FLOOD FREQUENCY ANALYSIS AND MODELLING OF FLOOD USING HEC-HMS FOR A RIVER BASIN –A CASE STUDY

By

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TAVANUR, MALAPPURAM-679573

KERALA, INDIA

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THESIS

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TAVANUR, MALAPPURAM-679573

KERALA, INDIA

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DECLARATION

I, hereby declare that this thesis entitled **"FLOOD FREQUENCY ANALYSIS AND MODELLING OF FLOOD USING HEC-HMS FOR A RIVER BASIN –A CASE STUDY"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society**.**

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CERTIFICATE

Certified that this thesis entitled **"FLOOD FREQUENCY ANALYSIS AND MODELLING OF FLOOD USING HEC-HMS FOR A RIVER BASIN –A CASE STUDY"** is a record of research work done independently by **Ms. Riyola George (2018-18-004)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

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Riyola George

Dedicated to

Agricultural

Engineers

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SYMBOLS AND ABBREVIATIONS

%	:	Percentage
<	:	Less than
>	:	Greater than
∑	:	Sum
≤	:	Less than or equal to
≥	:	Greater than or equal to
&	:	And
°C	:	Degree Celsius
AGCM	:	Atmospheric general circulation model
ASCII	:	American Standard Code for Information Interchange
CGWB	:	Central Ground Water Board
CN	:	Curve Number
DEM	:	Digital Elevation Model
DSS	:	Data Storage System
ERDAS	:	Earth Resources Data Analysis System
ET	:	Evapotranspiration
et al.	:	and others
Fig.	:	Figure
FPS	:	foot–pound–second
Geo-HMS	:	Geospatial Hydrological Modelling System
GIS	:	Geographical Information System
h	:	hour
ha	:	Hectare
HEC	:	Hydrologic Engineering Centre
HMS	:	Hydrological Modelling System
HSG	:	Hydrologic soil group
Int.	:	International

J.	:	Journal
km^2	:	Square kilometre
Landsat	:	Land Satellite
m	:	meter
mm	:	millimeter
Mm^3	:	Million cubic meter
MCM	:	Million cubic meter
MRI	:	Meteorological Research Institute
MSL	:	Mean sea level
NASA	:	National Aeronautics and Space Administration
NLCD	:	National Land Cover Database
No.	:	number
NSE	:	Nash Sutcliffe Efficiency
OLI	:	Operational Land Imager
PBIAS	:	Percentage Bias
Proc.	:	Proceedings
R^2	:	Coefficient of Correlation
RCP	:	Representative Concentration Pathways
RMSE	:	Root Mean Square Error
RS	:	Remote Sensing
s	:	second
Sci.	:	Science
SCS	:	Soil Conservation Service
SD	:	Standard Deviation
SI units	:	International System of units
Soc.	:	Society
SOI	:	Survey of India
SRTM	:	Shuttle Radar Topography Mission
SRTMGL	:	Shuttle Radar Topography Mission Global

SSP	:	Statistical software package
SWAT	:	Soil and Water Assessment Tool
SWM	:	Stanford Watershed Model
TIRS C1	:	Thermal Infrared Sensor Collection 1
UH	:	Unit Hydrograph
USGS	:	United States Geological Survey
viz.	:	Namely

INTRODUCTION

CHAPTER I
INTRODUCTION

Expressive economic damages and loss of livelihood due to severe flooding is common in most of the countries in Asia (Azam *et al.*, 2017). India also has continuously suffered many flood events during the current decade. In general, flood is an overflow of an expanse of water that submerges the land and as a result some of the water flows outside of the normal perimeter of the water body. The major causes of flood include climate change, tsunami, poor river management, cloud bursting phenomenon or silting of rivers (Tripathi, 2015). Flood frequently leads to serious water pollution and epidemiological problems. Due to recurrent prevalence of flood, this catastrophic event has put further burdens than any other natural disaster. Flood damage extent is often exacerbated due to following reasons: 1) inadequate flood warning systems 2) use of crude hydro informatics tools and 3) inadequately trained model users. Therefore, floods are an arena of concern of the hydrology discipline and a significant phenomenon in agriculture, civil engineering and public health. Hence, a proper assessment of flood peak, its occurrence and its return period are very much essential for proper development, planning and design of water resources projects.

Management of water resources and its planning can be effective only, if the basic scientific unit watershed is considered. It will produce a holistic approach of the scenario. Watershed can be interpreted as complex system that is embodied with various hydrologic processes such as precipitation, interception, surface runoff, infiltration, groundwater percolation and evapotranspiration that occur at diverse spatial and temporal scales. The interaction among all watershed components is collectively represented by watershed response in the form of runoff hydrograph. Watershed response mainly depends upon watershed topography (shape, size, slope, and orientation), land use pattern, soil types, magnitude and duration of rainfall events and human interventions. In order to obtain the accurate estimation of such a vast dome, the techniques of remote sensing, geographical information system (GIS) and modelling have been advocated in recent years. Remote sensing technology involves huge amount of spatial data management whereas GIS can store, analyse, retrieve and display spatial data for solving complex planning and management problems. Thus, the use of RS and GIS helps in geo-referencing of satellite data, creation of digital database, thematic map preparation and generation of spatial frame work. The modelling helps in depicting the actual phenomenon in nature into an understandable form. However, as natural phenomena are subjected to infinite number of influences, the complicated assignment is to develop useful simulations and regulate the most important factors. Therefore, modelling the hydrological processes with the aid of geospatial techniques (Remote Sensing and GIS) is very essential and it plays a crucial role in several complex analyses.

Hydrological phenomena are highly non-linear and highly variable with regard to space and time. “Hydrologic processes such as floods are exceedingly complex natural events. They are resultants of a number of component parameters and are therefore very difficult to model analytically. The floods in a catchment depend upon the characteristics of the catchment, rainfall and antecedent conditions, each one of these factors in turn depend upon a host of constituent parameters. This makes the estimation of the flood peak a very complex problem” (Subramanya, 2008). Hydrological model mathematically represents the response of a catchment to hydrologic events during the time period under concern with a precise approach. Hence, hydrological models are required to predict the watershed run-off for accurate and effective designing flood control projects and management of water resources.

Advanced knowledge of the project hydrology and hydrologic conditions are essential for management, improvement of plans and design techniques of water resources development projects. “It is the determination of these future hydrologic conditions that has long occupied the attention of engineering hydrologists who have attempted to identify acceptable simplifications of complex hydrologic phenomena and to develop adequate models for the prediction of the responses of catchments to various natural and anthropogenic hydrologic and hydraulic phenomena” (Oleyiblo and Li, 2010). Thus, numerous hydrologic models have been developed for the resolution of flood forecasting and study of rainfall-runoff transformation processes. Different types of hydrologic models available, differs according to the kind of results needed and availability of hydrological data. SWM-IV, HEC-HMS, MIKE etc. are some of the major hydrologic models used for the rainfall-runoff simulation.

In particular, HEC-HMS (Hydrologic Engineering Centre Hydrologic Modelling System) is a widely used numerical model (computer programme) designed to simulate the rainfall-runoff processes. It was established on the initiatives of US Army Corps of Engineers for simulating all hydrologic processes of a dendritic watershed system. “The HEC-HMS model is physically based and conceptually semi-distributed model designed to simulate rainfall-runoff processes in a wide range of geographic areas, from large river basin water supplies and flood hydrology to small urban and natural watershed runoffs” (Tassew *et al.,* 2019). The model simulates various scenarios both spatially and temporally, in flood forecasting and early flood warning system (Kishor *et al.*, 2014). This model encompasses losses, runoff transform, open channel routing, parameter estimation and analysis of meteorological data and rainfall-runoff simulation. The software contains an absolutely integrated work environment comprising a database, data entry utilities, computation engine.

The HEC-HMS is public domain software that confronts multiple options to simulate base flow, interflow and channel flow. The initial version HEC –I, that worked with MS-DOS program was successively updated to HEC-HMS with more function and additional capabilities. “A model of the watershed is constructed by separating the hydrologic cycle into manageable pieces and constructing boundaries around the watershed of interest” (USACE, 2000). “Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation and systems operation” (Scharffenberg and Harris, 2008). HEC-HMS is chosen by several modellers due to its easy operation, handling, availability and better technical advantage and support from its developers. Hence, HEC-HMS model is used in this study to simulate rainfall-runoff process in watershed.

“Flood-plain management needs up-to-date information and techniques for predicting floods to protect the public and minimize flood-related costs to government and private enterprise” (Law and Tasker, 2003). “The key challenge in developing a reliable Early Warning System for disaster mitigation is the development of modelling and simulation tools to accurately make flood predictions, simulate river channel breaching and flood propagation" (Toriman *et al.*, 2009). Concise ideas in the design of Early Warning Systems for flood prediction and disaster management strategies are extracted from flood modelling, peak discharge calculation and its associated empirical results in a computational environment such as GIS compactable software. Moreover, the runoff rate from a rainfall event is the key parameters in land use planning in flood-prone areas, designs of dams, culvert, bridges, etc.

Planners and engineers usually require reliable estimates of the magnitude and frequency of floods to design all the water resources projects in the preferred area. The flood frequency analysis is one of the main techniques used to find the relationship between magnitude of a flood event and its frequency with which that particular event is exceeded. It also encompasses the fitting of a probability model to the sample of annual flood peaks recorded over a period of observation, for a catchment. "Reliable flood frequency estimates are vital for floodplain management; to protect the public, minimize flood related costs to government and private enterprises, for designing and locating hydraulic structures and assessing hazards related to the development of flood plains" (Tumbare, 2000). For flood frequency analysis, frequency distributions such as Gumbel Extreme Value distribution, Log Pearson Type III distribution, Generalised Pareto (Pickands, 1975), Log Normal, Wakeby distribution are commonly used (Rahman *et al.*, 2015). The software HEC-SSP generally used to perform flood flow frequency analysis was used in this study.

Meenachil river face the threat of wide spread illegal sand mining. The sewage pollution is also another menace of the river. This river is highly dangerous and wild during flood season due to the depth of river. This river contributed vigorously to 2018 Kerala flood and major causality in the human history. An agricultural dominated watershed situated at the upstream of Meenachil river basin was selected in this study for flood frequency analysis and flood modelling. The watershed falls within the tropical humid climate with high variations in relief from the west coast to the hilly region of the Western Ghats in the east. The water resources planning and management is necessary in the watershed for irrigation scheduling, water harvesting, flood control and design of various engineering structures. Hence it is very important to understand rainfall-runoff relationship of the basin for precise planning and management by exploring the possibility of applying the semi distributed hydrological model HEC-HMS.

In view of all the above facts the present study entitled **“Flood frequency analysis and modelling of flood using HEC-HMS for a river basin –a case study”** was undertaken with the following specific objectives:

1. To conduct flood frequency analysis and predict the magnitude of flood for different return periods of the sub basin
2. To calibrate and validate HEC-HMS model for the sub basin
3. To estimate flood hydrograph using HEC-HMS model

REVIEW OF LITERATURE

CHAPTER II

REVIEW OF LITERATURE

The following section of this chapter scripts a brief review of significant contributions made by various researchers in the field of flood modelling and flood frequency analysis:

2.1 FLOOD FREQUENCY STUDIES

Flood Frequency Analysis, often coined as FFA, was stated as the estimation of how often a specified event will occur. Prior to the estimation, analysis of the stream flow data played a very significant role in finding probability distribution of floods (Ahmad, *et al*., 2011). Several studies have employed diverse statistical distributions to quantify the likelihood and intensity of floods. But none of them had ended up with worldwide acceptance due to the randomness in the rainfall event. Another report was that none of the frequency distributions are specific to any country (Law and Tasker, 2003).

Jesús *et al*. (2016) conducted a study on stream flow frequency analysis of rainfall and runoff. They have adopted methods such as a) gauged method that consist of study of maximum streamflow rate annual series and b) hydro-meteorological method that considered components and processes with rainfall–runoff transformation models. Actual rainfall and flow recorded for six different periods were analysed and the results were compared with observed historical series data. It was concluded that maximum rainfall was useful and valuable tool for the frequency studies.

Shakirudeen and Saheed (2014) performed flood frequency analysis of lower Ogun River basin, Nigeria using the Gumbel probability distribution method. Flood frequency was further tested with Log Pearson Type III distribution to determine the finest fitting statistical measure for hydrological variations using Chi Square test. The study had proved the importance of depicting the frequency of occurrence of flood for the effective production of GIS-based flood inundation mapping.

Aksara and Apiwit (2016) studied the flood frequency utilizing the hydrological model HEC-HMS by assessing peak flood characteristics in Yom river basin, Thailand. Historical rainfall and flood data in combination with rainfall products from MRI-AGCM3.2S were used in HEC-HMS model simulation. Correlation between a flood magnitude and its return period was developed by statistical modelling of a time series of peak flood. This helped in developing an Annual Exceedance Probability (AEP) of selected flood features, critical for design flood control and mitigation system.

George and Gary (2000) performed detailed examination on flood-frequency forecast strategies for unregulated, ungauged waterways and surges of Tennessee, U.S.A. Flood-peak evaluations appropriate for configuration purposes at gaged locations was best controlled by a consolidated utilisation of the log-Pearson Type III station gauges as portrayed in Bulletin 17B of the Interagency Advisory Committee on Water Data (1982). Thus, Flood recurrence at every one of the gaging stations utilised in this examination was figured by fitting the peak discharge utilising auxiliary historic information for each station to the log-Pearson Type III distribution.

Muhammad *et al.* (2018) used HEC-SSP software to analyse flood frequency and flood intensity for Kabul basin using the RCP 4.5 and RCP 8.5 scenarios. Altogether the scenario results clearly depicted that the current flow with a 1 in 50 year return period was likely to occur more frequently almost 1 in every 9–10 years and 2–3 years, for RCP 4.5 and RCP 8.5 scenarios respectively, during the near and far future periods in the Hindukush-Karakoram-Himalayas region. The results was used to study the vulnerability of various infrastructures to flood, and also the flood risk assessment of land and population.

Arturo (2018) conducted a study of historical and measured flood events using HEC-SSP software in the Papaloapan River basin of Mexico. The Log Pearson type III probability distribution was used to compute peak discharges for a certain return period in each hydrometric station. The logistic regression model correctly predicted 92 percent of the flood events. The final result was such that, when discharge was higher than the 50-year return period river discharge of 11,869 m^3/s, it was a catastrophic event. On the other hand, if it was seen higher than the 20-year return period river discharge of 9711 m^3/s, it was an extraordinary flood.

Joan *et al.* (2019) evaluated the Hydrologic Frequency Analysis (HFA), rational equation and Flow Duration Curve (FDC) using the actual and simulated streamflow data. HFA was conducted using HEC-SSP, in which Log Pearson III distribution was best fitted with both actual and simulated data.

Kristi and Tatiana (2010) performed hydrologic analysis of the Sana'a Basin in the capital of Yemen using HEC-SSP software. There were limited historical discharge data, short historical rainfall data, non-standard hydrologic input series data, poorly understood local hydrology in addition to major changes in the land use from rapid urbanization. Outcomes of the hydrologic analysis, thereafter performing hydraulic modelling helped in easily recognising the extreme storm events. This consecutively supported natural disaster risk evaluation in flood hazard areas.

Mike and Matthew (2019) evaluated the performance of 700 dams and 15,000 miles of levees throughout the United States, by risk assessments through hydrologic hazard curves and HEC-SSP software. They evaluated hydrologic risk for reservoirs and levees by developing "hydrologic hazard curve". This provided the extents and chances of flood for the entire range of peak flows, flow durations and stages.

Wai (2015) conducted a study using Gumbel Extreme Value Type I, Log-Normal, Log-Pearson Type III and Pearson Type III probability distribution function. Flood frequency analysis were executed with historical streamflow data. The parameters of all distribution functions were estimated using method of moments. Chi-square test and Kolmogorov-Smirnov test were chosen to study Goodness-of fit for return period of 5, 10, 25, 50, 75 and 100. Three software namely "Easyfit", "HEC-SSP" and "Microsoft Excel" were used to assist computing data, cross checking the results and fitting the distribution functions. Goodness-of-fit test for all the distributions was found satisfactory in every software.

Fisherman (2015) performed a volume frequency analysis of the river Sava Dolinka, Slovenia using HEC-SSP software to understand the containment of flood flows with different durations influence on flow, downstream of the barrier in reservoir HPP Moste. The necessary containment volume of the reservoir for a given maximum inflow volume and operational installed flow of the reservoir was found in the study.

Bagher *et al.* (2015) described the influence of outlier and excluding it in frequency analysis study. The results showed that exclusion of the outlier data although reduced the design streamflow by 60 percent in 10000 year return period from 3320 m^3/sec to 1340 m^3/sec. It did not affect the probability distribution function (particularly Log-Pearson type III). Outlier data involvement with other systematic data and modification of the statistical distribution parameter were carried out using the method suggested by the U.S. Water Resources Council (WRC) and the HEC-SSP software. The parameters of Log-Pearson type III distribution was revised about 43 percent decrease while including the outlier.

In interest to ensure safety and economic hydrologic design in the catchment area, flood frequency knowledge was appropriate for engineering purposes, such as designing infrastructure in or near the river that could be damaged by the flood, as well as designing the flood system to protect against predicted events (Izinyon and Igbinoba, 2011).

Rao and Hameed (2000) found out that availability of observed peak discharge data was the most beneficial data in flood frequency studies, but more often, it is limited or unavailable in many cases.

2.2 ROLE OF GIS, HEC-GEOHMS AND REMOTE SENSING

Kite and Pietroniro (1996) discussed the use of remotely sensed data in hydrology and water resources. It was analysed that the benefit cost ratios was estimated in the order of 100:1 from flood damage reserve. Further, it facilitated in improved planning of irrigation and hydroelectric production.

Hoblit and Curtis (2001) analysed the software HEC-GeoHMS by the US Army corps of Engineers Hydrological Engineering Centre (HEC) which was used in support of GIS software package for physically based hydrological model. They found that the recent development in Digital Elevation Model (DEM) can be easily downloaded and used in HEC-GeoHMS package for watershed delineation. Also, HEC-GeoHMS and HEC-HMS were established to be the effective software that could be used more accurately to create hydrological models for most of the basins in the US.

Alemaw and Chaukra (2003) addressed GIS's ability to manage huge spatial data derived from multiple sources, such as remote sensing and wide-area ground surveys. Physical-based hydrologic modeling has become significant in contemporary hydrology with the advent of rising computational power and GIS techniques. It also helped to determine the effect on basin hydrology and water resources of human activity and/or future climate change.

GIS was described by Seth et al. (2006) as an advantageous software developed to collect and store the voluminous data usually needed for hydrological studies. Ordered remote sensing and GIS data provide an important knowledge base for water resource efficiency management. The synoptic view provided by GIS's satellite remote sensing and analytical capability offers a technologically suitable approach for studying these tools.

A research was conducted by Santillan et al. (2011) to show the functional usefulness of multi-temporal Landsat images in the identification of land-cover changes. This helped to define the recovery areas and, eventually, to analyze the various rehabilitation methods for hydrological modeling for the management of tropical watersheds.

Singh *et al.* (2014) conducted large scale watershed analysis using GIS and remote sensing. It was observed that the Digital elevation Model (DEM) can be considered as an efficient tools in understanding any terrain parameters such as nature of bedrock, infiltration capacity, surface run off etc. These in turn helped in better understanding of the status of land form, landform processes, drainage management, evolution of groundwater potential for watershed planning and management.

Thakur et al. (2016) reported that the emerging research areas in the field of groundwater hydrology, resource management, environmental monitoring and emergency response are the collaboration of remote sensing (RS), geographic information systems (GIS) and global positioning system (GPS). The study insisted that advances in RS, GIS, GPS and higher computational levels helped provide and handle a wide range of data simultaneously over a given period of time and in a cost-effective manner.

2.3 HYDROLOGICAL MODELS

Hydrologic models in general helps in widening the range of hydrologic investigation arena through predictive capabilities. When subjected to situations such as changing land use, varying climate conditions or the addition of reservoirs, the sensitivity of a watershed's response was secured using the hydrological models as stated by Bhaduri et al (2000). The hydrological model helps in actually translating received precipitation into runoff through loss, routing and storage processes (Kult, 2013).

Watershed models have successively accomplished progress, since 1960 from lumped rainfall-runoff model such as Stanford Watershed Model (SWM) to more process based semi-distributed models such as SWAT which is capable of simulating runoff, sediment, nutrient and pesticide at various points in a watershed scenario (Arnold *et al.*, 1998).

A hydrologic model indicate a complex hydrologic system in a simple and readily comprehensible manner to permit simulation and prediction of events by establishing relationships between watershed components (Gayathri *et al.*, 2015).

The unit hydrograph introduced by Sherman (1932) was the foremost model used widely to estimate the entire shape of the hydrograph rather than simple hydrograph peak value. Later 1950s, hydrologist began to develop "conceptual model" that includes a Unit hydrograph i.e., direct runoff of 1 cm excess rainfall occurring uniform over that basin and at a unit rate for specified duration. The first attempt to predict an entire hydrograph was made by Kilgore et al. (1997), instead of just peak flow and time to peak.

Barry and Bajracharya (1995) stated that channel routing is an important component of a hydrologic simulation. The Muskingum Cunge method is an appropriate model that has a wide range of applicability and provides reasonably accurate results when deriving the outflow hydrograph from a given inflow hydrograph considering channel properties. There are several models that have been developed to perform this function.

SCS Curve Number method/model was found to be the omnipresent method in science and engineering by the findings of Ponce and Hawkins (1996), due to its straight forward conceptual basis of precipitation storage and its computational simplicity in itself. It was stated as a deterministic method that included all catchment properties especially antecedent moisture, land use, soils and surface condition.

Paudel *et al*. (2009) concluded that the Clark method (Clark, 1945) effectively describes the movement of excess rain to watershed outlet. This method utilized basin shape, temporary storage and timing in order to describe a catchment’s hydrologic response. More recently, the Modified Clark method has come into use as a good method of quasi-distributed version model for performing this function.

Wałęga *et al.* (2011) suggested the suitability of Snyder's and Clark's models to simulate flood discharges. Slightly better results were obtained using the former model. The efficiency coefficient values was higher for Snyder's SUH model (89 %) than Clark's SUH model (87 %). While considering both SUH, time to peak were same as the observed one, but the peak flow discharge was 0.11 % higher in Snyder's model and 1.9 % lower in Clark's model, when compared to the observed discharge. In case of limited data available, the objective function based on peak values of discharge gave better results than the objective function based on the complete hydrograph. In order to confirm the correctness of the results obtained, it was highly suggested to continue research on greater data set. Owing to the limited number of parameters included and relative ease of their acquirement, SUH was recommended especially for practical use in modelling.

Okkan and Serbes (2012) applied the least squares version of support vector machines (LS-SVM) model for hydrologic modelling to obtain monthly runoff on the basis of the meteorological data and antecedent runoff data. It was compared with those of feedforward neural networks (FFNN), autoregressive moving average (ARMA) and multiple linear regressions. The results revealed that the LS-SVM models could capture monthly runoff data easily.

Najmaddin *et al*. (2017) analysed that the runoff dynamics in a catchment was principally controlled by the soil moisture balance and groundwater dynamics of a watershed. However, snow melt made relatively small contributions to the shape and magnitude of the hydrograph (even though snow melt was predicted to be significant in spring and base flow was important in the dry season).

Legesse *et al*. (2003) discussed that distributed models can deterministically account for varying parameters in the watershed. Specific knowledge of each case of modelling was taken into account when determining how best representation of specific watershed models would deterministically account for varying parameters in the watershed.

2.4 CLASSIFICATION OF RAINFALL-RUNOFF MODELS

According to the study conducted by Džubáková (2010), and perception of behaviour of the hydrological system, he classified rainfall runoff models into three classes. They were metric, parametric and mechanistic model structures. Metric models (also called data-based, empirical or black box), in detail are those which usually derive both the model structure and the corresponding parameter values from available time-series. Whole catchment was treated as a single unit for the model processing. These were purely based on the information retrieved from the data and do not include any prior knowledge about catchment behaviour and flow processes, therefore called as black box. Popular examples of metric models are those based on ANN (Hsu *et al.*, 1995, Agarwal *et al.*, 2009) and transfer functions (Tessier *et al.*, 1996). Wagener *et al.* (2004) explained the parametric models (also called conceptual, explicit soil moisture accounting or grey box), created on the modelling of storages or reservoirs, which were filled through fluxes such as rainfall, infiltration or percolation, and emptied through evapotranspiration, runoff, drainage, etc. The structure of parametric model is specified before their use and hydrological system is being understood. These type of models depend on time-series of system output to derive the values of their parameters in a calibration process. The Stanford Watershed Model is one of the earliest and complex examples with some 16 - 24 parameters. These model depend on flow measurements, therefore it makes difficult in ungauged catchments application due to lack of information, and hence the problem of non-identifiability arises. Mechanistic models (also called physically based or white box) are constructed on understanding of the physics of hydrological processes and characterized by direct physical significance parameters. One of the best known mechanistic models is the System Hydrologique European (SHE) model, originally developed as multi-national European research collaboration.

Moradkhani and Sorooshian (2009) classified rainfall-runoff model as a) lumped in which the entire river basin is taken as one unit where spatial variability is disregarded. In this model, the outputs are explained without considering the spatial processes, patterns and organization of the catchment and b) the semi-distributed models may adopt a lumped representation for individual sub catchments. Other spatial classification divided models such as one-dimensional, two-dimensional and three-dimensional ones.

Wheater *et al.* (2008) distinguished the models on the basis of time representation as static and dynamic models. In the modelling process, the static model excluded time, while dynamic models specifically included it. The models were further categorized into event-based models that only produce output for specific time periods and continuous models that produce continuous output.

2.5 HYDROLOGIC ENGINEERING CENTER'S HYDROLOGIC MODELING SYSTEM

The US Army Corps of Engineers' Hydrologic Engineering Centre (HEC) generated the Hydrologic Modelling System (HEC-HMS) as a versatile runoff modelling software package to replace the popular HEC-1 program successively. It was proficient of modelling a wide range of watersheds by offering several different mathematical models, all of which are deterministic in nature (USACE, 2000). Improvements over HEC-1 included a graphical user interface that allowed the user with convenient editing and result viewing strata (Viessman and Lewis, 2003). It simulates the hydrologic response of a watershed subjected to a given hydro-meteorological input (Scharffenber and Fleming, 2010).

HEC-HMS has been described as a significant method for predicting and quantifying the impacts of a watershed's various inputs. Hydrological models such as HEC-HMS were more versatile and economical as compared to field experiments (Li and Wong, 2010). HEC-HMS is a graphic-oriented, hydrologic software program that offers a range of model components. Even though it is user-friendly and its flexible setup has led to widespread use, its capabilities still needed to be fully developed. HEC-HMS could benefit from stochastic approaches that look at parameter uncertainty. Despite this weakness, it still provided a valuable deterministic tool for investigating watersheds and predicting the implications of changing landscapes. Both individual storm events and continuous precipitation input for minute, hourly or daily time steps can be simulated with the HEC-HMS model software (Zhang *et al.*, 2013).

Abbott *et al*. (1996) pointed out that HEC-HMS offered model configurations that range from lumped to distributed model. Lumped models use composite parameters for large, grouped areas of land, while spatially variable parameters are maintained by distributed models. Based on the end goals of the study and the available data, the configuration selection was determined. Lumped models typically prevent problems with over-parameterization and data limitations, but they can struggle to describe evolving landscapes adequately.

Chu and Steinman (2009) explained about the application of joint event and continuous hydrologic modelling with the HEC-HMS in Michigan. For simulating surface runoff in the event and continuous models, the SCS curve number and soil moisture accounting methods in HEC-HMS were used respectively. Simulations that produced hydrological information about the level, variability and sources of runoff in the watershed analysed the relationship between the two rainfall-runoff methods. The model performance indicated that the hydrologic modeling of the fine-scale (5 min time step) case, supported by intensive field data, was useful for improving continuous coarse-scale (hourly time step) modeling by providing more precise and well-calibrated simulation parameters.

2.6 APPLICATIONS OF HEC-HMS MODEL

Waikhom and Manoj (2015) used continuous soil moisture accounting (SMA) algorithm in HEC-HMS in order to model the stream flow in Vamsadhara River Basin, India. Catchment was discretised spatially into smaller sub-watersheds which made the catchment heterogeneous in aspect of topographic characteristics, land-use, land cover and soil. Statistical and visual assessment of the model for the calibration period gave a result ranging from good to very good with a coefficient of determination $R^2 = 0.71$, N.S.E=0.701, percentage error in volume=2.64%, percentage error in peak PEP=0.21% and index of agreement d=0.94. The validation period performance evaluation ranges from good to very good with $R^2 = 0.78$, N.S.E=0.762, percentage error in volume=12.33%, PEP = -15.2% and d= 0.93. Sensitivity analysis of parameters was performed by ranking the parameters after checking the percent change in simulated runoff volume. Finally, it was concluded that SMA method in the HEC-HMS conceptual model gave desired results and can be further used for long-term rainfall- runoff modelling.

Adnan and Atkinson (2018) examined the effects of precipitation and land use changes in the hydrological response such as peak discharge and runoff volume in the catchment of River Kelantan, Malaysia. Simulation result of HEC-HMS hydrologic modelling concluded that upstream gauge had differences in peak discharge and runoff volume because of land use changes than compared to climate-related fluctuations. Conversely, downstream catchment were much more linked with precipitation changes. In Kelantan monsoonal catchment, the downstream catchment would be, therefore, more prone to flooding, according to the research.

Demetrio *et al*. (2016) conducted a study to identify the best infiltration method in HEC-HMS out of SCS-CN, Green-Ampt and 'Initial and Constant' methods. Evaluation of the runoff prediction by the available infiltration methods in the semi-arid torrents, was very relevant in action because they were small and intermittent water courses, which were often subjected to high-magnitude flash floods and erosive events. HEC-HMS performance of infiltration methods was incorporated in predicting runoff volume and peak flow. After calibration of the curve numbers, it was found that SCS-CN method gave accurate result in predicting runoff volume. On the other hand, peak flow was better valued using the 'Initial and Constant' method. However, calibrated hydrographs were very similar to results for both SCS-CN and 'Initial and Constant' methods, except Green-Ampt method which presented low reliability.

Hashmi (2005) used HEC-GeoHMS software in conjunction with HEC-HMS for rainfall-runoff modelling of the watershed. Calibration of HEC-HMS model carried out using daily historic rainfall data was used to simulate flood and matched well with observed flood peak.

Choudhari et al. (2014) indicated that, with the aid of geomorphological features of a watershed, the initial calibration parameters were extracted. The final validation parameter was derived and considered as global values for the model in the selected region by obtaining an optimization technique. The HEC-HMS model used for rainfall-runoff simulation resulted in 0.09 m3/s root mean square error (RMSE) and 0.06 for peak discharge mean absolute relative error (MARE) and 0.70 mm RMSE and 0.05 for runoff depth mean absolute relative error (MARE). Square functions obtained in the validated model suggested adequate HEC-HMS model output in the hydrograph runoff simulation. Another benefit of the model was to save time and resources instead of calculating runoff in the watershed by collecting the runoff data. In addition, it helped to simulate runoff in un-gauged watersheds where runoff was not calculated by a gauging station.

Hydrologic simulation was employed using three different approaches to calibrate and validate HEC-HMS model by Halwatura and Najim (2013). Calibration of the sub catchment was performed using daily flow data from 2005 to 2007 for the selected methods: Soil Conservation Service Curve Number loss method, deficit constant loss method, Snyder unit hydrograph method and Clark unit hydrograph method was computed. The flows simulated from each methods were tested statistically employing coefficient of performance, relative error and residual method. Finally it was observed that Snyder unit hydrograph method simulated the flows more reliably than the Clark unit hydrograph method.

Skhakhfa and Ouerdachi (2016) revealed that the overall consistency of simulated results was necessary to develop a validation process in HEC-HMS, particularly in regions where data are limited and unreliable. Calibration and validation processes were carried out using different sets of parameters (CN, SCS Lag and Muskingum K) in the study. Flood modelling was limited to short duration for which the process of evapotranspiration is negligible. Evaluation on the performance of developed flood model yielded a correlation coefficient R^2 close to 1 which was a desirable result.

Anand *et al.* (2013) performed hydrological modelling with the incorporation of snowmelt induced runoff in the streamflow perennial, during spring and summer in Beas sub-basin, Pirpanjal range of the lower Himalayas. HEC-HMS followed snow band methodology of US Corps of Engineers verified using a temperature index and spatio-temporal analysis of process variables. The daily and weekly simulations from simple temperature index method have found satisfactory results with R^2 value above 0.7. The simulations also revealed that ATI Cold/Melt rate functions and meteorological model Index (mm) was important parameter for the model.

Clay *et al.* (2005) selected HEC-HMS model for rainfall-runoff simulation to evaluate the effectiveness of storm water detention basins in Valley Creek watershed. They had considered the model in accessing the effect of alternate management practice in watershed. It was viewed that the most effective means of attenuating watershed peak flow rates was planning the watershed according to runoff volume.

Abdessamed *et al.* (2018) conducted hydrological modelling in semi-arid region of AinSefra, Algeria, using HEC-HMS. The frequency storm and SCS-CN methods were selected to compute the loss rate and unit hydrograph. After calibration and validation, N.S.E was obtained as 0.95, indicating satisfactory result for simulation of rainfall-runoff model.

Arash and Fardin (2013) examined rainfall-runoff simulation in Delibajak basin, Iran. The SCS curve number method was considered for runoff modelling. The model was calibrated and confirmed by historical data observed in the basin. For all the flood events, the determination coefficients and coefficients of agreement were all above 0.9. All of the percentage errors in peak flow and volume were within the appropriate value range. For the evaluation of the event model with three parameters, local sensitivity analysis was adopted: curve number, initial abstraction and event model lag time. The greatest differences between produced peak hydrographs and the baseline of peak hydrographs were caused by initial abstraction in both lumped and distributed models. The findings showed that peak runoff discharges and overall runoff volume were better captured by the semi-distributed model than the lumped model.

Anderson *et al.* (2002) performed a study using HEC-HMS watershed model for runoff prediction. HEC-HMS model was calibrated by means of point gauge precipitation data in the gauging station prevalent inside the boundary of watershed, driven by spatially distributed MM5 rainfall forecasts. The point gauge calibrated HEC-HMS revealed that the magnitude and timing of the peak runoff were to be matched in case of using point gauge rainfall as input in the model.

Kumar and Bhattacharjya (2011) reported that the rainfall-runoff process using of HEC-HMS (with both Distributed and Lumped modelling), was reliable for estimating infiltration parameters and simulating daily stream flow. The required precipitation and stream flow data were collected for 3 years (2006-2008) together with topographic maps and DEM images of study area as modelling data. SCS unit hydrograph transform method was used to compute direct surface runoff hydrograph, SCS curve number loss method was used to compute runoff volumes and constant monthly method was preferred for base flow separation. The performance of HEC-HMS model was assessed using various statistical and graphical indicators which exposed that distributed approach of simulated daily stream flow was better than lumped simulated stream flow.

Roy et al. (2013) concluded that the simulation of stream flow worked well in various watersheds of the Subarnarekha river basin and other hydro meteorologically similar river basins with the calibrated HEC-HMS model. Results of the model was adopted for further studies related to flood risk analysis. N.S.E value, percentage error in volume, percentage error in peak and difference of observed and simulated time to peak, which were seen as performance evaluation, was established to be in the range of 0.72-0.84, 4.39-19.47%, 1.9-19% and 0-1day respectively, signifying best performance in simulation of stream flow.

Improved land-use policy formulation at the watershed scale was possible with methodology suggested by McColl and Aggett (2007) through integration of land-use forecasting model along with rainfall-runoff model. For the years 2015, 2025, and 2050, predicted land-use distribution patterns were used as land-use data input for the hydrological model (HEC-HMS), keeping all other parameters unchanged. The initial results of this phase of integration demonstrated the synergy that could be created by linking the selected models. The integration of this model provided a unique perspective into understanding the possible future hydrologic impacts of land-use policies before their implementation which would enable the management of natural resources wisely.

Yusop *et al.* (2007) described the satisfactorily modelled hydrographs using HEC-HMS. Storm hydrographs showed rapid responses to rainfall with a short time to peak while the simulations were performed. Despite low initial loss, the catchment exhibited a high proportion of base flow approximately 54% of total runoff. Peak flow and storm flow volume were moderately correlated with rainfall. The efficiency indexes of the calibration and validation exercises were computed as 0.81 and 0.82, respectively which was in acceptable range.

Praveen *et al.* (2015) performed lumped continuous hydrological modelling using HEC-HMS accounted loss with the help of Green-Ampt method. Runoff estimation was performed using SCS unit hydrograph and Snyder Unit hydrograph methods. To assess the reference ET, FAO Penman-Monteith method was chosen. Results were acquired such that Nash-Sutcliffe coefficient values were more than 0.8 and correlation coefficient more than 0.9.

Yener *et al*. (2008) conducted hourly simulation of event- based runoff scenarios to obtain IDF curves for sub-basins to obtain seasonal (spring, summer and fall) average values of the watershed using HEC-HMS model. They suggested that runoff generated from frequency storm method was useful for future flood hazard and risk assessment studies supporting the flood management.

Arekhi (2012) applied HEC-HMS model results for six events to compare the results of Green and Ampt, initial and constant loss rate and deficit and constant loss methods for estimation of runoff losses. Percent error in peaks and volumes objective functions was considered for the selection criteria of the best method. The Initial and constant loss rate method had better results than Green and Ampt method. Deficit and constant loss rate method had less changes of simulated to observed discharges rather than Green and Ampt method. For objective functions, initial and constant loss rate method had less changes percent and it was selected as optimum method for simulation of surface runoff in the watershed with similar characteristics. Green and Ampt and constant loss rate methods were the next preferences in simulation methods based on this study.

Majidi and Shahedi (2012) performed simulation of rainfall-runoff process with rainfall events using HEC-HMS in Abnama watershed located in South of Iran. The model validation with optimized lag time values showed 9.1 % difference between the observed and simulated discharges and their coefficient of determination was 0.86. The results conveyed that the lag time was sensitive parameter and model.

Sardoii *et al*. (2012) attempted in comparing different methods in HEC-HMS model, i.e. initial and constant, Green- Ampt, SCS curve number with regard to various error functions (percent error in peak, peak-weighted root mean square etc.) by taking into account of the obtained results of different storm events simulation. Considering objective functions, result indicated that Green and Ampt, SCS and 'initial and constant' method were placed in first to three preferences in order, respectively. Therefore, Green- Ampt method was suggested as the suitable method that can be used in similar area and conditions.

Halwatura and Najim (2013) simulated using the HEC-HMS model for Attanagalu Oya (river) catchment, Sri Lanka. The model was calibrated adjusting parameters in following methods; SCS CN method, deficit constant loss method, Snyder unit hydro graph method and Clark unit hydrograph method in order to determine the most suitable simulation method for catchment area. The flows simulated from each method were tested statistically employing the coefficient of performance, the relative error and the residual method. The study concluded that the Snyder unit hydro graph method simulated flows more reliably than the Clark unit hydro graph method in the selected region.

Majidi and Vagharfard (2013) calibrated and validated HEC-HMS hydrological model for simulation of surface run-off to find the appropriate method among Green-Ampt method and Soil Conservation Service (SCS) method in HEC-HMS. A result of the model calibration and validation model showed that Green-Ampt method estimated peak discharge with lower difference in the observed and simulated discharges. Time to peak was also less in case of Green-Ampt method than SCS method. Moreover, correlation values in Minitab software showed that results based on the Green-Ampt method had a higher coefficient of determination (R^2= 0.71) and Pearson correlation = 0.84 than the SCS method R^2 = 0.46 and Pearson correlation = 0.7. Results concluded that simulation using Green-Ampt method was more precise than SCS method.

For effective management of flood water, Yaw *et al.* (2015) analysed relation between rainfall and runoff of Lawra District (Upper West Region of Ghana). It has several flash flood events of high intensity short duration rainfall periodically. Hydrological modelling (HEC-HMS) of 1178.38 mm annual rainfall gave a runoff of 1.134m and a volume of 36,065,515.893m^3. Consecutively, 31,313,221.5m^3 volume of water was obtained for August, September and October alone which indicate heaviest rainfall.

Knebl *et al.* (2005) developed a framework for regional scale flood modelling that integrated NEXRAD rainfall, GIS and a hydrological model for the purpose of flood management. Rainfall-runoff was modelled for San Antonio river basin, USA using HEC-HMS which translated the precipitation excess to overland flow and channel runoff. Hydraulic model (HEC-RAS) modelled the unsteady state flow through the river channel network based on the HEC-HMS-derived hydrographs that was capable of producing floodplain polygons comparable to the satellite imagery.

Hammouri and Naqa (2007) simulated the rainfall-runoff process to obtain the Intensity-Duration-Frequency (IDF) curves for 10 years and 50 years return periods, using HEC-HMS and GIS in a selected ungauged basin for the purpose of groundwater artificial recharge. The total direct runoff volume and the peak discharge for 10 years return period and 50 years return period, were estimated to be 151,000 m^3 and 5.43 m^3/s, respectively & 280,000 m^3 and 12.77 m^3/s, respectively. The flow comparison graph for calibrated model fits well with the observed runoff data with a peak weighted root mean square error of less than 2 percent.

Sampath *et al.* (2015) developed HEC-HMS 3.0.1 model for Deduru Oya River. Soil moisture accounting loss method for five layer of soil, Clark unit hydrograph (transformation method) and base flow (recession method) of the HEC-HMS model were adopted for the hydrological modelling. The results depicted by inputting long-time daily rainfall data, land use and soil data showed a great accuracy of model with Nash Sutcliffe efficiencies of 0.80.

2.7 COMPARISON OF HEC-HMS AND OTHER MODELS

HEC-HMS was found to be relatively simple-conceptual model, successfully implemented worldwide by many hydrologic modellers, convenient to simulate precipitation-runoff and routing processes in both natural and controlled environment. It was concluded to be the good model for simulation of peak flow as compared to Revitalised Flood Hydrograph (ReFH) model because of semi-distributed modelling concept as acclaimed by Sai *et al.* (2017).

Akbarpour (2004) carried out simulations of the rainfall-runoff process by using ANN and HEC-HMS model. Daily rainfall and runoff data, during the period of 1991-2000 were selected for calibration and validation of the HEC-HMS model. The study concluded that calibrated HEC-HMS model for a basin was more effective to estimate the flood discharges in ungaged catchments.

Verma *et al.* (2009) discussed rainfall runoff modelling using HEC-HMS and WEPP hydrologic models, with the support of remote sensing and GIS (geographical information system) techniques. After the simulation, root mean square error (RMSE) and standard deviation ratio (SDR) were obtained as lower values. Nash-Sutcliffe efficiency (NSE), percent deviation (Dv) and coefficient of determination (R^2) were all in higher range. Altogether it indicated better reliability of HEC-HMS than WEPP model, during calibration and validation periods.

Joo *et al.* (2013) tested the Revitalized Flood Hydrograph (ReFH) and HEC-HMS rainfall runoff model for two Korean catchments. The flood events were applied to ReFH model and HEC-HMS with calibration and validation approaches. ReFH model showed limitations in the simulation of peak flow in large catchment. On the other hand, HEC-HMS showed good simulations in both catchments.

Hu *et al.* (2006) applied input data in two models: distributed snow process model (DSPM) and HEC-HMS for gridded snowmelt. A set of events like snowmelt along with rain, snowmelt alone and rainfall alone flooding event records were considered. Through model calibration and validation, it was suggested that combined DSPM and HEC-HMS models could simulate the snowmelt/rainfall-runoff process.

Abed *et al*. (2005) developed the simulation using the Spatial Water Budget Model (SWBM) and HEC-HMS Model. The models were calibrated and validated based on inflow data from reservoir. The satisfactory results were obtained for both models with R^2 of 0.90 and 0.85 for calibration and 0.75 and 0.80 for validation, respectively. They paralleled the result from both the models and carried out the sensitivity analysis for the parameters used in HEC-HMS. They established that watershed characteristics such as imperviousness, curve number and base flow had durable influence on output except others in the parameter list. They claimed that more acceptable results were produced by HEC-HMS model.

2.8 FLOOD MANAGEMENT STUDIES

Knighton *et al.* (2018) conducted several studies which revealed that developments in bottom-up vulnerability-based decision analysis frameworks presented promising opportunities for flood practitioners. The study insisted that it played a vital role in simplifying the complex decisions regarding risk mitigation and climate adaptation. This sort of methodologies relied on strong social networks among flood practitioners and the public to support careful definition of stakeholder-relevant thresholds and vulnerabilities to hazards. Moreover, flood analysts straightforwardly considered distinct atmospheric mechanisms that incited flooding to promptly consolidate data for understanding future climate projections.

Nawaz and Han (2008) recognized that if the appropriate storage facility and modernized structures are empowered in hill torrent influenced regions, at that point the flood as well as the dry season conditions can be relieved. It will indeed improve the harvest yield of the farms of that area.

Nektarios and George (2011) aimed to seek a viable methodology for flood management strategy based on the European Floods Directive. They stated that reliable flood management plan has two vital constituents, namely, proper flood management strategy and determination of the flood-hazard areas. In addition to all these, a method to evaluate the benefits of a flood warning system, as well as a method to estimate the flood-hazard areas were presented. Flow accumulation, slope, land use, rainfall intensity, geology and elevation were the components regarded. This helped to estimate the spatial distribution of the hazardous zones in the study area. Based on this, the basin was classified into five provinces ranging from very low to very high. Identified areas and settlements in high risk of flooding were treated according to this outcome. The obtained results were also validated against data from historical flood discharge in the basin for the security of result.

MATERIALS AND METHODS

CHAPTER III

MATERIALS AND METHOD

This chapter deals with the description of the study area, details of data collected and generated, flood frequency analysis, preparation of input data files for running the HEC-HMS model and an overview of rainfall-runoff modelling using HEC-HMS. The theoretical consideration of various model components and the various methods applied to carry out the research are also explained briefly in this chapter.

3.1 DESCRIPTION OF STUDY AREA

3.1.1 Location

The Meenachil River (Meenachil-ar) is known to be one of the important rivers in Central Kerala located in Kottayam district. “Meenachil River is formed by confluence of several streams originating from the Western Ghats at Araikunnumudi (elevation=1097m above MSL) and flows through Erattupetta, Palai, Ettumanoor and successively merges into the Vembanad Lake at Kavanattinkara, Kumarakom” (CGWB, 2009). Watershed area lies in the southern districts of Kerala, India, and is hedged within 9°5’2’’N and 9°56’10’’N (latitudes), and 76°19’19’’E and 77°11’24’’E (longitudes). On the western side is the Arabian sea coast, and on the eastern side the area is enclosed by the Western Ghats. The river has a catchment area of 1208.1km² that is composed by 47 sub watersheds and 114 micro watersheds. Meenachil River is a 7^{th} order river, altogether with 38 tributaries including major and minor ones. “The major tributaries to be named are Kadapuzha, Kalathukadavu, Kurisumalai, Trikkoil, Punjar, and Meenadom” (CGWB, 2009). The location map of the sub-basin which is situated at the upstream of Meenachil river basin (an area of 444.12 Km² i.e., about 35% of the total area of Meenachil river basin), selected for this study is shown in Fig. 3.1.

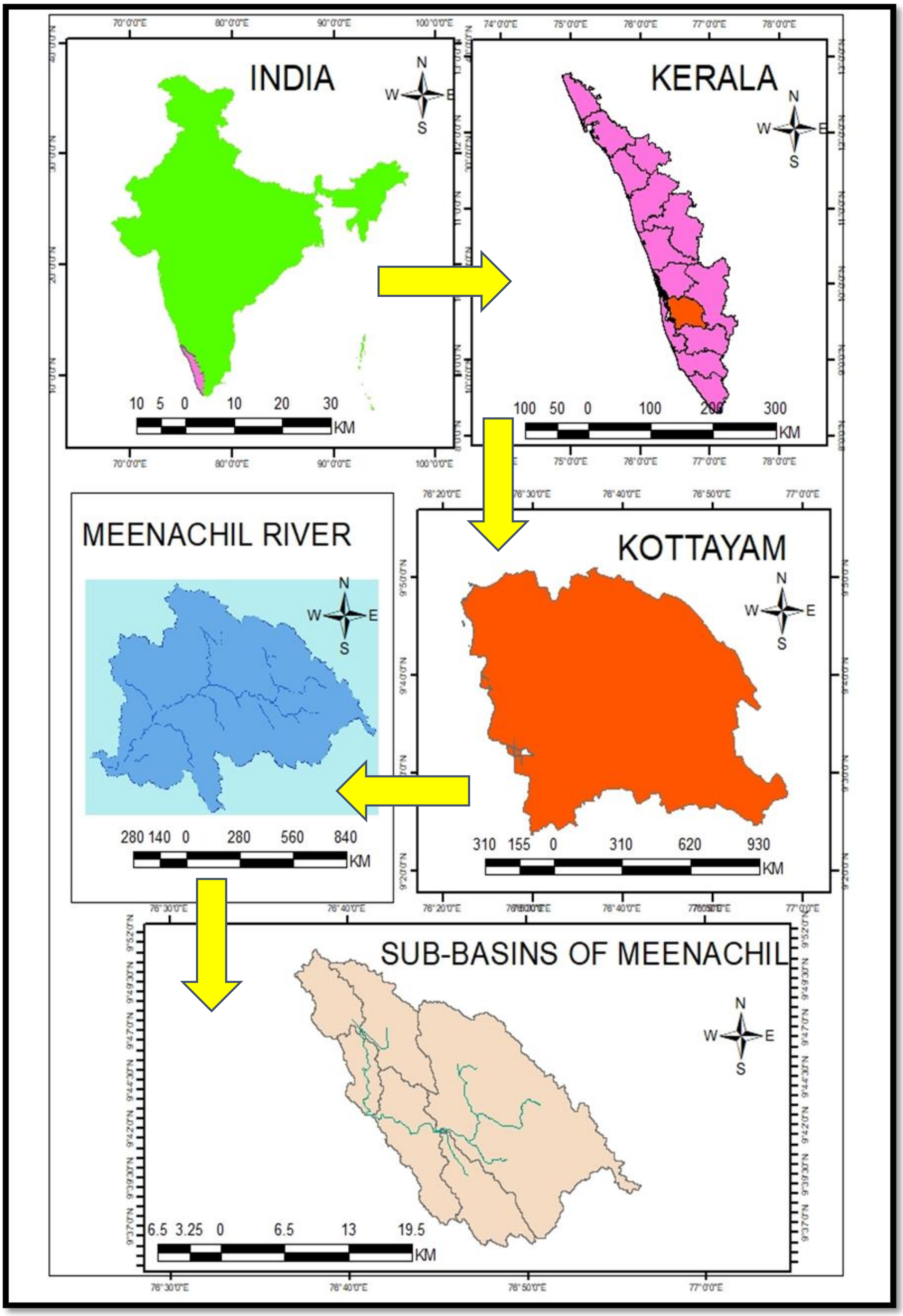


Fig. 3.1 Location map of the study area

3.1.2 Climate

The Meenachil river basin falls within tropical humid climate with high variations in relief from the west coast to the hilly region of the Western Ghats in the east. As per the records, during 2010-2014 period the mean annual temperature of the area was 32.5 °C, experiencing average annual rainfall of 3030 mm, while mean humidity is 88.6 percent. The basin experiences both south-west and north-east monsoons. The south-west monsoon starts during June and lasts till August. The north-east monsoon, which is uncertain strikes in October and continues till the end of November.

The river has a total annual yield of 2349 MCM with an annual utilizable yield of 1110 MCM. Large population of Kottayam district inclusive of many major towns and cities like Erattupetta, Palai, Ettumanoor and Kottayam depend on this river for drinking water as well as for commercial activities. Heavy precipitation during monsoon provides an important triggering mechanism causing landslides resulting in the development of new lower order streams on the slopes or widening of existing streams and subsurface seepages. Hence, "people who live near the river and its tributaries indeed are deeply concerned about the decreasing water holding capacity of the river due to loss of tree cover, top soil erosion and sand mining" (George *et al.*, 2011).

3.1.3 Soil Type

"The basin primarily comprises of precambrian metamorphic rock system with rock types such as charnockite gneiss, biotite gneiss, cordierite gneiss, magnetite quartzite and pyroxene granulite" (Kumar, 2014). "The major soil type prevalent in the area is well drained lateritic soils. In addition, there are also quaternary formations of fluvial deposit, fluvio marine and paleo marine deposits that were found in lower reaches of river" (GSI, 2002).

3.1.4 Physiography and Relief

"Major part (41 km i.e., 53%) of this river flowing through midland terrain, 21 km (27%) through the highland terrain and the rest (16 km i.e., 20%) through the low land terrain constitute the total river length of about 78 km" (KSLUB, 1996). General elevation of the watershed area ranges from 77 m – 1156 m in the highlands, 8 m – 68 m in the midlands and less than 2 m in the lowlands where the river exhibits a dendritic drainage pattern and splits into a number of distributaries.

"The study area is characterized by rugged hills with steep long side slopes on which rests the loose, unconsolidated soil and earth materials that have suffered a lot of damage due to landslides" (Vijith *et al.*, 2009). Irrational management of water supplies in the area results in irrevocable impacts on life, life-supporting processes and the region's growth. Therefore, the current state of the region calls for greater vigilance and well-planned initiatives in the management of water conservation and resource management projects that are closely linked to vulnerable habitats and the prevailing environment (Balchand, 1983).

3.2 SOFTWARE AND SYSTEM USED

The following software namely ArcGIS, HEC-GeoHMS, HEC-HMS, ERDAS Imagine, HEC-SSP and MS-Office suit were used for data creation, data analysis and output generation of this study. ArcGIS is an advanced tool that aids in mapping, geographic analysis, spatial analysis, hydrological analysis, overlay analysis, data editing etc. Hydrologic Engineering Center (HEC) has offered different tools for risk analysis, foundation technology for flood damage reduction planning and analysis, development and deployment of the Water Management System, real-time forecasting, decision-support system in water resource and water control management mission. Among that HEC-HMS and HEC-SSP are the two major software packages adopted for flood modelling and frequency analysis in this study. "The Hydrologic Modeling System (HEC-HMS) is designed to simulate the complete hydrologic processes of dendritic watershed systems" (USACE, 2000). HEC-SSP module attempts in presenting some statistical parameters for flood frequency analysis using peak flow. The utility of all the software used in this study are:

1) ArcGIS 10.3: creation of various thematic maps and pre-processing of the spatial data

2) ERDAS IMAGINE 2015: preparation of land use land cover map using supervised classification

3) HEC-GeoHMS 10.3: creation of required input file and background map for HEC-HMS software

4) HEC-HMS 4.3: parameter optimization and simulation of the watershed runoff

5) HEC-SSP 2.2: flood frequency analysis using statistical tools

6) MS Excel: preparation of input files and arrangement of collected data for the model

3.3 INPUT DATA USED

Different hydro-meteorological and remote sensing data and its sources used in this study for the rainfall- runoff modelling is presented in Table 3.1.

Table 3.1 Hydro-meteorological and remote sensing data used and their source

Sl. no.	Datatype	Description	Source
1	NASA DEM (NASA SRTM3 SRTMGL1) 21 Feb 2000 (30 m resolution)	Remote sensing data for terrain processing	U.S.G.S
2	Landsat 8 OLI/TIRS C1 (Level 1) 23 Feb 2019 (15-30m resolution)	Remote sensing data for preparing LULC	U.S.G.S
3	Soil data	For preparing soil map to determine the curve number	Department of Soil Survey and Soil Conservation, Trivandrum
4	Rainfall data (2013-2018)	For HEC-HMS model input and simulation	a) IDRB, Irrigation Design & Research Board, Trivandrum b) CWC, Central Water Commission
5	Discharge data (1985-2018)	For calibration of HEC-HMS model	IDRB, Trivandrum
6	Base map/Toposheet	Location	Survey of India

3.4 FLOOD FREQUENCY ANALYSIS

3.4.1 Hydrological Data Used for Frequency Analysis

Hydrological data of daily discharge measured at Palai gauging station for the last 34 years (1985-2018) collected from IDRB, Trivandrum was used as the basic input data for flood frequency analysis. The annual maximum discharge was extracted from the daily discharge data. The monthly average discharges of Palai gauging station is given in Appendix I.

3.4.2 Flood Frequency Analysis Using HEC-SSP

HEC-SSP software that encompasses executable code and documentation that is available in public domain, developed by the Hydrologic Engineering Center for the U.S. Army Corps of Engineers with United States Federal Government resources, was used to compute the statistical functions. This software is available in the HEC internet site (www.hec.usace.army.mil). Different frequency analysis could be executed with this software as specified. Firstly, the hydrologic data was used to acquire return period using plotting position method. Eventually it is fitted with distributions such as Gumbel and Log Pearson Type III distribution and after which the goodness of fit test was performed.

Frequency analysis intends to predict how often certain values of a variable hydrologic phenomenon may occur and to assess the reliability of the prediction of the variate. General Frequency Analysis component of the software was used to perform frequency analysis of hydrologic data. Type of data that was used in this analysis was annual maximum stream flow.

The following figure Fig. 3.2 shows the window of HEC-SSP which is comprised of Desktop Area, Study Explorer and Message Window.

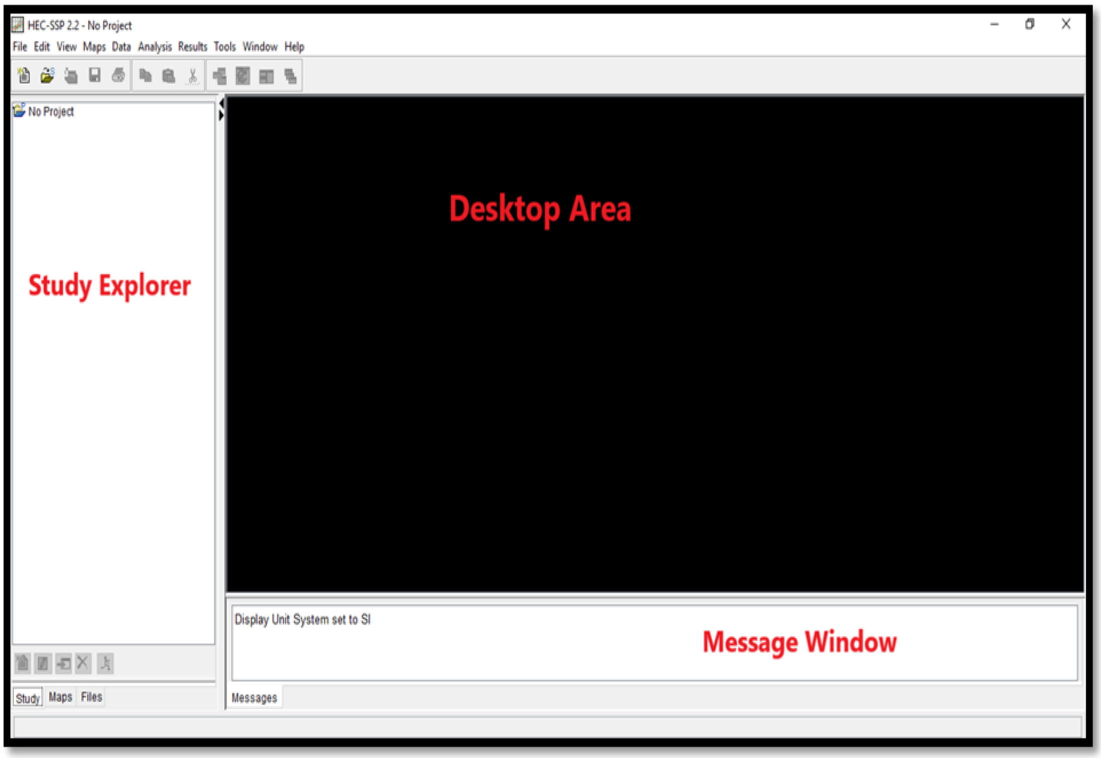


Fig. 3.2 Main window of HEC-SSP

3.4.3 General Frequency Analysis Editor

"General frequency analysis editor permits the user to perform frequency analyses on hydrologic data using various methods. Types of data that can be used in this analysis include flow, stage or precipitation. The input discharge data could be either imported from an HEC-DSS File, USGS Website, Excel Spreadsheet or entered manually. It was entered manually in this study. Importing, entering, and viewing data is accomplished in the Data Importer. To open the data importer, select the Data menu and opt for 'New' from the list of options, which will bring up a data importer" (USACE, 2019).

3.4.3.1 *Plotting Positions*

"Plotting positions are used for plotting the input flow data set on a probability scale along with the computed frequency curve and confidence limits. There are five options for computing plotting positions within HEC-SSP: Weibull, Median, Hazen, Hirsch/Stedinger, and user entered coefficients" (USACE, 2019). In this study, the Weibull plotting position was adopted. The selection of plotting position option varies from one frequency analysis to another according to the need of user. “Generalized plotting position equation used for the study is as follows:

$$P = \frac{(m - A)}{(N + 1 - A - B)}$$

Where, m is the rank of largest flood values and is equal to one, n is the number of flood peaks in the data set, A and B are the coefficients dependent on which equation is used (Weibull A and B=0; Median A and B = 0.3, Hazen A and B=0.5 and Hirsch/Stedinger A and B=0).

In brief, plotting positions can be stated as estimates of the exceedance probability of each data point. Different methods result in different values for the probabilities of highest and lowest points in the given data set. However, it is viewed that method selected for Plotting Positions does not have any impact on the computed curve” (USACE, 2019).

The procedure of plotting position was initiated by arranging the data in decreasing order of magnitude. The probability P of each event being equalled to or exceeded (plotting position) was calculated by the plotting-position formula as stated above in the equation with coefficients A and B inserted conferred to the Weibull method. Return period (also called the recurrence interval or frequency) T is defined by the equation (Haan, 1977):

$$T = \frac{1}{P}$$

Q versus T in a semi logarithmic graph was then plotted, which yielded probability distribution. In frequency analysis, the usual problem is to predict extreme flood events. To solve this issue, specific extreme value distributions were assumed and the required statistical parameters computed from the available data were used. Successively, this helped in the estimation of flood magnitude for specific return period. Subramanya (2008) and Chow (1951) found that most frequency distribution function applicable in hydrologic studies can be expressed by general equation of hydrologic frequency as below:

$$x_T = \overline{x} + K\sigma$$

Where x_T =value of variate x of a random hydrologic series with a return period T, $\bar{x}$ = mean of the variate, σ=standard deviation of the variate and K = frequency factor, which depends on the return period and assumed frequency distribution.

The tab of general frequency analysis editor opens a window as shown in Fig. 3.3 which provided an interface for selecting Weibull plotting position for the selected distribution functions.

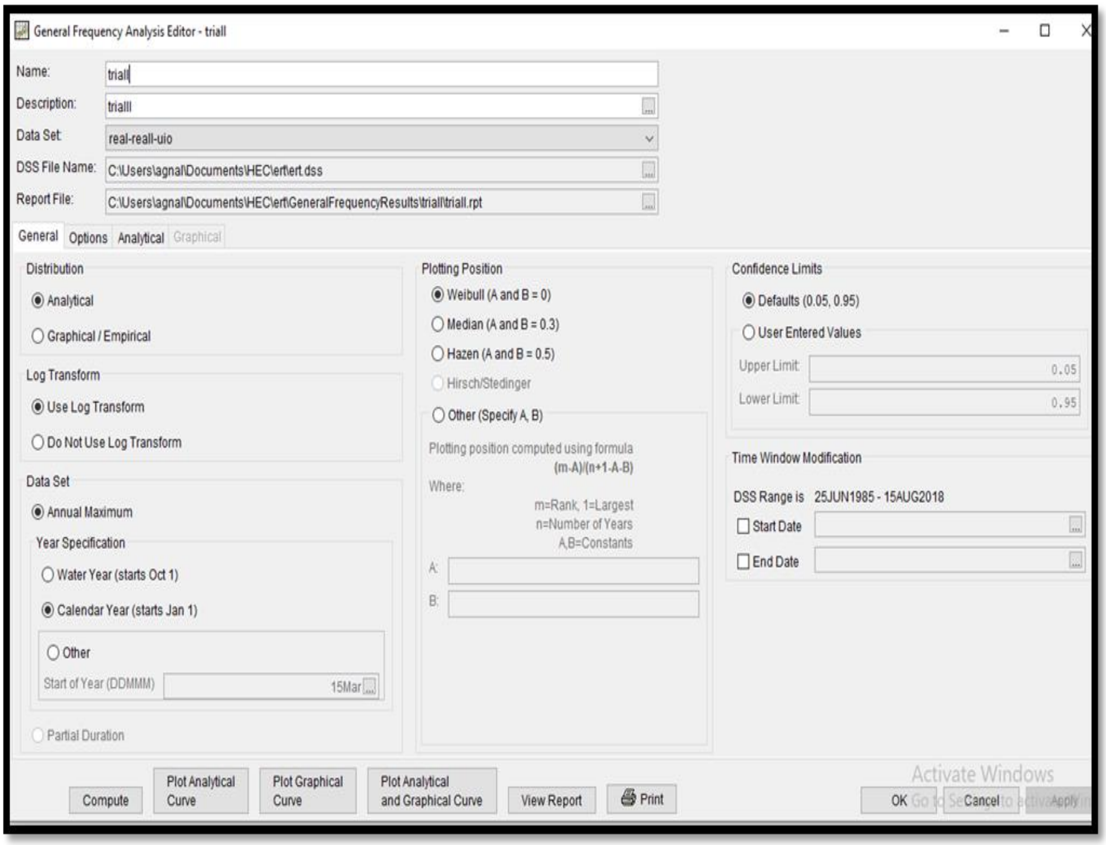


Fig. 3.3 HEC-SSP interface for selection of plotting position method

Log- Pearson Type III distribution and Gumbel distribution were then selected from the General Frequency Analysis Editor option. Interface to choose distribution functions is shown in Fig. 3.4.

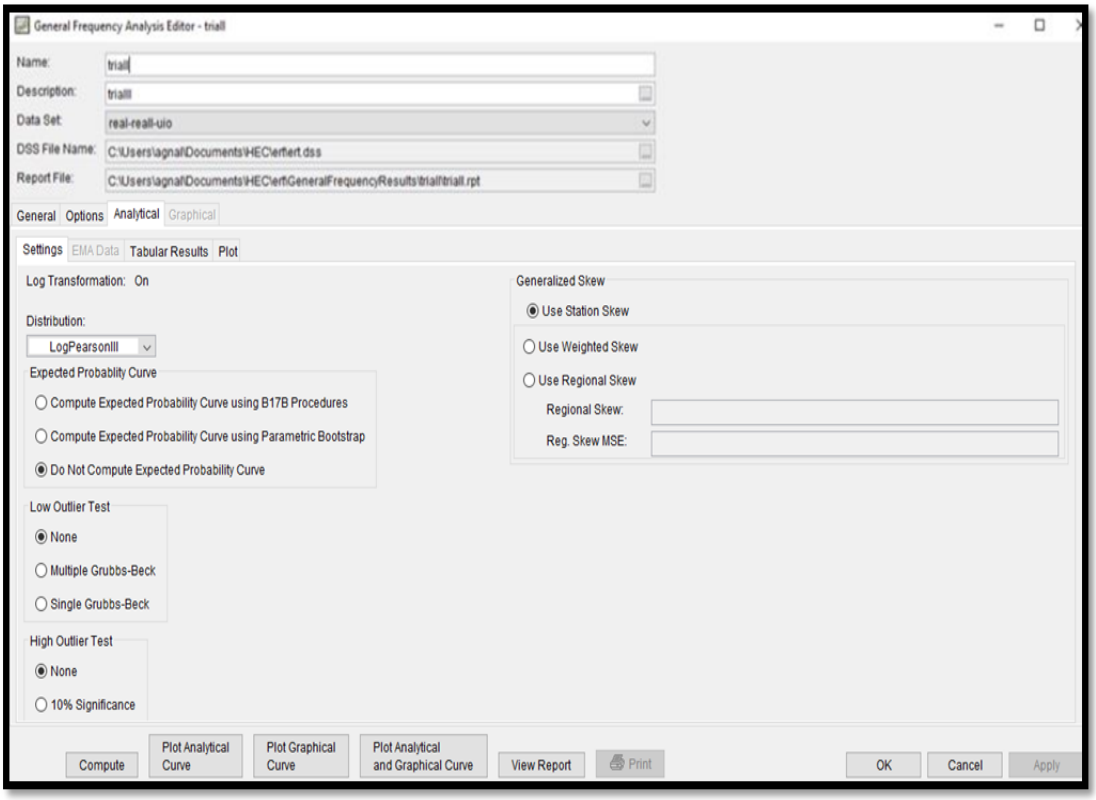


Fig. 3.4 HEC-SSP interface in General Frequency Analysis Editor option

3.4.4 Distribution Fitting

"Distribution fitting is the art of choosing a probability model for an unknown and unknowable population, and calibrating that model using a representative sample from the population. Such a model allows for inferences about the population to be made despite not knowing all of its properties. Uncertainty will always be part of the inference because of a limited sample size. However, choice of an appropriate model for the population can result in better inferences about its properties" (USACE, 2019). There are several distribution available totally in the software, including the combination with and without using log transform viz., Product Moments-Normal distribution, Product Moments –Pearson III distribution, Product Moments- Log Normal distribution, Product Moments –Log Pearson III distribution, Product Moments- Log Logistic distribution, EMA-Log Pearson III distribution, Product Moments-Normal distribution, Product Moments-Pearson III distribution, Product Moments-Logistic distribution, Product Moments- Gamma distribution, Product Moments-Gumbel distribution, Product Moments- Exponential distribution, Product

Moments- Beta distribution, Linear Moments-Generalized Extreme Value distribution, Linear Moments- Generalized Pareto distribution, Linear Moments, Generalized Logistic distribution. In this study, Flood frequency analysis was carried out by fitting the data into Gumbel and Log Pearson Type III distribution. Interface of HEC-SSP to perform the distribution fitting is depicted in the Fig. 3.5 and Fig. 3.6 for Log-Pearson III and Gumbel distribution respectively.

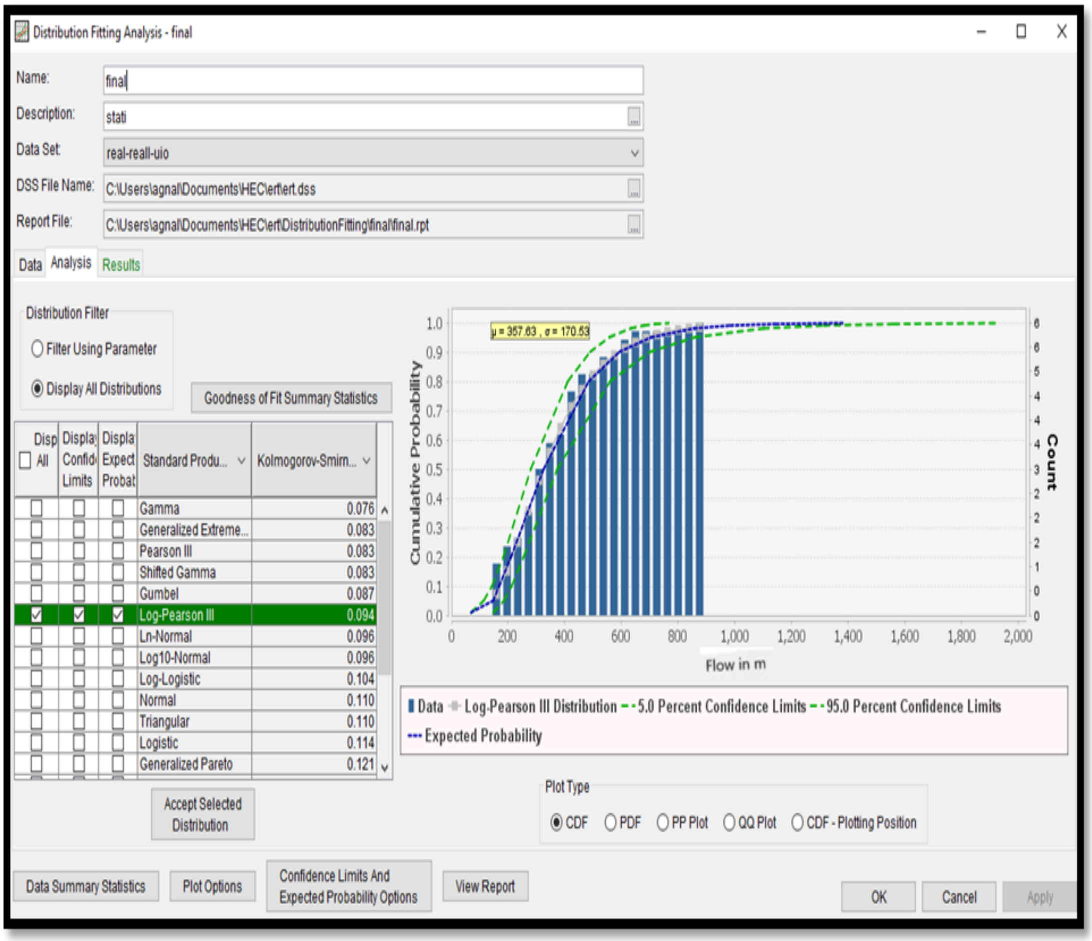


Fig. 3.5 Distribution fitting analysis of Log-Pearson Type III distribution

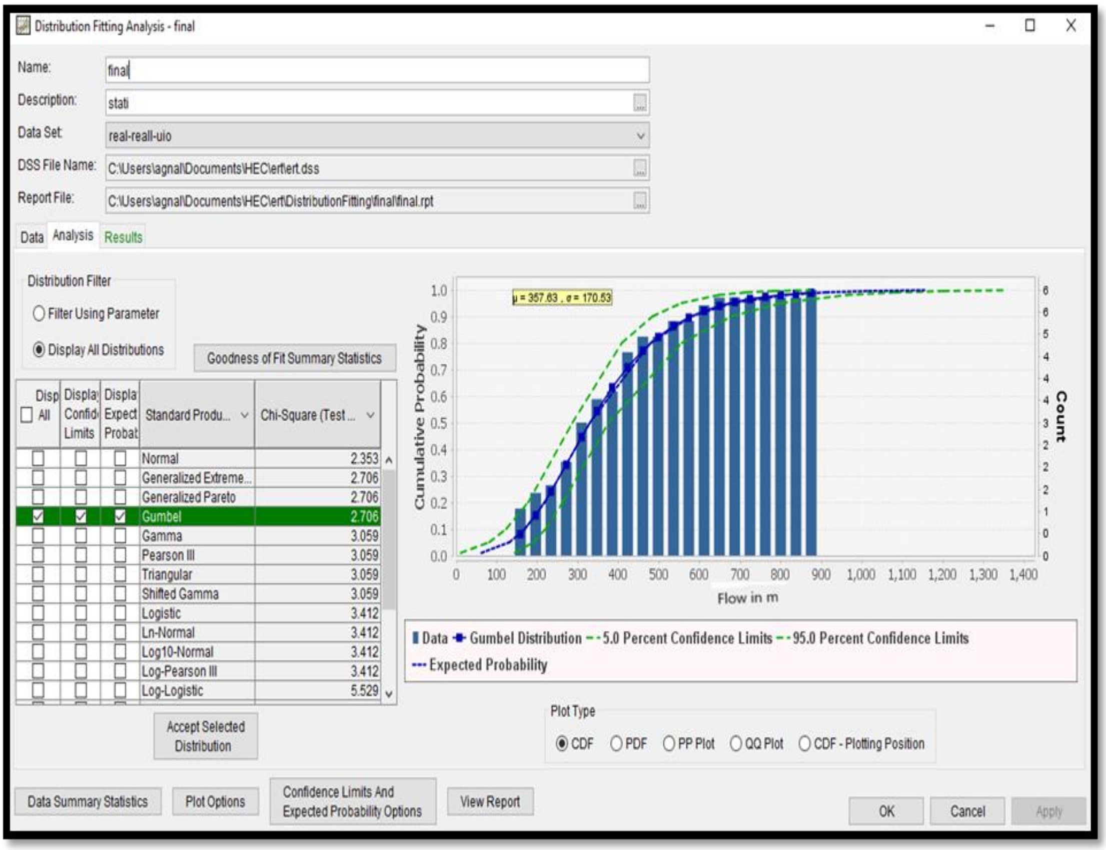


Fig. 3.6 Distribution fitting analysis of Gumbel distribution

3.4.4.1 *Log –Pearson Type-III Distribution*

Log-Pearson type-III distribution is a statistical technique for fitting frequency distribution to predict the design flood for a river basin. The probabilities of floods of various sizes and quantity can be extracted from the frequency curve plotted. Extrapolation can be made of the values for events with the return periods well beyond the observed flood events, which makes the distribution more reliable and useful one. Federal agencies in the United States use this as the standard technique for fitting the frequency distribution of flood. This frequency distribution tells you the likely values of discharges to expect in the river at various recurrence intervals based on the available historical record. This is helpful when designing structures in or near the river to protect against the floods or largest expected event. Therefore, it is customary to perform the flood frequency analysis using the instantaneous peak discharge data. However, the Log-Pearson Type III distribution can be constructed using the maximum values of mean daily discharge data.

If x is the variate of a random hydrologic series, then the series of Z value is calculated as:

$$Z = \log x$$

$$X_T = antilog(Z_T)$$

For this Z series, for any recurrence interval T,

$$Z_T = Z + K_Z \sigma_Z$$

Where K_Z represents the frequency factor which is a function of recurrence interval T. σ_Z represents standard deviation of Z variate sample and it is calculated by the formula $\sqrt{\frac{\sum(z-\bar{x})^2}{N-1}}$

Coefficient of skew C_s of z variate is computed by the following equation:

$$C_s = \frac{N\sum(z-\bar{z})^2}{(N-1)(N-2)(\sigma_Z)^3}$$

Log-Pearson type-III distribution has been widely and frequently used in hydrology and for hydrologic frequency analyses. The probability density function (PDF) and cumulative distribution function (CDF) of the Log-Pearson type-III distribution were calculated using following equations, respectively:

$$f(x) = \frac{1}{x|\beta|\tau(\alpha)}\left(\frac{\ln(x)-y}{\beta}\right)^{\alpha-1} e^{-\frac{\ln(x)-y}{\beta}}$$

$$F(x) = \frac{\tau_{\frac{\ln(x)-y}{\beta}}(\alpha)}{\tau(\alpha)}$$

Where, α, β and γ are shape, scale and location parameters, respectively.

3.4.4.2 *Gumbel Distribution*

The probability distribution function that is used most widely for the prediction of flood peaks is the Gumbel distribution (Zelenhasic, 1970). Gumbel distribution which was named in honour of Emil Gumbel, (also known as the Extreme Value Type I distribution), is a continuous probability distribution type. Gumbel defined flood as the largest of the 365 daily and the annual series of flood flows that constitute a series of largest values of flows. This method has been adopted for flood frequency analysis due to the following reasons: Foremost one is that peak discharge data are homogeneous and independent, therefore lack long term trends. Second reason is that the river is less regulated; therefore, it is not significantly affected by reservoir operations, diversions or urbanisation. Third reason is that discharge data cover relatively long record (more than 30 years) and is of good quality (Mujere, 2011). As per the Gumbel distribution fitting technique, following equations were used to predict the flood peaks at different return periods T, based on an annual series of flood (Sarma, 1999):

$$x_T = \overline{x} + K\sigma_{n-1}$$

Where, σ_{n-1} denotes standard deviation of the sample of size N, computed using the equation:

$$\sqrt{\frac{\Sigma(x-\overline{x})^2}{N-1}}$$

K is the frequency factor, computed by the equation $\frac{y_T - \overline{y_n}}{S_n}$

y_T is reduced variate corresponding to a recurrence interval T, obtained by the equation $-\left[\ln.\ln\frac{T}{T-1}\right]$

$\overline{y_n}$ and S_n is the reduced mean and standard deviation respectively, which is a function of sample size N (Subramanya, 2008).

Gumbel distribution can be applied to model maximum or minimum values (extreme values) of a random variable set. Generally, the graph for Gumbel max probability distribution function is as shown in Fig. 3.7. The probability density function (PDF) and cumulative distribution function (CDF) of the Gumbel distribution were calculated using the following equations, respectively:

$$f(x) = \frac{1}{\sigma}e^{\left(-\frac{x-\mu}{\sigma}-e^{\left(-\frac{x-\mu}{\sigma}\right)}\right)}$$

$$F(x) = e^{\left(-e^{\left(-\frac{x-\mu}{\sigma}\right)}\right)}$$

Where σ and μ are the scale and location parameters, respectively.

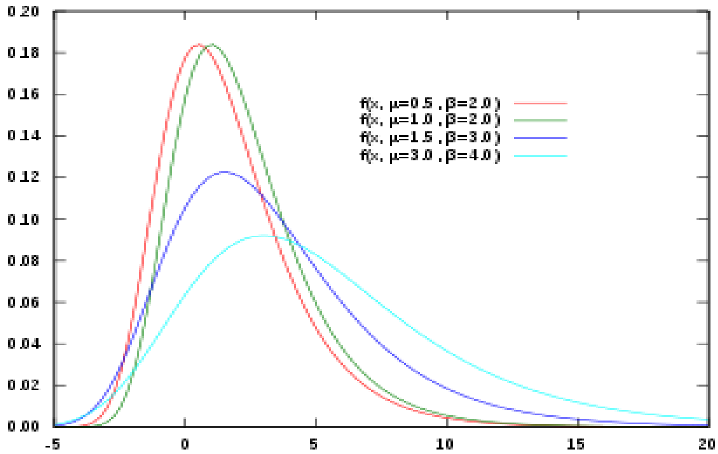


Fig. 3.7 Plot of Gumbel max probability distribution function

3.4.5 Procedure of Fitting of Distribution and Its Analysis

The term actually refers to the fitting of a probability distribution to a series of data concerning the repeated measurement of a variable phenomenon in the analysis. Distribution fitting helps to predict the probability or to forecast the frequency of occurrence of the magnitude of the hydrologic phenomenon in a certain interval. "Distribution Fitting Analysis menu of the software provides option for fitting different analytical distributions using possible fitting methods Standard Product Moments and Linear Moments. These can be used to visualise effectively distribution plotting original and/or processed data set on a probability scale. It also helps the user to assess the uncertainty in the fitting method and choice of the data series" (USACE, 2019). Standard Product Moments was chosen for the analysis in this study.

3.4.6 Test for Goodness of Fit

"Goodness of fit tests are intended to inform the user if there are large deviations in the data away from the selected and calibrated probability model" (USACE, 2019). Comparing the results of goodness of fit tests helps in understanding which probability distribution should be chosen for the basin. The tests outlined below were used to test the goodness of fit when one or more distributions are valid for the data being modelled. Assuming $(x_1, x_2, \ldots, x_n)$ as the samples from population *X*, hypothesis is created such that; H_0 : F(x) = F_0 (x), where F_0 (x) is the probability distribution function with the parameters estimated from the sample data for checking the goodness of fit for any population (Zeng *et al.*, 2015). Chi-Square test and

Kolmogorov-Smirnov test were adopted for testing the goodness of fit. In this study, the hypothesis H_0 and H_1 were taken as follows, H_0: the selected distribution is good fit for the discharge events and H_1: the selected distribution is not good fit for the discharge events.

3.4.6.1 *Chi-Square Test*

"The Chi-Squared Test (more specifically, Pearson's Chi-Squared Test) is a parametric goodness of fit test. The test behaves by creating a number of discrete classes or bins for the data, and comparing the observed proportion of the data in each bin compared to the expected proportion of the data according to the model. Similar to the K-S test, the program will provide a test statistic which is the result of previously-mentioned computations. In practice, if the proportions are significantly different, then the null hypothesis that the data arise from the proposed model would be rejected. The name for the test comes from the distribution of the differences of the proportion, which follow the Chi-Squared Distribution. The critical value for rejection can be computed from a Chi-Squared Distribution with k – 1 degrees of freedom, where k is the number of bins used in the test" (USACE, 2019). "Among statistical functions, Chi-Square (C-S) test is a simple and convenient method for hypothesis test, it is related to the overall fit, the process can be written as follows:

1) Choosing k-1 numbers as follows: $-\infty < t_1 < t_2 < \ldots < t_{k-1} < +\infty$, $k \approx 1.87(n-1)^{(0.4)}$, and the number axis is divided into k interval sections, $(-\infty, t_1]$, $(t_1, t_2]$, …, $(t_{k-2}, t_{k-1}]$, $(t_{k-1}, +\infty]$.

2) Collecting the number of samples dropped into the i^{th} interval n_i, i=1, 2, …, k, and then calculating the probability of the population which obeys alternative probability density function fallen into the i^{th} interval:

$$p_1 = P(X \le t_1) = F_0(t_1)$$
$$p_2 = P(t_1 < X \le t_2) = F_0(t_2) - F_0(t_1)$$
$$\ldots\ldots\ldots\ldots\ldots\ldots$$
$$p_{k-1} = P(t_{k-2} < X \le t_{k-1}) = F_0(t_{k-1}) - F_0(t_{k-2})$$
$$p_k = P(t_{k-1} < X) = 1 - F_0(t_{k-1})$$

Constructing a statistics:

$$\chi^2 = \sum_{i=1}^{k} \frac{(n_i - np_i)^2}{np_i}$$

Which obeys Chi-square distribution with the degree of freedom m, m=k-1, or m=k-1-r when there are r independent parameters of F_0(x) need to be estimated by samples. Examining the level of significance α, if p ($\chi^2 \geq \chi^2_{1-\alpha}$) ≥ α, then accept the hypothesis H_0, otherwise reject the hypothesis" (Zhang and Luo, 2000). In this study, level of significance α was taken as 5% and degrees of freedom as 33.

3.4.6.2 *Kolmogorov-Smirnov Test*

"The Kolmogorov-Smirnov, or K-S Test, is a nonparametric method for checking equality of two continuous probability distributions. When the distribution of data is approximated with an empirical distribution, equality can be checked between the empirical distribution and an alternative model for the data. The K-S Test behaves by finding the maximum difference in CDF between the proposed model for the data and the empirical distribution of the data. The program will provide a test statistic which is the result of previously-mentioned computations. In practice, if the difference is large based on the sample size, the null hypothesis that the data come from the proposed model would be rejected" (USACE, 2019). "Test computes the greatest discrepancy between the observed and hypothesized distribution. The process can be described as follows:

a) Sorting the samples X (x_1,x_2, …, x_n) in ascending order, and storing it to a new vector X ′ (x'_1 ,x'_2 , …, x'_n)

b) Calculating the empirical distribution function:

$$F_n(x') = \begin{cases} 0, x' < x'_1 \\ \frac{k}{n}, \ x'_k \leq x' < x'_{k+1} \\ 1, x' \geq x'_n \end{cases}$$

c) K-S statistics $D^{(n)}$ is calculated as:

$$D^{(n)} = max_{x'_i \leq x' < x'_n} |F_n(x') - F_0(x')|$$

$$= max_{1 \leq i < n} \| \frac{i}{n} - F_0(x'_i) \| \frac{i-1}{n} - F_0(x'_i) \|$$

d) Considering the significance level α, if *p* ($D^{(n)} \geq D^{(n)}$(1-α)) ≥ α, then accept the hypothesis H_0, otherwise reject the hypothesis" (Melo *et al.*, 2009; Wang and Wang, 2010). In this study, level of significance α was taken as 5%.

3.5 FLOOD MODELLING USING HEC-HMS

3.5.1 Analysis of Hydro-Meteorological and Remote Sensing Data

3.5.1.1 *Hydro-Meteorological Data Collection*

The hydrological data, daily discharge observed at Palai gauging station was collected from IDRB for a period of 34 years (1985-2018). The daily rainfall data of Erattupetta and Kozha station were also collected from the same source for the same period. The rainfall data of Kidangoor station was procured from CWC. These data were used for the different analysis. The monthly average precipitation of the three stations are given in Appendix II. The location details of hydro-meteorological stations are as given in Table 3.2.

Table 3.2 Location of hydro-meteorological stations

Sl. No.	Station	Longitude	Latitude
1	Erattupetta (rainfall)	76˚ 46' 03"E	9˚ 41' 19"N
2	Kozha (rainfall)	76˚ 34' 26"E	9˚ 45' 08"N
3	Kidangoor (rainfall)	76˚ 36'12.3"E	9˚ 40'22.4" N
4	Palai (discharge)	76˚ 41' 2.40"E	9˚ 42' 36"N

3.5.1.2 *Determination of Average Precipitation by Thiessen Polygon Method*

Thiessen Polygon approach is the most prominent and common, area-based weighting method, used in hydrometeorology for determining average precipitation when there is more than one measurement over a catchment area. The basic concept of the method lies in the assumption that the rainfall depth at any point within a watershed is the same as the rainfall depth at the nearest rain gauge station in the watershed. For assignment of method, perpendicular bisector line was constructed after connecting the rain gauge station graphically to form a network of triangles. This divided the watershed into several polygons, each part being the fraction of total area of that polygon. Based on the vicinity of station towards the watershed area, weighted average of the measurements based on the size of each one's polygon was enhanced. Measurements within large fraction of the polygons are assigned with more weight than measurements within small fraction of the polygons. Calculation of weighted average rainfall all over the catchment $\overline{P}$ was obtained by the formulae:

$$\overline{P} = \frac{P_1A_1 + P_2A_2 + P_3A_3 + \cdots + P_nA_n}{A_1 + A_2 + A_3 + \cdots + A_n} = \sum_{i=1}^{n} P_i \frac{A_i}{A}$$

$\frac{A_i}{A}$ is called the weightage factor, $P_1, P_2, P_3, \ldots P_n$ are the rainfall values and $A_1, A_2, A_3, \ldots A_n$ are the area of respective Thiessen polygons.

3.5.1.3 ***Preparation of Land Use/ Land Cover Map***

Land use land cover analysis plays a vital role in the study of watershed as it delivers the present status and pattern of land utilization in the area. In addition, it is also important in proper planning and management of natural resource. Hence, thematic map of the LULC were achieved through supervised classification of Landsat image in ERDAS IMAGINE software. The raster file of classification generated was used as input to the model. Each pixel in the satellite image depicts human interventions or natural resources.

3.5.1.4 ***Preparation of Soil Map***

Soil map contain the areal extent of different soil classes prevailing in the area, morphological description of the soil and its properties. Model requires soil hydrology groups for generation of curve number grid map. The hydrological soil group and soil characteristics were assigned to the soil type which aids in the modelling process.

3.5.1.5 ***Digital Elevation Model (DEM)***

The DEM was used to derive slope, aspect, flow direction and flow accumulation, stream network and watershed delineation. NASA DEM of 30m resolution was chosen to perform the terrain processing and basin processing.

3.6 ARC-GIS PRE-PROCESSING WITH EXTENSION HEC- GEOHMS

The HEC-GeoHMS (Geospatial Hydrologic Modelling Extension) is a public domain software package with the ArcView Geographic Information System for users that is supported by ArcView and Spatial Analyst tools for the creation of various kinds of inputs needed in hydrologic modelling. The DEM analysis transformed the drainage paths and watershed boundaries into a hydrologic data structure that represented the watershed response to precipitation. It also enabled in creating the HEC-HMS basin model, meteorological model, control specification model, time series data file and background map file, which were done precursor to HEC-HMS model (Maidment and Djokic, 2000).

3.6.1 Generation of CN Map

HEC-HMS model requires CN for the loss model. It was prepared basically from the combination of LULC map and soil map in HEC-GeoHMS. 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:

- 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, created a CN grid map.
- CN value determination for each sub-basin from the attribute table.

3.6.2 Terrain Pre-Processing

The primary step in HEC-GeoHMS was the terrain pre-processing, which is an input creation device that produces a hydrologically corrected terrain model. It defined the drainage patterns of the watershed that was utilised for stream and sub-watershed delineation. The results acquired after processes, were catchment area of each sub-basin, slope of each sub-basin, flow length etc which helped to calculate the time of concentration. In this study, six sub basins, three reaches, three junctions and one outlet had been finalized in HEC-Geo-HMS. The hydrologic results from HEC-GeoHMS produce number of files that can be imported and directly used in HEC-

HMS, where the simulations were performed finally. Using the DEM data as input, terrain processing with the following series of steps derived the drainage network and the related watershed characteristics.

Steps involved in the pre- processing were: -

(a) Fill DEM: Fill DEM was used to fill the depressions in the DEM by increasing the elevation of the pit cells to the level of the surrounding terrain. By filling the depression, it allows the water to flow through the landscape. The pits are often considered as errors in the terrain model due to re-sampling and interpolating the grid.

(b) Flow direction: Eight-point pour algorithm was functioned in this step, considering Hydro DEM as input data to define the direction of the steepest descent for each terrain cell. This finally computed the flow direction map.

(c) Flow accumulation: It defines the number of upstream cells draining to a given cell, considering flow direction as input data. Flow accumulation value multiplied by the grid cell area gave the upstream drainage area at a given cell.

(d) Stream definition: Stream network was formed by the classification of all cells with a flow accumulation greater than the user-specified threshold. To obtain greater number of sub basin, the threshold value should be chosen as smaller as possible.

(e) Stream segmentation: This step used flow direction and stream grids to separate the stream network into segments. To be specific, streams segments are the sections of a stream that connects a junction and the ridgeline, a junction and an outlet or two successive junctions.

(f) Catchment grid delineation: In this function, every stream segment attains sub-basins which were delineated using flow direction and stream link grids.

(g) Catchment polygon processing: Polygon sub-basin layer (a vector layer) using the catchment grid was generated in this step.

(h) Drainage line processing: Stream link and flow direction grid was utilised in this step, to secure a vector stream layer.

(i) Adjoint catchment processing: This step was performed to combine the upstream sub basins at every stream confluence. Although this step did not have hydrologic significance, this was an essential step in improving computational performance for interactive delineation of sub basins. In addition, it enhanced data extraction while defining HEC-GeoHMS project.

(j) Drainage point processing: Drainage points associated to the catchments were obtained with this step.

(k) Slope: This function helped in developing slope grid (percent or degree) for a given terrain model.

3.6.3 HMS project setup

The HMS project setup menu aids the user to define a study area that is used to organize the input file for HEC-HMS project analysis. This tool enabled the definition of outlet and demarcation of the watershed for the HEC-HMS project. It successively extracted the data from dataset created during terrain pre-processing where the outlet and boundary of watershed was developed. The requirement of multiple HMS basin models was managed by using the same spatial data with the definition of two feature classes namely Project Point and Project Area. The function helped to view the area of interest for which HMS basin models were already created. Further, it recreated models with different stream network threshold. It was also possible to delete projects and associated HMS files through this option.

3.6.4 Basin processing

The basin processing menu was used to revise the sub-basin delineation after the generation of new project and the succeeding the terrain processing. The indication of the points such as stream flow gauging station, flood damage centre, environmental concern spots, hydrologic control points etc., where information is needed, is solemnly encapsulated in the customized sub-basin and reach delineation. The tool contains data management processing including basin merge, sub-basin divided by maximum area, river merge, split basin at confluence, import batch points and delineate batch points. In this study, the functions namely basin merge was performed in order to merge multiple basins into one basin. This helped in reducing the number of smaller basins and hence management of area could be done effectively.

3.6.5 Stream and watershed characteristic

This tool helps in extracting the physical characteristics of watershed after the creation of stream and sub basin and thereby estimate the hydrological parameters. Physical characteristics of stream such as the length, upstream and downstream elevation and slope and sub-basin parameter such as longest flow lengths, centroidal flow lengths and slopes were computed here. These information were obtained from terrain data and were stored in attribute table that are exportable to other programs.

(i) River length: River length was calculated using river layer of routing reaches in the river.

(**ii) River slope**: The slope of the river, upstream and downstream elevation of the river reach was extracted using 'RawDEM' and river layer which were taken as the input.

(iii) Basin Slope: Average basin slope in the catchment was computed using sub basin and slope grid. This result was later used for the calculation of the CN Lag time parameter.

(iv) Longest flowpath: Physical characteristics such as the longest flow length, slope between endpoints, upstream and downstream elevation were extracted using 'RawDEM', flow direction grid and sub-basin layer. Longest flowpath layer enfolds all the obtained characteristics.

(v) Basin centroid: Basin centroid for each sub-basin was located using this option. There are three methods with different algorithms, centre of gravity method, longest flow path method and 50% area method. Another option is a user-defined basin centroid location method, which is required when the location is secured beyond the specific area. Among that centre of gravity method was used in this study.

(vi) Basin centroid elevation: Using 'RawDEM' as the input data, elevation for each centroid point was acquired.

(vii) Centroidal flow path: Centroidal flow path was calculated using sub basin, centroid and longest flow path by performing the projection of centroid point onto the longest flow path.

3.6.6 Hydrologic parameter

After extracting the physical characteristics, the hydrologic parameter option estimated the values of various hydrologic parameters such as curve number, time of concentration, percentage impervious area etc. These were calculated from different data including terrain, precipitation, basin average and grid-based values. Hydrologic parameters were defined by tools, namely 'HMS process', 'river auto name', 'basin auto name', 'sub basin parameter from raster', 'CN Lag method', etc. Select 'HMS process' tool which enabled to select the method of loss, transform, baseflow and routing model in HEC-GeoHMS software. 'River auto name' and 'basin auto name' tool labelled the reach in sequence from upstream to downstream. 'Sub basin parameter from raster' defined the hydrologic parameters for each basin.

3.6.7 Hydrological model file

Hydrologic input files that are used directly in HEC-HMS were generated with HEC-GeoHMS. These data consisted of background shape file, basin model file, meteorological model file, grid-cell parameter file and project file. These files functioned in HEC-HMS project directly when it was imported to the platform of HEC-HMS. Provision for addition and removal of hydrologic element, their connectivity and several tools for creating HEC-HMS model were also available in the menu. They are:

(i) Map to HMS units: Physical characteristics such as RawDEM, sub-basin, longest flow path, centroidal longest flow path etc. persisting in the map was converted to user-selected unit system (English or SI units). In this study, SI units were chosen for the depiction of measurements.

(ii) HMS data check: This option checks the dataset for consistency, further tracks the relationship between the stream segments, sub basins and outlet points. These checks were essential because the hydrologic structure of model may have been sometimes fragmented by unintentional use of subdivide and merge tools.

(iii) HEC-HMS basin schematic: GIS representation of the HEC-HMS model was been illustrated by this program. It developed a simple hydrologic network of model elements along with their connectivity.

(iv) HMS legend: This tool enabled to make point and line features of the HMS Node and HMS Link layers represented in HEC-HMS element icons.

(v) Add coordinates: Geographic coordinates were assigned to features in the HMS Node and HMS Link layers using this tool. It allowed the GIS data to be exported to ASCII format and still preserve the geospatial information.

(vi) Prepare data for model export: Basin model file that holds hydrologic elements, their connectivity and related parameters was exported from HEC-GeoHMS to HMS file with the service of this tool.

(vii) Background shape file: Background map layers contained the geographic information of the sub-basin boundaries and stream reaches and were represented by shape files, polygon and line properties.

(viii) Basin model file: This tool captured the hydrologic features and their related geographic information in ASCII text file that is to be loaded into an HEC-HMS project.

(ix) Meteorological model: The meteorological Model is a set of information required to state historical precipitation used in conjunction with a basin model. There are options for creating the model namely, specified hyetograph, gage weights and inverse distance method. Specified hyetograph method was adopted in this study.

(x) Create HEC-HMS project: This function creates a subdirectory and copies all HEC-HMS project files that was generated by HEC-GeoHMS to this sub-directory. This included the basin model file, meteorological model, gage or grid cell files and background map files, which were created in HMS file which comprises of all HEC-HMS project information.

3.7 PROCESSING WITH HEC-HMS MODEL

HEC-HMS encompasses with various methods to simulate surface runoff and river or reservoir flow in river basin, which is more specifically an empirical watershed model. The HEC-HMS Version 4.3 was used in this study which is primarily applicable for runoff and flood simulation in a river basin. The hydrological model, together with flood damage computation is also included in the model which provides a basis for evaluation of flood control project in a wider basis. This model simulated the runoff response of a watershed to precipitation by representing the catchment with interconnected hydrologic and hydraulic elements. Basin model in HEC-HMS comprises of five processes namely surface method, loss method, transform method, canopy loss method and base flow method. Each component in the basin, sub basin or stream is assigned with a variable, which define a particular attribute of the element and empirical relationship between them, describing the physical processes in the hydrology. The result of modelling in a catchment is the computation of discharge hydrograph at the watershed outlet.

3.7.1 HEC-HMS Model Components

HEC-HMS project requires the primary data components of the model such as Basin Model, Meteorological Model and Control Specifications for performing the simulations. Data can be entered for individual basin elements such as sub-basins and river reaches or simultaneously for entire classes of similar components. Tables and forms for entering necessary data are accessed from a visual schematic of the basin or there are even options for entering them after selecting the component. The data given as input can be of the form gridded, paired or time series data. In this study, the time series data of rainfall was entered simultaneously for entire classes of similar sub basin.

1. Basin model: It contains the main components of the project, especially elements of the basin, their connectivity and runoff parameters. The physical description of the watershed is also generated in this model to form a dendritic network of stream system. Atmospheric conditions are made into stream flow at specific location with the aid of basin model. Hydrologic components enabled to break the basin into manageable pieces, with the support of background maps (in spatial context) to place the hydrologic element in it. Different hydrologic elements in the basin model are as follows:

a) Sub-basin: It represents the physical watershed that holds data for sub-basins such as losses, UH transform, and base flow

b) Reach: It conveys stream flow downstream in the basin model and contains flood routing data of rivers and streams.

c) Reservoir: It indicates an area of impounded water that is bounded by lines. It has one or more inflow and only one outflow that are to be simulated. It is used to model the detention and attenuation of a hydrograph caused by the presence of reservoir or detention pond.

d) Junction: It combines the stream flow from the upstream hydrologic element and serves as connection point between outflows of one or more upstream elements.

e) Diversion: It denotes the diversion of specified amount of flow to an element based on a rating curve used for detention storage elements or overflows.

f) Source: It is a hydrologic element with outflow (user-defined) but no inflow.

g) Sink: It represents component with inflow but no outflow.

2. Metrological model: It contains the precipitation input data required by the sub basin and can perform the meteorological data analysis. It accepts both gridded and point value of precipitation for the simulation. It has advance capability to model snowmelt and evapotranspiration. Different meteorological component that could be added to the software are precipitation, ET, long wave radiation, snow melt, etc. For analysing precipitation data, several options are available such as frequency storm, gage weights, gridded precipitation and user specified hyetograph. User specified hyetograph method was used in this study for computing the precipitation data.

3. Control specifications: It contains the start and stop timing and also calculation interval for the simulation run of the model. However, this component does not contain parameter data but still stands as main component in a project. Time interval for which this study simulated was on daily basis with 100 iterations. Simulation was started from 1st Jan 2013 to 31st Dec 2018 with daily time steps for the calibration and validation of the model.

3.7.2 HEC-HMS Model Set-up

HEC-HMS model provides options with a variety of methods for simulating rainfall- runoff processes. The hydrologic components included in the watershed were arranged in a dendritic stream network. Computations were performed in an upstream to downstream sequential order in SI units as preferred. A schematic flow chart of the different process involved in the rainfall- runoff transformation in HEC-HMS model is shown in Fig. 3.8.

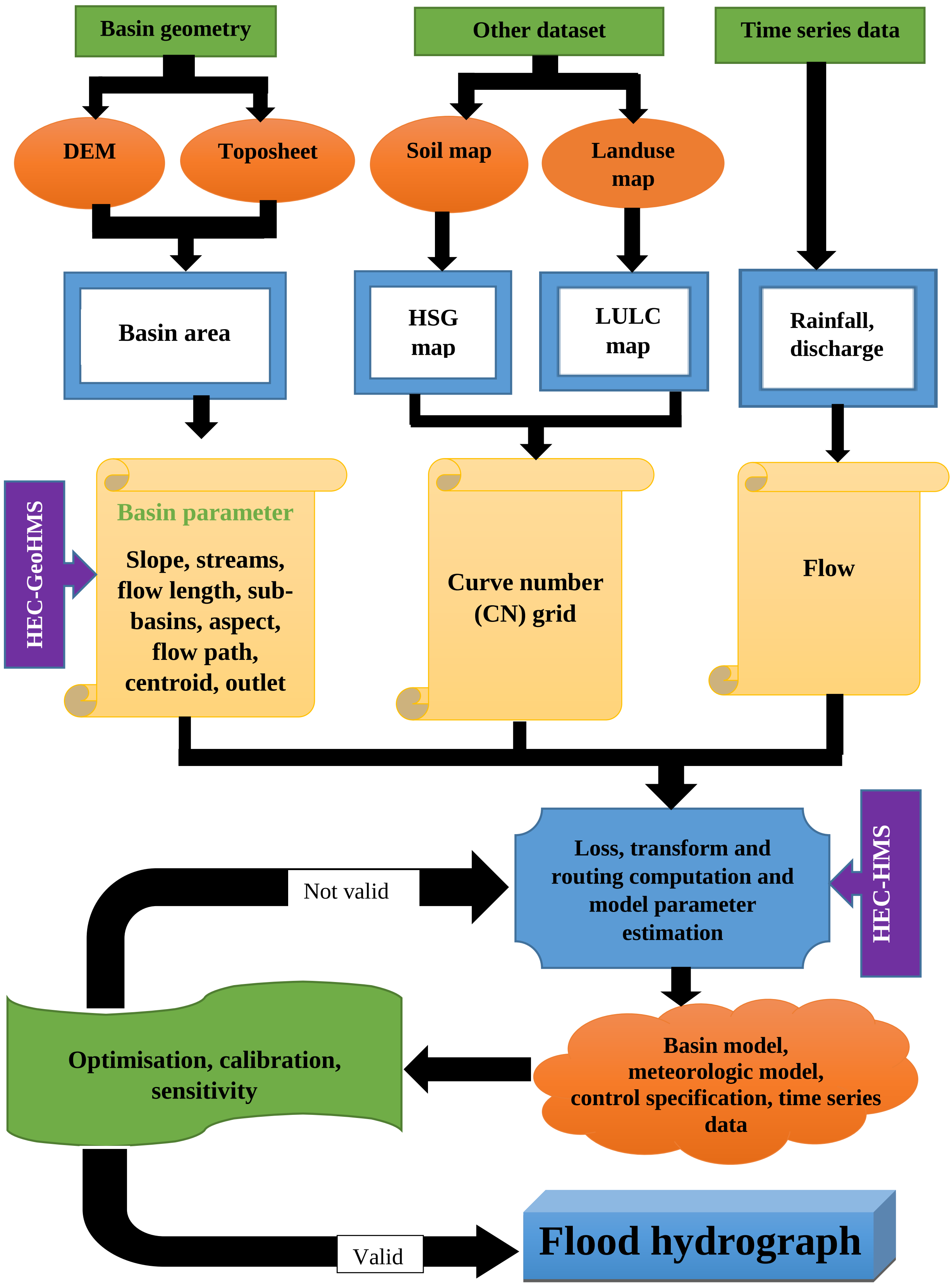


Fig. 3.8 HEC-HMS model flow chart

The various methods selected for HEC-HMS model simulation in this study are as follows:

3.7.2.1 *Loss Rate Methods*

Precipitation loss is the prominent factor that influences direct runoff in a watershed. Normally, after rainfall, precipitation loss is caused by interception, storage, evaporation and infiltration. However, the influences caused by infiltration, evapotranspiration and interception are considered and storage is ignored in storm stimulation. Among these, infiltration is an important factor in estimating precipitation loss. In HEC-HMS, any sub-basin can be classified on the basis of soil type, either pervious surface or impervious surface and expressed in the percentage of basin area. All the precipitation transforms to the runoff in the case of impervious and if there is any reduction in runoff transformed, it would be due to pervious land. "Exponential, Smith Parlange, Deficit and constant, Gridded deficit and constant rate, Soil moisture accounting (SMA), Gridded SMA, Initial and constant, SCS curve number (CN), Green-Ampt etc. are some of the methods included in HEC-HMS to compute the loss rate" (USACE, 2018). Among the 12 different loss methods available in HEC-HMS model, SCS-CN method developed by U.S Soil Conservation Service was selected to estimate the direct runoff in this study.

3.7.2.1.1 *SCS-CN method*

The SCS-CN method was adopted because this method is simple, widely used and efficient method for determining the approximate amount of runoff from precipitation. The data requirements for this method is also very less, i.e. only rainfall and curve number. Curve number is in turn a function of land use, soil type and slope. Even though the method is designed for a single storm event, it can be scaled to find average annual runoff values. SCS-CN method is presently renamed as Natural Resources Conservation Service (NRCS) method. The method was developed for estimating the volume of direct runoff from precipitation and it was empirically developed for small agricultural watersheds. Analysis of rainfall- runoff records for a storm event indicates that there is a threshold rainfall, comprised of interception, depression storage and infiltration volume called as initial abstraction (I_a) that must be exceeded before onset of runoff. Additional losses in precipitation will occur as infiltration after runoff begins. Accumulated infiltration rises with rainfall up to some maximum retention amount. The runoff also increases with rainfall. The standard SCS-CN method is mainly based on the following relationship between factors such as rainfall P and runoff Q in mm (Soil conservation service engineering division, 1986; Schulze *et al*., 1992):

$$\boldsymbol{Q} = \begin{cases} \frac{(P - I_a)^2}{(P - I_a) + S} & \mathrm{P} > I_a \\ 0 & \mathrm{P} \leq I_a \end{cases}$$

Where, S is potential maximum retention after runoff starts in mm. It shows the ability of catchment to abstract and retain storm precipitation. I_a is all loss before runoff starts (initial loss) which includes water retained in surface depressions, evaporation, rainfall intercepted by vegetation, and infiltration. Initial abstraction although can be highly variable, it generally correlates with soil and land cover factors. A linear relationship between Ia and S was suggested by Soil conservation service engineering division (1986) as: I_a = Sλ, where λ is an initial abstraction ratio which in turn eliminated the necessity for an independent estimation of I_a. The various researchers concluded that the values of λ may vary in the range of 0- 0.3, in different geographic locations in the U.S and other countries (Shrestha and Shrestha, 2003). "In the curve number method, the runoff is directly proportional to the precipitation with an assumption that the runoff is produced after the initial abstraction of 20% of the potential maximum storage" (Heshmatpoor, 2009). Therefore, for small agricultural catchments, I_a was found to be approximated by the empirical equations I_a= 0.2S. Substituting this value in the above equation give:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

The variable S, which varies with antecedent soil moisture and other variables, can be estimated as following:

$$S = \frac{25400}{CN} - 254$$

Where, CN is a dimensionless catchment parameter, curve number (0 - 100). A CN of 100 conceptually indicates a perfectly impermeable watershed with all rainfall transformation as runoff. A CN of zero instead represents the catchment with no runoff from the corresponding rainfall. The Engineering Division of the Natural Resource Conservation Service, United States Department of Agriculture has developed standard tables of curve number values determined from empirical information, as functions of catchment land use and land cover conditions in conjunction with HSG (hydrologic soil group), for the reference of users in determining the hydrologic parameters. These are listed in their Natural Resource Conservation Service Technical, Release-55, 1986. The HSG refer to the standard NRSC soil classifications based on infiltration capacity and rate of water transmission (permeability) through the soil. The intake and transmission of water are considered for soils under the conditions of maximum yearly wetness (i.e. thoroughly wet) and are regarded only for unfrozen soil. The HSG were assigned when the bare soil surface was considered. All these quality parameters classified the soil into four classes of hydrologic soil groups namely A, B, C and D (Mihalik *et al*., 2008; Matziaris *et al*., 2005). According to this classification, group A indicates the soil group with low run off potential, and group D with highest run off potential. Brief description of the classification and characteristics of hydrologic soil groups is shown in Table 3.3.

Land use and land cover map of the study area prepared from satellite imagery was used to find and evaluate the CN values for further assessment of the impact of land use/land cover in runoff generation. Numbers of categories of land use and land cover were determined according to the accuracy and level of details required for modelling. The CN characterize the combined effects of the primary features of the catchment area, including soil type, land use, and the previous moisture condition. The standard CN associated with the most frequent land use classification, for each hydrologic soil groups are displayed in Table 3.4. These CN values were used for the SCS-CN method computation in this study.

Table 3.3 Classification and characteristics of hydrologic soil groups

Hydrologic Soil Group (HSG)	**Types of soil**	**Characteristics of soil**	**Infiltration rate (mm/h)**	**Permeability rate (mm/h)**
A	Sand, loamy sand or sandy loam	Low run off potential, high infiltration rate	25	> 7.6
B	Silt loam or loam	Moderate infiltration rate	13	3.8 - 7.6
C	Sandy clay loam	Low infiltration rate	6	1.3 - 3.8
D	Clay loam, silty clay loam, sandy clay, silty clay or clay	Very low infiltration rate	3	< 1.3

Table 3.4 Runoff CN for hydrologic soil group (AMC II) for Indian condition

Sl. No.	**Land use**	**Curve Number for Soil Hydrologic Group**			
		A	**B**	**C**	**D**
1	Agricultural land	59	69	76	79
2	Barren land	71	80	85	88
3	Built up area	77	86	91	93
4	Canal	100	100	100	100
5	Forest	26	40	58	61
6	Plantation	41	55	69	73
7	River	100	100	100	100
8	Scrubland	33	47	64	67
9	Tanks / water body	100	100	100	100

There exist spatial and temporal variability of rainfall, quality of measured rainfall runoff data, antecedent rainfall and associated soil moisture amount in the study area; hence the SCS-CN method has sufficient room for variability (Ponce and

Hawkins, 1996). Antecedent moisture condition (AMC) also has a source of variability. Even though the term antecedent is taken to vary from previous 5 days to 30 days (Soil conservation service engineering division, 1986), there is no obvious guideline for varying the soil moisture with the antecedent rainfall of certain duration. The SCS methodology represents this parameter based on the cumulated precipitation over the previous five days as stated below (McCuen, 1982):

1. AMC I represents dry soil, with cumulated precipitation < 12.7 mm in the dormant season and < 35.6 mm in the growing season.
2. AMC II represents medium soil moisture, with cumulated precipitation of 12.7 - 28 mm in the dormant season and 35.6 – 53.4 mm in the growing season.
3. AMC III represents moist or saturated soil, with cumulated precipitation > 28 mm in the dormant season and > 53.4 mm in the growing season.

These values of AMC correspond, respectively, to 90, 10, and 50% cumulative probability of exceedance of runoff depth for a given rainfall (Hjelmfelt *et al.*, 1991). Table 3.5 shows the values corresponding to each AMC according to rainfall and season.

Table 3.5 Antecedent moisture conditions

AMC	**Five-day Precipitation**	
	Dormant season	**Growing season**
I	<12.7 mm	<35.6 mm
II	12.7-28 mm	35.6-53.4 mm
III	>28 mm	>53.4 mm

Curve Numbers are initially calculated for Antecedent Moisture conditions II (AMC II). In this study, AMCII condition was considered for the watershed. According to the need, it can be adjusted by addition or subtraction to obtain AMC III and AMC I, respectively. CNII is considered as the base CN because it is applied for moderate antecedent moisture condition (AMC-II). It can be further adapted for CN III, which is applied for near-saturated antecedent moisture condition (AMC-III), and CNI, is applied for dry antecedent moisture condition (AMC-I). Different formulas used to adapt the AMC II curve number values to another AMC conditions are as shown as follows (Chow *et al.*, 1988):

$$CN_I = \frac{CN_{II}}{2.334 - 0.01334CN_{II}}$$

$$CN_{III} = \frac{CN_{II}}{0.4036 + 0.059CN_{II}}$$

For a watershed with several sub basins, have different soil types and land covers, that ends up with composite curve number, computed by weighing the curve number for different sub basin areas in proportion to the land area associated with each one:

$$CN_c = \frac{CN_1A_1 + CN_2A_2 + \cdots CN_iA_i + \cdots + CN_nA_n}{\sum_{i=1}^{n} A_i}$$

Where, CN_i is the curve number of i^{th} sub basin area, A_i is the area of the i^{th} sub basin area, and n is the total number of sub basin areas.

3.7.2.2 *Unit Hydrograph Transform Methods*

Direct runoff is that part of precipitation drained through the outlet of watershed after satisfying the entire basin requirement such as infiltration, initial abstraction, storage, etc. There are seven different methods in HEC-HMS to simulate the transformation of excess precipitation into the direct runoff such as user-specified unit hydrograph method, Clarks Unit hydrograph method, Snyders Unit hydrograph method, Kinematic wave method, SCS Unit hydrograph method, Modclark method and User-specified S-graph, for the calculation of rainfall transformation to direct runoff. Among those, SCS Unit hydrograph method was used in this study to simulate transformation of rainfall to direct runoff.

3.7.2.2.1 *SCS unit hydrograph*

The Soil Conservation Service (SCS) proposed a parametric unit hydrograph model in Soil Conservation Service, Technical Report 55 (1986) and the National Engineering Handbook (1971). The averages of unit hydrographs derived from rainfall-runoff gauged for a large number of small agricultural watersheds was determined and was analysed throughout the U.S. for the development of this model. Being more reliable than any other methods, the SCS unit hydrograph method was chosen in this study to transform excess precipitation into runoff.

3.7.2.2.2 *Basic concepts and equations of SCS unit hydrograph*

SCS UH model is a predominant, dimensionless, single-peaked unit hydrograph. This dimensionless unit hydrograph expresses the unit hydrograph discharge (Ut) as the ratio to the unit hydrograph peak discharge (Up) for any time t, in the fraction of time Tp which is the time of unit hydrograph peak. Researchers suggests that the following relation between unit hydrograph peak (Up) and time of unit hydrograph peak (Tp) as:

$$U_p = C\frac{A}{T_p} \qquad \text{……..a)}$$

Where, A is the area of watershed, C is the conversion constant (2.08 in SI and 484 in FPS). The time of peak or the time of rise is related to the duration of the unit of excess precipitation in the following manner:

$$T_p = \frac{\Delta t}{2} + t_{lag} \qquad \text{………b)}$$

Where, Δt is the excess precipitation duration that serves as the computational interval in HEC-HMS model, t_{lag} is the basin lag time which is defined as difference in time between the centre of mass of rainfall excess and the peak of the unit hydrograph. When the lag time is specified, Equation b) and Equation a) can be solved successively to find the time of UH peak and the UH peak in HEC-HMS respectively. It is also interesting that lag time $t_{lag}$is the only input for this method in the model. With U_p and $T_p$parameters known, by their multiplication, the UH can be found from this method and that is included in HEC-HMS model.

3.7.2.2.3 *Estimation of SCS UH model parameters*

The SCS UH lag can be estimated through calibration of gauged sub watersheds. On the other hand, for ungauged catchment, the SCS suggests that it is related to time of concentration t_c (min) in the following way:

$$t_{lag} = 0.6t_c$$

“Time of concentration is a quasi-physically based parameter which can be estimated as:

$$t_c = t_{sheet} + t_{shallow} + t_{channel}$$

Where, t_{sheet} is the sum of travel time in sheet flow segments over the land surface in catchment, $t_{shallow}$ is the sum of travel time in shallow flow segments, shallow rills, down streets, gutters or rivulets and $t_{channel}$ is the sum of travel time in channel segment” (USACE, 2000). The channel flow velocity is calculated by Manning’s equation:

$$V = \frac{CR^{2/3}.S^{1/2}}{n}$$

Where, V is the average velocity, R is the hydraulic radius i.e., the ratio of channel cross-section area to wetted perimeter, S is the slope of the energy gradient line, often approximated as channel bed slope, and C = conversion constant (1.00 for SI and 1.49 for FPS). Values of n are commonly known as Manning’s roughness coefficient, can be estimated from standard tables. Hence, the velocity thus computed using above equation was taken for the calculation of channel travel time as:

$$t_{channel} = \frac{L}{V}$$

Where, L is length of the channel. Sheet flow is the flow over the watershed land surface on the order of 10-100 meters, before water reaches a channel. The SCS suggests that sheet-flow travel time can be obtained using the equation:

$$t_{sheet} = \frac{0.007(NL)^{0.8}}{(P_2)^{0.5}S^{0.4}}$$

Where, N is the overland-flow roughness coefficient; L is the length of flow, P_2 is the 2-year, 24- hour rainfall depth (in) and S is the slope of hydraulic gradient line which may be approximated by the land slope. Sheet flow usually turns to be shallow concentrated flow after 100 m. The average velocity for shallow concentrated flow can be computed as:

$$\boldsymbol{V} = \begin{cases} 16.1345\sqrt{S} & for\ unpaved\ surface \\ 20.3282\sqrt{S} & for\ paved\ surface \end{cases}$$

From this velocity calculation, the travel time can be estimated.

The parameter that is specified in SCS unit hydrograph method is tp, time of unit hydrograph peak. The program in the software computed Tc (time of concentration) and Up (peak flow) to rescale the SCS dimensionless unit hydrograph. This was then used to compute the direct runoff hydrograph for the sub-basin.

3.7.2.3 ***Flood Routing Methods***

Storage properties of the watershed system creates a difference in quantity of precipitation received as input and produce runoff as output. Hence the out-flow hydrograph (runoff) differs from the inflow hydrograph (precipitation) in shape, duration and magnitude. The technique that involves in determining the output flood hydrograph, when the input hydrograph and physical dimensions of one or more upstream sections are known is called flood routing. The hydrologic analysis of problems such as flood forecasting, design of spillways, reservoir and flood protection works, etc. invariably requires flood routing. Flood routing procedure is broadly classified into reservoir routing and channel routing. Reservoir routing examines the modulation effect of flood wave when it passes via reservoir. Such events result in outflow hydrographs with attenuated peaks and enlarged with time variations in reservoir elevation. Outflow is predicted with respect to time, when the relationships between both elevation-volume and elevation-outflow of the reservoir are known, using reservoir routing simulations.

Conversely, channel routing observes the changes in the shape of the input hydrograph while the flood waves pass through channel downstream. Flood hydrographs at various sections of the channel are predicted when the input hydrograph and channel-reach characteristics are known, using channel routing. Attenuation of the hydrograph peak and durations of high-water levels, aids in forecasting floods and taking preventive measures against floods as part of flood management. Flood routing is basically accounted by either hydraulic or hydrologic routing techniques. “Hydraulic routing is based upon the equation of motion of unsteady flow, together with the equation of continuity. The differential equation which determines this flow is known as the St. Venant's equation. But hydrologic routing is based mainly on the equation of continuity alone" (Subramanya, 2008). It is usually used in hydrologic studies as it is a simple approximate method. Kinematic wave, Lag, Modified Puls, Muskingum and Muskingum-Cunge are some of the hydrologic routing methods included in HEC-HMS model. Among those Muskingum method was selected in this study.

3.7.2.3.1 *Muskingum method*

Muskingum is a straight forward hydrological flood routing technique used in natural channels, among many models used for flood routing in rivers. It has been extensively used in river engineering practice since its implementation in the 1930s (Tewolde and Smithers, 2006).

The Muskingum method, which was developed by McCarthy (1938), is a popular lumped flow routing method. "For the calibration of this model, two parameters are needed; travel time (K) of the flood wave through routing reach (length of reach divided by the average flow velocity) and dimensionless weight (X) which corresponds to the attenuation of the flood wave as it moves through the reach. The routing parameters in the models are usually derived through calibration using measured discharge hydrographs of river" (Birkhead and James, 2002). Muskingum channel routing method is derived based on two equations (Linsley *et al*., 1982). The first is the continuity equation or conservation of mass as shown below:

$$\frac{I_1 + I_2}{2}\Delta T - \frac{O_1 + O_2}{2}\Delta T = S_1 - S_2$$

Where I_1 and $I_2$are inflow discharges at time 1 and time 2, O_1 and $O_2$are outflow discharges at time 1 and time 2, ΔT is the time difference between time 1 and time 2, S_1 and S_2 are values of reach storage at time 1 and time 2. The second equation is a relationship of storage, inflow, and outflow of the reach as indicated below:

$$S = K[XI + (1 - X)O]$$

Where S is the reach storage, I is the inflow discharge, O is the outflow discharge, K is the storage constant or proportionality coefficient, X is weighting factor having a range of $0 \leq X \leq 0.5$. A value of zero gives maximum attenuation and 0.5 provides the minimum attenuation.

Value of K and X of Muskingum method was determined in HEC-HMS for channel routing. These parameters are fitted in the model while calibrating the observed hydrograph.

3.7.3 Computation of Hydrological Parameters for Calibration

Using the HEC-GeoHMS utility, the sub-basin parameters (area, lag-time and average curve number) were determined. Other parameters required to estimate the lag-time, such as the length and slope of the longest flow path, were also determined and automatically stored by the program in the sub-basin attribute table. These files instinctively build a topologically accurate schematic network of sub-basins and reaches, with hydrological parameters, when opened in HEC-HMS.

By dragging and dropping hydrological element representing icons, a graphical representation of the watershed network was developed, and connections between them were thus formed. Using the HEC-HMS sub-basin editor option, hydrologic parameters were entered for each sub-basin. Sub-basin area, loss rate method parameters (SCS-CN method), transform method (SCS Unit Hydrograph method) and channel routing method (Muskingum method) are the necessary data. The HEC-HMS model's next part is a precipitation model. In this analysis, the stated hyetograph method was used in order to model the precipitation.

The method used for determining the gage weighting factors for mean area precipitation depth computation was Thiessen polygon method. “This is an area-based weighting scheme, based upon an assumption that the precipitation depth at any point within a watershed is the same as the precipitation depth at the nearest gage in or near the watershed. Thus, it assigns a weight to each gage in proportion to the area of the watershed that is closest to that gage” (USACE, 2000).

3.7.4 Model Calibration, Parameter Optimisation and Validation

Model calibration is an essential process needed to ensure similarity of simulation output and real observations. Once a model was developed and simulated for the initial parameter estimates, it was calibrated against known discharge rates measured at the gaging station during a storm event that occurred between selected time events.

The model calibration was attained by adjusting the parameter values until the results matched with the observed data. 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.

Daily available rainfall and discharge data from year 2013 to 2016 were used for model calibration whereas the data from year 2017 to 2018 were used for validation. The same parameters, obtained after calibration, were used for validation and thus the flood hydrographs of the catchment were generated. Using the fine-tuned parameters in the calibration process, the model was validated.

Meteorological data of three stations and hydrological data from one gauging station, within the study area, was used to calibrate and validate the model. The parameters required for rainfall-runoff transformation were estimated from the catchment properties, soil properties and land use and land cover data. Initial parameters were entered into the model and simulation of the selected parameters was done. The output of the model has been observed after each simulation and the effect of initial parameter affecting the runoff can be known, if any alteration is needed to be performed. Several adjustments of the parameters like CN, initial abstraction, lag time, Muskingum K and X etc. have been done in step by step procedure in order to match observed hydrograph with the simulated hydrograph. HEC-HMS itself provides an option for optimization of the model parameters with user-defined numbers of iteration which is termed as the automatic calibration system. Different types of statistical evaluations were also present in the model, in order to ensure the consistency of calibrated results. In this study, rainfall-runoff simulations were done using SCS unit hydrograph. The loss method adopted was SCS curve number. Initial values of the parameters required for SCS unit hydrograph and SCS curve number loss method were estimated from the physical characteristics of the catchment and the soil properties. Muskingum routing parameters K and X were also entered initially.

The procedural flow chart of calibration and parameter estimation is as shown in Fig. 3.9.

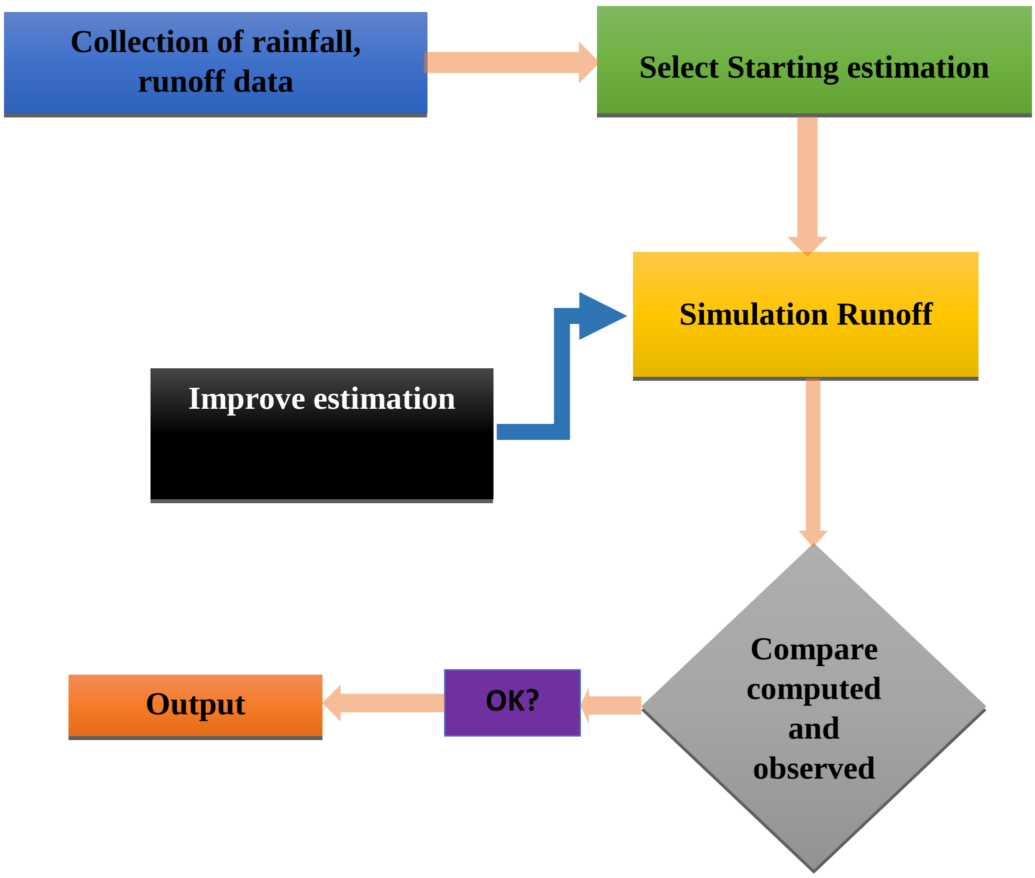


Fig. 3.9 Schematic diagram of calibration procedure

The minimum and maximum parameter values in simulation of rainfall-runoff models and the range of feasible and acceptable parameters is limited. The assumed maximum and minimum range of parameter values is shown in Table 3.6. Optimization options in HEC-HMS include methods such as simplex method, univariate and Markov Chain Monte Carlo method, in which simplex technique was adopted for optimization of parameters in this study.

Table 3.6 Calibration parameter constraints

Model	Parameter	Minimum value	Maximum value
SCS UH	Lag time	0.1 hr	500 hr
SCS loss	Initial abstraction	0 mm	500 mm
	Curve number	1	100
Muskingum routing	K	0.1 hr	150 hr
	X	0	0.5
	Number of steps	1	100

3.7.5 Performance Evaluation of HEC-HMS Model

Performance of the model was evaluated during calibration and validation on the basis of the following performance indicators:

1) Nash Sutcliffe efficiency (NSE):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O_i})} \times 100$$

Where, P_i represents predicted runoff, O_i represents observed runoff and $\overline{O_i}$ represents mean of observed runoff. The value of Nash–Sutcliffe efficiency varies between 0 and 1. Closer value to 1 indicates the better is model performance.

2) Percent bias (PBIAS):

$$PBIAS = \frac{P_P - O_P}{O_P} \times 100$$

Where, O_p and P_p are the peak value of observed and predicted runoff, respectively.

3) Root mean Square error-standard deviation Ratio (RSR):

$$RSR = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (O_i - P_i)^2}$$

Where, O_i and P_i are the peak value of observed and predicted runoff RSR is always greater than 0 and closer the values to 1 indicates better the model performance.

Performance ratings of NSE, PBIAS and RSR to be obtained for the HEC-HMS model calibration as reported by Rossi *et al*., 2008 is shown in Table 3.7.

Table 3.7 General performance ratings for statistics

No	Criteria	Value	Rating
1	**NSE**	>0.65	Very good
	NSE	0.54-0.65	Adequate
	NSE	≥0.50	Satisfactory
2	**PBIAS**	≤±20%	Good
	PBIAS	±20% to±40%	Satisfactory
	PBIAS	≥±40%	Unsatisfactory
3	**RSR**	0.00≤RSR≤0.50	Very good
	RSR	0.50<RSR≤0.60	Good
	RSR	0.60<RSR≤0.70	Satisfactory
	RSR	RSR>0.70	Unsatisfactory

NSE=Nash-Sutcliffe efficiency value

PBIAS= Percent bias

RSR=Root mean square error-standard deviation ratio

RESULTS AND DISCUSSION

CHAPTER IV

RESULTS AND DISCUSSION

The present study was aimed to analyse the flood frequency and simulation of flood in Meenachil river basin based on the hydrology of the basin. The flood frequency analysis was carried out using HEC-SSP tool. Flood modelling was conducted using HEC-HMS model. The various results obtained from the study are explained and discussed in this chapter under the following subheads.

4.1 FLOOD FREQUENCY ANALYSIS

Frequency analysis was achieved using the HEC-SSP software for major examination of the statistical distribution and functions.

4.1.1 General Frequency Analysis Editor

In this study the annual maximum discharge data of 34 years (1985-2018) was entered manually to avoid any occurrence of error. General frequency analysis editor option in the software, computed the probability distribution using maximum discharge data as input. Data was plotted on the probability scale with the aid of Weibull plotting position method. This was then followed by computing the expected probability discharge using distribution functions of Log- Pearson Type III and Gumbel extreme value distribution.

In the 34 years of stream flow data, the minimum and maximum value of discharge was found 139.280 m^3/s and 894.094 m^3/s respectively. The statistical parameters such as median, mode and mean were computed as 333.715 m^3/s, 139.280 m^3/s and 357.631 m^3/s respectively. The asymmetry of the probability distribution of variable about its mean or the skewness was obtained as 1.056. Sharpness of the central peak relative to a standard bell curve termed as the kurtosis value was calculated as 1.581. This showed that the distribution has shorter and thinner tails than normal distribution. Besides, the peak is lower and also broader than the normal distribution.

a) Log- Pearson Type III distribution

'Log transformation' option was enabled in the Log- Pearson Type III distribution for the analysis. The Weibull plotting position method followed by the Log Pearson type III distribution gave the following results as displayed in Table 4.1. The results depict the expected probability discharge for different per cent chance exceedance. It was observed that there was only a 0.2 percent chance exceedance that the discharge value would be occurred as 1421.967 m^3/s and 99 percent chance exceedance that the discharge value would be obtained as 93.535 m^3/s. The discharge value of 99 percent chance exceedance has the highest chance of occurrence among the different discharge values. However, for design purposes the discharge values of percent chance exceedance greater than 1 percent was usually chosen and it also differs based on the type of hydraulic structure that is to be constructed.

Table 4.1 Statistical analysis using Log-Pearson Type III distribution

Percent chance exceedance	**Computed curve discharge based on sample statistics in m³/s**	**Expected probability discharge in m³/s**	**Confidence limits discharge in m³/s**	
			0.05	**0.95**
0.2	1193.771	1421.967	1721.146	926.395
0.5	1047.848	1234.312	1466.171	828.596
1.0	939.873	974.953	1283.241	754.613
2.0	833.559	905.587	1108.398	680.164
5.0	694.549	741.388	888.696	579.850
10.0	589.190	613.505	729.992	500.896
20.0	481.291	492.929	575.977	416.347
50.0	323.779	326.721	371.794	282.177
80.0	215.117	216.050	248.585	179.896
90.0	172.848	174.113	203.550	139.212
95.0	143.900	139.938	172.987	111.770
99.0	101.378	93.535	127.644	72.962

Frequency analytical plot according to the Log Pearson type III distribution is represented in Fig. 4.1. The plot indicated the discharge values for different return periods from 1 to 1000 year with their corresponding probability of occurrence in the range of 0.9999 to 0.0001. The curves plotted consisted of expected probability with their confidence limit in 5% and 95%. The curves of computed and the observed events were also seen in the plot. According to the required return periods of the structure, design strategy and peak discharge values were selected.

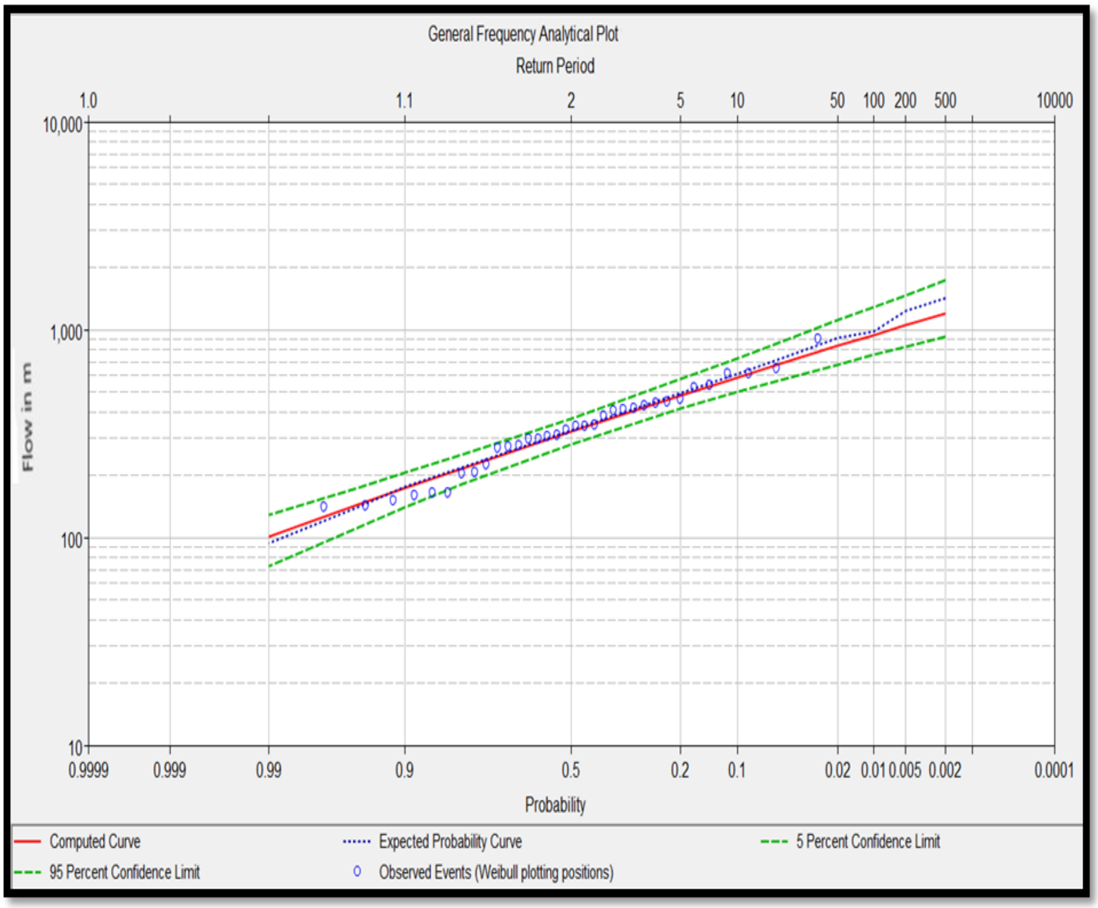


Fig. 4.1 General Frequency Analytical plot of Log-Pearson type III distribution

b) Gumbel Distribution

The Weibull plotting position method followed by the Gumbel Distribution gave the following results as displayed in Table 4.2. It shows the percent chance exceedance and expected probability discharge. From table, it was seen that there is 0.2 percent chance exceedance that the discharge value would be occurred as 1161.834 m^3/s and 99 percent chance exceedance that the discharge value would be obtained as 65.685 m^3/s, while performing Gumbel distribution function.

Table 4.2 Statistical analysis using Gumbel distribution

Percent Chance Exceedance	**Computed curve discharge based on sample statistics in m³/s**	**Expected probability discharge in m³/s**
0.2	1107.065	1161.834
0.5	985.032	1018.696
1.0	892.534	913.552
2.0	799.698	811.183
5.0	675.810	679.458
10.0	580.099	580.253
20.0	480.319	479.294
50.0	329.615	329.324
80.0	217.607	219.223
90.0	169.986	169.522
95.0	134.996	131.688
99.0	77.823	65.685

Frequency analytical plot according to the Gumbel distribution is represented in Fig. 4.2. The graph pointed out the discharge values for different return periods from 1 to 1000 year with their corresponding probability of occurrence in the range of 0.9999 to 0.0001. The plot also presented the expected probability of discharge for different return periods and this curve might be extended further to obtain the discharge values of desired return period.

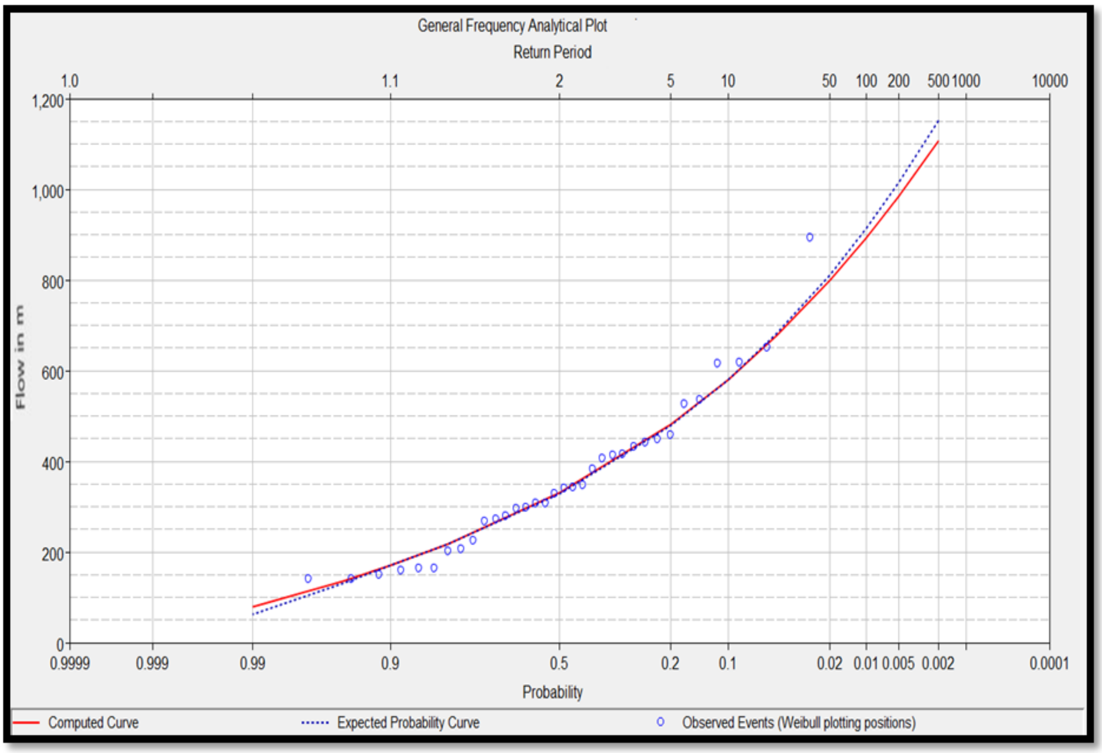


Fig. 4.2 General Frequency Analytical plot of Gumbel distribution

4.1.2 Distribution Fitting

The distribution fitting of the Gumbel and Log-Pearson type III was examined using HEC-SSP Distribution Fitting Analysis option. Both the distributions fitted well for the sub basin. The HEC-SSP software showed good adaptability and easiness in executing flow frequency analysis in this study.

"Not all distribution fitting method combinations will converge to and result in real-space parameter estimations when subjected to different data sets" (USACE, 2019). Hence tolerance and z alpha parameters were included to increase the accuracy and expediency of data. The convergence was obtained at 2% tolerance and 95% z-alpha for the sample data after parameter optimisation.

a) Log Pearson type III distribution

The log mean value, standard deviation and adopted skew of the Log-Pearson III distribution parameters computed by the software were 2.506, 0.208, -0.111 respectively for the 34 events or observations. The expected probability discharge with confidence limits 5% and 95% using Log-Pearson III distribution is shown in the Table 4.3. Expected flood flow estimates are the vital results in this study. "The expected values were used because they are higher and therefore more conservative"

(McCall, 2007). The expected probability discharge for 1, 10 and 50 percent chance exceedance were 984.601 m³/s, 592.788 m³/s and 325.010 m³/s, for the Log-Pearson III distribution. For 0.2 percent chance exceedance, an expected probability discharge of 1382.963 m³/s occurred with a confidence limit 0.05 and 0.95. The confidence limit discharge ranged between 1932.946 m³/s and 766.054 m³/s. On the other hand, for 99 percent chance exceedance, an expected probability discharge of 68.879 m³/s occurred with a confidence limit 0.05 and 0.95. The confidence level discharge resulted in the range of 147.142 m³/s and 69.120 m³/s respectively.

Table 4.3 Expected probability discharge using Log-Pearson type III distribution

Percent Chance Exceedance	**Median curve discharge (m³/s)**	**Expected probability discharge (m³/s)**	**Confidence limits discharge (m³/s)**	
			0.05	**0.95**
0.2	1193.747	1382.963	1932.946	766.054
0.5	1047.848	1145.416	1561.153	718.102
1	939.881	984.601	1314.421	678.044
2	833.573	856.776	1100.642	631.616
5	694.563	705.738	859.384	557.195
10	589.202	592.788	700.282	489.381
20	481.300	484.438	560.129	410.547
50	323.786	325.010	373.300	279.721
80	215.113	210.050	254.500	182.990
90	172.844	167.904	211.951	142.465
95	143.897	146.830	184.885	113.287
99	101.376	68.879	147.142	69.120

Log-Pearson type III plot comprising of both CDF and plotting position histogram with expected probability is shown in Fig. 4.3. “Tiny circular points in blue colour were the annual peaks and occupied their position on the probability sheet, according to probability assigned to them by 'Weibull method'. A line in red denotes Log Pearson Type-III 'Theoretical Distribution Curve'. For a majority of hydrological and hydraulic related studies, flood magnitude of return period of 50 year or more is needed. Such estimations were usually extracted with the help of this distribution plot, which can also be extended further mathematically for other values. The dotted line in blue colour is the expected probability curve. These estimated probabilities are useful for water resources development decisions.

A pair of green lines indicated 5% and 95% confidence limit specified to the Log Pearson Type III distribution. The green lines on either side represented the 90% confidence band. The two limits of 0.05 and 0.95, or 5% and 95% chance exceedance curve, imply that there is 90% probability that discharge value will lie between these bounds; and it was found that only 10% of observation fall outside this band. If certainty of probability is warranted for any project, flow of this magnitude may be chosen for design, but only after considering the cost of project. In fact, this choice is a trade-off between cost of the project and safety of the structure” (Anup, 2017).

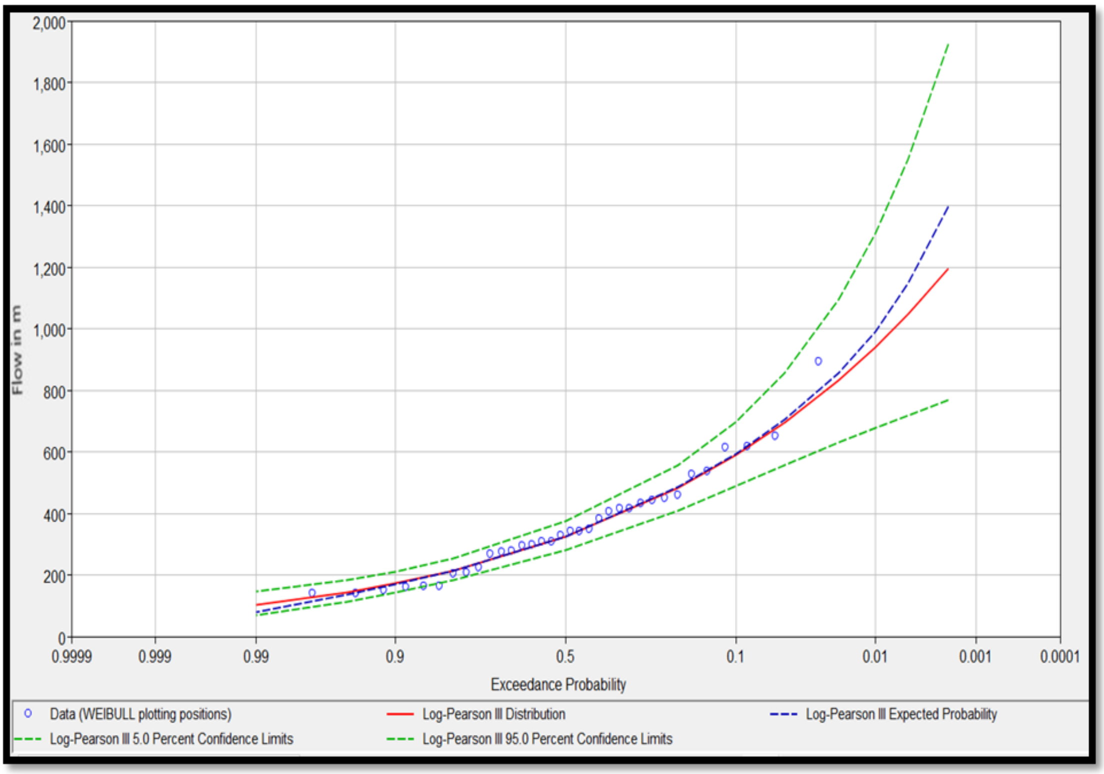


Fig. 4.3 Log-Pearson type III plot for the watershed from HEC-SSP software

b) Gumbel distribution

Discharge values of Gumbel probability distribution differ mainly with respect to their parameters, such as location and scale. Location indicates the mean or average of the distribution and scale indicates the standard deviation or variability. Location and scale parameters for Gumbel were obtained as 280.882 and 132.964 respectively for the discharge values.

Expected probability discharge with confidence limits using Gumbel distribution is shown in the Table 4.4. The expected probability discharge for 1, 10 and 50 percent chance exceedance were 912.093 m^3/s, 580.211 m^3/s and 329.124 m^3/s. For 0.2 percent chance exceedance, an expected probability discharge of 1152.144 m^3/s was observed with a confidence limit 0.05 and 0.95. The confidence limit discharge was found in the range of 1355.455 m^3/s and 873.142 m^3/s. The 99 per cent chance exceedance, probability discharge was found as of 63.574 m^3/s. The confidence limit 0.05 and 0.95 discharges were found in the range between 144.411 m^3/s and 11.236 m^3/s.

Table 4.4 Expected probability discharge using Gumbel distribution

Percent Chance Exceedance	Median curve discharge (m³/s)	Expected probability discharge (m³/s)	Confidence limits discharge (m³/s)	
			0.05	**0.95**
0.2	1107.065	1152.144	1355.455	873.142
0.5	985.032	1014.875	1199.424	783.740
1	892.534	912.093	1081.544	715.801
2	799.698	811.254	961.378	647.448
5	675.810	679.947	802.275	555.717
10	580.099	580.211	680.251	484.155
20	480.319	478.069	555.654	408.308
50	329.615	329.124	374.375	285.669
80	217.607	219.110	262.758	177.369
90	169.985	169.526	219.775	123.251
95	134.995	131.569	190.321	81.523
99	77.823	63.574	144.411	11.236

Gumbel plot containing both cumulative distribution function (CDF) and plotting position histogram with the expected probability is shown in Fig. 4.4. Blue circular points on the plot indicated the annual peaks occupying their position, according to the probability assigned to them by 'Weibull method'. The red line denoted the Gumbel 'Theoretical Distribution Curve'. Percent chance exceedance computed in this study was useful in finding the return period of flow. This helps in selecting design flood while constructing the structures for flood control.

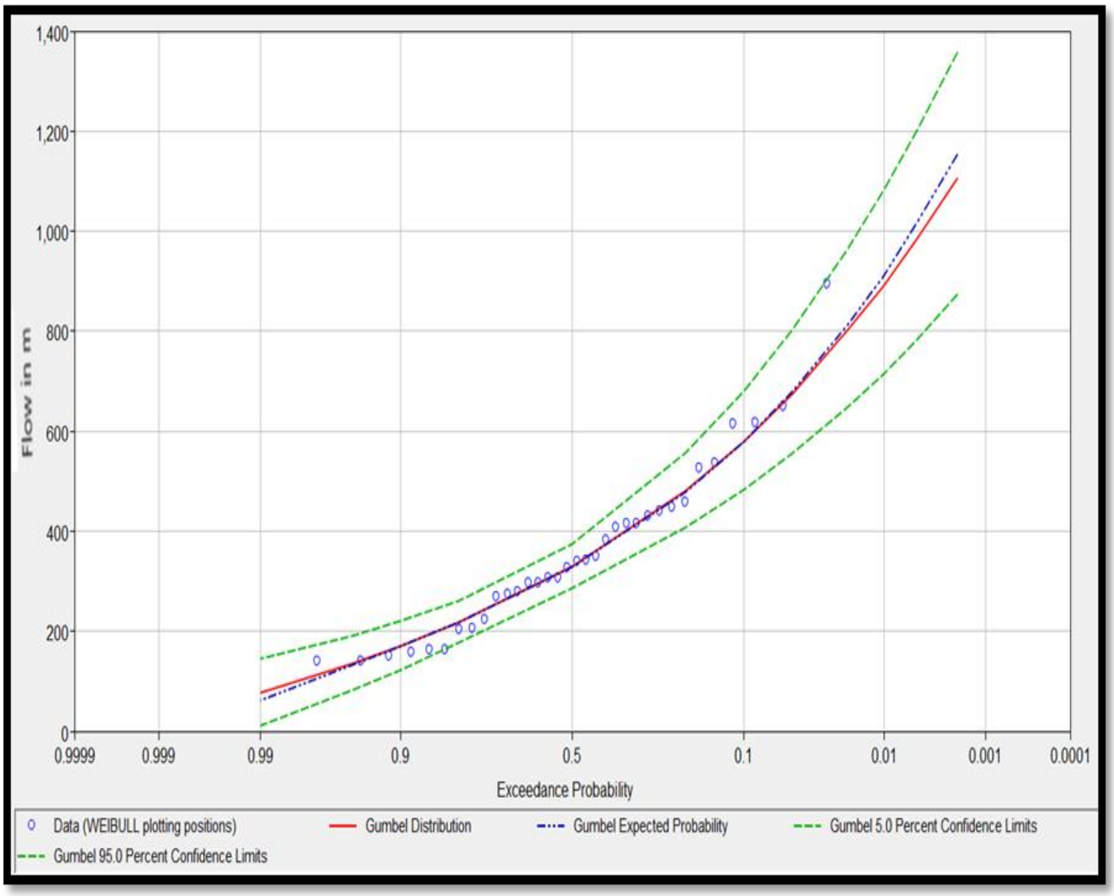


Fig. 4.4 Gumbel plot for the watershed from HEC-SSP software

4.1.3 Determination of Probability Distribution Functions (PDF)

The probability distributions, Log-Pearson III and Gumbel distribution were evaluated and probability distribution functions (PDF) were fitted for the annual discharge and are presented in Fig 4.5 and 4.6 respectively.

The cumulative distribution functions (CDF) for Log-Pearson III and Gumbel distribution were also fitted for the annual discharge and are presented in Fig 4.7 and 4.8 respectively.

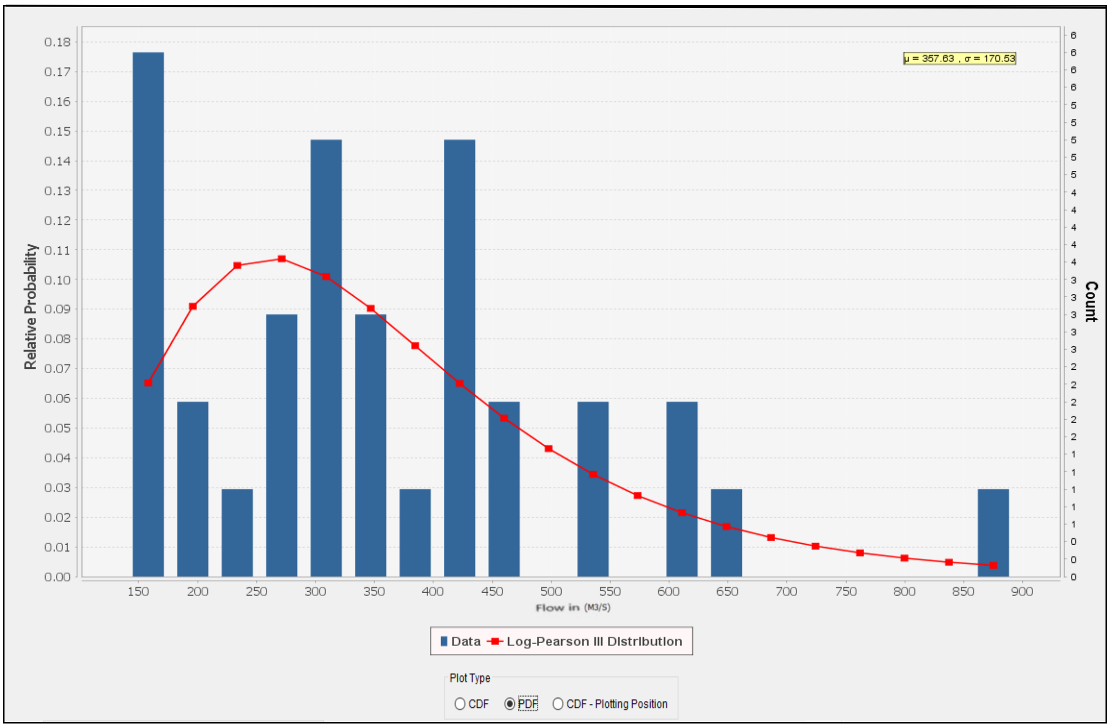


Fig. 4.5 PDF of Log-Pearson III probability distribution of annual discharge

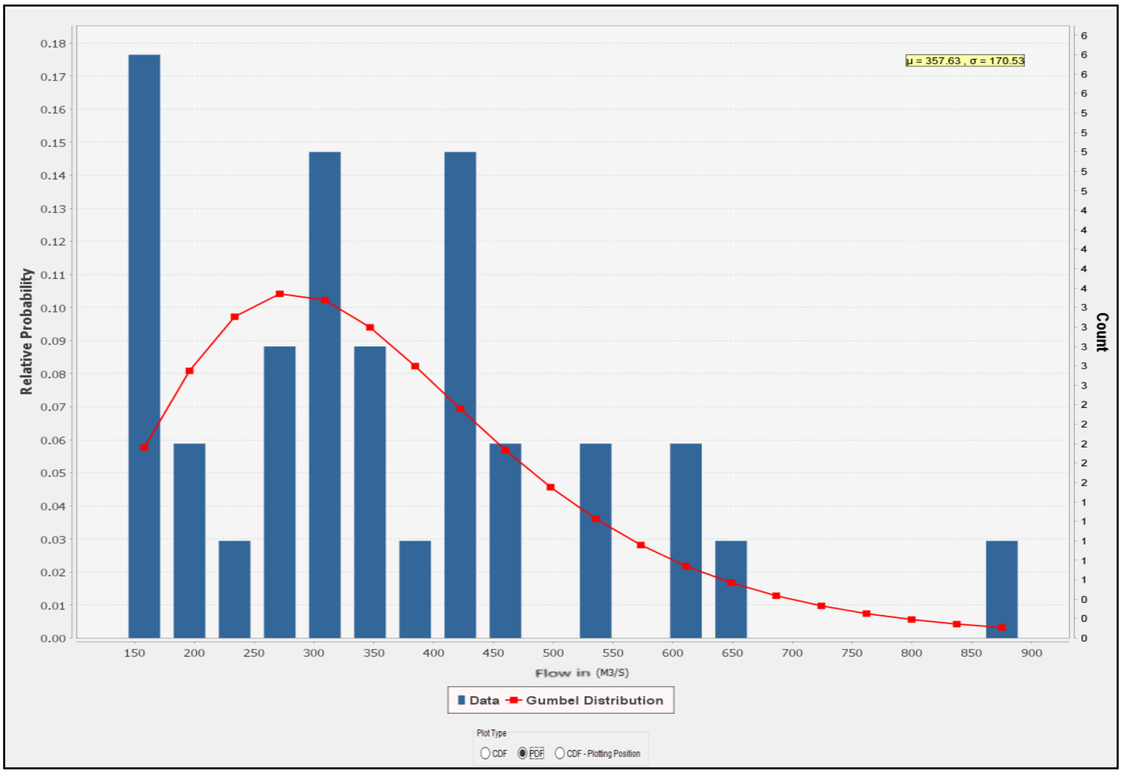


Fig. 4.6 PDF of Gumbel probability distribution of annual discharge

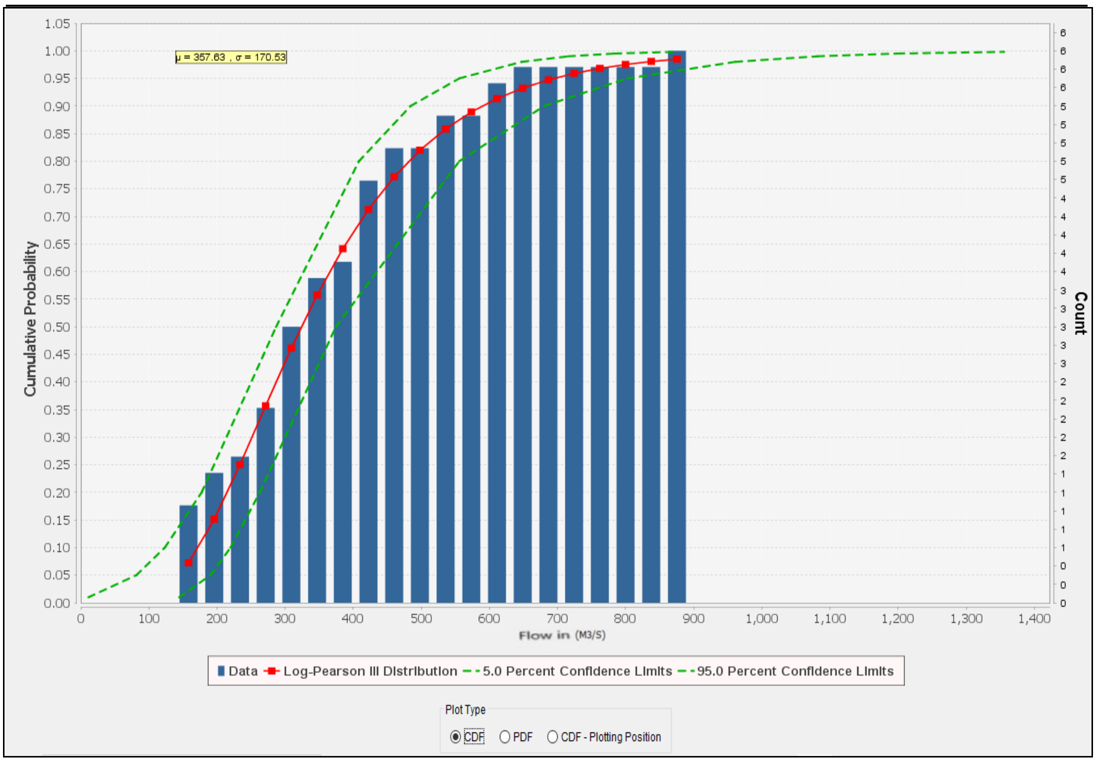


Fig. 4.7 CDF of Log-Pearson III probability distribution of annual discharge

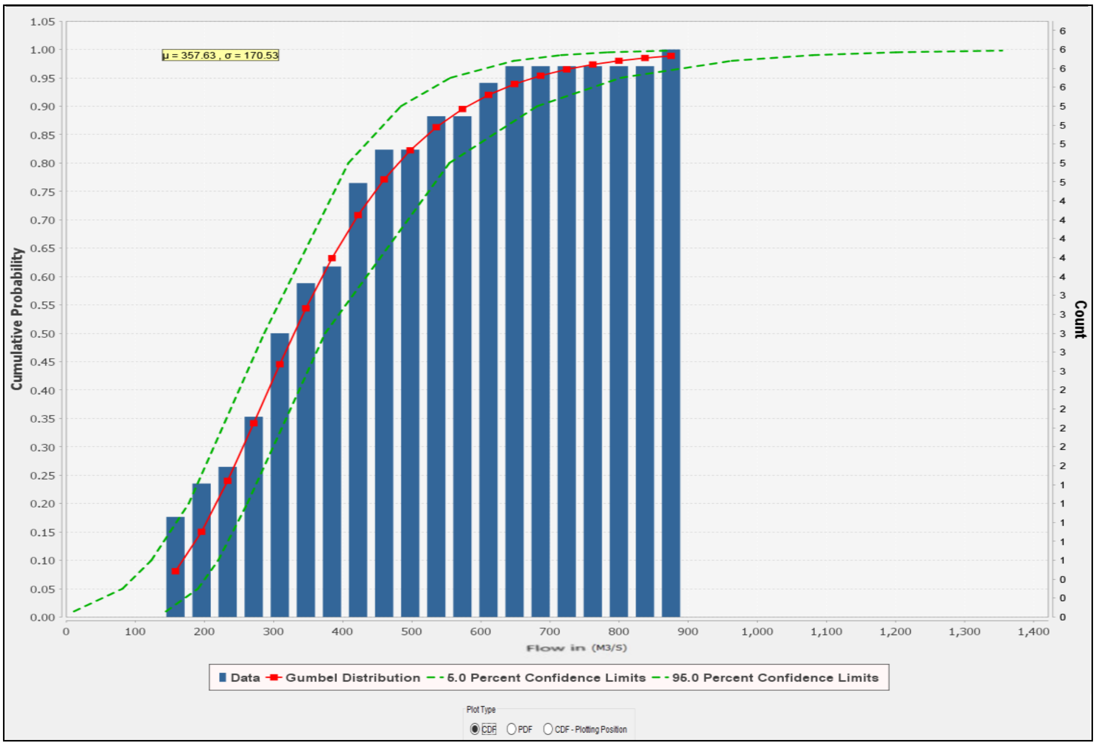


Fig. 4.8 CDF of Gumbel probability distributions of annual discharge

The parameters of the fitted probability distribution functions of Log-Pearson III and Gumbel for the annual discharge is shown in Table 4.5. The parameters of Log Pearson III were shape, scale and location while the parameters for Gumbel were scale and location.

Table 4.5 Parameters of the fitted probability distribution of annual rainfall

Sl. No	Distribution	Parameters
1.	Log-Pearson III	α=-0.111 β=0.208 γ=2.506
2.	Gumbel	σ =132.964 μ=280.882

4.1.4 Goodness of Fit Test

Goodness of fit test ensures the reliability of Gumbel and Log Pearson type III distributions to represent the sample. The goodness of fit summary statistics using Chi-Square test and Kolmogorov Smirnov test are shown in Table 4.6.

Table 4.6 Goodness of fit test statistics

Sl. No.	Type of Distribution	Test statistics	
		Standard Product Moments	
		Chi – Square	Kolmogorov-Smirnov
1.	Gumbel	0.087	2.706
2.	Log-Pearson III	0.094	3.412
Table value		0.23	47.4

The statistical table value for Chi-Square and Kolmogorov-Smirnov test were obtained as 0.23 and 47.4 respectively. The computed value, also called as the test statistic values, obtained for Chi-Square and Kolmogorov-Smirnov test were found less than that of the statistical table value. Therefore, by statistical theory, the hypothesis was accepted and it indicated the best fit of both distributions for the sub basin (Thomas and Mark, 2015).

4.1.5 Comparison of Gumbel and Log –Pearson Type III Distribution

A comparison of expected probability discharge of Gumbel and Log –Pearson Type III Distribution is shown in Table 4.7. The expected probability maximum discharge showed by Log – Pearson type III distribution were 484.438 m^3/s, 592.788 m^3/s, 856.776 m^3/s, 984.601 m^3/s and 1382.963 m^3/s for the return periods 5, 10, 50, 100, 500 year respectively, while the same showed by Gumbel distribution were 478.069 m^3/s, 580.211 m^3/s, 811.254 m^3/s, 912.093 m^3/s and 1152.144 m^3/s respectively for the same return periods. Both the distribution showed good relation with each other and found best fitted for the sub basin.

Table 4.7 Comparison of Gumbel and Log –Pearson Type III distribution

Percent Chance Exceedance	**T, Return Period in year**	**Expected probability discharge in m³/s**	
		Log-Pearson III distribution	**Gumbel distribution**
0.2	500	1382.963	1152.144
0.5	200	1145.416	1014.875
1	100	984.601	912.093
2	50	856.776	811.254
5	20	705.738	679.947
10	10	592.788	580.211
20	5	484.438	478.069
50	2	325.010	329.124
80	1.25	210.050	219.110
90	1.111111	167.904	169.526
95	1.052632	146.830	131.569
99	1.010101	68.879	63.574

Fig. 4.9 showed that the prediction of peak flood values corresponding to different percent chance exceedance using Gumbel and Log-Pearson Type III

distribution. Both the distributions showed almost similar trends. Design flood peak for the required return period and percent chance of discharge exceedance can be decided based on these charted values of flow shown in the figure.

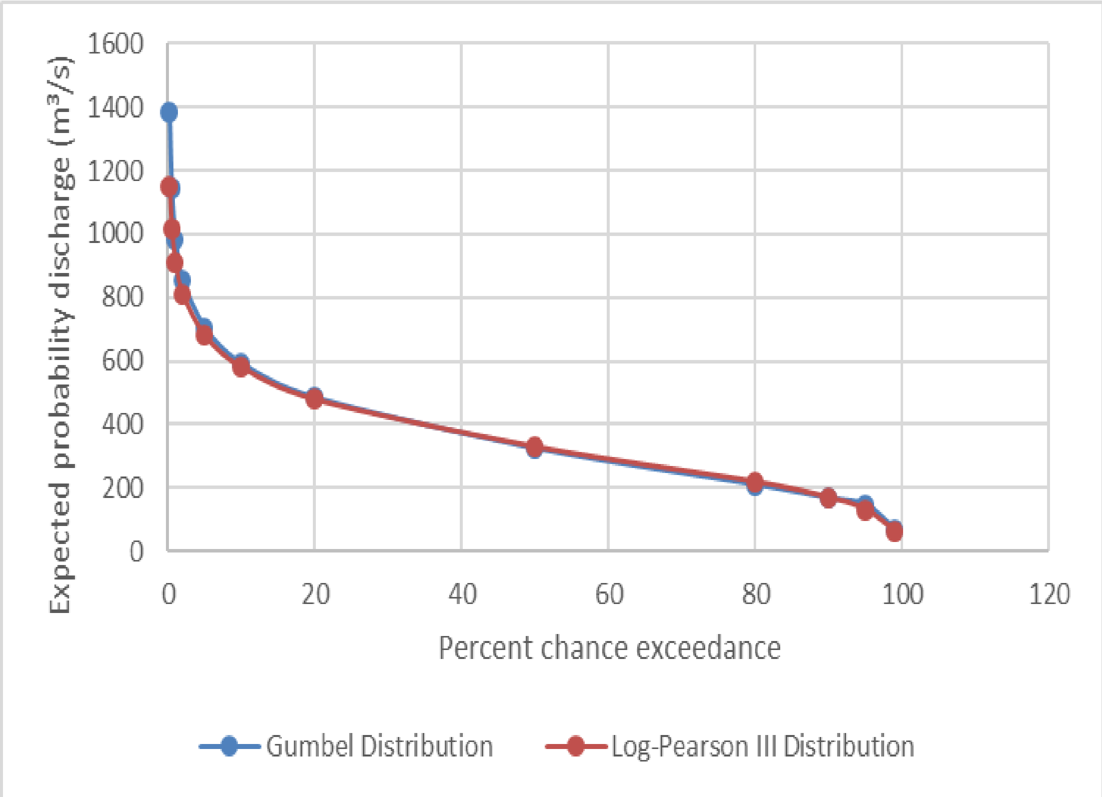


Fig. 4.9 Comparison of Gumbel and Log –Pearson Type III distribution

4.2 HEC-HMS MODEL INPUT DATA PREPARATION

The different input data for the HEC-HMS model setup for flood modelling studies in the sub basin of Meenachil river included Digital Elevation Model (DEM), rainfall data, stream flow data, soil type and land use/land cover (LULC) data. The input data files were prepared using HEC-GeoHMS, ERDAS Imagine and ArcGIS. The data describing the terrain was in vector format. Therefore, DEM was initially analysed through the HEC-GeoHMS (which function in Arc-GIS software platform) for creating the input file. Delineation of the watershed using Digital Elevation Model was performed after selecting appropriate DEM. Delineation of watershed using DEM required a sequence of pre-processing steps like fill sinks, flow direction, flow accumulation, stream definition and catchment grid delineation, catchment polygon, watershed aggregation, project setup, stream and sub-basin characteristics.

4.3 DEM SELECTION, TERRAIN PROCESSING AND BASIN PROCESSING

As topographical factors influence the hydrological modelling, choosing the appropriate DEM is crucial. DEM identify drainage related characteristics such as ridges, valley bottoms, channel networks and patterns of surface drainage and sub-watershed. Channel characteristics such as size, length and slope of watershed are also quantified. The accuracy of the DEM was dependent on the elevation model's quality and resolution and the DEM processing algorithms that extract the DEM data. Elevation dataset of NASA (30×30 m resolution) was selected as input DEM data to generate HEC-HMS input files in HEC-GeoHMS. The derivation of drainage network using terrain data as an input by the terrain processing option comprised of a series of steps. The step included different terrain processing stages such as clipped raw DEM of the Watershed, Fill sink map, Flow direction map, Flow accumulation map, Stream definition map, Stream segmentation map, Catchment grid delineation map, Catchment polygon map etc. After the completion of terrain processing, a new project for basin processing was developed to revise sub-basin delineations. Basin processing option included Sub-basin Merge and River Map, Longest Flow path Map, Sub-basin Centroid Map, Centroidal Longest Flow path, Thiessen Polygon Map and HEC-HMS Schematics tools. All the above processes mentioned, were used to extract the physical characteristics of streams and sub basin, and to develop the hydrological parameters and HEC-HMS inputs. Some of the pre-processing steps are as shown in the Figs. 4.10 to 4.16.

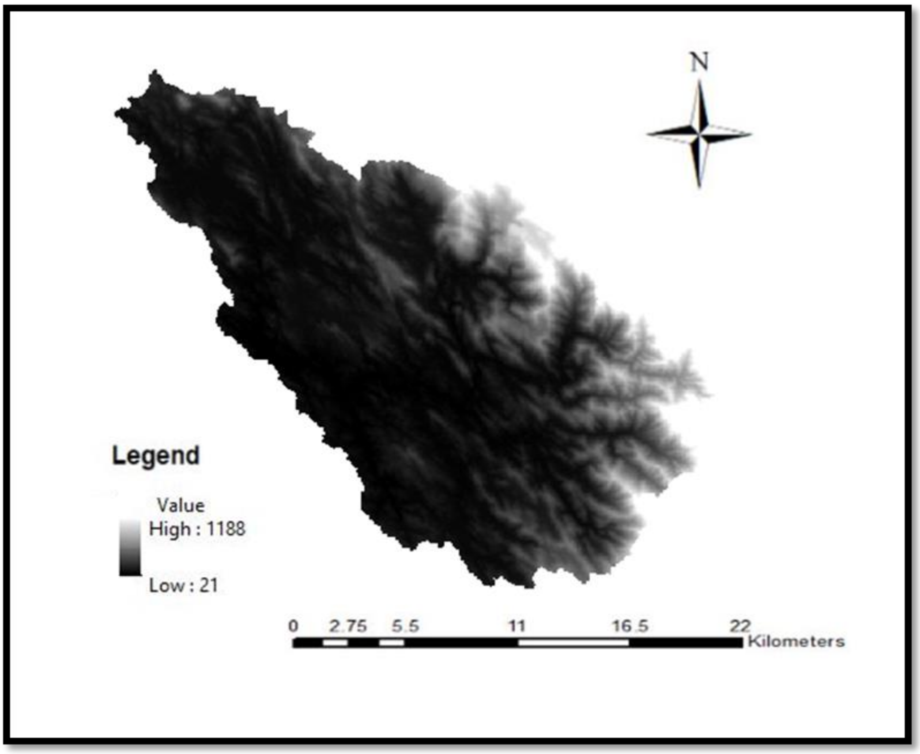


Fig. 4.10 DEM of Meenachil sub basin

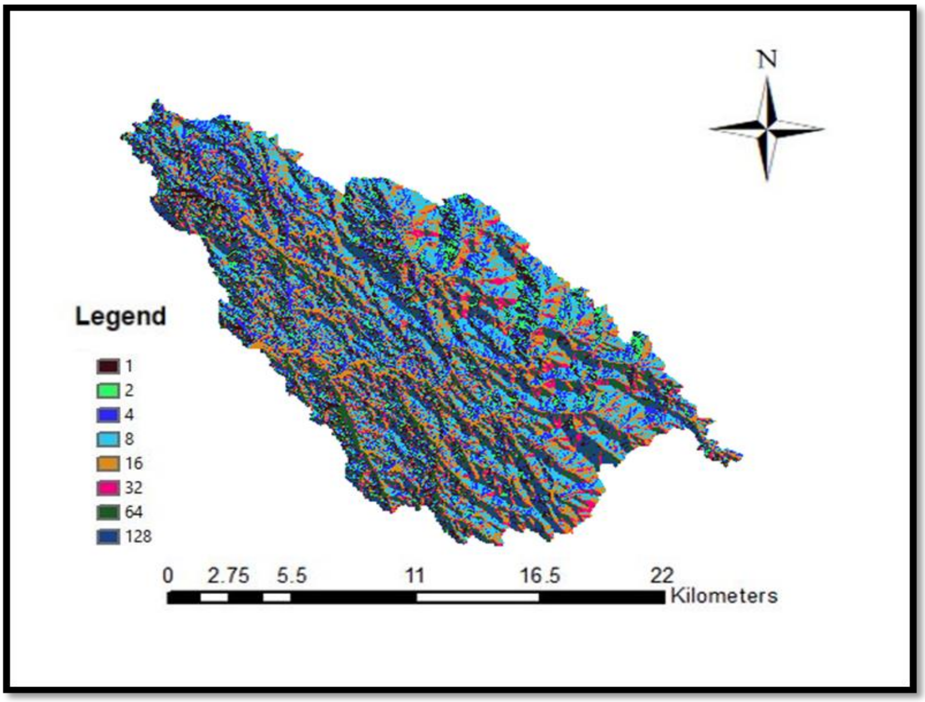


Fig. 4.11 Flow direction map of Meenachil sub basin

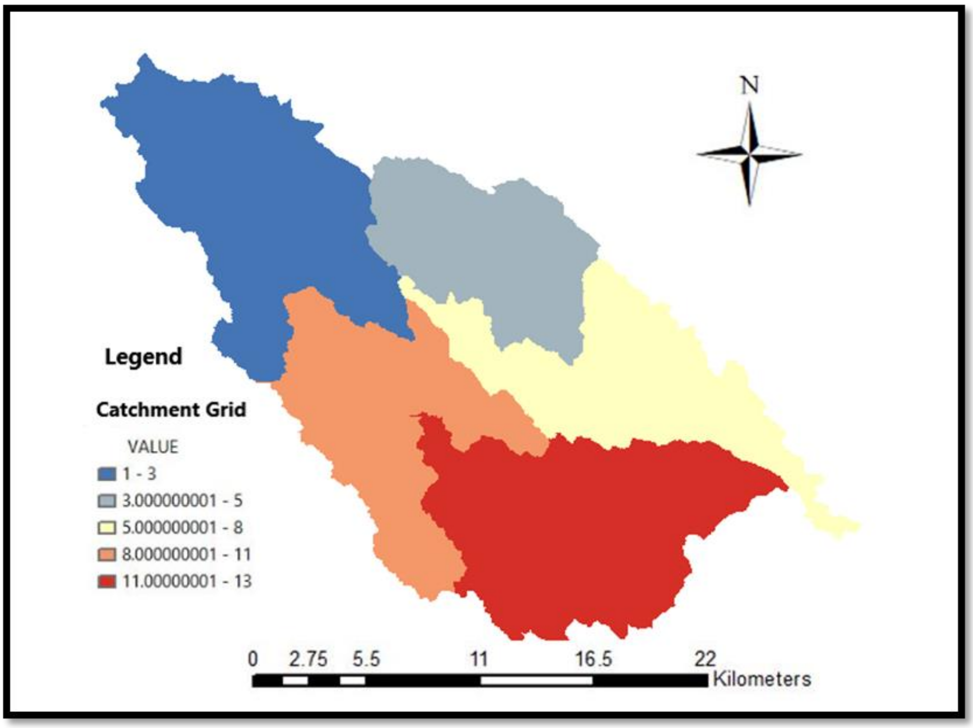


Fig. 4.12 Catchment grid delineation map of Meenachil sub basin

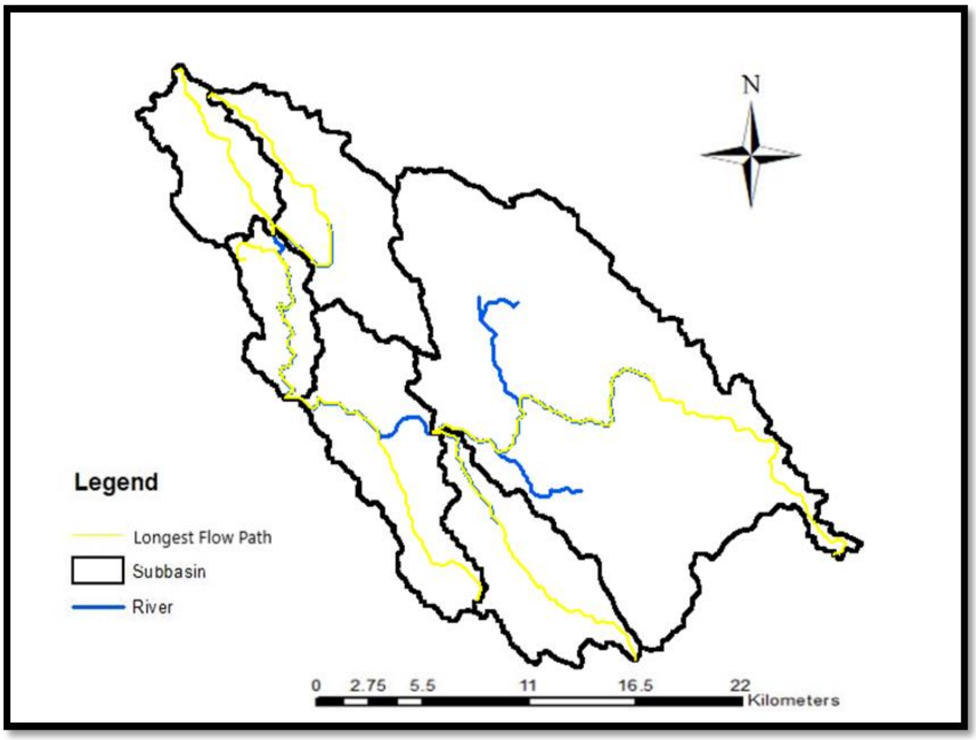


Fig. 4.13 Longest flow path map of Meenachil sub basin

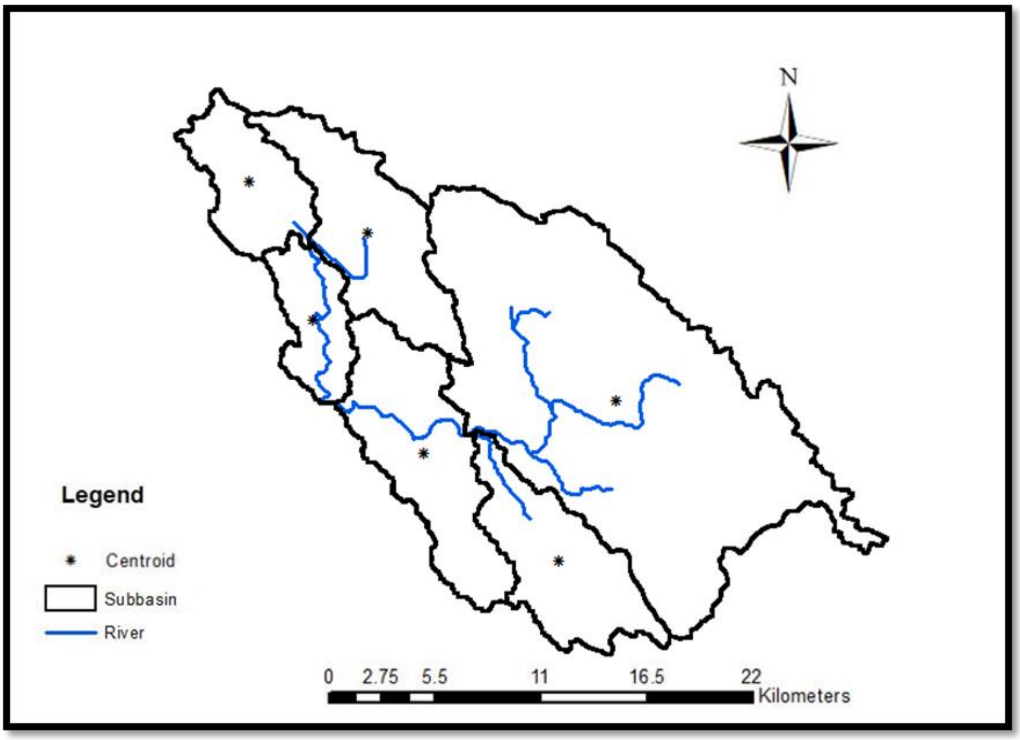


Fig. 4.14 Sub basin centroid map of Meenachil sub basin

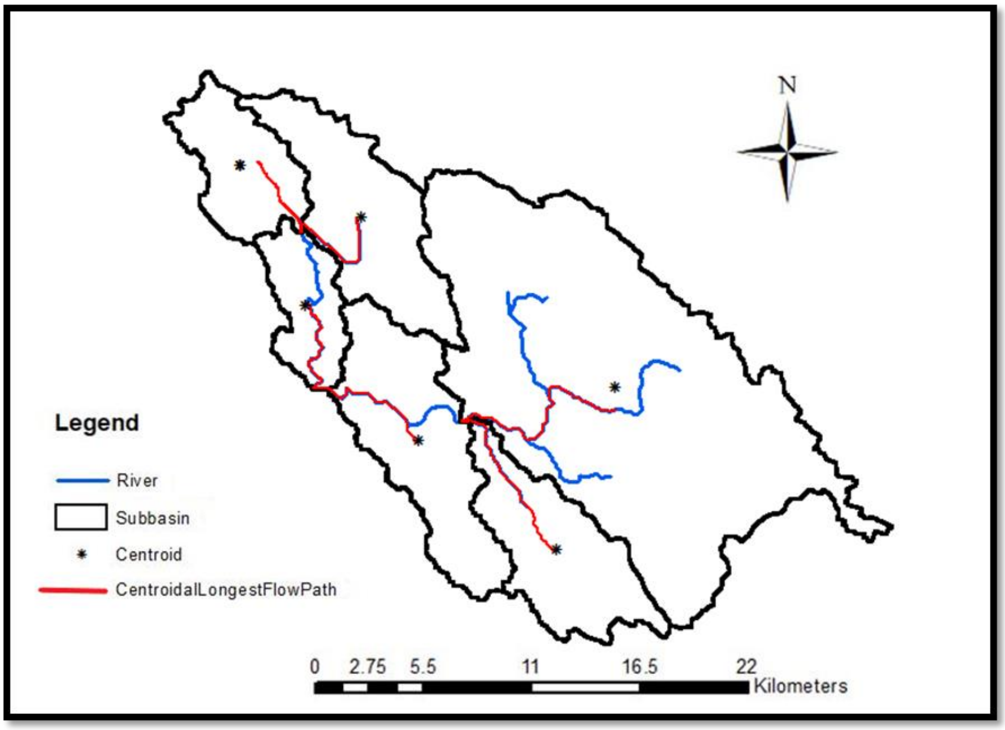


Fig. 4.15 Centroidal longest flow path of Meenachil sub basin

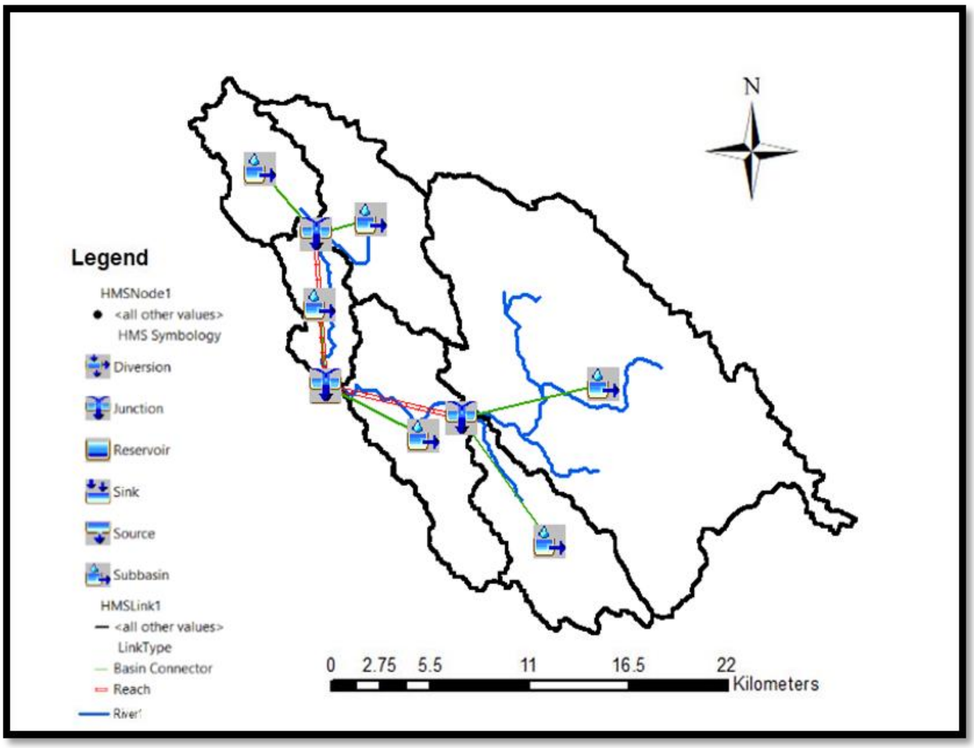


Fig. 4.16 HEC-HMS schematics of Meenachil sub basin

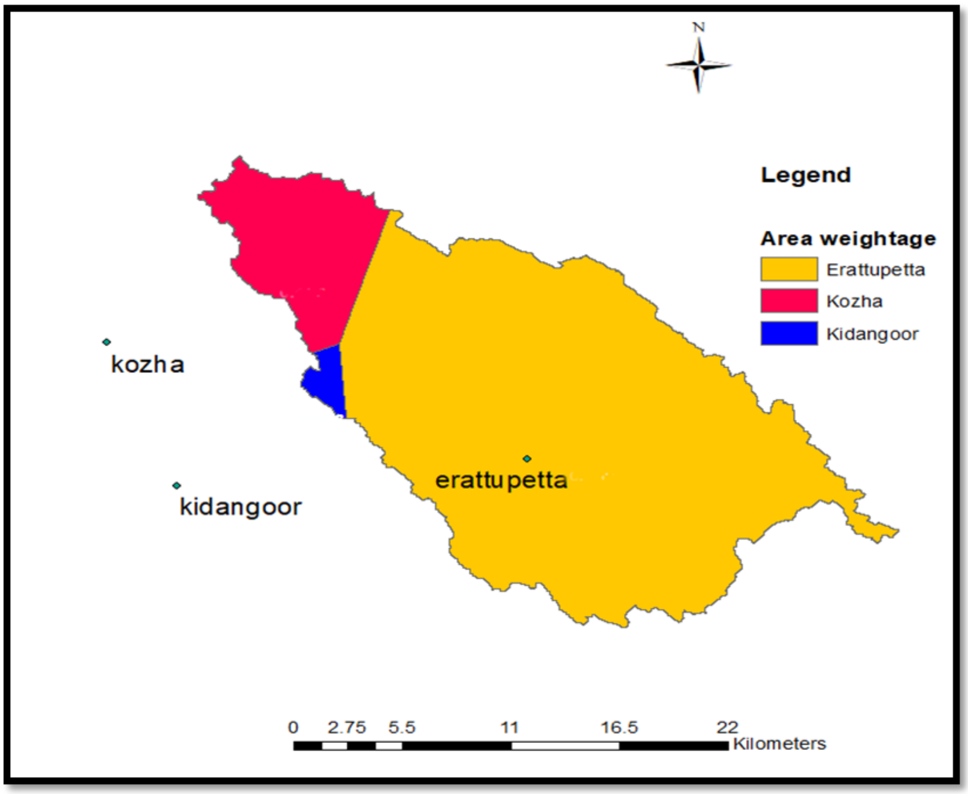


Fig. 4.17 Thiessen Polygon Map for calculating areal mean precipitation

Thiessen polygon map for calculating areal mean precipitation was prepared using the rainfall data from three rain gauge stations as shown in Fig. 4.17. The weighted area of Kozha, Kidangoor and Erattupetta gauging station, and their respective weightage of received rainfall at the outlet is shown in Table 4.8. The mean precipitation computed by Thiessen polygon is shown in Table 4.9.

Table 4.8 Weighted area and weightage of different stations

Station	**Weighted Area (km^2)**	**Weightage**
Kozha	59.9	0.13
Kidangoor	5.72	0.01
Erattupetta	378.5	0.85
Total	444.12	0.99

Table 4.9 Mean monthly precipitation of Meenachil sub basin

Month	**Precipitation (mm)**					
	2013	**2014**	**2015**	**2016**	**2017**	**2018**
Jan	0.20	0.00	1.60	1.54	0.37	0.00
Feb	0.42	2.34	1.50	0.43	0.00	1.88
Mar	6.90	2.36	7.93	4.68	10.96	3.00
Apr	6.16	9.06	13.21	2.77	2.93	10.35
May	3.96	12.02	11.38	15.11	13.45	19.21
Jun	33.37	13.95	15.20	16.13	17.66	22.14
Jul	24.44	18.26	9.81	14.13	8.71	30.96
Aug	18.06	30.19	12.63	7.30	16.71	22.51
Sep	13.23	10.20	13.86	2.87	18.14	8.00
Oct	12.22	20.98	13.81	3.31	9.66	16.05
Nov	18.93	13.44	13.38	2.50	8.99	8.84
Dec	0.61	3.82	5.65	0.54	3.66	1.71

4.4 LAND USE / LAND COVER MAP

Surface runoff generation process depends on many factors. The land use/land cover of the area is one of the main factors. Hence, the effect of land use/land cover was incorporated in the model, by sorting it into six land use/ land cover classes namely built up, rubber plantation, paddy, mixed vegetation, waterbody and barren land.

Landsat-8 data was processed in ERDAS Imagine 2015 version. Classification was based on the probability that a pixel belongs to a particular class. Supervised classification was performed to categorize the different classes. The reclassification of land use classes was done on the basis of criteria shown in table in Appendix 3, which was recommended by National Land Cover Database (NLCD) – USGS. Reclassification was done with the intention of creating the land use/ land cover classes adoptable for appropriate extraction in the software. Land use/ land cover classes was further analysed by means of Arc GIS 10.3 for quantification of spatial phenomena of the land use/ land cover map. Area coverage of the different land use/ land cover classes was estimated using Arc GIS software.

It was found that the foremost portion of land use of the study area was under rubber plantation (65.8%) which occupied more than half of the total geographical area of the watershed (442.5 km^2). As agriculture is the main occupation of the people in the area and agricultural activities were practiced in almost all portions of watershed. The rubber plantation was found predominant in the study area. The dwellings of people were only in minor proportion, due to hill slopes and highland topographic features of the area. The spatial distribution of land use/ land cover of the watershed is shown in Fig. 4.18 and its details are presented in Table 4.10.

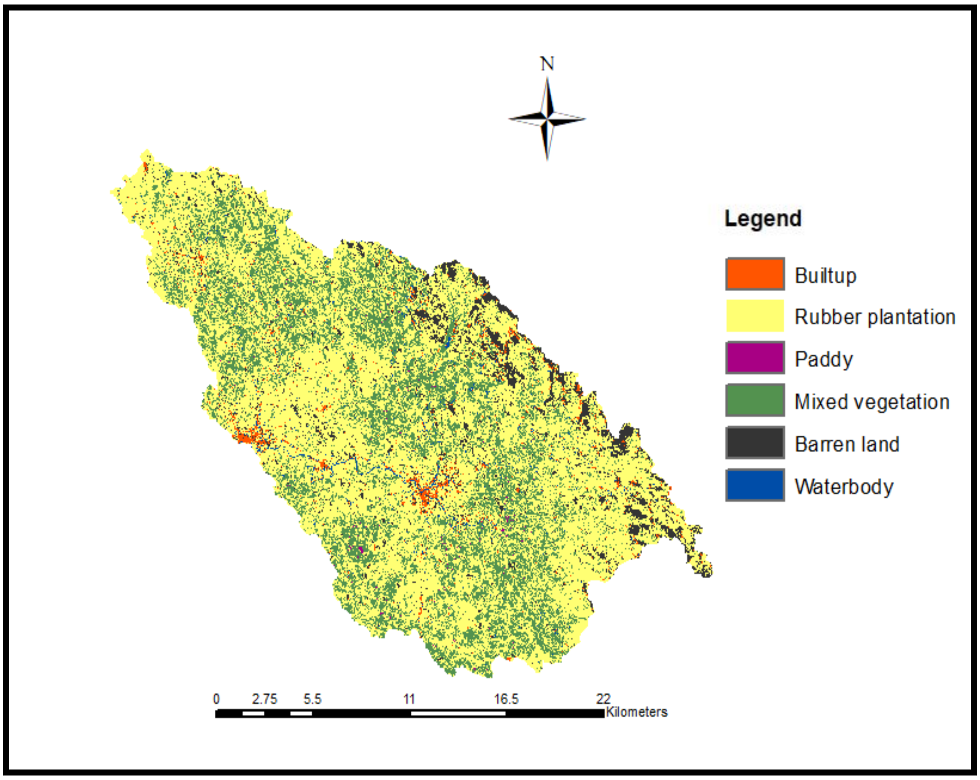


Fig. 4.18 Land use /land cover map of Meenachil sub basin

Table 4.10 Distribution of Land use/land cover of Meenachil sub basin

Land use class	Area (km²)	Area (%)
Built-up	8.13	2.0
Rubber Plantation	291.07	65.8
Paddy Fields	0.75	0.17
Mixed Plantation	107.15	24.0
Rock or Barren Land	30.80	7.0
Stream	4.60	1.03
Total	442.50	100

4.5 SOIL MAP

Soil characteristics and its extent in the watershed is another important feature affecting the transformation of precipitation into runoff. Soil series map for Meenachil river basin, published by Department of Soil Survey and Soil Conservation, Trivandrum, Kerala at scale of 1:225,000 was used as the source of soil database in this study. After pre-processing of soil maps using GIS, the soil types were identified on the basis of texture of soil in the study area. They were loamy sand, Sandy clay loam and silty clay which covers an area of 50.4, 107.1 and 286.5 km² respectively. The area under different soil types are presented in Table 4.11. The spatial map of soil series and hydrological soil groups are shown in Fig. 4.19 and 4.20.

Table 4.11 Different types of soil in Meenachil sub basin

Different Soil Types	**Area (km²)**	**Area (%)**	**Hydrologic Soil Group**
Sand, loamy sand, sandy loam	50.4	11.3	A
Sandy clay loam	107.1	24.2	C
Clay loam , silty clay loam, sandy clay, silty clay, clay	286.5	64.5	D
Total	444	100	

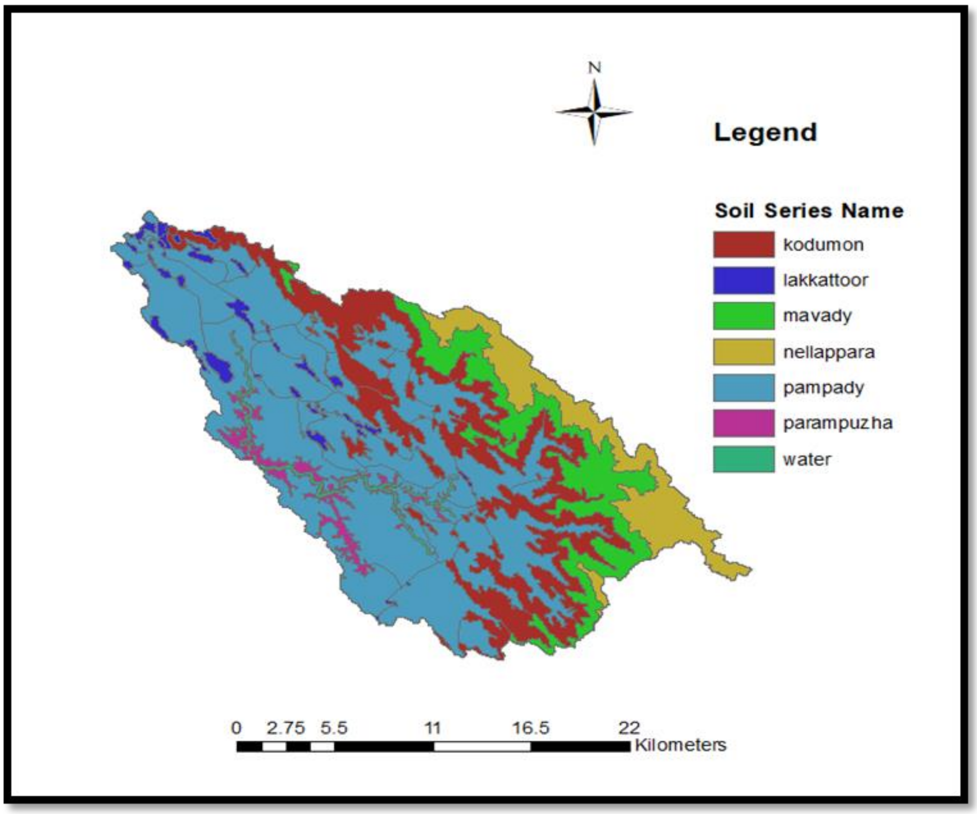


Fig. 4.19 Soil Map showing the distribution of soil series in Meenachil sub basin

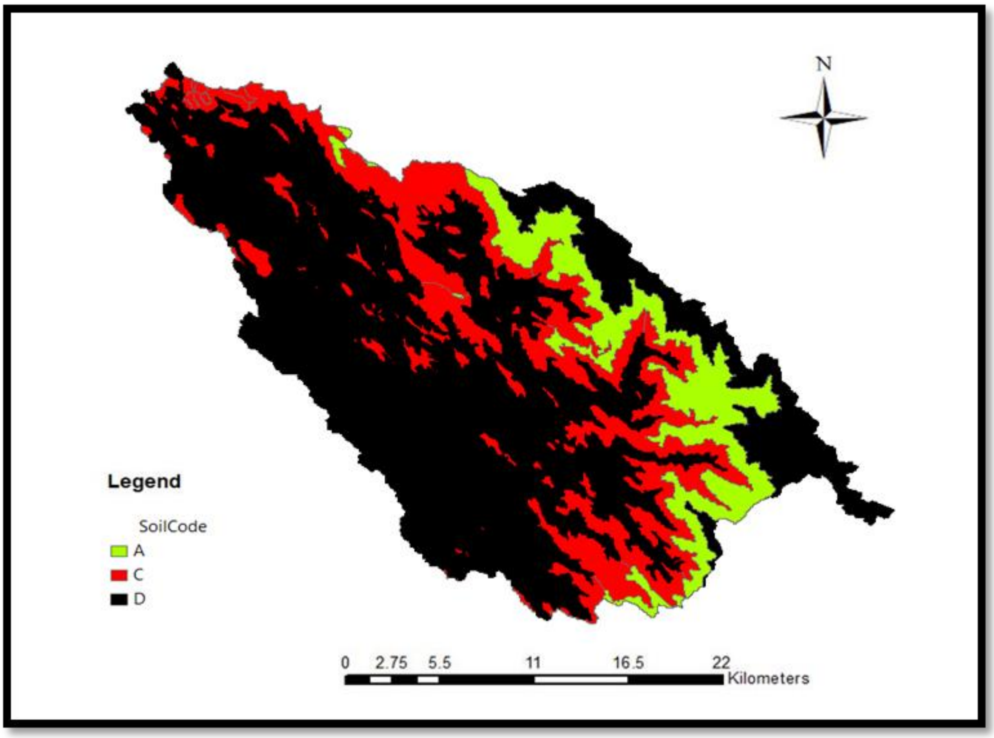


Fig. 4.20 Hydrological soil group map of the Meenachil sub basin

4.6 CURVE NUMBER (CN) GRID MAP

Curve number grid map was prepared by overlaying soil map and LULC map. The CN grid map is shown in Fig. 4.21. Curve number estimation was done with the help of this CN grid map.

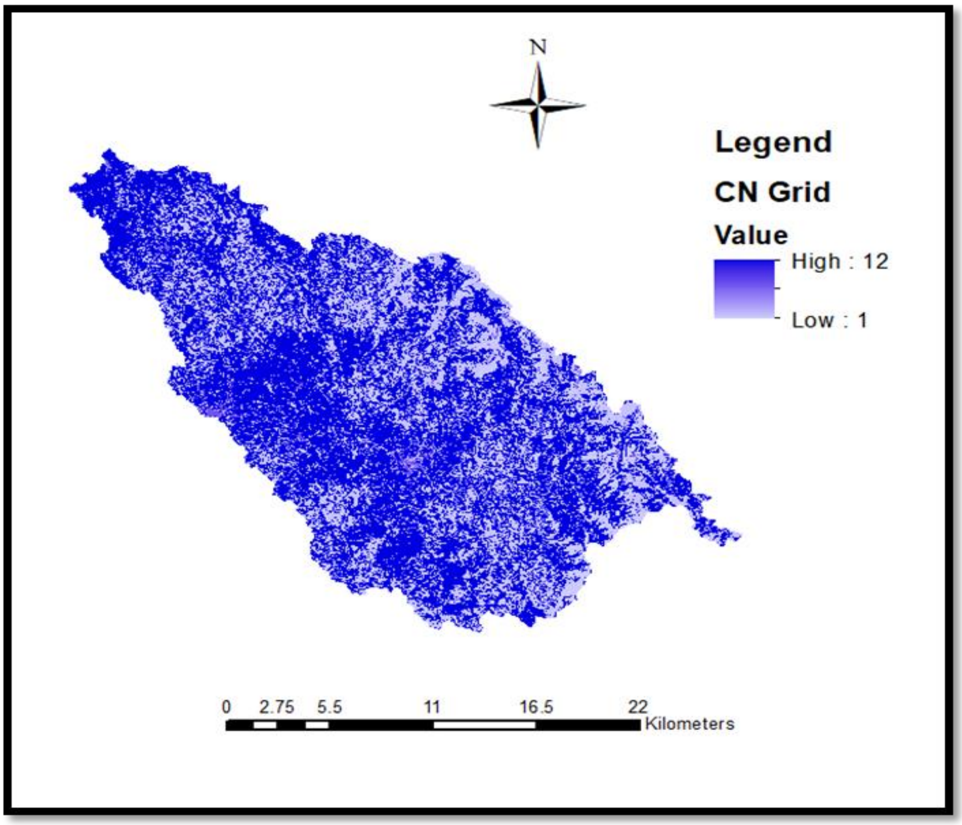


Fig. 4.21 CN grid map of the Meenachil sub basin

4.7 BASIN MODEL IN HEC-HMS

Hydrological elements, their connectivity and related geographical details are included in the basin model that can be loaded into a HEC-HMS project. It represents the physical watershed of Meenachil sub basin and it was embodied as displayed in Fig. 4.22. The drainage area of sub basins are presented in the Table 4.12.

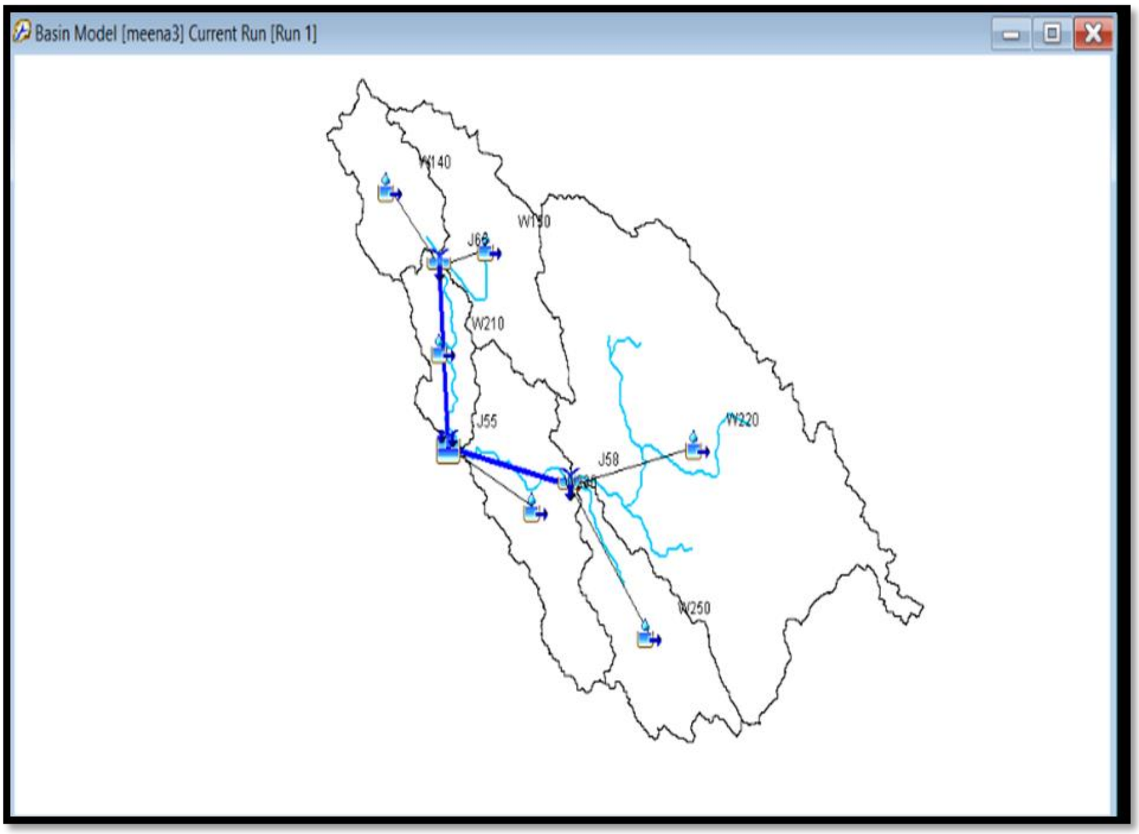


Fig. 4.22 Basin model of Meenachil sub basin in HEC-HMS

Table 4.12 Sub basins with their drainage area

Sl. no.	Sub- basin	Drainage area (Km^2)
1	W220	229.561
2	W250	46.9772
3	W150	54.034
4	W140	31.4502
5	W230	58.7254
6	W210	23.3660
Total		**444.11**

4.8 OPTIMIZATION OF MODEL 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 optimisation 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.

Using the optimised parameters, there was a desired increase in the NSE values as shown in the Table 4.13 which indicated the better accuracy of the model for the simulation of rainfall-runoff for the sub basin.

Table 4.13 NSE values before and after optimisation

Year	N.S.E value	
	Before optimisation	**After optimisation**
2013	0.512	0.725
2014	0.543	0.751
2015	0.575	0.708
2016	0.804	0.868

The initial and optimized parameter values for different sub-watershed W230, W220, W210, W150, W250 and W140 of Meenachil River are shown in Table 4.14, where 'I' represents the initial parameter and 'O' represents the optimised parameter.

Table 4.14 Initial and optimised parameter values for different sub-watersheds

S.No	Parameter	Sub-Watershed											
		W230		W220		W210		W150		W250		W140	
		I	O	I	O	I	O	I	O	I	O	I	O
1	CN	75.88	79.93	61.46	65.73	68.93	66.28	69.98	64.84	71.46	74.10	78.70	71.46
2	I_a (mm)	16.00	16.15	11.86	31.87	12.89	22.89	11.70	21.79	10.29	20.29	13.75	13.75
3	LT (min)	1636.3	564.4	4456.2	3678.6	1446.5	1625.9	1832.8	1544.7	2964.3	307.8	1963.3	208.27
4	CN scale factor	0.24		0.24		0.24		0.24		0.24		0.24	
5	I_a scale factor (mm)	1.03		1.03		1.03		1.03		1.03		1.03	
6	Muskingum k (hr)	0.37		0.37		0.37		0.37		0.37		0.37	
7	Muskingum x	0.29		0.29		0.29		0.29		0.29		0.29	

4.9 CALIBRATION OF HEC-HMS MODEL

The applicability of a hydrological model depends on model parameters, quality of data and technical capability of model. Hence, calibration of a model is very important. Hydro-meteorological data sets were used for calibration. The rainfall data collected from three rain gauge stations namely Kidangoor, Kozha and Erattupetta Stations were used for calibration. The weighted rainfall was calculated using Thiessen polygon method. The Meenachil watershed was modelled by dividing it into 6 sub basins: W230, W220, W210, W150, W250, W140, W700 and W800. Four years (2013-2016) discharge and rainfall data were taken for calibration of the model and the results were presented as hydrograph for the selected events. The simulated hydrograph was compared with the historically observed hydrograph at outlet of the watershed to determine the accuracy of modelled hydrograph.

4.9.1 Results of calibration

Daily rainfall and other hydro-meteorological data, from 2013 to 2016 were selected for calibration. The calculated initial parameters, as shown in Table 4.14, 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. It was found that there was a definite variance between observed and simulated value in all sub basin, when simulated discharge value was compared with observed discharge value. In order to get satisfactory result, the initial parameters were optimized with the help of automatic optimization tool provided in the model. Using optimized parameters (Table 4.14), model was again calibrated to secure peak discharge, total volume and time to peak. It was witnessed that the optimized value gave close value hydrograph with that of the observed one. Hence, optimized values of parameters were used for model calibration and accurate simulation.

Figs. 4.23-4.26 represent 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.

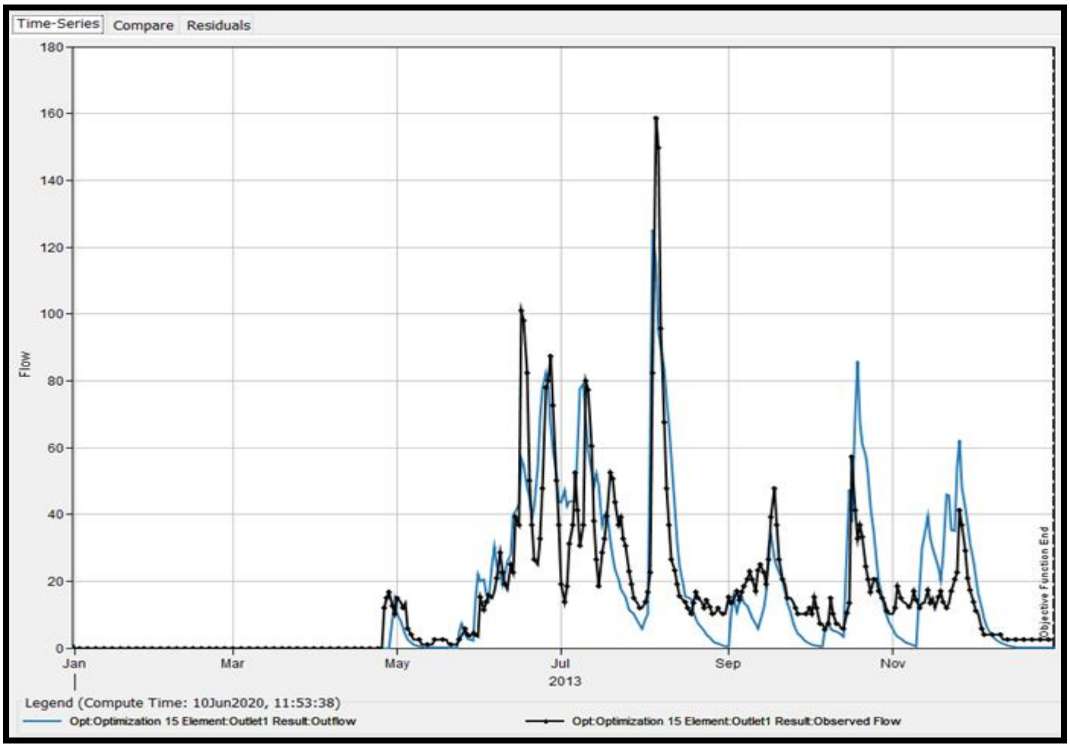


Fig. 4.23 Simulated and observed hydrograph for the year 2013

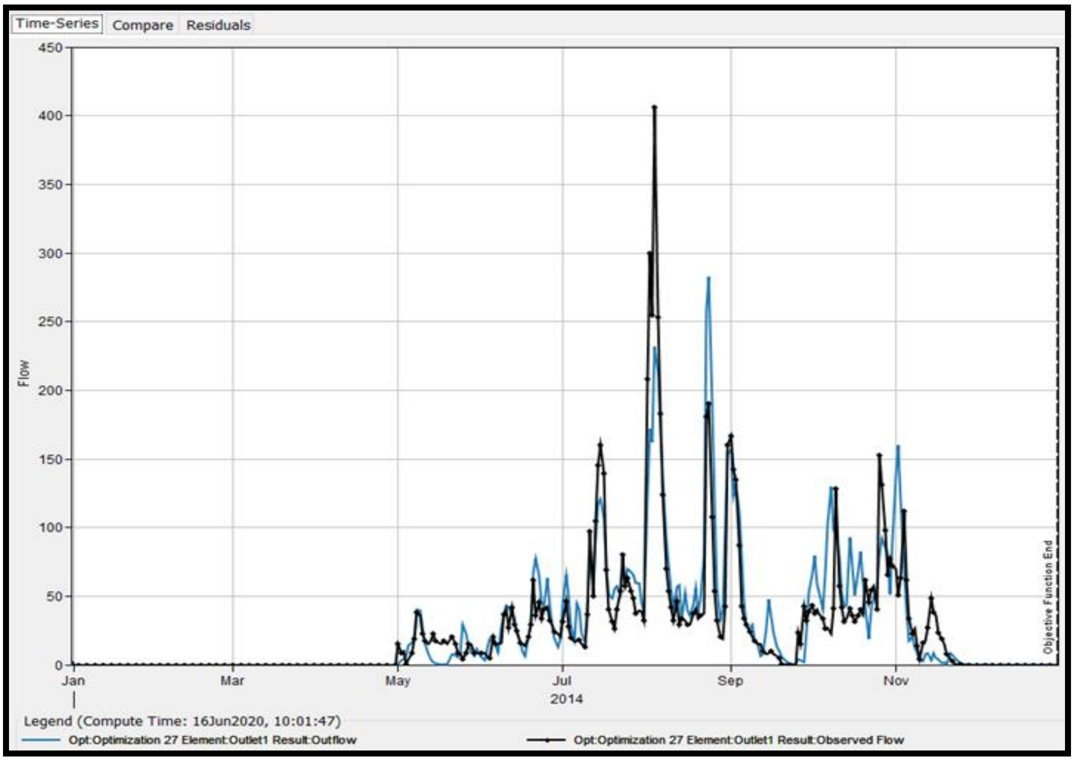


Fig. 4.24 Simulated and observed hydrograph for the year 2014

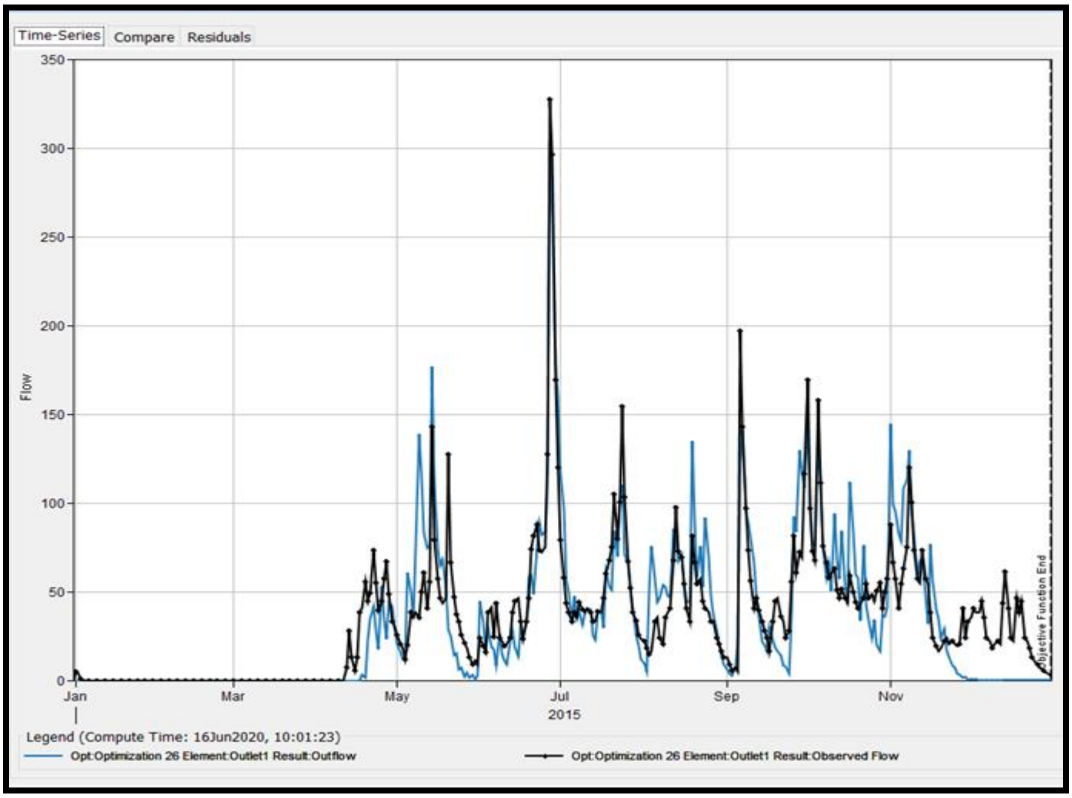


Fig. 4.25 Simulated and observed hydrograph for the year 2015

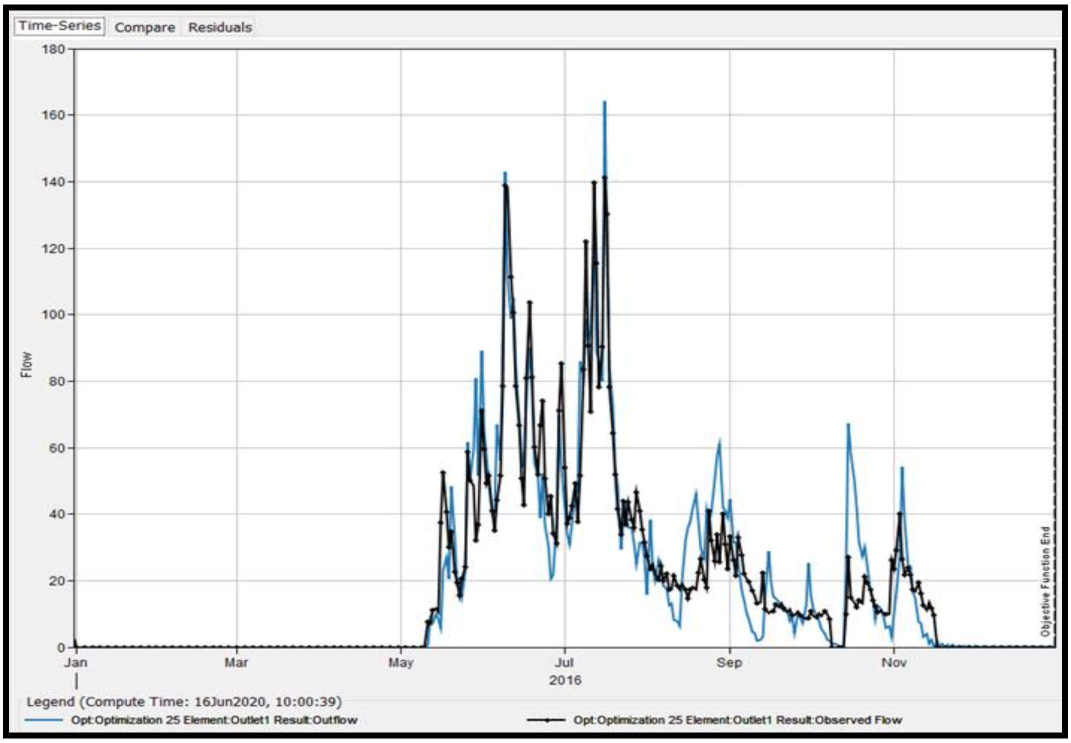


Fig. 4.26 Simulated and observed hydrograph for the year 2016

Referring to above hydrographs, it was visible that during summer season, only base flow might have been contributed to the discharge at outlet when there was no or least precipitation occurrence over the watershed. But in monsoon season, the maximum precipitation that fell over the watershed created high discharge at the outlet, which caused the situation of flood in the catchment. The maximum peak discharge was befallen in the year 2014 during the calibration period with a peak flow of 406.2 m^3/s. At some points in graphs it was also visible that the peak of the hydrographs of calibrated one was not matching with the peak of observed hydrographs. This might be due to the fact that watershed physical parameters are not appropriate with watershed characteristics due to the changes in physical parameters alteration from time to time and point to point in the drainage area.

In addition, initial loss, imperviousness and curve number of the sub basin areas may also create some effect on the runoff in the watershed. Areas with more imperviousness lead to reduced infiltration and thereby surface runoff was increased in some part of the catchment. This made an effect in volume of discharge, peak discharge and time of attaining peak discharge. Increased imperviousness and curve number influenced the time of peak which eventually resulted in rise in peak discharge and volume. That is, imperviousness of the basin showed high correlation with changes in hydrological indicators, time to peak, peak discharge and volume. In addition to these factors, the soil property of the catchment was highly clay mineral distributive; hence, larger volume of storm water drains into the streams quickly. However, the initial losses including interception loss and surface depressions reduced the surface runoff at some stages of flow because of more resistance caused in flow path and the availability of more opportunity time for initial loss.

Scatter plot of observed and simulated flow (Fig. 4.27) for different time period showed that the respective R^2 values were also in the acceptable range (i.e. greater than 0.7).The RSR (Root mean square error-standard deviation ratio) values less than 0.5 revealed that the estimation has good performance rating. Moreover, Nash Sutcliffe Efficiency (NSE) value for calibration period was obtained in the range of 0.74-0.87, which was also found satisfactory.

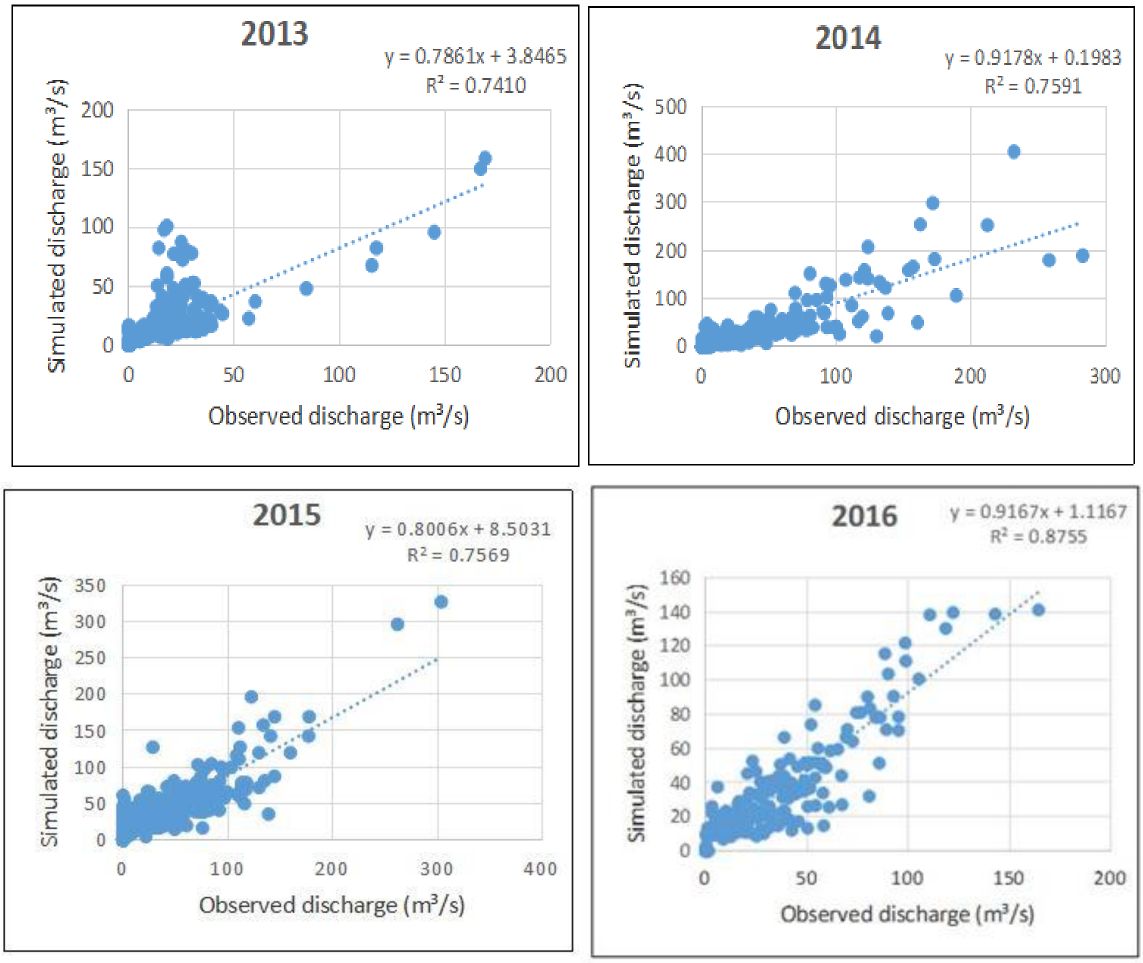


Fig. 4.27 Scatter plot of observed vs simulated flow during calibration

Evaluation of the calibrated model in terms of various measures like Nash Sutcliffe efficiency, error in peak flow, error in volume and coefficient of determination were determined and it is presented in Table 4.15.

Table 4.15 Performance indices of the model during calibration

S.N.	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)
1	2013	0.725	6.50	-7.12	0.7410	0.5
2	2014	0.751	-30.4	8.14	0.7591	0.5
3	2015	0.708	-7.30	-5.56	0.7569	0.5
4	2016	0.868	16.40	2.21	0.8755	0.4

Error in peak flow (%) indicated that results are close to observed flood peak within accessible limit of 20%. It was found that maximum peak discharge occurred between June and August months. The total volume discharge from watershed after deducting all losses showed that calibrated discharge volume was close to the observed discharge volume (limited to 20% of total volume) which was also found valid in further continuous calibration. These results were in acceptable range according to Najim *et al.* (2006) and Sabzevari *et al.* (2009) who mentioned that the relative percent errors between the observed and simulated values should be below ±20 percent. The study by Cheng *et al.* (2002) also suggested that the runoff model is only considered good if the runoff volume percent error is less than 20 percent. The positive values of percent error indicated model underestimation bias while the negative values indicated model overestimation bias as per the statistical evaluation criterion.

Overall results of the simulation were depicted as objective function and summary results table which shows a comparison between observed and computed flow. These are shown in Figs. 4.28- 4.31. Objective function is used to compute model performance by comparing the percent difference of simulated and observed flow. “Algorithms included in the program search for the model parameters that yield the best value of an index, also known as objective function” (USACE, 2000). Objective function result helped in figuring out the Error in Peak Flow (%) and Error in Volume (%). Error in Peak Flow (%) was low in the simulation carried out during the year 2013 which was only 6.5 percent and the highest percent error of 30.4 percent was observed in the year 2014. On the other hand, Error in Volume was the lowest (2.21%) in the year 2016, and it was still higher (8.14%) for the year 2014. During calibration period (2013-2016), the highest volume of flow of 1040.642 Mm^3 as simulated and 1101.858 Mm^3 as observed was seen in the year 2015. Similarly, lowest volume of flow of 418.394 Mm^3 as simulated and 450.455 Mm^3 as observed was seen in the year 2013. The summary result illustrated model performance in terms of indices like RMSE standard deviation, NSE and percent bias by associating the simulated and observed flow of the watershed.

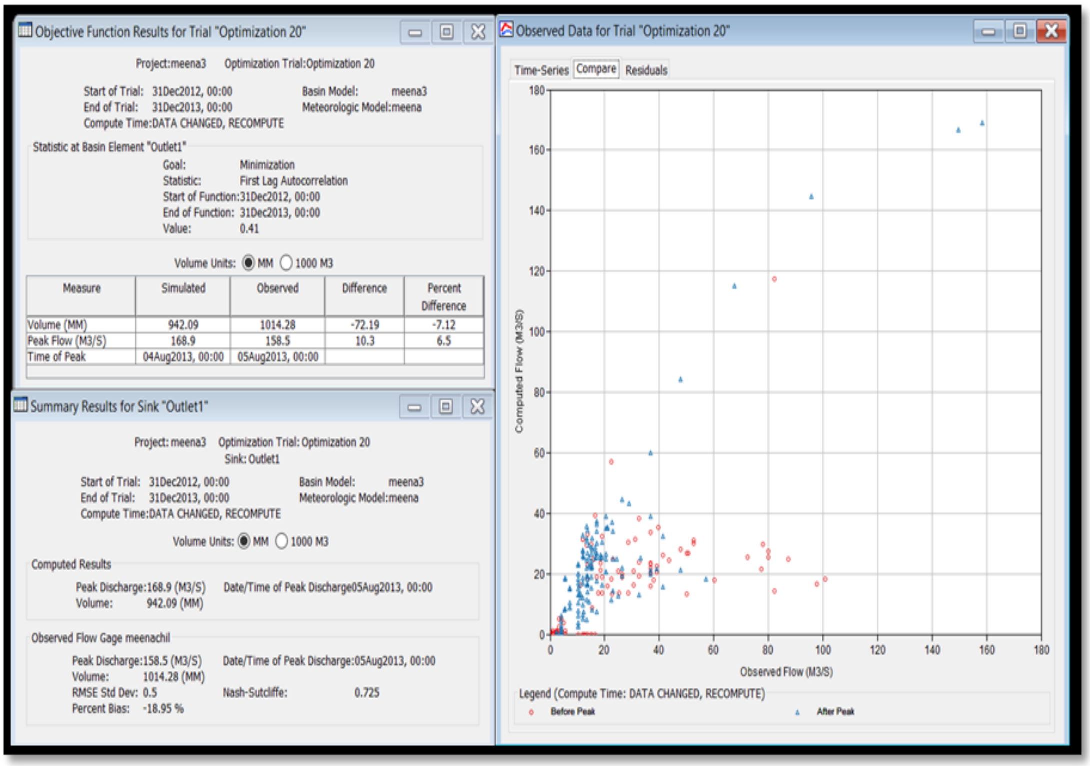


Fig. 4.28 Objective function and summary result for the year 2013

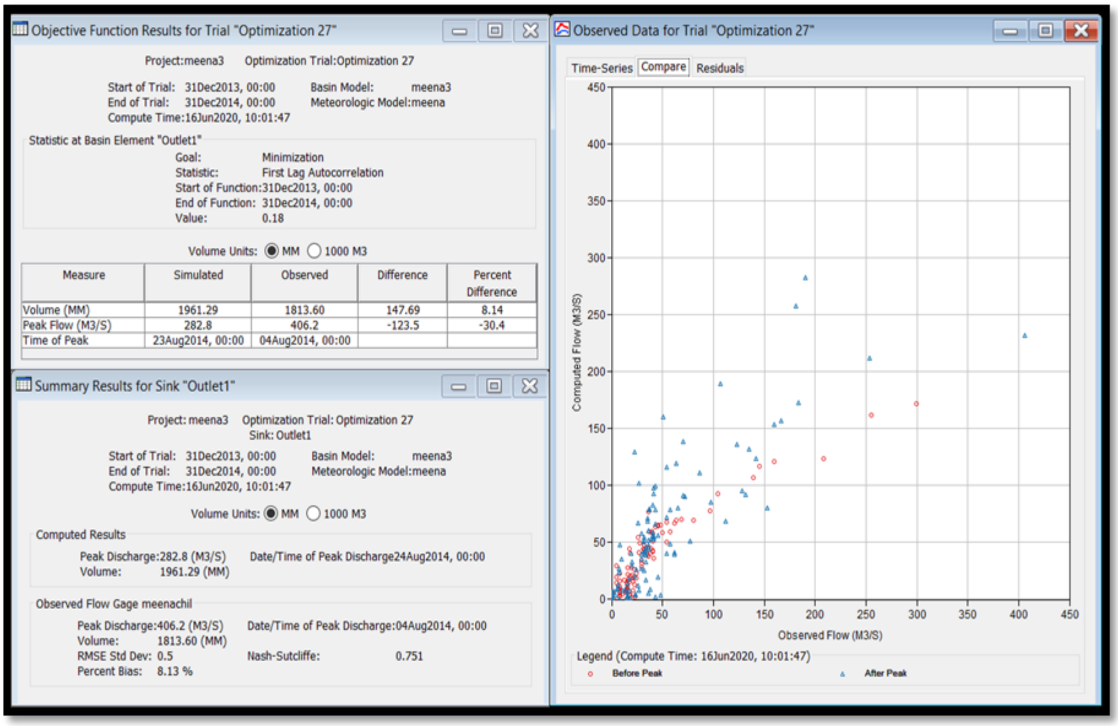


Fig. 4.29 Objective function and summary result for the year 2014

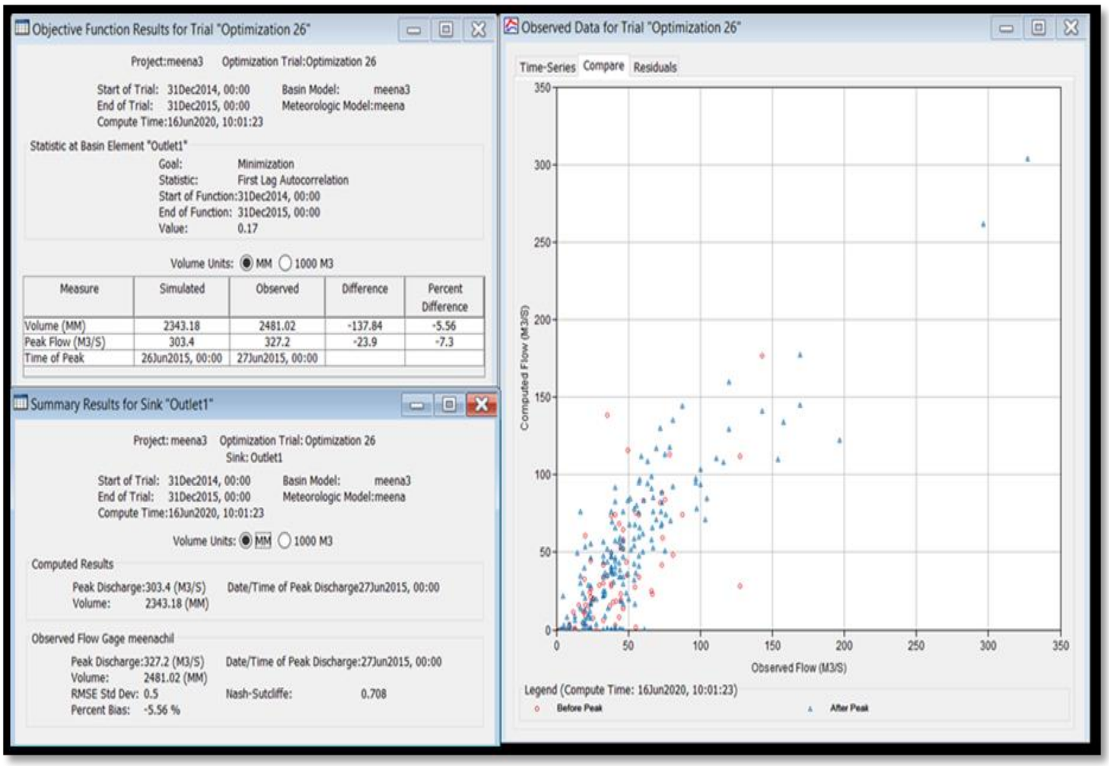


Fig. 4.30 Objective function and summary result for the year 2015

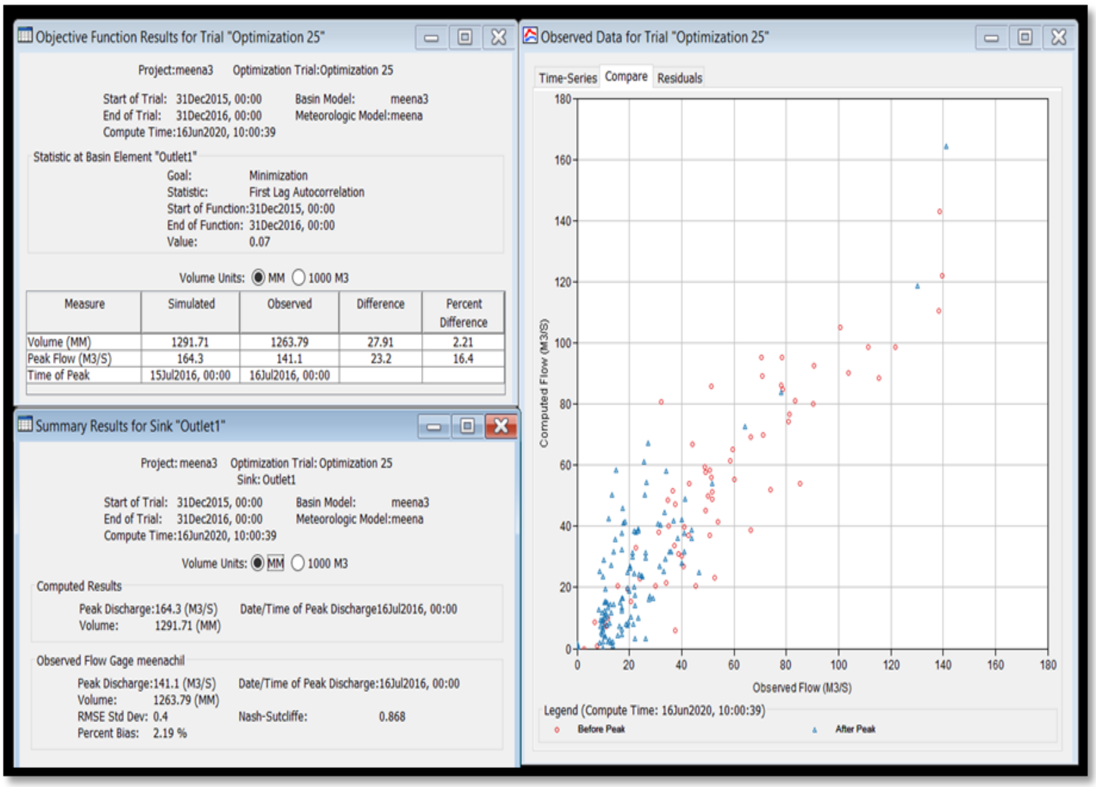


Fig. 4.31 Objective function and summary result for the year 2016

Global summary results of the watershed modelling in calibration period are shown in Fig. 4.32- 4.35. Global summary results, gave the results for each element of watershed namely individual sub basins, reach, junction etc. which were present in the model. For each hydrologic element and its final outlet, their respective area, peak discharge, time of peak and volume of stream flow was depicted clearly in the global summary. This could help in effective management of sub basin in region wise.

Global Summary Results for Run "Run 43"

Project: meena3 Simulation Run: Run 43

Start of Run: 31Dec2012, 00:00
End of Run: 31Dec2013, 00:00
Compute Time: DATA CHANGED, RECOMPUTE

Basin Model: meena3
Meteorologic Model: meena
Control Specifications: run1_control

Show Elements: All Elements Volume Units: MM 1000 M3 Sorting: Hydrologic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
W220	229.56100	83.8	07Aug2013, 00:00	858.91
J58	276.53820	101.9	06Aug2013, 00:00	868.54
W250	46.97720	22.0	06Aug2013, 00:00	915.63
R90	276.53820	101.8	06Aug2013, 00:00	868.56
J65	85.48510	50.1	05Aug2013, 00:00	923.44
W150	54.03490	31.7	05Aug2013, 00:00	908.01
W140	31.45020	18.4	05Aug2013, 00:00	949.95
R60	85.48510	50.2	05Aug2013, 00:00	923.66
W230	58.72540	35.6	05Aug2013, 00:00	937.19
J55	420.74870	164.4	05Aug2013, 00:00	889.33
R50	420.74870	164.1	05Aug2013, 00:00	889.33
W210	23.36609	13.9	05Aug2013, 00:00	902.45
Outlet1	444.11479	178.0	04Aug2013, 00:00	890.02

Fig. 4.32 Global summary result of all the watershed elements for the year 2013

Global Summary Results for Run "Run 27"

Project: meena3 Simulation Run: Run 27

Start of Run: 31Dec2013, 00:00
End of Run: 31Dec2014, 00:00
Compute Time: DATA CHANGED, RECOMPUTE

Basin Model: meena3
Meteorologic Model: meena
Control Specifications: run1_control

Show Elements: All Elements Volume Units: MM 1000 M3 Sorting: Hydrologic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
W220	229.56100	124.1	06Aug2014, 00:00	2587.84
J58	276.53820	152.3	25Aug2014, 00:00	2598.75
W250	46.97720	32.5	25Aug2014, 00:00	2652.09
R90	276.53820	152.1	25Aug2014, 00:00	2598.76
J65	85.48510	76.7	24Aug2014, 00:00	2660.48
W150	54.03490	49.0	24Aug2014, 00:00	2643.65
W140	31.45020	27.7	24Aug2014, 00:00	2689.39
R60	85.48510	76.7	24Aug2014, 00:00	2660.56
W230	58.72540	54.6	24Aug2014, 00:00	2675.66
J55	420.74870	245.0	24Aug2014, 00:00	2622.05
R50	420.74870	244.4	24Aug2014, 00:00	2622.05
W210	23.36609	21.9	24Aug2014, 00:00	2637.45
Outlet1	444.11479	266.3	23Aug2014, 00:00	2622.86

Fig. 4.33 Global summary result of all the watershed elements for the year 2014

Global Summary Results for Run "Run 17"

Project: meena3 Simulation Run: Run 17

Start of Run: 31Dec2014, 00:00 Basin Model: meena3
End of Run: 31Dec2015, 00:00 Meteorologic Model: meena
Compute Time: DATA CHANGED, RECOMPUTE Control Specifications: run1_control

Show Elements: All Elements Volume Units: ◉ MM ○ 1000 M3 Sorting: Hydrologic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
W220	229.56100	80.5	29Jun2015, 00:00	2622.27
J58	276.53820	99.8	29Jun2015, 00:00	2633.24
W250	46.97720	19.3	29Jun2015, 00:00	2686.81
R90	276.53820	99.8	29Jun2015, 00:00	2633.23
J65	85.48510	41.7	07Sep2015, 00:00	2695.42
W150	54.03490	26.8	07Sep2015, 00:00	2678.60
W140	31.45020	15.0	28Jun2015, 00:00	2724.33
R60	85.48510	41.6	07Sep2015, 00:00	2695.48
W230	58.72540	30.6	07Sep2015, 00:00	2710.66
J55	420.74870	157.5	28Jun2015, 00:00	2656.69
R50	420.74870	157.2	28Jun2015, 00:00	2656.68
W210	23.36609	12.6	07Sep2015, 00:00	2672.47
Outlet1	444.11479	168.8	27Jun2015, 00:00	2657.51

Fig. 4.34 Global summary result of all the watershed elements for the year 2015

Global Summary Results for Run "Run 18"

Project: meena3 Simulation Run: Run 18

Start of Run: 31Dec2015, 00:00 Basin Model: meena3
End of Run: 31Dec2016, 00:00 Meteorologic Model: meena
Compute Time: DATA CHANGED, RECOMPUTE Control Specifications: run1_control

Show Elements: All Elements Volume Units: ◉ MM ○ 1000 M3 Sorting: Hydrologic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
W220	229.56100	71.2	11Jun2016, 00:00	1365.44
J58	276.53820	87.8	11Jun2016, 00:00	1375.72
W250	46.97720	18.0	10Jun2016, 00:00	1425.98
R90	276.53820	87.8	11Jun2016, 00:00	1375.77
J65	85.48510	36.7	10Jun2016, 00:00	1434.09
W150	54.03490	22.9	09Jun2016, 00:00	1417.94
W140	31.45020	13.7	10Jun2016, 00:00	1461.83
R60	85.48510	36.9	10Jun2016, 00:00	1434.56
W230	58.72540	27.1	09Jun2016, 00:00	1448.57
J55	420.74870	142.3	10Jun2016, 00:00	1397.88
R50	420.74870	142.5	10Jun2016, 00:00	1397.88
W210	23.36609	11.2	09Jun2016, 00:00	1412.05
Outlet1	444.11479	151.9	09Jun2016, 00:00	1398.62

Fig. 4.35 Global summary result of all the watershed elements for the year 2016

4.10 Validation

Model validation is the method of checking the ability of the model to replicate observed data with reasonable precision using events other than those used for calibration. All through this procedure, calibrated model parameters were not subjected to changes, instead the values were kept constant. The grade of variation between computed and observed hydrograph was checked in this process too, as in calibration. The discharge data and 24 hr rainfall data of the year 2017-2018 was used for validation purposes. Based on the calibrated parameters, model output for the validation period was computed.

The graphical comparison of simulated and observed hydrograph during the validation period at the outlet is presented in Fig. 4.36 and Fig. 4.37. There appeared a similarity in the trend of simulated and observed hydrograph for relatively longer duration of storms. It was also found that simulated values were near to observed value. 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 basin that was not been denoted by the gauge record at that particular time.

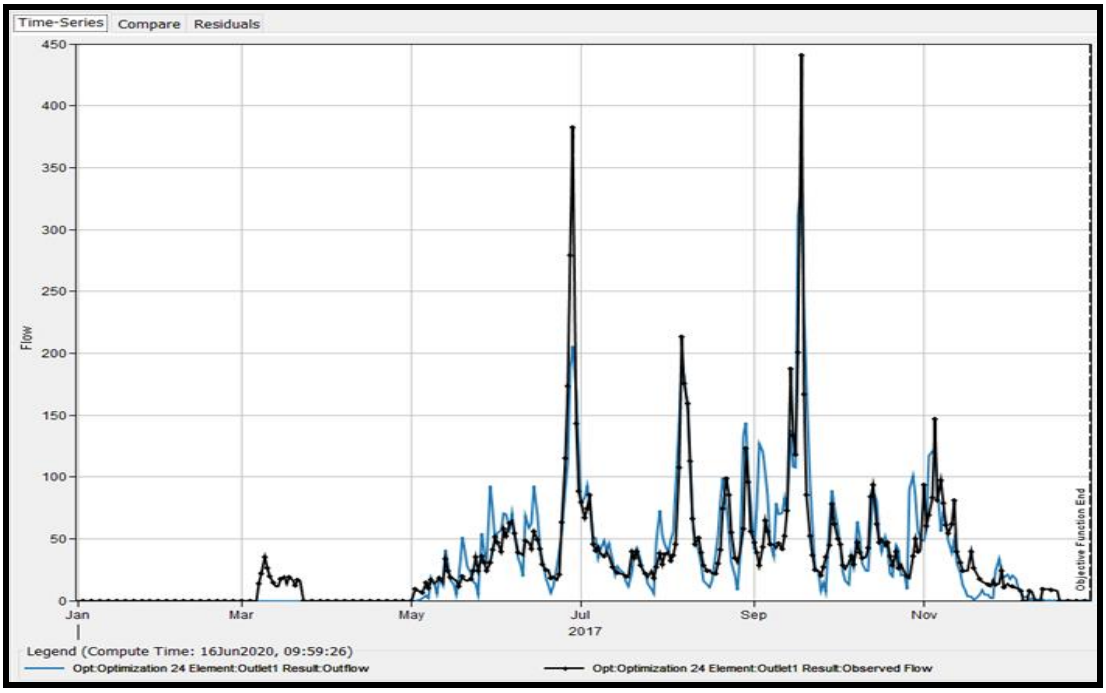


Fig. 4.36 Simulated and observed hydrograph for the year 2017

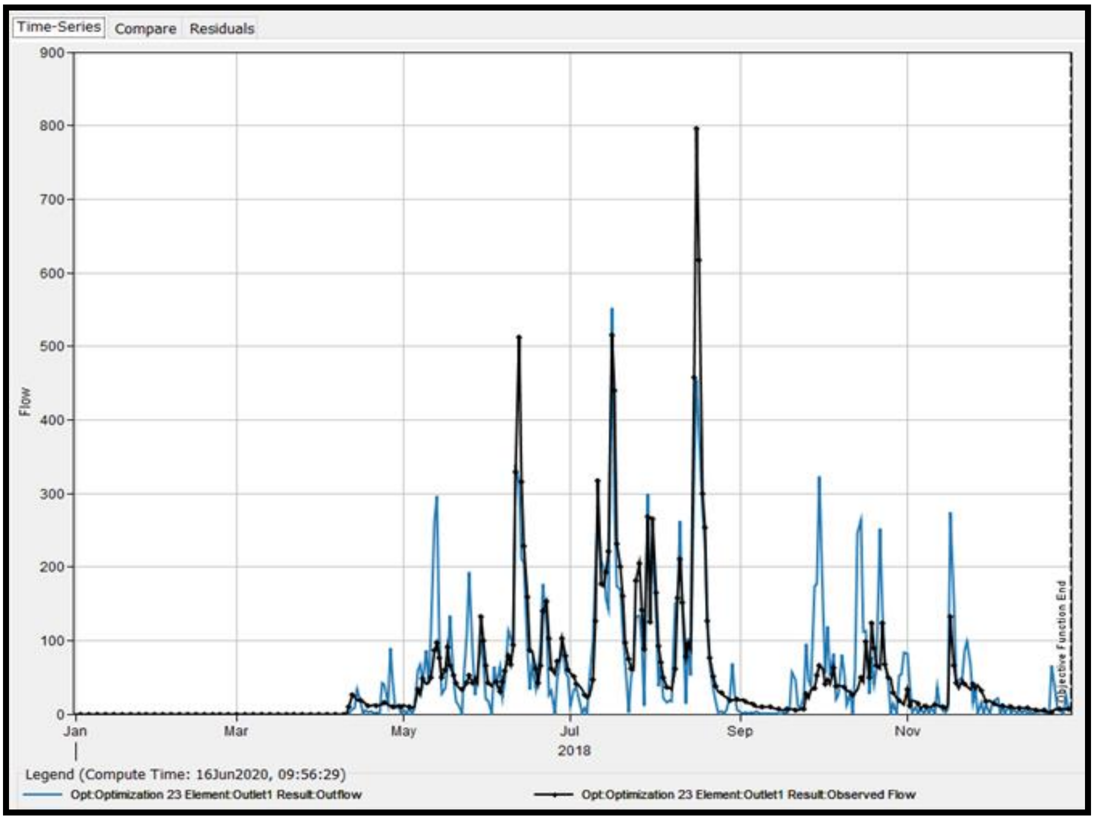


Fig. 4.37 Simulated and observed hydrograph for the year 2018

The value of coefficient of correlation (R^2) was found greater than 0.7 in all the validation years as shown in Fig. 4.38 which indicated the satisfactory performance of the model.

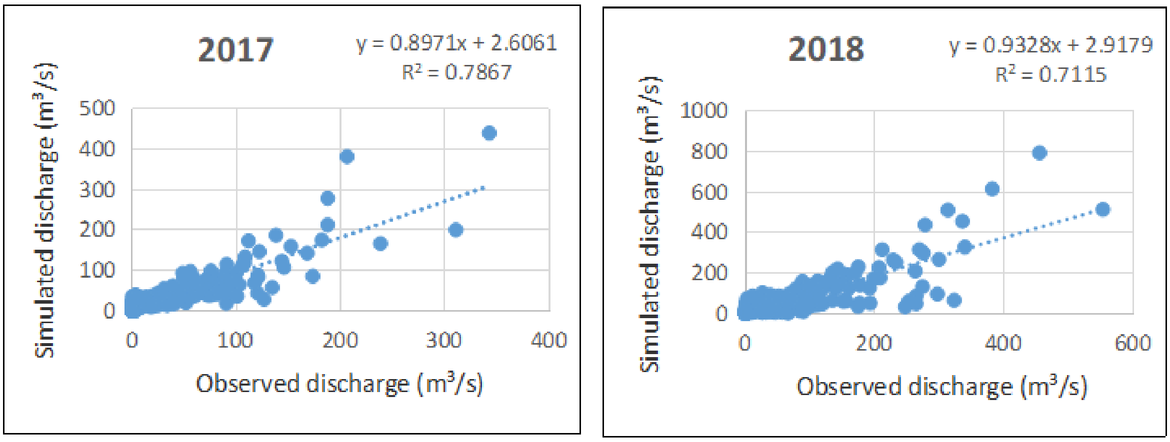


Fig. 4.38 Scatter plot of observed vs simulated flow during validation

The model performance during validation estimated in terms of various efficiencies like NSE, error in peak flow, error in volume and coefficient of correlation are displayed in Table 4.16.

Table 4.16 Performance indices of the model during validation

S.N.	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)
1	2017	0.776	12.3	2.10	0.7867	0.5
2	2018	0.708	-20	0.51	0.7115	0.5

Percentage error in peak flow is small and close to observed flood peak within accessible limit 20% that was clearly revealed in the results. The maximum peak discharge occurred between July and September in validation period. The maximum peak discharge occurred in the validation period was about 795.3 m^3/s. For estimating the volumetric error, the total volume 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 acquired in the range of 0.71-0.79 which was also satisfactory.

Objective function, used to compute model performance by comparing the simulated and observed flow is displayed in Fig. 4.39- 4.40 for the validation period. Error in Peak Flow (%) was lower in simulation carried out for 2017 year which was only 12.3 and highest percent error was observed as -20 in the year 2018. On the other hand, Error in Volume (%) was lower in the year 2018, i.e. 0.51 and higher for 2017 year which was 2.10 %. During the validation period (2017-2018), the highest volume of flow of 1482.385 Mm^3 as simulated and 1474.842 Mm^3 as observed was seen in the year 2018. Similarly, lowest volume of flow of 1001.895 Mm^3 as simulated and 981.299 Mm^3 as observed was seen in the year 2017.

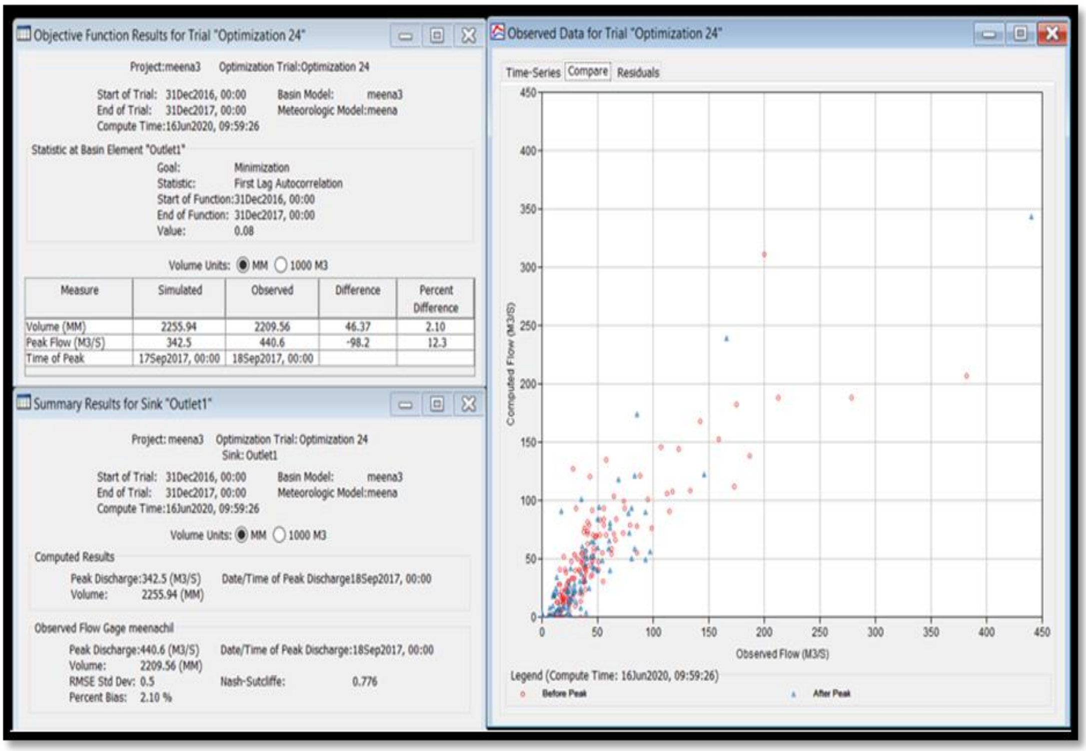


Fig. 4.39 Objective function and summary result for the year 2017

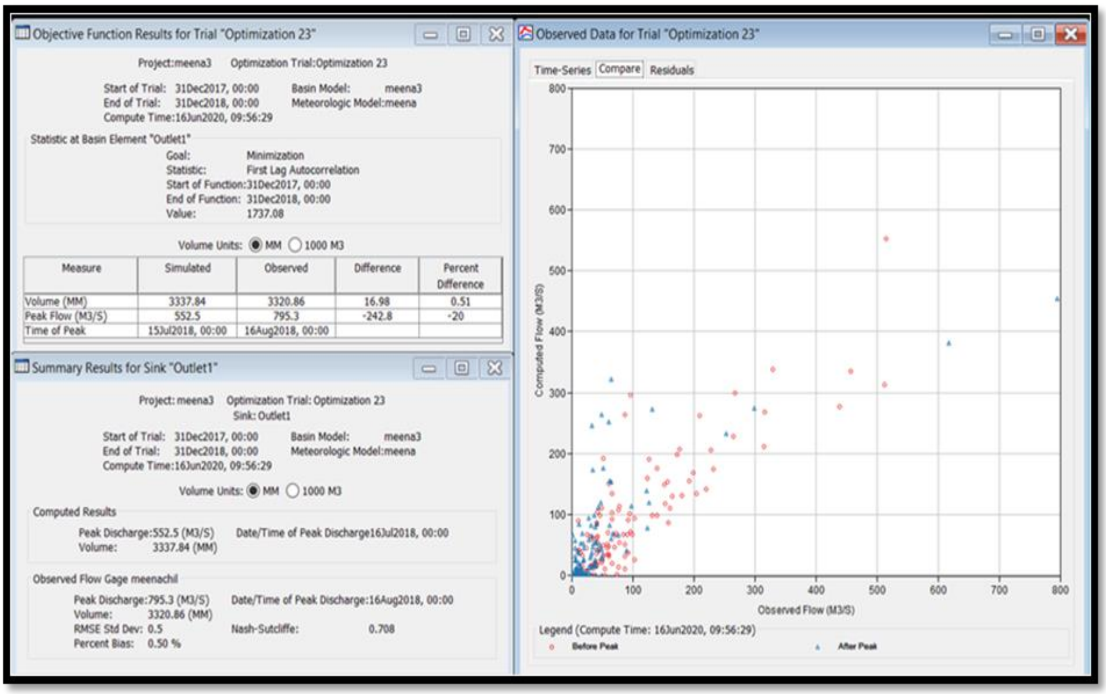


Fig. 4.40 Objective function and summary result for the year 2018

The global summary results of the watershed in validation period are displayed in Fig. 4.41 and Fig. 4.42.

Global Summary Results for Run "Run 29"

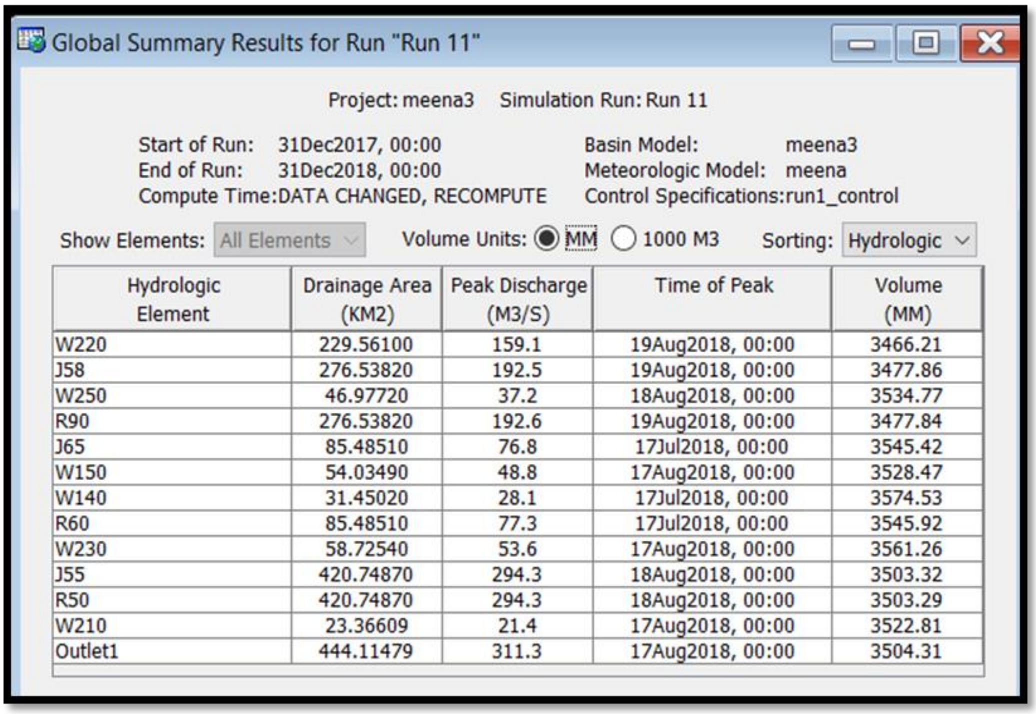
Project: meena3 Simulation Run: Run 29

Start of Run: 31Dec2016, 00:00
End of Run: 31Dec2017, 00:00
Compute Time:DATA CHANGED, RECOMPUTE
Basin Model: meena3
Meteorologic Model: meena
Control Specifications:run1_control

Show Elements: All Elements Volume Units: MM 1000 M3 Sorting: Hydrologic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
W220	229.56100	88.0	30Jun2017, 00:00	2129.64
J58	276.53820	108.0	29Jun2017, 00:00	2140.39
W250	46.97720	22.1	29Jun2017, 00:00	2192.94
R90	276.53820	107.8	29Jun2017, 00:00	2140.41
J65	85.48510	47.0	28Jun2017, 00:00	2201.25
W150	54.03490	29.8	28Jun2017, 00:00	2184.60
W140	31.45020	17.2	28Jun2017, 00:00	2229.87
R60	85.48510	47.0	28Jun2017, 00:00	2201.61
W230	58.72540	33.4	28Jun2017, 00:00	2216.25
J55	420.74870	171.3	29Jun2017, 00:00	2163.43
R50	420.74870	171.7	29Jun2017, 00:00	2163.43
W210	23.36609	13.3	28Jun2017, 00:00	2178.48
Outlet1	444.11479	182.6	27Jun2017, 00:00	2164.22

Fig. 4.41 Global summary result of all the watershed elements for the year 2017



Global Summary Results for Run "Run 11"

Project: meena3 Simulation Run: Run 11

Start of Run: 31Dec2017, 00:00 Basin Model: meena3
End of Run: 31Dec2018, 00:00 Meteorologic Model: meena
Compute Time: DATA CHANGED, RECOMPUTE Control Specifications: run1_control

Show Elements: All Elements Volume Units: MM 1000 M3 Sorting: Hydrologic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
W220	229.56100	159.1	19Aug2018, 00:00	3466.21
J58	276.53820	192.5	19Aug2018, 00:00	3477.86
W250	46.97720	37.2	18Aug2018, 00:00	3534.77
R90	276.53820	192.6	19Aug2018, 00:00	3477.84
J65	85.48510	76.8	17Jul2018, 00:00	3545.42
W150	54.03490	48.8	17Aug2018, 00:00	3528.47
W140	31.45020	28.1	17Jul2018, 00:00	3574.53
R60	85.48510	77.3	17Jul2018, 00:00	3545.92
W230	58.72540	53.6	17Aug2018, 00:00	3561.26
J55	420.74870	294.3	18Aug2018, 00:00	3503.32
R50	420.74870	294.3	18Aug2018, 00:00	3503.29
W210	23.36609	21.4	17Aug2018, 00:00	3522.81
Outlet1	444.11479	311.3	17Aug2018, 00:00	3504.31

Fig. 4.42 Global summary result of all the watershed elements for the year 2018

4.11 COMPARISON OF OBSERVED AND SIMULATED MEASURES OF FLOW FOR THE SUB BASIN

Comparison of different measures of flow such as observed and simulated peak flow, volume and time of peak for Meenachil sub basin is shown in the Table 4.17. During the entire period of simulation (2013-2018), the highest volume of flow was seen in the year 2018 with 1482.385 Mm^3 as simulated one and 1474.842 Mm^3 as observed one which were the values corresponding to 2018 Kerala flood. Similarly, lowest volume of flow was seen in the year 2013 with 418.394 Million m^3 as simulated and 450.455 Million m^3 as observed.

The highest peak flow of river was found during the year 2018 and it was predicted as 552.5 m^3/s and observed as 795.3 m^3/s. It was the rare flood peak event of 2018 Kerala flood. The lowest peak flow of river was found during the year 2013 and it was predicted as 168.9 m^3/s and observed as 158.5 m^3/s. Overall, it was found that all observed and simulated values of all the measures shown in the table depicted good relation between them. This similarity of trend inferred the better accuracy of the model for simulating the stream flow in Meenachil sub basin.

Table 4.17 Comparison of observed and simulated measures for the sub basin

Measure	Simulated	Observed	Year	Time of peak
Peak flow (m^3/sec)	168.9	158.5	2013	5 Aug 2013
Volume (M m^3)	418.3944	450.4555		
Peak flow (m^3/sec)	382.8	406.2	2014	24 Aug 2014
Volume (M m^3)	871.0372	805.4446		
Peak flow (m^3/sec)	303.4	327.2	2015	27 Jun 2015
Volume (M m^3)	1040.6423	1101.8583		
Peak flow (m^3/sec)	164.3	141.1	2016	16 Jul 2016
Volume (M m^3)	573.6673	561.2699		
Peak flow (m^3/sec)	342.5	440.6	2017	18 Sep 2017
Volume (M m^3)	1001.8950	981.2999		
Peak flow (m^3/sec)	552.5	795.3	2018	16 Aug 2018
Volume (M m^3)	1482.3850	1474.8428		

SUMMARY AND CONCLUSIONS

CHAPTER V

SUMMARY AND CONCLUSIONS

A watershed situated at the upstream of the Meenachil river basin was selected for flood frequency analysis and flood modelling studies in this research. The study area lies between 9°38'56.89''N and 9°49'50.64''N latitude, and 76°36'57.57''E and 76°56'17.99''E longitude. The watershed enfolds an area of 444.12 Km^2 which is roughly 35% of the entire area of Meenachil river basin. It is an area liable to flood and principally dominated by agricultural land. The area comes under the tropical humid zone, where water resources planning and management is necessary for irrigation scheduling, flood control and design of several engineering structures. In view of the importance of water management in this humid region, it is necessary to understand the rainfall-runoff relationship of watershed along with its land characteristics. The HEC-HMS model which is a widely used rainfall-runoff modelling was chosen for the simulation of watershed responses and generation of flood hydrographs in this study. The simulated runoff is useful for well-planned programmes in water conservation resource management projects and future prediction of runoff for flood mitigation strategies in the catchment. Meenachil River is highly hazardous and wild during flood season as a result of depth of the river and illegal sand mining in it. This river contributed vigorously to 2018 Kerala flood and major causality in the human history. Hence to address the above issues, an attempt was made to conduct flood frequency analysis for predicting the magnitude of flood for different return periods and to calibrate and validate HEC-HMS model for simulating the flood hydrograph for the sub basin of Meenachil river.

The geo-spatial analysis of the catchment is carried out using the capabilities of remote sensing and GIS. Later, conceptual hydrological HEC-HMS model was developed to transform precipitation into runoff for the selected rainfall events. The parameters related to initial loss, hydrographs and channel routing were calibrated and validated using the observed stream flow data of the watershed. Simplex method of optimisation assisted to find the optimised parameter for better simulation values. The influence of different land use/ land cover on runoff generation was also considered for the study. Effectiveness of rainfall- runoff modelling was assessed using different statistical performance measures. Capabilities of HEC-HMS model using SCS-UH, SCS-CN, Muskingum were applied to find out the loss rate, runoff transformation and routing of flood in the watershed. In addition, flood frequency analysis was carried out for annual maximum discharge data using Log-Pearson type III distribution and Gumbel distribution, to estimate the expected probable flow and its percent chance exceedance. The following conclusions were drawn from the study:

- The expected probable discharge showed by Log – Pearson type III distribution were 484.438 m^3/s, 592.788 m^3/s, 856.776 m^3/s, 984.601 m^3/s and 1382.963 m^3/s for the return periods 5, 10, 50, 100, 500 year respectively, while the discharge showed by Gumbel distribution were 478.069 m^3/s, 580.211 m^3/s, 811.254 m^3/s, 912.093 m^3/s, 1152.144 m^3/s respectively for the same return periods.

- Test statistic values of Chi-Square and Kolmogorov-Smirnov test were found 0.087 and 2.706 for Gumbel distribution and 0.094 and 3.412 for Log-Pearson type III distribution respectively, which indicated the best fit of both distributions for the sub basin.

- Flood frequency analysis clearly indicated the good capability of the Gumbel and Log-Pearson Type III distribution function to predict flood magnitudes of the river flow in sub basin of Meenachil.

- HEC-HMS model was developed for the sub basin in which curve number, initial abstraction and lag time were found to be the most sensitive parameters of model simulation.

- The loss rate parameters viz. curve number and initial abstraction were calibrated using SCS curve number model and the optimised values were obtained in the range between 61.46-79.93 mm and 10.29-31.87 mm respectively for the sub-watershed.

- The SCS-UH model parameter, lag time was calibrated and the value was obtained between 208.27 min and 4456.2 min for the sub-watershed.

- It was also found that optimization of the parameters significantly improved the model performance in both calibration and validation period.
- The observed and simulated hydrographs were found similar during calibration and validation for all the years. The simulated stream flow and the observed stream flow values indicated that the model is able to predict and present credible results for the sub-basin.
- During the calibration period (2013-2016), the highest flow volume was seen in the year 2015 with 1040.642 Million m^3/year as the simulated one and 1101.858 Million m^3/year as the observed one. Similarly, lowest volume of flow was seen in the year 2013 with 418.394 Million m^3/year as simulated and 450.455 Million m^3/year as observed.
- During the validation period (2017-2018), the highest volume of flow was seen in the year 2018 with a flow of 1482.385 Million m^3/year as simulated and 1474.842 Million m^3/year as observed. Likewise, lowest volume of flow was seen in the year 2017 with a flow of 1001.895 Million m^3/year as simulated and 981.299 Million m^3/year as observed.
- The highest peak flow of river was observed during the year 2018 and it was predicted as 652.5 m^3/s whereas as the observed value was 795.3 m^3/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 limited data availability.

- The findings in the present study are very useful for water resources engineers and researchers for efficient planning and management of water resources. All these are useful information for policy makers to adopt suitable flood control measures and construction of structures which are important to protect the area from future floods.

Suggestions for Future Research

1. Forecasted rainfall data may be used for prediction of future runoff that can be used in flood alert application.
2. Availability of long records of annual maximum discharge data may enhance the accuracy of flood frequency analysis and flood modelling studies.

REFERENCES

REFERENCES

Abbott, M.B. and Refsgaard, J.C. 1996. *Distributed Hydrological Modeling*. In: Water Science and Technology Library (Eds.). doi: 10.1007/978-94-009-0257-2.

Abdessamed, D., Abderrazak, B. and Kamila, B. 2018. Modelling rainfall runoff relations using HEC-HMS in a semi-arid region: Case study in Ain Sefra watershed, Ksour Mountains (SW Algeria). *J. water land Dev*. 36 (3): 45–55.

Abed, N.A., Abdulla, F. and Khayarah, A.A. 2005. GIS-hydrologic models for managing water resources in the Zarqa river basin. *Environ. Geol*. 47: 405-411.

Adnan, N.A. and Atkinson, P.M. 2018. Disentangling the effects of long-term changes in precipitation and land use on hydrological response in a monsoonal catchment. *J. Flood Risk Manag*. 11: 1063–1077.

Agarwal, A., Rai, R.K. and Upadhyay, A. 2009. Forecasting of Runoff and Sediment Yield Using Artificial Neural Networks. *J. Water Resour. Prot*. 1: 368-375.

Ahmad, U.N., Shabri, A. and Zakaria, Z.A. 2011. Flood frequency analysis of annual maximum stream flows using L-Moments and TL-Moments. *Appl. Math. Sci*. 5: 243– 253.

Akbarpour, M. 2004. Simulation of Rainfall-Runoff Process by Artificial Neural Networks and HEC-HMS Models in Zard River Basin. In: *Proceedings of the Fourth International Iran and Russia Conference*. pp. 1143-1148.

Aksara, P. and Apiwit, J. 2016. *Flood Frequency Analysis for Extreme Events under Climate Change in Yom River Basin of Thailand*. 2^{nd} World Irrigation Forum (WIF2) 6, Chiang Mai, Thailand.pp.1-10.

Alemaw, B.S.F. and Chaukra, T.R. 2003. A continental water balance model: a GIS approach for southern Africa. *Phys. Chem. Earth Parts*. 20 (28): 957-966.

Anand, V., Chahar, B.R. and Sharma, O.P. 2013. Snowmelt Runoff Simulation using HEC-HMS in a Himalayan Watershed. *World Environmental and Water Resources Congress 2013: Showcasing the Future*. pp. 3206-3215.

Anderson, M.L., Chen, Z.Q., Kavvas, M.L. and Feldman, A. 2002. Coupling HEC-HMS with atmospheric models for prediction of watershed runoff. *J. Hydrol. Eng., ASCE*, 7 (4): 312-318.

Anup, K.S. 2017. Flood frequency analysis part II, National Water Academy, Pune, India.Available:https://nwa.mah.nic.in/Dl_modules/FFA_module/FFA_module/index.htm#REF.

Arash, A. and Fardin, B. 2013. Performance Evaluation of the HEC-HMS Hydrologic Model for Lumped and Semi-distributed Stormflow Simulation (Study Area: Delibajak Basin). *Am. J. Eng. Res.* 2(11): 115-121.

Arekhi, S. 2012. Runoff modeling by HEC-HMS Model (case study: Kan watershed, Iran). *Int. J. Agric. Crop Sci*. 4(23): 1807-1811.

Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J. R. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. *J. Am. Water Resour. Assoc.* 34 (1): 73-89.

Arturo, V.M. 2018. Effect of climatic oscillations on flood occurrence on Papaloapan River, México, during the 1550–2000 period. *Nat. Hazards*. 94: 167–180.

Azam, M., Hyung, S.K. and Seung, J.M. 2017. Development of flood alert application in Mushim stream watershed Korea. *Int. J. Disaster Risk Reduction.* 21: 11-26.

Bagher, H., Bahram, S. and Saeed, G. 2015. The Effect of Involving Exceptional Outlier Data on Design Flood Magnitude. *Curr. World Environ*. 10 (2): 698-706.

Balchand, A.N. 1983. Kuttanad: A Case Study on Environmental Consequences of Water Resources Mismanagement. *Water Int*. 8 (1): 35-41.

Barry, D.A. and Bajracharya, K. 1995. On the Muskingum-Cunge flood routing method. *Environ. Int.* 21 (5): 485-490.

Bhaduri, B., Harbor, J., Engel, B.A. and Grove, M. 2000. Assessing watershed-scale, long-term hydrologic impacts of land use change using a GIS-NPS model. *Environ. Manag.* 26(6): 643–658.

CGWB. 2009. Groundwater Information Booklet of Kottayam District. Ministry of Water Resources, Government of India.

Cheng, C.T., Ou, C. and Chau, K. 2002. Combining a fuzzy optimal model with a genetic algorithm to solve multi-objective rainfall–runoff model calibration. *J. Hydrol*. 268: 72–86.

Choudhari, K., Panigrahi, B. and Paul, J.C. 2014. Simulation of rainfall-runoff process using HEC-HMS model for Balijore Nala watershed, Odisha, India. *Int. J. Geomatics Geosciences*. 5 (2): 253-264.

Chu, X. and Steinman, A. 2009. Event and continuous hydrologic modeling with HEC-HMS. *J. Irrig. Drain. Eng.* 135 (1): 119-124.

Clark, C.O. 1945. Storage and the unit hydrograph. *Trans. ASCE*. 110 (2261): 1419-1446.

Clay, H.E., Claire, W. and Travere, R.G. 2005. Watershed scale evaluation of a system of storm water detention basin. *J. Hydrol. Eng*. 3: 237-242.

Demetrio, A.Z., Antonino, L., Domenico, M. and Santo, M.Z. 2016. Comparing Different Infiltration Methods of the HEC-HMS Model: The Case Study of the Mésima Torrent (Southern Italy*). Land degradation and Dev*. 28(1): 294-308.

Džubáková, K. 2010. Rainfall-runoff modelling: its development, classification and possible applications. *Acta Geographica Universitatis Comenianae*. 54(2): 173-181.

Gayathri, K.D., Ganasri, B.P. and Dwarakish, G.S. 2015. A Review on Hydrological Models. *Aquatic Procedia 4*. pp: 1001 – 1007.

George, C., Jayakumar, K.V. and James, E.J. 2011. Changes in streamflow regime as indicator of upstream urbanization in a humid tropical river basin. *Meteorol. Appl*. 19: 334-345.

George, S.L. and Gary, D.T. 2000. *Flood-Frequency Prediction Methods for Unregulated Streams of Tennessee*. U.S. Geological Survey Water-Resources Investigations Report 03-4176, Nashville, Tennessee, U.S. pp.1-79.

GSI. 2002. District Resource Map, Geology and Minerals, Kottayam District, Kerala.

Haan, C.T. 1977. *Statistical Methods in Hydrology*. Iowa State University Press, Iowa.

Halwatura, D. and Najim, M.M.M. 2013. Application of the HEC_HMS model for runoff simulation in a tropical catchment. *J. Environ. Modeling Software*. 46: 155-162.

Hammouri, N. and Naqa, A.E. 2007. Hydrological modeling of ungauged wadis in arid environments using GIS. *Revista Mexicana de Geologicas*. 24(2): 185-196.

Hashmi, A. K. 2005. Rainfall- Runoff modeling from Kaha Hill Torrent Watershed D. G. Khan District, M.Sc. Thesis, University of Engineering and Technology, Lahore.

Hjelmfelt, A.T. 1991. Investigation of curve number procedure. *J. Hydraulic Eng*. 117(6): 725-737.

Hoblit, B.C. and Curtis, D.C. 2001. Integrating radar rainfall estimates with digital elevation models and land use data to create an accurate hydrological model. In: *Flood Plain Management Association Spring 2001 Conference*. 13-16 March 2001, San Diego, California.

Hsu, K.L., Gupta, H.V. and Sorooshian, S. 1995. Artificial neural network modeling of the rainfall-runoff process. *Water Resour. Res*. 31(10): 2517–2530.

Hu, H.H., Kreymborg, L.R., Doeing, B.J., Baron, K.S. and Jutila, S.A. 2006. Gridded Snowmelt and Rainfall-Runoff CWMS Hydrologic Modeling of the Red River of the North Basin. *J. Hydrol. Eng.* 11(2): 91-100.

Interagency Advisory Committee on Water Data. 1982. Guidelines for determining flood flow frequency: U.S. Geological Survey, Office of Water Data Coordination Bulletin 17B. 186p.

Izinyon, O.C. and Igbinoba, E. 2011. Flood Frequency Analysis of Ikpoba River Catchment at Benin City using Log Pearson Type III distribution. *J. Emerging Trends Eng. and Appl. Sci*. 2 (1): 50-55.

Jesús, M.L., José, A.S.N, Alejandro, G.G. and Vanesa, E.R. 2016. Flood Frequency Analysis (FFA) in Spanish catchments. *J. Hydrol*. 538: 598–608.

Joan, C.C., Maurice, D., Rosa, D.L.R. and Julie, C.U. 2019. Potential of the Molawin creek for micro hydro power generation: An assessment. *Sustain. Energy Technol. Assess*. 32: 111-120.

Joo, J., Kjeldsen, T., Kim, H. and Lee, H. 2013. A comparison of two event-based flood models (ReFH-rainfall runoff model and HEC-HMS) at two Korean catchments, Bukil and Jeungpyeong. *KSCE J. Civil Eng*. 18: 330–343.

Kilgore, J.L. 1997. Development and evaluation of a GIS-based spatially distributed unit hydrograph model. *J. Hydol*. 23 (4): 233-234.

Kishor, C., Balram, P. and Jagadish, C.P. 2014. Simulation of rainfall-runoff process using HEC-HMS model for Balijore Nala watershed, Odisha, India. *Int. J. Geomatics Geosciences*. 5 (2): 253-264.

Kite, G.W. and Pietroniro, A. 1996. Remote sensing applications in hydrological modelling. *Hydrol. Sci. J*. 41 (4): 63-591.

Knebl, M.R., Yang, Z.L. Hutchison, K. and Maidment, D.R. 2005. Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event. *J. Environ. Manag*. 75 (4): 325-336.

Knighton, J.O., Tsuda, O., Elliott, R. and Walter, M.T. 2018. Challenges to implementing bottom-up flood risk decision analysis frameworks: how strong are social networks of flooding professionals? *Hydrol. Earth Syst. Sci*. 22: 5657–5673.

Kristi, R. and Tatiana, H.P. 2010. Hydrologic Analysis of Flash Floods in Sana'a, Yemen. *Watershed Management Conference.* Washington University, St. Louis, Missouri. pp 1248-1259. https://doi.org/10.1061/41143(394)112.

KSLUB. 1996. Watershed atlas. Kerala State Land Use Board. Govt.of Kerala. Publ.

Kumar, A.B., Girish, G. and Shylesh, C.M.S. 2014. River sinuosity in a humid tropical river basin, south west coast of India. *Arab J. Geosci*. 7:1763–1772.

Kumar, D. and Bhattacharjya, R.K. 2011. Distributed rainfall runoff modeling. *Int. J. Earth Sci. Eng.* 4 (6): 270-275.

Law, G.S. and Tasker, G.D. 2003. *Flood-Frequency prediction methods for unregulated streams of Tennessee*. Water Resources Investigations Report No. 03-4176, Nashville, Tennessee.

Legesse, D., Vallet, C.C. and Gasse, F. 2003. Hydrological response of a catchment to climate and land used changes in Tropical Africa: case study South Central Ethiopia. *J. Hydrol*. 275:67-85.

Li, J. and Wong, D.W. 2010. Effects of DEM sources on hydrologic applications. *Comput., Environ. Urban Syst*. 34 (3): 251-261.

Maidment, D.R. and Djokic D. 2000. Hydrologic and Hydraulic Modeling Support with GIS. ESRI Press, Redlands California. pp. 1-232.

Majidi, A. and Shahedi, K. 2012. Simulation of Rainfall-Runoff Process Using Green-Ampt Method and HEC-HMS Model (Case Study: Abnama Watershed, Iran). *Int. J. Hydraulic Eng*. 1 (1): 5-9.

Majidi, A. and Vagharfard, H. 2013. Surface runoff simulation with two methods using HEC-HMS model. *Curr. Advantages Environ. Sci*. 1 (1): 7-11.

Matziaris, V., Ferentinou, M. and Sakellariou, M. 2005. *Slope Stability Assessment in Unsaturated Soils under Rainfall Conditions*. International Workshop in Geoenvironment and Geotechnics (GEOENV2005), Agioutantis & Komnitsas (eds.), Milos. pp. 91-97.

McColl, C. and Aggett, G. 2007. Land use forecasting and hydrologic model integration for improved land use decision support. *J. Environ. Manag*. 84(4): 494-512.

McCuen, R.H. 1982. A Guide to Hydrologic Analysis Using SCS Methods Prentice Hall, Inc. Englewood Cliffs, New Jersey, USA.

Melo, I., Tomasik, B., Torrieri, G., Vogel, S., Bleicher, M., Korony, S. and Gintner, M. 2009. Kolmogorov-Smirnov test and its use for the identification of fireball fragmentation. *Phys. Rev. C*. 80 (2): 1-8.

Mihalik, E.N., Levine, S.N. and Amatya, M.D. 2008. Rainfall-Runoff Modeling of Chapel Branch Creek Watershed using GIS-based Rational and SCS-CN Method. *ASABE Annual International Meeting*, June 29 – July 2, 2008, ASABE Rhode Island Convention Center Providence, Rhode Island, USA. pp. 1-15.

Mike, B. and Matthew, F. 2019. Paleoflood Enhancements within HEC-SSP. *AGU's Fall Meeting*. December 9 – 13, 2019. Moscone South - Poster Hall, San Francisco.

Moradkhani, H. and Sorooshian, S. 2009. General Review of Rainfall-Runoff Modeling: Model Calibration, Data Assimilation, and Uncertainty Analysis. *Hydrol. Modelling Water Cycle*. 63: 1–24.

Muhammad, S.I., Zakir, H.D., Erik, P.Q., Asif, K. and Nynke, H. 2018. Impact of Climate Change on Flood Frequency and Intensity in the Kabul River Basin. *Geosciences.* 8(114): 2-16. doi:10.3390/geosciences8040114.

Mujere, N. 2011. Flood Frequency Analysis using the Gumbel Distribution. *International J. Comput. Sci. and Eng*. 3: 2774-2778.

Najim, M.M.M., Babelb, M.S. and Loofb, R. 2006. AGNPS Model Assessment for a Mixed Forested Watershed in Thailand. *Sci. Asia*. 32: 53–61.

Najmaddin, P.M., Whelan, M.J. and Balzter, H. 2017. Application of satellite based precipitation estimates to rainfall-runoff modelling in a data-scarce semi-arid climate. *J. Hydrol*. 5 (2): 32.

National Engineering Handbook. 1971. United States Department of Agriculture.

Nawaz, M. and Han, M. 2008. Hill Torrents Management for Increasing Agricultural Activity in Pakistan [on-line]. Available: http://www.spate-irrigation.org [18 Nov. 2019].

Nektarios, N.K. and George, P.K. 2011. Flood management and a GIS modelling method to assess flood-hazard areas—a case study. *Hydrological Sci. J*. 56 (2): 212-225.

Okkan, U. and Serbes, Z.A. 2012. Rainfall–runoff modeling using least squares support vector machines. *Environmetrics*. 23 (6): 549-564.

Oleyiblo, J.O. and Li, Z. 2010. Application of HEC-HMS for flood forecasting in Misai and Wan'an catchments in China. *Water Sci. Eng.* 3 (1): 14-22.

Paudel, M., Nelson, E.J. and Scharffenberg W. 2009. Comparison of lumped and quasi-distributed Clark runoff models using the SCS Curve Number Equation. *J. Hydrol. Eng.* 14 (10): 1098-1106.

Pickands, J. 1975. Statistical inference using extreme order statistics. *Ann Stat*. 3:119–131.

Ponce, V.M. and Hawkins, R.H. 1996. Runoff curve number: has it reached maturity. *J. Hydrol. Eng*. 1 (1): 11-19.

Praveen, R., Kalpesh, B. and Manekar, V.L. 2015. Simulation of Rainfall - Runoff Process using HEC-HMS (Case Study: Tapi River, India). *Hydro 2015 International*, 20th International Conference on Hydraulics, Water Resources and River Engineering, 17-19 December, IIT Roorkee, India.

Rahman, A., Zaman, M.A. and Haddad, K. 2015. Applicability of Wakeby distribution in flood frequency analysis: a case study for Eastern Australia. *Hydrol. Process*. 29: 602–614.

Rao, A.R. and Hameed, K.A. 2000. Flood frequency analysis. CRC press, Washington D.C.

Roy, D., Begam, S., Ghosh, S. and Jana, S. 2013. Calibration and Validation of HEC-HMS Model for a River Basin in Eastern India. *ARPN J. Eng. Appl. Sci*. 8(1): 40-56.

Sabzevari, T., Ardakanian, R., Shamsaee, A. and Talebi, A. 2009. Estimation of flood hydrograph in no statistical watersheds using HEC-HMS model and GIS (Case study: Kasilian watershed). *J. Water Eng.* 4:1–11.

Sai, V.K., Muthappa, K.J, Gowtham, P.M.E, Shruthi, H.G., Shivaprasad, H. and Nagaraj, S.R. 2017. Applicability of HEC-HMS tool to Western Ghats - Nethravathi River basin. *Int. J. Advanced Res. Eng. Manag*. 3(4): 70-79.

Sampath, D.S., Weerakoon, S.B. and Herath, S. 2015. HEC-HMS model for runoff simulation in a tropical catchment with Intra-Basin diversions - Case study of the Deduru Oya river basin, Sri Lanka. *Inst. Eng*.1: 1-9.

Santillan, J., Makinano, M. and Paringit, E. 2011. Integrated Landsat image analysis and hydrologic modeling to detect impacts of 25-year land-cover change on surface runoff in a Philippine watershed. *Remote Sensing*. 3: 1067–1087.

Sardoii, E.R., Rostami, N., Sigaroudi, S.K. and Taheri, S. 2012. Calibration of loss estimation methods in HEC-HMS for simulation of surface runoff. *Adv. Environ. Biol*. 6(1): 343-348.

Sarma, P. 1999. Flood risk zone mapping of Dikrong sub basin in Assam, available at: http://www.gisdevelopment.net/application/natural_hazards/floods.

Scharffenberg, W. A. and Fleming, M. J. 2010. *Hydrologic Modeling System HEC-HMS v 3.5: User's Manual*. US Army Corps of Engineers, Hydrologic Engineering Center, Davis, California. p. 318.

Scharffenberg, W. and Harris, J. 2008. Hydrologic Engineering Center Hydrologic Modeling System, HEC-HMS: Interior Flood Modeling. In: *World Environmental and Water Resources Congress*, 12-16, May 2008, Honolulu, Hawaii, U.S.A [On-line]. Available: https://doi.org/10.1061/40976(316)632.

Schulze, R.E., Scmidt, E.J. and Smithers, J.C. 1992. PC-based SCS design flood estimates for small catchments in Southern Africa. Department of Agricultural Engineering, University of Natal.

Seth, I., Soonthornnonda, P. and Christensen, E.R. 2006. Use of GIS in urban storm-water modelling. *J. Environ. Eng.* Vol 132. 12p.

Shakirudeen, O. and Saheed, A.R. 2014. Flood Frequency Analysis and Inundation Mapping of Lower Ogun River Basin. *J. Water Resour. Hydraulic Eng.* 3(3): 48-59.

Shrestha, K.L. and Shresta, M.L. 2003. Climate change and water resources of Nepal. In: *Climate change and water resources in South Asia.* Asianics Agro-Development International Private Limited.

Singh, P., Gupta, A. and Singh, M. 2014. Hydrological inferences from watershed analysis for water resource management using remote sensing and GIS techniques. *Egyptian J. Remote Sensing Space Sci.* 17 (2): 111-121.

Skhakhfa, I.D. and Ouerdachi, L. 2016. Hydrological modelling of wadi Ressoul watershed, Algeria, by HEC-HMS model. *J. Water and Land Dev*. 31 (1): 139-147.

Soil conservation service engineering division. 1986. Urban Hydrology for Small Watersheds TR-55. U.S. Department of Agriculture (USDA), Technical Release.

Subramanya, K. 2008. *Engineering Hydrology*. Tata McGraw-Hill Publishing Company Limited, New Delhi, India.

Tassew, B.G., Belete, A.M. and Miegel, K. 2019. Application of HEC-HMS Model for Flow Simulationin the Lake Tana Basin: The Case of Gilgel Abay Catchment, Upper Blue Nile Basin, Ethiopia. *Hydrol*. 6 (21):1-17.

Tessier, Y., Lovejoy, S., Hubert, P., Schertzer, D. and Pecknold, S. 1996. Multifractal analysis and modeling of rainfall and river flows and scaling causal transfer functions. *J. Geophys. Res.* 26: 427– 440.

Thakur, J.K., Singh, S.K. and Ekanthalu, V.S. 2016. Integrating remote sensing, geographic information systems and global positioning system techniques with hydrological modeling. *Appl. Water Sci*. 34 (3): 1-14.

Toriman, E.M., Hassan, J.A., Gazim, B.M., Mokhtar, M., Mastura, S.S.A., Jaafar, O., Karim, O. and Aziz, A.A.N. 2009. Integration of 1-d Hydrodynamic Model and GIS Approach in Flood Management Study in Malaysia. *Res. J. Earth Sci*. 1 (1): 22-27.

Tripathi, P. 2015. Flood Disaster in India: An Analysis of trend and Preparedness. *Interdisciplinary J. Contemporary Res.* 2 (4):91-98.

Tumbare, M.J. 2000. Sustainable Use of Water Resources. Mitigating floods in Southern Africa. In: *1st WARSFA/Water Net Symposium*. Maputo: Univ. of Zimbabwe Press. pp. 1-8.

USACE. 2000. *HEC-HMS Hydrologic Modeling System Technical Reference Manual*. Hydrologic Engineering Center, Davis, California. 103p.

USACE. 2000. *HEC-HMS Hydrologic Modeling System User's Manual.* Hydrologic Engineering Center, Davis, California.

USACE. 2018. *HEC-HMS Hydrologic Modeling System User's Manual.* Hydrologic Engineering Center, Davis, California.

USACE. 2019. *HEC-SSP Statistical Software Package 2.2 User's Manual*. Hydrologic Engineering Center, Davis, California.

Verma, A.K., Jha, M.K. and Mahana, R.K. 2009. Evaluation of HEC-HMS and WEPP for simulating watershed runoff using remote sensing and geographical information system. *Paddy and Water Environ*. 8 (2): 131-144.

Viessman, W. and Lewis, G.L. 2003. Introduction to Hydrology. Prentice Hall Publishers, New Jersey.

Vijith, H., Rejith, P.G. and Madhu, G. 2009. Using Info Val Method and GIS techniques for the spatial modelling of landslides susceptibility in the Upper catchment of River Meenachil in Kerala. *Indian Soc. Remote Sensing.* 37: 241–250.

Wagener, T., Wheater, H.S. and Gupta, H.V. 2004. *Rainfall-Runoff, Modelling in Gauged and Ungauged Catchments* [e-book] Imperial College Press, London. Available: https://doi.org/10.1142/p335 [Sept. 2004]

Wai, J.X. 2015. Comparative Study of Flood Frequency Method on Selective Rivers. Other thesis, INTI International University, Malaysia, 2p.

Waikhom, R.S. and Manoj, K.J. 2015. Continuous Hydrological Modeling using Soil Moisture Accounting Algorithm in Vamsadhara River Basin, India. *J. Water Resour. Hydraulic Eng.* 4 (4): 398-408.

Wałęga, A., Grzebinoga, M. and Paluszkiewicz, B. 2011. On using the Snyder and Clark unit hydrograph for calculations of flood waves in a highland catchment (The Grabinka River example). *Acta Sci. Polonorum - Formatio Circumiectu.* 10 (2): 47–56.

Wang, F.G. and Wang, X.D. 2010. Fast and Robust Modulation Classification via Kolmogorov-Smirnov Test. *IEEE Trans. Commun*. 58(8): 2324-2332.

Wheater, H.S., Sorooshian, S. and Sharma, K.D. 2008. Hydrological modelling in Arid and Semi-arid Areas. Cambridge University Press, Cambridge, p. 195.

Yaw, D.T., John, A. and Edward, M.O. 2015. Computing Flood Volume of Dikpe Catchment using HEC-HMS. *Glob. J. of Hum. - Social Sci.: Geogr., Geo-Sciences, Environ. Sci. Disaster Manag*. 15 (2): 9-15.

Yener, M.K., Sorman, A.U., Sorman, A.A., Sensoy, A. and Gezgin, T. 2008. Modeling studies with HEC-HMS and runoff scenarios in Yuvacik basin, Turkiye. *International Congress on River Basin Management*. pp. 621- 634.

Yusop, Z., Chan, C.H. and Katimon, A. 2007. Runoff characteristics and application of HEC-HMS for modelling storm flow hydrograph in oil palm catchment. *Water Sci. Technol.* 56 (8): 41-48.

Zelenhasic, E. 1970. *Theoretical Probability Distributions for Flood Peaks*. Colorado University Press, Colorado.

Zeng, X., Dong, W. and Jichun, W. 2015. Evaluating the Three Methods of Goodness of Fit Test for Frequency Analysis. *J. Risk Anal. Crisis Response*. 5: 178-187.

Zhang, D.P. and Luo, Y.L. 2000. Applied Probability and Statistic. Higher Education Press, Beijing.

APPENDICES

Appendix 1

Monthly average of discharge (m³/s) during 1985-2018

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	7.9	2.51	11	10.65	17.44	187.46	87.58	41.82	18.28	0	24.84	11.3
1986	1.9	0	0	0	5.06	79.28	42.22	108.2	24.94	0	57.3	2.03
1987	0	0	0	0	5.21	39.99	28.58	59.6	41.34	0	34.1	7.72
1988	0	0	3	12.57	12.44	42.44	84.69	64.54	74.9	0	15.2	1.384
1989	0	0	0	26.97	33.58	150.67	162.63	69.36	104.64	0	43.5	18.12
1990	0	0	0	0	50.11	117.14	119.76	78.35	0	0	47.2	0
1991	0	0	0	0	0	152.63	152.57	145.34	0	0	0	0
1992	0	0	0	0	8.24	73.34	114.4	55.25	45.92	0	32.9	3.32
1993	0	0	0	0	6.4	60.09	91.92	39.35	17.67	0	16.73	4.22
1994	12	13.8	11	14.93	15.33	64.78	73.79	80.42	34	0	31.11	13.23
1995	0.5	0	0	3.37	107.3	110.4	174.63	147.8	110.25	35.7	62.33	3.24
1996	0	0	0	4.81	2.282	26.32	61.13	30.43	36.78	31.22	4.13	5.30
1997	0	0	0	2.88	7.78	8.44	73.69	26.44	23.72	19.48	27.1	2.94
1998	0	0	0	2.03	3.37	44.18	34.74	39.83	47.87	50.70	8.95	0
1999	0	0	0	2.16	24.33	52.72	0	12.98	3.61	60.90	1.25	0
2000	2	4.44	4.12	2.79	1.96	19.24	15.14	48.85	12.22	9.43	4.34	1.87
2001	0	0	0	0	2.08	56.29	68.26	28.23	7.53	40.81	30.18	0
2002	1.5	1.09	0.26	2.83	9.53	16.86	8.04	24.57	2.5	12.56	7.93	1.37
2003	0.6	0.19	3.45	4.35	4.99	18.31	22.53	16.92	6.03	23.46	5.14	3.24
2004	0	0	0	0	37.72	43.18	35.93	33.78	10.16	28.67	16.97	0
2005	0	0	0	3.65	13.23	49	64.49	36.06	69.31	21.20	26.33	1.43
2006	0	0	0	10.35	29.94	51.45	47.17	36.63	35.28	40.09	41.87	4.30
2007	0	0	0	3.82	6.84	52.68	63.81	25.78	39.70	35.04	24.34	1.03
2008	0	0	1.75	9.22	3.915	26.1	47.13	33.88	41.52	20.98	7.46	0
2009	0	0	0	0	22.76	25.38	49.69	24.11	26.08	32.38	24.96	15.66
2010	0	0	0	0.97	5.72	49.89	33.69	27.11	24.44	35.95	29.84	0.85
2011	0	0	0	6.69	5.48	72.57	35.20	45.2	22.68	15.84	12.68	0
2012	0	0	0	2.45	3.55	10.04	19.94	24.64	15.08	12.55	6.58	1.72
2013	0	0	0	2.2	3.99	40.43	33.88	32.22	19.39	16.14	16.65	3.83
2014	0	0	0	0	14.16	24.40	51.45	96.31	29.20	50.49	21.19	0
2015	0.3	0	0	22.93	38.32	64.89	52.07	38.59	48.33	58.37	42.49	23.43
2016	0	0	0	0	18.77	61.18	60.30	21.85	14.63	10.72	9.69	0
2017	0	0	8.76	0	19.05	70.60	33.34	63.88	74.51	36.65	39.66	4.18
2018	0	0	0	8.52	45.17	103.45	149.59	131.01	14.95	44.10	25.94	7.84

Appendix 2

Monthly average of precipitation (mm) during 2013-2018 in Kidangoor, Erattupetta and Kozha gauging station

Year	Station	Monthly average precipitation (mm)											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
2013	Kidangoor	0.16	0.06	0.13	0.27	0.40	3.49	3.50	2.54	2.10	1.77	1.93	0.70
	Erattupetta	0.23	0.44	7.63	6.57	3.79	31.91	23.97	19.01	13.75	12.95	21.27	0.51
	Kozha	0.00	0.35	2.92	4.10	5.23	44.35	28.74	13.39	10.84	8.55	5.94	1.23
2014	Kidangoor	0.25	0.10	0.11	0.06	1.23	1.90	2.66	3.50	1.87	2.96	1.69	0.72
	Erattupetta	0.00	2.69	2.52	9.98	12.63	13.62	19.46	30.75	10.34	22.13	14.58	3.50
	Kozha	0.00	0.36	1.55	4.15	9.11	16.83	12.10	28.67	9.90	15.30	7.36	5.99
2015	Kidangoor	0.33	0.17	0.28	0.85	1.51	1.51	1.90	1.63	1.78	2.23	1.93	1.20
	Erattupetta	1.81	1.75	8.68	14.36	11.76	11.76	9.35	12.39	13.43	13.50	14.73	6.03
	Kozha	0.41	0.04	3.96	7.11	9.82	9.82	13.18	14.86	17.32	16.49	5.98	3.64

2016	Kidangoor	0.40	0.27	0.30	0.28	0.80	2.18	2.42	1.31	0.91	0.86	1.00	0.36
	Erattupetta	1.81	0.26	5.32	3.16	16.24	15.97	14.41	7.51	3.05	3.43	2.33	0.63
	Kozha	0.00	1.45	1.12	0.59	9.23	18.09	13.28	6.46	1.93	2.75	3.59	0.05
2017	Kidangoor	0.18	0.08	0.60	0.17	0.89	2.33	1.82	2.53	2.71	1.80	1.92	0.63
	Erattupetta	0.13	0.00	12.35	3.12	14.56	17.02	8.54	16.65	18.41	9.87	9.31	4.03
	Kozha	1.84	0.00	3.30	1.92	7.59	22.66	10.19	18.10	17.62	8.94	7.54	1.59
2018	Kidangoor	0.27	0.14	0.09	0.45	1.80	6.96	12.40	10.43	6.64	1.56	0.80	0.59
	Erattupetta	0.00	2.21	3.35	10.47	20.55	21.97	30.92	23.48	9.12	16.65	7.92	1.49
	Kozha	0.00	0.01	1.03	10.33	12.33	24.27	32.49	17.49	1.29	13.44	15.00	3.13

Appendix 3

Land use classification:

Original NLCD Classification		**Revised classification (re-classification)**	
Number	*Description*	*Number*	*Description*
11	Open water	1	Water
90	Woody wetlands		
95	Emergent herbaceous wetlands		
21	Developed open space	2	Medium residential
22	Developed low intensity		
23	Developed medium intensity		
24	Developed high intensity		
41	Deciduous forest	3	Forest
42	Evergreen forest		
43	Mixed forest		
31	Barren land	4	Agricultural
52	Shrub/ scrub		
71	Grassland /herbaceous		
81	Pasture/hay		
82	Cultivated crops		

FLOOD FREQUENCY ANALYSIS AND MODELLING OF FLOOD USING HEC-HMS FOR A RIVER BASIN –A CASE STUDY

By

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ABSTRACT OF THESIS

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ABSTRACT

Meenachil river basin, located in southern part of Kerala, is an area frequently liable to flood. The area is predominant with agricultural land and falls under the tropical humid zone, where water resources planning and management is necessary for irrigation scheduling, flood control and design of various engineering structures. In view of the importance of water resources management especially in this humid region, it is necessary to understand the rainfall-runoff relationship along with its land characteristics. HEC-HMS model which is widely used rainfall-runoff modelling was chosen for the simulation of watershed responses and generation of flood hydrographs of Meenachil sub basin. The simulated runoff is useful for well-planned programmes in water resource management and future prediction of runoff for flood mitigation strategies in the catchment. Hence, an attempt was made to conduct flood frequency analysis for predicting the magnitude of flood for different return periods and to calibrate and validate the HEC-HMS model for simulating the flood hydrographs of Meenachil sub basin.

Flood frequency analysis was carried out using annual maximum discharge data for 34 years (1985-2018) using HEC-SSP software. The HEC-HMS model for the sub basin was developed using SCS-UH, SCS-CN and Muskingum methods to find out the loss rate, runoff transformation and routing of flood respectively.

Flood frequency analysis clearly indicated the good capability of the Gumbel and Log-Pearson Type III distribution function to predict flood magnitudes of the river flow in the sub basin of Meenachil River. Test statistic values of Chi-Square and Kolmogorov-Smirnov test showed the best fit of both the distributions for the basin. HEC-HMS model of the sub basin was developed with good accuracy. The performance indices of the model NSE and R^2 were obtained above 0.7. The Error in Peak Flow and Error in Volume were figured below 20% where as RSR was found 0.5 and below. All these values indicated satisfactory performance of HEC-HMS model simulation both in calibration and validation. The close agreement of simulated stream flow and observed stream flow indicated that the model was able to simulate flood hydrograph and present credible results for the sub basin.