MODELLING OF A RIVER SYSTEM USING MIKE-11

A DISSERTATION

Submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
HYDROLOGY

By
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MAY, 2016

CANDIDATE'S DECLARATION

I hereby certify that the work which is presented under the present dissertation work, entitled, "**Modelling of a River System Using MIKE-11**", submitted in partial fulfilment of the requirements for the award of the degree of Master of Technology in Hydrology, submitted to the Department of Hydrology of the Indian Institute of Technology Roorkee, India, is an authentic record of my work carried out during the period of July, 2015 - May, 2016, under the supervision of Dr. M. K. Jain, Associate Professor, Department of Hydrology, IIT Roorkee.

The matter embodied in this report has not been submitted by me for the award of any other degree

(Sabah Parvaze)

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CERTIFICATE

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

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ACKNOWLEDGEMENT

I would like to express with profound sense of gratitude, my cordial thanks to my supervisor Dr. Manoj Kumar Jain, Associate Professor, Department of Hydrology, IIT Roorkee, for his unstinting assistance, valuable suggestions, keen interest and constructive criticism in completion of this work by abetting me in understanding the whole work and presenting it in a better manner.

My sincere vote of thanks also goes to the entire faculty and staff of Department of Hydrology, IIT Roorkee for their valuable cooperation. This page of report will remain incomplete if I fail to thank my friends and classmates for their wonderful company. Their love and support even in tough times will always be imprinted in my memories.

I would like to dedicate this endeavour to my parents, who always remained with me to support and guide me. Their blessings and good wishes have always guide us on the right path in all walks of life. Without their support this work would not have reached its logical end.

Sabah Parvaze

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LIST OF ABBREVIATIONS AND SYMBOLS

AD	anno Domini
ANFIS	Adaptive Neural Fuzzy Inference System
d	Index of Agreement
DEERS	Department of Ecology, Environment and Remote Sensing
DEM	Digital Elevation Model
DFW	Design Flood for Window
DHI	Danish Hydraulic Institute
ECMWF	European Centre for Medium-Range Weather Forecast
EI	Nash and Sutcliffe Efficiency Index
FEH	Flood Estimation Handbook
FF	Flood Forecasting
GIS	Geographic Information System
HBV	Hydrologiska Byråns Vattenbalansavdelning
HD	Hydrodynamic
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
ICID	International Commission on Irrigation and Drainage
IFC	Irrigation and Flood Control Department
IHDM	Institute of Hydrology Distributed Model
IMD	India Meteorological Department,
INR	Indian Rupee
JKSPDCL	Jammu and Kashmir State Power Development Corporation Limited
LASCAM	Large Scale Catchment Model
MIKE SHE	MIKE Système Hydrologique Européen
NAM	Nedbør-Afstrømnings-Model
NDSI	Normalized Difference Snow Index
NRMSE	Normalized Root Mean Square Error
NRSC	National Remote Sensing Centre
R M Bagh	Ram Munshi Bagh
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
ROC	Relative Operating Characteristic
RR	Rainfall-Runoff
Sac-SMA	Sacramento Soil Moisture Accounting
SCE	Snow Cover Extent
SRTM	(Shuttle Radar Topography Mission
WRIS	Water Resources Information System

ABSTRACT

An integrated MIKE 11 NAM and HD model has been developed to simulate the rainfall-runoff process in the Ram Munshi Bagh Sub-basin of Jhelum Basin. The model was calibrated using daily rainfall, evaporation, temperature and discharge data of the period 1985 to 2005. The model was then validated by calculating the daily discharge values for next 10 years. The coefficients of determination for the model calibration and validation were 0.749 and 0.792 respectively, indicating good agreement between the observed and simulated runoff. The performance of the model was evaluated on the basis of Nash–Sutcliffe Efficiency Index (EI) and Index of Agreement (d). The EI and d values obtained were 0.75 and 0.93 respectively for calibration period while the values of EI and d for validation period were 0.79 and 0.94 respectively. Sensitivity analysis showed that Coefficient of Overland flow (*CQOF*) was the most sensitive parameter affecting model efficiency as well as peak and low flows significantly.

The calibrated model was also used to simulate extreme flood events occurred in the study basin. History of Kashmir is full of the tragic accounts of floods, which mostly occur due to insufficient carrying capacity of its only drainage channel i.e. Jhelum. The simulated extreme flood events showed a difference of 3-17% in their peaks for different flood events. For the 2014 flood event the simulated discharge was 2055 m^3/s which was only 3.2% more than the observed discharge indicating suitability of present model setup for simulating rainfall runoff process in the Jhelum basin including simulation of extreme flood events.

***Key Words**: Rainfall-runoff modeling, MIKE 11 NAM, HD, Efficiency Index, Index of Agreement, Sensitivity analysis, Jhelum, Flood*

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Modelling of rainfall-runoff response from a catchment is required for many purposes like flood forecast, planning, design, operation and management of the water resources systems, pollution control and many other applications. Planning, design and management of rivers as well as flood forecasting depends on precise estimation of the runoff volume, peak runoff and variability of runoff with time (Abu El-Nasr, 2000). Modelling of the rainfall-runoff process is a complex activity, which is influenced by various implicit and explicit factors like precipitation, evaporation, transpiration, abstraction, catchment topography and soil types (Shamsudin and Hashim, 2002).

A rainfall-runoff model is a mathematical representation defining the rainfall-runoff relations of a catchment area, drainage basin or watershed. Rainfall-runoff models allow abstraction of complex hydrological systems in order to control or understand some aspects of their behaviour. The hydrologic models have various forms depending on the purpose for which they have been developed. Generally two primary objectives are to be met by these models. First is to improve the understanding of the hydrologic processes operating in a basin and how changes in the basin may affect these processes. Secondly, they can be used for generation of synthetic sequences of hydrologic data for design or forecasting (Xu, 2003). Rainfall-runoff models are categorised as stochastic, deterministic, conceptual, theoretical, black box, continuous, event, complete, routing or simplified (Linsley, 1982).

Various hydrological models have been developed and widely used as tools for water and environmental resources management. Some of these models are lumped and conceptual, while others are distributed and physically based. Some of the well-known distributed and physically based models are SHE (Abbott et al., 1986), Thales (Grayson et al., 1992), IHDM (Beven et al., 1987; Calver and Wood, 1995), MIKE SHE (Refsgaard and Storm, 1995) and many more. Conceptual models comprise the most extensively developed and practically applied group of hydrological models (Zhang, 2005). Some of the conceptual models are HBV (Bergstr¨om and Forsman, 1973; Bergstr¨om and Singh, 1995), Sac-SMA (Burnash and Singh, 1995), and LASCAM (Sivapalan et al., 1996). NAM has been employed to model the hydrological processes in a substantial number of catchments encompassing nearly all climatic regimes of the world (Refsgaard and Knudsen, 1996). NAM can be used for development and management of water resources in a catchment. It can also be applied to ungauged basins or basins where limited stream-flow data is available (Galkate et al.).

The State of Jammu and Kashmir has plenty of water resources such as springs, lakes, rivers, and glaciers besides groundwater. Jhelum, Chenab, Indus and Tawi are the chief rivers flowing through the state. All these rivers have their origin in the Himalayas. There are 1230 water bodies in the State (J&K ENVIS Centre). However, the availability and distribution of water resources is rather uneven in different areas of the State. Water plays a limited though vital role in the economy of Kashmir. Water is used traditionally for gradient irrigation, navigation and primitive fishing. The chief use of water is in agriculture. However, water is not available for irrigation in many areas including the Karewas which occupy about 32% of the cultivated area. The generation of hydroelectricity is only marginal. Compared with the available hydropower potential, the generation is quite insignificant (Nawaz and Taseem, 2013). The estimated hydropower potential in the state is about 20,000 MW, while the current installed capacity is 758.70 MW (JKSPDC).

Floods in the Kashmir valley, have been a recurring phenomenon. Jhelum carries the cumulative discharge of all its streams through a narrow passage down the valley. Silting in the main channel causes choking, which incapacitates the river from performing its primary function. The discharge capacity of Jhelum is nearly half of high flood discharges, which leads to breaching of embankments during floods. Thus, in this situation, the floods are but a natural phenomenon.

Very few hydrological studies have been conducted for the Jhelum Basin in Jammu and Kashmir (India). The hydrological data is not consistent for any reasonable time period, making significant temporal study of the regional phenomena difficult. Although rainfall is measured at several places, the historical records are available at a very few sites only. These records do not exceed 80 years with large gaps in between. Snowfall, which is a major contributor to the valleys precipitation is measured very casually and occasionally.

An integrated MIKE 11 NAM and HD model has been developed for the Jhelum Basin at Ram Munshi Bagh site. Jhelum is lifeline of the city of Srinagar and is the main waterway of Kashmir valley. The study was carried out to simulate the rainfall-runoff process in the Ram Munshi Bagh Sub-basin of Jhelum Basin by using an integrated MIKE 11 hydrologic and hydraulic setup. This included setup, calibration and validation of the model. In order to identify the most sensitive parameters affecting the rainfall-runoff process in the basin, sensitivity analysis was then performed. The integrated NAM and HD model was calibrated, validated and then used to simulate 4 extreme flood events in the basin during last 30 years. MIKE 11 NAM was selected for the study keeping in view its wide range of applicability for different catchments. It also includes a snow-melt component with snow storage, which is a vital component of the rainfall-runoff process in the basin. HD model simulates the river system in detail. The main channel is treated different from the flood plains and flood plain branches can be added to the main channel which dissipate excess runoff in case of extreme events. HD model was thus used to perform detailed hydraulic modelling of the Jhelum River system.

1.2 OBJECTIVES

The present study has been undertaken to understand the rainfall -runoff behaviour of Jhelum Basin using integrated MIKE 11 NAM and HD modelling system with the following objectives:

- To carry out Rainfall- Runoff modelling for Jhelum Basin
- To calibrate and validate integrated NAM-HD model for the basin using 30 years rainfall –runoff data for the basin
- To carry out sensitivity analysis of the model parameters
- To simulate extreme flood events in the basin using the developed model

1.3 LAYOUT OF THESIS

The thesis has been divided into six chapters.

Chapter 1 entitled “Introduction” gives brief information about the background for the present study and the objectives of the study.

Chapter 2 entitled “Review of Literature” covers the works and papers reviewed associated with the study.

Chapter 3 named “Study Area and Data Availability” presents the details of the study area and the data available’

Chapter 4 named “Models Used and Methodology” covers the details of models used and methodology adopted for carrying out the study.

Chapter 5 entitled “Results and Discussions” presents the results obtained from the study

Chapter 6 entitled “Conclusions” gives the summary and conclusions of the study and suggests some further scope of the study.

CHAPTER 2

REVIEW OF LITERATURE

Over the years, several hydrological models have been developed and applied to a number of catchments to model their hydrological response. Catchment models have also been integrated with other models like ecological and physiological ones, erosion and sediment-transport models and hydraulic models. MIKE 11 has been used to model the hydrological processes in a considerable number of catchments. MIKE HD has been used either independently or in combination with other models like MIKE 11 NAM, HEC-HMS, MIKE FLOOD, etc. by many researchers for flood forecasting, flood plain inundation mapping and flood level predictions. Some of the studies which have direct relevance to the present study have been reviewed and discussed briefly in this chapter.

Abu El Nasr et al. (2000) used two approaches to perform the comparative analysis of runoff-generation in the Jeker catchment of Belgium. A lumped semi-empirical NAM-module of the MIKE 11 model, and a fully distributed, physically-based deterministic watershed model, the MIKE SHE model were used to model the 465 km^2 area of the basin. The main discharge station, Kanne was selected for the study. 6 years continuous data of rainfall and discharge was used, three years for calibration and three for validation. The values of R^2 for calibration and validation for the NAM were 0.75 and 0.78 respectively while those for MIKE SHE were 0.69 and 0.78. No significant difference between the behaviours of two models was observed during validation. NAM model was found to perform better than MIKE SHE for calibration period.

Shamsudin and Hashim (2002) carried rainfall-runoff estimation of Layang River using MIKE 11 NAM model. The catchment area of Layang has two reservoirs, Upper and Lower Layang reservoir with a total area of 50 km^2. Simulation was carried out for a period of 12 years (1988 to 2000). The occurrence of simulated peak flows in 1992 and 1995 showed values of about 21 cumecs and 19 cumecs respectively. Root Mean Square Error (RMSE) and Efficiency Index (EI) were used to find out the reliability of the model. The value of RMSE was 0.08 and that of EI was 0.75.

Gautam et al. (2004) developed a NAM model for assessment of variation in surface as well as sub-surface water resources of Nan Basin in Thailand. 5 years data from 1987 to 1992 was used for simulating the 10,335 km^2 area of the basin. Daily values of precipitation for three years (1987-1990) were used for calibration and two years data (1991-1992) was used for validation. Calibration and validation showed R^2 values of 0.70 and 0.63.

Thompson et al. (2004) developed a coupled MIKE11-MIKE SHE model for Elmley Marshes, England for evaluating ditch surface evaporation. The basin encloses an area of 8.7 km^2.model calibration and validation was carried out using two consecutive periods of 18 months each. The period 25 June 1997 to 31 December 1998 was used for calibrating the model and its following span of 18 months (1 Jan 1999 to 29 June 2000) was used for validation. The model gave results consistent with the observed values of seasonal ditch water and groundwater. The results demonstrated close association of flooding with both ditch water and ground water levels.

Keskin et al. (2007) applied MIKE 11 NAM for modelling the runoff due to snowmelt in Yuvacık Dam Catchment in Turkey. The time period (2001-2006) was used for modelling the 257.8 km^2 of the catchment. The catchment was divided into three sub-catchments, each divided into several elevation zones. The dam reservoir has snowmelt along with rain on snow as its major inflow. The basin model was calibrated and then validated using hydrological and meteorological data of the catchment. Daily values of hydrological and meteorological data and monthly evaporation values were used for simulation. Calibration of the model was done for snowmelt events and for events of rain on snow, followed by validation. R^2 value was greater than 0.7 for most of the snowmelt events.

Archer and Fowler (2008) used meteorological data to predict seasonal runoff in the River Jhelum, Pakistan. The links between runoff and climate were studied for 8 gauging stations within the Jhelum Basin. The main aim of the study was to forecast the spring and summer season inflows to Mangla Dam. Models using multiple linear regression were built for a time period of 1965 to 1979. Good forecasts were demonstrated by the analysis within 15% of actual values for more than 90% of the years with an ROC score =0.77 for flows during summer i.e. April to September for the validation period (1980-1991). For spring season the forecasts were demonstrated within 15% of actual values for 83% of the years (ROC score =0.93).

Anh et al. (2008) compared NAM (DHI), FEH ((UK), and TVM. Models for the Bradford catchment (UK) based on seasonal data (summer and winter). The basin area is about 58.4 km^2, which consists of both rural and urban area. Model calibration was done for time period June 2000 to June 2001 while validation was done for January 1999 to January 2004. The time steps taken were 15 minutes and 1 hour. Long term time series rainfall data were better simulated by FEH model, while NAM could continuously simulate data. Intermediate flows were over estimated by NAM. The shortcomings of NAM model were overcome by TVM Model.

Kamel (2008) applied MIKE11 HD Model to the Euphrates River in Iraq for a stream length of 1.6 km. Surveyed stream cross section data was used to develop MIKE HD Model for the river. The estimated and observed stage hydrograph on comparison showed good simulation. The stage hydrograph of another model, the Uday model for the same river was compared with the MIKE 11 HD stage hydrograph. MIKE 11 model gave better results of the two.

Knapton (2009) developed MIKE 11 NAM Model for simulating the surface water flows of Roper River, giving emphasis to flows during the dry season, which are associated with groundwater discharge. . The Roper River lies in the Northern Australia and has a drainage area of 82,000 km^2. Depending upon the location of discharge stations, 12 sub-basins were defined in the area. Initially the manual calibration of the model was performed for upstream basins with available discharge data. For downstream basins, combined runoff from the basins was used for comparison. NAM parameters of similar basins were transposed in order to calibrate the model in ungauged catchments. Rainfall-runoff modelling was done from 1 January 1900 to 01 September 2008, i.e. 108.8 years. The instantaneous discharge hydrographs of simulated and observed flows showed a sound match, while there was some inconsistency in the accumulated discharge values of some stations.

Maity (2009), applied 1-D Hydrodynamic modelling to Manali Sub-basin of Beas River, in Himachal Pradesh, India for flood plain inundation mapping. HEC-HMS was used to generate the upstream boundary condition for the HD model. Daily rainfall and temperature data at two stations Bahang SASE and Dhundi for the years 1995, 1999 and 2000 was used. The model was simulated from May to October for these years. The Curve Number (CN) was found to have the most impact on the total discharge. The accuracy for validation of the model was about 83%. The resulting hydrographs from HEC-HMS were input to the MIKE 11 HD Model as upstream boundary conditions. The unsteady simulation showed 86% model accuracy, where the bed slope and conveyance of the channel had much influence on simulated discharge.

Giang and Phuong (2010) carried out the calibration and validation of MIKE 11 NAM using event data instead of continuous long time-series data. The model was applied to Gia Vong, a small watershed in Quang Tri province in Vietnam having an area of about 275 km^2. Around 70% of the annual rainfall occurs during the wet season, which leads to severe floods every year. Fine flooding events which had occurred in the years 1999, 2004, 2005, 2007 and 2009 were selected for study. The precipitation data at Gia Vong station was collected with a temporal resolution of six hours. The evaporation data at a daily time step from Khe Sanh station was used for the model. Discharge data from Gia Vong station at the outlet of the watershed was used for study. NAM model was calibrated using four out of five flooding events (2004, 2005, 2007 and 2009) in order to determine the best set of parameters of the model. The calibrated model was then validated for the 1999 flood event. The correlation coefficient in both cases, calibration and validation was more than 0.84. The simulated and observed peak flows had a difference of less than 8%.

Chibole (2011) carried out rainfall-runoff estimations from River Sosiani Basin in Kenya using MIKE 11 NAM, which was then used to develop a HD model for the river. The Basin has 21 Sub- Basins having an area of 225 km^2 and has two important water reservoirs. The basin was divided into three zones. These were the agricultural zone, the forested zone and the urban zone. The meteorological data were obtained from the three gauging stations in Uasin-Gishu district. MIKE 11 model application involved two phases for rainfall-runoff estimation. In the first phase the model was calibrated to estimate optimum model parameter values followed by stream flow simulation using the calibrated model. The value of EI during the study was 0.70 and RMSE value was 0.08.

Doulgeris et al. (2011) applied the MIKE-11 NAM to the Strymonas River Basin in order to simulate the daily runoff in the basin. The basin, which lies in the Balkan Peninsula has an area of 16,747 km^2. Precipitation data was collected from 19 stations: 8 in Bulgaria and 11 in Greece. Discharge measurements along the Strymonas River were obtained at four gauging sites from 2003-2006 on a daily basis. The model was calibrated from 1 January 2003 to 31 December 2004 and then validated from 1 January 2005 to 31 December 2006. Calibration was done using both auto-calibration and a trial-and-error method for a period of two years. The results improved with the use of snow-melt parameters and extended groundwater parameters. The results obtained for model validation were also satisfactory.

Dar and Ramshoo (2012), used Snowmelt Runoff Model (SRM) for estimation of snowmelt runoff from the Lidder Basin in Kashmir Valley. Lidder basin is a glacierized basin having an area of 1263 km^2. Snow covered area, temperature and precipitation data along with MODIS satellite images were used to simulate the data for the year 2002-2003. The model gave a computed runoff of 9.587 m^3/s compared with the measured average runoff of 9.782m^3/s. the coefficient of determination was 0.8676, indicating a good fit of the model.

Sharma et al. (2012), studied the variation of snow cover and simulation of stream-flow in Jhelum Catchment. MODIS (Moderate Resolution Imaging Spectrometer) sensor imageries were used for estimating the Snow Cover Extent (SCE) in the catchment. Snow cover maps having multiple temporal resolutions were generated using Normalized Difference Snow Index (NDSI) algorithm. The results specified large variation in the distribution pattern of snow cover and had a decreasing trend in different sub-catchments of the Jhelum River. Stream-flow simulation for the entire Basin was done using the Snow-melt Runoff Model with good correlation between observed and simulated discharge.

Zakaullah et.al. (2012) carried out flood frequency analysis for 15 rain gauge stations of Jhelum River Basin in Pakistan up to the Mangla Dam. Flood frequency analysis was carried out using Design Flood for Window (DFW) software while MINITAB-11 was used to perform Multiple Linear Regression. An equation was developed for homogenous catchments to basins to relate the discharge (Q) and basin area (A):

$$Q_{mean} = 514 + 0.10*A$$

Where A = Basin Area (km^2); Q_{mean} = Mean annual flood (m^3/s)

Amir et al. (2013) used MIKE 11 NAM to estimate the rainfall-runoff discharges for the Fitzroy Basin in Australia. The basin consists of 6 sub-basins with a total area of 144,000 km^2. The model was developed for a time period of 1972 to 2011. Data was collected for 40 rainfall stations and 4 evaporation stations. The model was calibrated using 5 year data from 1 January 2007 to 31 January 2011and then validated using another 5 year data from 1 January 1987 to 31 December 1991. Automatic calibration was used to determine the hydrological model parameters for each sub-basin. The range of d and EI for different sub-basins was 0.821-0.951 and 0.849-0.961, respectively.

Hafezparast et al. (2013) applied a conceptual MIKE 11 NAM model to study the peak flows and monthly flows at the Sarisoo catchment in Iran. The catchment has a total area of 2470 km^2. Temperature and precipitation data were obtained from the Bazergan and Sangar-Sarisoo stations for a time period of 12 years (1996-2008). The observed discharge data for two and a half years (1 October 2003 to 31 March 2006) was used for model calibration and the model was validated for 3 years. The month of February in 2003, 2006 and 2007 gave simulated peak flows having values 6.32, 9.35 and 6.13 m^3/s respectively. The correlation coefficient obtained was 0.74 during calculating daily discharges and 0.72 for monthly values.

Karlsson et al. (2013) studied the historical trends in precipitation and streamflow at the Skjern River Basin, Denmark using MIKE 11 NAM. The Alergaarde River gauging site is located downstream of the Skjern Catchment, which has an area of 1055 km^2. A dataset of precipitation, evapotranspiration, temperature and discharge for 133 years (1875-2007) was analysed to examine the degree of change using non-parametric Mann–Kendall test. . NAM was calibrated for the time period 1951 to 1980 and showed an excellent agreement between measured and simulated discharge. Only some of the hydrological changes in the basin could be explained, especially after the 1980s. Since 1875, there had been a 26% rise in precipitation and 52% increase in the simulated discharge. The relative occurrences of high flow and drought had not changed between the years 1875 and 2007.

Lafdani et al. (2013) performed rainfall-runoff simulation using ANFIS (Adaptive Neural Fuzzy Inference System) and MIKE 11 NAM Models for the Qaleh Shahrokh Catchment in Iran. The most important river in the catchment is the Zayandehrood River and the area of the catchment is 1525.67 km^2. Daily time series of river discharge, rainfall, evaporation and temperature were used for the years 1999-2009. The calibration (training) period of 1999-2006 and validation (testing) period of 2006-2009 were chosen for the study. 3-day, 5-day, and 7-day moving averages of rainfall were taken to predict rainfall using ANFIS. Gamma Test was used to identify the best input combination. MIKE 11 NAM was used to simulate the runoff. The values of EI, R^2 and NRMSE (Normalized Root Mean Square Error) during the NAM model calibration were equal to 0.7, 0.71 and 0.54 m^3/s respectively. The results indicated that NAM model was better than the ANFIS- NAM model to simulate runoff. The use of predicted rainfall in place of observed rainfall resulted in lower efficiency of the ANFIS- NAM model and simulation of runoff.

Khan et al. (2014) developed a rainfall-runoff model for a part catchment of river Dhünn using an integrated NAM and MIKE BASIN model. River Dhünn is located in Germany and has a catchment area of 197.72 km^2. The portion of the basin taken up for study had an area of 25 km^2 and has an elevation of 270-315 m above sea level. Three years data from 1 January 2003 to 31 December 2005 was used for model calibration. A total of 9 NAM parameters NAM were estimated by manually calibrating the model. The value of Nash-Sutcliffe Efficiency (EI) was 0.62 and that of correlation coefficient was 0.713. Three scenarios, namely; meadow, forest and urban were used to predict the hydrological consequences land use change. Result of the scenarios showed that water yield had increased from catchment area due to urbanization, while forestation reduced the water yield.

Singh et al. (2014) conducted a study to ascertain the availability of water and analyze supply-demand in Kharun Sub-Catchment of Seonath Catchment in Chhattisgarh State, India. The Rainfall-Runoff Modeling for the basin was carried out using MIKE11 NAM model using observed discharge at Patherdihi gauging site. The area of Kharun river basin is 4112 km^2 and area up to Patherdihi site is 2112 km^2. The daily rainfall data was collected from 13 rain gauge stations inside and around Kharun river basin. The meteorological data from 1971 to 2008 consisting of sunshine hours, temperature, wind velocity, evaporation and humidity was also collected. The Rainfall-Runoff simulation was carried out for the time period from 1993 to 2007. The values of coefficient of determination (R^2) for model calibration and validation were 0.858 and 0.764 respectively, indicating good agreement between the measured and simulated runoff. The model had an efficiency of 81%, showing relevant choice of model parameters.

Timbadiya et al. (2014) used MIKE 11 HD model to carry out the simulation of floods and for developing the relationship between stage and discharge for lower Tapi River in India for the years 2003 and 2006. Flood hydrograph from the Ukai Dam and Arabian Sea tidal water level during 1993 flood were used as the upstream and downstream boundary conditions respectively for the calibration of the model. The low flood data of 2003 and high flood data of 2006 were used for model validation. The Root Mean Square Error or the Standard Performance Index was used to evaluate the model performance, which was reasonably satisfactory. The calibrated model was then used to develop the rating curves for the basin.

Haldar and Khosa (2015) used 1-D Hydrodynamic Modelling for flood level mitigation study in Lhasi Nadi. The Lhasi Nadi is a small tributary of the Andheri River, which in turn joins the Parvati River of the Chambal River system. A one-dimensional HD was developed for the Lhasi and Andheri rivers using MIKE 11 software. The model validation was done for the year 2000 with small amount of input data. The highest water level of 312.5 m was simulated in the model in accordance with the ground reality. The developed model was then used as an initial point for the flood mitigation study. The maximum water levels were less than 310m for simulated flood events.

Galkate et al. applied the MIKE NAM to Bina river basin of Madhya Pradesh, India in order to investigate its efficiency, performance and suitability to the basin. The discharge data at Rahatgarh gauging site was used for development, calibration and validation of the model. The model was calibrated using three years data from 1990 to 1992 to obtain the optimum model parameters. The remaining time period of two years, 1993 to 1994 was used for model validation.

The model was found appropriate in simulating the rainfall-runoff process of the basin with appreciable degree of accuracy. The coefficient of determination (R^2) values of model calibration and validation were observed 0.796 and 0.609 respectively with a model efficiency of 81%. Sensitivity analysis indicated Coefficient of Overland flow (CQOF) as the only model parameter which showing significant effects on peak flows and low flows both.

Contrary to the case of other northern rivers, Jhelum River has received less scientific research attention concerning catchment modelling for rainfall-runoff simulation. Very few hydrological studies have been conducted at regional level, particularly in Jammu and Kashmir (India). One of the major reasons being general dearth of consistent hydrological data for the region for any reasonable period of time. Very few rainfall-runoff simulation studies have been reported for the Jhelum Basin. Also, most of these studies have been carried out for the portion of the basin in the Pakistan region. Hence, in the present study for the first time integrated hydrologic and hydraulic modelling has been attempted for the Jhelum basin at R M Bagh site and its corresponding sub-basins.

CHAPTER 3

STUDY AREA AND DATA USED

3.1 STUDY AREA

3.1.1 Location and Extent

The Jhelum Basin lies between 32°58'42" to 35°08'02" north latitude and 73°23'32" to 75°35'57" east longitude and is mostly confined within the Kashmir Valley in India. It is drained by River Jhelum and its tributaries. Jhelum (Vyeth in Kashmiri, Vetesta in Sanskrit and Hydaspes in Greek) is the main waterway of the Kashmir valley. Jhelum River emerges from a magnificent spring called "Chashma Verinag". The total geographical area of Jhelum basin up to Indo-Pakistan border is about 34775 km^2. The river has a length of 402 km, but the length of the river in India up to current ceasefire line is about 165 km with a catchment area of nearly 17622 km^2 (IndiaWRIS).

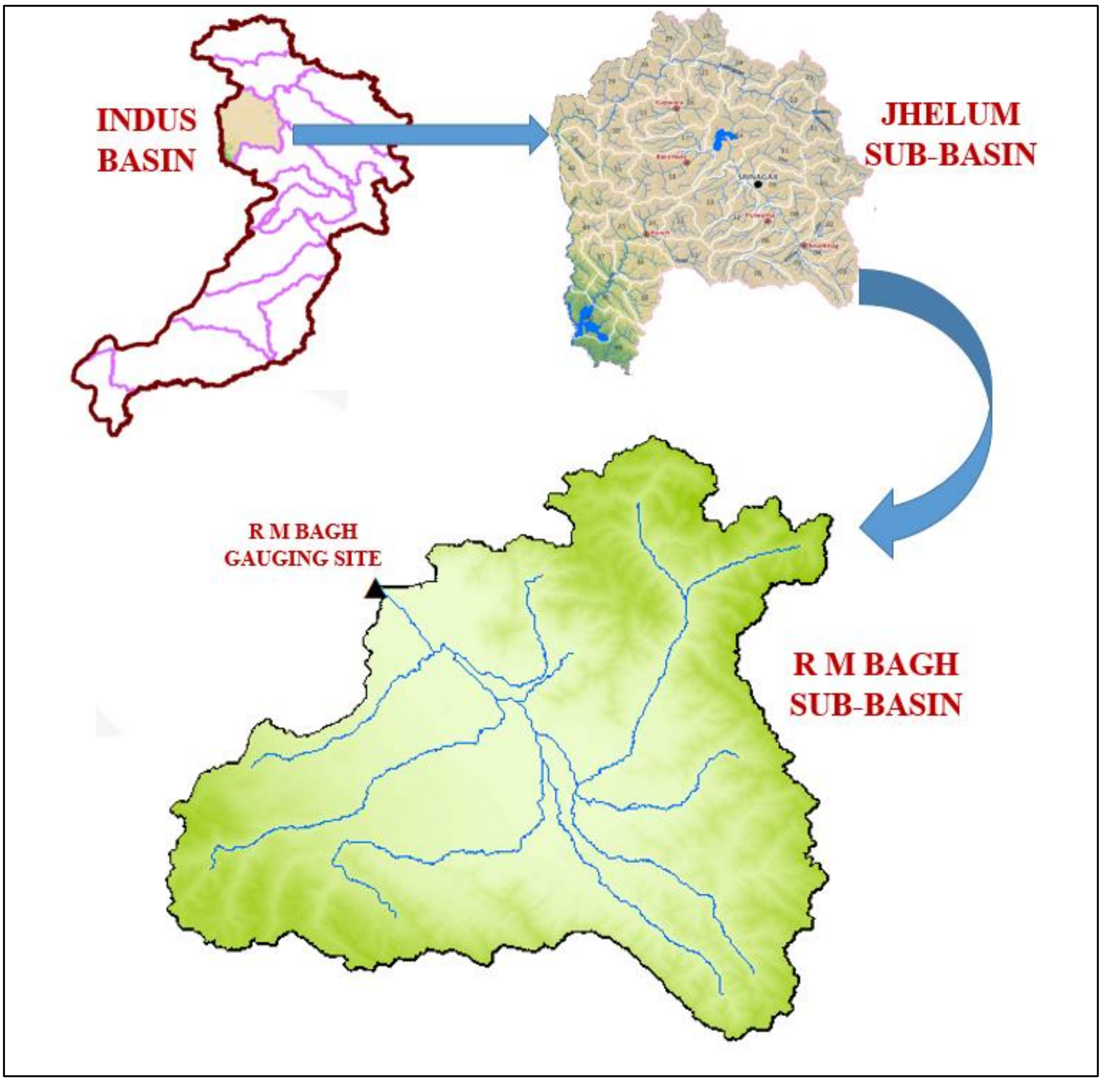


Figure 3.1 Study Area

The elevation of Kashmir valley is nearly 1500m above the sea level. The topography of the region is very rugged with highest elevation of about 5600 m above the sea level (Zaz and Ramshoo, 2013). The area of the basin up to Ram Munshi Bagh gauging site, shown in Figure 3.1 has been taken for the present study.

3.1.2 Climate

Climate of Kashmir valley has its own peculiarities. Winters last from November to March with January being the coldest month. The day time average temperature during January is 2.5°C while the mercury dips below freezing point during nights. Precipitation is mostly in the form of snowfall during winter. Heavy rainfall is experienced during March to May, which is the wettest part of the year. Rainy Season is from July 15 to September 15, but due to its natural location, Kashmir Valley does not witness a proper monsoon season. Summer season is warm with a daytime average temperature of 24.1°C in July (IMD, Pune).

3.1.3 Jhelum Basin

The birth of the Jhelum is connected with the origin of the Kashmir valley itself, which according to geologists started emerging as a land like rest of the Himalayan mountain range, out of Tethys Ocean, after collision of the Indian plate with the Asian plate some 50 million years ago. With continued collision there developed a large depression at the beginning of the Pliocene epoch nearly 4 million years ago. Soon this depression started getting filled with water as a result of drainage impoundment. At this point in time the Kashmir intermountain depression assumed the status of large inland lake. The lake or lacustrine conditions attained greater depth, when its western margin, the Pir Panjal range rose to its present height due to tectonic reactivation about 25000 years ago. Concurrent with this the Baramulla gorge opened and the entire lake water got drained restoring the valley to terrestrial conditions once again. The river Jhelum which became oriented towards the north-west carried out uneven erosion of the emerged lake deposits due to which the present day lakes (Dal, Wullar, and Anchar) and swamps were formed (Raina, 2002).

The scientific explanation apart, there is a legend based on Hindu mythology, woven around the emergence of the Kashmir valley to explain the river's taking form out of vast lake known as Satisar. The river is also known by many names –Vitasta, Vyath, Bihat, Hydapes and Jhelum to different people depending on their language. The basin journey of the Jhelum in the valley begins, after the hamlet of Verinag, through the twin villages of Dooru and Shahabad.

3.1.4 Source and Traverse

The main source of the Jhelum is Verinag spring. It is joined by various spring fed and snow fed tributaries. The left bank tributaries drain the slopes of the Pir Panjal range before joining the river. The right bank tributaries come from the Himalayan slopes. The river winds through many towns like Anantnag, Bijbehara, Awantipora, Pampore, Srinagar, Shadipora, and Sumbal. From there, the river falls into the lake Wullar which may be regarded as the delta of the river and passes through Ningli, Sopore, Baramulla, Banyari, Uri and Muzzafarabad, and then ultimately passes along the western boundary of the Kashmir via Palandari and Mirpora into Pakistan.

The total length of the river Jhelum from Verinag to Uri is 239 Km. The approximate width of the river is 150” at Khanabal, 350” at Sangam, 250” at Ram Munshi Bagh and 692” at Asham. The Jhelum river system is fed both by rain and snow. As such flow remains very low during winter. During the summer months, April to August surface run-off increases as the snow melts and with rain generates higher runoff. This constitutes nearly three-fourth of the annual discharge of the river. Only about 10% of the annual discharge flows during November-February (Nawaz and Taseem, 2013). The flow is perennial in nature. The topography of the basin is predominantly characterized by alluvial plains, plateaus and karewas. The water in the basin is usually clear but during spring the basin becomes muddy. The tributaries flow between high defined banks while the banks of the river are mostly lean and weak and are relatively elevated than the adjoining low lying areas.

3.1.5 History of Floods in Kashmir Valley

In Kashmir Valley, floods occur mainly and very often in the Jhelum Basin. These floods cause extreme damage to life and property from time to time. Excessive rainfall, particularly in higher catchments causes the snow to melt and precipitate downhill to the streams causing floods. The primary reason for this being the insufficient carrying capacity of the river Jhelum. The safe carrying capacity of the Jhelum from Sangam to Wullar Lake ranges from 40,000 to 50,000 cusecs. For the Srinagar city, this value is merely about 35,000 cusecs. However, the flood discharge at Sangam, in 1957 increased to about 90,000 cusecs and to over 100,000 during 1959 floods. A flood spill channel was constructed at Padshahi Bagh in 1904 in order to regulate the flow of Jhelum as it passes through the Srinagar City. This channel has a carrying capacity of 17,000 cusecs. The insufficient carrying capacity of the Jhelum results in a number of flood problems in various reaches of the study area (Tali, 2011).

Historically, the valley had witnessed many spates of floods, the worst being the one which occurred in 879 AD. The slipping of the Khadanyar Mountains below Baramulla blocked the channel of the Jhelum River. A large part of the valley was submerged. In 1841, another major flood occurred, causing considerable damage to life as well as property. However, the first flood of devastating proportions to hit the Valley happened half a century later in 1893, when 52 hours of warm and continuous rainfall, beginning 18 July, resulted in a great calamity. The flood cost the state Rs. 64,804 in land revenue alone, 25,426 acres of crops were submerged, 2,225 houses were wrecked and 329 cattle killed (Lawrence, 1895). Subsequently the valley has experienced a number of floods which were recorded in the years 1903, 1905, 1909, 1928, 1948, 1950, 1951, 1953, 1954, 1956, 1957, 1959, 1962, 1963, 1964, 1969, 1972, 1973, 1976, 1986. The gauge and discharge values at R M Bagh site for the highest floods witnessed by the valley in the past 30 years are given in Table 3.1.

Table 3.1 Highest gauge and discharge values at R M Bagh in the past 30 years

Year	Date	Gauge (ft.)	Discharge (cusecs)
1988	9/26	20.96	36400
1992	9/10	22.20	40926
1993	7/12	22.00	38780
1995	7/28	22.60	45380
1996	6/21	22.40	39900
2014	9/08	29.50	72585

3.1.6 September 2014 Floods

In September 2014, the state of Jammu and Kashmir witnessed the most severe flood in the past 60 years. These floods occurred due to unprecedented and intense rains in the first week of September. The state received catastrophic rainfall from 1st to 6th September. On September 4th, 30 hour long rainfall broke the record of many decades with certain parts of the state receiving more than 650mm of rainfall in just 3 days (NRSC/DEERS, 2014). The water level in the river Jhelum at Sangam in south Kashmir on September 6 was 34.7 feet, which is about 12 feet above the danger mark. This was the highest water level of Jhelum recorded at Sangam, while the discharge was 115,218 cusecs. The gauge reading at R M Bagh was 29.50 feet on September 8 with a discharge of 72,585 cusecs which was more than twice the safe carrying capacity of the river.

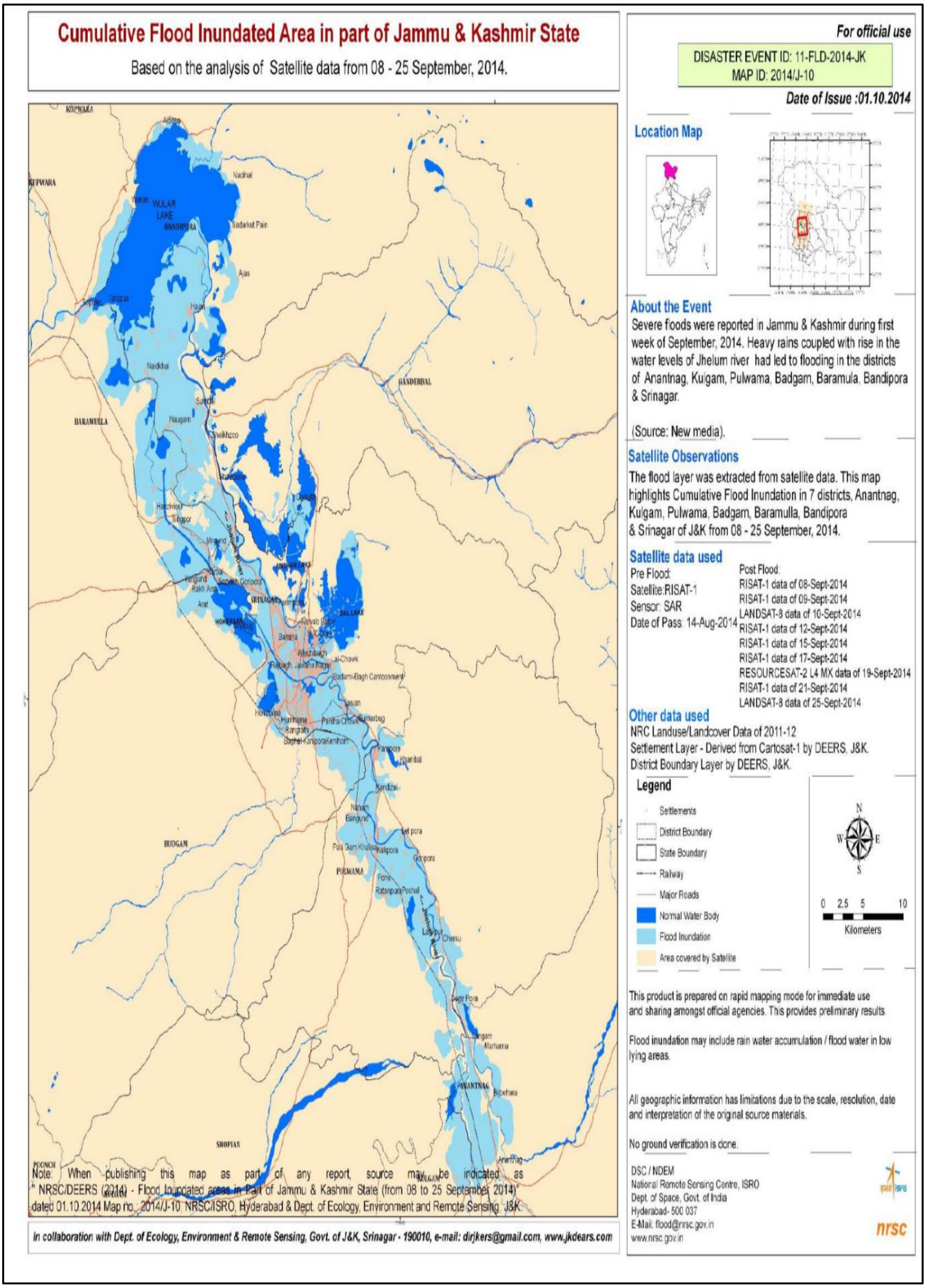
Figure 3.2 Satellite Images of Srinagar at Ram Munshi Bagh before and after September 2014 Floods

Figure 3.2 shows pre and post 2014 flood situation in the vicinity of Ram Munshi Bagh Gauging Site, Srinagar. Table 3.2 gives the district-wise flood inundation of Kashmir Valley.

Table 3.2 District-wise inundation of Kashmir Valley

S.No.	District	Area(km^2)
1	Anantnag	43
2	Bandipora	148
3	Baramulla	89
4	Budgam	54
5	Ganderbal	6
6	Kulgam	15
7	Pulwama	102
8	Srinagar	100
Total		**557**

The flood caused inundation in large parts of the valley. About 557 km^2, which encompasses nearly 3.5% of the geographical area of the Valley was flooded (NRSC/DEERS, 2014). Thousands of villages throughout the valley were affected by floods and 390 villages completely submerged. Major parts of the Srinagar city, including the Lal Chowk, Army Cantonment and Civil Lines areas were submerged. The preliminary property damage assessment was estimated between INR 50,000 million to INR 60,000 million. Nearly 277 people died due to the flood. (Home Ministry of India). Figure 3.3 shows the cumulative area inundated due to floods from 8-25 September 2014.



Cumulative Flood Inundated Area in part of Jammu & Kashmir State

Based on the analysis of Satellite data from 08 - 25 September, 2014.

For official use

DISASTER EVENT ID: 11-FLD-2014-JK
MAP ID: 2014/J-10

Date of Issue :01.10.2014

Location Map

About the Event

Severe floods were reported in Jammu & Kashmir during first week of September, 2014. Heavy rains coupled with rise in the water levels of Jhelum river had led to flooding in the districts of Anantnag, Kulgam, Pulwama, Badgam, Baramula, Bandipora & Srinagar.

(Source: New media).

Satellite Observations

The flood layer was extracted from satellite data. This map highlights Cumulative Flood Inundation in 7 districts, Anantnag, Kulgam, Pulwama, Badgam, Baramulla, Bandipora & Srinagar of J&K from 08 - 25 September, 2014.

Satellite data used

Pre Flood:	Post Flood:
Satellite:RISAT-1	RISAT-1 data of 08-Sept-2014
Sensor: SAR	RISAT-1 data of 09-Sept-2014
Date of Pass: 14-Aug-2014	LANDSAT-8 data of 10-Sept-2014
	RISAT-1 data of 12-Sept-2014
	RISAT-1 data of 15-Sept-2014
	RISAT-1 data of 17-Sept-2014
	RESOURCESAT-2 L4 MX data of 19-Sept-2014
	RISAT-1 data of 21-Sept-2014
	LANDSAT-8 data of 25-Sept-2014

Other data used

NRC Landuse/Landcover Data of 2011-12
Settlement Layer - Derived from Cartosat-1 by DEERS, J&K.
District Boundary Layer by DEERS, J&K.

Legend

This product is prepared on rapid mapping mode for immediate use and sharing amongst official agencies. This provides preliminary results.

Flood inundation may include rain water accumulation / flood water in low lying areas.

All geographic information has limitations due to the scale, resolution, date and interpretation of the original source materials.

No ground verification is done.

DSC / NDEM
National Remote Sensing Centre, ISRO
Dept. of Space, Govt. of India
Hyderabad- 500 037
E-Mail: flood@nrsc.gov.in
www.nrsc.gov.in

Note: When publishing this map as part of any report source may be indicated as " NRSC/DEERS (2014) - Flood Inundated areas in Part of Jammu & Kashmir State (from 08 to 25 September 2014)" dated 01.10.2014 Map no. 2014/J-10, NRSC/ISRO, Hyderabad & Dept. of Ecology, Environment and Remote Sensing, J&K.

In collaboration with Dept. of Ecology, Environment & Remote Sensing, Govt. of J&K, Srinagar - 190010, e-mail: dirjkers@gmail.com, www.jkdears.com

Figure 3.3 Cumulative Flood Inundated Area from 8-25 September, 2014

(Source: “NRSC/DEERS (2014) - Flood Duration Map in part of J&K state (from 8-25 September 2014” dated 01-10-2014 Map no 2014/J-10, NRSC/ISRO, Hyderabad & Dept. of Ecology, Environment and Remote Sensing, J&K)

3.2 DATA USED

The following data were obtained from different sources and used for this study.

1. **DEM (Digital Elevation Model):** DEM of the basin from SRTM (Shuttle Radar Topography Mission): The SRTM 90m DEM’s are available in mosaiced 5° x 5° tiles and have a resolution of 90m at the equator. DEM was used for extracting the catchment in addition to river network details
2. **Meteorological Data:** Meteorological inputs are required to calibrate and validate in the NAM model. 30 years’ meteorological data for the study was obtained at five stations namely, Srinagar, Shalimar, Qazigund, Kokernag and Pahalgam. Daily time series of rainfall, temperature and evaporation were used for the model simulation.
3. **Discharge Data:** Discharge Data time series is used as an input for NAM model during model calibration and for checking the reliability of the calibrated model during validation. The discharge data at R M Bagh site was obtained from Irrigation and Flood Control Department (IFC), Srinagar for a period of 30 years (1985-2014). Occasional discharge data for the same time period of various tributaries of the River Jhelum up to gauging site was also procured from IFC, Srinagar.
4. **River Cross Section Data:** Channel and flood cross sections of the plain give the topographical description of the basin to be modelled. These lie approximately perpendicular to the direction of flow. The cross section data for the main river as well as the tributaries were obtained from IFC Srinagar. The cross sections of the flood plains were extracted from the SRTM DEM of the basin.

CHAPTER 4

MODELS USED AND METHODOLOGY

An integrated MIKE 11 NAM and HD model was developed to perform hydrological and hydraulic modelling for the Jhelum Basin. MIKE 11 NAM was used for hydrological simulation, while hydraulic routing was carried out using MIKE 11 HD Model. The models used and the methodology adopted for the study has been discussed in this chapter.

4.1 MODELS USED

4.1.1 MIKE ZERO

MIKE Zero is a hydrological Modelling software developed by DHI. MIKE Zero is the common name of DHI's fully Windows integrated graphical user interface for setting up simulations, pre- and post-processing analysis, presentation and visualization within a project oriented environment. Presently, the MIKE Zero framework gives access to the following DHI modelling systems:

- MIKE HYDRO - A physical and conceptual model system for catchments, rivers and floodplains
- MIKE 11 - a 1D modelling system for rivers and channels
- MIKE 21 - a 2D modelling system for estuaries, coastal water and seas
- MIKE 3 - a 3D modelling system for deep seas, estuaries and coastal waters
- MIKE 21/3 Integrated Models
- MIKE FLOOD - a 1D-2D modelling system for inland flood and urban flood studies
- LITPACK - a modelling system for littoral processes and coastline kinetics
- MIKE SHE - a modelling system for coupled groundwater and surface water resources

4.1.2 MIKE 11

The MIKE 11 is an implicit finite difference model for one dimensional unsteady flow computation MIKE 11 is a professional engineering software for simulation of flows, water quality and sediment transport in irrigation systems, channels and other water bodies. MIKE 11 is a user-friendly, fully dynamic, one-dimensional modelling tool for the detailed analysis, design, management and operation of both simple and complex river and channel systems. MIKE 11 provides a complete and effective design environment for water resources, water quality management and planning applications.

The Hydrodynamic (HD) module is the nucleus of the MIKE 11 modelling system and forms the basis for most modules including Flood Forecasting, Advection- Dispersion, Water Quality and Non-cohesive sediment transport modules.

NAM Model

DHI’s *Nedbør-Afrstrømnings-Model* (NAM) is a lumped conceptual model for simulating stream flows based on precipitation at a catchment scale. Since its creation in 1973 (Nielsen and Hansen), NAM has been used worldwide in a variety of climatic and hydrologic settings to simulate runoff from precipitation events (Refsgaard and Knudsen, 1996). The model can be used independently, dynamically with MIKE11, or to develop input time series for MIKE BASIN catchment nodes.

NAM is a Rainfall-Runoff model that operates by continuously accounting for the moisture content in three different and mutually interrelated storages that represent overland flow, interflow and base-flow (DHI, 2014). As NAM is a lumped model, it treats each sub-catchment as one unit, therefore the parameters and variables considered represent average values for the entire sub-catchments. The structure of NAM model is given in Figure 4.1.

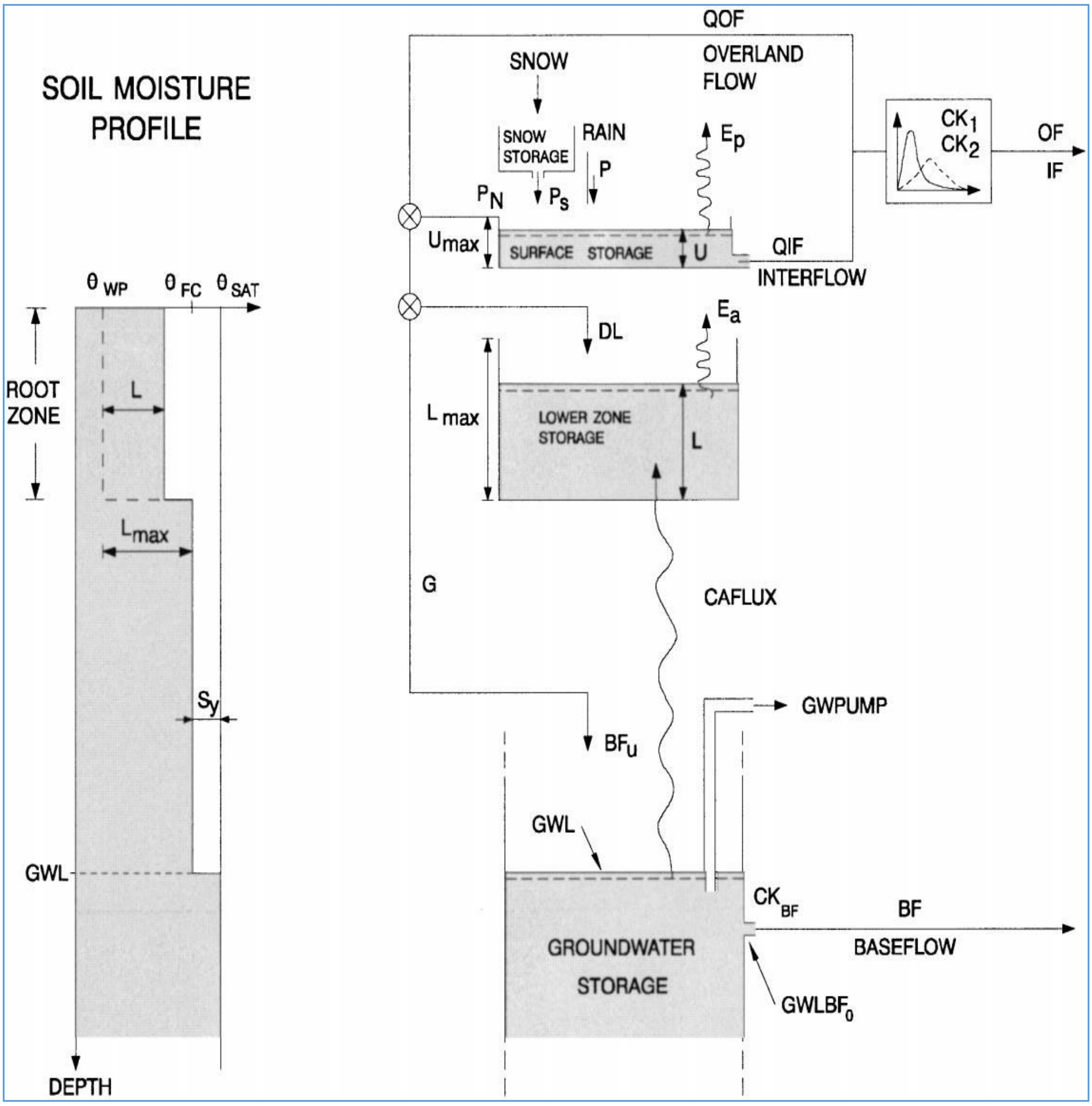


Figure 4.1 Structure of NAM Model

Precipitation in the form of snow is modelled as a fourth storage unit. Water use associated with irrigation or groundwater pumping can also be accounted for in NAM. The result is a continuous time series of the runoff from the catchment throughout the modelling period. Thus, the NAM model provides both peak and base flow conditions that accounts for antecedent soil moisture conditions over the modelled time period. NAM model is a deterministic, lumped and conceptual rainfall-runoff model accounting for the water content in up to 4 different storages. NAM can be prepared in a number of different modes depending on the requirement. As default, NAM is prepared with 9 parameters representing the Surface zone, Root zone and the Ground water storages. Description of the parameters and their effects is presented in Table 4.1.

Table 4.1 Different parameters of the NAM Model

Parameter	Unit	Description	Effects	Common Range
U_{max}	mm	Maximum water content in surface storage	Overland flow, infiltration, evapotranspiration, interflow	5-35
L_{max}	mm	Maximum water content in lower zone/root storage	Overland flow, infiltration, evapotranspiration, base flow	50-400
CQOF	-	Overland flow Coefficient	Volume of overland flow and infiltration	0.0-0.1
CKIF	mm	Interflow drainage constant	Drainage of surface storage as interflow	200-2000
TOF	-	Drainage of surface storage as interflow	Soil moisture demand that must be satisfied for overland flow to occur	0-0.9
TIF	-	Interflow threshold	Soil moisture demand that must be satisfied for interflow to occur	0-0.9
TG	-	Groundwater recharge threshold	Soil moisture demand that must be satisfied for groundwater recharge to occur	0-0.9
C_{K1}	hrs	Timing constant for overland flow	Routing overland flow along catchment slopes and channels	3-72
C_{K2}	hrs	Timing constant for interflow	Routing interflow along catchment slopes	3-72
CK_{BF}	hrs	Timing constant for base flow	Routing recharge through linear groundwater recharge	500-5000
C_{SNOW}	mm/°C/day	Degree-day coefficient	Rate of melt/ freezing	1-4
T_0	°C	Base Temperature	Snow melt takes place above this temperature	-

For the present study NAM has been setup with parameters representing surface zone, root zone, ground water and snow storage. Surface storage includes interception storage and depression storage with upper limit U_{max}. When the maximum surface storage is reached, part of excess water, P_N will enter streams as overland flow. The remainder flow is diverted to lower zone and ground water storage. L_{max} is the upper limit of lower root zone storage. Overland flow

QOF is proportional to P_N and varies linearly with relative moisture content, L/L_{max} of lower zone storage.

$$QOF = \begin{cases} CQOF \times \dfrac{L/L_{max} - TOF}{1 - TOF}, & L\,/\,L\_max > TOF \\ 0, & L\,/\,L\_max \leq TOF \end{cases}$$

Where,

CQOF = overland flow runoff coefficient ($0 \leq CQOF \leq 1$)

TOF = threshold value for overland flow ($0 \leq TOF \leq 1$).

The interflow contribution, QIF, is assumed to be proportional to U and to vary linearly with the relative moisture content of the lower zone storage.

$$QIF = \begin{cases} (CKIF)^{-1} \times \dfrac{L/L_{max} - TIF}{1 - TIF} \times U, & L\,/\,L\_max > TIF \\ 0, & L\,/\,L\_max \leq TIF \end{cases}$$

Where,

CKIF = time constant for interflow

TIF = threshold value for overland flow ($0 \leq TOF \leq 1$).

A single time constant, CK_{12} is used for routing interflow through two linear reservoirs in series. The overland flow is also routed by means of a linear reservoirs but with a variable time constant.

$$CK = \begin{cases} CK_{12}\,, & OF < OF_{min} \\ CK_{12}\left(\dfrac{OF}{OF_{min}}\right)^{-\beta}, & OF \geq OF_{min} \end{cases}$$

Where

OF = overland flow (mm/hour),

OF_{min} = upper limit for linear routing (= 0.4 mm/hour),

β = 0.4

The constant β corresponds to the Manning formula for modelling the overland flow.

The root zone soil moisture content in the root zone determines the amount of infiltrating water, G which recharges the groundwater storage.

$$G = \begin{cases} (P_N - QOF) \times \dfrac{L/L_{max} - TG}{1 - TG}, & L\,/\,L_{max} > TG \\ 0, & L\,/\,L_{max} \leq TG \end{cases}$$

Where,

TG = root zone threshold value for groundwater recharge ($0 \leq TG \leq 1$).

The moisture content in the lower zone storage increases by the amount ΔL, given as

$$\Delta L = P_N - QOF - G$$

The base-flow BF is routed by means of a linear reservoir with time constant CK_{BF}.

A degree day approach is used for calculating snowmelt, QS.

$$QS = \begin{cases} C_{snow}(T - T_0), & T > T_0 \\ 0, & T \leq T_0 \end{cases}$$

Where,

C_{snow} = degree-day coefficient.

The excess snowmelt water PS contributes to surface storage, which is routed to the NAM model.

$$P_s = \begin{cases} Q_{melt}, & WR \geq C_{wr}S_{snow} \\ 0, & WR < C_{wr}S_{snow} \end{cases}$$

Where,

WR = water retention in the snow storage,

C_{wr} = water retention coefficient,

S_{snow} = snow storage.

Hydrodynamic Model

Hydrodynamic model, popularly known as MIKE 11 HD is the core of MIKE modelling system. MIKE 11 HD developed by Danish Hydraulic Institute, is a one-dimensional, unsteady, non-uniform flow simulation model. It contains all core functionality for simulating hydrodynamic processes of the model. The MIKE 11 hydrodynamic module (HD) uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. The module can describe sub-critical as well as supercritical flow conditions through a numerical scheme which adapts according to the local flow conditions (in time and space). Advanced computational modules are included for description of flow over hydraulic structures, including possibilities to describe structure operation.

It gives

- Fully dynamic solution to the complete non-linear St. Venant equations for open channel flow

- Muskingum and Muskingum-Cunge routing method options for simplified channel routing
- Automatic adaptation to sub-critical and super-critical flow
- A large suit of standard hydraulic structures, such as weirs, bridges, pumps, culverts, energy loss and tabulated structures
- Extremely flexible control module for movable gates, pumps, turbines, etc.
- Choice of fixed, tabulated or adaptive simulation

Saint Venant Equations

MIKE 11 HD applied with the dynamic wave description solves the vertically integrated equations of conservation of continuity and momentum (the 'Saint Venant´ equations), based on the following assumptions:

- the water is incompressible and homogeneous, i.e. negligible variation in density
- the bottom-slope is small, thus the cosine of the angle it makes with the horizontal may be taken as 1
- the wave lengths are large compared to the water depth. This ensures that the flow everywhere can be regarded as having a direction parallel to the bottom, i.e. vertical accelerations can be neglected and a hydrostatic pressure variation along the vertical can be assumed
- the flow is subcritical (Supercritical flow is modelled in MIKE 11, using more restrictive conditions),

The equations are:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

And

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\alpha \frac{Q^2}{A} \right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2AR} = 0$$

Where,

Q = discharge

A = flow area

q = lateral inflow

h = stage above datum

C = Chezy resistance coefficient

R = hydraulic or resistance radius

α = momentum distribution coefficient

These equations can simulate flow through cross sections of any shape when divided up into a series of rectangular cross sections. The hydraulic resistance is based on the friction slope from the empirical equation, Manning or Chezy, with several ways of modifying the roughness to account for variations throughout the cross-sectional area.

In MIKE 11, the rivers and floodplains are depicted as a system of interconnected branches by means of a network configuration. Water levels and discharges (h and Q) are calculated at alternating points along the river branches as a function of time. It operates on basic information from the river and floodplain topography to include man-made features and boundary conditions (Kamel, 2008).

4.2 METHODOLOGY

The methodology has been divided into various steps based on techniques employed and data used. A flow chart depicting methodological framework adopted in present study is shown in Figure 4.2. Various major methodological steps are as follows

- Catchment Delineation and Shape-file Generation
- Mike 11 NAM Model Setup
- Mike 11 HD Model Setup
- Integration of NAM and HD Models
- Model Calibration and Validation
- Evaluation of Model performance
- Sensitivity Analysis
- Simulation of Extreme Historical Flood Events

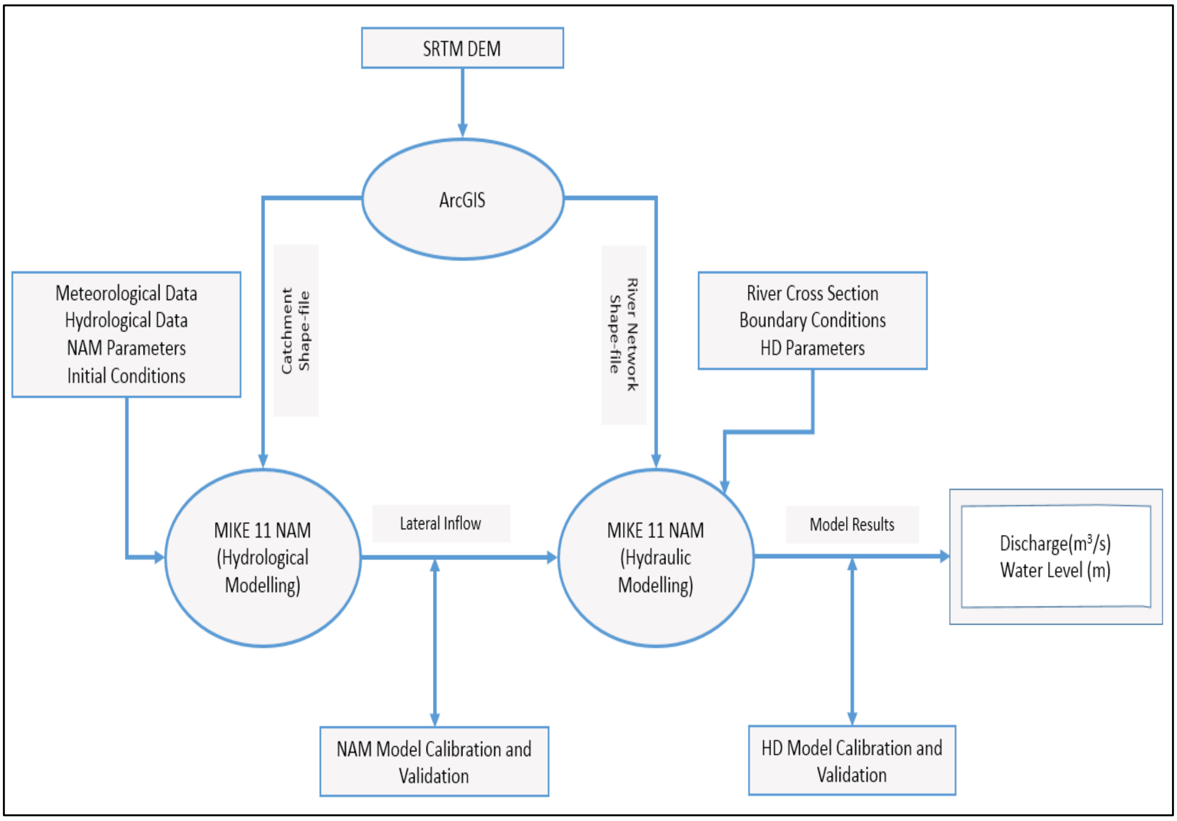


Figure 4.2 Flow chart showing methodological framework of the study

4.2.1 Catchment Delineation and Shape-File Generation

The catchment at Ram Munshi Bagh gauging site was delineated from 90m SRTM DEM using HEC-GeoHMS extension of Esri’s ArcGIS Desktop 10.2.2 software. The sub-catchments for each tributary were also delineated within the main catchment. The catchment was divided into 10 sub-catchments on the basis of tributaries of the river Jhelum draining them. All the catchments were grouped into one discharge basin with RM Bagh as the main discharge outlet. The shape files of the river system comprising of the main channel and the tributaries up to the gauging site as well as the catchment were then extracted, as given in Figure 4.3. These were used as input for the Mike 11 Software.

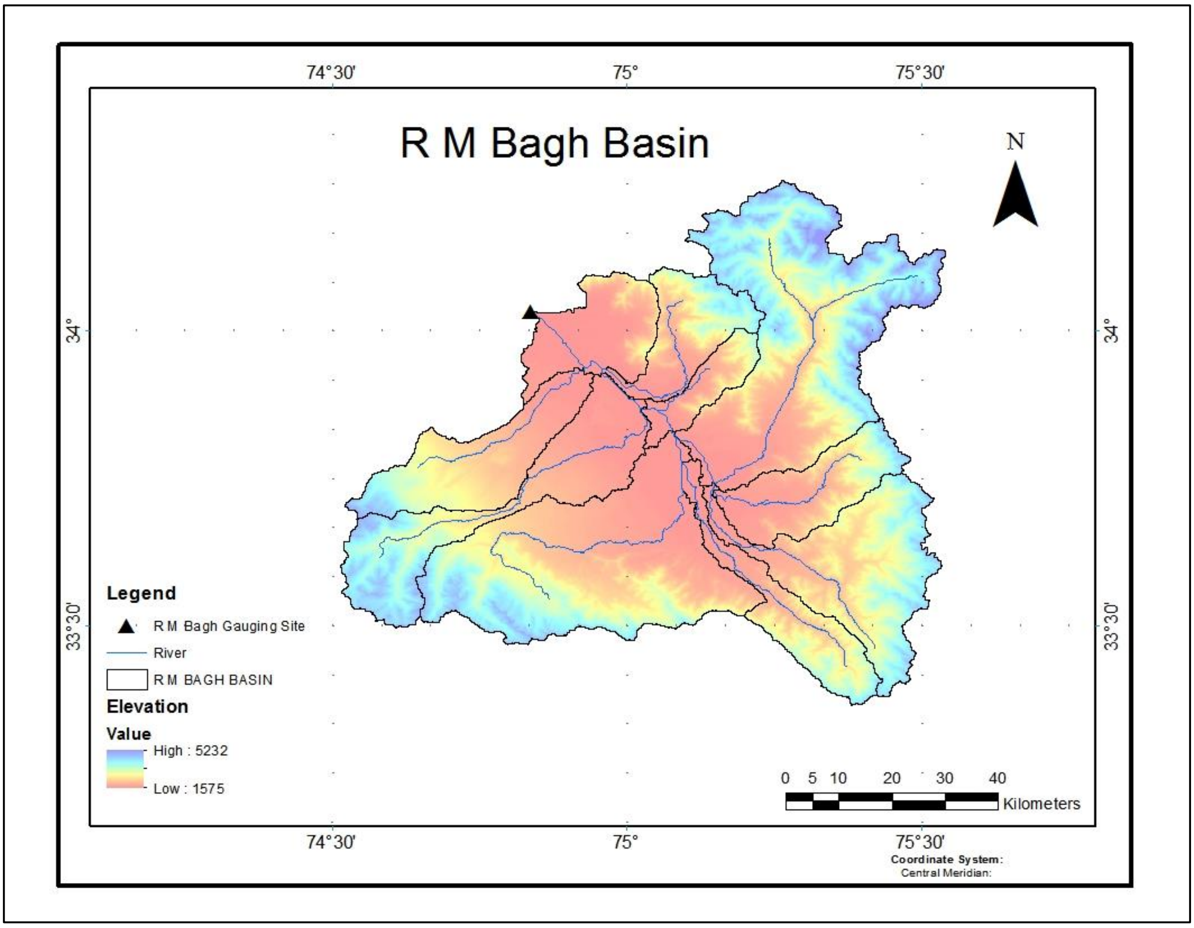
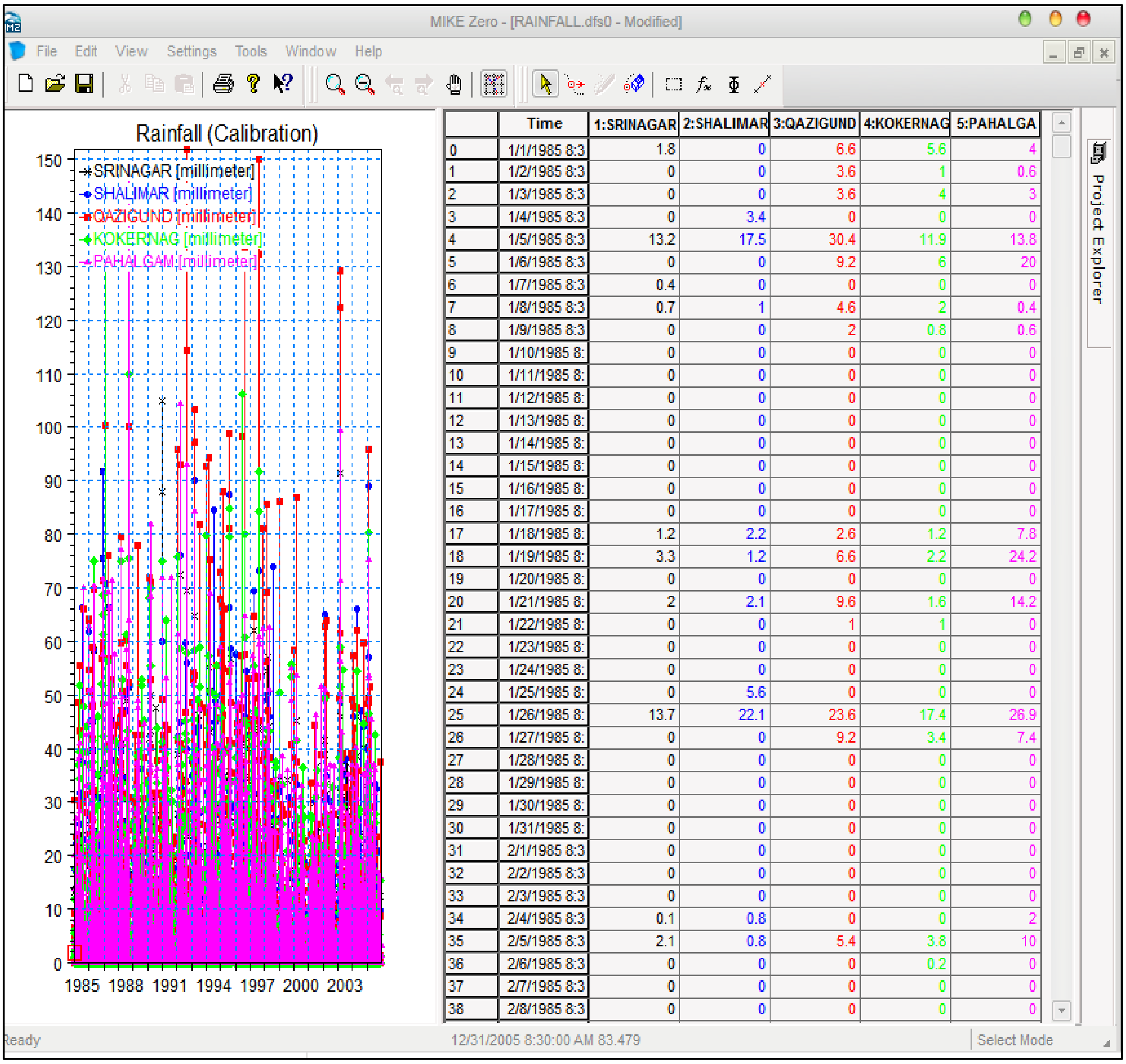


Figure 4.3 Delineated Catchment and River Network for the Study Area

4.2.2 MIKE 11 NAM Setup

The NAM Model setup requires input parameters as NAM catchment, surface root-zone parameters, initial conditions, rainfall time series, evaporation time series and daily discharge time series. Daily time series of temperature was required for the snowmelt module as snowfall is significant in the catchment. MIKE 11 uses .dfs0 format for time series. The .dfs0 time series for the input datasets were prepared using MIKE Zero interface. The .dfs0 time series of rainfall at five stations is shown in Figure 4.4.



	Time	1:SRINAGAR	2:SHALIMAR	3:QAZIGUND	4:KOKERNAG	5:PAHALGA
0	1/1/1985 8:3	1.8	0	6.6	5.6	4
1	1/2/1985 8:3	0	0	3.6	1	0.6
2	1/3/1985 8:3	0	0	3.6	4	3
3	1/4/1985 8:3	0	3.4	0	0	0
4	1/5/1985 8:3	13.2	17.5	30.4	11.9	13.8
5	1/6/1985 8:3	0	0	9.2	6	20
6	1/7/1985 8:3	0.4	0	0	0	0
7	1/8/1985 8:3	0.7	1	4.6	2	0.4
8	1/9/1985 8:3	0	0	2	0.8	0.6
9	1/10/1985 8:	0	0	0	0	0
10	1/11/1985 8:	0	0	0	0	0
11	1/12/1985 8:	0	0	0	0	0
12	1/13/1985 8:	0	0	0	0	0
13	1/14/1985 8:	0	0	0	0	0
14	1/15/1985 8:	0	0	0	0	0
15	1/16/1985 8:	0	0	0	0	0
16	1/17/1985 8:	0	0	0	0	0
17	1/18/1985 8:	1.2	2.2	2.6	1.2	7.8
18	1/19/1985 8:	3.3	1.2	6.6	2.2	24.2
19	1/20/1985 8:	0	0	0	0	0
20	1/21/1985 8:	2	2.1	9.6	1.6	14.2
21	1/22/1985 8:	0	0	1	1	0
22	1/23/1985 8:	0	0	0	0	0
23	1/24/1985 8:	0	0	0	0	0
24	1/25/1985 8:	0	5.6	0	0	0
25	1/26/1985 8:	13.7	22.1	23.6	17.4	26.9
26	1/27/1985 8:	0	0	9.2	3.4	7.4
27	1/28/1985 8:	0	0	0	0	0
28	1/29/1985 8:	0	0	0	0	0
29	1/30/1985 8:	0	0	0	0	0
30	1/31/1985 8:	0	0	0	0	0
31	2/1/1985 8:3	0	0	0	0	0
32	2/2/1985 8:3	0	0	0	0	0
33	2/3/1985 8:3	0	0	0	0	0
34	2/4/1985 8:3	0.1	0.8	0	0	2
35	2/5/1985 8:3	2.1	0.8	5.4	3.8	10
36	2/6/1985 8:3	0	0	0	0.2	0
37	2/7/1985 8:3	0	0	0	0	0
38	2/8/1985 8:3	0	0	0	0	0

Figure 4.4 Input Rainfall Time Series for NAM

The catchment area up to R M Bagh gauging site has been divided into ten sub-catchments having different areas by using rainfall-runoff editor in MIKE 11. The shape-file of the catchment extracted from DEM was imported in the MIKE 11 rainfall-runoff editor and NAM polygons representing different sub-catchments were generated using the Basin View of rainfall-runoff editor. The NAM catchments in Basin View are shown in Figure 4.5. A Combined catchment was defined as the sum of the ten sub-catchments as shown in Figure 4.6.

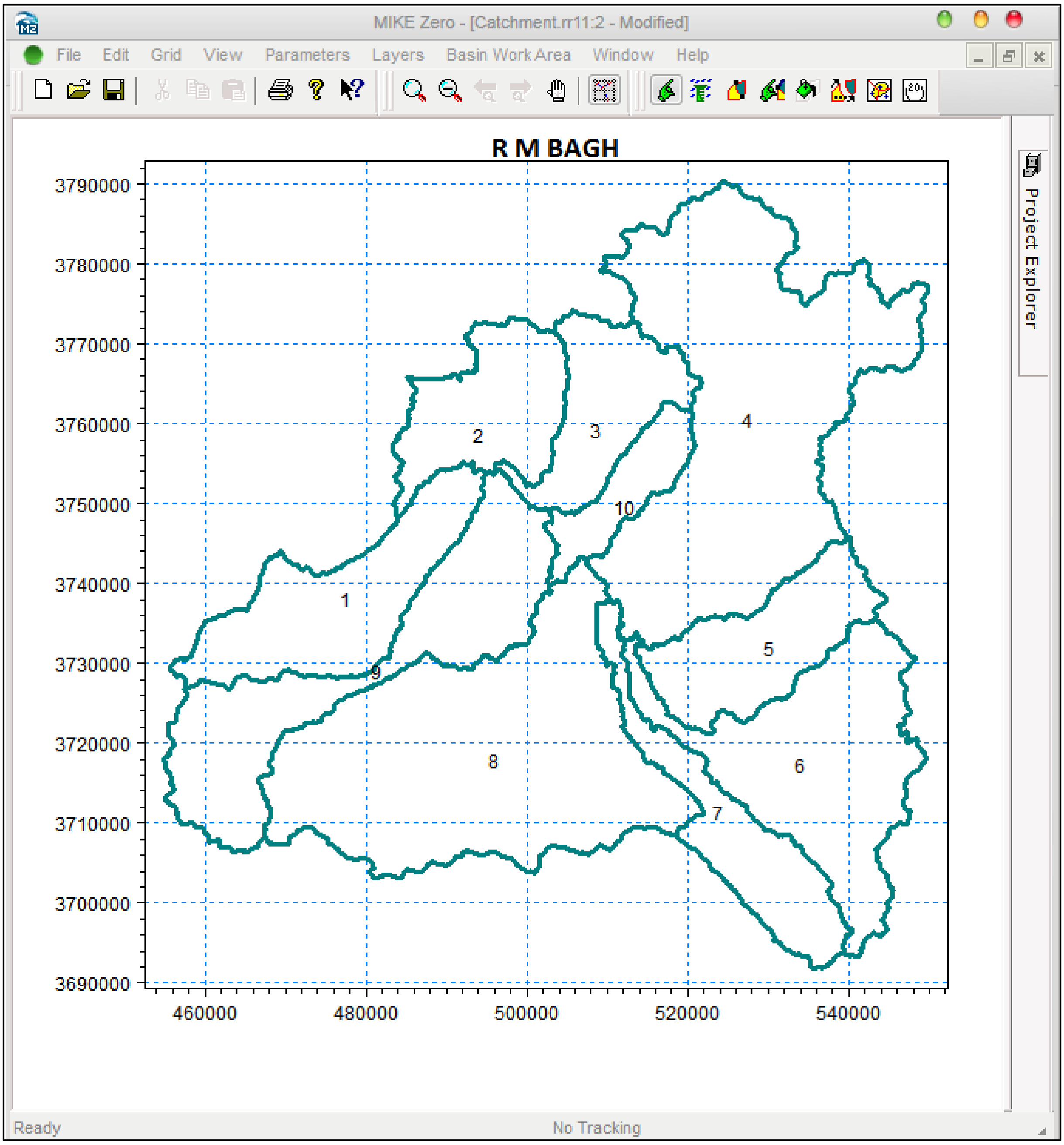
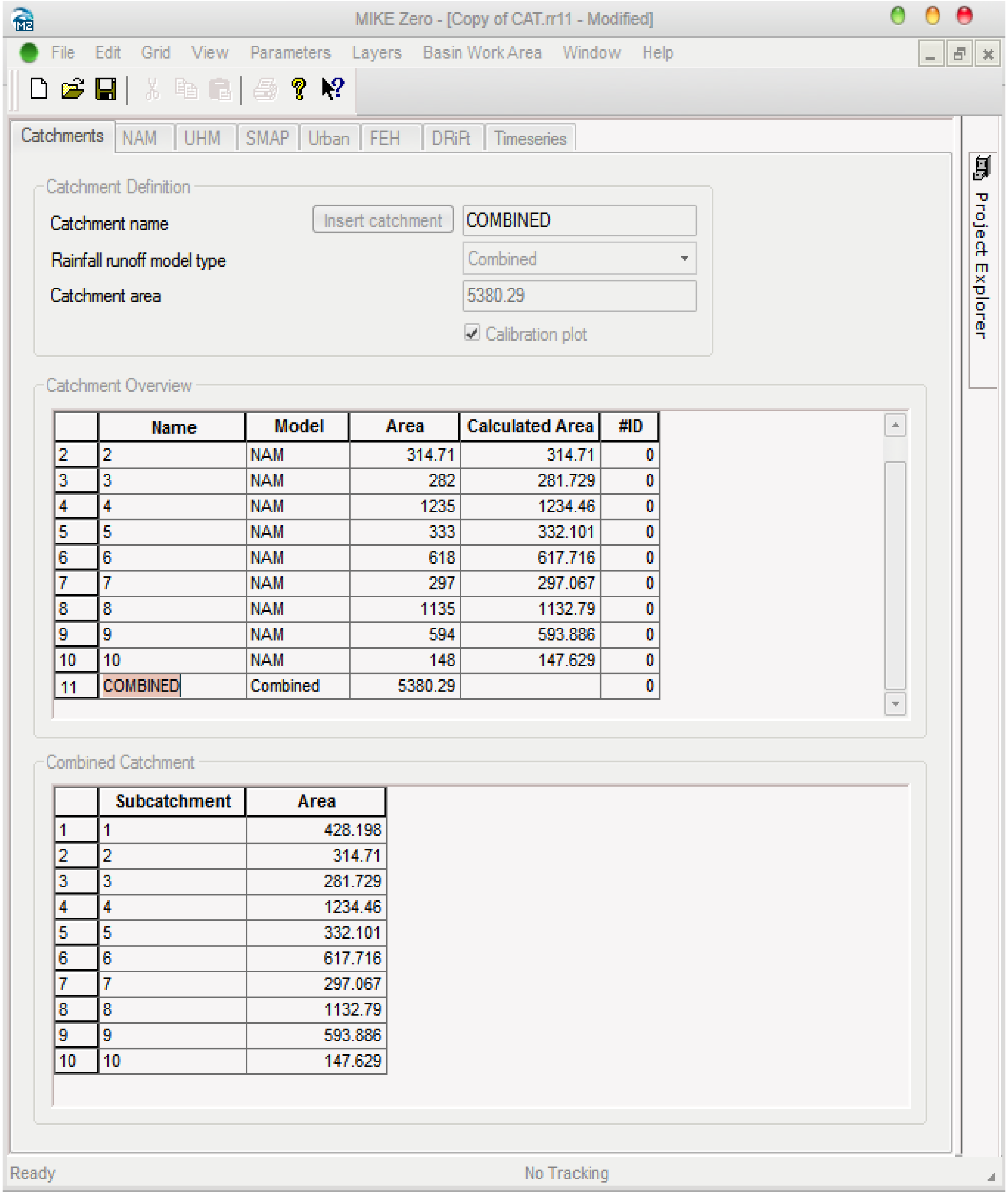


Figure 4.5 Catchment Details (Basin View)



Catchment Definition

Catchment name: COMBINED
Rainfall runoff model type: Combined
Catchment area: 5380.29
☑ Calibration plot

Catchment Overview

	Name	Model	Area	Calculated Area	#ID
2	2	NAM	314.71	314.71	0
3	3	NAM	282	281.729	0
4	4	NAM	1235	1234.46	0
5	5	NAM	333	332.101	0
6	6	NAM	618	617.716	0
7	7	NAM	297	297.067	0
8	8	NAM	1135	1132.79	0
9	9	NAM	594	593.886	0
10	10	NAM	148	147.629	0
11	COMBINED	Combined	5380.29		0

Combined Catchment

	Subcatchment	Area
1	1	428.198
2	2	314.71
3	3	281.729
4	4	1234.46
5	5	332.101
6	6	617.716
7	7	297.067
8	8	1132.79
9	9	593.886
10	10	147.629

Figure 4.6 Catchment Details

The rainfall stations were inserted within the catchment using Basin View of Rainfall-Runoff editor, which were then used to prepare Theissen's polygons, thus the weighted rainfall for the catchment. Figure 4.7 shows the rainfall stations and the prepared Theissen's polygons for the catchment. The station weightage for each sub-catchment is given in Table 4.2. Input Time series for Evaporation, Temperature and Observed Discharge were included on the Time series Page of Rainfall-Runoff editor.

Table 4.2 Theissen’s weights for different sub-catchments

Catchment	Rainfall Stations				
	SRINAGAR	SHALIMAR	QAZIGUND	KOKERNAG	PAHALGAM
1	0.16	0.08	0.00	0.76	0.00
2	0.00	0.76	0.00	0.00	0.24
3	0.00	0.00	0.00	0.00	1.00
4	0.00	0.00	0.00	0.09	0.91
5	0.00	0.00	0.00	0.64	0.36
6	0.00	0.00	0.27	0.65	0.07
7	0.00	0.00	0.66	0.34	0.00
8	0.00	0.00	0.05	0.95	0.00
9	0.00	0.01	0.00	0.97	0.02
10	0.00	0.00	0.00	0.19	0.81

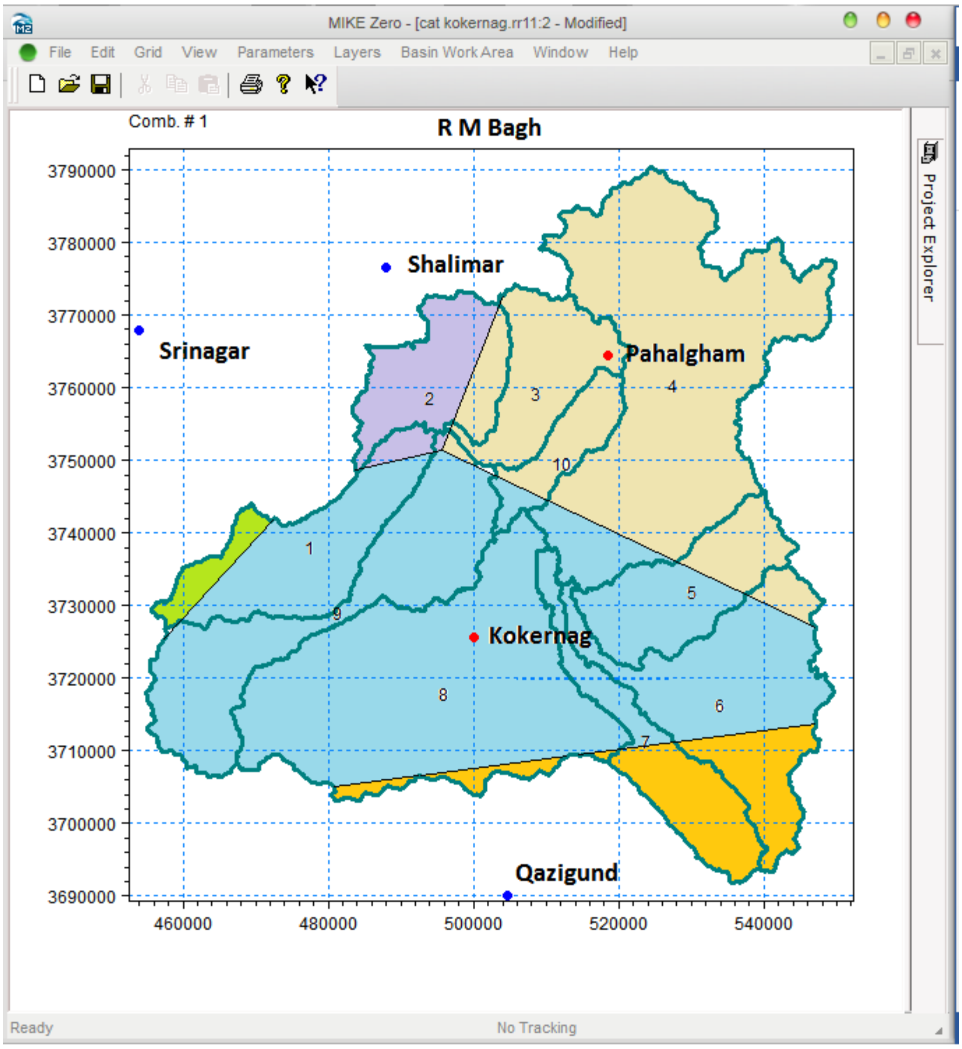


Figure 4.7 Rainfall Stations with Thiessen's Polygons

The runoff at the R M Bagh Site is influenced from snow-melt in the upper catchments for part of the year, while during winter most of the precipitation occurs in the form of snow throughout the catchment. The NAM setup was prepared with snowmelt component. Initially the model was run using default model parameters and a set of initial conditions for base-flow, C_{SNOW}, base temperature and snow storage.

4.2.3 MIKE 11 HD Model Setup

The HD model setup requires river network and river cross section details, boundary conditions and HD parameter file. The river network of Jhelum as well as its tributaries was extracted using SRTM 90m DEM. The extracted shape files were then imported in the MIKE 11 river network editor in order to generate the river network. The upstream boundary condition for the tributaries was taken as a constant zero discharge. The Manning's coefficient for tributaries has been assigned in the range between 0.035-0.065 depending on tributary bed surface condition. For the main river the value of Manning's roughness has been assigned as 0.035 based on experience. The river system was simulated considering high order fully dynamic wave approximation.

River Network

The river network model of the river Jhelum and its major tributaries in the basin was extracted from the SRTM DEM of the basin in order to setup the HD model. MIKE 11 River Network Editor interface was used to generate the river network from the shape file of the river system. The drainage network of the study area comprises of the River Jhelum and its associated streams. They comprise the Rembiara, Vishow and Lidder river systems which are fairly developed, as well as small rivulets such as the Sandran, Bring and Arapat Kol. A flood plain branch was added to the river network near the gauging site which carries excess runoff from the main channel in case of extreme flood events. The Graphical view of the river network generated using MIKE 11 River network Editor is given in Figure 4.8. The flow direction was taken positive with minimum distance between two adjacent points (dx) 1000m.

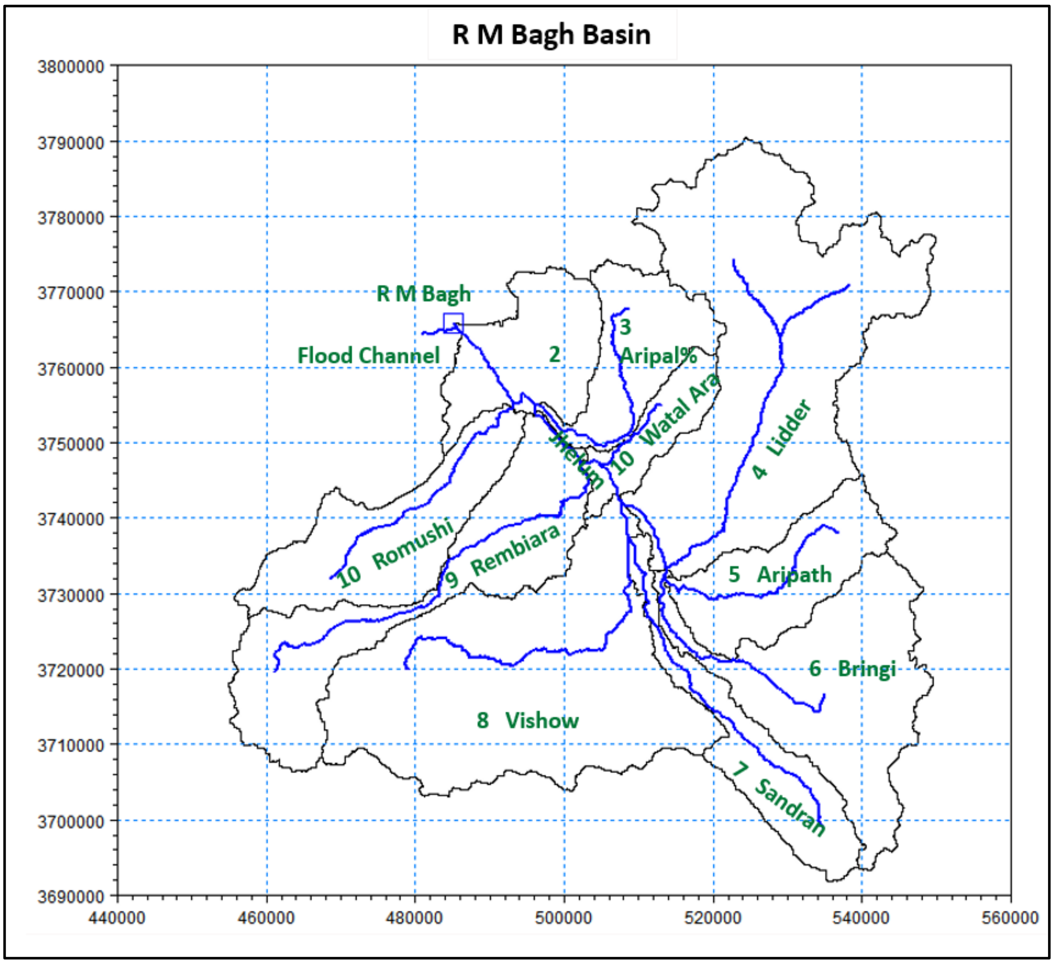


Figure 4.8 River Network for MIKE 11 HD Model

River Cross Sections

There are two types of cross section data; the raw survey data and the derived processed data. The raw data describes the shape of the cross section. The cross section details of the main river as well as the tributaries were obtained from IFC, Srinagar. The processed data was derived from the raw data and contains all information used by the computer model (e.g. level, cross section area, flow width, hydraulic/ resistance radius). The processed data was calculated by the cross section editor of river network editor. River Cross sections are the main input for MIKE 11 HD Model for simulation of water level and discharge. The raw and processed cross sections for the main channel at the outlet, i.e. R M Bagh gauging site are shown in Figure 4.9 and Figure 4.10, respectively.

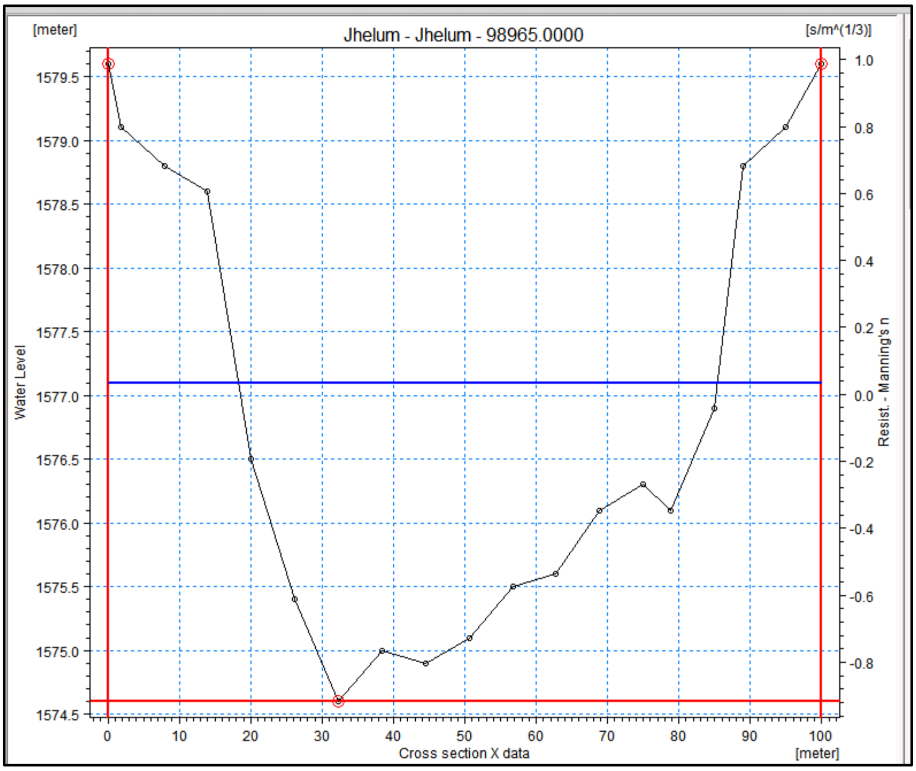


Figure 4.9 Raw Cross section at R M Bagh Gauging Site

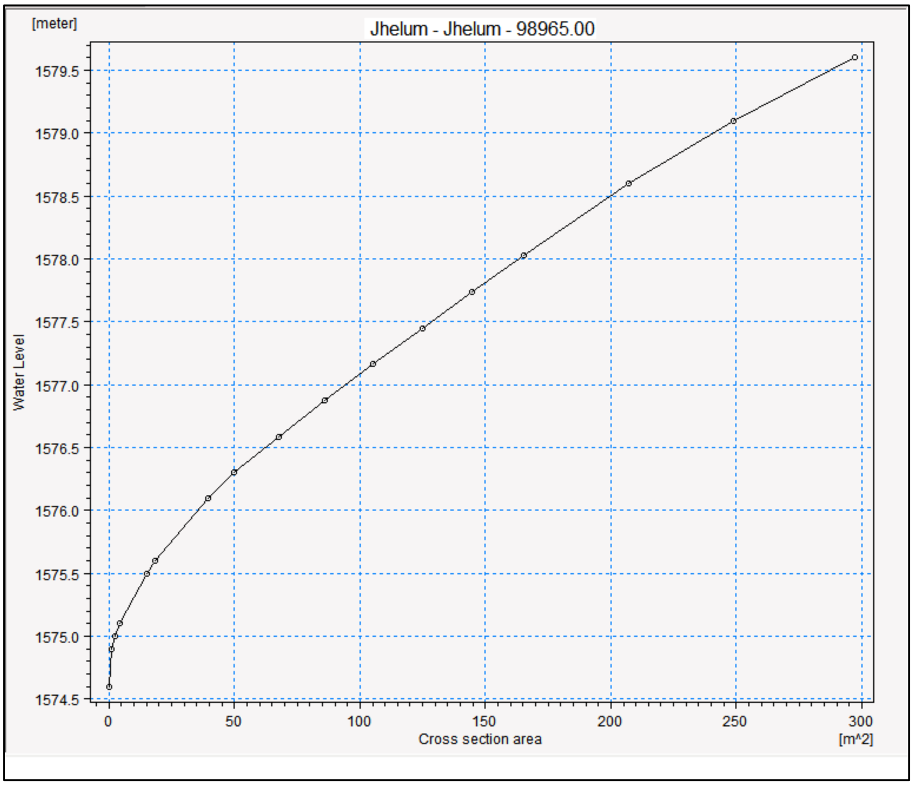
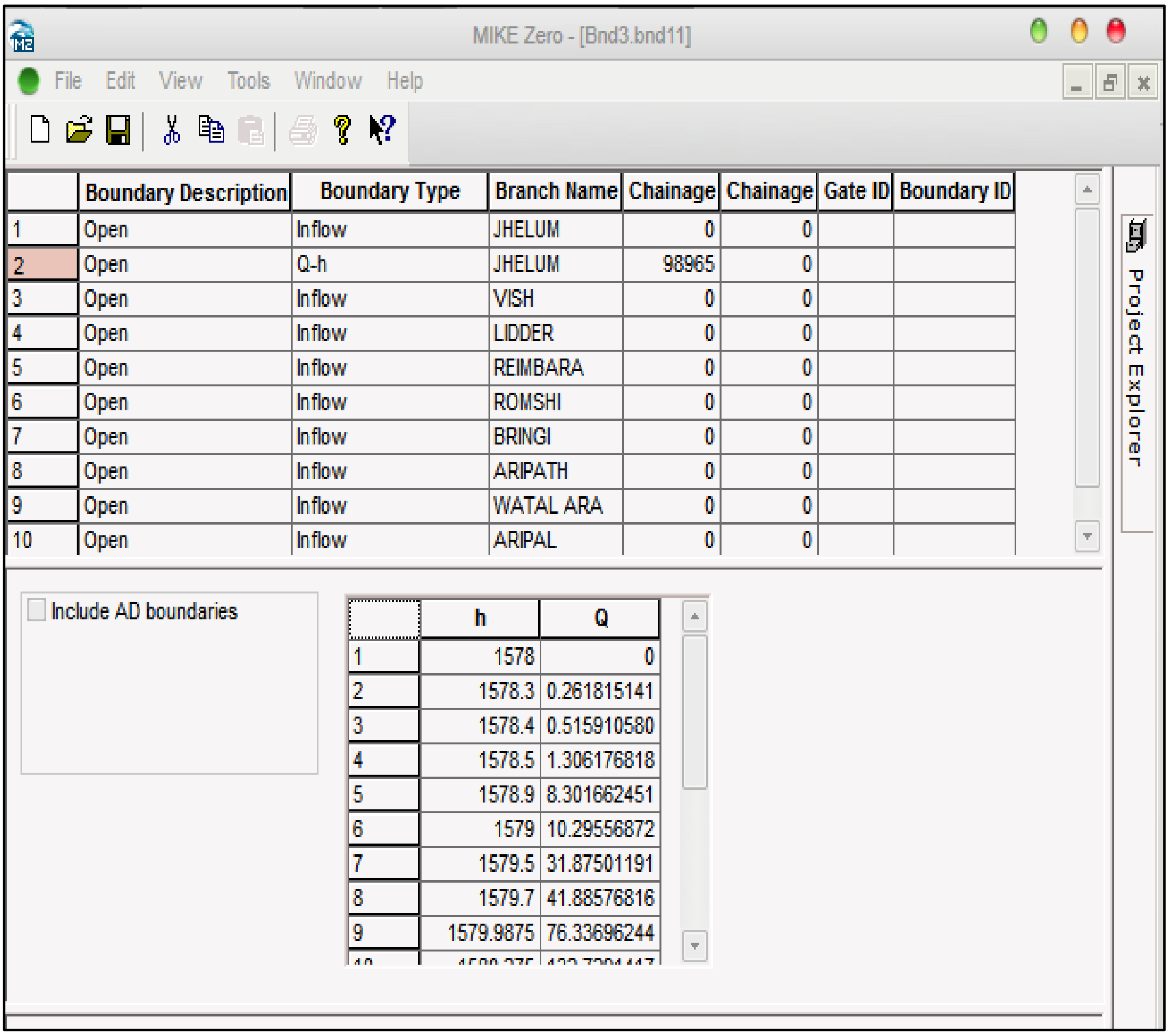


Figure 4.10 Processed Cross Section at R M Bagh Gauging Site

Boundary Conditions

The selection of boundary conditions depends on the availability of data and the physical situation of the model area. Boundary conditions could be constant discharge from a reservoir, a discharge hydrograph of a specific event, constant water level, e.g., in a large receiving water body, time series of water level, e.g., tidal cycle, and a reliable rating curve, e.g., from a gauging station. The upstream boundary condition for the main river and the tributaries was taken to be a constant zero discharge while a Q-h curve at the outlet calculated using Mike 11 Boundary Editor was taken as the downstream boundary condition. Figure 4.11 shows the MIKE 11 Boundary Editor.



	Boundary Description	Boundary Type	Branch Name	Chainage	Chainage	Gate ID	Boundary ID
1	Open	Inflow	JHELUM	0	0		
2	Open	Q-h	JHELUM	98965	0		
3	Open	Inflow	VISH	0	0		
4	Open	Inflow	LIDDER	0	0		
5	Open	Inflow	REIMBARA	0	0		
6	Open	Inflow	ROMSHI	0	0		
7	Open	Inflow	BRINGI	0	0		
8	Open	Inflow	ARIPATH	0	0		
9	Open	Inflow	WATAL ARA	0	0		
10	Open	Inflow	ARIPAL	0	0		

☐ Include AD boundaries

	h	Q
1	1578	0
2	1578.3	0.261815141
3	1578.4	0.515910580
4	1578.5	1.306176818
5	1578.9	8.301662451
6	1579	10.29556872
7	1579.5	31.87501191
8	1579.7	41.88576816
9	1579.9875	76.33696244

Figure 4.11 Boundary Editor, MIKE 11

HD Parameter

The Global Manning number of M = 20 $m^{1/3}/s$ and the Delta (Default Values) of 0.6 were used. The Wave approximation of ‘High Order Fully Dynamic’ was considered to simulate the river system.

4.2.4 Integration of NAM with HD Model

NAM and HD models were integrated and the lateral inflow from the sub-catchments was given as input to the river channels. A Q-h relationship at the outlet was taken as the boundary condition at the outlet at R M Bagh site. The model was run with a fixed time step of one minute. The integrated model generates a time series of discharge and water level at each 1000m point at 1 minute time interval for every alternate point.

4.2.5 Model Calibration and Validation

Model calibration is the process of estimation of model parameters. The deviations from the observed values are used to standardize predicted values, such that they are consistent with the observed values. The parameters of the models cannot, in general be determined from the basin characteristics. Hence, the parameters values are estimated by calibration against the observed data (Madsen, 2000). The parameters of NAM model were calibrated using observed rainfall-runoff data for 21 years period from 1985-2005. The observed discharge values of tributaries were also compared with the simulated values of their respective catchments for the available time periods to increase the confidence of the calibration. A long calibration period with a variety of hydrological conditions increases confidence in model results (James and Burges, 1982). Initially the model was run in auto-calibration mode using default model parameters. The predicted values were compared with the observed values graphically and statistically to assess degree of agreement. The model parameters were then adjusted one by one by trial and error method in order to obtain set of model parameters which produce good fit between observed and model predicted stream flow. Having a good fit between predicted and observed stream-flow for the calibration period is a necessary test of a model's applicability to a watershed, but it is insufficient because it does not guarantee that the model will properly simulate runoff for non-calibrated periods (Todini and Wallis, 1977; Beven, 1989). The calibrated model was then validated by simulating the discharge for next 9 years from 2006-2014 to ascertain applicability of the model.

4.2.6 Evaluation of Model Performance

The performance of the model was analysed by using graphical plots between observed and simulated daily discharges and cumulative annual flows. Annual peak flows and low flows were also analysed separately to test the model's efficiency. Statistical parameters like R^2, EI and d were used to evaluate the reliability of the model.

The coefficient of determination R^2 is defined as the squared value of the coefficient of correlation according to Bravais- Pearson. It is calculated as:

$$\boldsymbol{R^2} = \left(\frac{\sum_{i=1}^{n}(q_o - \overline{q}_o)(q_s - \overline{q}_s)}{\sqrt{\sum_{i=1}^{n}(q_o - \overline{q}_o)^2}\sqrt{\sum_{i=1}^{n}(q_s - \overline{q}_s)^2}} \right)^2 \quad \dots \quad \textbf{(4.1)}$$

Where,

n = No. of observations

q_s = simulated value

q_o = observed value

$\overline{q}_o$ = mean value of observed values

$\overline{q}_s$ = mean value of simulated values

The range of R^2 lies between 0 and 1 which describes how much of the observed dispersion is explained by the prediction. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation (Krause et al., 2005).

The efficiency EI proposed by Nash and Sutcliffe (1970) is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation. It is calculated as:

$$\boldsymbol{EI} = 1 - \frac{\sum_{i=1}^{n}(q_s - q_o)^2}{\sum_{i=1}^{n}(q_o - \overline{q}_o)^2} \quad \dots \quad \textbf{(4.2)}$$

The range of EI lies between $-\infty$ and 1.0 (perfect fit). An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model (Krause et.al, 2005).

The index of agreement d proposed by Willmot (1981) represents the ratio of the mean square error and the potential error (Willmot, 1984) and is defined as:

$$\boldsymbol{d = 1 - \frac{\sum_{i=1}^{n}(q_s - q_o)^2}{\sum_{i=1}^{n}(|q_o - \bar{q}_o| + |q_s - \bar{q}_o|)^2}} \ldots \textbf{(4.3)}$$

The range of d is similar to that of R^2 and lies between 0 (no correlation) and 1 (perfect fit).

4.2.7 Sensitivity Analysis

In order to identify the most sensitive parameters, the model was run with one parameter variable keeping others constant for the calibration period. The model parameters were increased and decreased at an interval of 10% for each run of their calibrated values to determine the effect on R^2 and EI. The results were analysed by means of comparison plots. In addition, the effect of model parameters on peak flows, low flows and accumulated volume was also analysed by means of graphical plots.

4.2.8 Simulation of Extreme Historical Flood Events

The developed model was used to simulate some of the extreme historical flood events that had occurred in the basin in order to check the ability of the model to simulate extreme floods. The model was also used to simulate the September 2014 flood event, which was the most extreme event in the past 60 years.

CHAPTER 5

RESULTS AND DISCUSSIONS

An integrated NAM and HD model was developed to simulate the rainfall-runoff process in the Jhelum River Basin at R M Bagh gauging site. The model parameters were obtained during calibration and then the model was validated. The integrated model was also used to simulate some historical extreme flood events in the basin. The results obtained from the study have been discussed in this chapter.

5.1 CALIBRATION AND VALIDATION

The NAM model parameters for each sub-catchment were obtained during model calibration using procedure discussed in section 4.2.5. The final values of the calibrated parameters for different sub-catchments are given in Table 5.1. The set of model parameters obtained during model calibration were found to be within their specified range. The efficiency of NAM model during calibration runs was analysed graphically and by Coefficient of determination.

Table 5.1 NAM model parameter values after calibration and their range

PARAMETER	TYPICAL PARAMETER RANGE	SUB-CATCHMENT									
		1	2	3	4	5	6	7	8	9	10
Umax	5-35 mm	12.6	11.45	11.45	11.45	11.45	11.57	11.57	12.02	11.57	11.45
Lmax	50-400 mm	142	150.22	149.2	151.24	151.24	148.18	133.87	152.27	152.27	152.27
CQOF	0-1	0.58	0.57	0.5	0.51	0.5	0.51	0.51	0.52	0.57	0.6
CKIF	200-2000 mm	316.7	314.4	331.2	321.9	328.3	279.4	307.7	317.4	322.6	325.5
$CK_{1,2}$	3-72 h	36.7	48.19	47.4	51.44	50.21	55.04	48.41	36.84	53.01	54.03
TOF	0-0.9	0.59	0.59	0.12	0.03	0.15	0.59	0.59	0.6	0.3	0.27
TIF	0-0.9	0.84	0.52	0.13	0.42	0.71	0.58	0.06	0.47	0.86	0.15
TG	0-0.9	0.15	0.03	0.16	0.51	0.3	0.07	0.02	0.15	0.34	0.14
CK_{BF}	500-5000 h	2269	2196	2279	2272	2276	2267	2249	2225	2280	2140
T_0	-	2	2	3	4	3	3	3	3	3	2

The values of the parameters indicate substantial surface as well as groundwater storage in nearly all the catchments. The precipitation is more or less uniformly distributed between overland flow and infiltration with no or little delay in the runoff generation. The basin has a snow dominated runoff regime, i.e. snowmelt forms an important component of the discharge in the basin. Snowmelt runoff increases in spring and is potentially reduced during late summer.

The calibration and validation plots of NAM model are shown in Figure 5.1 and Figure 5.2. The graphical plots indicate close agreement between observed and simulated runoff values on a daily basis in both calibration and validation periods.

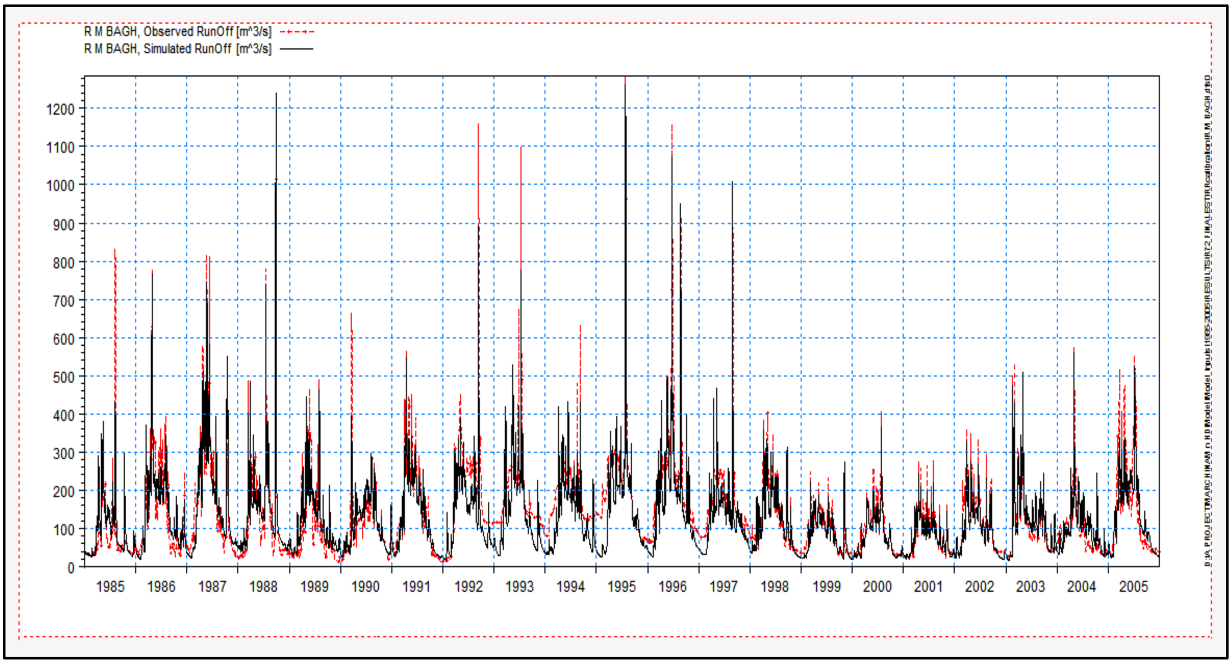


Figure 5.1 Observed and simulated hydrograph during model calibration

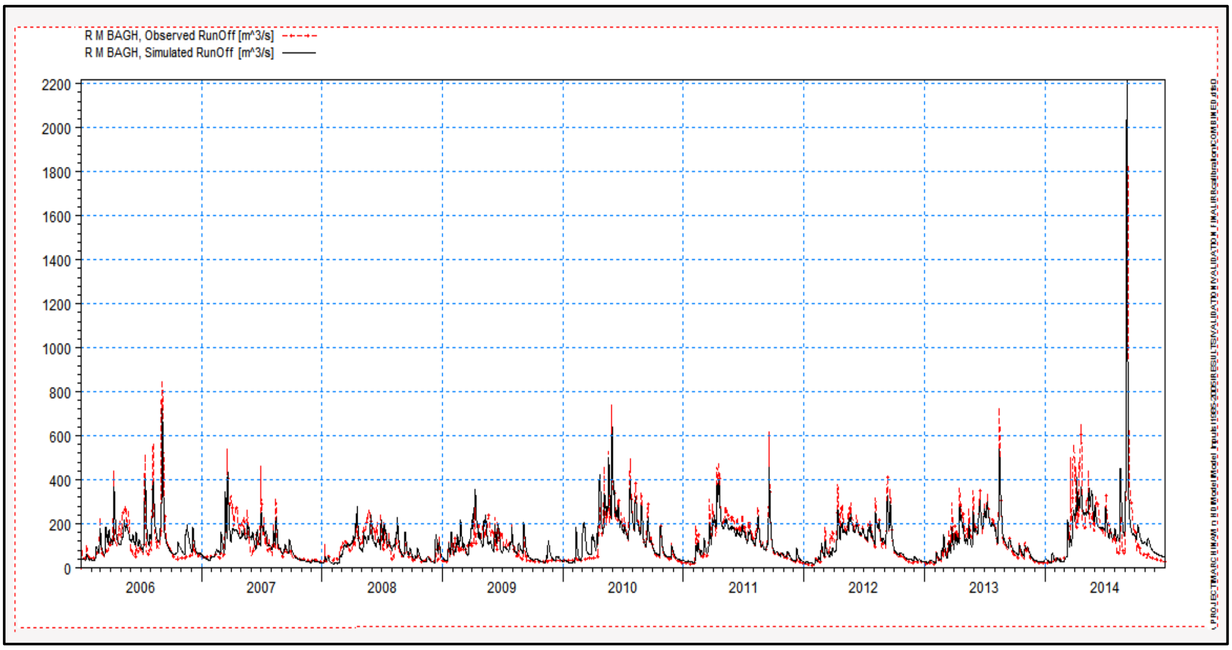


Figure 5.2 Observed and simulated hydrograph during model validation

The integrated NAM and HD model was calibrated after several simulation runs. The calibration time series was 1985-2005. The value of Manning's roughness coefficient for the main channel was 0.035. The model was then run for a time period of 2006-2014 for validation. The results were a continuous series of discharge and water level at various locations along the river. Figure 5.3-5.8 show the graphical plots of observed and simulated discharges for some years from calibration and validation period.

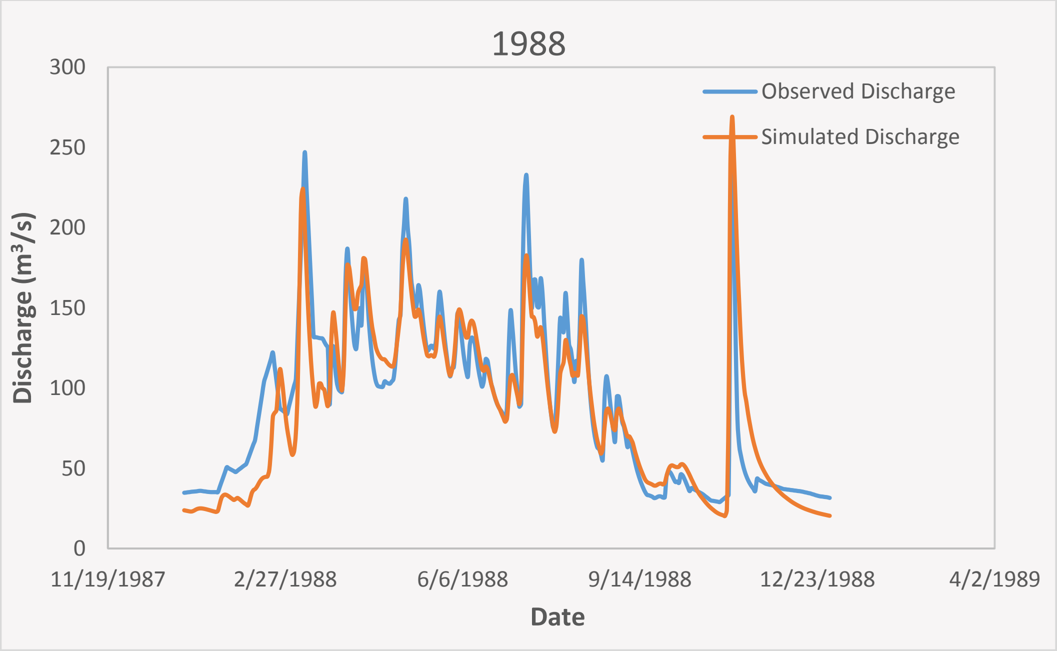


Figure 5.3 Observed and simulated hydrograph for the year 1988

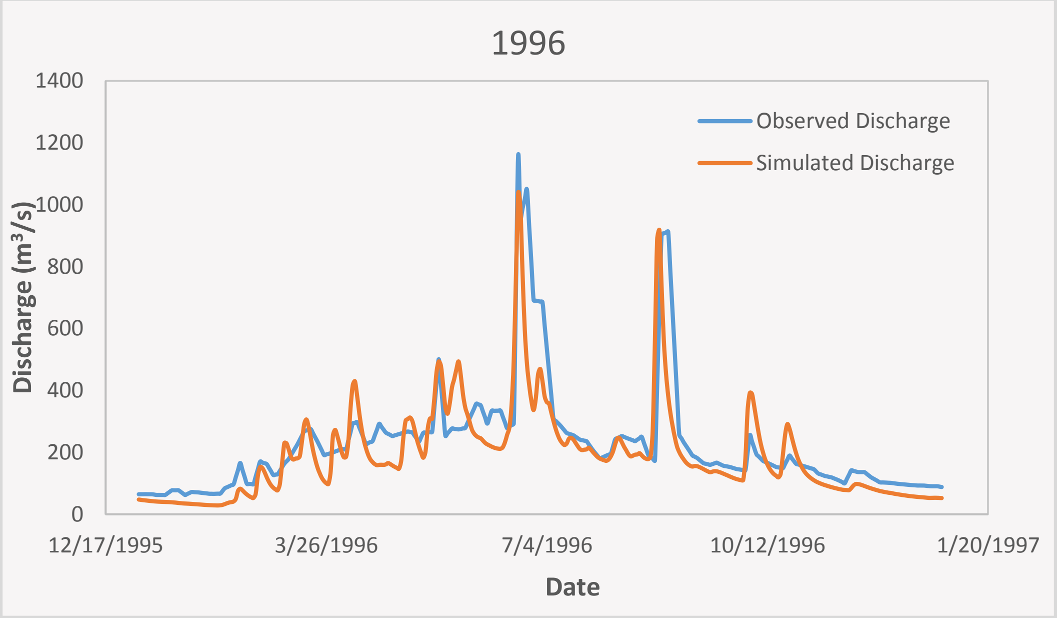


Figure 5.4 Observed and simulated hydrograph for the year 1996

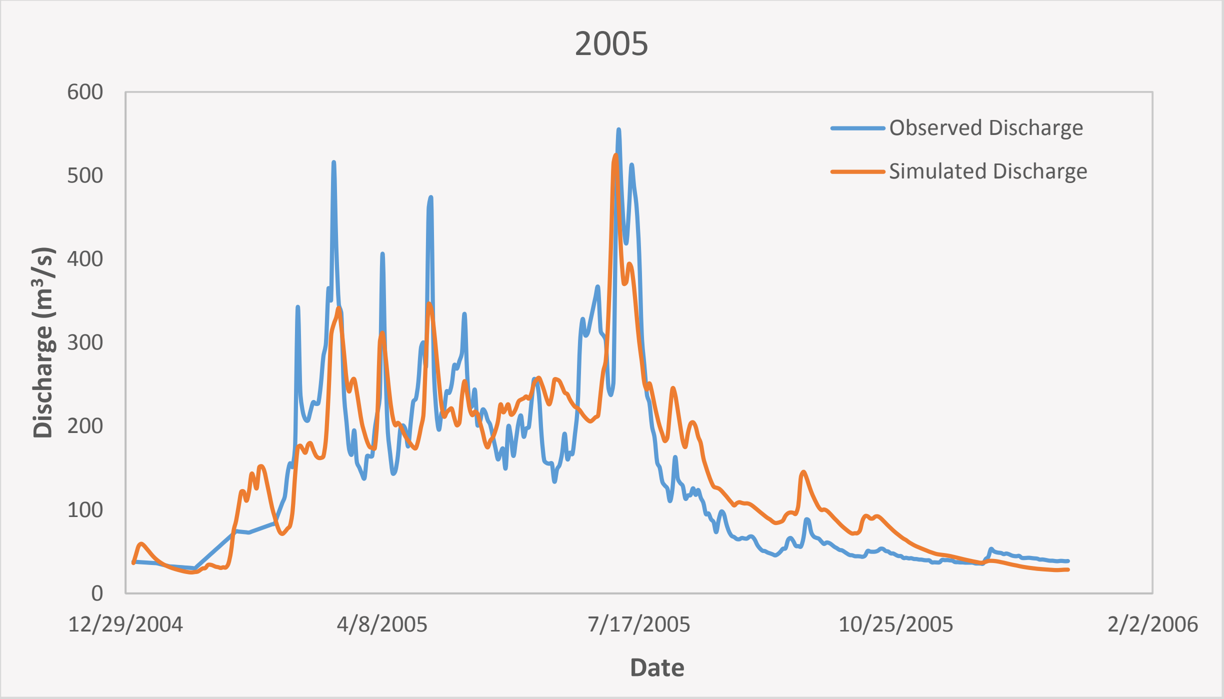


Figure 5.5 Observed and simulated hydrograph for the year 2005

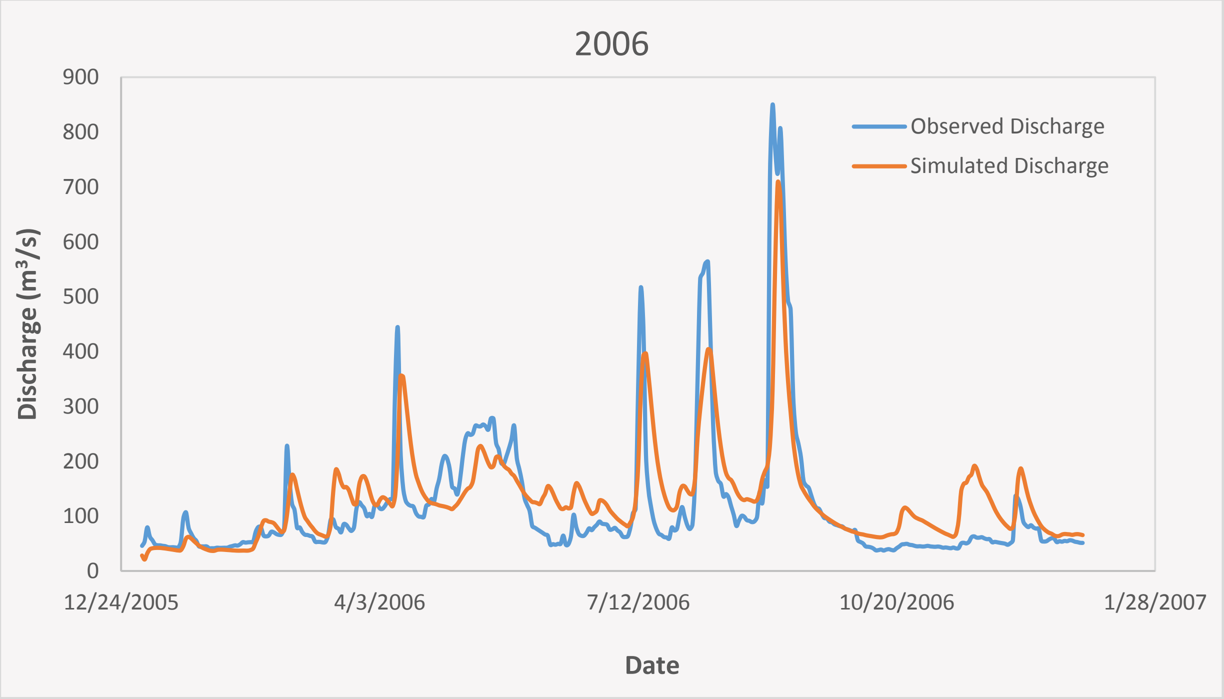


Figure 5.6 Observed and simulated hydrograph for the year 2006

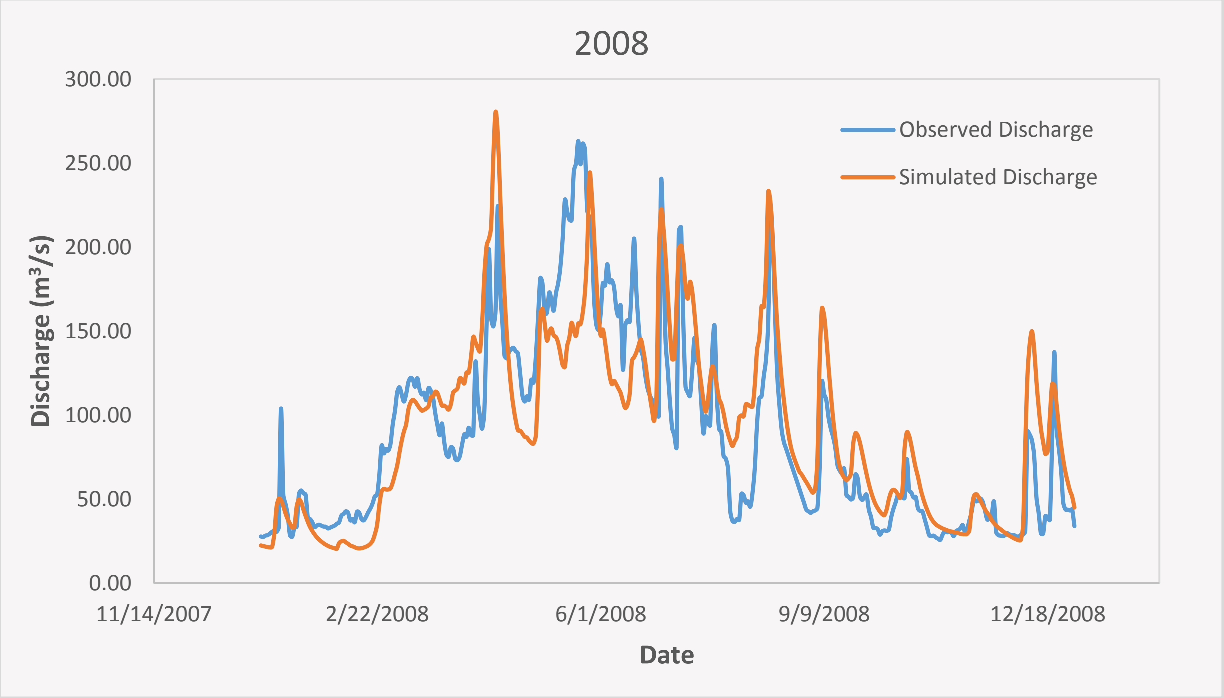


Figure 5.7 Observed and simulated hydrograph for the year 2008

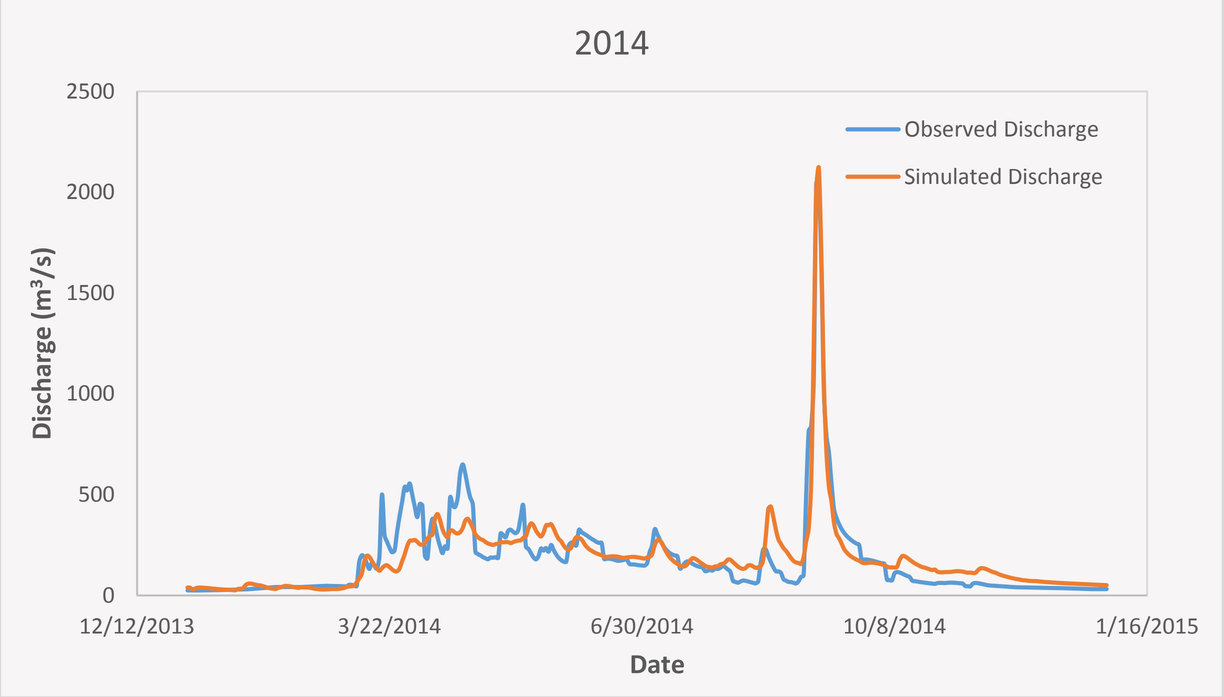


Figure 5.8 Observed and simulated hydrograph for the year 2014

5.2 EVALUATION OF MODEL PERFORMANCE

The simulated discharge values at the outlet were found to be consistent with the observed values. The statistical indices for the model are given in Table 5.2.

Table 5.2 Statistical Indices for model performance

	R^2	EI	d
Calibration (1985-2006)	0.751	0.749	0.872
Validation(2006-2014)	0.794	0.792	0.884

The high values of statistical indices in both calibration and validation periods indicate that good performance of model for simulating runoff in the catchment. The simulated annual peak flows and low flows were analysed separately. The simulated and observed peaks were in good agreement with each other in both calibration and validation periods. However, the simulated low flows did not show as much of agreement with the observed values, particularly during the calibration period. The scatter plots of cumulative annual flows and peak flows during calibration and validation periods have been given in Figure 5.9 and Figure 5.10.

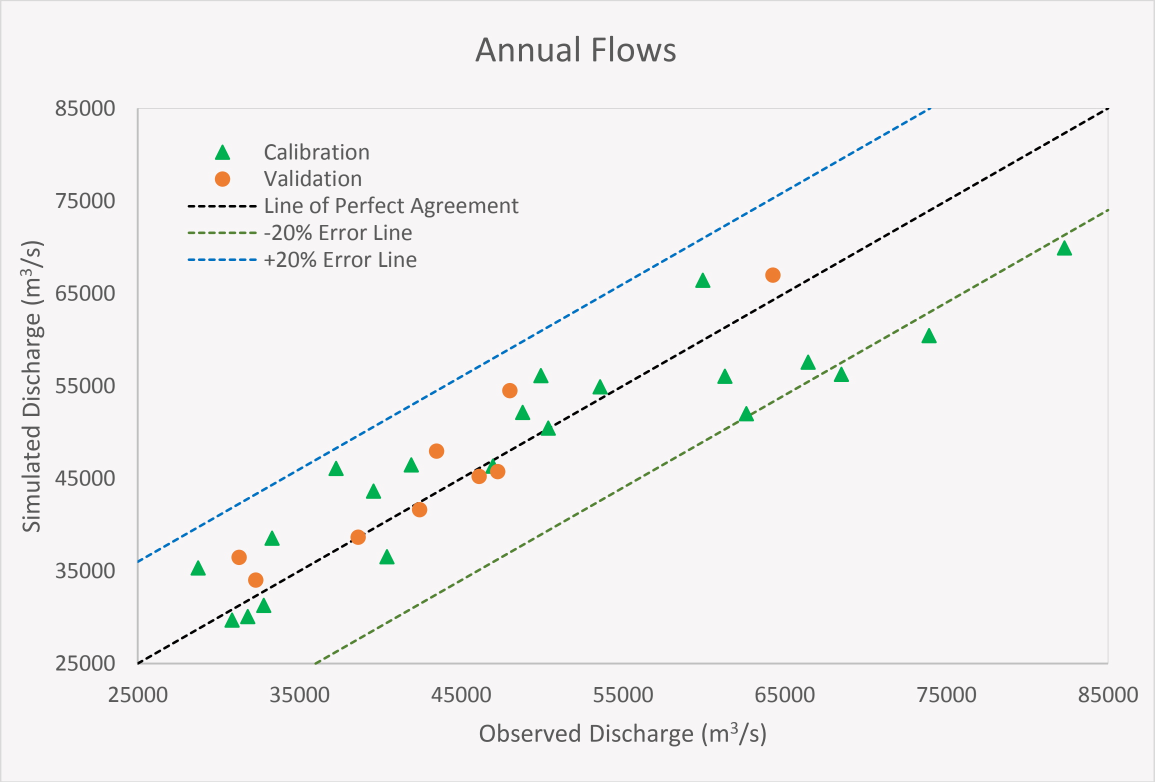


Figure 5.9 Scatter plot showing Cumulative Annual observed and simulated discharge values

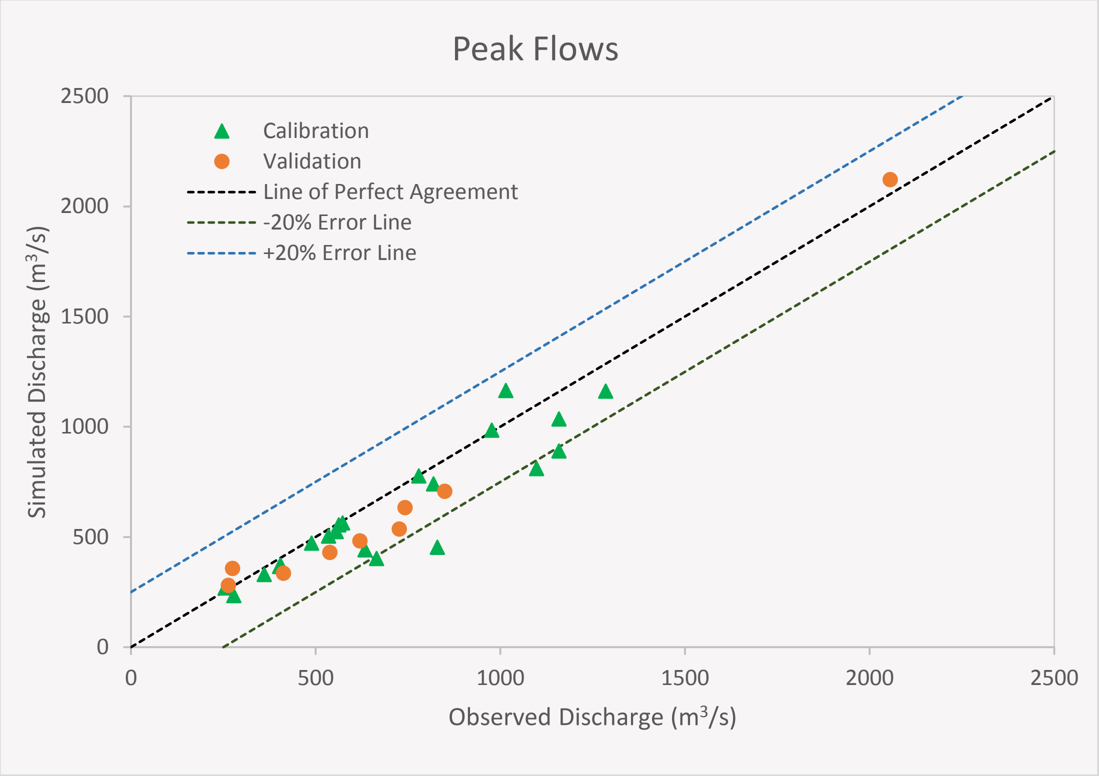


Figure 5.10 Scatter plot of observed and simulated peak flows

The line of perfect agreement corresponds to the value of R^2 equal to 1 between observed and simulated values. The lines below and above the line of perfect agreement represent the underestimates and overestimates of 20% of that of line of perfect agreement. The plots shows good agreement between the simulated and observed values of discharge for cumulative annual flows and peak flows. Nearly all the values fall in the interval of ±20% of the line of perfect agreement indicating a good reproduction.

5.3 SENSITIVITY ANALYSIS

The effect of change of model parameters on the model efficiency was carried by plotting R^2 and EI against the respected parameters. It was observed that CQOF, CK_{12} and T_0 were the most influencing and sensitive parameters as shown in Figure 5.11. Other parameters either had no or very little influence on model efficiency. Some of these are shown in Figure 5.12.

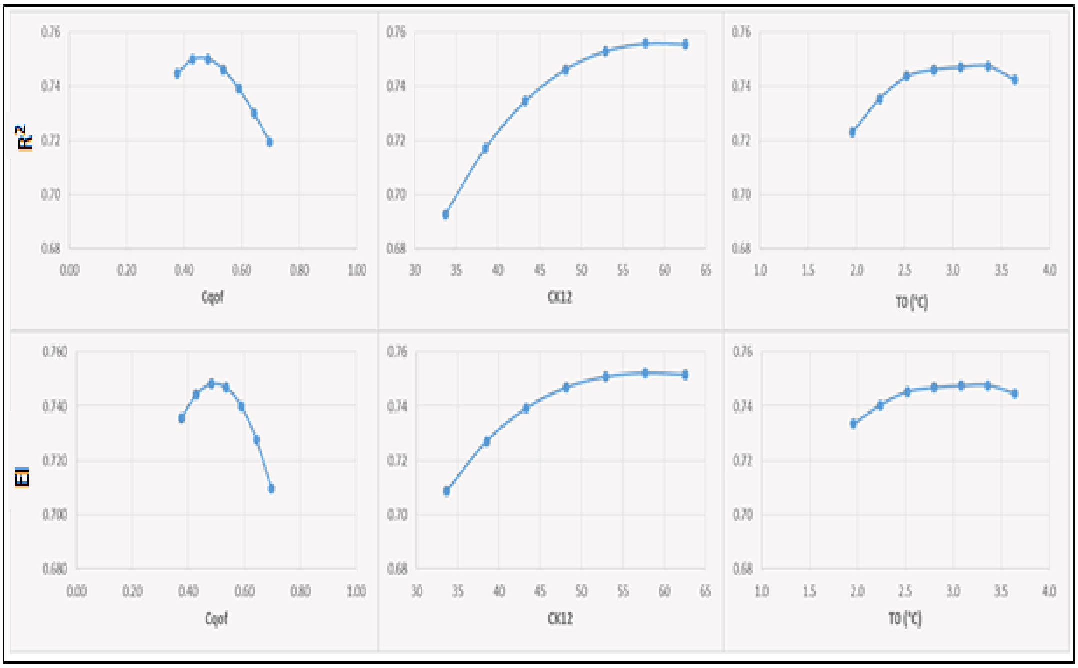


Figure 5.11 Graph between R^2 and EI against the sensitive model parameters

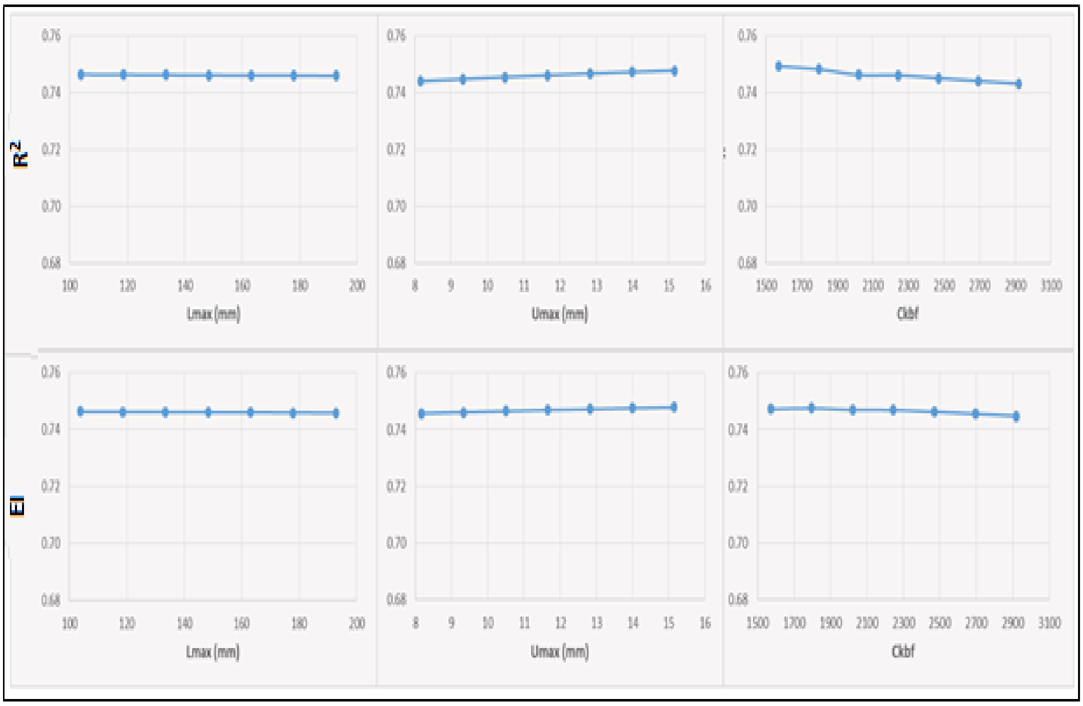


Figure 5.12 Graph between R^2 and EI against the non-sensitive model parameters

In case of HD model the only calibration parameter was Manning's roughness coefficient, which was found to affect both R^2 and EI as shown in Figure 5.13.

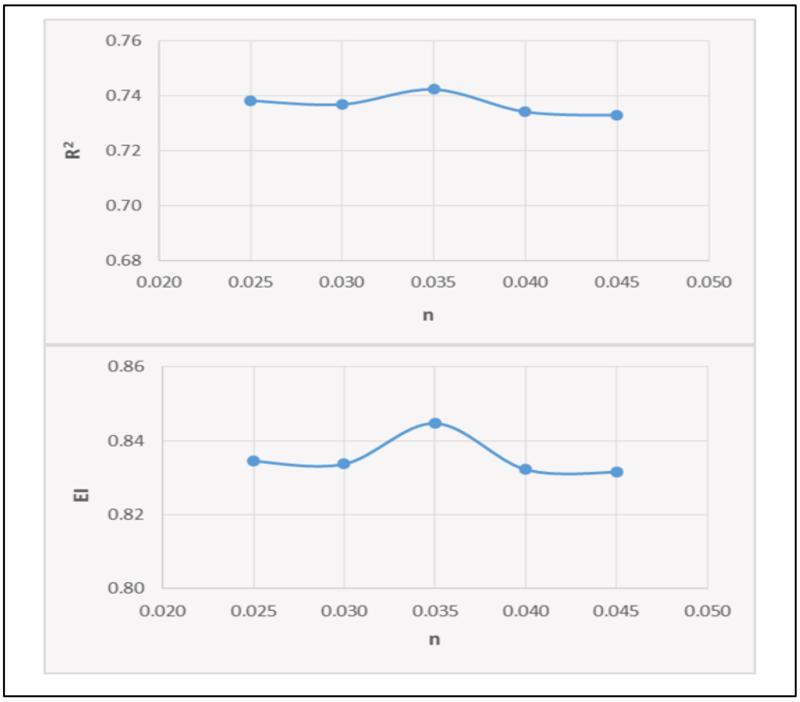


Figure 5.13 Graph of R^2 and EI against Manning's roughness coefficient

Effect of Model Parameters on Runoff

The model parameters were one by one increased and decreased at an interval of 10% for each run to study the effect on peak flows, low flows and accumulated volume. CQOF was found to be only parameter affecting peak flows, low flows and accumulated volume. Some parameters were found to affect either peak flows or low flows and accumulated volume while others had no effect on these values as shown in Figure 5.14 and Figure 5.15. The results are given in Table 5.3.

Table 5.3 Effect of increase on model parameters on peak flows, low flows and accumulated volume

Parameter	Effect on Peak Flows	Effect on Low Flows	Effect on Accumulated Volume
U_{max}	No Effect	Decreases	Increases
L_{max}	No Effect	No Effect	Decreases
CQOF	Increases	Decreases	Increases
CKIF	No Effect	Increases	Decreases
TOF	No Effect	No Effect	No Effect
TIF	No Effect	No Effect	No Effect
TG	No Effect	No Effect	No Effect
$CK_{1,2}$	Decreases	No Effect	No Effect
CK_{BF}	No Effect	Increases	Decreases
T_0	No Effect	Increases	Decreases

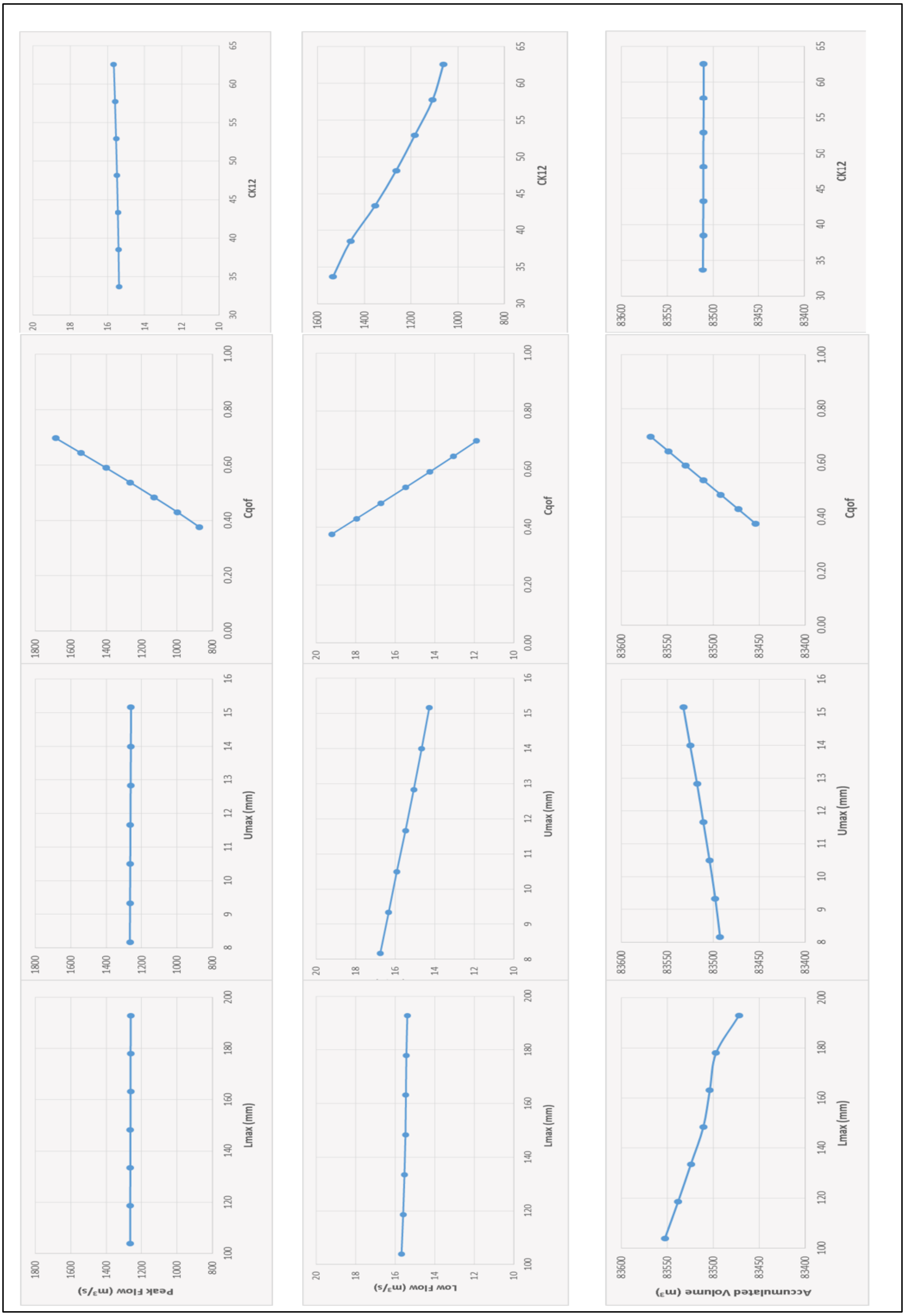


Figure 5.14 Effect of model parameters on peak flows, low flows and accumulated volume

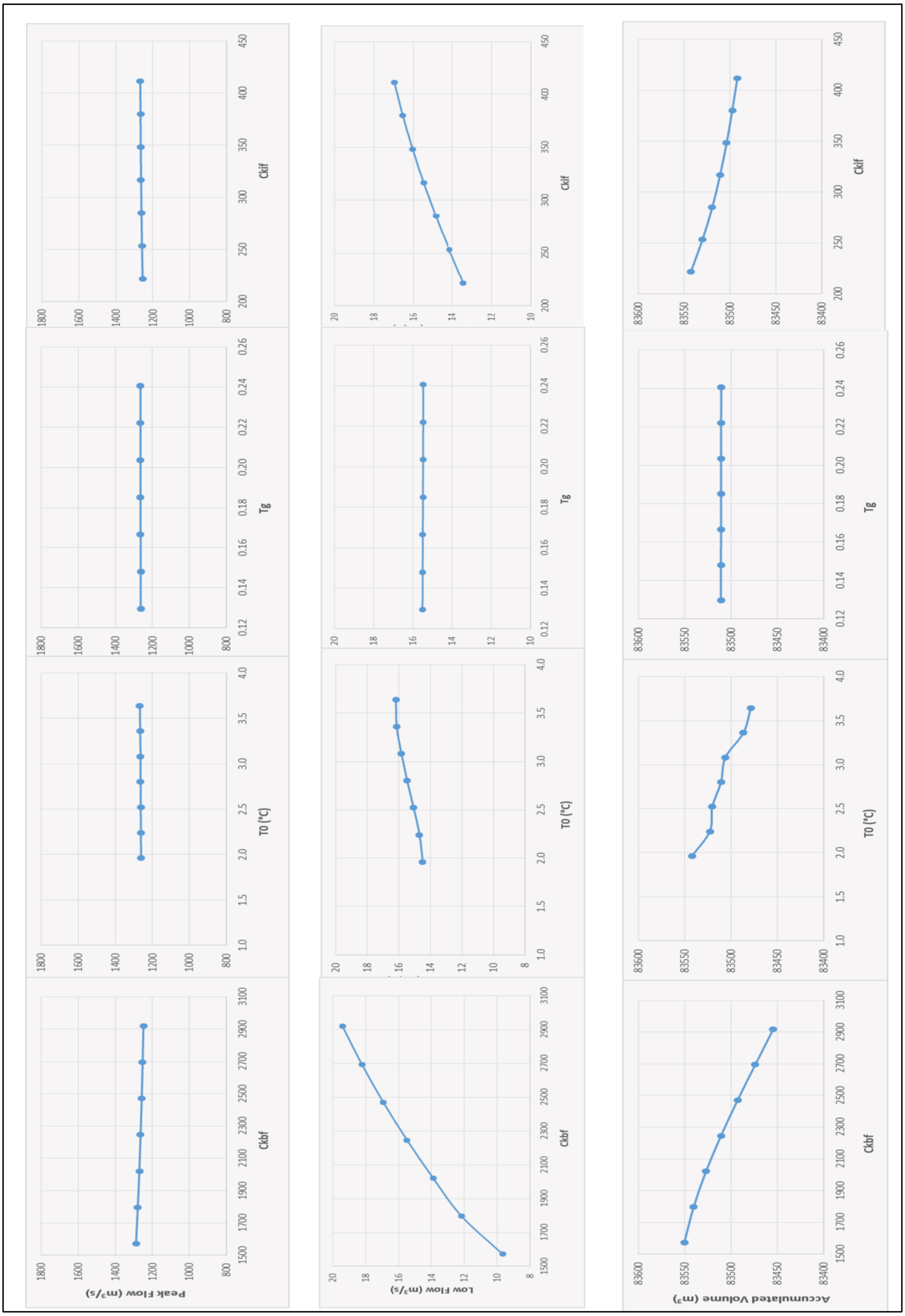


Figure 5.15 Effect of model parameters on peak flows, low flows and accumulated volume

The values of peak flows, low flows and accumulated volume decreased by increasing as well as decreasing the Manning's roughness coefficient for the main channel. The values were found maximum at the calibrated value i.e. 0.035. The time of peak decreased on decreasing the value of n and increased on increasing its value as shown in Figure 5.16.

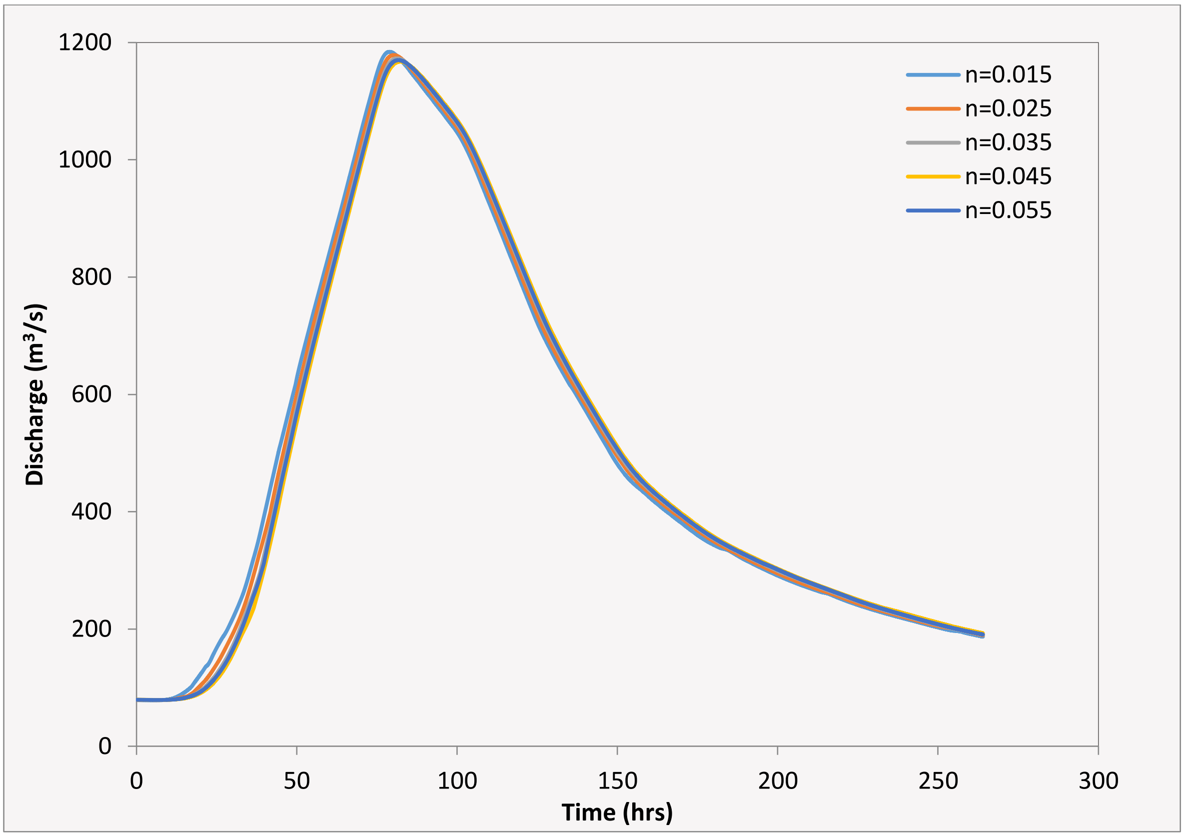


Figure 5.16 Variation of time of peak with n

5.4 SIMULATION OF EXTREME HISTORICAL FLOOD EVENTS

Four extreme events in the data series were examined separately, two each from calibration and validation period to study the behaviour of the model in extreme flood situations. Table 5.4 shows comparison between observed and simulated discharge for 4 extreme flood events.

Table 5.4 Observed and simulated peaks for extreme flood events

Year	Observed Discharge	Simulated Discharge	Percentage Difference
1988	1015	1164	15
1995	1285	1162	-10
2006	850	707	-17
2014	2055	2122	3

The comparison plots of observed and simulated data for the flood event of 1988, 1995 and 2006 are given in Figure 5.17, Figure 5.18 and Figure 5.19. The plots indicate good agreement between observed and simulated data. Simulated hydrographs show smooth and recession limbs in all cases with a single peak for a continuous rainfall event.

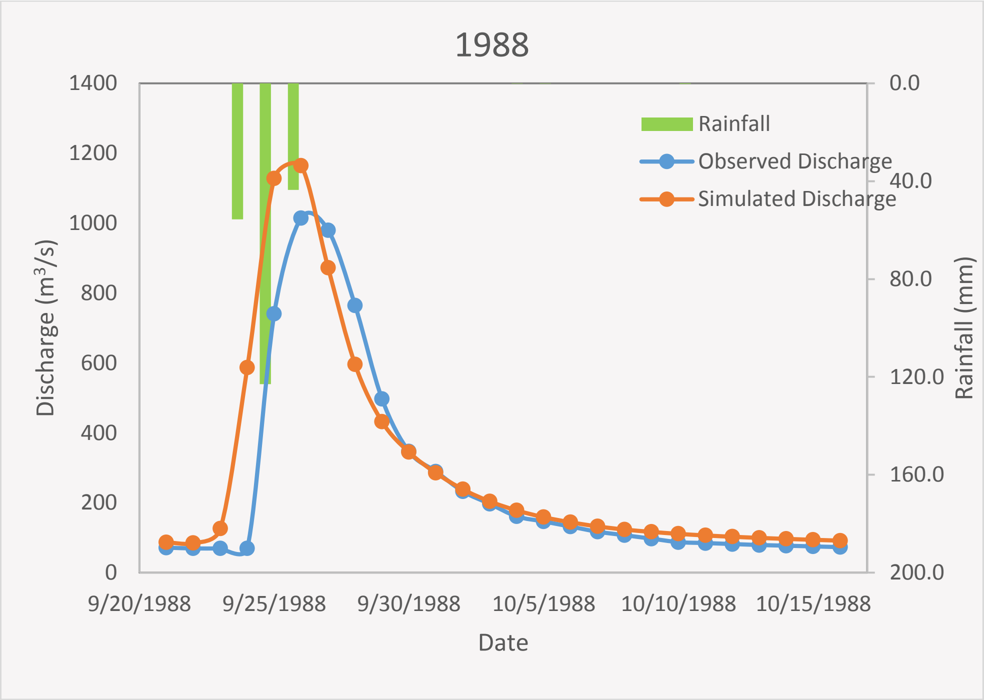


Figure 5.17 Observed and simulated hydrograph for 1988 flood.

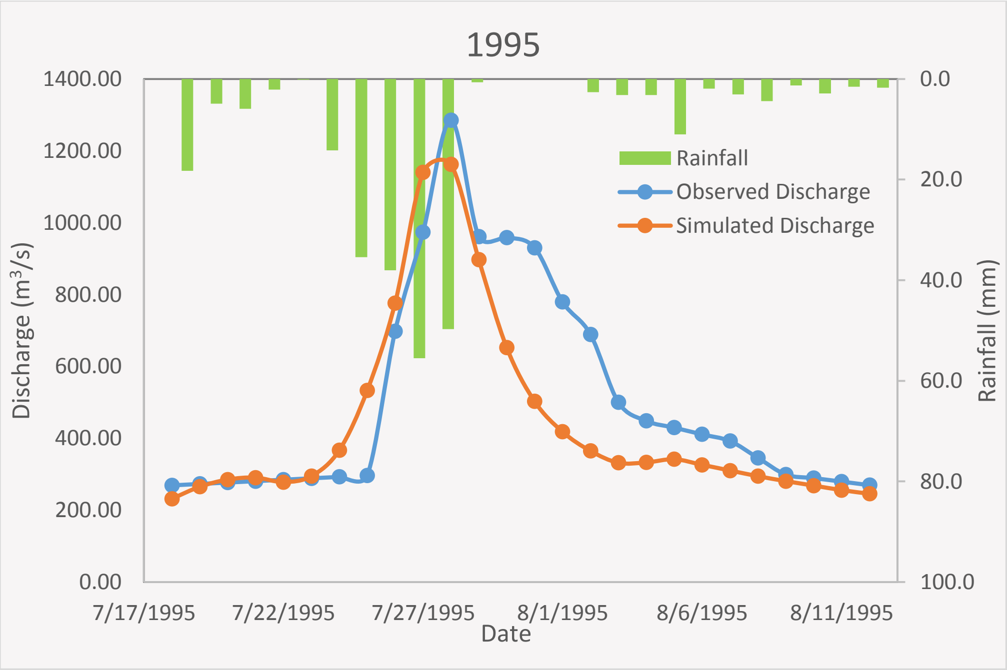


Figure 5.18 Observed and simulated hydrograph for 1995 flood.

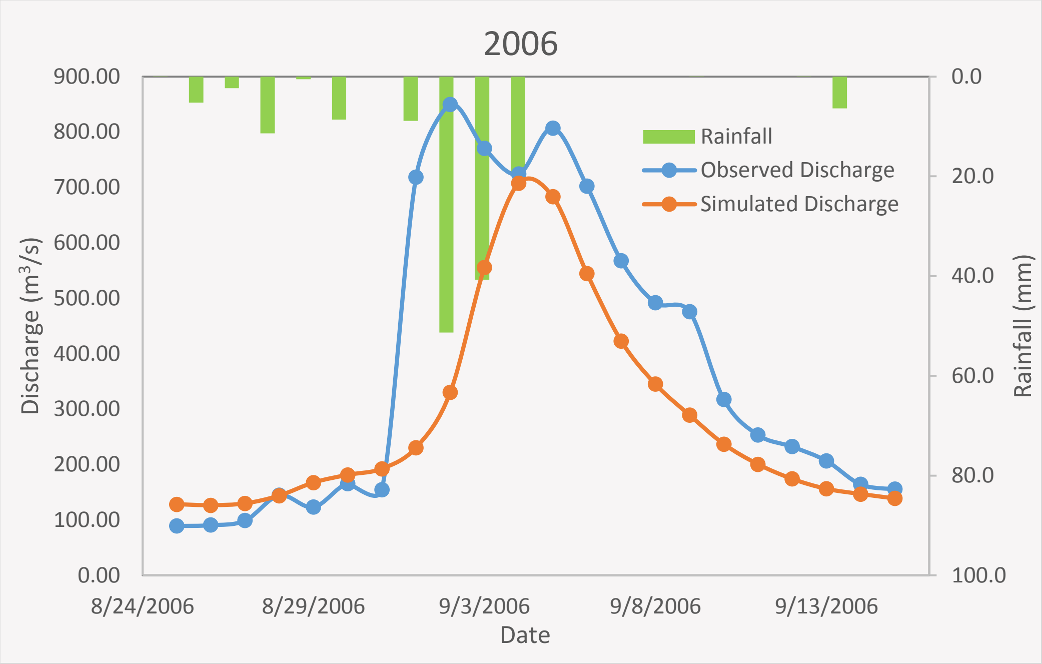


Figure 5.19 Observed and simulated hydrograph for 2006 flood.

SIMULATION OF 2014 FLOOD EVENT

The simulated peak discharge for the 2014 flood was 2122 m^3/s which is nearly 3% above the observed discharge at the Gauging site. The comparison plot shown in Figure 5.20, also illustrates good agreement between observed and simulated daily values. The value of coefficient of determination, R^2 for the flood event was 0.95. The simulated date of peak was also same as that of the observed date, indicating that the model is good for simulating extreme flood events.

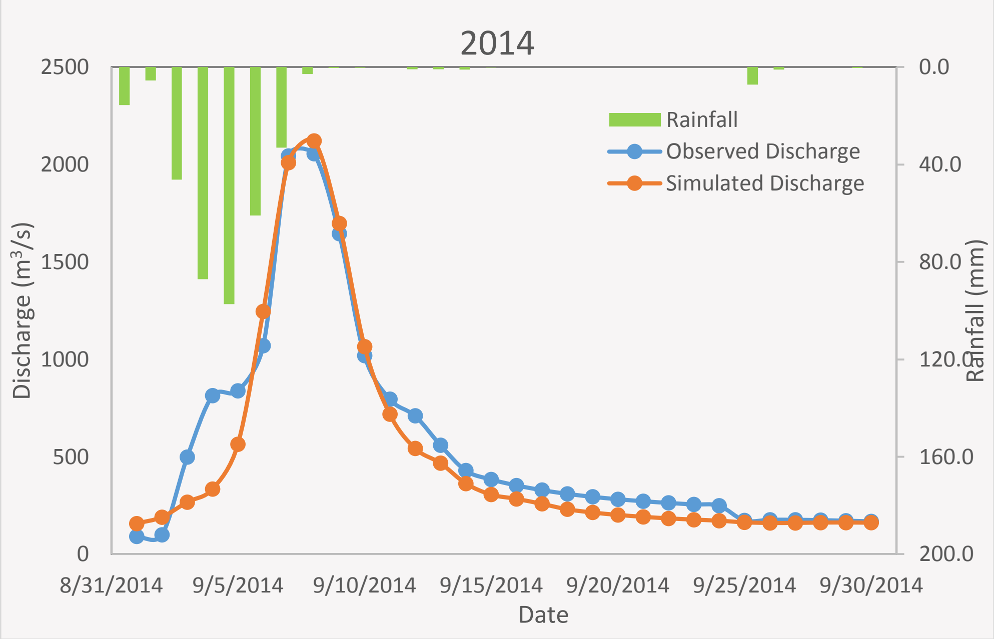


Figure 5.20 Observed and simulated hydrograph for 2014 flood.

CHAPTER 6

CONCLUSIONS

The integrated MIKE 11 NAM and HD model was found suitable for hydrological and hydraulic modelling of the Jhelum Basin up to Ram Munshi Bagh gauging site. Daily runoff values were predicted with an appreciable degree of accuracy. The values of efficiency indices were high for both calibration as well as validation periods. The peak flows were simulated more efficiently as compared to the low flows. The simulated annual discharges and peak flows were in the interval of ±20% of the line of perfect agreement corresponding to R^2 value of 1. The most sensitive parameters affecting the rainfall-runoff process in the basin were also identified. The coefficient of overland flow (CQOF) was found to be the most sensitive parameter, affecting the peak flows, low flows, accumulated volume as well as the model efficiency. Other sensitive parameters were interflow drainage constant (CKIF), timing constant for interflow (CK_{12}) and base temperature (T_0). For HD model, the Manning's roughness coefficient (n) affected the peak volume as well as time of peak. The model was found to be suitable for simulating extreme flood events in the basin and can be further used for flood plain inundation mapping in the basin. The 2014 flood event, which was the most extreme rainfall and flood event in the basin was also simulated very effectively by the developed model indicating applicability of the model to simulate rainfall runoff process in this basin.

LIMITATIONS OF THE PRESENT STUDY

1. The hydro-meteorological data was available at a time step of 24 hours. Lack of high resolution precipitation and discharge data is a major limitation of the present study especially for the simulation of extreme rainfall-runoff events.
2. Measured cross section data was available only at a few sites for tributaries as well as the main river. The cross sections did not include the details of the flood plains beyond the river banks.

FUTURE RECOMMENDATIONS

1. The calibrated model can be used for preparation of flood maps, flood risk analysis and classification of flood vulnerability zones.
2. The calibrated model can also be used for flood forecasting studies in the basin.
3. The snow storage in the basin can be divided into different zones depending upon elevation to improve snowmelt simulation.

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