A

DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

On

INUNDATION MAPPING OF THE KADALUNDI RIVER BASIN USING HEC SOFTWARES

in

MASTER OF TECHNOLOGY

By

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(Enrolment No-17552001)

Centre of Excellence in Disaster Mitigation and Management

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CANDIDATE'S DECLARATION

I hereby, declare that the work presented in this dissertation entitled **"Inundation mapping of the Kadalundi river basin using HEC softwares",** in partial fulfillment of the requirement forth award of the degree of **Master of Technology** submitted to Centre of Excellence in Disaster Mitigation and Management**, Indian Institute of Technology Roorkee, India,** under the supervision of **Dr. Sumit Sen,** Associate Faculty for Centre of Excellence in Disaster Mitigation and Management, IIT Roorkee. It is an authentic record my work done during out during a period from July 2018 up to June 2019.

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

Place: **Roorkee**

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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I would also want to thank my senior Atul sir who guided me in learning the programs involved in this study.

Place: Roorkee: **Ahmad Rashiq**

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ABSTRACT

Hydrological simulations using computer modelling has recently advanced significantly. Computerized models have become an essential tool for understanding changes in river flow due to human intervention and encroachments on river flows and designing water management approaches which are ecologically sustainable. The Malappuram district has been taken up as the study area since it experiences an average rainfall of 2900mm as compared to the national average of 1200mm. The region has experienced flooding in the years 2007, 2009 and 2018. The HEC-HMS software was used to simulate rainfall-runoff processes for the Kadalundi river flowing through the Malappuram district. The objective behind hydrologic simulation was to develop a model which is representative of the natural hydrological process of the river basin.

Results in the form of hydrographs (discharge *vs.* time curve) has been obtained from hydrological modeling. The results obtained were validated using various statistical parameters such as NSE, RMSE and PBIAS. The value of NSE changed from 0.69 during the calibration phase of model to 0.52 during validation which is within the acceptable range. The value of PBIAS improved from -21.75 during calibration to -16.78 during the validation phase. The correlation coefficient remained nearly constant with a value of about 0.74 during the modeling. Based on these statistical parameters, the model could be used to predict discharge in the river basin from future precipitation events. The results also explain the sensitivity of the various process viz. transform, loss and baseflow methods, which are used in hydrologic simulations.

Hydrographs obtained from hydrologic simulation in HEC-HMS are further used in HEC-RAS to prepare inundation maps for the year 2007. The result has been compared with inundation map due to actual discharge for the same year and a raster comparison has been done using the spatial analyst tool in Arc GIS which yields nearly 72% accuracy.

CHAPTER 1

INTRODUCTION

Floods and their causes:

Flood maybe defined as the phenomenon where land that is usually dry is inundated by water because of several reasons.

A flood is defined as **“an unusally high stage in a river, normally the level at which the river overflows its bank and inundates the joining area”** *(Subramanya, 2008)*.

“A flood is a relatively high flow which overflows the natural channel provided for the runoff” *(Parker, 2000)*.

Floods, as defined by the **WMO** *(WMO, 2011)*, is as follows**:**

i. **Rise, usually brief, in the water level in a stream to a peak from which the water level recedes at a slower rate.**

ii. **Relatively high flow as measured by stage height or discharge.**

iii. **Rising tide.**

There are numerous reasons for flooding such as:

- Extreme rainfall
- Prolonged rainfall
- Rapid melting of ice in the mountains
- Ruptured dam or levee
- Silting of river due to sediments
- River blockage due to landslides
- Tsunamis and cyclones in coastal areas
- Uncontrolled reservoir management
- Changes in landuse
- Lack of vegetation
- Cloud bursts

Meteorological Factors

- Rainfall
- Cyclonic storms
- Small-scale storms
- Temperature
- Snowfall and snowmelt

Hydrological factors

- Soil moisture level
- Groundwater level prior to storm
- Natural surface infiltration rate
- Presence of impervious cover
- Channel cross-sectional shape and roughness
- Presence or absence of over bank flow, channel network
- Synchronization of runoffs from various parts of watershed
- High tide impending drainage

Human factors

- Land use changes increase runoff and sedimentation
- Occupation of the flood plain and thereby obstructing flows
- Inefficiency or non-maintenance of infrastructure
- Too efficient drainage of upstream areas increases flood peaks
- Climate change effects, magnitude and frequency of precipitation and floods
- Urban micro-climate may enforce precipitation events
- Sudden release of water from dams located upstream of cities/towns
- Failure to release water from dams resulting in backwater effect
- Indiscriminate disposal of solid waste

Figure 1.1: Causes of floods as per NDMA

Flooding inundates the low lying region around the river, known as the **floodplain.** This region is made up of the sediments brought down by the river. The floodplain stretches from the banks of the river to the edges of the valley.

Most of the floods take a lot of time to develop (hours to days), which gives residents plenty of time to prepare or evacuate to safe places. Other floods like flash floods or cloud bursts give little to no warning. These flash floods are extremely dangerous, as they instantly turn a quiet stream into a thundering wall of water, which sweeps everything in its path.

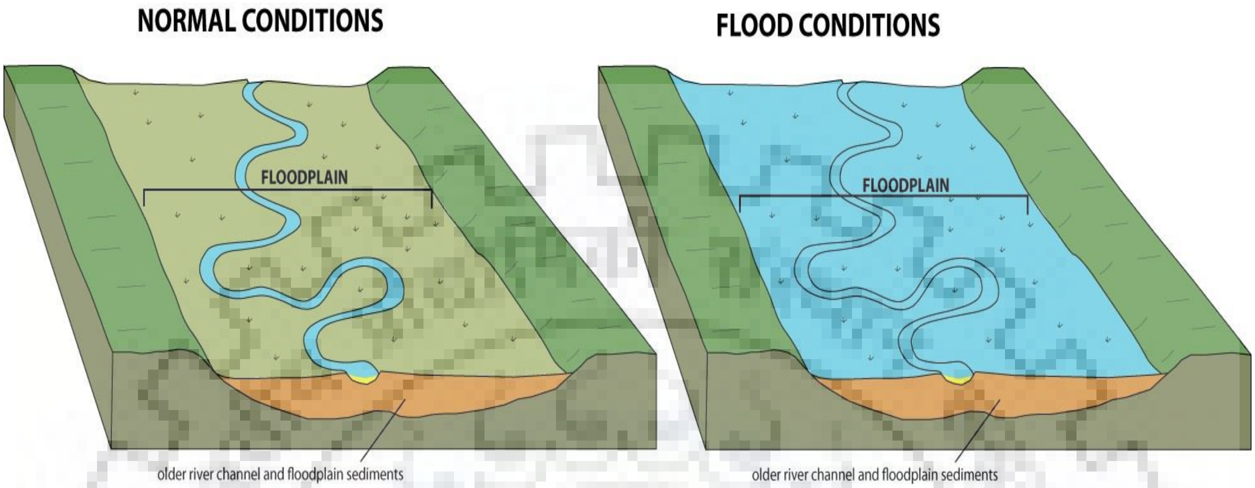


Figure 1.2: Flood and floodplain

Figure 1.3: Inundation due to flood in Chennai (2015)

1.2 Flood scenario in India

The intensity and frequency of floods in India has increased over the past years, mainly due to the invasion of floodplains in the form of unplanned construction along the river banks. Interestingly, although the number of losses in terms of human life due to floods has declined significantly over the past decade, the economic losses and the multitude of affected people has increased significantly (Alam 2015). These developments require better preparation at the national, state and district levels to ensure an effective and appropriate response during emergency flood prevention to reduce the damages. In India, about three-fourth of the entire precipitation is taking place in the four-month monsoon (June to September), so nearly all the streams have high discharges during this period. About 12% of India's total land area is vulnerable to inundation (Alam 2015). This amounts to nearly 40 million hectares of land area prone to flooding, with an average of 8 million hectares per year affected by flooding (Alam 2015). The basins most prone to flooding are the Brahmaputra River, the Ganges and the Meghana basin. The states which are most flood prone are Uttar Pradesh, Orissa, Bihar, West Bengal, and Assam (Alam 2015).

As of recently, flooding events have also become a grim problem in the states of Gujarat and Andhra Pradesh. More than 30 million people are displaced each year due to floods. Recognizing the need of the hour, the years 1990 - 1999 were declared as the "International Decade for Natural Disaster Reduction" and its main goal was to focus on disaster management planning to prevent, reduce, mitigate, prepare and respond to reduce the loss of life and property which occur due to natural disasters.

Normally, due to floods, about 750,000 hectares of land is affected each year, and 1,600 people lose their lives (NDMA). The damage to crops, houses and public services amounts to nearly Rs 2,000 crore. The biggest loss of life in took place in 1977 when nearly 11,316 people perished because of floods. The average annual flood damage in the last 10 years period from 1996 to 2005 was Rs. 4745 crore as compared to Rs. 1805 crore, the corresponding average for the previous 53 years (NDMA). Areas not considered to be prone to flood are now also being inundated because of changing land practices, human encroachment of natural drains and climate change. Heavy loads of sediments are brought to the basin by rivers every monsoon. All of the above factors, combined with insufficient carrying capacity of the river, are the causes of flooding, drainage system blockage and river bank erosion.

Table 1.1 Significant flood events in India since 2000

Year	Event
2005	Chennai flood
2005	Maharashtra flood
2007	Bihar flood
2009	India flood (affected Orissa, Kerala, Karnataka and North-East states)
2013	Uttarakhand flood
2014	Jammu and Kashmir flood
2015	Chennai flood
2016	Brahmaputra flood
2017	Mumbai flood
2018	Kerala flood

1.3 Hydrologic Modeling

With the availability of digital computers, it has become feasible to use water budget equations to determine runoff. The method of forecasting overflow which is the response of a basin to a given precipitation event, is known as watershed simulation. Here, first, a mathematical relationship relating the interdependence of numerous factors in the system is prepared, which is called a model. The model is then calibrated, i.e. the values of several coefficients are determined by simulating the known rainfall runoff records. The accuracy of the model is then verified by reproducing the results of another series of rainfall data for known runoff. This part of modelling is called verification of the model. Henceforth, the results are compared using various coefficients like Nash-Sutcliffe efficiency coefficient (ENS), root mean square (RMSE), mass balance error (MBE), coefficient of determination (R2) and peak flow rate error (PE) (Moriasi et al. 2007).

In order to improve the understanding of complex hydrologic processes between the amount of rainfall on a basin and the amount of runoff from that basin, many variable parameters such as meteorological, drainage basin and stream channel characteristics need to be considered (Yanmaz 2017). Many studies are carried out to assess the hydrologic processes and try to relate these parameters quantitatively to the discharge. One area of such research includes the usage of hydrologic modelling software such as Precipitation Runoff Modeling System (PRMS), Hydrologic Simulation Model (HYSIM), Model for Urban Storm Water Improvement Conceptualization (MUSIC), Soil and Water Assessment Tool (SWAT), Storm Water

Management Model (SWMM), MIKE - SHE and HEC-HMS (Yanmaz 2017). Current study makes use of HEC-HMS to simulate rainfall-runoff for the study area.

1.4 Hydrologic Engineering Center – Hydrologic Modeling System

The hydrological simulation system (HEC-HMS) aims to simulate the rainfall runoff process in dendritic drainage basins (Figure 1.4). Dendritic basins are characterized by the fact that the streams converge at acute angles. HEC-HMS has been designed such that it can be applied to a wide spectrum of geographical area to solve the widest possible range of problems. This includes hydrology of water and floods in large river basins and runoff in natural or urban watersheds. The discharge *vs.* time curves produced by the model is used directly or in combination with other programs to study availability of water, future flow projections, drainage in urban areas and impact of urbanization in coming future, design of reservoir spillways, system operations, flood disaster reduction and regulation of floods.

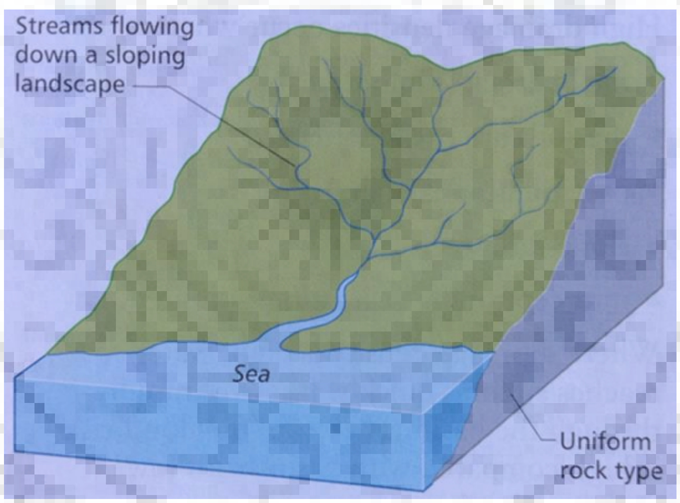


Figure 1.4: Dendritic river basin

HEC-HMS program can represent different types of basins such as dendritic, trellis, rectangular and parallel drainage basins. A model of a basin is built by sub-dividing the water cycle into smaller more manageable parts like initial abstraction, runoff and baseflow. Any kind of mass or energy flow like runoff, evapotranspiration, infiltration is represented by different processes such as transform, runoff and baseflow. In most of the cases, there are a number of model options that can be used to represent each process. For example, there are a total of seven methods to transform excess precipitation into surface runoff like Clark, Snyder, SCS techniques etc. Selecting the right method for all the different processes involves a good understanding of the basin, the aim of the research, and standards which are expected out of the study.

The components of HEC-HMS are as follows:

1. An analytical model to calculate overland flow runoff as well as channel routing.
2. An advanced and interactive graphic based user interface which illustrates constituents of hydrologic structure
3. Data storage and management system.
4. Graphical user interface for displaying and reporting model outputs (Bajwa and Tim, 2002).

There are a total of nine different methods present in HEC-HMS to calculate losses which occur during any rainfall event. Out of these methods, some have been primarily designed to simulate models which are event based, while others are useful to model events which are continuous in nature. Event based methods reveal how the basin responds to an individual rainfall event. Continuous hydrologic modeling synthesizes response of a basin over a longer period of time which includes both dry and wet conditions (Chu and Steinman 2009). Initial constant, SCS CN, exponential, Green Ampt and Smith Parlange are methods which can be used for event modeling. Soil moisture accounting method can be used to model evapotranspiration and infiltration. The SCS CN (Soil Conservation Services – Curve Number) method is chosen to compute runoff losses in the study. This method is relatively easy and simple since it demands only a single parameter i.e. the Curve Number (CN). The CN depends on a total of three different factors. They are

1. Type of soil
2. Antecedent Moisture Condition (AMC)
3. Land use / Land cover

There are a total of seven different transform methods present in HEC-HMS like Clark, Snyder and SCS unit hydrograph. S-graph and Modified Clark (ModClark) methods can also be used. Transform methods convert the excess rainfall into discharge. A few of these methods are quite complicated as they require more parameters for input (Halwatura and Najim 2013). Most of the time, these parameters are unavailable for catchments which are ungauged i.e. where no hydrological instruments have been setup to take measurements of rainfall, temperature, humidity etc. Clark unit hydrograph method has been used in the study to find out the transformation of excess rainfall to runoff. The inputs required in Clark's unit hydrograph are the time of concentration and storage coefficient.

The base flow component can be calculated by a total of five different methods like bounded recession, constant monthly, linear reservoir etc. Recession method has been used in the study to compute the base flow component as it only requires one input i.e. the recession constant. The recession method is highly sensitive and slight changes in the recession constant yield significant changes in the modeled discharge (Yanmaz 2017).

1.5 Hydrologic Engineering Center – River Analysis System (HEC – RAS)

This program has been designed with the purpose of letting the users perform stable one-dimensional flow, one- and two-dimensional non-static calculations of flow, transport of sediment and calculations of moving bed, and water temperature and water quality models.

This program is capable of carrying out hydraulic calculations for both one and two-dimensional network of natural and man-made (artificial) channels. Following list shows the major capabilities of this program.

- Data Storage and Management
- Graphics and Reporting
- Components of Hydraulic Analysis
- RAS Mapper
- User Interface

Interface for Users

A graphical user interface (GUI) has been designed so that the user can interact with HEC-RAS. One of the major objectives in the design of this GUI was to make it more user friendly, while still preserving an acceptable level of productivity for the user.

Steady Flow Water Surface Profiles

This component of the modeling system is intended for calculating water surface profiles for steady and gradually varied flow. The system is designed to handle a full network of channels, a dendritic system, or a single river reach. Subcritical, supercritical, and mixed flow regimes for water surface profiles can be modeled using the steady flow component.

Analysis of Water Quality

This particular module of the program allows users to perform analysis of the water quality in rivers and streams. Water temperature modelling can be done through advection-dispersion module which is included within the program.

Graphics and Reporting

Graphics in HEC-RAS includes X-Y plans of cross-sections of rivers and streams, river profiles, the schematics of river system, hydrographs, rating curves, and inundation mapping. RAS Mapper, which is an important part of this program, helps in carrying out inundation mapping of the study basin.

RAS Mapper

This component of HEC-RAS is intended to perform inundation mapping of water surface profile. RAS Mapper helps in creating the boundaries for floodplains and preparing inundation datasets by defining the RAS geometry and the water profile.

1.6 OBJECTIVES OF THE STUDY

The current study has been taken up with the following objectives

1. To prepare a watershed for the Kadalundi river basin in Arc GIS using Arc Hydro Tools and HEC GeoHMS and extract basin parameters namely slope and river length.
2. To calibrate and validate a HEC-HMS model for simulating rainfall-runoff process in the Kadalundi river basin and evaluate the model performance using various goodness of fit parameters.
3. To develop an inundation map for the Kadalundi river basin using HEC-RAS for the year 2007 flood event in the basin.

1.7 OUTLINE OF THE STUDY

Chapter 1 provides an overview about the flood, causes of floods, the aim and objectives for taking up the study, and briefs about the HEC-HMS and HEC-RAS.

Chapter 2 provides the review of the study carried out by various researchers and suitable model to model rainfall-runoff and produce inundation maps.

Chapter 3 discusses in brief about the study area and data used for further study process.

Chapter 4 is about an overview of the method to conduct rainfall runoff modelling. It explains the steps involved while conducting modelling using HEC-HMS and preparing inundation map using HEC-RAS.

Chapter 5 provides the final results and conclusions related to the study. It also shows model evaluation using statistical parameters.

Chapter 6 provides conclusions derived from the analysis and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

This chapter briefly discusses about various studies carried out in the field of floods in India, flood modeling and inundation mapping.

Studies related to floods:

Kulkarani, Mandal and Sangam, 1994 study the heavy rainfall of 22-23 August, 1990 over Vidarbha region of Maharashtra. Present information is useful to the hydrologists for planning and design of water resources projects in the Vidarbha region of Maharashtra.

Alam and Muzammil, 2006 describe the grave situation of floods in India. They show the vulnerability of the Indian states and the losses which occur due to flooding every year. Alam and Muzammil mention the importance of flood preparedness in order to mitigate the losses of life and property. The authors comment of flood management, flood management plans and flood simulation. This study has been taken up understanding the need of flood simulation as a measure to be prepared for floods.

Dikshit 2010 highlights some of the major natural catastrophes that occurred during 2010 monsoon. The most severe and far reaching catastrophes, was the mega flood in Pakistan. Besides looking into some causes and effects of this flood, this paper also focuses on the flash flood that occurred in Leh in Ladakh, India and the mudslides that devastated in Zhugqu region in China.

Guhathakurta, Sreejith and Menon, 2011 focused on the impact of climatic change on extreme rainfall events and flood risk in India and tries to bring out some of the interesting findings which are useful for hydrological planning and disaster management. The authors conclude that extreme rainfall and flood risk are increasing significantly in India.

Report by **Central Water Commission (CWC)** on the Kerala floods of 2018 shows how extreme rainfalls were the cause of the floodings in the state as opposed to the claims of reservoir mismanagement being the culprit behind the catastrophic floods. The study stated that the rainfall events from 15-17 August, 2018 was 160% above the normal rainfall.

Sudheer and Bhallamudi, 2018 have discussed the role of dams on the floods of August 2018 in the Periyar river basin, Kerala. The study concludes that the dams played a critical role in mitigating the impact of floods due to extreme rainfall. The study suggests developing integrated reservoir practices to strike a balance between flood control and other objectives of the reservoir such as hydropower generation.

Studies related to flood modelling:

Chu and Steinman, 2009 carry out event based and continuous hydrologic modelling for the Mona lake watershed, which is located in Western Michigan. Event hydrologic modeling shows the response of a basin to an individual rainfall event. Hydrologic processes and phenomena are synthesized in continuous hydrologic modeling which is the synthetic responses of the watershed to a multitude of rain events and their combined effects.

Gebre, 2015 carried out hydrologic simulation for the Upper Blue Nile river basin. The study concludes that base flow coefficients and the soil moisture storage coefficient are the most sensitive parameters for computing baseflow components and runoff respectively. The model developed in HEC-HMS can be used for future projection of runoff in the Upper Blue Nile river basin. The author also recommends further studies of the basin which incorporate the land use changes of the basin.

Halwatura and Najim, 2013 carry out study for the Attanagalu Oya catchment using HEC-HMS 3 model. The study concludes that the Snyder unit hydrograph is a more reliable method to simulate runoff than the Clark unit hydrograph. Also, the deficit and constant method is a better method than the SCS CN to compute the losses in the basin.

Choudhari and Paul, 2014 carry out study for the Balijore Nala watershed located in Odisha, India. HEC-HMS model is used to transform rainfall to runoff in Balijore Nala. To compute the volume of runoff, base flow, peak runoff rate, and flow routing methods SCS curve number, Exponential recession, SCS unit hydrograph, and Muskingum routing methods were chosen. The authors conclude that the model can be used to simulate runoff in ungauged watershed where no gauging station is present to measure runoff.

Baduna and Akay, 2017 carry out the modeling of the Kocanaz watershed using HEC-HMS. The authors carried out the study without dividing the basin into sub basins i.e. the watershed was modeled as a single basin as increasing the number of sub basins affects the model results inversely (Zhang 2013). Also, increasing the number of sub basins means more hydrologic parameters need to be calibrated which would increase uncertainty of the parameters determined by the model.

Studies related to HEC-RAS

Duvvuri and Narasimhan, 2013 prepare inundation maps for the Thamiraparani River using HEC-RAS. The extent of one dimensional inundation was determined using HEC-RAS (Hydraulic Engineering Center-River Analysis System). The hydrologic analysis from this study concludes that the SWAT model can be used to get a realistic approximation of the hydrology with minimal calibrations. Dense network of weather stations and a good network of stream gauge, if used, can further improve the results.

Javadnejad, 2013 carried out study for the Wolf River located in Shelby County, Tennessee. HEC-RAS was used to prepare the inundation maps which was used to compare results obtained from the LITE flood approach.

Ali and Khan, 2016 have carried out inundation mapping of the Jamuna river using the HEC-RAS program. Boundary conditions in the study are defined by discharge and water level for upstream and downstream respectively, while floodplain discharge data is used as unsteady flow data. The authors conclude that the study will help in managing and planning the floodplain area of the Jamuna river against any future disaster.

Aschwanden and Cepero, 2000 in their study of the Tar river, North Carolina have compared water surface profiles which are made from steady and unsteady flow hydraulic models. These profiles are then used to prepare the inundation for the river. The study is carried out to ascertain as to how far away from the forecast points the inundation maps are valid. This will further help in static forecast mapping of the region.

Lamichhane and Sharma, 2017 in their study of the Grand river, Painesville, Ohio generate flood inundation maps using HEC-RAS. The travel time for flood is also calculated by integrating LiDAR data so that an estimate for evacuation time could be done in the event of a flood. Inundation map along with evacuation time would help in developing a flood warning system for the region.

CHAPTER 3

STUDY AREA AND DATA USED

With its headquarters at Malappuram, **Malappuram** is a district in the state of Kerala. Malappuram district was formed on 16 June 1969. This district is composed of portions of the former Kozhikode and Palakkad districts: portions of Perinthalmannna and Ponnani taluks in Palakkad district and Ernad taluk and portions of Tirur taluk in Kozhikode district. This region lies in the tropical zone and experiences heavy rainfall during the monsoon season with a short dry season. The **average annual temperature is 27.3°C** and the **average annual rainfall is about 2952mm.**

Kadalundi River also known as **Kadalundipuzha** is one of the four most important rivers flowing through the district. The Bharathappuzha, the Chaliyar and the Tirur River are the remaining three rivers. About 130 kilometres long, the Kadalundi is primarily fed by rain. It is formed by the convergence of the **Veliyar** River and the **Olipuzha** River. Kadalundi is one of the most important rivers in the Malappuram district. The river has its origin in the Western Ghats which happens to be the Western boundary of the Silent Valley. The drainage area of the Kadalundi River is around 1274 km².

At the downstream of the Malappuram town is the Karathodu hydro observation station, from where the runoff data for the Kadalundi River has been collected.

Table 3.1: Location of Karathodu hydro observation station

Station name	Karathodu
Station code	KL000L7
District	Malappuram
Latitude	11°03'23"
Longitude	76°02'23"
Altitude	16.26m

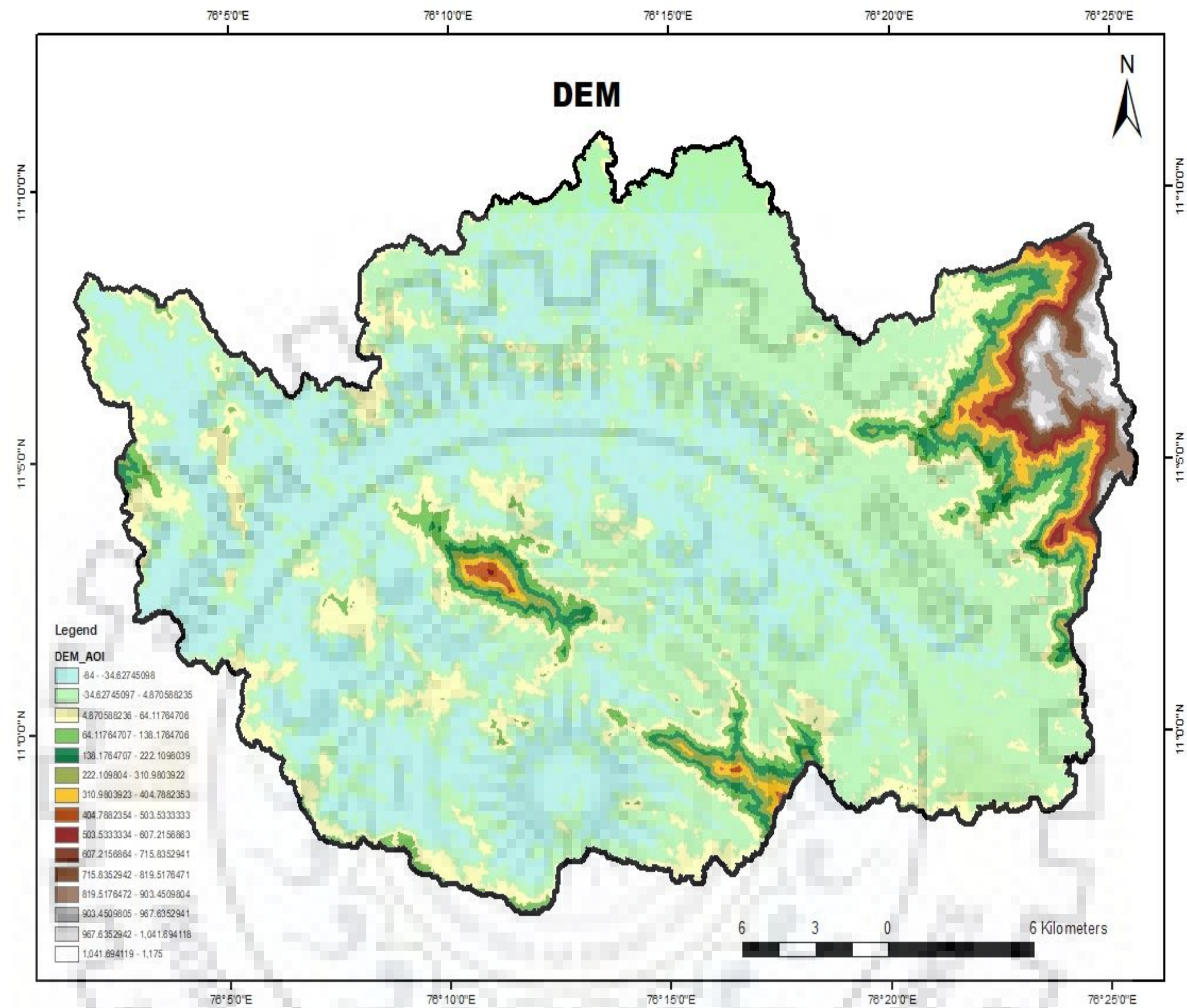


Figure 3.1: Digital elevation map of Kadalundi river basin

Data Collection

Daily rainfall data was collected from the Indian Meteorological Department (IMD) which has two stations in the basin, Angadipuram and Perinthalamanna for the past 21years (1996-2016). The daily discharge data was obtained from India WRIS website for the past 32 years (1985-2016). The name of the gauging station is Karathodu. DEM files of 30 meter resolution that have been used to delineate the watershed (Figure 3.1) for the study area were obtained from BHUVAN website. CARTOSAT I tiles were used. Soil data was obtained from the website of the Department of Soil Survey and Soil Conservation website (Figure 3.2).

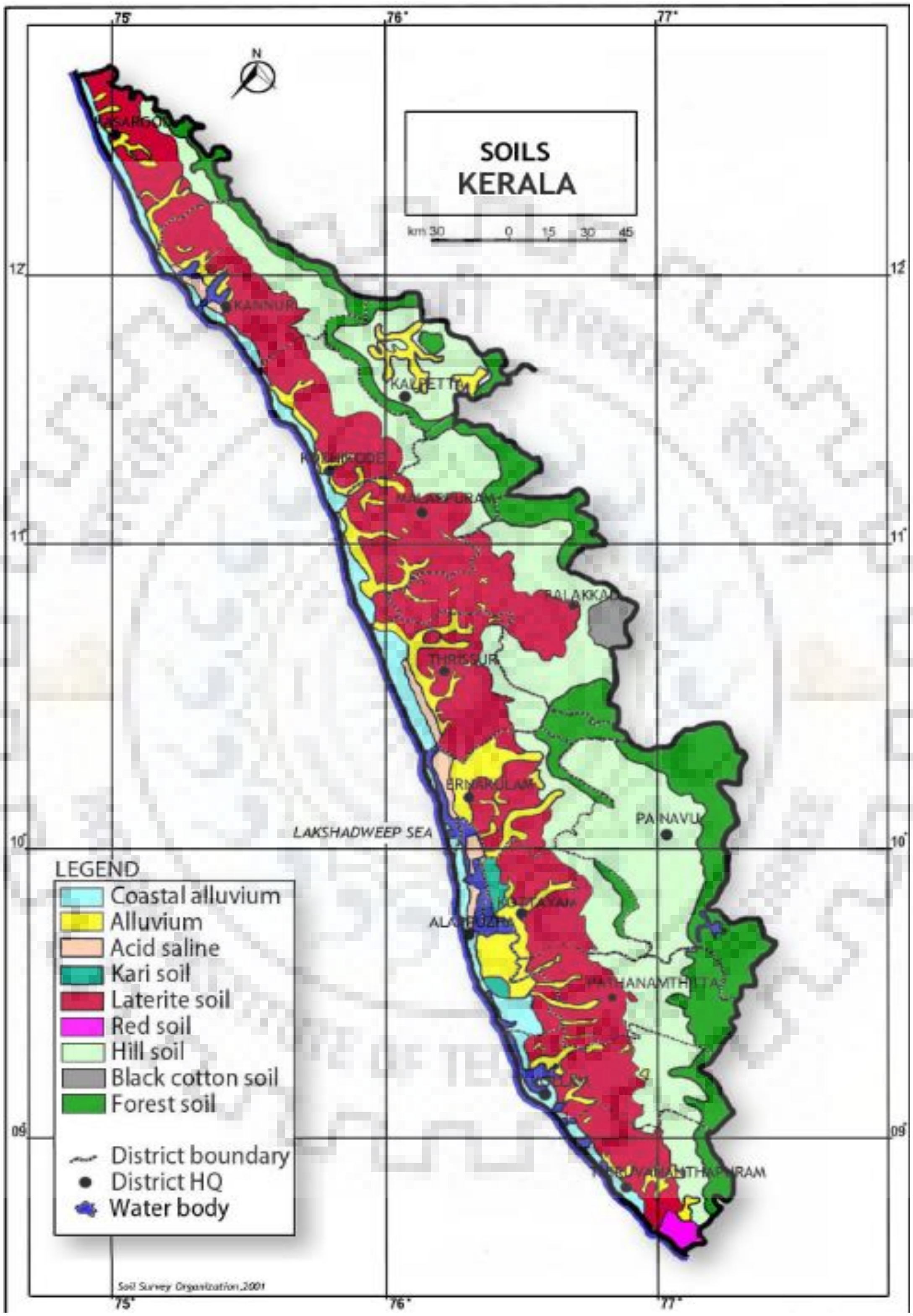


Figure 3.2: Soil map for the state of Kerala

Source: (keralasoils.gov.in)

CHAPTER 4
METHODOLOGY

The first and the foremost step was to select site for the study. The area of interest should have been flood prone to justify the study (Figure 4.1). Further, both rainfall and discharge data should be present for sufficient number of years. Based on these criteria's, Kadalundi river was selected for the study.

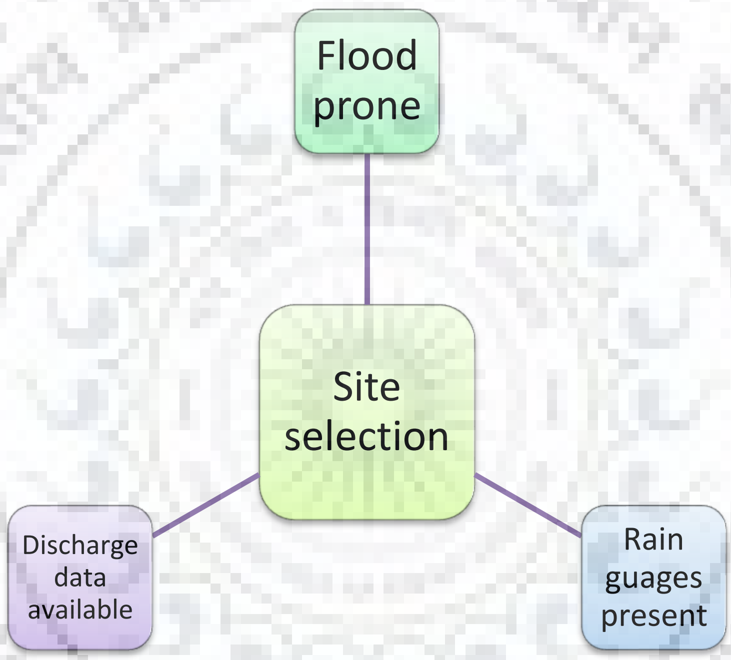


Figure 4.1: Criteria's for site selection during present study

Figure 4.2 shows the flow of process/steps taken to carry out rainfall-runoff simulation for the Kadalundi catchment. Watershed delineation is first carried out using DEM files for the study area in ARCGIS 10.3. The basin has been delineated and subdivided using ArcHydro tools 10.3. HEC-GeoHMS is then used to obtain the river basin in its final form and stream shape files. These files are then imported to HEC-HMS.

The model has been setup in HEC-HMS and a warm up simulation is run. This is followed by calibration of the model using the observed rainfall data. The parameters are adjusted in the calibration phase to achieve desirable results. The model is then validated by another set of observed rainfall data. Input for HEC-RAS has been obtained from the HEC-HMS model in the form of flood hydrographs. These hydrographs along with the terrain data (DEM files) help in preparing the inundation map for the area of interest. Figure 4.4 lists the steps followed to prepare the inundation map.

4.1 Watershed delineation

ArcHydro Tools 10.3 and Hec-GeoHMS 10.3 have been used along with ArcGIS 10.3 to delineate the basin for the area of interest (Figure 4.2). The delineation process using Arc Hydro Tools included the following steps:

1. Terrain preprocessing,
2. Watershed processing and
3. Flow path tracing.

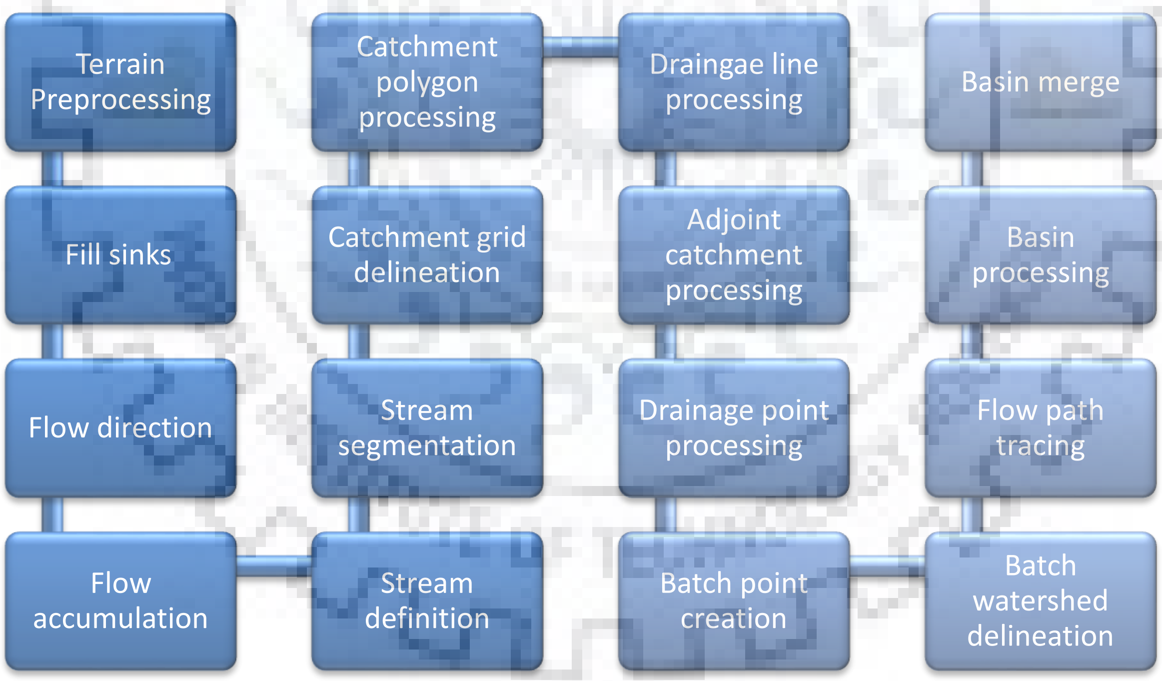


Figure 4.2: Steps to delineate watershed using Arc Hydro tools

The project was then setup in Hec-GeoHMS before finally exporting the files to HEC-HMS for calibration and validation.

4.2 Watershed map: Figure 4.3 shows the basin map for the study area. A basin is an area of land that feeds all the water running under it and draining off of it into a body of water like river.

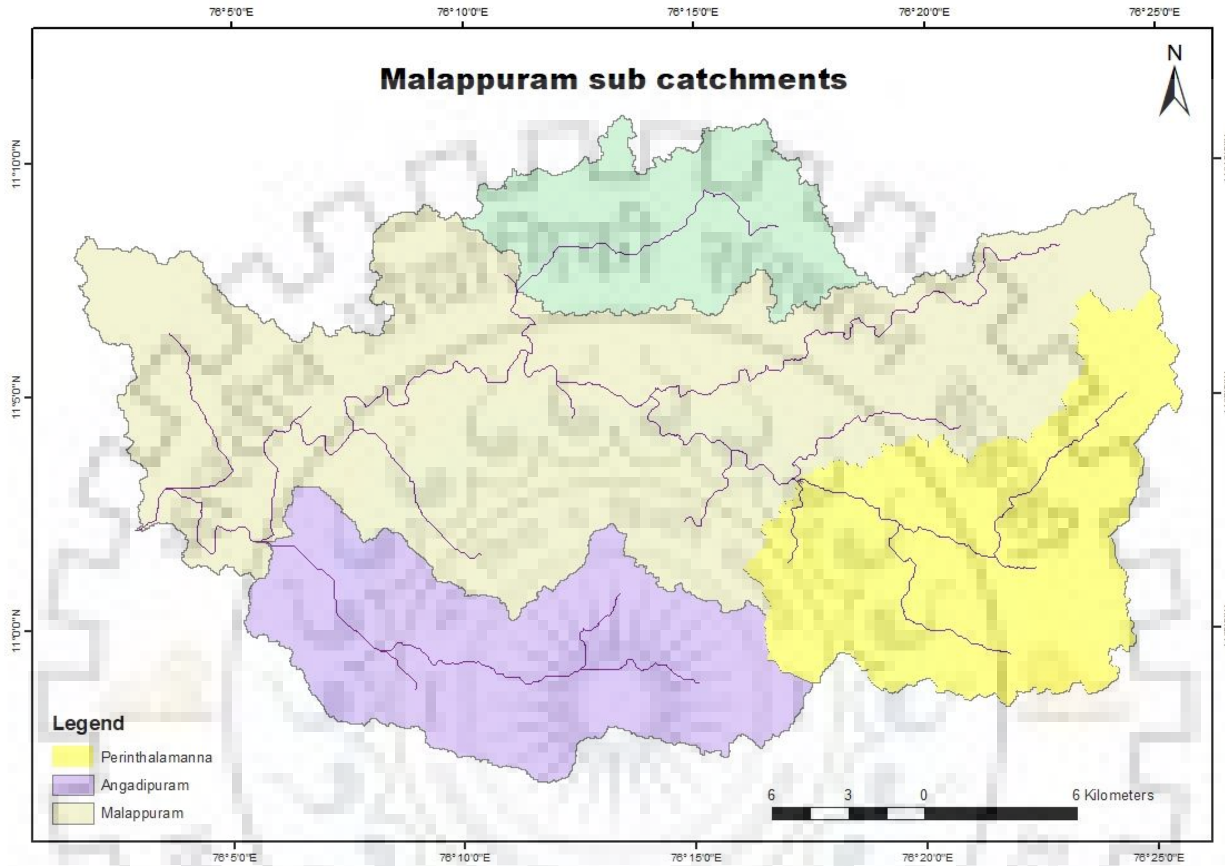


Figure 4.3: Sub basins in the Kadalundi basin

Table 4.1: Area of sub basins in the Kadalundi basin

Sub basin	Area (sq. km.)
Malappuram	376.779
Angadipuram	138.006
Perinthalamanna	150.508

4.3 River map: The following map shows the important streams which have been considered for rainfall-runoff modeling of the study area.

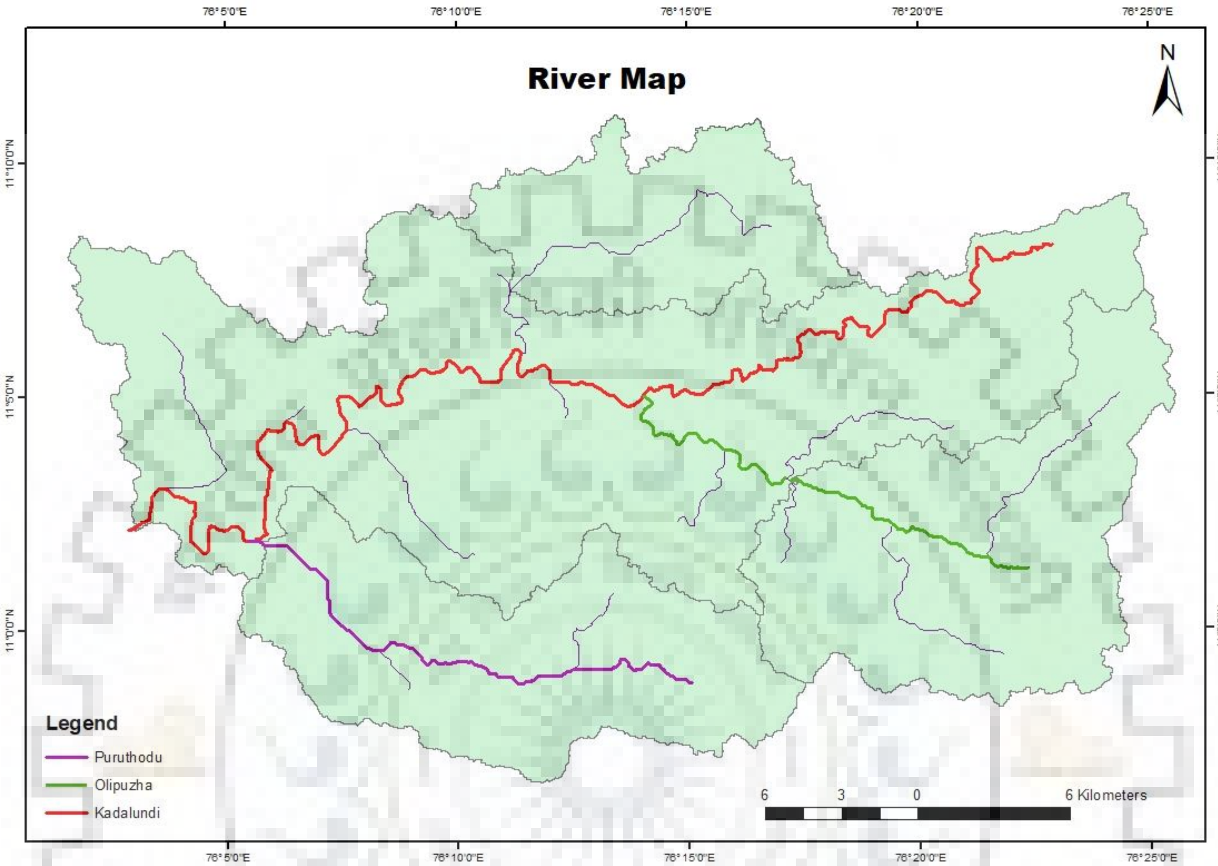


Figure 4.4: Streams in the Kadalundi basin

Table 4.2: Length of streams in the Kadalundi basin

Stream	Length (km)
Kadalundi	58.21
Olipuzha	29.69
Puruthodu	28.32

4.4 Slope map: The following figure shows the slope map of the study area. Slope is one of the important parameters to compute time of concentration in Clark's unit hydrograph method.

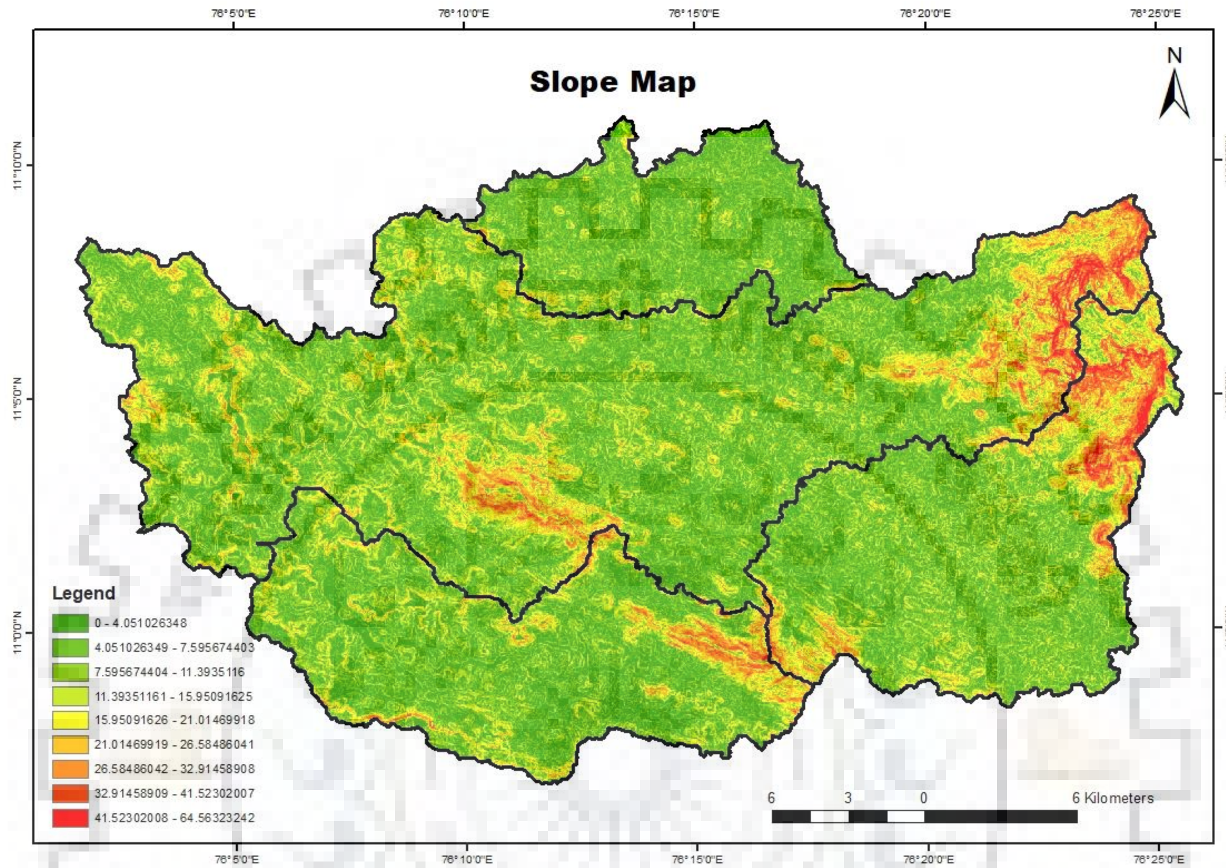


Figure 4.5: Slope of sub basins in the Kadalundi basin

Table 4.3: Slope of sub basins in the Kadalundi basin

Sub Catchment	Min. Slope (%)	Max. Slope (%)	Avg. Slope (%)
Angadipuram	0	47.37	8.73
Perinthalamanna	0	63.95	11.00
Malappuram	0	64.56	9.97

Flow estimation requires several data maps as input. Based on the maps, which were digitized in Arc GIS 10.3. The total area enclosed by different landuses, the entire area of the watershed and sub basin (Figure 4.3), length of the streams (Figure 4.4) and the slope of each sub basin (Figure 4.5) were measured. Within the basin, four sub basins (Malappuram, Angadipuram, Karipur and Perinthalamanna) were digitized using Arc GIS 10.3.

4.5 Setup of model in HEC-HMS: The flowchart below (Figure 4.6) summarizes the entire process of calibrating and validating the model in HMS. The model was set up in HEC-HMS using the different parameters that were obtained from the mentioned maps. The basin parameters were given as input after defining different processes to calculate baseflow, loss and runoff. The different processes have been explained below with the flowchart explaining how the calibration and simulation has been carried out.

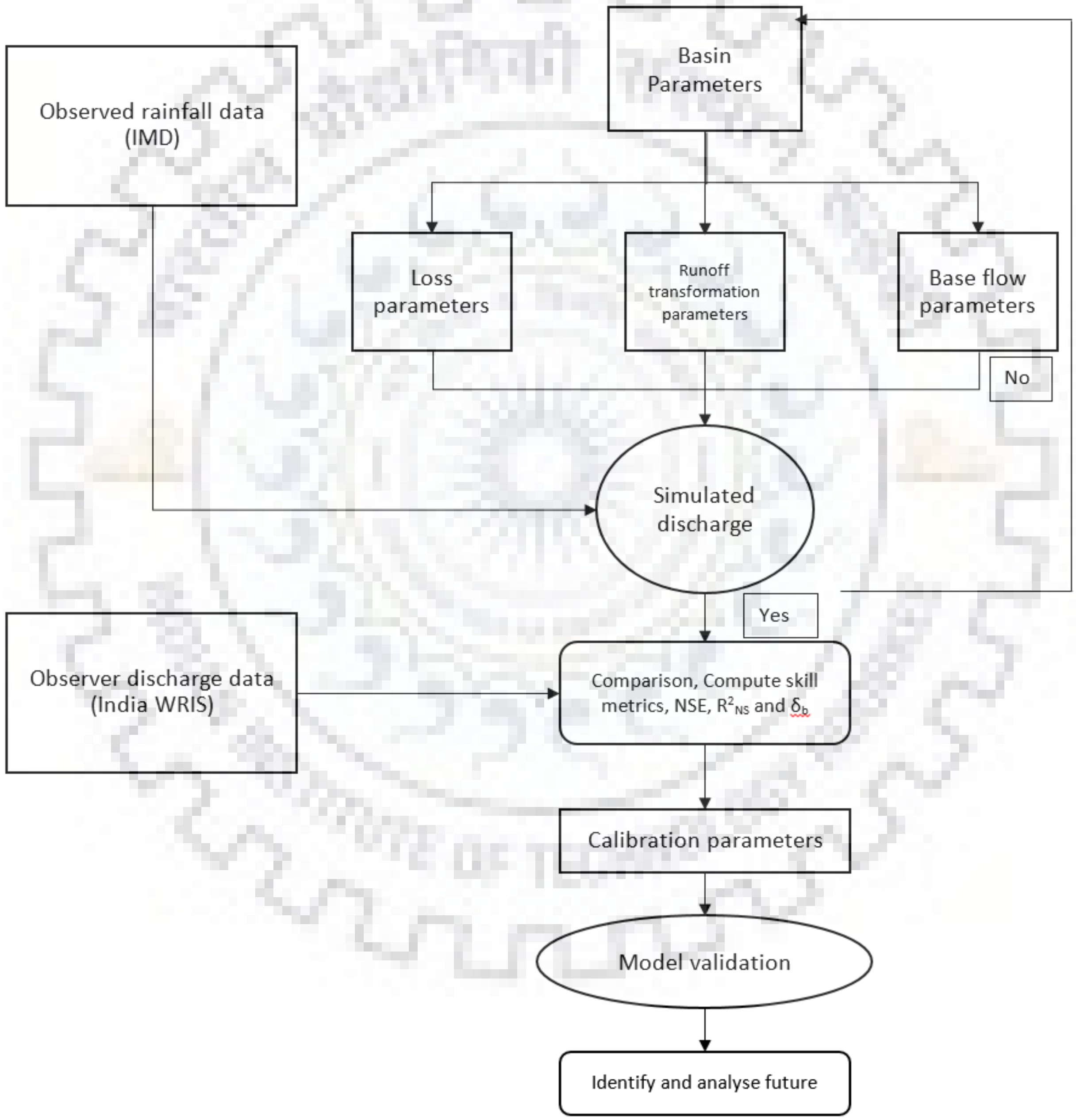


Figure 4.6: Steps to carry out rainfall runoff simulation in HEC-HMS

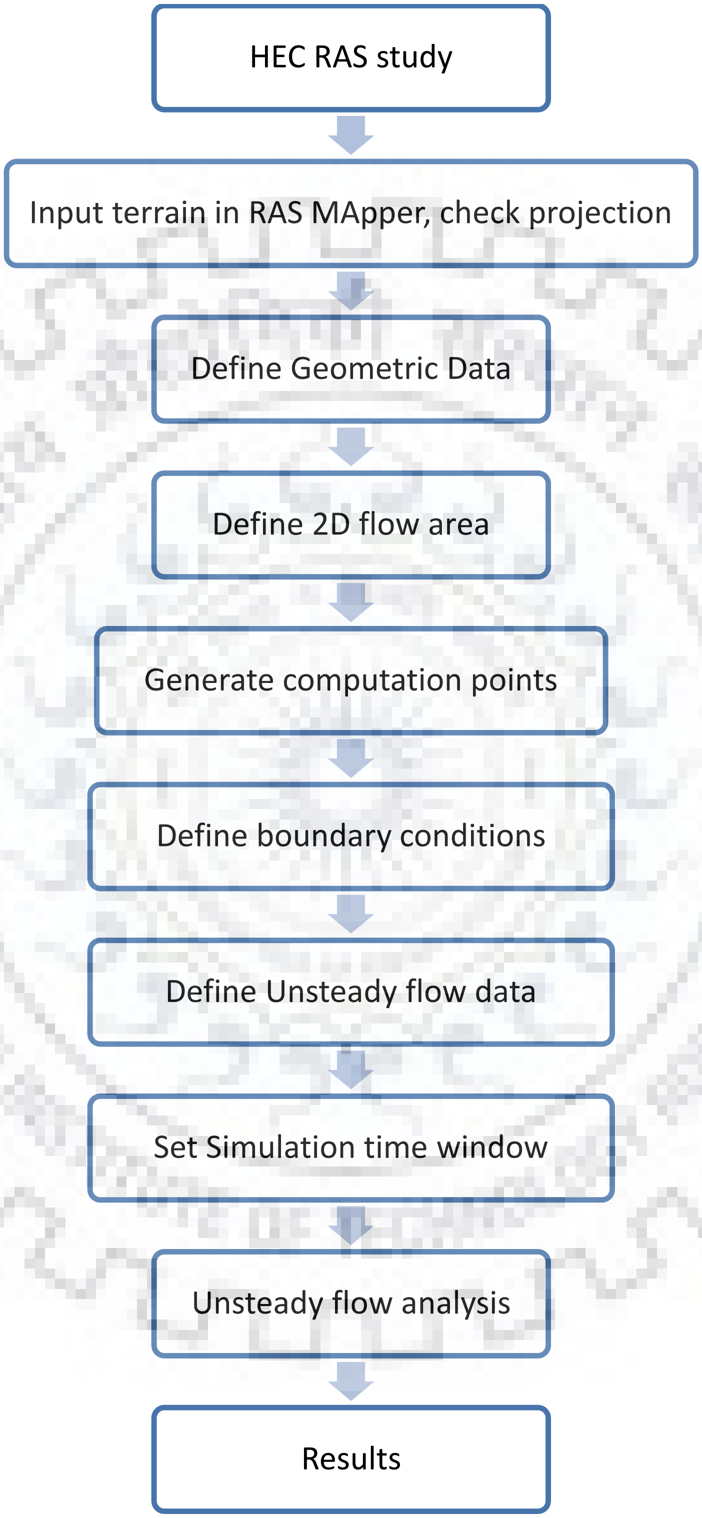


Figure 4.7: Steps to prepare inundation map in HEC-RAS

4.5.1 **Transform method:** Clark's Unit Hydrograph

In this method of transform, the user is not required to develop a unit hydrograph. This synthetic unit hydrograph method has a curve for time versus area inbuilt in the HEC-HMS. This curve is further used to produce the translation hydrograph resulting from a rainfall event. Change in storage across the watershed is accounted for by routing the resultant hydrograph through a linear reservoir.

$$T_C = (2.587L^{0.8}(\frac{1000}{CN} - 9)^{0.7})/1900S^{0.5}$$

$$S_C = cT_C$$

The major inputs required here are **time of concentration T_c** and **storage coefficients S_c** which are calculated as per the above equation. Time of concentration is the time required for the most remote or distant point in the watershed to reach the outlet. The time of concentration is a function of curve number, the length of the stream and the slope of the catchment. Storage coefficient depends directly on the time of concentration. It affects the peak discharge characteristics of the hydrograph. The higher the value of 'c', the lower the peaking of the runoff hydrograph will be. The total impervious area of the basin needs to be specified since there will be no runoff generation for that particular area of the basin. Table 4.4 shows the calculations done to compute the time of concentration for the study.

Table 4.4: Time of concentration for sub basins using Clark's unit hydrograph method

Sub catchment	Curve number (CN)	Length (L) of stream in sub catchment (km)	Mean slope (S) of sub catchment (%)	T_C (hours)
Malappuram	80	58.21	9.96	0.63
Angadipuram	80	28.32	8.728	0.371
Perinthalamanna	80	29.69	11.038	0.331

4.5.2 Baseflow Method: Recession method

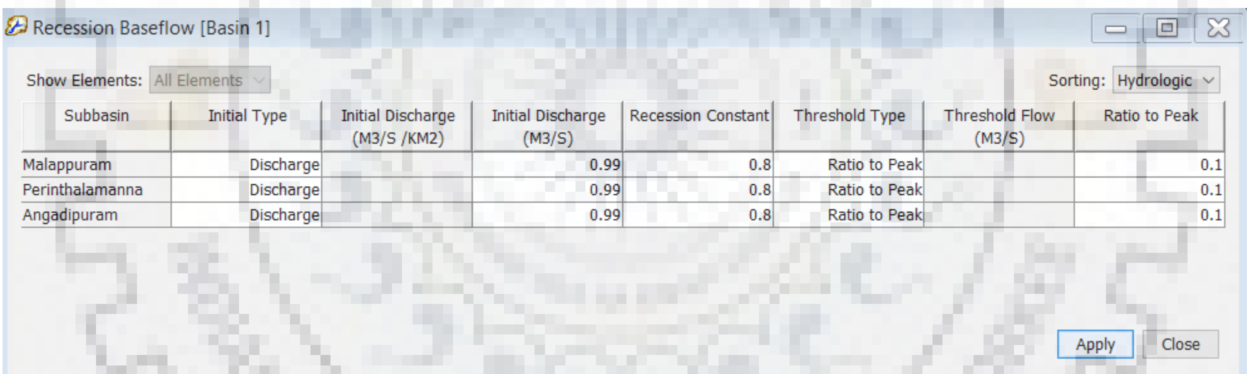
$$Q_B = Q_0 e^{-kt}$$

Baseflow is computed as per the equation given above. Q_b is the baseflow at any time'tʼ. Q_b or the baseflow decays or decreases with the progress of time.

Q_o is the initial discharge whereas k is the recession constant which has been taken as 0.8 during the calibration phase and is adjusted as the simulation progresses. The unit of the recession constant is day inverse. The recession constant k is the product of the following three components.

1. Recession constant for surface storage
2. Recession constant for interflow
3. Recession constant for baseflow.

Initial discharge is taken as the one which is present at the start of the simulation for that particular year. Figure 4.8 shows the inputs given in the HEC-HMS model for the baseflow.



Recession Baseflow [Basin 1]

Show Elements: All Elements   Sorting: Hydrologic

Subbasin	Initial Type	Initial Discharge (M3/S /KM2)	Initial Discharge (M3/S)	Recession Constant	Threshold Type	Threshold Flow (M3/S)	Ratio to Peak
Malappuram	Discharge		0.99	0.8	Ratio to Peak		0.1
Perinthalamanna	Discharge		0.99	0.8	Ratio to Peak		0.1
Angadipuram	Discharge		0.99	0.8	Ratio to Peak		0.1

Apply   Close

Figure 4.8: Input of data in HEC-HMS for recession method

4.5.3 Loss Method: SCS curve number

SCS – curve number method which has been developed by Soil Conservation Services (SCS) of USA is a simple, and established theoretical method for estimating the depth of direct runoff based on a particular precipitation event. This method depends on solely one factor i.e. the CN. The equation is adjusted for Indian conditions as the method was originally developed for the conditions in USA.

This method is the most time taking process because of the inputs required to calculate the Curve Number (CN)

The value of CN is dependent on following parameters:

1. Type of soil
2. AMC or Antecedent moisture condition
3. Land use and Land cover

4.5.4 Soil type: In order to determine the curve number, a hydrological sorting of soil is implemented. In this classification, the soils have been sub divided into four distinct classes namely A, B, C and D. This sub classification is based upon infiltration and other characteristics such as actual depth of soil, average clay content and permeability.

The classified hydrological groupings of soils are:

1. **Soil type A**: These kinds of soils are supposed to have large rates of infiltration when they are exhaustively wetted. These soils consist of deep, well to excessively drained sands or gravels. Runoff potential for these soils is low.
2. **Soil type B**: These soils have moderate rates of infiltration when completely wetted. They comprise of moderately well to well drained soils with moderate fine to moderately coarse texture. Runoff potential is moderately low
3. **Soil type C:** These soils are characterized by small rates of infiltration when completely wetted. They comprise of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. Runoff potential is moderately high.
4. **Soil type D**: When completely wetted, these soils are characterized by very low rates of infiltration. They consist of clayey soils which have a large potential for swelling (black soil) and soils which are present is locations where water table is permanently high. They have high potential of runoff.

The soil data for the study area can be found from the Department of Soil Survey and Soil Conservation website (http://www.keralasoils.gov.in/). The soil was found to be laterite and can be categorized as Group B (moderately low runoff potential) as per SCS method.

4.5.5 Antecedent moisture condition (AMC): The amount of wetness (moisture) which is existing in the soil at the commencement of any precipitation event is known as Antecedent Moisture Condition (AMC). To realize the practical application of AMC, it has been subdivided into three levels (Table 4.5):

1. AMC I: The soil is dry but not to wilting point
2. AMC II: Conditions are average
3. AMC III: Adequate precipitation has taken place over previous 5 days. Soils are fully saturated.

Table 4.5: Antecedent Moisture Condition for defining curve number values

Type of AMC	**Dormant Season**	**Growing Season**
I	< 13mm	< 36mm
II	13-28mm	36-53mm
III	> 28mm	> 53mm

The study region is put under the Antecedent Moisture Condition III condition since most of the rainfall is occurring during the monsoon season and it can be safely assumed that there was sufficient rainfall for the previous five days. CN is calculated for the same condition as per the following equation and the results are given by Figure 4.9.

$$CN_{III} = CN_{II} / (0.427 + 0.00573 CN_{II})$$

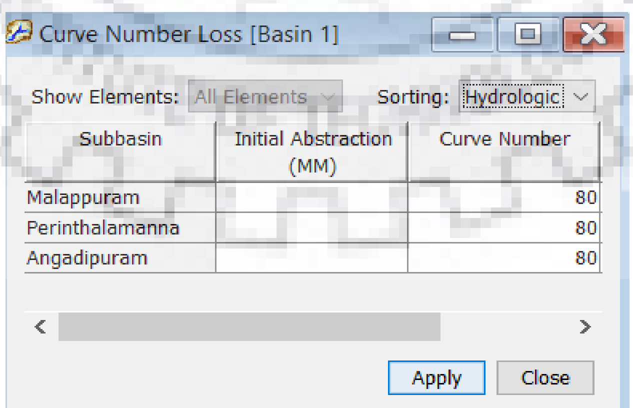


Figure 4.9: Input of data in HEC-HMS for curve number

4.6 Statistical methods for model evaluation: There are several statistical methods to evaluate the performance of the model, where basically the modelled and observed data are compared on a one by one basis. Based on the results of these statistical parameters, one can comment on the model's performance. The ones which have been used in current study are as follows:

4.6.1 NSE (Nash-Sutcliffe efficiency): It is a coefficient which normalizes the statistics and defines the comparative degree of the remaining variance (also known as noise) with respect to variance of the observed data (also known as information). This coefficient basically shows how well the plot of measured versus modeled data fits the 1:1 line. The range of NSE is from -∞ (minus infinity) to one (inclusive), where NSE = 1 is the most optimal value. NSE value of 1 means that there is no discrepancy in the observed and modeled discharge, hence the model is perfect. In general, values lying in between 0 and 1 are considered as acceptable for performance of the model. Values of this coefficient, which are less than 0 imply that the mean of measured values is a better predictor that the modeled values, hence the model's performance is not acceptable.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{observe} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{observe} - Y_i^{mean})^2} \right]$$

4.6.2 Coefficient of determination (R^2): Coefficient of determination (R^2) describe the degree of collinearity between modeled and observed data. R^2 basically defines the proportion of the variance in observed data.

The values of R^2 range from a lowest value of 0 to a highest value of 1, with greater values signifying a lesser amount of variance in error, and normally values which are more than 0.5 are suitable (Santhi et al., 2001, Van Liew et al., 2003).

4.6.3 PBIAS or Percent bias: PBIAS also known as Percent Bias calculates the average inclination of the modeled figures to be greater or smaller than the measured figures (Gupta et al., 1999). This parameter is computed as per the following formula

$$PBIAS = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{observe} - Y_i^{sim}) * 100}{\sum_{i=1}^{n} (Y_i^{observe})} \right]$$

where PBIAS is the deviation of the evaluated data and is expressed in percent.

The optimum value of this coefficient is 0.0 percent. Smaller values represent precise model imitation. The values of PBIAS can be either positive or negative with positive values indicating model underestimation and negative values indicating model overestimation.

4.6.4 Root mean square error (RMSE)-observations standard deviation ratio (RSR): This coefficient is one of the most frequently adopted statistical parameter (Chu and Shirmohammadi, 2004; Singh et al., 2004; Vasquez-Amábile and Engel, 2005). It is usually acknowledged that smaller values of this coefficient represent an acceptable performance of the model. Singh et al. (2004) issued a guideline stating as to what is deliberated as a low RMSE based on the observations standard deviation. Based on the recommendations made by Singh et al. (2004), a new statistical parameter to evaluate the performance of the model was developed. It was given the name RMSE-observations standard deviation ratio (RSR). RMSE is basically standardized by RSR. RSR is basically the ratio of the RMSE and standard deviation of observed data and is calculated as per the following formula

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2} \right]}{\left[\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{mean})^2} \right]}$$

The advantages of RMSE are integrated by RSR. This coefficient also includes a scaling factor, which helps in applying the ensuing statistic and reported values to numerous elements. The value of RSR varies from the optimal value of 0, to a maximum value of 1. RSR value of 0 means a perfect model. The lower the value of RSR, the lower the RMSE, and the better the model simulation performance.

4.7 Preparing inundation maps using HEC-RAS-: Once the modeled flood hydrographs are obtained, terrain data for the area of interest is given as input in the RAS mapper. This is basically the digital elevation model (DEM) of the study area. The projection of the file is checked before it is used in RAS mapper. The geometric data is defined for the area of interest in form of 2D flow area which is itself defined by selecting points in the basin. This creates a computation grid (Figure 4.10) where the RAS will carry out the computation.

The boundary conditions (upstream and downstream) for the river basin are defined in this computation grid. Following this, the unsteady flow data (hydrographs) are given as input for the upstream boundary condition and the simulation time window is set. Since the year 2007 has been used as the modeling year, time window for this year is defined. Unsteady flow analysis is then carried out, the results of which is given in the form of inundation maps.

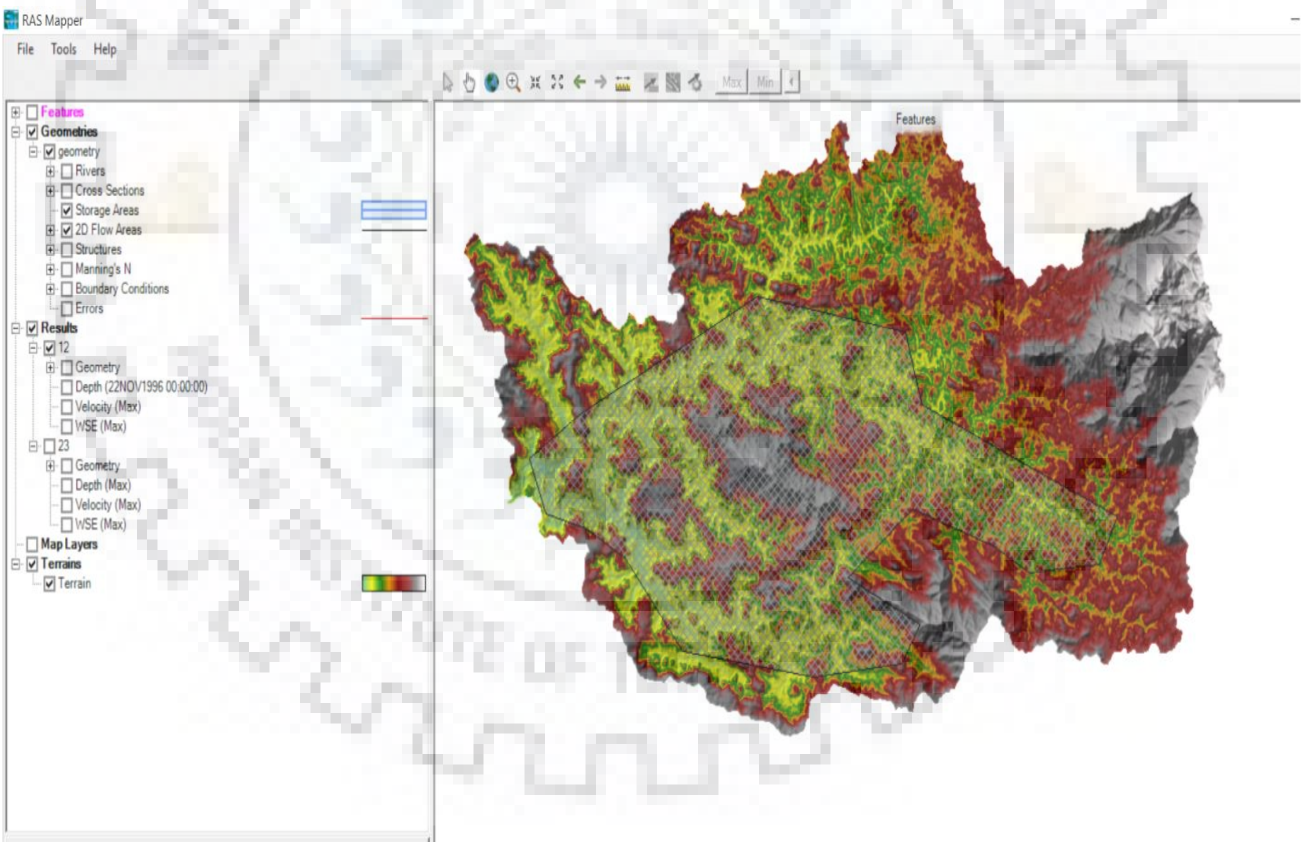


Figure 4.10: Development of 2D flow area in RAS

CHAPTER 5
RESULTS AND ANALYSIS

5.1 Rainfall variability: The following figure 5.1 show the variation of the rainfall in the Angadipuram and Perinthalamanna gauging locations.

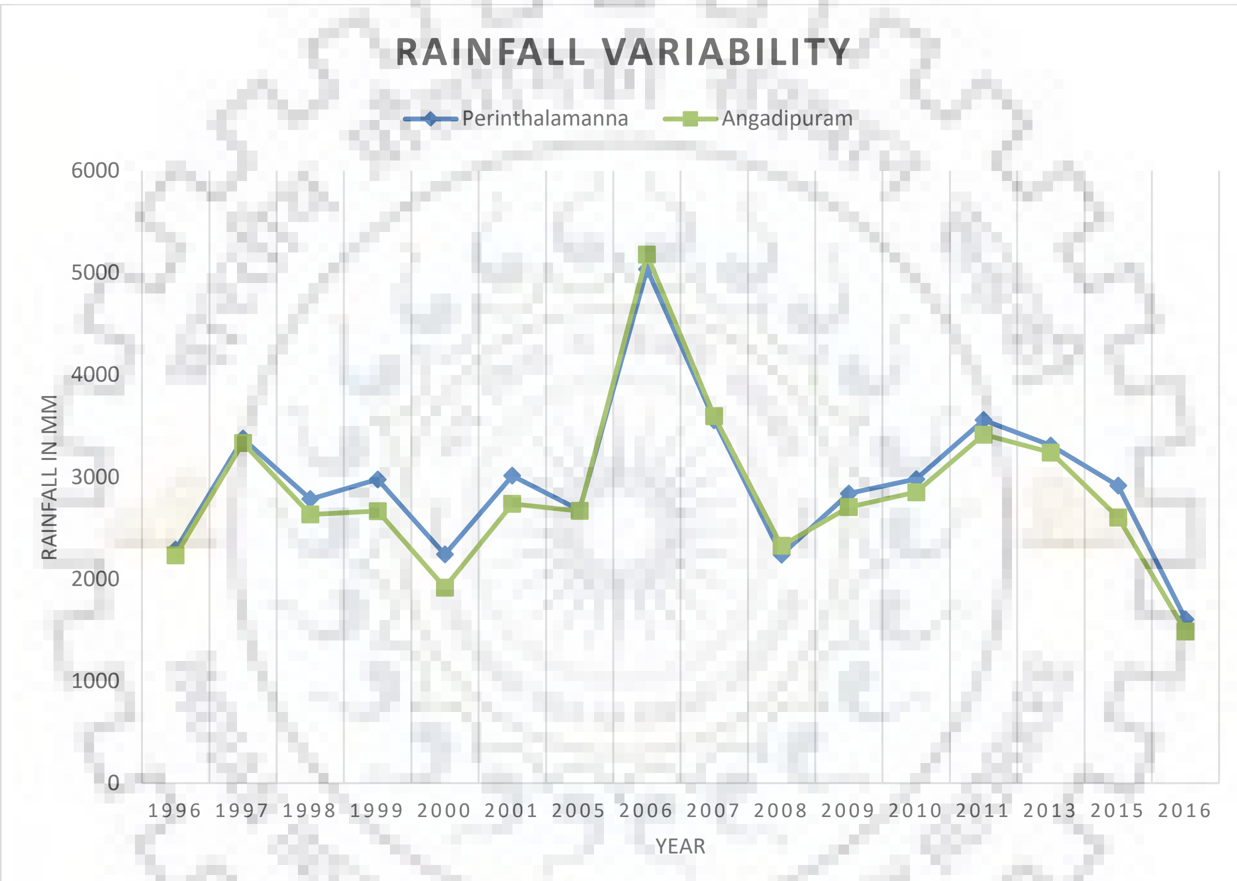


Figure 5.1: Rainfall variability in Perinthalamanna and Angadipuram

As is evident from the graphs, the rainfall in the sub basins of Angadipuram and Perinthalamanna is above the national average rainfall of 1200mm. The average rainfall for these basins is nearly 2900mm which nearly 250% more than the national average rainfall. So it can be safely concluded that the study region is prone to flooding.

It can also be observed that the year 2006 had abnormally high rainfall. This is due to the fact that the data was inconsistent for this year and hence this year was not considered in the validation phase of the model. Also the year 2007, with nearly an average 3600mm of rainfall experienced flooding. The floodings can be attributed to the above average rainfall for the study area.

5.2 Model Warm Up: The model was run for the years 1996 and 1997 for warm up to check the connections between various elements of the model such as junctions, streams, basins etc. The connections are adjusted and modified to give the elements a logical relation so that further calibration and validation can be carried out using the model.

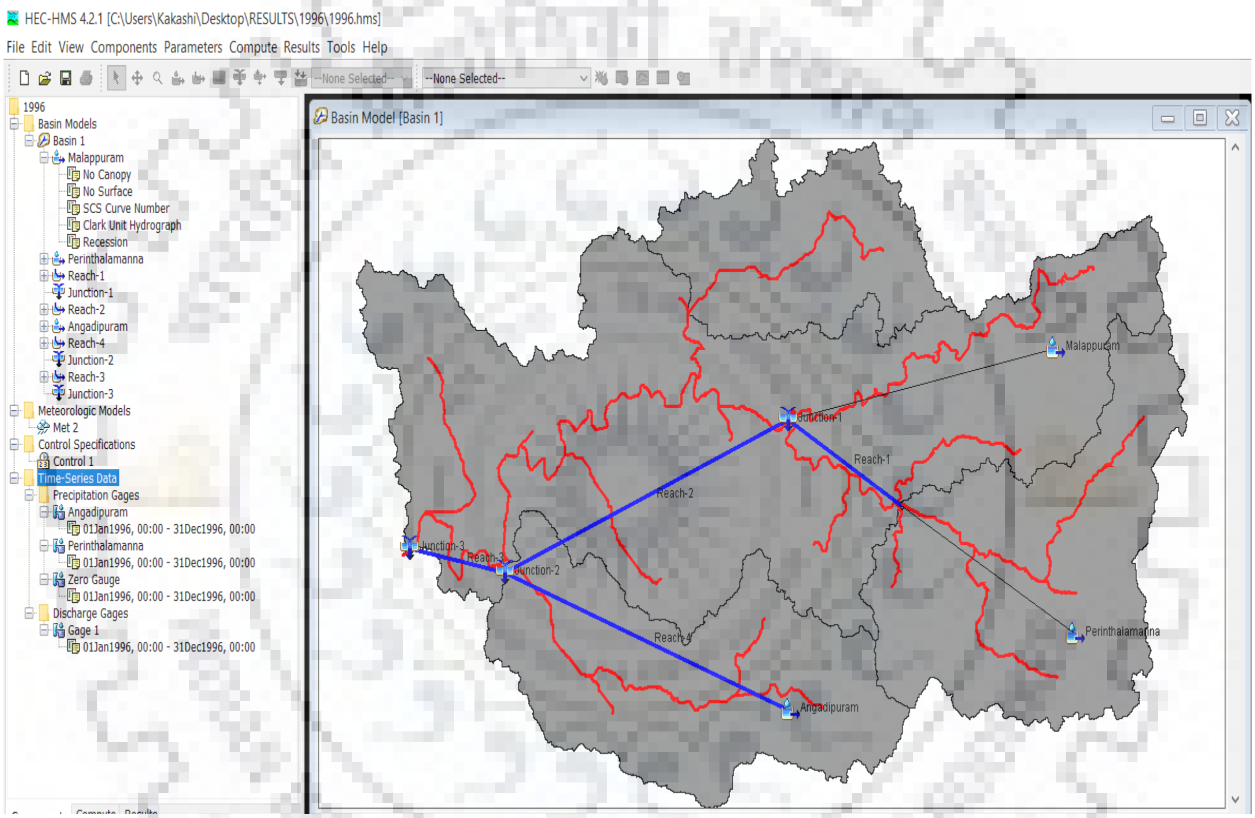


Figure 5.2: Setting up HEC-HMS for a warm up simulation of model

5.3 Model calibration: Rainfall discharge data for the years 1999-2005 has been used to calibrate the model (Figure 4.3). Since no data for the Malappuram sub catchment was available, the average of the rainfall of the Perinthalamanna and Angadipuram was used as the rainfall input for this basin. The model is initially calibrated with curve number value of 80 and recession constant as 0.8. This yielded over estimation of simulated discharge values and the statistical parameters were not in the acceptable range. To reduce the runoff, the curve number is reduced since lower the curve number, more is the infiltration and lower will be the surface runoff. However, significant changes in the simulated discharge values is not observed by reducing the curve number.

Recession constant (k) is then adjusted to 0.85 which gives significant improvement in the results as is reflected from the values of various statistical parameters (Table 5.2). This significant change in simulated discharge from changing the recession constant indicates that it is the most sensitive parameter for the basin.

A final value of 55 for curve number and 0.98 for recession constant is obtained from the calibration process. The time of concentration which depends on the curve number is also adjusted when the changes in curve number are made. The calibration results are shown by Figure 5.9.

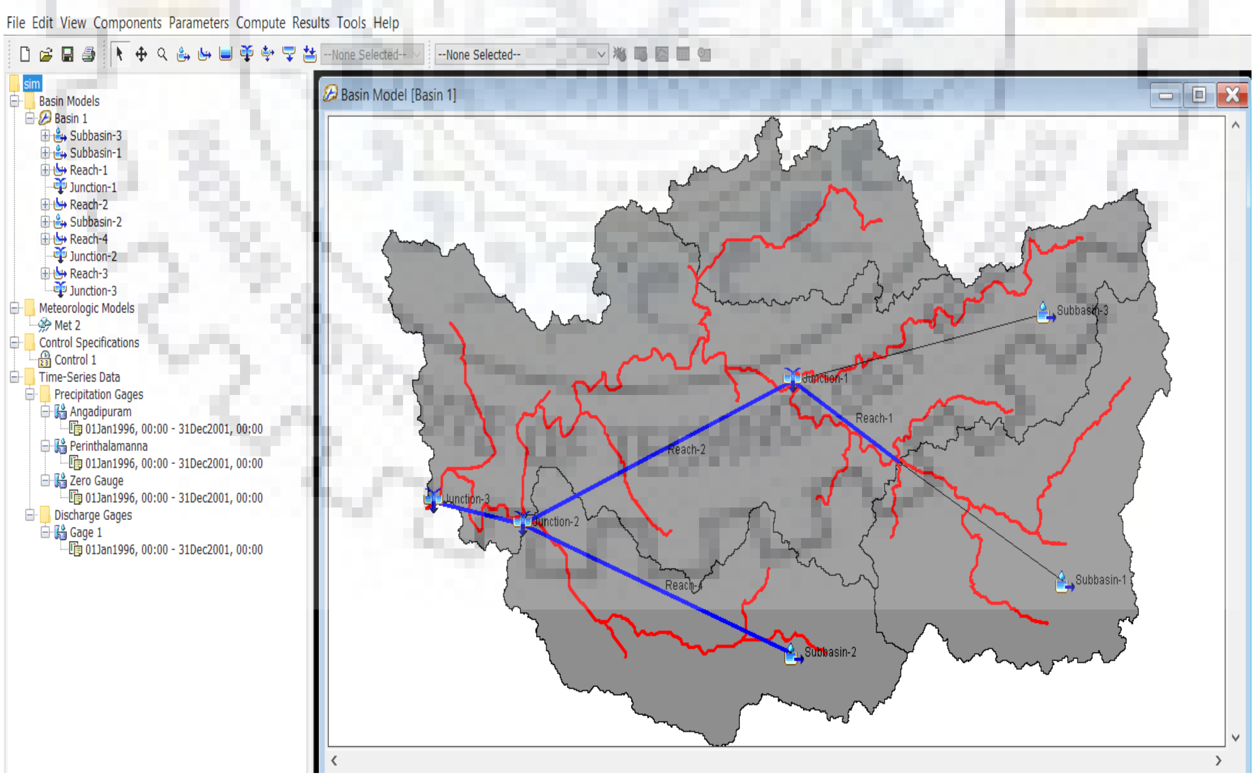


Figure 5.3: Setting up HEC-HMS for model calibration

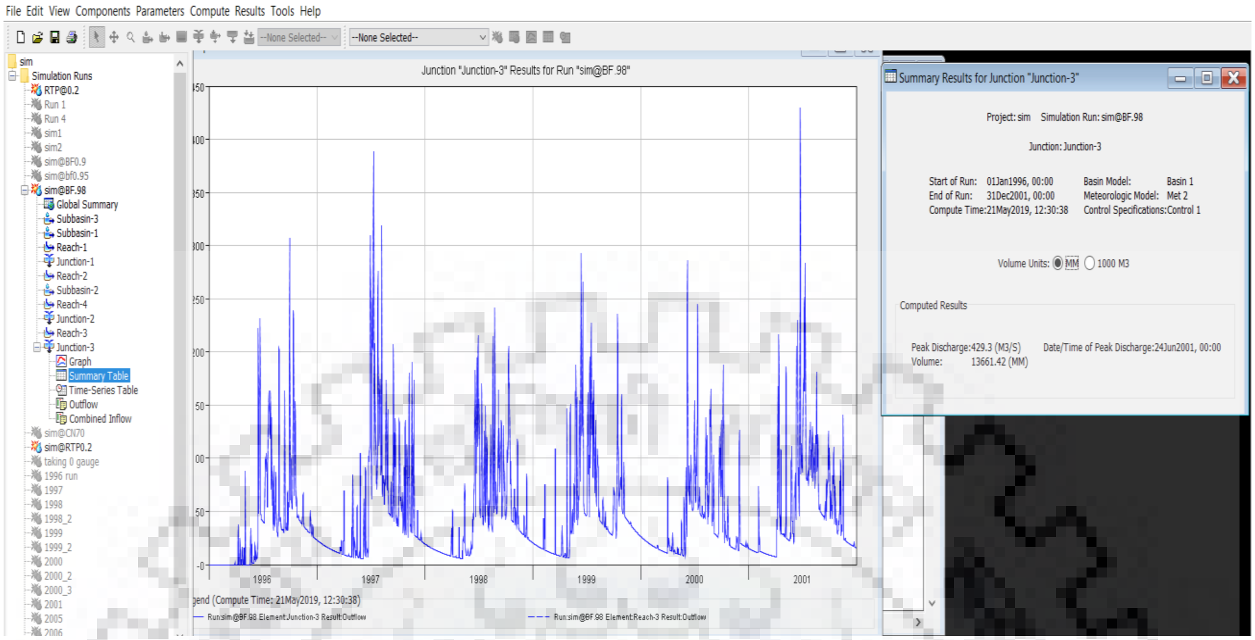


Figure 5.4: Flow hydrographs obtained in HEC-HMS from model calibration

5.4 Model validation: Rainfall and discharge data from the years 2006-2011 is used for model validation (Figure 5.5). The results however are not quite as expected as is indicated by the statistical parameters. There are significant differences in the values of the statistical parameters from the calibration phase. Upon closely observing the rainfall data, it is found that in the year 2006, the rainfall values are significantly high during the monsoon season (nearly 8000mm) but the discharge values are quite low. So we can conclude that the data for the year 2006 is not consistent. Figure 5.7 shows the inconsistency between the rainfall and discharge data for the year 2006. So the year 2006 is discarded from the validation phase and hence, validation is carried out from the years 2007 to 2010.

The simulation results (Figure 5.10) for discharge now obtained are in accordance with the calibration results as is indicated by the acceptable values of statistical parameters (Table 5.2). At this phase, the model is said to have been validated and now the model can be used to predict runoff generation from future rainfall events in the study area.

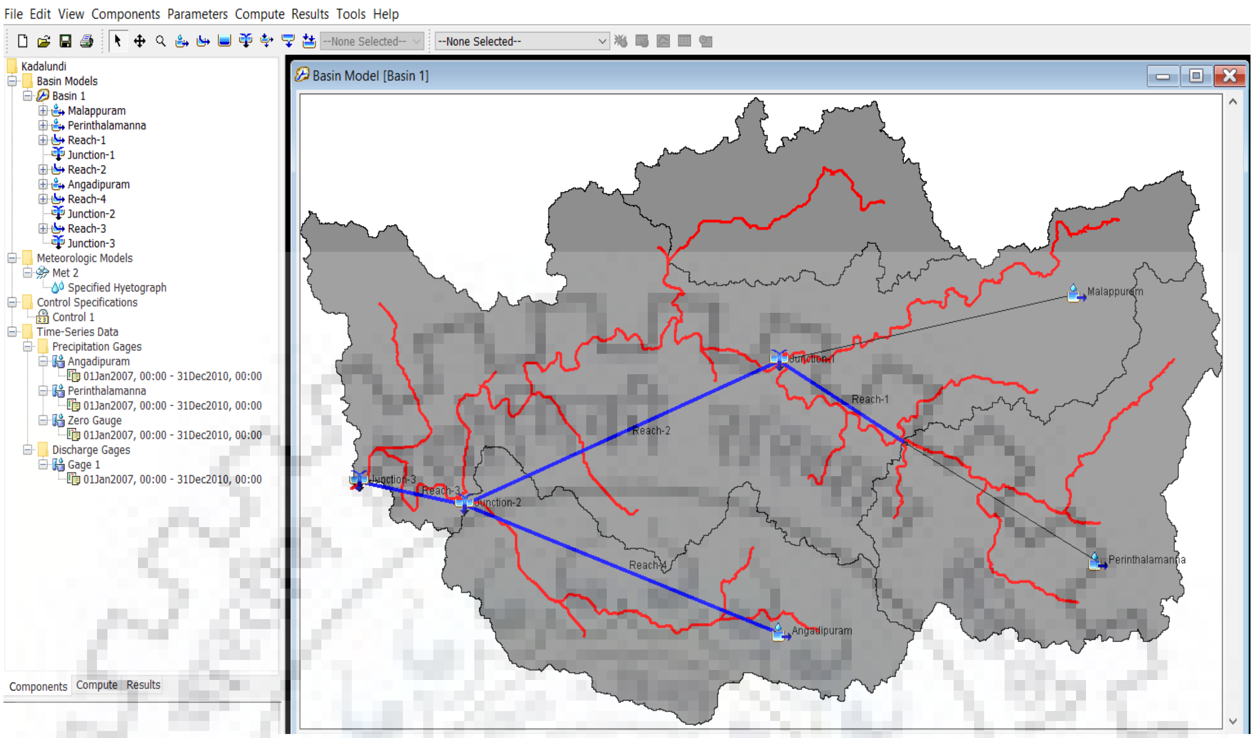


Figure 5.5: Setting up HEC-HMS for model validation

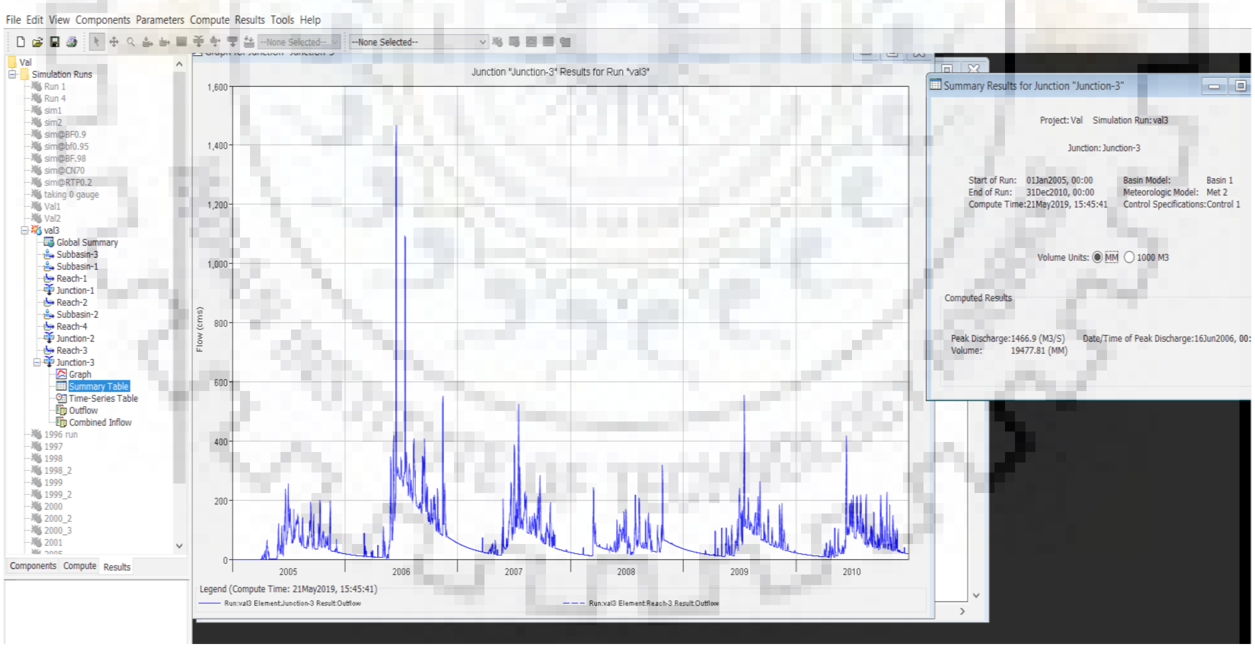


Figure 5.6: Flow hydrographs obtained in HEC-HMS from model validation with year 2006

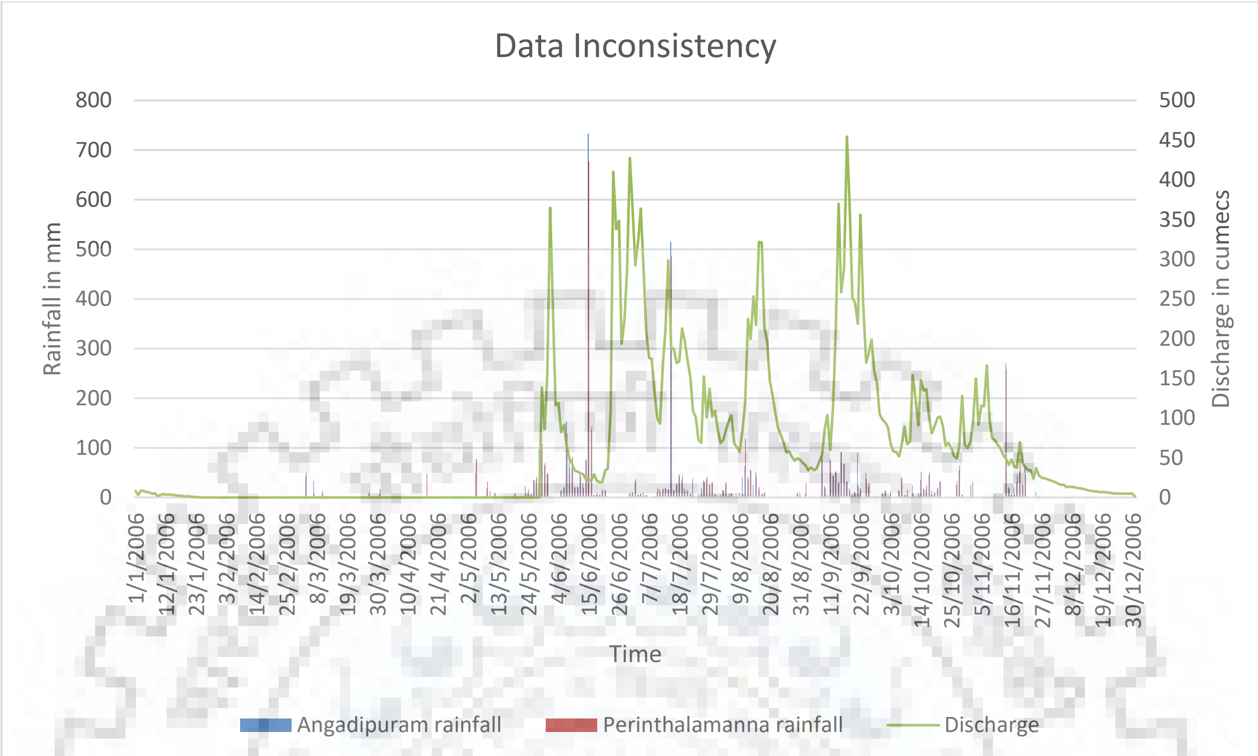


Figure 5.7: Graph showing inconsistent data for the year 2006

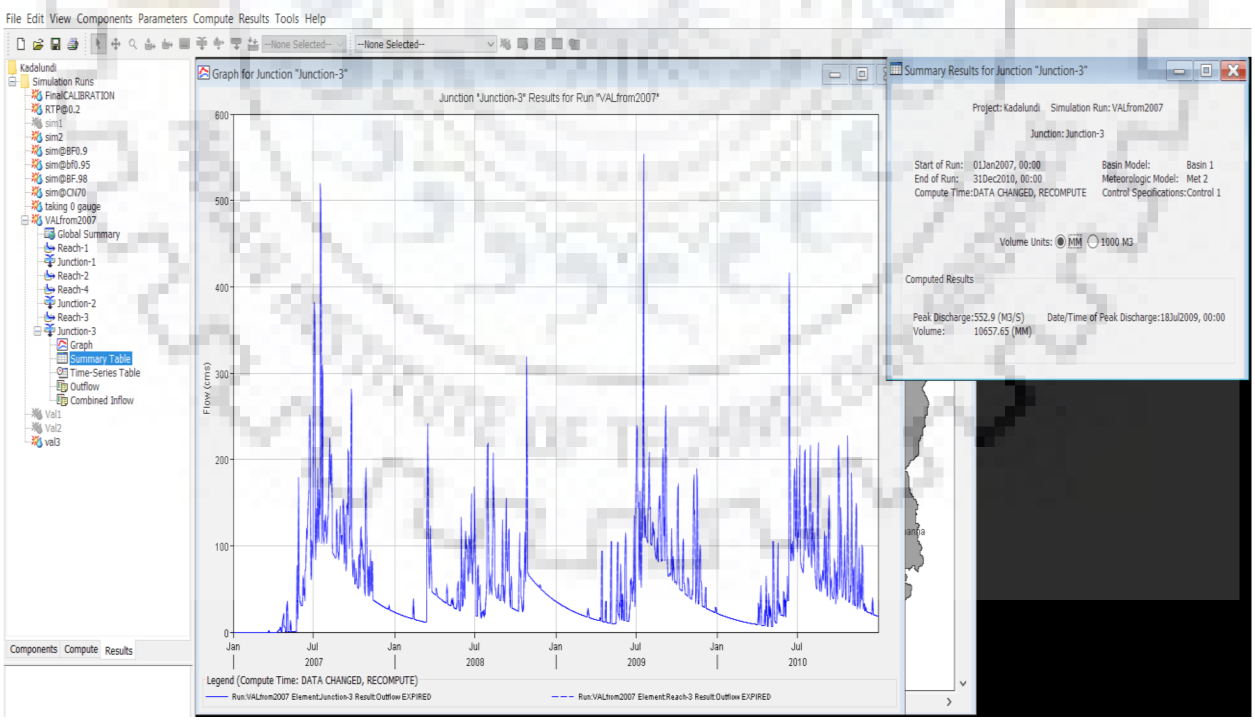


Figure 5.8: Flow hydrographs obtained in HEC-HMS from model validation without year 2006

The model was initially calibrated using curve number as 80, recession constant as 0.8 and ratio to peak as 0.1. This calibration yielded unsatisfactory results as the discharge was overestimated by a large amount. The peak observed discharge was 257 cms (cubic meters per second) as compared to the computed discharge of 393 cms when curve number was taken as 80. The peaks of the observation were however consistent with time. Since curve number is the method to compute loss in the present model, the value of curve number was reduced step by step to check the consistency of results. Reducing the curve number increases the infiltration which would in turn reduce the surface runoff. To deal with the irregularity in results, the curve number was decreased to 78, then 75 and finally to 70 after which the differences in simulated peak discharge and observed peak discharge was less than 80 cms. However, further changes in the CN did not yield significant improvements in the results.

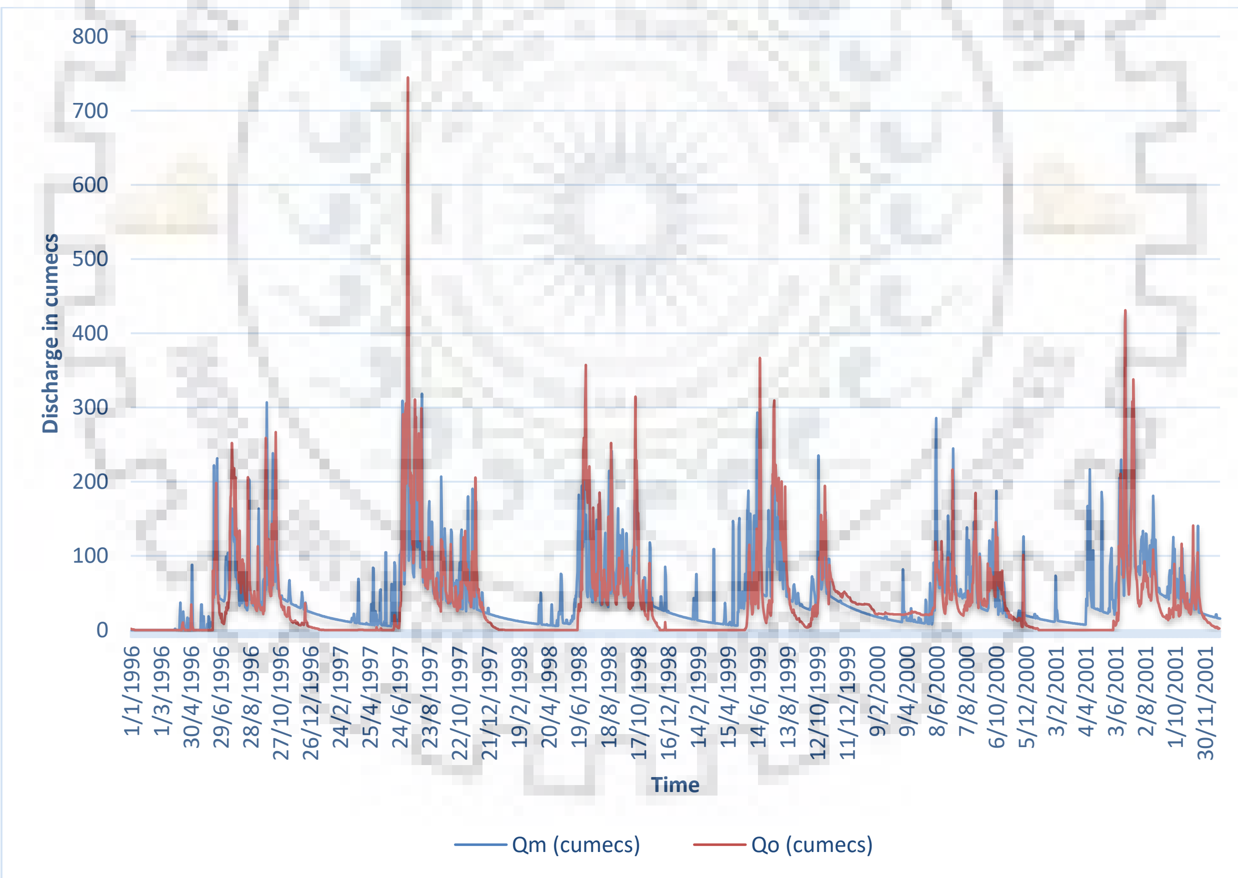


Figure 5.9: Plot of flow data obtained during model calibration

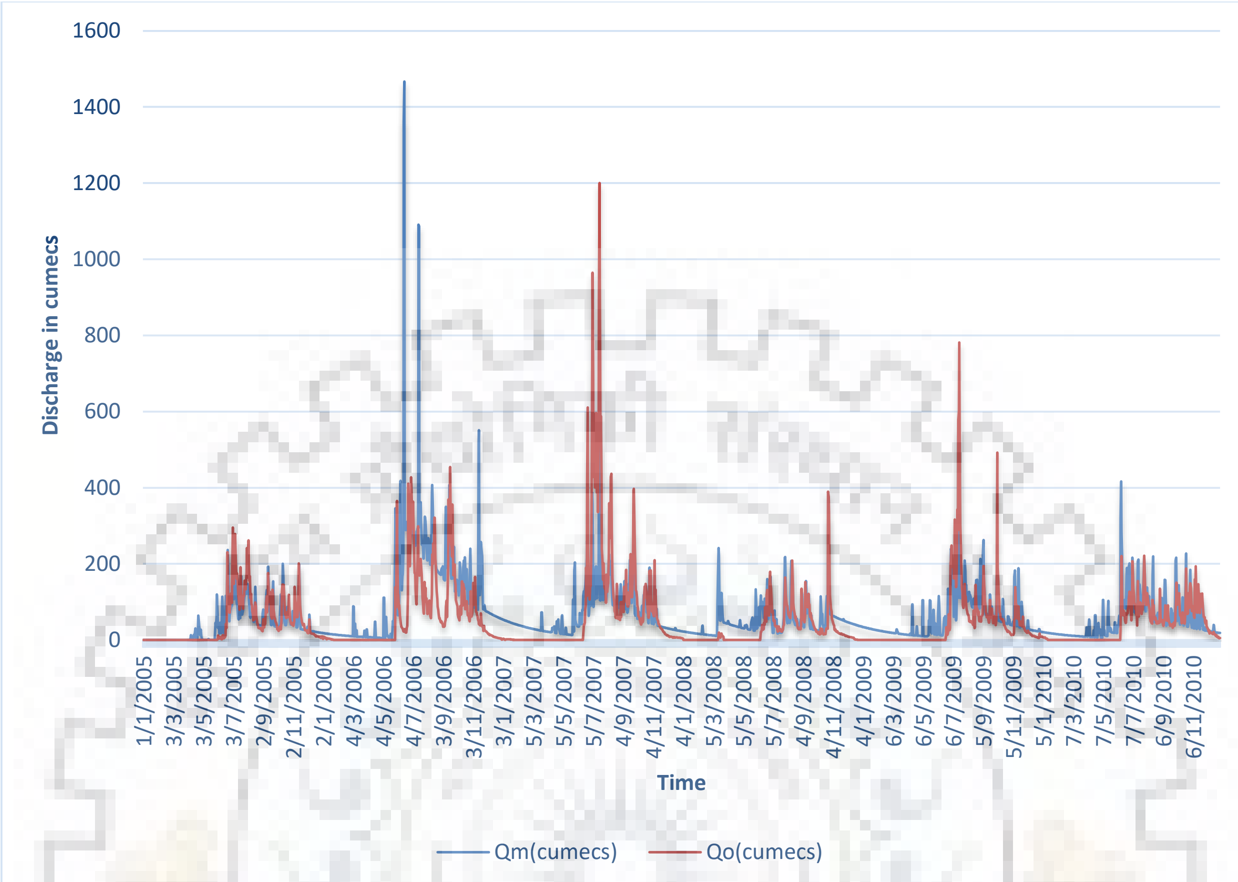


Figure 5.10: Plot of flow data obtained during model validation with year 2006

Since time of concentration also depends on the CN, the values for T_c and S_c were also adjusted accordingly. A decrease in the CN resulted in the increase of T_c and S_c as they vary inversely with the CN as shown here

$$T_C = (2.587L^{0.8}(\frac{1000}{CN} - 9)^{0.7})/1900S^{0.5}$$

Increase in T_c and S_c did not alter the peaks but residual flow was observed post the rainy season as water was now taking more time to reach the outlet of the catchment.

Table 5.1: Acceptable range of various statistical parameters (Moriasi et al. 2007)

Performance Rating	RSR	NSE	PBIAS (%)
			Stream Flow
Very Good	0.00 - 0.50	0.75 - 1.00	0.00 - ±10
Good	0.50 - 0.60	0.65 - 0.75	±10 - ±15
Satisfactory	0.60 - 0.70	0.50 - 0.65	±15 - ±25
Unsatisfactory	≥ 0.70	≤ 0.50	≥ ±25

The NSE values improved from -0.38 to 0.40 upon the changes made in the model but they were still below the acceptable range of 0.50 (Moriasi et al. 2007). PBIAS also showed negative deviation of -75 which was well below the acceptable of -25 to 25. The values of RSR and R^2 were also not within the acceptable ranges.

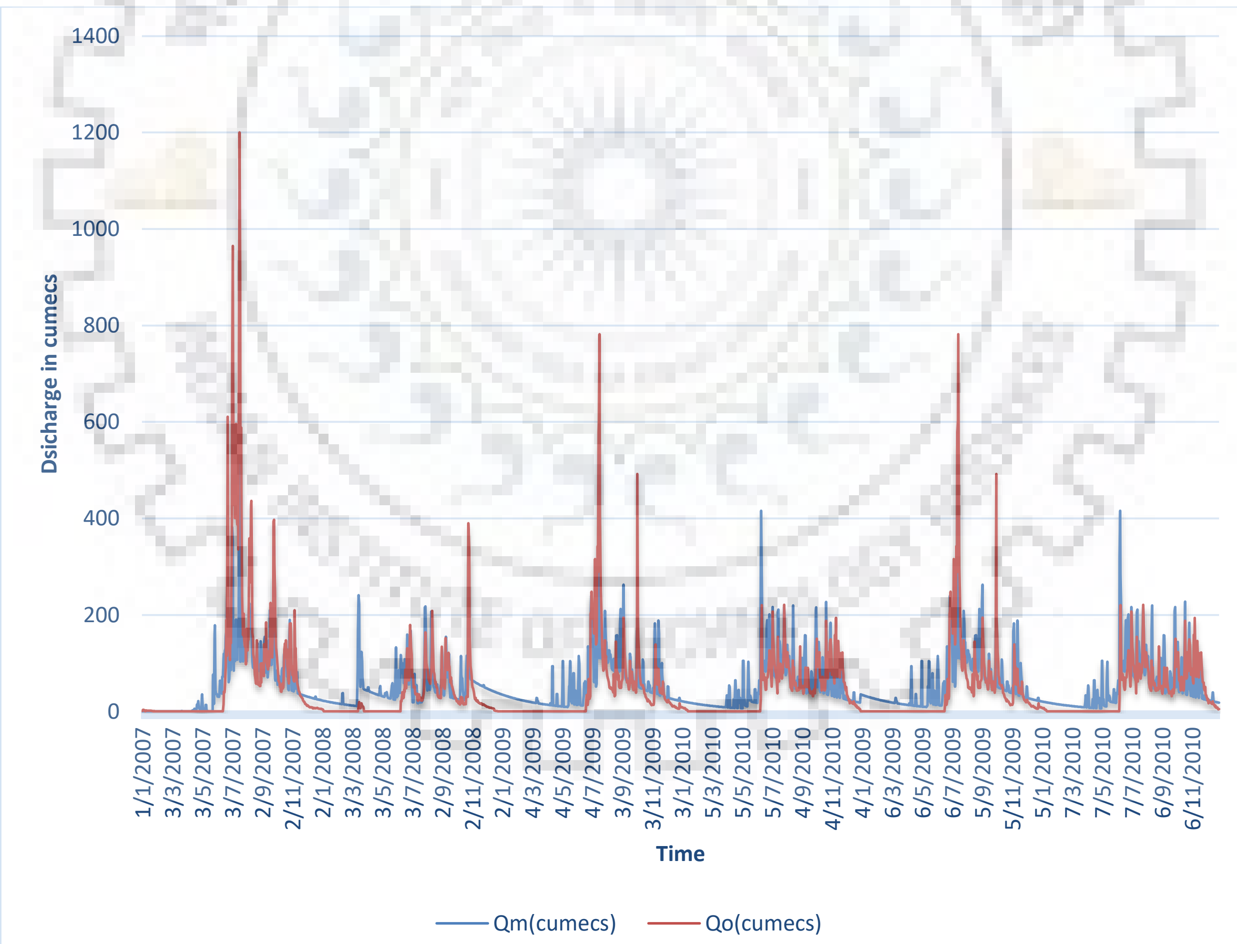


Figure 5.11: Plot of flow data obtained during model validation without year 2006

The recession constant ‘k’ has been adjusted from a value of 0.8 to 0.9 which yielded significant improvement in the results with the peak discharge difference between simulated and observed data coming down to less than 50 cms. This results implies that the recession constant is the most sensitive parameter in the Kadalundi river basin. The value of recession constant as 0.98 and ratio to peak as 0.2 yielded all the statistical parameters within the satisfactory range (Moriasi et al. 2007).

The model was then run to validate data from the year 2005-2010 with the CN as 70, recession constant as 0.98 and ratio to peak as 0.2. The model yielded highly unacceptable results with the value of NSE being 0.12 and RSR as 0.93. The discrepancy in the result was due to the inconsistency in the observed rainfall data for the year 2006 (Figure 5.7). Once the inconsistent data was removed from the model and validation was re-run for the years 2007-2010, the observed NSE value decreased from 0.69 to 0.53, which is within the satisfactory range. The values of coefficient PBIAS came down to -16.78 from -21.75 while the value of RSR also improved from 0.693 to 0.629. The negative values of PBIAS ascertain the fact that the modeled discharge is under estimated than the observed discharge values. So the value of PBIAS is in accordance with the model results. The minute changes in the values of PBIAS during the modeling also highlight the fact that it is a highly sensitive parameter (Moriasi et al. 2007).

Table 5.2: Observed values of various statistical parameters during modeling

Coefficient	NSE	PBIAS	RSR	Correlation R2
Calibration	0.697	-21.75	0.693	0.749
Validation(Inc. 2006	0.120	-25.85	0.937	0.563
Validation(exc. 2006)	0.539	-16.78	0.629	0.732

5.5 Inundation Map: Flood hydrograph obtained from the HEC-HMS modelling has been used to prepare the Inundation maps for the Kadalundi river basin. HEC-RAS requires terrain (DEM) and flow data as the major inputs for flood modeling. The terrain is checked for projection and geometric data is defined to find out the computational extent for the model. The upstream and downstream boundary conditions are defined next. The RAS mapper is then given the input discharge after which the model runs to generate the inundation map.

Inundation map has been prepared for the year 2007 when actual flooding took place in the Kadalundi river basin. The year had an average rainfall of 3600mm which is more than the normal annual average rainfall of 2900mm for the Kadalundi river basin. The flood hydrographs (modeled discharge) is given as input for the upstream boundary condition in the unsteady flow data. Model is then run for a simulation window for the year 2007 and inundation due to this discharge is obtained (Figure 5.12). Then another flood hydrograph, which is the observed discharge data for the study area is used to prepare inundation map which would give the actual flooding for the year 2007 (Figure 5.13).

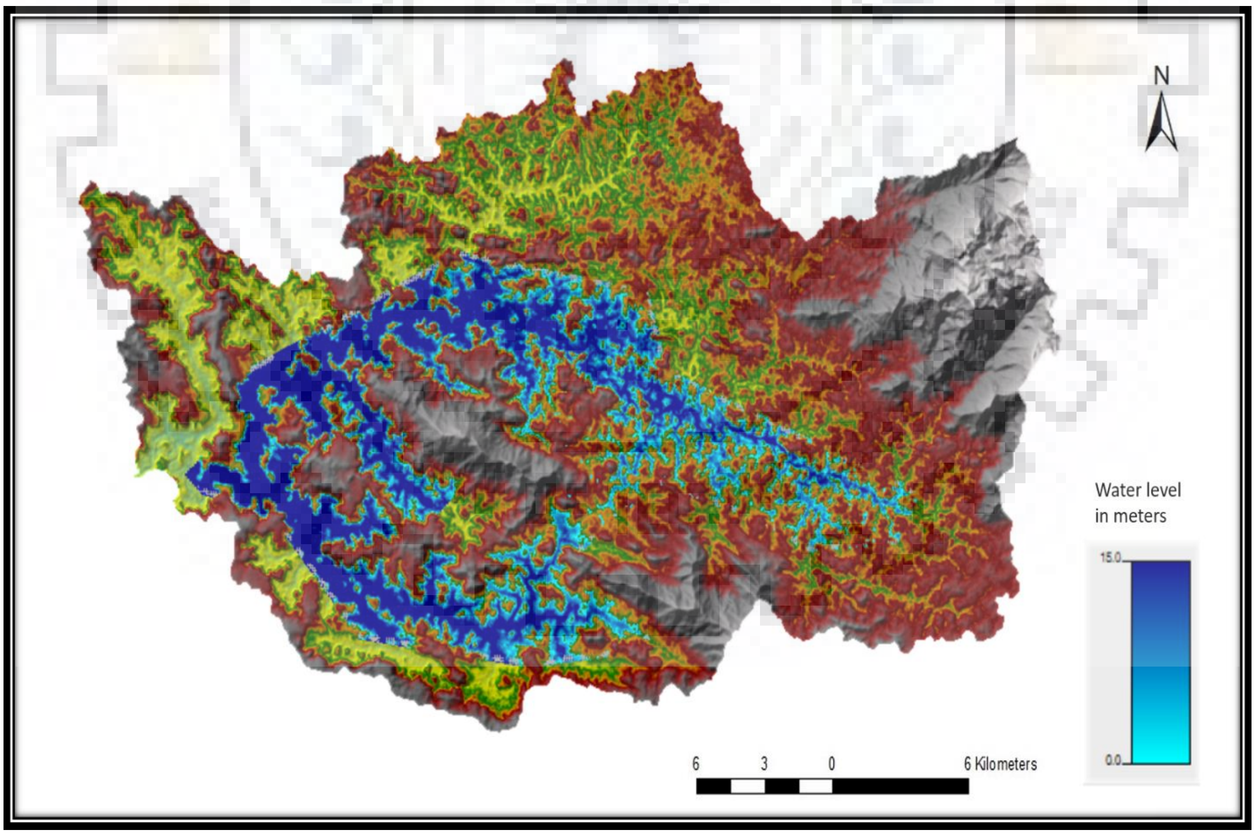


Figure 5.12: Inundation map produced using observed flow hydrograph

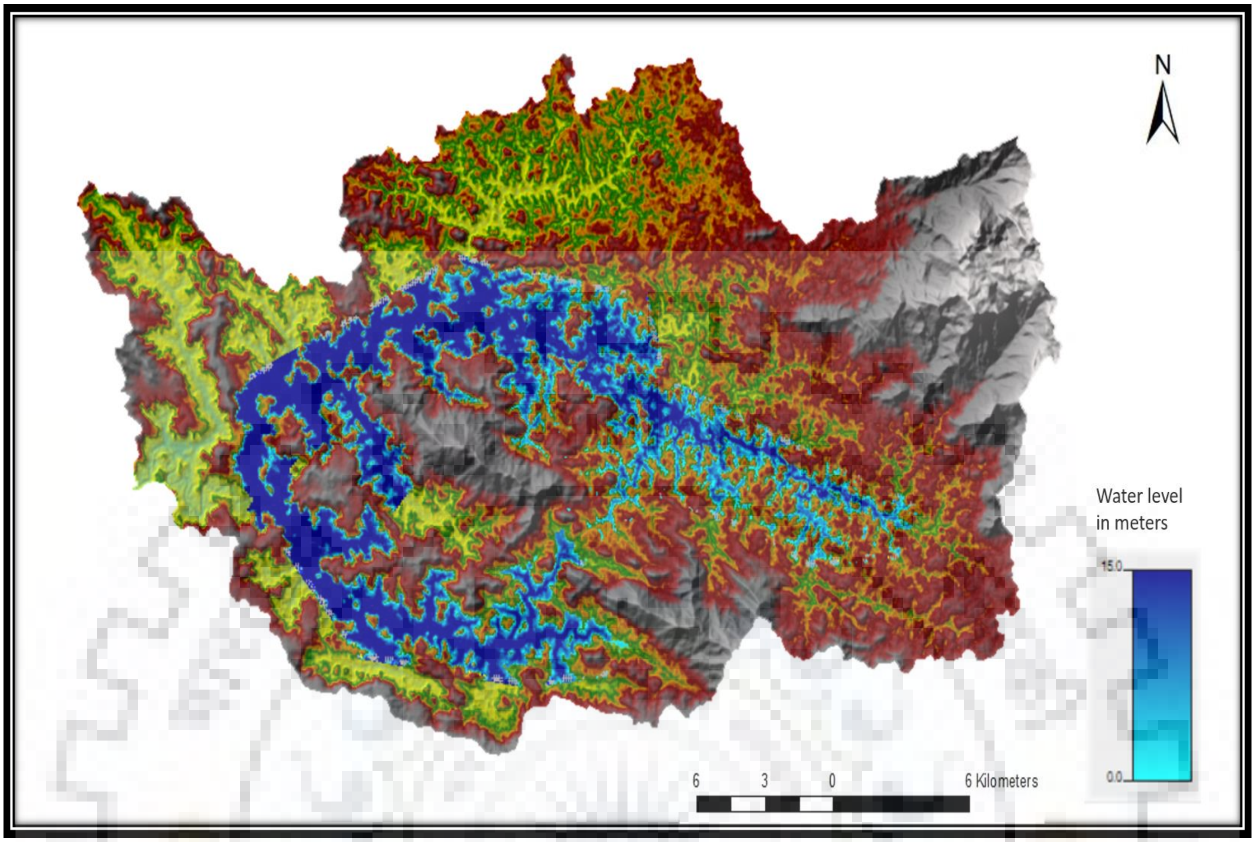


Figure 5.13: Inundation map produced using simulated flow hydrograph

The inundation maps are exported as raster files from the RAS mapper so that they can be further used in Arc GIS. After doing a raster comparison of the inundation maps using spatial analyst tool in Arc GIS, it can be concluded that inundation map produced using the actual discharge data gives more inundation in the Kadalundi river basin than the simulated discharge obtained from HEC-HMS. This compliments the fact that the modeled discharge was under estimated during the modelling phase and hence the lower inundation. The under estimation of simulated discharge was also concluded by the negative value of Percent BIAS. The raster comparison using the spatial analyst tool in Arc GIS returns a 72% match between the observed and modeled inundation map. Figure 5.14 shows the raster comparison results of Arc GIS.

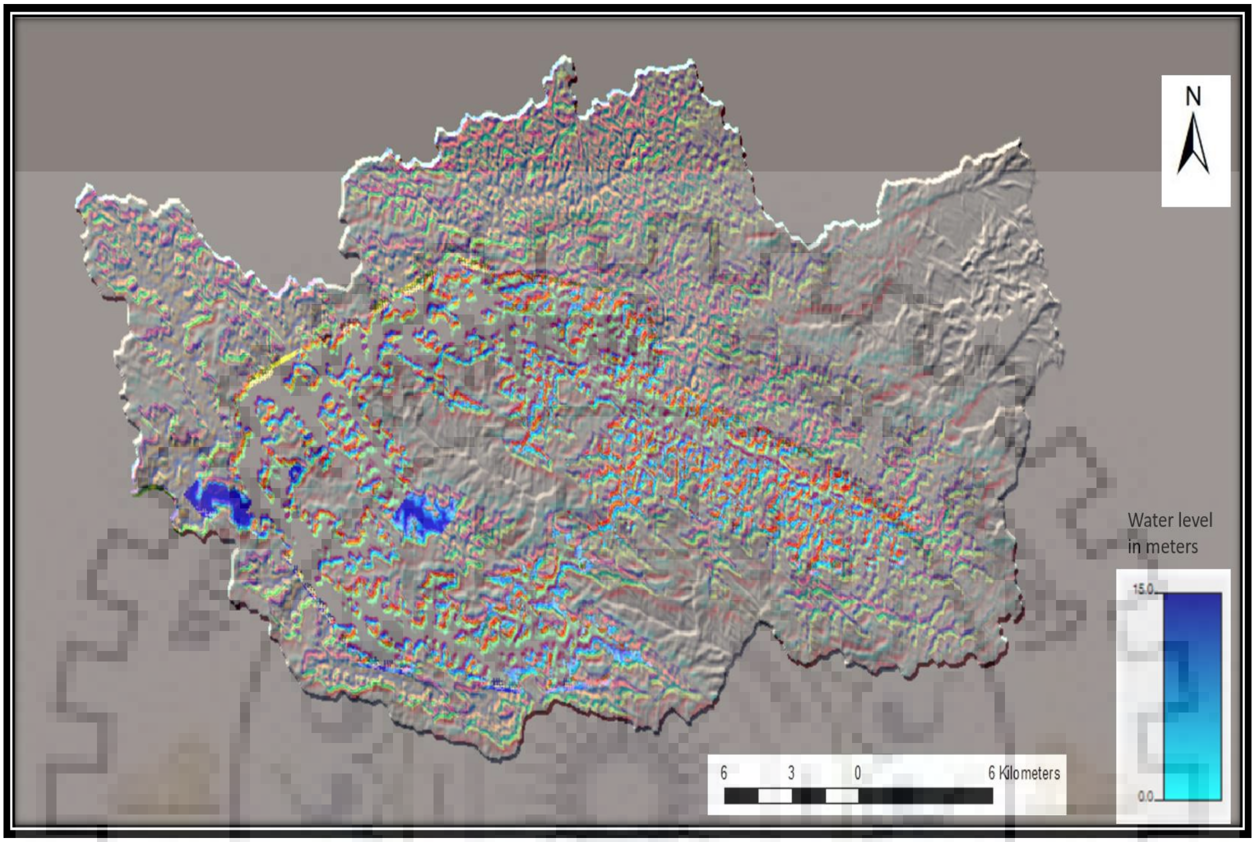


Figure 5.14 Raster comparison of observed and modeled inundation map

CHAPTER 6
CONCLUSIONS

The study focused on the Kadalundi river basin where major flooding events have occurred in 2007, 2009 and 2018. The idea of the study was to develop a hydrological model which is representative of the physical properties of the study area and could be further used to produce inundation maps.

Keeping in view the objectives set at the start of the study, the following conclusions could be made:

1. Basin parameters like slope and stream length for the Kadalundi river basin have been extracted in Arc GIS and a watershed has been prepared to carry out modeling. These parameters are further used in modeling.
2. Calibration and validation of the model for the Kadalundi river basin has been done in HEC-HMS with satisfactory results as is indicated by the goodness of fit parameters like NSE, RMSE, PBIAS and RSR. The values of all these parameters are within the acceptable range and the model can be said to be a satisfactory representation of the Kadalundi river basin.
3. Inundation maps due to the observed and modeled flood discharge (obtained from HEC-HMS) are prepared in HEC-RAS for the year 2007. The accuracy of the maps is validated by doing a raster comparison of the inundation maps using the spatial analyst in Arc GIS which returns a 72% accuracy.

In future, the inundation map along with a vulnerability map for the Kadalundi river basin can be used to assess the risk posed by floods in the study area by developing a risk map for the region, so that further measures to ensure mitigation of life and property can be taken up. Inundation maps are a crucial part of flood risk management and can help in flood forecasting and issuing warning. Loss of life and property can be estimated using the inundation maps based on which mitigation measures can be proposed. The viability of these measures can be ascertained by doing a cost benefit analysis.

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