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Rainfall-Runoff Modeling of Karamana River Basin Using HEC-HMS

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***Abstract* - Floods are the most frequently occurring natural phenomenon. It is the temporary inundation of the dry land due to the overflow of water, endangering both property and life. Hence, there is a need to study the possibility of floods and measures to reduce the effects of flooding. Karamana River which flows through the Thiruvananthapuram district of Kerala, often gets flooded during Monsoon season, causing continuous waterlogging issues in its downstream region. This study is intended to develop rainfall-runoff model of the Karamana River Basin using Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) in integration with Aeronautical Reconnaissance Coverage Geographic Information System (ArcGIS). The factors considered in the study were elevation, land use and land cover, soil type, and drainage of the region. The rainfall losses were estimated by the Soil Conservation Service - Curve Number method while the Soil Conservation service - Unit Hydrograph method was used to transform excess rainfall into a direct rainfall hydrograph. The Routing of the total runoff from the outlet of the sub-basin to the outlet of the Mangattukadavu discharge gauging station was achieved by using the Muskingum method. The model was calibrated using the daily rainfall data for the grid point at 8.5^0 N & 77^0 E and the daily discharge data of Mangattukadavu discharge gauging station, from 1st January 1992 to 31st December 2016. The validation of the model was performed for the period from 1st January 2017 to 31st December 2021 on the daily time step. The developed model has an R^2 value of 0.91, which signifies sufficient accuracy for the runoff generated from it.**

Keywords – Hydrologic model, curve number, hydrograph.

I. INTRODUCTION

Runoff and precipitation are the two crucial elements of the hydrological cycle. On the surface of the land, runoff is produced by the build-up of extra precipitation. After infiltration and evaporation, any excess precipitation in a watershed builds up as runoff at drainage points and finally drains to an outlet [1]. A combination of the catchment's climatic, physiographic, and geologic variables affects how much runoff is produced. The climate change influences the amount, intensity, and frequency of precipitation, which in turn affect the amounts of Peak flows and stream-flow. Flooding is mostly caused by runoff quantities that flow into channels at levels greater than the capacity of the streams. Knowing the amount of runoff can help with a number of watershed management issues. For the purpose of managing

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flood risk, it is crucial to assess the magnitude, frequency, and intensity of floods. Urbanisation alters these factors by raising the peak. Peak discharges and peak flow have both changed as a result of the climate variability. For example, early flood alerts may be possible when peak flows can be predicted in advance, that improves flood preparedness. Peak flow is also essential for evaluating the methods for various management alternatives and resolving water related problems. The use of surface runoff in agriculture is another example of its significance. In agricultural fields, surface runoff carries nutrients, and runoff determination can assist in improved agricultural management by assisting in understanding the transport mechanisms. Therefore, comprehending the rainfall-runoff mechanism is crucial for creating sustainable systems and managing watersheds. But, because of the nonlinear and complex dynamics, rainfall- runoff is difficult to grasp, and estimating the quantity of runoff produced can be problematic. Hydrological modellingis often used to assess the hydrological response within a basin for a given depth of rainfall. A simplified portrayal of the real world is what is meant by the term "model". Hydrological modelling has been utilised in numerous studies for a variety of purposes, including estimation of stream-flow in un-gauged stations, examination of the effects of change in climate and urbanisation, forecasting of floods, and managing water resources. Karamana river basin is located in the Thiruvananthapuram district of Kerala. The area around this river basin is excellent for agriculture. However, alterations to the flow regime and changes in land use have resulted in a rise in flood occurrences, which has ultimately put agriculture and the natural variety at risk. The hydrology of the Karamana River Basin has not been extensively studied in recent years. Changes in vegetation into built-up areas increase the rate of evaporation and surface runoff, which has an impact on the hydrology of the watershed. The quantity of runoff can also be affected by changes in routing by other characteristics such as channel slope, channel length, and roughness. In order to describe the runoff, it is important to identify the variables that influence it in a particular place. The main objective of this study is the simulation of the peak stream-flow event in Karamana River basin, followed by the evaluation of the sensitivity of the parameters in the model. The hydrological model thus developed can be used in various other applications such as forecasting of floods, examination of the effects of change in climate on runoff and management of watersheds.

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II. STUDY AREA

The area of study, the Karamana River Basin, spans an area of 702 km^2 and is located between the latitudes of 8°05' and 8°45' in the north and longitudes of 76°45' and 77°15' in the east. The river is named after the neighborhood of Karamana in Thiruvananthapuram, through which it runs. The Karamana River is a tiny mountainous river that flows through the Kerala's capital city of Thiruvananthapuram and empties into lowland, midland, and highland physiographic zones. The Karamana River originates at Agastyarkoodam at the southernmost point of the Western Ghats, flows 66 km west, and merges with the Arabian Sea at Panathura not far from Kovalam. Before the Karamana River meets with the Arabian Sea, the rivers Killiyar and Parvathyputhanar also converge with it. There are two important dams built on the Karamana River. These are the Aruvikkara Dam, built in the 1930s and the Peppara Dam which lies further upstream and was built in 1983. The Aruvikkara Dam was constructed with the aim of providing piped drinking water to the city. The Peppara Dam controls the flow of water into the Aruvikkara Dam by unifying all the upper tributaries of the Karamana River. At Peppara Dam, there is also a 3 MW hydel power station. The average annual rainfall in the Karamana river basin is 2600 mm which varies from less than 400 mm in coastal region to about 4200 mm in the north-eastern regions. The Thiruvananthapuram Corporation area is the specific study area selected and has about 16 lakhs of population as per 2011 census. Major land use classes are forests, forest plantations, mixed crops, paddy lands and water bodies. The drainage map of Karamana river basin is shown in figure 1.

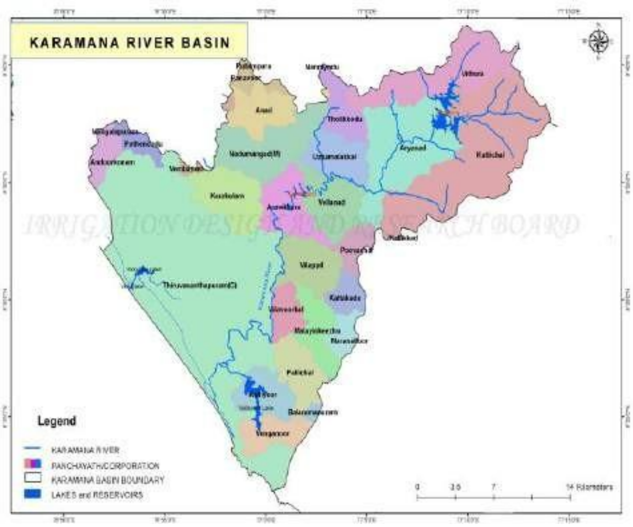
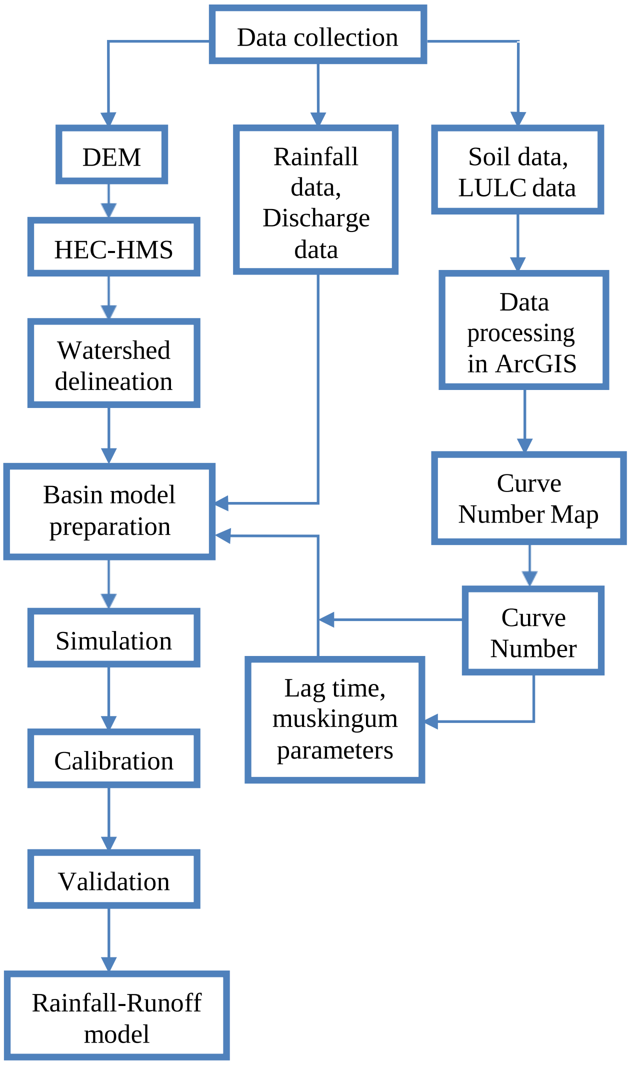


Fig. 1 Drainage map of Karamana river basin

III. METHODOLOGY



The rainfall-runoff model is developed from a complex method incorporating numerous calculations. The relevant details of the study area, the input data requirement of the selected model and the methodology adopted are described in the following sections. The flowchart of the methodology adopted for the study is shown in figure 2.

Fig. 2 Flowchart of the methodology adopted for the study

A. Data Used

The data used for the study includes digital elevation model, rainfall data, discharge data, soil data, and LULC data. The details about the data used in the study and their sources are discussed in the sections below.

i. Digital Elevation Model (DEM)

DEM of the study area was downloaded from the website of United States Geological Survey (USGS). Shuttle Radar Topographic Mission (SRTM) DEM of 30m x 30m resolution was used for the study. DEM was used in HEC-HMS to delineate basin and sub basin boundaries, to delineate the stream network, and to calculate average sub basin curve numbers. The elevation ranges from 0 to 65535 meters. Figure 3 shows the DEM of the study area.

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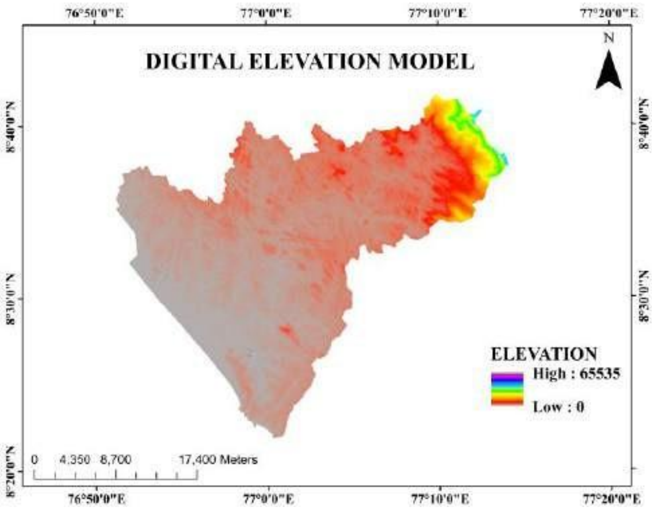

Fig. 3 DEM of Karamana river basin

ii. Rainfall Data

Daily Gridded Rainfall Data of 0.25 x 0.25 degree resolution for 30 years duration for the period from 1992-2021 was downloaded from the website of Indian Meteorological Department (IMD). Then it was processed in QGIS for converting it into .csv format. It contains the rainfall data for whole India. It was further processed in ArcGIS to convert it into shape file from which the rainfall data for the study area is clipped out. There is only one grid point in the Karamana River Basin for which the rainfall data is available and the grid point is at 8.5^0 N & 77^0 E. From this, Rainfall of 25 years duration from 1992-2016was used for rainfall-runoff model calibration in HEC-HMS and that of 5 years duration from 2017-2021 was used for validation of the model. Grid point at Karamana river basin is shown in figure 4.

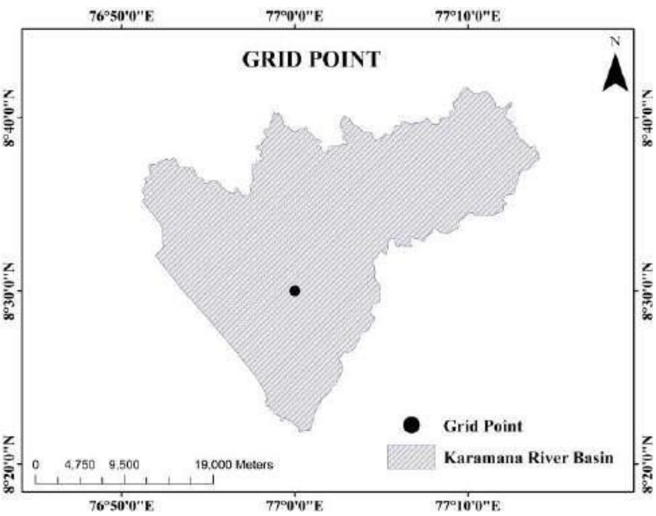

Fig. 4 Karamana river basin showing Grid Point at 8.5^0 N &77^0 E

iii. Discharge Data

Daily Discharge data at Mangattukadavu River gauging station for 30 years duration for the period from 1992-2021 was downloaded from Global Runoff Data Centre (GRDC).

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From this, discharge data for 25 years duration from 1992-2016 was used for rainfall-runoff model calibration in HEC- HMS and that of 5 years duration from 2017-2021 was used for validation of the model.

iv. Soil Map

The Global Soil Map was downloaded from the website of FAO (Food and Agricultural Organization). It was processed in ArcGIS software to clip the study area from the global soil map. A symbology had been performed afterwards. Sandy clay loam, Sandy loam, Clay loam etc. are the major soil types in Karamana river basin. The obtained soil map in raster form was further converted to shape file format for using it along with LULC map in the Curve Number map generation. Figure 5 shows soil map of Karamana river basin.

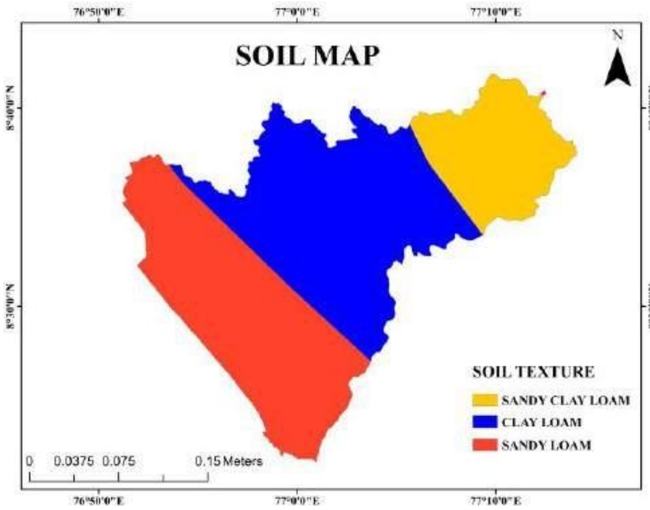

Fig. 5 Soil map of Karamana river basin

v. Land Use and Land Cover (LULC) Map

Land Use and Land Cover is an important factor in determining the amount of runoff to be generated in an area. The Global Land use and Land cover map was downloaded from the website of Environmental System Research Institute (ESRI) in the raster format. It was processed in ArcGIS software to clip the study area from the Global Land Use and Land Cover map. A symbology had been performed afterwards followed by reclassification of the LULC map. Water body, vegetation, crop land, built up area and bare land were the five classes of LULC identified in the Karamana river basin. Out of these five classes, built up area and vegetation are the predominant land use pattern. Also, built up area and bare land are highly impervious than the other three classes and causes increased runoff in these areas. The reclassified Land use and Land Cover can be used as an input for a catchment model as it can affect surface erosion and water runoff. The obtained LULC map in raster form was further converted to shape file format for using it along with soil map in the Curve Number map generation. Figure 6 shows LULC map of Karamana river basin.

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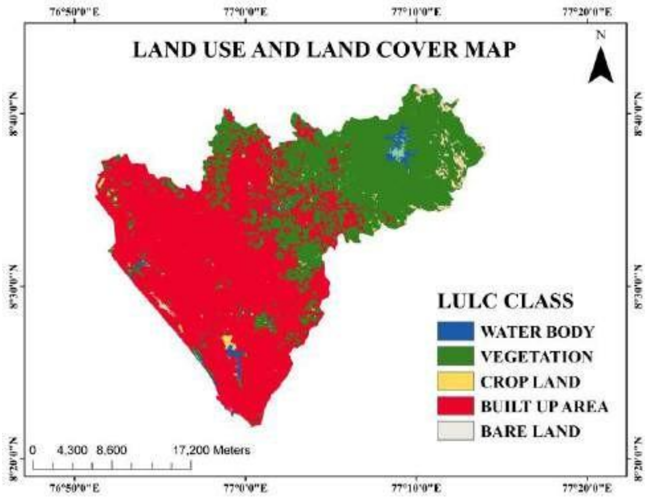

Fig. 6 LULC map of Karamana river basin

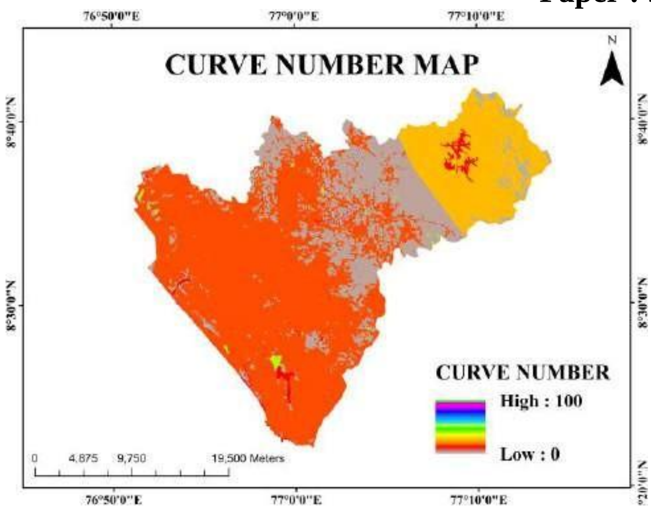

Fig. 7 Curve Number grid map of Karamana river basin

vi. Curve Number (CN) Grid Map

The curve number (CN) is a function of land use, cover, soil classification, hydrologic conditions and antecedent runoff conditions [2]. The variation in infiltration rates of different soils is incorporated in curve number selection through the classification of soils in to four hydrologic soil groups; A, B, C, D. These groups representing soil having high, moderate, low, and very low infiltration rates. Curve number grid map gives the utility of extracting curve number for any area in the watershed without performing any calculation. The CN grid map was prepared by merging soil map and LULC map using ArcGIS software and from which CN values were obtained. CN was used to determine the sub-basin characteristics and to estimate the hydrological parameters used in the HEC-HMS model. Table 1 shows the curve number values corresponding to each land use pattern in the Karamana river basin. The CN map of Karamana river basin is shown in figure 7.

Table 1. Curve Number Values
(Source: United States Department of Agriculture)

Sl. No.	Land Use Pattern	A	B	C	D
1	Water body	100	100	100	100
2	Vegetation	30	55	70	77
3	Crop land	39	61	74	80
4	Built up area	57	72	81	86
5	Bare land	41	62	74	85

B. Watershed delineation using HEC-HMS software

As a representation of surface elevation, a Digital Elevation Model (DEM) was extracted, and the depressions were altered by enlarging the pixel size of the surrounding terrain. The steepest descent direction for each terrain was then specified. The downstream draining cell was then identified and categorized according to a stream network threshold. By adding segments and links to each network, it is possible to define the connection junctions and outlet or junction and drainage. The creation of a stream vector and the delineation of a sub-basin for each stream segment were both aided by this. After delineating, the basin model was created. Watershed delineation up to Mangattukadavu station of Karamana River was done using HEC-HMS software. The USGS, SRTM Digital elevation model (DEM) of 30m*30m resolution was used for the watershed delineation. Watershed delineation process includes pre-processing of sinks, pre-processing of drainage, and stream identification. After Stream generation, the break point was assigned to locate the outlet. Here, the selected outlet point was at Mangattukadavu gauging station. Then selected the ‘delineate element’ for watershed delineation.

C. Basin Model Preparation

An important part of the study is figuring out how many basins and river reach segments there are. The position of the stream flow gauge, which was later used to calibrate and validate the model, is utilized to separate the sub-basins. Basin model represents the physical description of the watershed in a HEC-HMS model. Sub basins and reaches are connected to the outlet point during the basin model preparation. Then hydrological parameters for each sub-basin have to be generated for each sub-basin. For this, the mean CN value of each sub-basin in the delineated watershed has to be calculated. It was done by processing the CN Grid map corresponding to the delineated watershed in ArcGIS using zonal spatial analyst tool. The mean CN values obtained was used as an input in developing loss model in HEC-HMS. Then time of concentration, potential abstraction, and lag time were calculated using this meanCN values.

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D. Model Input Parameters

The parameters required for Hydrological modeling using HEC-HMS model are listed in Table 2.

Table 2. Parameters used in HEC-HMS model

Model	Method	Parameters
Loss model	SCS - Curve Number	Initial abstraction (mm), Curve Number, Impervious area (%)
Transform model	SCS Unit Hydrograph	Lag time (min)
Routing model	Muskingum	Travel time (k) and dimensionless weight (x)

a) *Soil Conservation Service Curve Number (SCS-CN) Method*

The loss model in HEC-HMS was calculated by subtracting the volume of water that was intercepted, infiltrated, stored, evaporated or transpired to the rainfall water volume. In this study, the Soil Conservation Service - Curve Number (SCS-CN) loss method was used to calculate the direct runoff from a design rainfall. For the loss model, the SCS-CN has two parameters: the curve number (CN) and the initial abstraction (I_a). The initial abstraction was assumed zero in this study to achieve maximum runoff from the obtained rainfall. The CN is a function of land use and soil type, which was obtained from the CN Grid map prepared by merging soil map and LULC map in ArcGIS. The percentage of impervious for each sub-basin was assumed to be 0%, which indicates the entire catchment was assumed to be completely pervious. The CN values for each sub-basin were calculated by using the following formula.

$$A = \frac{\sum A_i CN_i}{\sum A_i} \tag{1}$$

Where, A_i is the area of the sub-basin in km^2 and CN_i is the corresponding curve number.

b) *Soil Conservation Service Unit Hydrograph Method*

The transform prediction models in HEC-HMS simulate the

$$S = \frac{1000}{CN} - 10 \tag{2}$$

$$T_C = \frac{l^{0.8}(S+1)^{0.7}}{1140Y^{0.5}} \tag{3}$$

$$L = 0.6T_C \tag{4}$$

Where, 'L' is the lag time in hours, 'T_c' is the time of concentration in hours, 'l' is the flow length in feet, 'Y' is the average watershed land slope in %, and 'S' is the maximum potential retention in inches.

c) *Muskingum Method*

The Muskingum method is a common lumped flow routing technique. The parameters used in this model are x and k. The Muskingum parameter 'x' is a dimensionless coefficient that lacks a strong physical meaning. x value ranges between 0 and 0.5. x = 0 for channels with mild slopes and over-bank flow and x = 0.5 for steeper streams with well-defined channels that do not have flows going out of bank. In this study, an average value of 0.25 was provided for x, assuming that the river bank slope is neither steeper nor mild. The Muskingum parameter 'k' is the travel time of the flood wave through the routing reach. In this study, k value is assumed as 0.5 based on the previous literatures reviewed.

E. Calibration and Validation

The rainfall-runoff model developed was calibrated for the identified sensitive parameters to improve the agreement between the simulated and observed data [3]. The calibration was done for a period of 25 years using daily rainfall data and daily discharge data at Mangattukadavu station from January 1st 1992 to 31st December 2016. For this, the parameters such as x and k were adjusted according to the optimization method, keeping the other parameters unchanged till a satisfactory agreement between the simulated and observed runoff was obtained. Model parameters were optimized in such a way that model efficiency becomes maximum.

The calibrated model was then validated for a period of 5 years from January 1st 2017 to December 31st 2021.

Usually in rainfall-runoff modeling, the generated model is process of excess rainfall direct runoff in the catchment and transform the rainfall excess in point runoff. The SCS - Unit Hydrograph model was used to transform the excess rainfall into runoff. The basin lag time parameter values have been calculated from the CN values of each sub-basin. The time of concentration, Lag time and maximum potential abstraction are calculated using the following formula.

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explained in terms of the following efficiency parameters: Coefficient of Determination (R^2), Nash Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and Root Mean Square Error (RMSE). These parameters measure the goodness-of-fit between the computed outflow and observed stream flow at the selected element [3]. R^2 is used to maximize the explained variance in the observed data for the model and ranges between 0 and 1, indicating 0 for highly inefficient model and 1 for highly efficient model. NSE is used to measure the forecasting efficiency of the model and ranges between $-\infty$ to 1, wherein the model is considered very well for the values ranging from 0.75 to 1. PBIAS is used to assess the normal drift of the simulated data to be larger or smaller than their observed counterparts. The optimal value

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of PBIAS is 0.0, with low values indicating realistic model simulation. RMSE is a good measure of how accurately the model predicts the response and is used to minimize the average distance between observed and simulated data. RMSE ranges between 0 to ∞, wherein the lower values of RMSE indicate better fit of the model.

IV. RESULTS AND DISCUSSIONS

The results obtained from the rainfall-runoff modeling of Karamana river basin are described in the following sections.

1) *Basin Model*

The basin model for rainfall-runoff modelling of Karamana river basin was prepared using Mangattukadavu river gauging station as the outlet point. It was created from the DEM of the study area by performing pre-processing of sinks, pre-processing of drainage, stream identification followed by watershed delineation. The model has 7 sub-basins and 3 reaches. The basin model prepared up to the Mangattukadavu gauging station is shown in figure 8.

Fig. 8 Basin Model prepared up to Mangattukadavu gauging station

The developed basin model was converted into shape file format. The mean CN for each sub-basin was calculated by processing CN grid map and the basin model in shape file format in ArcGIS using zonal as the spatial analyst tool. The obtained values of curve numbers were used to develop loss model in HEC-HMS and to calculate lag time for each sub-basin. The values of CN and lag time for each sub-basin are tabulated in table 3.

Table 3. Values of CN and lag time for each sub-basin

SUB-BASIN	CURVE NUMBER	LAG TIME (min)
Sub-basin 1	75.129	73.297
Sub-basin 2	73.440	151.937138
Sub-basin 3	70.984	119.0901116
Sub-basin 4	71.566	113.5406899
Sub-basin 5	69.635	87.522
Sub-basin 6	72.377	158.9579955
Sub-basin 7	71.541	112.0930575

2) *Simulated Runoff v/s Observed Runoff*

The rainfall-runoff model was developed in HEC-HMS by simulating the daily rainfall data and daily runoff data for the study area for a period of 30 years duration from 1992-2021. The results show that the peak values of simulated runoff is more compared to that of the observed runoff. The comparison of the simulated and observed runoff for the developed rainfall-runoff model for the period 1992-2021 is shown in figure 9.

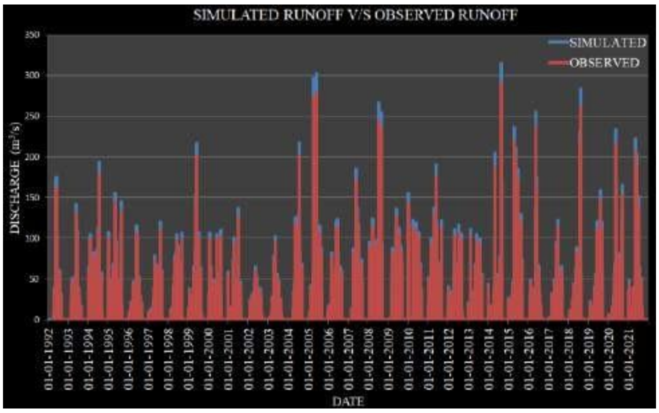

Fig. 9 Comparison of Simulated and Observed Runoff for the period from 1992-2021

3) *Model Calibration*

The rainfall-runoff model developed was calibrated for the identified sensitive parameters to improve the agreement between the simulated and observed data. Calibration was performed for a period of 25 years from 1992-2016. For this, the basin parameters x and k were adjusted according to the optimization method, keeping the other parameters unchanged till a satisfactory agreement between the

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simulated and observed runoff was obtained. The calibration result shows that the peak values of the simulated flow match well with the peak values of the observed flow. The simulated and the observed runoff for the calibration period of 1992-2016 are shown in figure 10.

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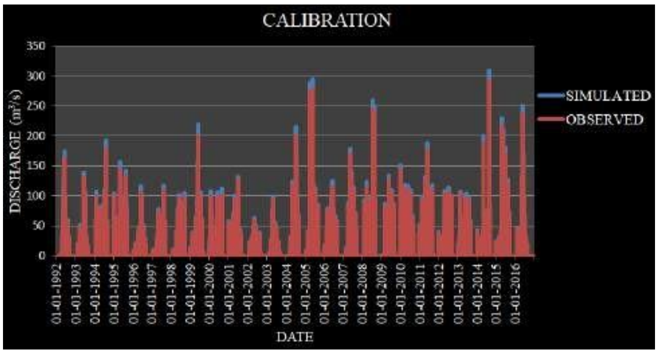

Fig. 10 Comparison of simulated and observed runoff for the calibration period of 1992-2016

4) Model Validation

The calibrated model was then validated for a period of 5 years from 2017-2021. The simulated and observed runoff for the validation period of 2017-2021 is shown in figure 11.

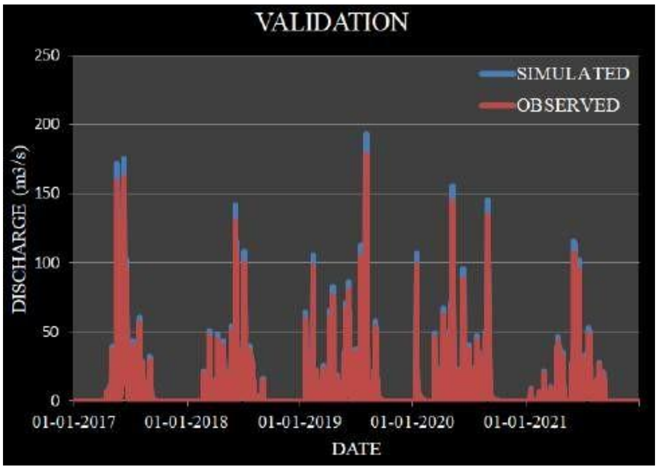

Fig. 11 Comparison of observed and simulated runoff for the validation period of 2017-2021

Usually in rainfall-runoff modelling, the generated model is explained in terms of the following efficiency parameters: Coefficient of Determination (R2), Nash Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and Root Mean Square Error (RMSE). These parameters measure the goodness-of-fit between the computed outflow and observed stream flow at the selected element. R2 is used to maximize the explained variance in the observed data for the model and ranges between 0 and 1, indicating 0 for highly inefficient model and 1 for highly efficient model. NSE is used to measure the forecasting efficiency of the model and ranges between -∞ to 1, wherein the model is considered very well for the values ranging from 0.75 – 1. PBIAS is used to assess the normal drift of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low values indicating realistic model simulation. RMSE is a good measure of how accurately the model predicts the response and is used to minimize the average distance between observed and simulated data. RMSE ranges between 0 to ∞, wherein the lower values of RMSE indicate better fit of the model. The values of efficiency parameters for the validated model are tabulated in table 4.

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Table 4. Efficiency parameters for the developed model

Efficiency parameter	Value
RMSE	0.1
NSE	0.991
PBIAS	7.83 %
R^2	0.91

The results indicate that the efficiency parameters are within the range of values corresponding to an efficient model. Hence, this model can predict the stream flow for the study area with sufficient accuracy.

V. CONCLUSION

Rainfall-Runoff model of Karamana river basin was developed in HEC-HMS using Mangattukadavu gauging station as the outlet point. The model was calibrated for a period of 25 years from 1991-2016. The model was validated for a period of 5 years from 2017-2021. The performance of the validated model was measured using the efficiency parameters such as R^2, RMSE, NSE, and PBIAS. The R^2 value of the validated model was obtained as 0.91. It indicates that the model is sufficiently accurate in predicting the runoff with 91% accuracy. Hence, this model can be further used for rainfall runoff generation for the region with good accuracy.

VI. SCOPE FOR FUTURE WORK

- The developed rainfall-runoff model can be used for predicting runoff for the study region for a given rainfall.
- The hydrographs obtained from the model can be used in HEC-RAS for flood inundation study of thestudy area.
- The DEM with better resolution may be used for increasing the accuracy of the developed model.
- The use of IDF Curve specifically generated for thestudy region based on climate change model inputs can be used for better and realistic projection of runoff due to design storm events.

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