation (R^2)	Root mean square error-standard deviation ratio (RSR)
2005	0.762	-1.7	-0.47	0.8239	0.5
2006	0.751	-20.9	4.27	0.7034	0.5
2007	0.812	-23.7	9.45	0.8367	0.5

Fig. 12. Simulated and observed hydrograph for the year 2009

Fig. 13. Simulated and observed hydrograph for the year 2010

y = 0.8109x + 10.214
2009 R² = 0.7877

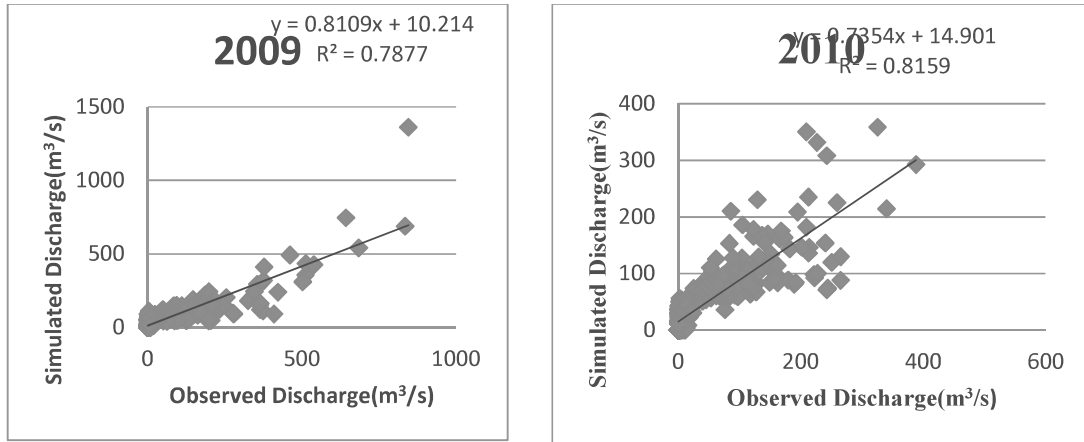y = 0.7354x + 14.901
2010 R² = 0.8159

Fig.14. Scatter plot of observed versus simulated flow during validation

Table 7. Performance indices of the model during validation

S.N.	Year	Nash Sutcliffe Efficiency (NSE)	Error in Peak Flow (%)	Error in Volume (%)	Coefficient of correlation (R²)	Root mean square error-standard deviation ratio (RSR)
1	2009	0.726	-19.20	0.82	0.7677	0.5
2	2010	0.764	8.2	-2.91	0.7159	0.5

Table 8. Comparison of observed and simulated flows for Chalakudy river basin

Measure	Simulated	Observed	Year	Time of peak
Peak flow rate (m³/s)	866.60	881.80	2005	01Aug2005
Volume (M m³)	1591.84	1599.33		
Peak flow rate (m³/s)	365.00	359.00	2006	17Aug2006
Volume (M m³)	1401.75	1344.34		
Peak flow rate (m³/s)	965.70	1264.80	2007	10Aug2007
Volume (M m³)	2757.76	2519.68		
Peak flow rate(m³/sec)	844.90	905.70	2009	18Jul2009
Volume (M m³)	1394.30	1383.02		
Peak flow rate (m³/s)	388.40	359.00	2010	23Nov2010
Volume (M m³)	1246.99	1284.39		

Percentage error in peak flow is small and close to observed flood peak within acceptable limit of 20% which was clearly revealed in the results. The maximum peak discharge occurred between July and September in validation period. The maximum peak discharge in the validation period was about 844.90 m³/s. For estimating the volumetric error, the total volume of discharge from watershed after settlement of all losses was computed and it was found that calibrated discharge volume was close to the observed discharge volume within the accessible limit of 20% of total volume. RSR value less than 0.5 revealed that it was also in the acceptable range.

Besides, Nash Sutcliffe Efficiency (NSE) value for validation period was obtained in the range of 0.71-0.77 which was also satisfactory.

3.6 Comparison of Observed and Simulated Measures of Flow for the Sub Basin

During the entire period of simulation (2005-2010), the highest volume of flow was seen in the year 2007 with 2757.76 Mm³ simulated value and 2519.68 Mm³ observed value. Similarly, lowest volume of flow was seen in the year 2010 with 1246.99 Million m³ as simulated

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and 1284.39 Million m³ as observed value.

The highest peak flow of river was found during the year 2007 and it was predicted as 965.70 m³/s and observed value as 1264.80 m³/s. The lowest peak flow was found during the year 2010 and it was predicted as 388.40 m³/s and observed value was 359.00 m³/s. Overall, it was found that all observed and simulated values shown in the table depicted good positive correlation between them.

4. CONCLUSION

The HEC-HMS model which is a widely used hydrological model was chosen for river basin management, simulation of watershed responses and generation of flood hydrographs in this study. The simulated runoff will be useful for well-planned programmes in water conservation and resource management projects and future prediction of runoff for flood mitigation strategies in the catchment.

During the calibration period (2005-2007), the highest flow volume was seen in the year 2007 with 2757.76 Mm³/year as the simulated flow and 2519.68 M m³/year as the observed flow. Similarly, lowest volume of flow was seen in the year 2006 with 1401.75 Mm³/year as simulated and 1344.34 Mm³/year as observed. During the validation period (2009-2010), the highest volume of flow was seen in the year 2009 with a flow of 1394.30 Mm³/year as simulated and 1383.02 Mm³/year as observed. Likewise, lowest volume of flow was seen in the year 2010 with a flow of 1246.99 Mm³/year as simulated and 1284.39 Mm³/year as observed. The highest peak flow of river was observed during the year 2010 and it was predicted as 844.90 m³/s whereas as the observed value was 905.70 m³/s. Since the error in peak flow was in the range of ±20% the predicted value may be accepted. Statistical Performance indices of the model, Nash-Sutcliffe efficiency (NSE) and Coefficient of correlation (R^2) values were obtained above 0.7, Error in Peak Flow (%) and Error in Volume (%) were figured below 20 and Root mean square error-standard deviation ratio (RSR) was acquired as 0.5 and below. All these values indicated satisfactory performance of model simulation both in calibration and validation. The better performance of model in rainfall-runoff transformation proved applicability of HEC-HMS model in the study area in spite of the limited data availability.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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