NTNU – Trondheim
Norwegian University of
Science and Technology

Regional modelling for estimation of runoff from ungauged catchment, case study of the Saptakoshi basin, Nepal.

Jayandra Prasad Shrestha

Hydropower Development
Submission date: June 2012
Supervisor: Knut Alfredsen, IVM
Co-supervisor: Netra Prasad Timalsina, IVM

Norwegian University of Science and Technology
Department of Hydraulic and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Faculty of Engineering
Science and Technology
Department of Hydraulic and
Environmental Engineering

M.Sc. THESIS IN HYDROPOWER DEVELOPMENT

Candidate: Jayandra Prasad Shrestha

Title: **Regional modelling for estimation of runoff from ungauged catchment, case study of the Saptakoshi basin, Nepal.**

1 BACKGROUND

Obtaining reliable runoff from ungauged sites is a topic that receives considerable attention in hydrological research, and also a big challenge in many practical applications. For many Nepalese developments, the discharge gauges are placed in the lower parts of the rivers while the intake sites for power plants are in the headwaters of the rivers. Scaling is a challenge and other methods either to provide data or to verify scaling methods are needed. The ENKI modelling system is developed by SINTEF Energy and is equipped with tools for regional model setup and calibration, and through this inflow from ungauged sites can be extracted with a measure of uncertainty derived from the calibration. The objective of this thesis is to test ENKI on a regional calibration the Saptakoshi region in Nepal and to evaluate generated inflow to intake sites against scaled data used for planning.

2 MAIN QUESTIONS FOR THE THESIS

1. Background literature review on regional modelling, regional calibration and how this can be used to determine runoff from ungauged sites.

2. Prepare input data for the Saptakoshi basin from observed data and maps as input for the ENKI modelling system, and select the period for calibration and validation
   a. Digital maps of evaluation, land use and other distributed variables
   b. Discharge data must be controlled and selected based on the calibration method.
   c. Precipitation stations must be verified and selected.
   d. Potential evaporation must either be found from data or computed.

3. Precipitation input must be interpolated and prepared for the model run. This must be done outside the ENKI system and should take care of the precipitation gradients and the high elevation precipitation process.

4. Calibrate the region in ENKI for multiple gauges for the selected period. Evaluate the results for the different calibration gauges concerning parameter distributions and model uncertainty.

5. Use the ENKI model calibrated in 4) to extract runoff from the intake sites and compare them to the scaled data used in the planning process.

6. Discuss the application of regional modelling and ENKI compared to the traditional one-catchment approach by using existing HBV calibrations on one sub catchment in the region.

3 SUPERVISION, DATA AND INFORMATION INPUT

Professor Knut Alfredsen will be the formal supervisor of the thesis work, and Netra Prasad Timalsina will supervise the work and help with the setup of the ENKI model.

Discussion with and input from colleagues and other research or engineering staff at NTNU, SINTEF, power companies or consultants are recommended. Significant inputs from others shall, however, be referenced in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are therefore free to introduce assumptions and limitations, which may be considered unrealistic or inappropriate in a contract research or a professional engineering context.

4 REPORT FORMAT AND REFERENCE STATEMENT

The thesis report shall be in the format A4. It shall be typed by a word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary, a table of content, lists of figures and tables, a list of literature and other relevant references and a signed statement where the candidate states that the presented work is his own and that significant outside input is identified.

The report shall have a professional structure, assuming professional senior engineers (not in teaching or research) and decision makers as the main target group.

The summary shall not contain more than 450 words it shall be prepared for electronic reporting to SIU. The entire thesis may be published on the Internet as full text publishing through SIU. Reference is made to the full-text-publishing seminar during NORADS winter-seminar. The candidate shall provide a copy of the thesis (as complete as possible) on a CD in addition to the A4 paper report for printing.

The thesis shall be submitted no later than 11th of June 2011.

Trondheim 15th of January 2012

____

Knut Alfredsen

Professor

PREFACE

This thesis report entitled “Regional modelling for estimation of runoff from ungauged catchment, case study of the Saptakoshi basin, Nepal” is submitted to the Department of Hydraulics and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway which is partial fulfillment of the M.Sc. degree in Hydropower Development Program.

One of the great challenges in hydrology is to get the accurate simulation of an ungauged river basin. The most of the gauge stations are at the lower altitude rather than in higher altitude like mountainous country Nepal. The intake sites are situated at high altitude and the unavailability of runoff data for planning hydropower projects from these sites are the main problem. This report represents the regional model simulation of the Saptakoshi basin, the largest river basin of Nepal, with the application of ENKI system which is developed by SINTEF Energy. This work helps to solve the problem of extracting runoff data from ungauged basins in this region.

This thesis will be very useful to planning process of hydropower projects in the Saptakoshi basin and good reference to hydrological study like regional modelling and ENKI model.

Jayandra Prasad Shrestha

June 2012

Trondheim, Norway

ACKNOWLEDGEMENTS

At the very first, I would like to acknowledge my humble and sincere thanks to Course Coordinator Mrs. Hilbjørg Sandvik, at Department of Hydraulics and Environmental Engineering, for arrangement and support for thesis work.

I would like to extend my thanks and gratitude to my thesis supervisor Prof. Knut Alfredsen and assistant adviser Mr. Netra Prasad Timalsina, a PhD student at NTNU, for their constructive and encouraging suggestion, regarding the thesis and leading me towards the goal of the thesis.

I would also like to sincerely acknowledge my hearty gratitude to Prof. Ånund Killingtveit, Professor in-charge, for his suggestions and guidance during study at NTNU.

I am very grateful to my family members for their inspiration and blessing during my study in Trondheim.

Last but by no means least; I would also have high sense of appreciation to my classmates, friends in Trondheim and senior students from NTNU for their direct and indirect supports and suggestions for thesis work.

ABSTRACT

The accurate simulation of an ungauged basin is one of the great challenges in hydrology. In case of Nepal, most of the gauge stations are located at low level land and getting reliable hydrological data at intake sites, most of which are located at high mountains, are almost impossible. The regional model calibration attempts to make a relationship between parameters of model and characteristics of the modelling units so that the calibrated parameters can be applied to ungauged basin. The main objective of the study is to apply ENKI model system to the Saptakoshi basin and to test the reliability of the model in this area and extract the runoff at ungauged sites. The processed climatic data from 1999 to 2008 are applied to the ENKI model system, which is equipped with tools for regional model setup, for different calibration cases.

In case I, all the 16 catchments are included for calibration and average Nash-Sutcliffe Efficiency R^2 of -1.57 is obtained which is comparatively very low. The R^2 value of Uwa Gaon basin is -27.76; the reason may be due to missing precipitation data of Tibet. Hence, this catchment is excluded for further analysis.

Excluding Uwa Gaon catchment in calibration case II, the improved average R^2 of 0.33 is achieved. The hydrographs of simulated runoff seem in realistic shapes and patterns. Then validation is carried out for the period from 2004 to 2008. The average R^2 of the validation is equal to 0.14 which is less than calibration result. The individual R^2 value of the catchments is nearly equal with calibration results except of Pachuwar Ghat basin.

In case III, only 8 independent catchments are selected for calibration and rest catchments are applied for validation. The average R^2 of 0.59 is achieved which is the best result among the 3 cases. The R^2 is found at the range of 0.54 to 0.78 for most of the catchments. Similarly, the average R^2 of validation is achieved 0.15 which is greater than calibration case II. While processing data, some errors and inconsistency in flow data were found. The results show that the R^2 of independent and upstream catchments are well fitted with observed data and less with downstream basins where observed data were inconsistent. The good quality of observed data and availability of enough data governs the best simulation of the model and best value of the R^2.

The 30 parameter values are obtained and among these some are less sensitive to the output results which are kept constant. Finally, the obtained regional parameter sets are applied to extract the runoff data at the intake site of Tamor Hydropower project and compared with scaled data.

Further improvement of simulation results can be achieved with good quality of data and thus uncertainties in parameters can be reduced.

ACRONYM

AET	Actual Evapotranspiration
ASCII	American Standard Code for International Interchange
β	Parameter in soil moisture routine
CPRO	Liquid water
CDMA	Code Divison Multiple Access
CX	Degree-day factor
DEM	Digital Elevation Model
DEMLab	Dynamic Environmental Laboratory Model
DHM	Department of Hydrology and Meteorology
DLL	Dynamic Link Library
DRO	Direct Runoff
ESRI	Environmental System Research Institute
E	Easting or Longitude
FC	Field Capacity
GIS	Geographical Information System
GCS	Geographic Coordinate System
GoN	Government of Nepal
HBV	A precipitation runoff model Hydrologiska Byråns avdelig for Vattenbalans
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
KLZ	Recession constant for lower zone IN HBV
KUZ1	Slow drainage coefficient
KUZ2	Fast drainage coefficient
LP	Threshold value for potential evapo-transpiration in soil moisture
masl	meters above sea level
N	Northing or Latitude
PERC	Percolation from upper zone to lower zone
PKORR	Precipitation correction - Rainfall
PREC	Percolation from upper zone to lower zone
PET	Potential Evapotranspiration
PUB	Predictability for ungaged
R^2	Nash Sutcliffe Efficiency
SKORR	Snow correction
SHE	Sanima Hydro and Engineering (P). Ltd.
SINTEF	Stiftelsen for industriell og teknisk forskning
TS	Threshold snowmelt
TX	Threshold rain/snow
TRMM	Tropical Rainfall Measuring Mission

UZ1	Threshold for upper zone in HBV model
UTM	Universal Transverse Mercator
USGS	United State Geological Survey
WECS	Water and Energy Commission Secretariat
WCRP	World Climate Research Program

TABLE OF CONTENTS

LIST OF APPENDICES

Appendix 1: VBA Codes

Appendix 2: Precipitation Gradients in Saptakoshi basin

Appendix 3: ENKI Model Simulation Results

Appendix 4: Calibration of parameters in ENKI system for Saptakoshi basin

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

"He is able who thinks he is able."

-Buddha

1.1 BACKGROUND

The runoff of the streams and the elevation difference between intake and power house is the main governing factors to produce hydropower energy from the nature. The available head can be simply derived from the topographic map of the area. Information about runoff can be found from various sources and with varying degree of accuracy and cost such as Runoff maps, hydrological databases, Runoff measurements and Correlation with neighbor stations [1]. In case of Nepal, the specific runoff maps are not available yet and the most of the gauge stations are at low level land. So there is the great challenge of getting reliable hydrological data at intake sites, most of which are at high mountains. The main purpose of this study is to estimate the reliable temporal runoff in the streams by using regional rainfall runoff models. The ENKI model system, developed by SINTEF Energy, is applied to the Saptakoshi basin (Nepal) to test the reliability of the model in this area. The model is set up and calibrated to obtain the regional parameter sets in order to get the good fit between observed and simulated variables. From this simulation, the runoff at ungauged sites can be extracted to estimate hydropower generation capacity and other purposes like irrigation, flood forecasting.

1.2 OBJECTIVE

The main objective of the study is to test the ENKI modelling system on regional calibration of the Saptakoshi basin in Nepal and to evaluate generated inflow to intake sites against scaled data used for planning. The ENKI model is equipped with tools for regional model setup and calibration and through this discharge from ungauged sites can be interpolated by measure of uncertainty derived from the calibration.

1.3 SCOPE OF THE WORK

The ENKI model is setup and calibrated for the Saptakoshi basin in Nepal. The following systematic tasks have been performed to meet the required scope of study.

1. Background literature review on regional modelling, regional calibration and how this can be used to determine runoff from ungauged sites.
2. Prepare input data for the Saptakoshi basin from observed data and maps as input for the ENKI modelling system, and select the period for calibration and validation
    a. Digital maps of evaluation, land use and other distributed variables
    b. Discharge data must be controlled and selected based on the calibration method.
    c. Precipitation stations must be verified and selected.
    d. Potential evaporation must either be found from data or computed.

3. Precipitation input must be interpolated and prepared for the model run. This must be done outside the ENKI system and should take care of the precipitation gradients and the high elevation precipitation process.
4. Calibrate the region in ENKI for multiple gauges for the selected period. Evaluate the results for the different calibration gauges concerning parameter distributions and model uncertainty.
5. Use the ENKI model calibrated in 4) to extract runoff from the intake sites and compare them to the scaled data used in the planning process.
6. Discuss the application of regional modelling and ENKI compared to the traditional one-catchment approach by using existing HBV calibrations on one sub catchment in the region.

1.4 STRUCTURE OF THESIS

The structure of the thesis organized with following chapters:

Chapter 2: This chapter deals with details of study area, its land features and hydro-meteorology.

Chapter 3: This chapter includes a literature review of hydrological modelling and ENKI modelling system.

Chapter 4: This chapter deals with application of GIS in hydrological models.

Chapter 5: This chapter presents the collection of data and discusses data processing for ENKI models.

Chapter 6: This chapter deals with methodology and procedure in ENKI modelling system.

Chapter 7: This chapter represents the simulation of the model and their validation.

Chapter 8: This chapter concludes the results from simulation.

2 STUDY AREA

"Eventually, all things merge into one, and a river runs through it."
-Norman Maclean

2.1 BACKGROUND

Nepal is a Himalayan country in South Asia and, is bordered to the north by the People's Republic of China (Tibet), and to the south, east, and west by the Republic of India and extends between 26°22' and 30°27' North latitude and 80°04' and 88°12' East longitude.

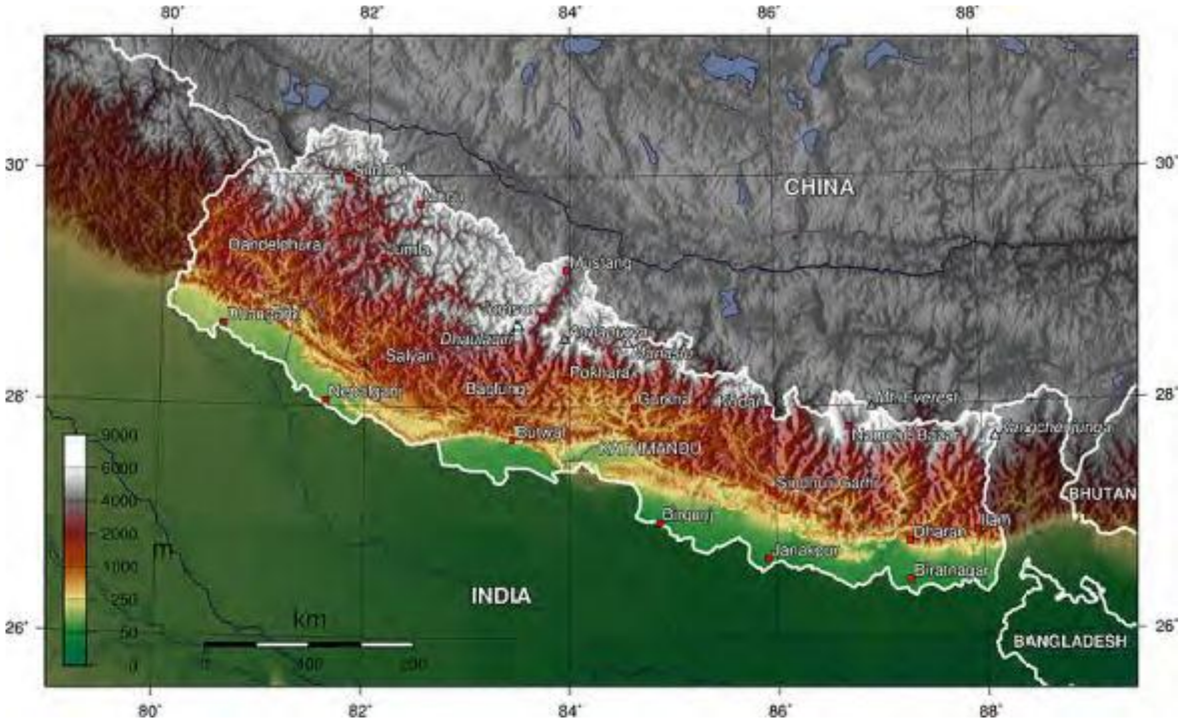


Figure 2.1: Geo-physical map of Nepal [2]

Nepal is the mountainous country, among the total area of 147,181 square kilometers almost three fourth of land is covered by mountains. The most of the rivers originate from the high mountains and finally merge to the Ganges in India. So Nepal is one of the richest countries in hydropower resources.

2.2 RIVER BASINS IN NEPAL

There are lot of small and large rivers flow in Nepal most of which originate from the Himalayas and merge to the Ganges. Among them for hydrological studies, Nepalese river basins can be classified into mainly seven drainage basins as follows the Kankai Mai River Basin, Sapta-Koshi River Basin, the Bagmati River Basin, the Rapti River Basin, the Karnali River Basin and the Mahakali River Basin [3]. Among these river basins, the Koshi basin is study area for this task and other basins are only breifly explain here.

2.2.1 Kankai River Basin

The Kankai is a rain fed Perennial River of eastern Nepal. The Kankai originates in the Mahabharat Range in Nepal. It flows through Nepal and then flows through the Indian state of Bihar to join the Mahananda. The Kankai has a drainage area of 1,148 square kilometers.

2.2.2 Bagmati River Basin

The Bagmati River flows through the Kathmandu valley and meets with the Ganges. It is the mansoon rain fed Perennial River. This basin covers whole Kathmandu valley. The basin comprises of 75% of mountainous area, and the remaining part consists of flat land with an altitude of less than 100 meters above masl.

2.2.3 Gandaki or Narayani River Basin

The river network of central Nepal is occupied by the Gandaki (Narayani in southern Nepal) River system. This basin comprises the Trishuli River, the Budhi Gandaki River, the Marsyangdi River, the Seti and Kali Gandaki River. It has a total catchment area of 46,300 square kilometers.

The West-Rapti River drains Rapti Zone in Mid-Western Region, Nepal, then Awadh and Purvanchal regions of Uttar Pradesh state, India before joining the Ghaghara a major left bank tributary of the Ganges.

2.2.4 Karnali River Basin

The Karnali River is a perennial, turbulent and undisturbed river of the Himalayas, which is the longest rivers of Nepal. It originates from Mansarover and Rakes lake and receives many snow fed rivers such as Mugu Karnali and Humla Karnali at Himalayan belt. The Karnali basin lies between the mountain ranges of Dhaulagiri and Nanda Devi, in the western part of Nepal.

2.2.5 Mahakali River Basin

The Mahakali River flows between the countries of India and Nepal acts as the west boundary of Nepal. It originates from Kalapaani at an altitude of 3600 m and finally joins with the Ganges River System. There are two important tributaries of the Mahakali River in Nepal. These two rivers are the Chamelia river and the Limpiyadhura river. The snow capped mountain peaks are the major origins of the Mahakali River in Nepal.

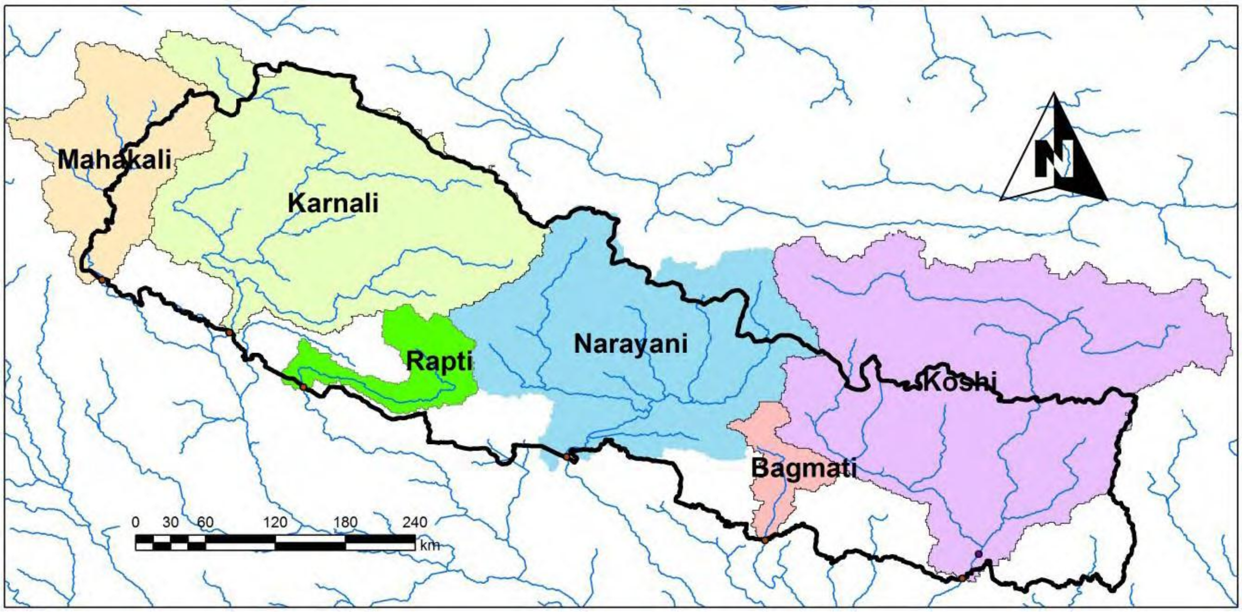


Figure 2.2: Major river basins in Nepal [4]

2.3 SAPTAKOSHI RIVER BASIN

2.3.1 Location

The Koshi also called Saptakoshi for its seven Himalayan tributaries— the Tamor River, the Arun River, the Dudh Koshi River, the Likhu River, the Tama Koshi (Bhote Koshi) River, the Sun Koshi River and the Indrawati River. Some of the rivers of the Koshi system, such as the Arun, the Sun Koshi and the Tama Koshi originate in the Tibet. It is one of the largest tributaries of the Ganges.

Nepal has a total estimated potential of 83,290 MW out of which economically exploitable potential is 42,140 MW. The Koshi river basin contributes 22,350 MW of this potential (360 MW from small schemes and 1875 MW from major schemes) and the economically exploitable potential is assessed as 10,860 MW [5].

It is the largest river basin of Nepal and lies between latitudes 26°52’0” to 29°6’41”N and longitude 85°44’51” to 89°14’53”E. The location of the confluence of three major tributaries Arun, Tamor and Sun Koshi rivers is at 26°54’47”N, 87°09’25”E, Tribenighat, Nepal. According to DHM Nepal, it comprises an area of about 54, 100 sq.km at the Chatara-Kohtu gauge station and drains eastern part of the country. Out of a total catchment area, 29,400 sq.km. lies in China (Tibet) and the remaining in Nepal. The highest elevation in this basin is 8848 masl (Mt. Everest) to 140 masl.

The major rivers which are responsible for flow in the Saptakoshi are the Tamor River, the Arun River and the Sun Koshi River. But there are other many small rivers which join to the Saptakoshi. The sub-catchments of the Saptakoshi are shown in Figure 2.3 and their areas at the gauge stations are shown Table 2.1.

Table 2.1: Description of the rivers and gauge stations in the Saptakoshi basin

S. No	Staion Index	Name of River	Location	Latitude(N)	Longitude (E)	Elevation (m)	Catchment Area (Sqkm)		Discrepancy	Local CA (Sqkm)
							From DHM	From GIS		
1	600.1	Arun	Uwa Gaon	27 35 21	87 20 22	1294	26750	29616	11%	29616
2	647	Tamakosi	Busti	27 38 05	86 05 12	849	2753	2898	5%	2898
3	695	Saptakosi	Chatara- Kothu	26 52 00	87 09 30	140	54100	58053	7%	200
4	681	Sunkosi	Hampuachuwar	26 55 15	87 08 45	150	18700	17936	-4%	4315
5	627.5	Melamchi	Helambu	28 02 21	85 32 07	2134	84	117	39%	117
6	602.5	Hinwakhola	Pipletar	27 17 45	87 13 30	300	110	112	2%	112
7	620	Balephi	Jalbire	27 48 20	85 46 10	793	629	659	5%	659
8	652	Sunkosi	Khurkot	27 20 11	86 00 01	455	10000	10201	2%	1974
9	684	Tamur	Majhitar	27 09 30	87 42 45	533	4050	4530	12%	4530
10	690	Tamur	Mulghat	26 55 50	87 19 45	276	5640	6008	7%	1477
11	630	Sunkosi	Pachuwar Ghat	27 33 30	85 45 10	602	4920	5004	2%	4227
12	670	Dudhakosi	Rabuwa Bazar	27 16 14	86 40 02	460	4100	3419	-17%	3419
13	650	Khimtikhola	Rasnalu Village	27 34 30	86 11 50	1120	313	326	4%	326
14	602	Sabayakhola	Tumlingtar	27 18 36	87 12 45	305	375	406	8%	406
15	606	Arun	Simle	26 55 42	87 09 16	152	30380	33503	10%	1721
16	604.5	Arun	Turkeghat	27 20 00	87 11 30	414	28200	31670	12%	2053

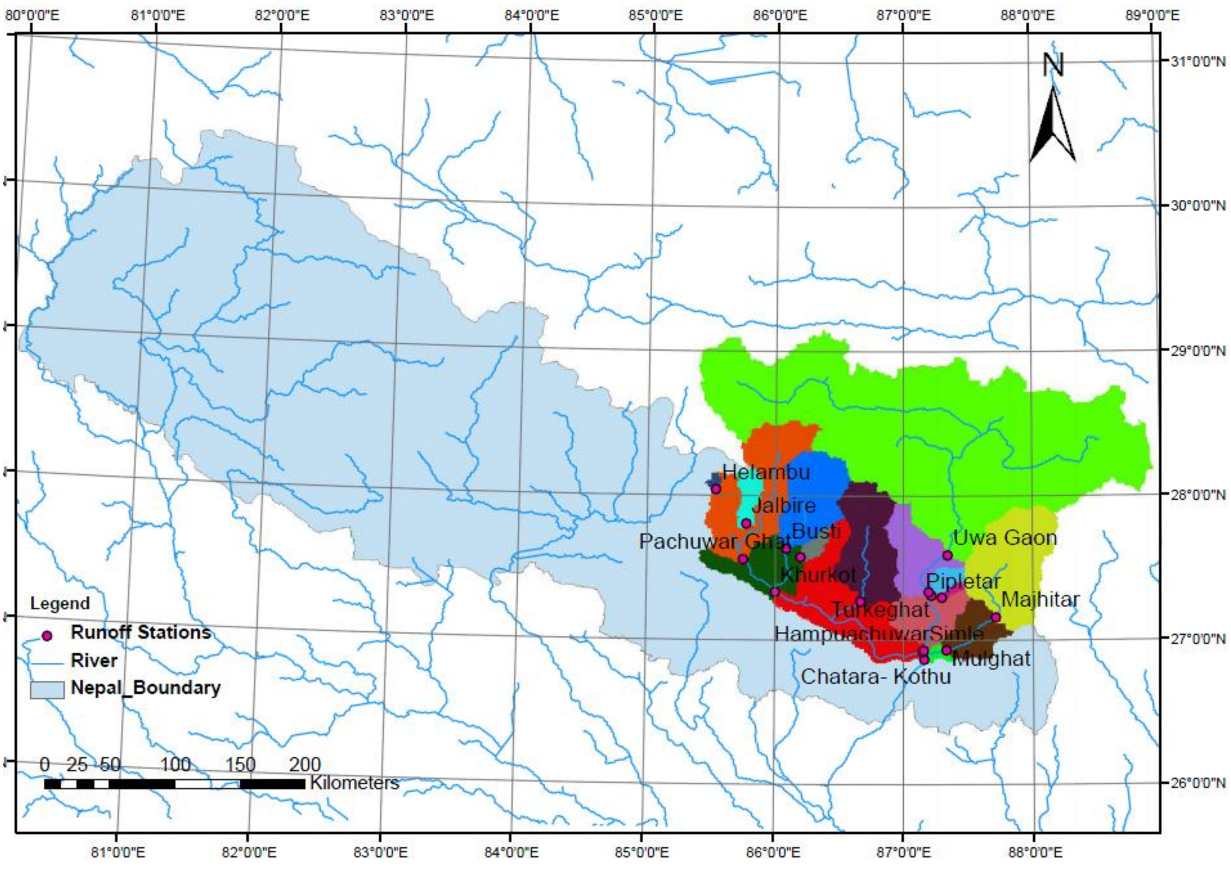


Figure 2.3: Sub-catchments at different gauge stations of the Saptakoshi basin

2.3.2 Hydro-meteorology

The rainfall probabilities, the space and time distribution of rainfall and evaporation, the recurrence interval of major storms, snow melt and runoff, and probable wind tides and waves around the study area determines by the hydro-meteorological study of area. For this study all the reference data i.e. precipitation, temperature, evaporation and runoff are taken from DHM (Department of Hydrology and Meteorology, Nepal).

2.3.3 Climate

The basin's climate ranges passing through warm temperate, cool temperate and alpine conditions as elevation increases. The basin's climate changes from tropical in the Terai (the low and plain land of Nepal) and low river valleys to arctic on mountain peaks. The humidity on north-facing slopes is relatively higher for a longer time after the monsoon ends than on south-facing slopes because radiation on the north-facing slopes is diffuse compared to that on south-facing slopes. Due to the combination of radiation effects and altitude, two areas in close proximity might have very different moisture regimes that can also vary significantly from year to year. Valleys and deep gullies are characterized by humid and wet micro-climates and perennial water sources.

There is intense rainfall during the monsoon, which lasts from June to September. The orographic effect causes large local variations even within a small valley. In the hills, sudden cloudbursts are common and can generate almost 500 millimetres of rainfall in a day [6]. However, in the rain-shadow regions of the Tibetan plateau, the conditions are dry and desert-like. The Koshi River has seasonal variations in flow and sediment charge. In the smaller tributaries of the Koshi, the impact of flooding is localised, but can become widespread when there is greater volume, extent, and/or duration of rainfall.

The combination of upstream rainfall and river characteristics governs the behaviour of the Sapta Koshi River on the plains. During the monsoon, the Koshi River transports about 120 million cubic metres of sediment. The annual deposition of this sediment has caused the river to shift its course about 115 kilometers to the west in the last 200 years [6].

The basin can be divided into five characteristic climatic zones showing a trend from south to north.

- Hot monsoon and tropical zone of below 500 meters in altitude
- Subtropical zone extending up to 1200 meters in altitude
- Warm temperate zone of 1,200 to 2,400 meters in altitude
- Cold temperate zone of 2400 to 3600 meters in altitude
- Subarctic or alpine climatic zone of 3,600 to 4,400 meters in altitude
- Arctic zone above 4,400 meters in altitude

The climatic condition of the Koshi basin can be further clarified by analyzing the precipitation, air temperature, evaporation and relative humidity pattern.

2.3.4 Precipitation

Strong spatial and temporal variations exist in rainfall distributions of Nepal (Shrestha et al., 1999, 2000; Shrestha). July is the wettest month which receives about 26 % of the total annual rainfall and November is the driest month in Nepal which receives below 1% of the annual total rainfall. The seasonal mean rainfall is highest during summer monsoon season and lowest during winter. Summer season receives about 80% of the annual total rainfall contributed by southwest monsoon system. Rainfall during winter season is mainly contributed by western disturbance [7]. During pre-monsoon and post-monsoon season, thunder activities and occasional passage of the western disturbances make rainfall. However, the variability is found highest during post-monsoon and lowest during monsoon seasons.

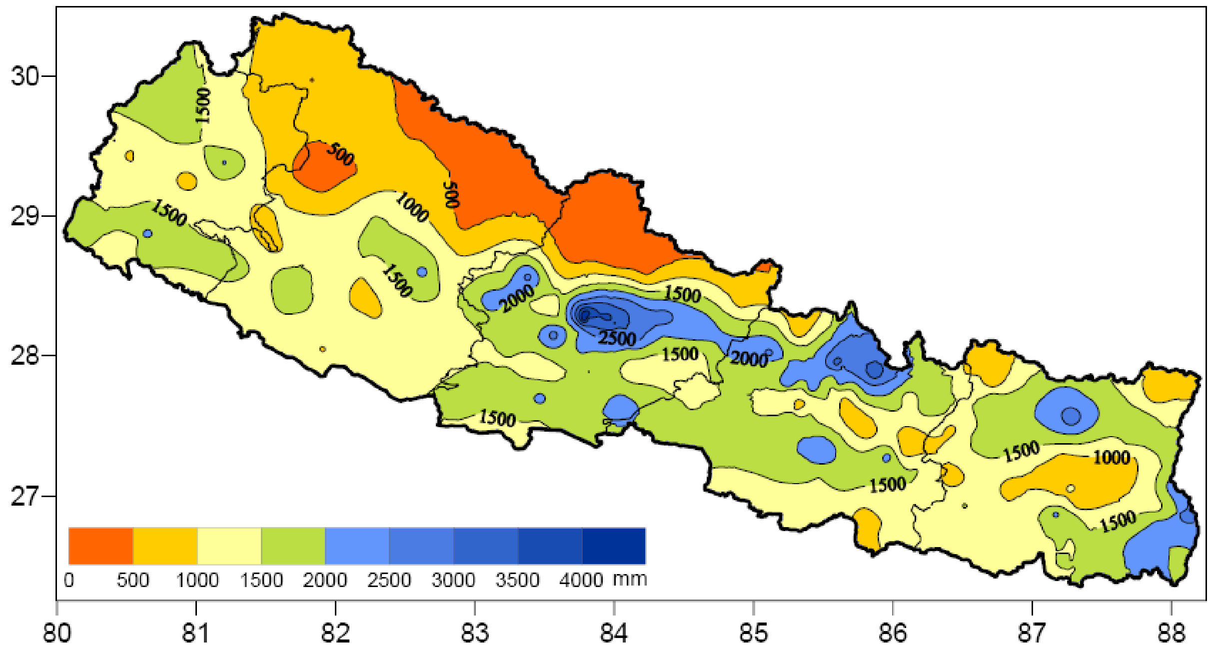


Figure 2.4: Spatial distribution of Monsoon Season Rainfall [8]

Like the rest of Nepal, The Koshi basin exhibits considerable macro, meso, and micro scale variations .The Koshi river can respond rapidly to widespread rain in the catchment with flooding [6]. In general the precipitation above 5000 to 6000 meters falls as snow during summer monsoon period [9].

The main contribution of runoff in the Koshi River is due to monsoon rainfall and melting of snow cover from the mountains. The following figures show the mean annual rainfall, monsoon precipitation and highest 24 hours rainfall events in the Saptakoshi basin from ICIMOD reports.

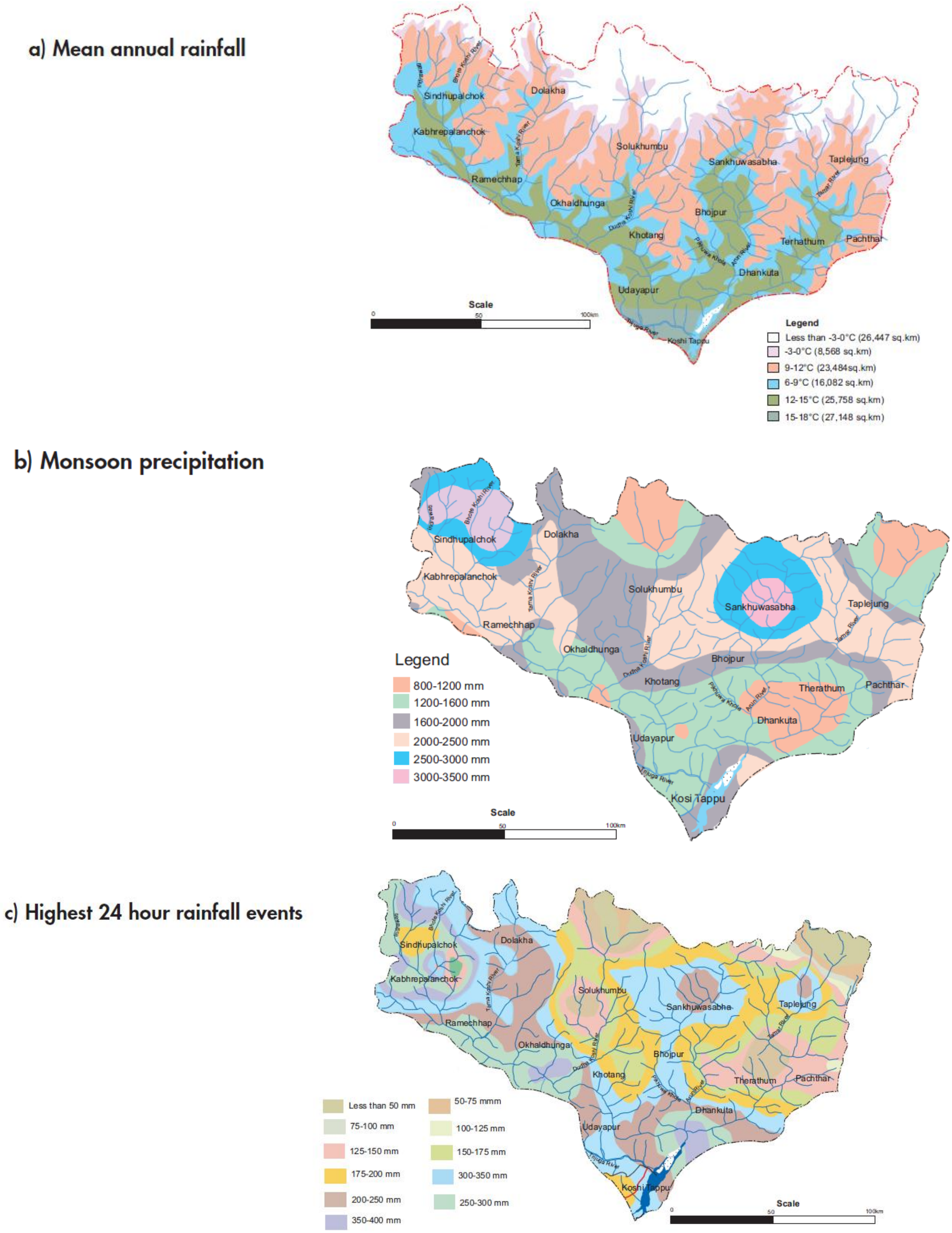


Figure 2.5: a) Mean Annual rainfall, b) Monsoon precipitation and c)Highest 24 hours rainfall events in the Saptakoshi basin [6]

2.3.5 Temperature

The air temperature is another main meteorological factor that governs the analysis of hydro-meteorological system. The air temperature varies with time-space and depends on the solar radiation, topography and atmospheric cycle in the area. The Figure 2.6 shows the mean annual air temperature of overall Nepal. The air temperature decreases with increased in altitude. This phenomenon is defined by the parameter called Lapse Rate. The environmental lapse rate is around –0.005°C/m (Alford 1992). There are altogether 18 temperature stations in the Koshi basin. These basins are used for analysis and interpolation of temperature at rest of other stations where temperature data are not available.

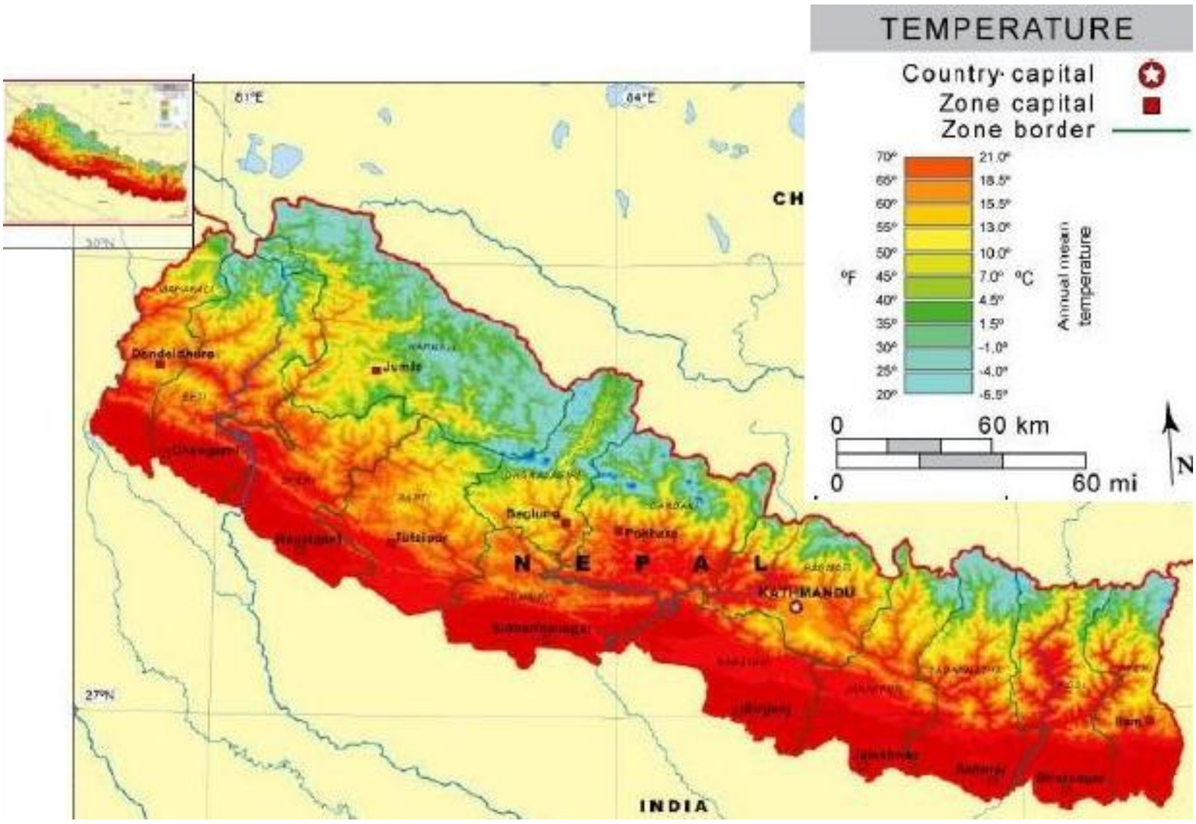


Figure 2.6: Annual Mean Temperature map of Nepal [10]

2.3.6 Evaporation

Evaporation is the loss of water from the surface water sources due to temperature, humidity, solar radiation and wind speed. The balance between precipitation and evaporation determines the stream flow. There are very limited numbers of evaporation measurement stations in Nepal. So, the evaporation has been derived by using methods of Penman equation (1956), Thornhwaite (1948) and Morton (1983) in Nepal. Both measured and derived values are adequate to characterize the spatial variation of evaporation in Nepal.

Potential evaporation or potential evapotranspiration (PET) is defined as the amount of evaporation that would occur if a sufficient water source were available. If the actual evapotranspiration is considered the net result of atmospheric demand for moisture from a surface and the ability of the surface to supply moisture, then PET is a measure of the demand side.

Mean Monthly and Annual Evaporation Measurements for Eastern Nepal

EVAPORATION MEASUREMENTS – EASTERN NEPAL(mm/d)														
STATION	ALTITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1007	2064	2	3	4	4	4	3	2	4	3	2	3	2	1043
1029	1350	2	3	4	5	5	4	3	4	3	2	2	1	1165
1206	1720	2	2	5	7	4	4	3	3	3	2	2	2	1186
1320	200	1	3	4	7	7	5	4	4	4	3	3	2	1363
1324	1595	2	2	4	6	2	2	1	1	1	2	2	2	803

Source: Department of Irrigation, Hydrology, and Meteorology 1976

2.3.7 Land use

The physical surface of the earth, including various combinations of vegetation types, soils, exposed rocks and water bodies as well as anthropogenic elements, such as agriculture and built up environments are refered as the land cover. The latest physiographic data indicate that Nepal comprises around 4.27 million hectares of forest (29% of total land area), 1.56 million hectares of scrubland (10.6%) and degraded Forest, 1.7 million hectares of grassland (12%); 3.0 million hectares of farmland (21%), and about 1.0 million hectares of uncultivated lands (7%) [3]. It has been reported that forest cover in the Terai and hill areas decreased at an annual rate of 1.3%, and 2.3% between 1978/79 and 1990/91, respectively (HMGN-DFRS 1999). The overall land use of Nepal is shown in Figure 2.7 below which is extracted from ICIMOD home page.

The Koshi basin can be divided into three major physiographic units: the mountainous zone, Himalayan zone, and Tibetan Plateau. The mountainous zone of the basin is primarily dominated by schist, phyllite, and quartzite whereas the high Himalayan zone consists of mainly gneiss and granite. The Tibetan plateau comprises up to ten kilometers thick layer of Tethys' sediment (Hagen, 1980; Sharma, 1990).

In the ENKI model system, land use value is reclassify in GIS DEM as greater than 1 for land and 0 for no data and is equal to 1 when there is lake.

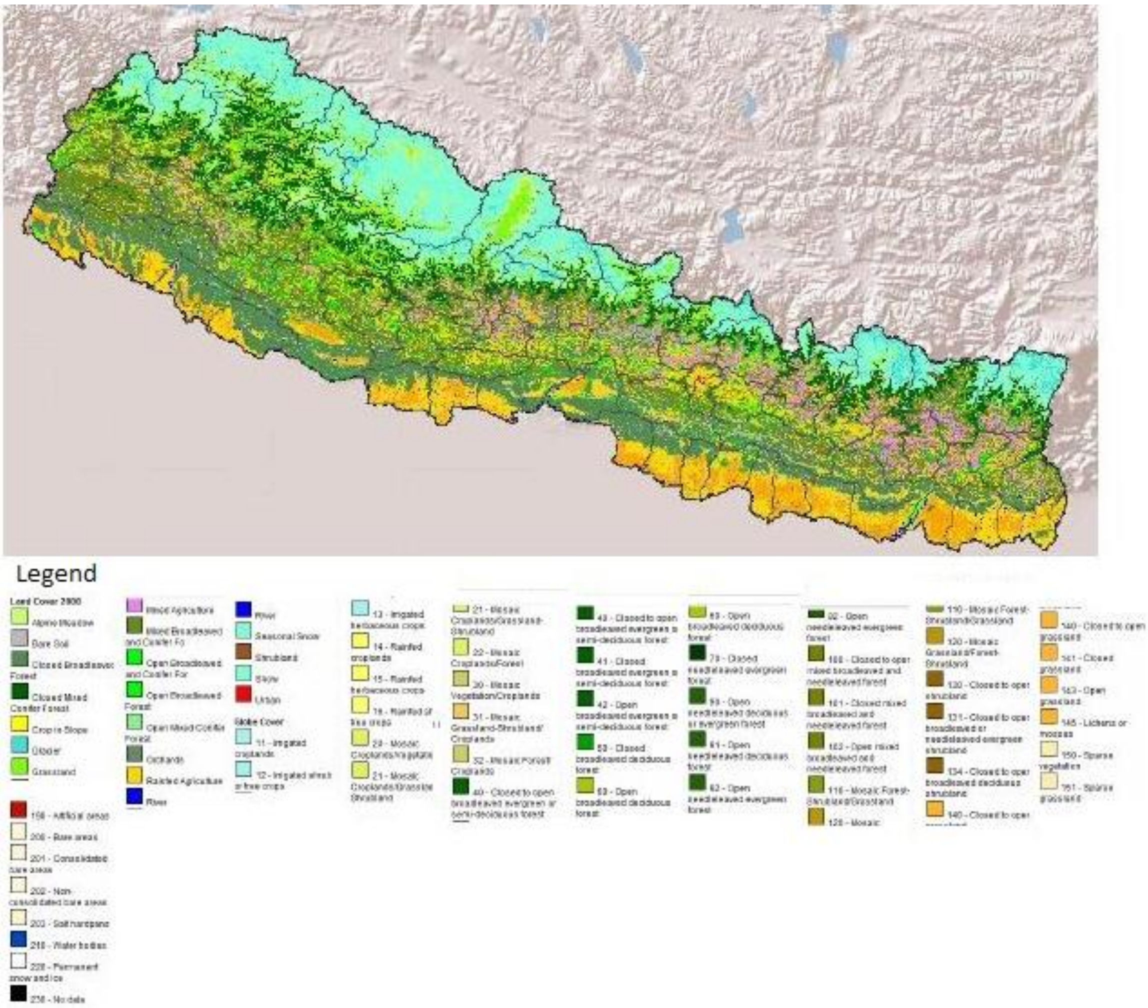


Figure 2.7: Land use map of Nepal [11]

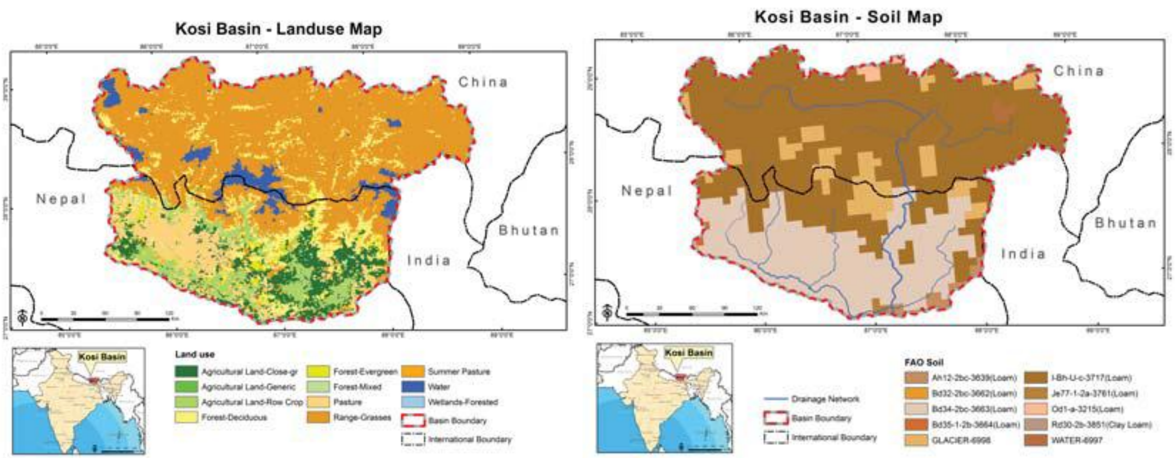


Figure 2.8: Land use (A) and soil type (B) geographical information system (GIS) layers of the Koshi River basin [12]

3 LITERATURE REVIEW

"It is to be fear that a number of hydrologists fall in love with the models they create."

- James Clement Dooge

3.1 INTRODUCTION

Hydrology is the study of the movement, distribution, and quality of water on Earth and other planets, including the hydrologic cycle, water resources and environmental watershed sustainability. Hydrological phenomena are extremely complex, and difficult both to measure and understand in full detail. In the absence of perfect knowledge, however, they may be represented in a simplified way by means of the system concept.

The hydrological cycle may be treated as a system whose components are precipitation, evaporation, snow melt, infiltration, runoff and other processes in the hydrological cycle. The different components can each be grouped together into subsystem or broken down into new sub-process, depending on the level of detail in the analysis and purpose of the analysis. The global hydrological cycle can be divided into three subsystems.

- Atmospheric water system; precipitation, evaporation, interception, and transpiration.
- Surface water system; snow accumulation and melt, overland flow, surface runoff, subsurface runoff, groundwater outflow, and runoff to stream and oceans.
- The subsurface water system; infiltration, ground water recharge, subsurface flow, groundwater flow.

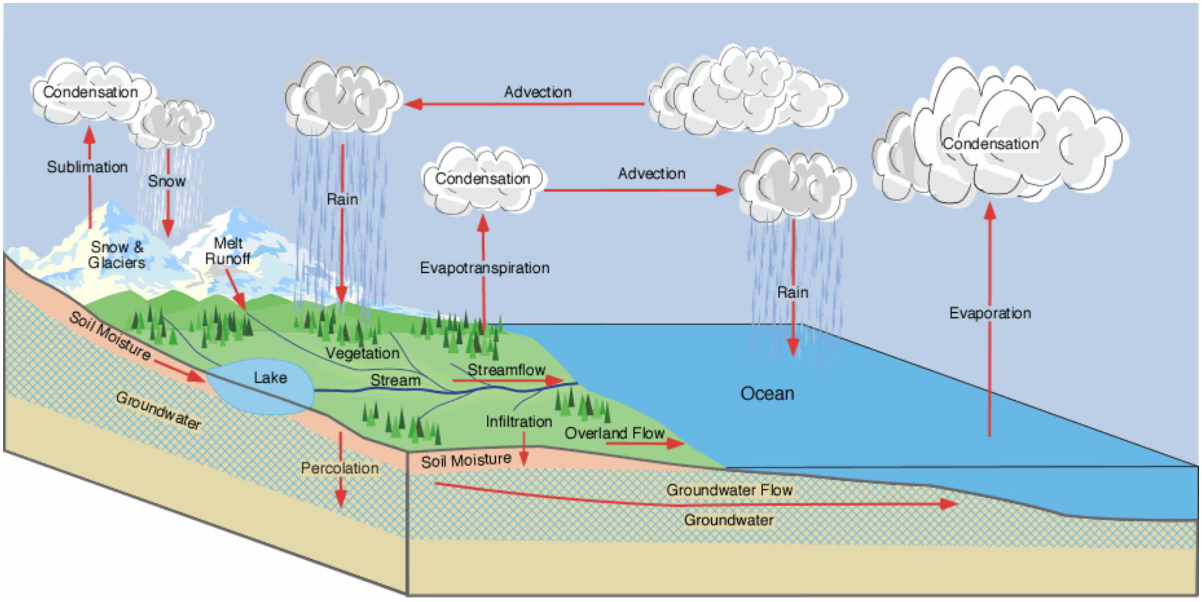


Figure 3.1: Hydrological cycle [10]

3.2 HYDROLOGICAL MODELLING

A hydrological system model is an approximation of the actual system. A hydrological system can be defined as a structure of volume in space, surrounded by a boundary that accepts water and other inputs, operates on them internally and produces an output. The objective of hydrological system analysis is to study the system operation and predict its internal states and output.

A mathemathical model is an explicit sequential set of equations and numerical and logical steps that converts numerical inputs to numerical outputs [13]. The equations represents the qualitative behaviour of flows and storage and the parameters- numerical constants- that dictate the quantitative behaviour.

Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding hydrologic processes. Hydrological models are widely used for the proper design and management of water resources projects. These are the basis for flood forecasting and early warning systems. Simulated series of river flows are used in the design and operation of system of multipurpose reservoirs to optimize the conflicting uses of water resources.

3.3 MODELLING PROCESS

There are many different procedures for hydrological modelling. The first step of the modelling is perceptual model and it's not constrained by mathematical theory [14]. The mathematical description of the model is the conceptual model. These mathematical equations are coded in suitable computer program to run and the model parameters are estimated. Once the model parameters have been specified, the next stage is validation of those predictions. The following flow chart describes the modelling process in the hydrological system.

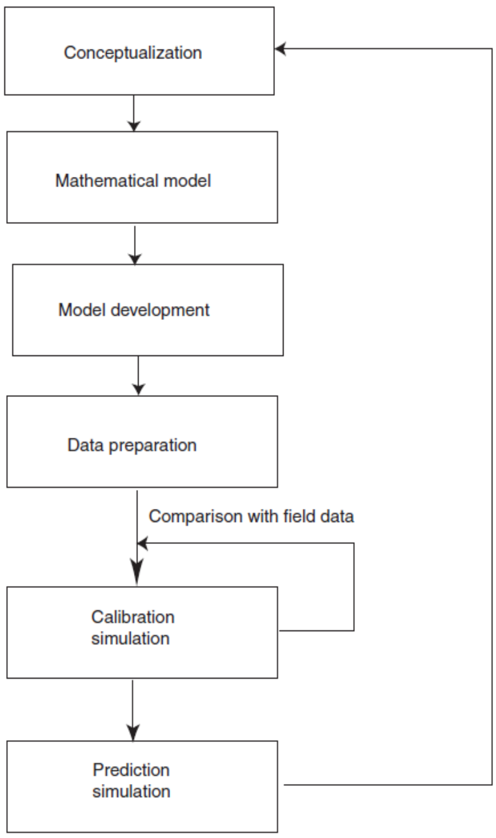


Figure 3.2: A schematic outline of the different steps in the modelling process [15]

3.4 CLASSIFICATION OF HYDROLOGICAL MODEL

The hydrological models can be mainly classified into two main categories i.e. 1) physical models and 2) abstract models. The physical models are scaled models. The abstract models refer the system in mathematical and logical form. The operation of system is described by forming set of equations and logical statements. The models are classified according to three main criteria:

- Randomness (deterministic or stochastic)
- Spatial variation (lumped or distributed)
- Time variability (time-dependent, time-independent)

There are several systems of classification of hydrological models and one of these is shown in Figure 3.3.

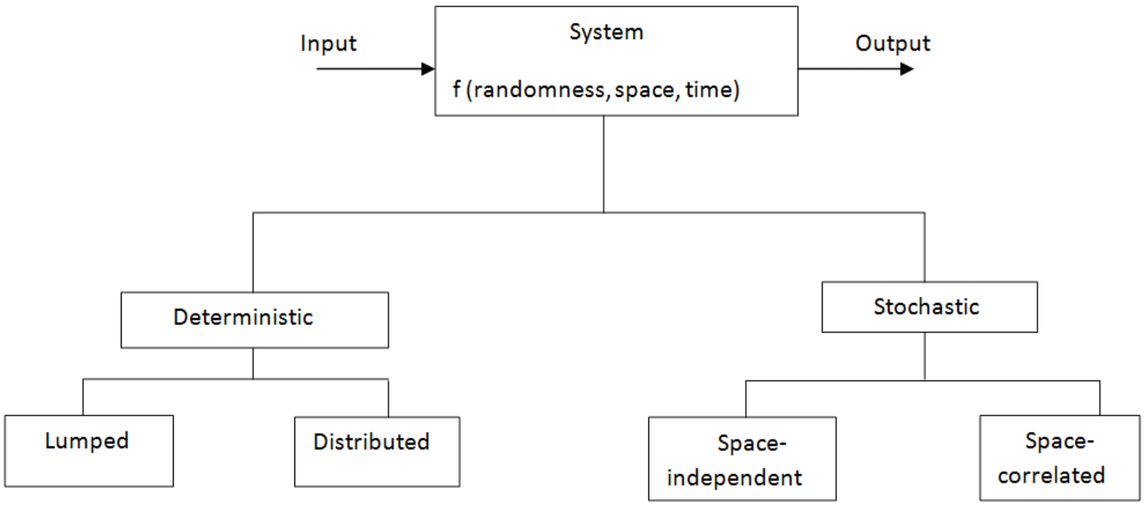


Figure 3.3: Classification of hydrological models Reproduced from [16]

3.4.1 Lumped and distributed models

The models that have been typically used are the lumped models. Lumped models are systems where all of the parameters which impact the hydrologic response of a watershed are spatially averaged together to create uniformity across the basin. (HEC 2000) (Johnson 1997) (Shah 1996a) Lumped models consider a watershed catchment as one complete unit, characterized by a relative small number of parameters and variables (Refsgaard 1997). The discharge at the watershed outlet is described based on a global dynamic of the system. There are numerous lumped hydrological models such as HBV, IHACRES, Stanford Watershed Model, TOPMODEL etc.

Figure 3.4: Concept of lumped and distributed model [17]

Distributed hydrologic models feature the capability to incorporate a variety of spatially varying data from a proliferating set of databases on land use, land and soil characteristics, and high resolution precipitation, temperature, and other forcing input. There are many distributed models such as EcoMAG, Landpine, MIKE_SHE, Gridded Urban Hydrological Model, ENKI etc.

3.5 THE HBV MODEL

The HBV model is a conceptual precipitation-runoff model which is used to simulate the runoff process in catchment based on data for precipitation, air temperature and potential evapotranspiration. The HBV model was developed by Dr. Sten Bergström at Swedish Meteorological and Hydrological Institute (SMHI) [18]. HBV is an acronym formed from **H**ydrologiske **B**yrån avdeling för **V**attenbalans.

HBV has been used for discharge modelling in many countries worldwide, including Brazil, China, Iran, Mozambique, Nepal, Norway, Sweden and Zimbabwe.

The main properties of HBV model are:

- Mathematical model of the hydrological process in a catchment
- Some extent a linear model
- Basically a lumped model
- A deterministic model

3.5.1 The HBV model structure

It is based on a conceptual representation of a few main components in the land phase of

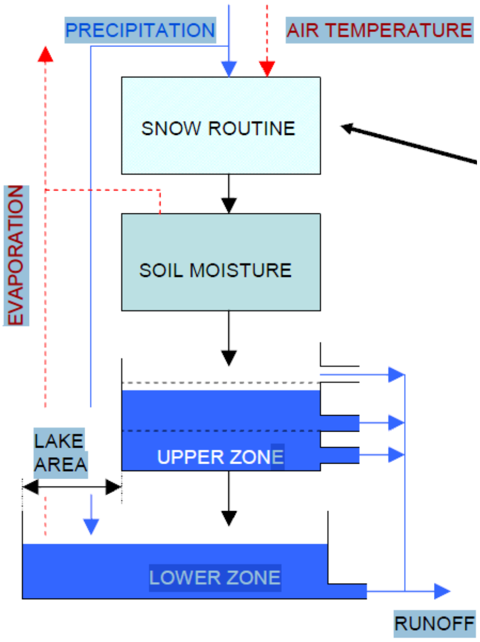


Figure 3.5: Main structure of the HBV-model [19]

the hydrological cycle as shown in Figure 3.5. Runoff from a catchment is computed from meteorological data like precipitation, air temperature, and potential evaporation. The standard version of the HBV model has four main components: Snow, Soil moisture, Upper zone and Lower zone.

3.5.1.1 The Snow Routine

This routine computes snow accumulation and melt based on precipitation and air temperature data within each elevation zone of the catchment by the help of the degree-day model. The catchment is sub-divided into elevation zones according to area-elevation curve as shown in Figure 3.6. The main outputs of snow routine are:

- Snow storage in mm of water equivalent
- Free water contents in snow in mm
- Snow melt in mm/timestep

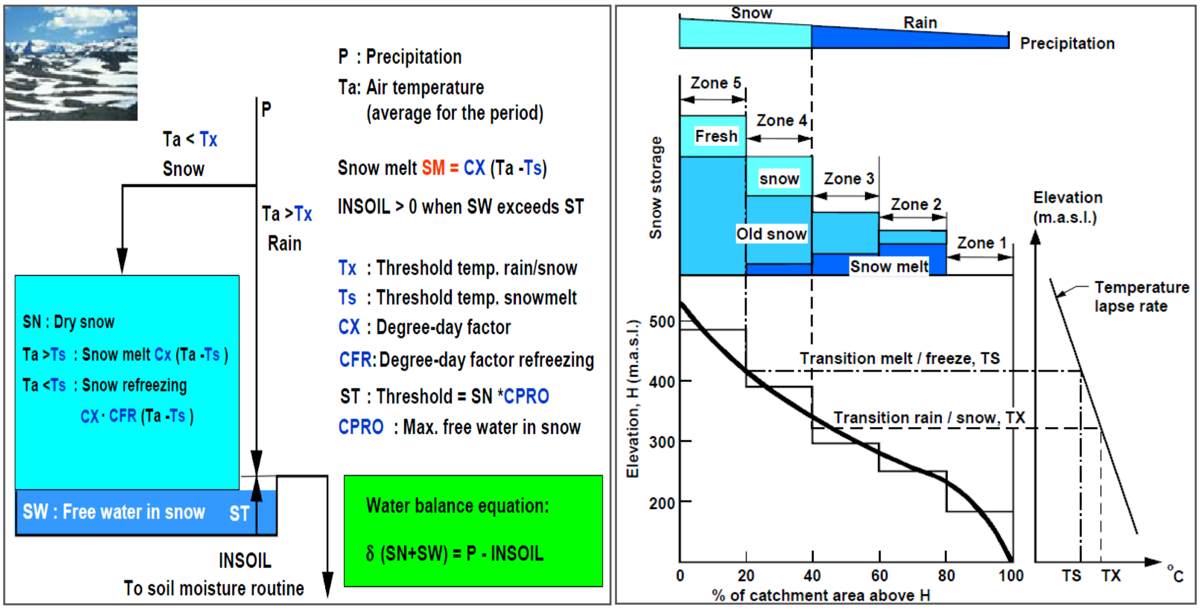


Figure 3.6: The snow routine in the HBV model and the area-elevation curve with snow accumulation and snow melt [19]

3.5.1.2 The Soil Moisture Routine

The soil moisture routine receives rainfall or snow melt as input from snow routine and computes the storage of water in soil moisture, actual evapotranspiration and net runoff generating precipitation as output to the runoff response routine.

This routine is based on two simple equations with three empirical parameters, beta, FC and LP. The beta parameter controls the contribution to the runoff response routine duz and the increase in soil moisture storage (dsm) for precipitation or snow melt input of one mm into the soil moisture storage.

Field capacity (FC) is the maximum soil moisture storage in the model. If the soil moisture storage is filled up to FC no more precipitation or snow melt can be stored as soil moisture and all input to soil moisture storage will be transformed directly to runoff.

The soil moisture storage is depleted by evapotranspiration. The computation of actual evapotranspiration (EA) is a function of potential evapotranspiration (EP) and relative soil storage SM/FC. If the soil moisture exceeds a threshold value evapotranspiration decreases linearly with the decrease in storage.

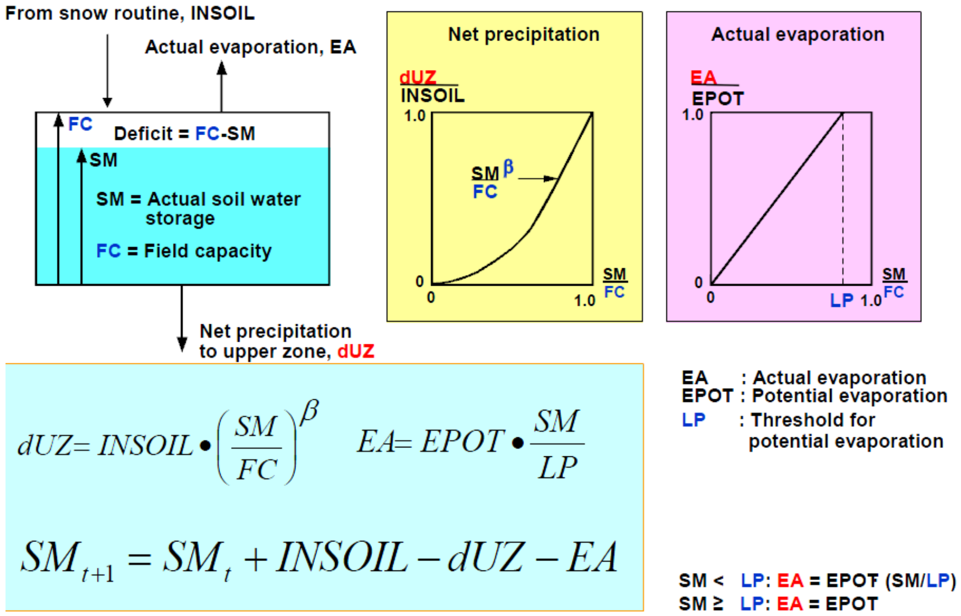


Figure 3.7: The soil moisture routine in the HBV-model [19]

3.5.1.3 The Runoff Response Routine

The runoff response routine transforms the net precipitation produced in the soil moisture routine into runoff. It consists of two linear tanks in the HBV model.

Upper zone represents the quick runoff components from overland flow and from groundwater drained through more superficial channels, interflows. It is equivalent to the unit hydrograph method.

Lower zone represents the groundwater and lake storage which contributes to the base flow or slow runoff in the catchment. This flow continues for a long time even after precipitation or snow melt has been stopped.

The total combined flow from upper and lower zones can finally be filtered through a separate routine for river routing. The total effect of the runoff response function is very similar to the use of a unit hydrograph and transforming a sequence of net precipitation values into a runoff hydrograph.

Note: Some symbols used in ENKI model are different than in HBV model.

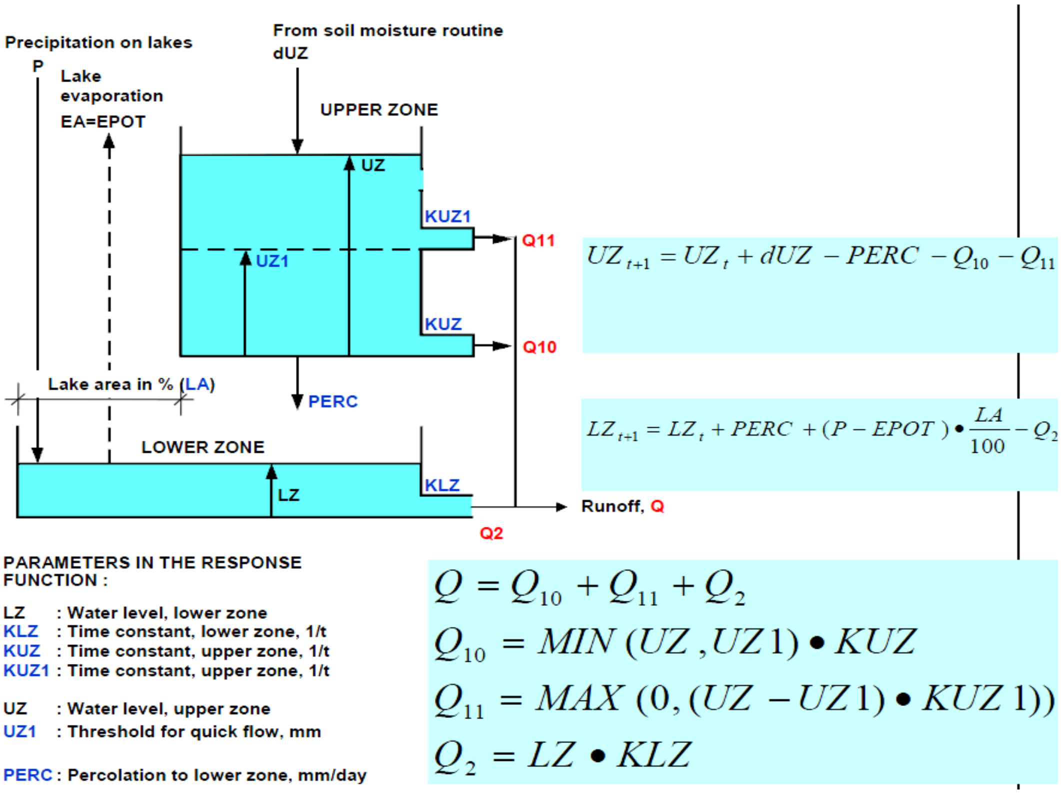


Figure 3.8: The runoff response routine in the HBV-model [16]

3.6 REGIONAL MODELLING

One of the great challenges in hydrology is the accurate simulation of an ungauged basin. A regional hydrological model allows predicting the dynamics of hydrology, water balance and the statistics of hydrological variables at the ungauged basins [20]. Regional hydrological modelling or hydrological macro modelling implies a repeated use of a model everywhere within a region using a global set of parameters [21]. Observations for calibration and validation of the model are only available at a subset of sites where the model is applied. So, the regional model calibration attempts to make a relationship between model parameters and characteristics of the modelling units so that the calibrated parameters can be applied to ungauged area.

The ungauged catchment problem has a long history. Early methods were mostly based on regressions of the model parameters values or runoff coefficients determined for gauged catchments against variables representing the characteristics of those catchments [22]. Once the regression equations have been developed then they can be used for estimating the parameters for ungauged areas. In the hydrologic literature there are at least two approaches that can serve as appropriate tools - the multi-objective method (Gupta *et al.,* 1998) and the Bayesian method (Binley and Beven, 1991)[21]. In the first case the model is executed for several possible parameter sets and catchments. On the basis of one or several error criteria it is possible to judge which parameter sets give acceptable simulations and which do not. The method provides a decision rule as how to select the parameter sets that performs satisfactory for all catchments. The result will be several possible parameter sets. The Bayesian method aims to estimate a probability distribution of the parameters. Parameter sets are given likelihoods based on a quality measure describing the goodness of fit between observed and simulated values. Both the multi-objective method and the Bayesian method consider the uncertainty in the choice of parameter values. The ENKI system uses the similar procedure as in the multi-objective method so that the ENKI model is executed for several numbers of catchments and iterated for possible range of several free parameters. These calibrated parameters are judged by Nash efficiency, which is described in later chapter, and transferred to ungauged basins to predict the runoff.

3.7 ENKI IN REGIONAL MODELLING

The term 'Enki' is the Sumerian mythology god of water, wisdom and magic [23]. The Enki project has been a part of research and development agreement between SINTEF Energy and Statkraft, and work has gone for five years. This project has initiated the development towards the operationalization of distributed hydrological models for the power industry in Norway.

The ENKI modelling system is equipped with tools for regional model setup and calibration, and through this inflow from ungauged sites can be extracted with a measure of uncertainty derived from the calibration. As described in above heading, the ENKI system uses the regional modelling to calibrate the parameters in the several catchments at one time and to validate the results. The framework of the ENKI modelling system can be described as per technical report of SINTEF Energy Research.

3.7.1 DEMLab

DEMLab (Dynamic Model Environmental Laboratory) is a framework for implementation of process models in time and space, primarily hydrological models. The framework itself contains no simulation routines or process data, only the administrative and user interfaces. A process model consists of a number of subroutines, called in the order determined for each time step. A subroutine is an instance of a method, and it is the method that implements the simulation equations. The method is coded in a special program for a specified pattern, and compiled as a dynamic library (Dynamic Link Library - DLL). The operator can build a model by creating subroutines based on this method DLLs and can define a variable interface between them.

A DLL is a collection of precompiled routines that a program can use. The subroutines, sometimes called modules, are stored in object format. Libraries are particularly useful for storing frequently used subroutines because one does not need to explicitly link them to every program that uses them. The program automatically looks in libraries for subroutines that it does not find elsewhere. In MS-Windows environments, library files have a .DLL extension. Thus a DLL is a library of executable functions or modules that can be used by other programs. Typically, a DLL provides one or more particular functions and a program accesses these functions by creating either a static or a dynamic link to the DLL. A static link remains constant during program execution while a dynamic link is created by the program as needed.

The most important two devices in DEMLab are the region and the model. One cannot build or used a model without a region, while one can to some extent; build up a region without having any specific model associated.

3.7.2 Model

The model contains a number of subroutines, called in sequence determined for each time step. A subroutine is an instance of a method, and it is the method that implements the simulation equations. The method is coded in a program after a fixed pattern, and compiled as a DLL. The operator then builds a model by creating subroutines based on this method DLL, and defines a variable interface between them. Subroutine in a model do not communicate among them, each subroutine only know the variables it operates. When a subroutine produces the input to another operator must therefore ensure that the first writes to the same variables as the second reading from. These variables belong to the region, not the model, including model-specific variables such as calibration parameters.

3.7.3 Region

The region is a collection of GIS data, which currently has one of three formats, raster (regular grid), network (Point) and scalar (single value). Line and surface data are not represented. All GIS data sets must refer to the same geographic coordinate system, and all must have a defined missing code. DEMLab uses IDRISI format internally so the raster and vector data in .asc format should be converted into IDRISI. Similarly, it is convenient to use IDRISI to facilitate data input and the necessary maps. Furthermore, the region has two time series databases, one for input and one for output. It is the input database that defines the time step in the model, and the limits of what period it can be simulated in.

DEMLab is in its present form a suitable tool for development and testing of various model routines, auto calibration and uncertainty estimation, evaluation of information sources and other hydrological analysis. In many ways, DEMLab fills the gap between a general purpose GIS tools and operational hydrological models [24].

4 GIS IN HYDROLOGICAL MODELLING

"The map is not the territory"

- Alfred Korzybski

4.1 INTRODUCTION

A geographic information system (GIS) is a system developed to manage, disseminate, visualize and analyze all types of geographic data. GIS technology integrates common database operations such as query and statistical analysis with the unique visualization and geographic analysis benefits offered by maps. These abilities distinguish GIS from other information systems and make it valuable to a wide range of public and private enterprises for explaining events, predicting outcomes, and planning strategies. GIS is considered to be one of the most important new technologies, with the potential to revolutionize many aspects of society through increased ability to make decisions and solve problems.

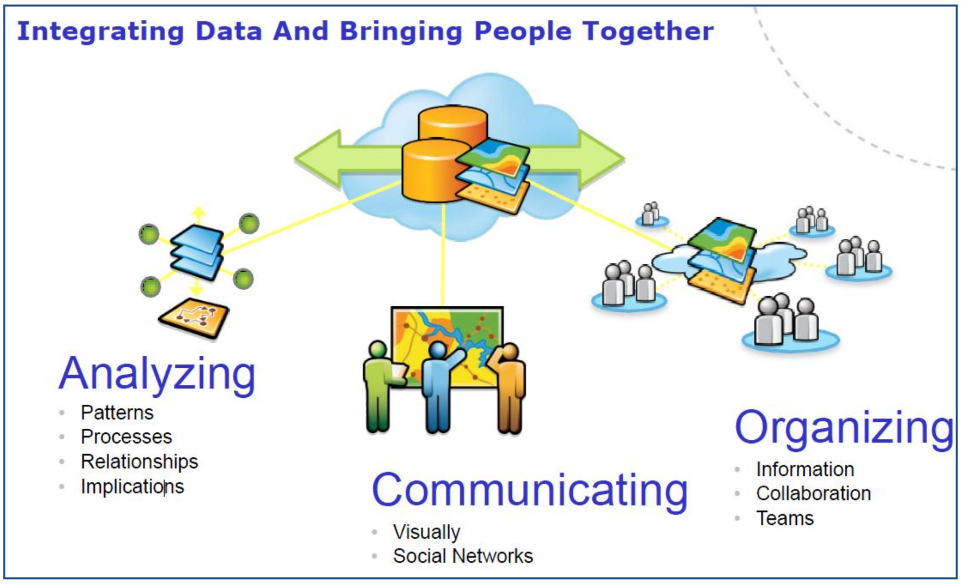


Figure 4.1: Concept of GIS [19]

The ability of GIS to search databases and perform geographic queries has revolutionized many areas of science and business. It can be invaluable during a decision-making process. The information can be presented clearly in the form of a map and accompanying report, allowing decision makers to focus on the real issues rather than trying to understand the data. Because GIS products can be produced quickly, multiple scenarios can be evaluated efficiently and effectively. For this reason, in today's world, the ability to use GIS is increasingly important.

A GIS consists of:

- Computer Hardware – computers used for storing data, displaying graphics and processing data.
- Computer Software – computer programs that run on the computer hardware and allow users to work with digital data. A software program that forms part of the GIS is called a GIS Application.
- Digital Data – the geographical information that can be viewed and analysed using computer hardware and software. Vector and raster data.
- People- GIS users range from technical specialists who design and maintain the system to those who use it to help them perform their everyday work.
- Methods- a successful GIS operates according to a well-designed plan and business rules, which are the models and operating practices unique to each organization.

GIS is a relatively broad term, which can refer to a number of technologies and processes, so it is applicable to many operations, in engineering, planning, management, and analysis.

4.2 GIS IN HYDROLOGICAL MODELLING

GIS offer new opportunities for the collection, storage, analysis, and display of spatially distributed meteorological and geophysical data. The use of GIS enables one to implement geographic data more efficiently for hydrological monitoring, analyzing, planning and management.

GIS hydrological models can provide a spatial element that other hydrological models cannot, with the analysis of variables such as slope, aspect and catchment area [23]. Since water always flows down a slope, terrain analysis is always basic problem in hydrology. As fundamental terrain analysis of a digital elevation model (DEM) involves calculation of slope and aspect, DEMs are very useful for hydrological analysis. Slope and aspect are used to determine direction of surface runoff, and hence flow accumulation for the formation of streams, rivers and lakes. Another important application of DEMs is catchment area delineation of the sub regions. For distributed models more detail data such as land use, vegetation cover, soil types, and terrain roughness can be defined by application of GIS. These maps and databases can be integrated using GIS data management tools. The presentation of spatial results from hydrological analysis like snow, soil water, and runoff can be represented in GIS thematic maps.

5 DATA COLLECTION AND PROCESSING

"Everything of importance has been thought of before by someone who did not invent it."

-Alfred North Whitehead

5.1 INTRODUCTION

Almost all meteorological and hydrological data are collected from Department of Hydrology and Meteorology (DHM), Nepal. There are 282 meteorological stations and 51 hydrological stations throughout the nation [8]. The 10 years data from 1999 to 2008 was collected for the Saptakoshi basin from DHM. The first five years were used for model calibration and rest for validation of the model.

5.2 METEOROLOGICAL DATA

5.2.1 Precipitation

The rainfall data for the Koshi basin and around the basin are collected from the DHM, Nepal. There are altogether 67 precipitation stations are found which are shown in given Figure 5.1. All these stations are applicable for the study and analysis. Most of these stations lie inside the Saptakoshi catchment and some are south-east of the catchment which are outside the catchment boundary of drainage point Chatara. Almost half of the total catchment area lies in Tibet (China) and information from those parts are not available. The detail locations of the all the rainfall stations in the Saptakoshi basin are tabulated in the Table 5.1.

Table 5.1: Description of precipitation stations in the Saptakoshi basin

STNR	Point ID	Station name	Longitude	Latitude	Elevation (m)
1006	1	GUMTHANG	85° 52' 0.000" E	27° 52' 0.000" N	2000
1008	2	NAWALPUR	85° 37' 0.000" E	27° 48' 0.000" N	1592
1009	3	CHAUTARA	85° 43' 0.000" E	27° 47' 0.000" N	1660
1016	4	SARMATHANG	85° 36' 0.000" E	27° 57' 0.000" N	2625
1017	5	DUBACHAUR	85° 34' 0.000" E	27° 52' 0.000" N	1550
1020	6	MANDAN	85° 39' 0.000" E	27° 42' 0.000" N	1365
1023	7	DOLAL GHAT	85° 43' 0.000" E	27° 38' 0.000" N	710
1024	8	DHULIKHEL	85° 33' 0.000" E	27° 37' 0.000" N	1552
1027	9	BAHRABISE	85° 54' 0.000" E	27° 47' 0.000" N	1220
1028	10	PACHUWAR GHAT	85° 45' 0.000" E	27° 34' 0.000" N	633
1036	11	PANCHKHAL	85° 38' 0.000" E	27° 41' 0.000" N	865
1049	12	KHOPASI(PANAUTI)	85° 31' 0.000" E	27° 35' 0.000" N	1517
1058	13	TARKE GHYANG	85° 33' 0.000" E	28° 0' 0.000" N	2480
1062	14	SANGACHOK	85° 43' 0.000" E	27° 42' 0.000" N	1327
1063	15	THOKARPA	85° 47' 0.000" E	27° 42' 0.000" N	1750
1078	16	DHAP	85° 38' 0.000" E	27° 54' 0.000" N	1310
1101	17	NAGDAHA	86° 6' 0.000" E	27° 41' 0.000" N	850
1102	18	CHARIKOT	86° 3' 0.000" E	27° 40' 0.000" N	1940
1103	19	JIRI	86° 14' 0.000" E	27° 38' 0.000" N	2003
1108	20	BAHUN TILPUNG	86° 10' 0.000" E	27° 11' 0.000" N	1417
1115	21	NEPALTHOK	85° 49' 0.000" E	27° 27' 0.000" N	1098
1123	22	MANTHALI	86° 5' 0.000" E	27° 28' 0.000" N	495
1202	23	CHAURIKHARK	86° 43' 0.000" E	27° 42' 0.000" N	2619

1203	24	PAKARNAS	86° 34' 0.000" E	27° 26' 0.000" N	1982
1204	25	AISEALUKHARK	86° 45' 0.000" E	27° 21' 0.000" N	2143
1206	26	OKHALDHUNGA	86° 30' 0.000" E	27° 19' 0.000" N	1720
1207	27	MANE BHANJYANG	86° 25' 0.000" E	27° 29' 0.000" N	1576
1210	28	KURULE GHAT	86° 26' 0.000" E	27° 8' 0.000" N	497
1211	29	KHOTANG BAZAR	86° 50' 0.000" E	27° 2' 0.000" N	1295
1212	30	PHATEPUR	86° 56' 0.000" E	26° 44' 0.000" N	100
1219	31	SALLERI	86° 35' 0.000" E	27° 30' 0.000" N	2378
1222	32	DIKTEL	86° 48' 0.000" E	27° 13' 0.000" N	1623
1223	33	RAJBIRAJ	86° 45' 0.000" E	26° 33' 0.000" N	91
1224	34	SIRWA	86° 23' 0.000" E	27° 33' 0.000" N	1662
1226	35	BARMAJHIYA	86° 54' 0.000" E	26° 36' 0.000" N	85
1301	36	NUM	87° 17' 0.000" E	27° 33' 0.000" N	1497
1303	37	CHAINPUR (EAST)	87° 20' 0.000" E	27° 17' 0.000" N	1329
1304	38	PAKHRIBAS	87° 17' 0.000" E	27° 3' 0.000" N	1680
1305	39	LEGUWA GHAT	87° 17' 0.000" E	27° 8' 0.000" N	410
1306	40	MUNGA	87° 14' 0.000" E	27° 2' 0.000" N	1317
1307	41	DHANKUTA	87° 21' 0.000" E	26° 59' 0.000" N	1210
1308	42	MUL GHAT	87° 20' 0.000" E	26° 56' 0.000" N	365
1309	43	TRIBENI	87° 9' 0.000" E	26° 56' 0.000" N	143
1311	44	DHARAN BAZAR	87° 17' 0.000" E	26° 49' 0.000" N	444
1312	45	HARAINCHA	87° 23' 0.000" E	26° 37' 0.000" N	152
1314	46	TERHATHUM	87° 33' 0.000" E	27° 8' 0.000" N	1633
1316	47	CHATARA	87° 10' 0.000" E	26° 49' 0.000" N	183
1317	48	CHEPUWA	87° 25' 0.000" E	27° 46' 0.000" N	2590
1319	49	BIRATNAGAR AIRPOART	87° 16' 0.000" E	26° 29' 0.000" N	72
1320	50	TARAHARA	87° 16' 0.000" E	26° 42' 0.000" N	200
1321	51	TUMLINGTAR	87° 13' 0.000" E	27° 17' 0.000" N	303
1322	52	MACHUWAGHAT	87° 10' 0.000" E	26° 58' 0.000" N	158
1325	53	DINGLA	87° 9' 0.000" E	27° 22' 0.000" N	1190
1403	54	LUNGTHUNG	87° 47' 0.000" E	27° 33' 0.000" N	1780
1405	55	TAPLEJUNG	87° 40' 0.000" E	27° 21' 0.000" N	1732
1406	56	MEMENG JAGAT	87° 56' 0.000" E	27° 12' 0.000" N	1830
1407	57	ILAM TEA ESTATE	87° 54' 0.000" E	26° 55' 0.000" N	1300
1408	58	DAMAK	87° 42' 0.000" E	26° 40' 0.000" N	163
1409	59	ANARMANI BIRTA	87° 59' 0.000" E	26° 38' 0.000" N	122
1410	60	HIMALI GAUN	88° 2' 0.000" E	26° 53' 0.000" N	1654
1412	61	CHANDRA GADHI	88° 3' 0.000" E	26° 34' 0.000" N	120
1415	62	SANISCHARE	87° 58' 0.000" E	26° 41' 0.000" N	168
1416	63	KANYAM TEA ESTATE	88° 4' 0.000" E	26° 52' 0.000" N	1678
1419	64	PHIDIM (PANCHTHER)	87° 45' 0.000" E	27° 9' 0.000" N	1205
1420	65	DOVAN	87° 36' 0.000" E	27° 21' 0.000" N	763
1421	66	GAIDA (KANKAI)	87° 54' 0.000" E	26° 35' 0.000" N	143
1422	67	KECHANA	88° 1' 0.000" E	26° 24' 0.000" N	60

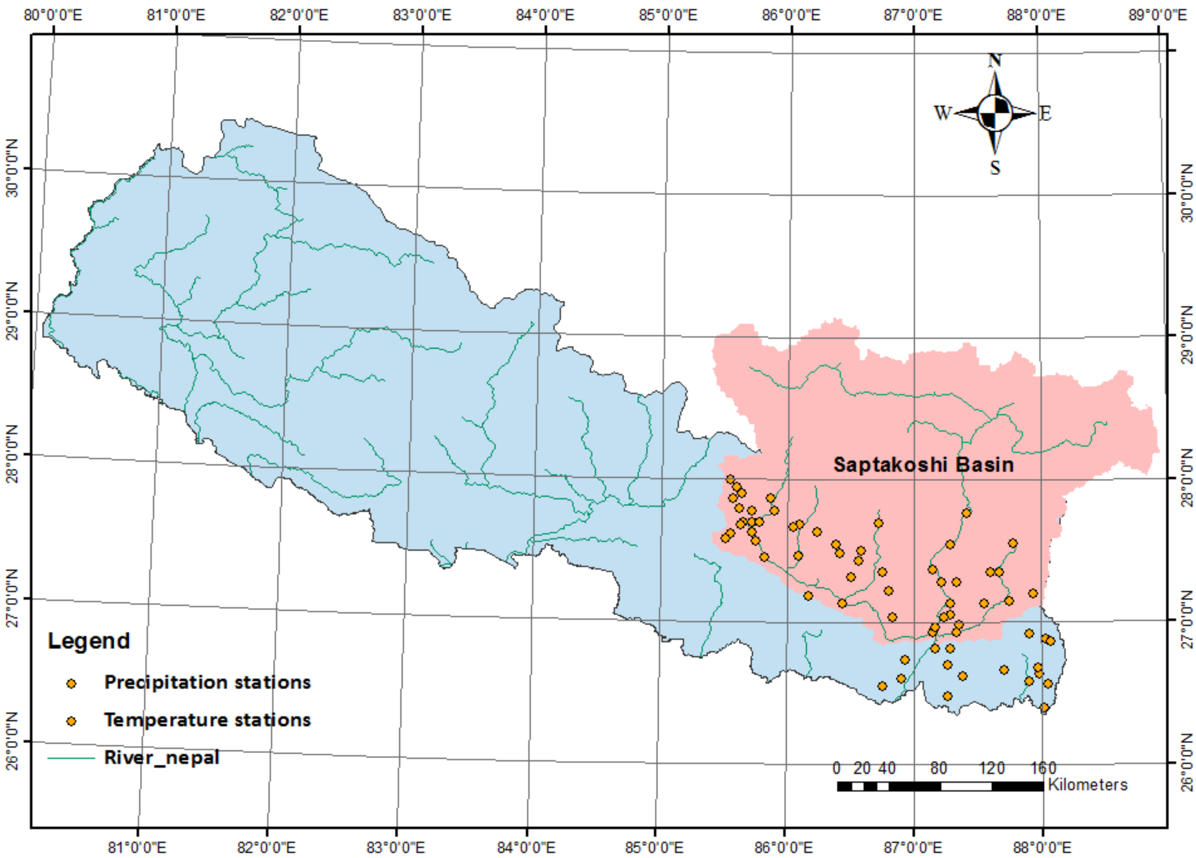


Figure 5.1: Precipitation stations in the Saptakoshi basin

5.2.1.1 Missing data Interpolation

It is very necessary to check the continuity and consistency of the rainfall data before using in hydrological models. The data may be missed due to different reasons such as errors in gauge, personal errors or operation difficulties. These missing data can be interpolated by simple following arithmetic procedure from neighboring stations.

$$p_{0=}\frac{1}{G}\sum_{1}^{G} p_g$$

If the annual average precipitation of each station differs by more than 10%, then following Normal Ratio Method is applied [13]. For simplicity of calculation, here it is assumed that all the annual precipitation differ by more than 10%.

$$p_{0=}\frac{1}{G}\sum_{1}^{G}\frac{P_0}{P_g} p_g$$

Where,

p_0 = Estimated missing data for a particular day at the gauge

P_0 = Annual average precipitation at the gauge with missing values

P_g = Annual average precipitation at the nearby gauge stations

p_g = Observed precipitation for corresponding day at g=1, 2, 3…G

The VBA application is used in Excel sheets for filling the gaps of missing data series. By the application of the VBA tool the missing values are filled and sufficient random manually checked [3]. For the reference, VBA code is attached in Appendix 1.1.

Some data are denoted as "T" (trace) in the collected data. A trace of precipitation, snowfall or snow on the ground indicates that some occurred or is present, but it was below the detectable limit. Generally, this limit for precipitation is 0.005 inch, for snowfall 0.05 inch and for snow depth 0.5 inch [10]. These trace "T" values are replaced by 0.12 mm.

5.2.1.2 Data Quality Check

The quality of data should be verified before use in analysis. The changes in gauges locations, exposure by vegetation growth removal, instrumentation or system change and observational procedures may cause a relative change in the precipitation data collection. The trends and non-homogeneity test of data may help to determine the possible error on data. The consistency of the records data are checked and inconsistent data are dropped or corrected before further analysis.

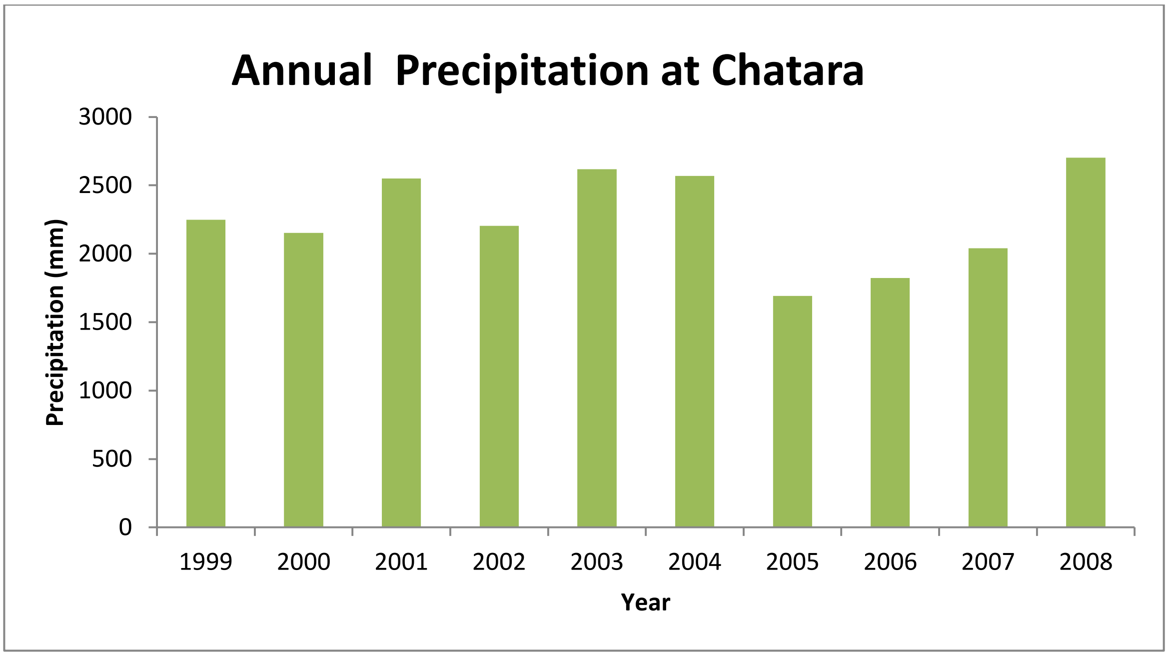


Figure 5.2: Annual precipitation at Chatara staion

The annual mean rainfall from year 1999 to 2008 and elevation of these stations are shown in Figure 5.3. The annual precipitation is decreasing with increased of elevation up to 600m and then remains constant up to 1400m if station Num excluded and then the annual rainfall increases with elevation. The precipitation gradients in the Saptakoshi region are shown in Appendix 2. The annual average precipitation in the station Gumthang and Num is much higher than other stations and in the stations Leguwa Ghat, Nepalthok, Pachuwar Ghat and Dhankuta have very low precipitation. But when these values compared with ICIMOD report as shown in Figure 2.5, they are reasonably ok. So, all these stations are applied for analysis.

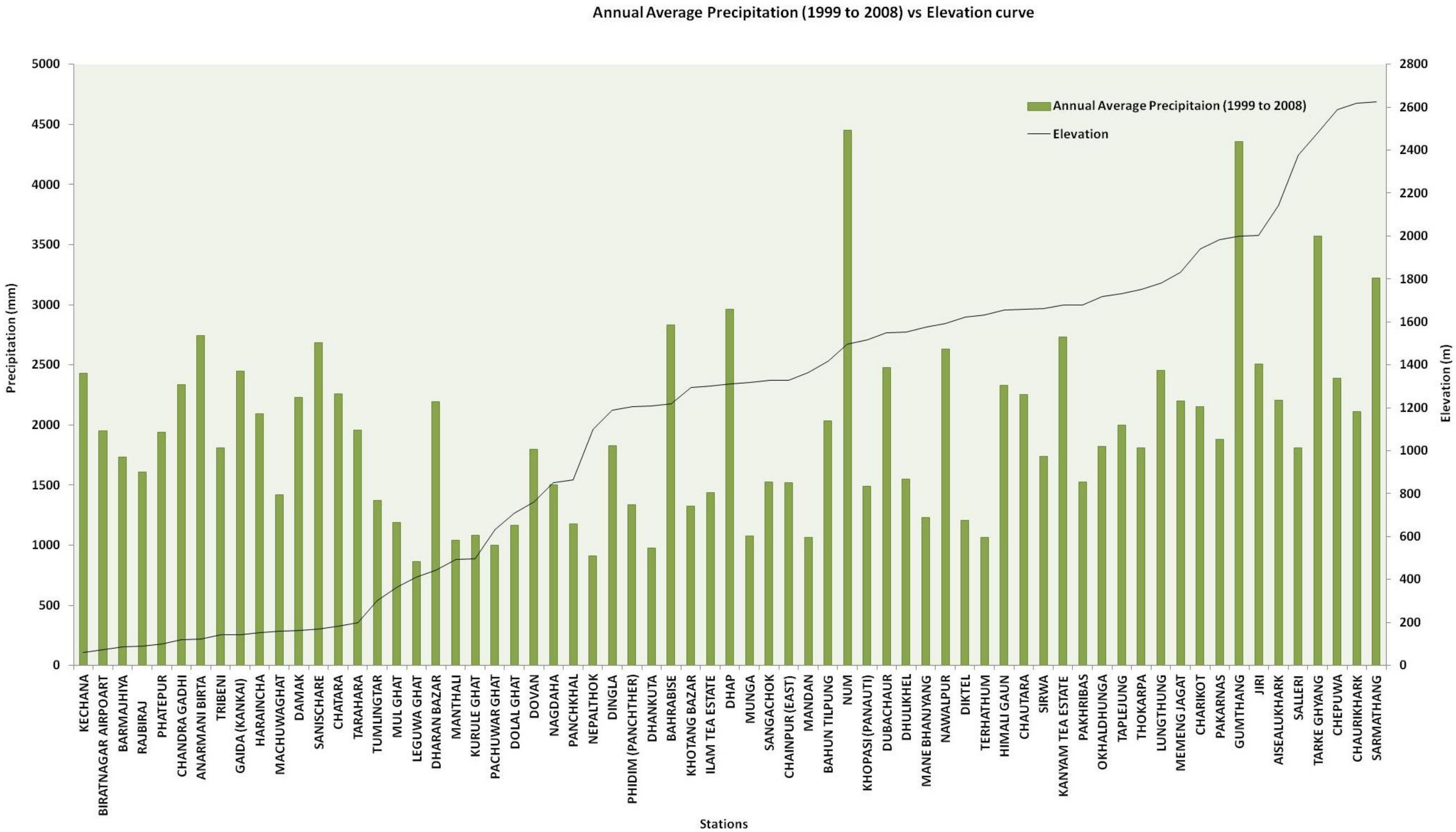


Figure 5.3: Annual average precipitation (1999 to 2008) vs. elevation of the stations

Table 5.2: Monthly average precipitation (1999-2008) at different stations at the Saptakoshi basin

Station ID	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (mm)
1006	GUMTHANG	32	53	63	117	354	685	992	1033	755	229	24	15	4353
1008	NAWALPUR	18	27	26	64	186	437	717	688	376	103	5	6	2652
1009	CHAUTARA	16	27	43	73	150	383	529	593	344	75	4	7	2244
1016	SARMATHANG	25	27	44	85	230	553	847	812	454	135	6	4	3224
1017	DUBACHAUR	21	35	46	75	203	411	633	659	313	77	3	6	2483
1020	MANDAN	12	11	11	40	98	183	280	242	153	35	1	3	1069
1023	DOLAL GHAT	10	15	21	52	119	206	283	269	142	47	2	4	1170
1024	DHULIKHEL	16	26	28	67	139	251	403	358	206	61	1	7	1563
1027	BAHRABISE	18	25	40	76	220	513	685	741	419	107	9	5	2857
1028	PACHUWAR GHAT	16	13	12	48	102	185	266	188	132	36	1	3	1002
1036	PANCHKHAL	10	16	14	38	98	202	282	291	162	65	2	4	1184
1049	KHOPASI (PANAUTI)	14	25	31	78	146	244	378	296	213	61	3	3	1492
1058	TARKE GHYANG	19	19	53	86	210	591	962	970	546	96	5	7	3564
1062	SANGACHOK	14	23	28	61	143	276	383	336	210	56	1	2	1534
1063	THOKARPA	15	25	18	78	148	302	478	420	247	74	3	4	1814
1078	DHAP	20	40	35	68	215	495	814	773	430	94	5	4	2993
1101	NAGDAHA	4	19	31	69	198	285	340	320	202	44	4	4	1519
1102	CHARIKOT	14	27	36	81	174	332	571	565	296	64	6	4	2170
1103	JIRI	14	32	42	90	191	424	661	635	375	90	6	5	2566
1108	BAHUN TILPUNG	18	30	35	118	209	358	491	326	289	124	5	7	2009
1115	NEPALTHOK	4	18	17	39	77	126	312	167	112	35	0	6	914
1123	MANTHALI	13	18	24	50	81	152	317	177	150	48	1	5	1035
1202	CHAURIKHARK	14	25	23	66	119	335	571	579	295	57	4	4	2093
1203	PAKARNAS	12	29	34	56	126	273	471	496	273	79	1	3	1853
1204	AISEALUKHARK	15	22	37	63	163	334	590	566	314	94	9	5	2213
1206	OKHALDHUNGA	11	18	25	74	154	317	473	395	253	80	7	7	1814
1207	MANE BHANJYANG	12	17	17	57	108	215	354	247	149	39	1	4	1219
1210	KURULE GHAT	11	14	18	59	89	160	344	189	122	57	3	6	1072
1211	KHOTANG BAZAR	23	13	35	58	142	196	329	263	163	82	0	6	1310
1212	PHATEPUR	13	12	20	75	161	314	554	360	274	123	3	4	1912
1219	SALLERI	11	24	28	54	121	284	442	488	268	65	3	3	1792
1222	DIKTEL	11	14	24	45	167	242	293	213	136	35	7	7	1195
1223	RAJBIRAJ	12	8	8	59	144	313	483	242	213	98	0	2	1583
1224	SIRWA	12	20	35	52	130	243	434	457	249	82	21	3	1738
1226	BARMAJHIYA	11	13	5	68	169	286	496	301	255	113	4	3	1723
1301	NUM	26	59	106	412	572	829	827	727	620	238	29	13	4458
1303	CHAINPUR (EAST)	12	27	36	120	185	272	313	295	194	66	5	4	1530
1304	PAKHRIBAS	14	18	32	76	157	293	386	282	187	68	1	7	1520
1305	LEGUWA GHAT	6	17	14	76	93	160	179	172	104	31	0	3	855
1306	MUNGA	10	17	18	62	100	157	300	233	140	49	1	3	1090
1307	DHANKUTA	12	19	27	54	111	149	267	170	105	54	2	4	974
1308	MUL GHAT	14	21	33	65	129	201	319	193	136	68	1	4	1184
1309	TRIBENI	10	21	25	80	162	321	490	350	267	55	10	4	1795
1311	DHARAN BAZAR	15	18	32	90	189	340	558	451	323	162	5	4	2186
1312	HARAINCHA	20	24	24	95	164	378	714	342	249	82	4	6	2102
1314	TERHATHUM	18	19	23	92	137	191	233	188	118	40	0	6	1065
1316	CHATARA	9	17	39	102	200	327	570	396	373	190	9	6	2237
1317	CHEPUWA	29	54	106	180	254	363	480	442	321	125	34	10	2398
1319	BIRATNAGAR AIRPORT	14	12	11	71	195	316	542	376	291	125	0	1	1955

1320	TARAHARA	21	16	27	83	211	322	559	321	271	95	5	4	1936
1321	TUMLINGTAR	2	11	15	120	174	266	276	217	212	75	7	4	1378
1322	MACHUWAGHAT	18	14	29	49	157	263	377	258	208	61	1	8	1444
1325	DINGLA	11	25	32	104	189	338	406	327	307	88	4	4	1832
1403	LUNGTHUNG	16	45	62	116	203	362	566	602	346	124	10	6	2459
1405	TAPLEJUNG	16	32	46	156	214	306	444	428	255	99	6	8	2010
1406	MEMENG JAGAT	24	38	44	149	261	334	454	449	298	125	12	11	2199
1407	ILAM TEA ESTATE	11	15	16	51	128	286	410	296	143	88	2	6	1453
1408	DAMAK	15	17	24	84	178	410	607	453	306	125	7	7	2233
1409	ANARMANI BIRTA	14	9	20	86	196	441	859	634	327	172	8	2	2767
1410	HIMALI GAUN	12	20	30	80	197	473	664	483	286	104	3	6	2359
1412	CHANDRA GADHI	14	9	23	93	176	398	693	488	319	128	3	2	2348
1415	SANISCHARE	12	10	23	85	182	467	828	570	334	176	6	2	2695
1416	KANYAM TEA ESTATE	12	25	32	92	247	568	749	563	337	127	3	6	2761
1419	PHIDIM (PANCHTHER)	11	24	32	76	150	202	329	298	144	67	1	9	1342
1420	DOVAN	16	29	50	160	206	306	399	317	222	82	1	12	1802
1421	GAIDA (KANKAI)	14	16	18	72	178	379	788	523	321	161	11	2	2482
1422	KECHANA	17	10	21	83	213	451	675	490	368	117	0	3	2447

Table 5.3: Seasonal distribution of average precipitation (1999-2008)

Month/Station	Dec-Feb Winter	Mar-May Pre-Mansoon	Jun-Sep Mansoon	Oct-Nov Post-Mansoon	Total
GUMTHANG	2.3%	12.3%	79.6%	6.2%	100%
NAWALPUR	1.9%	10.4%	83.6%	4.3%	100%
CHAUTARA	2.3%	11.9%	82.4%	3.8%	100%
SARMATHANG	1.7%	11.2%	82.7%	4.5%	100%
DUBACHAUR	2.5%	13.0%	81.2%	3.5%	100%
MANDAN	2.4%	14.0%	80.2%	3.7%	100%
DOLAL GHAT	2.5%	16.4%	76.9%	4.6%	100%
DHULIKHEL	3.1%	14.9%	77.9%	4.5%	100%
BAHRABISE	1.7%	11.7%	82.5%	4.2%	100%
PACHUWAR GHAT	3.2%	16.1%	77.0%	4.0%	100%
PANCHKHAL	2.5%	12.7%	79.2%	6.0%	100%
KHOPASI (PANAUTI)	2.9%	17.1%	75.8%	4.5%	100%
TARKE GHYANG	1.3%	9.8%	86.1%	3.0%	100%
SANGACHOK	2.6%	15.1%	78.6%	3.9%	100%
THOKARPA	2.5%	13.5%	79.8%	4.5%	100%
DHAP	2.1%	10.6%	84.0%	3.5%	100%
NAGDAHA	1.8%	19.6%	75.4%	3.4%	100%
CHARIKOT	2.1%	13.4%	81.3%	3.4%	100%
JIRI	2.0%	12.6%	81.7%	3.9%	100%
BAHUN TILPUNG	2.7%	18.0%	72.9%	6.7%	100%
NEPALTHOK	3.0%	14.6%	78.5%	4.5%	100%
MANTHALI	3.4%	15.0%	76.8%	5.2%	100%
CHAURIKHARK	2.0%	10.0%	85.1%	3.1%	100%
PAKARNAS	2.3%	11.7%	81.7%	4.4%	100%
AISEALUKHARK	1.9%	11.9%	81.5%	4.9%	100%
OKHALDHUNGA	2.0%	13.9%	79.3%	5.2%	100%
MANE BHANJYANG	2.7%	14.9%	79.1%	3.6%	100%
KURULE GHAT	2.9%	15.5%	76.1%	6.1%	100%
KHOTANG BAZAR	3.2%	17.9%	72.6%	6.7%	100%
PHATEPUR	1.5%	13.4%	78.5%	6.8%	100%
SALLERI	2.1%	11.3%	82.7%	4.0%	100%

DIKTEL	2.7%	19.8%	74.0%	4.1%	100%
RAJBIRAJ	1.4%	13.3%	79.1%	6.4%	100%
SIRWA	2.0%	12.5%	79.5%	6.1%	100%
BARMAJHIYA	1.6%	14.0%	77.7%	7.0%	100%
NUM	2.2%	24.5%	67.3%	6.3%	100%
CHAINPUR (EAST)	2.8%	22.3%	70.2%	4.9%	100%
PAKHRIBAS	2.5%	17.4%	75.5%	5.0%	100%
LEGUWA GHAT	3.1%	21.3%	72.0%	4.0%	100%
MUNGA	2.7%	16.5%	76.1%	4.9%	100%
DHANKUTA	3.5%	19.8%	70.9%	6.2%	100%
MUL GHAT	3.2%	19.2%	71.8%	6.1%	100%
TRIBENI	1.9%	14.9%	79.6%	3.8%	100%
DHARAN BAZAR	1.7%	14.2%	76.4%	7.8%	100%
HARAINCHA	2.4%	13.5%	80.1%	4.4%	100%
TERHATHUM	4.1%	23.6%	68.5%	4.4%	100%
CHATARA	1.4%	15.2%	74.5%	9.2%	100%
CHEPUWA	3.9%	22.5%	67.0%	7.0%	100%
BIRATNAGAR AIRPOART	1.4%	14.2%	78.0%	6.5%	100%
TARAHARA	2.2%	16.6%	76.1%	5.4%	100%
TUMLINGTAR	1.2%	22.4%	70.5%	6.2%	100%
MACHUWAGHAT	2.8%	16.3%	76.6%	4.8%	100%
DINGLA	2.1%	17.7%	75.2%	5.2%	100%
LUNGTHUNG	2.7%	15.5%	76.3%	5.7%	100%
TAPLEJUNG	2.8%	20.7%	71.3%	5.6%	100%
MEMENG JAGAT	3.4%	20.7%	69.7%	6.7%	100%
ILAM TEA ESTATE	2.2%	13.5%	78.1%	6.6%	100%
DAMAK	1.7%	12.8%	79.5%	6.2%	100%
ANARMANI BIRTA	0.9%	10.9%	81.7%	6.6%	100%
HIMALI GAUN	1.6%	13.0%	80.8%	4.8%	100%
CHANDRA GADHI	1.1%	12.4%	80.9%	5.7%	100%
SANISCHARE	0.9%	10.7%	81.6%	6.8%	100%
KANYAM TEA ESTATE	1.6%	13.4%	80.3%	4.9%	100%
PHIDIM (PANCHTHER)	3.2%	19.3%	72.5%	5.7%	100%
DOVAN	3.2%	23.1%	69.1%	5.3%	100%
GAIDA (KANKAI)	1.3%	10.8%	81.0%	7.0%	100%
KECHANA	1.2%	13.0%	81.0%	4.9%	100%

According to above Table 5.3, the monthly average precipitation and seasonal distribution of precipitation shows that approximately 15% of the total precipitation occurs during pre-monsoon and nearly 80% of the total during monsoon. So, these two tables show that the data are not skewed and in uniform distribution.

5.2.2 Temperature

Air temperature data are also collected from DHM, Nepal. The obtained temperature data are in the form of daily mean values. Air temperature data are available from only 18 stations among the 67 precipitation stations. The air temperature data is needed in the HBV model for computation of type of precipitation (snow or rain), snow melt and potential evapotranspiration. So, the remaining temperature data form respective stations are interpolated.

The lapse rate of air temperature is needed to compute temperature at elevations different from the air temperature stations. The lapse rate may be different in clear weather situations and during precipitation events as in Figure 5.4. For interpolation, an average value of the temperature lapse rate -0.6°c/100m elevation is used.

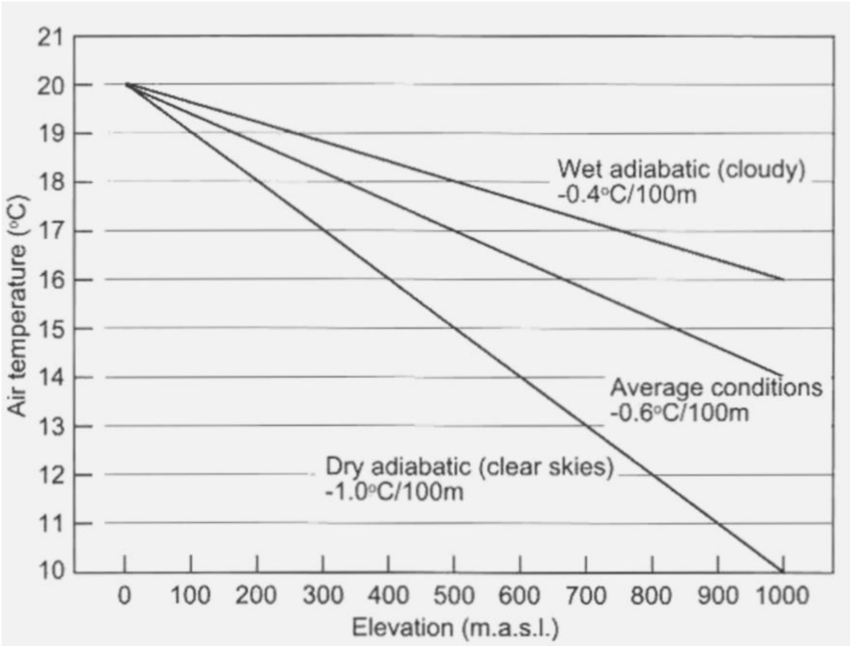


Figure 5.4: Air temperature lapse rates for three different meteorological conditions [18]

5.2.2.1 Missing data Interpolation

Here, interpolation of air temperature at specific unknown station is carried out from known 18 stations. First, the air temperatures at these 18 stations are converted into respective elevation of unknown station by applying temperature lapse rate. Then air temperature at unknown station is interpolated from these converted 18 stations air temperature by method of Inverse-Distance Weighting [13] as shown in below:

$$D_{=} \sum_{1}^{G} d_g^{-b}$$

$$T_{0=} \frac{1}{D} \sum_{1}^{G} d_g^{-b}\, T_g$$

Where,

d_g = distance from the gauge with missing data to the gauge with data

b = weights to the distance and here taken as 2

T_g = Daily mean air temperature at the known gauge stations g=1, 2, 3…G

T_0 = Interpolated Daily mean air temperature at unknown station

The VBA application is used in Excel sheets for interpolation of unavailable data series. By the application of the VBA tool the values are calculated and sufficient random manually checked [3]. For the reference, VBA code is attached in Appendix 1.2.

5.2.3 Data Quality Check

To know the continuity and homogeneity of temperature data, it is carried out by comparison of all the stations' mean monthly temperatures. For convenient and limit of pages, only some of these are shown in figures below. It can be concluded from analyzing and comparing mean monthly temperature of all the 67 stations that the temperature data are reliable and consistent.

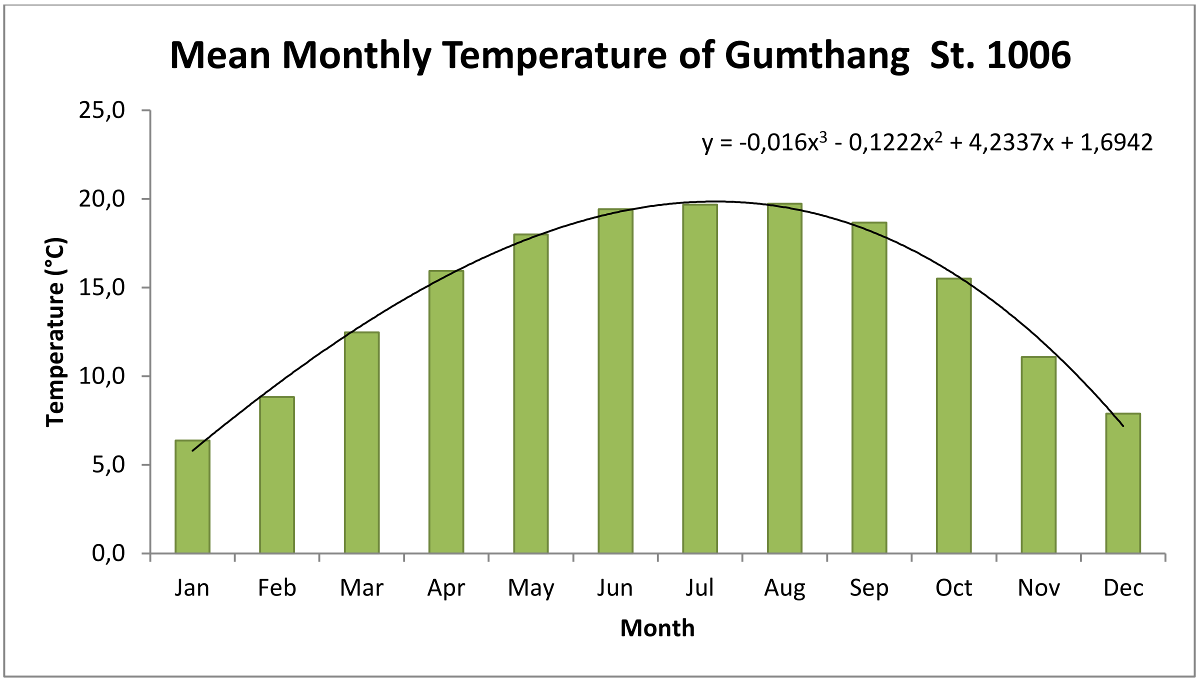


Figure 5.5: Mean monthly temperature at station Gumthang (1999-2008)

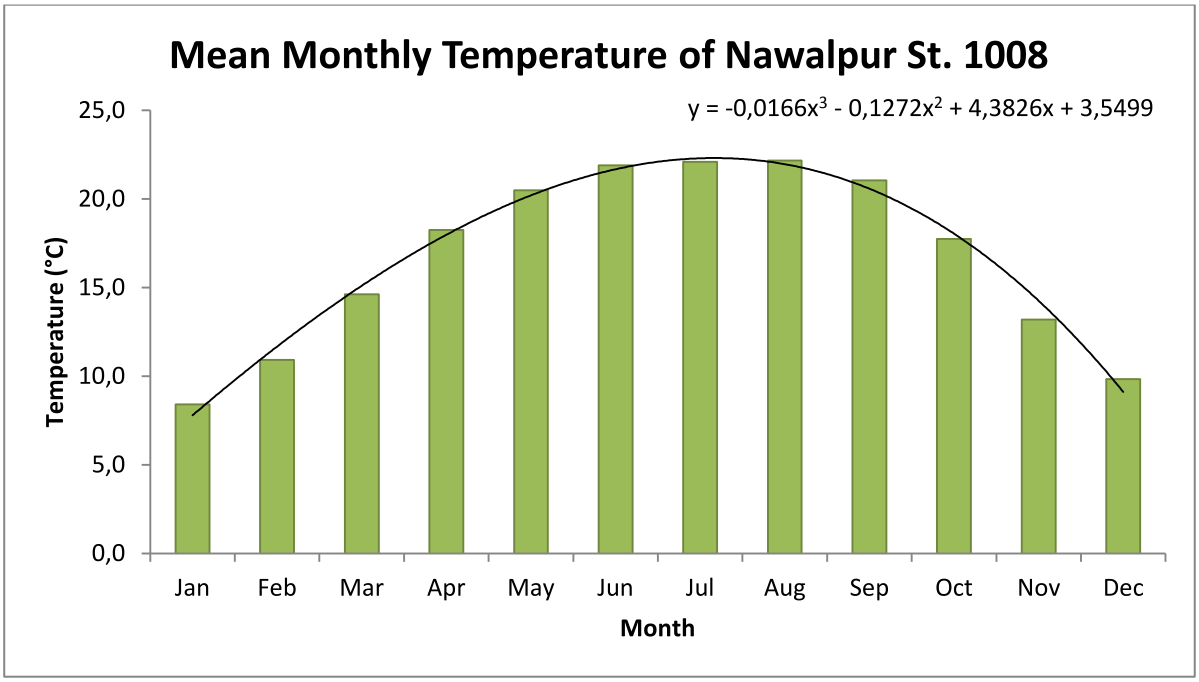


Figure 5.6: Mean monthly temperature at station Nawalpur (1999-2008)

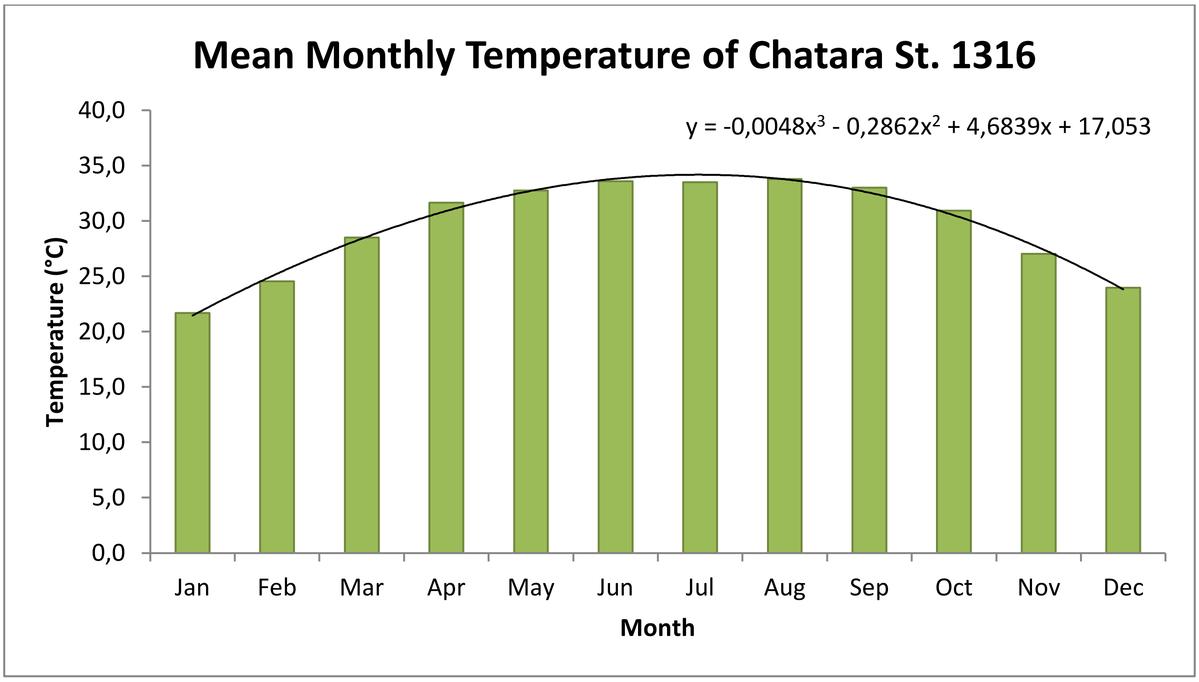


Figure 5.7: Mean monthly temperature at station Chatara (1999-2008)

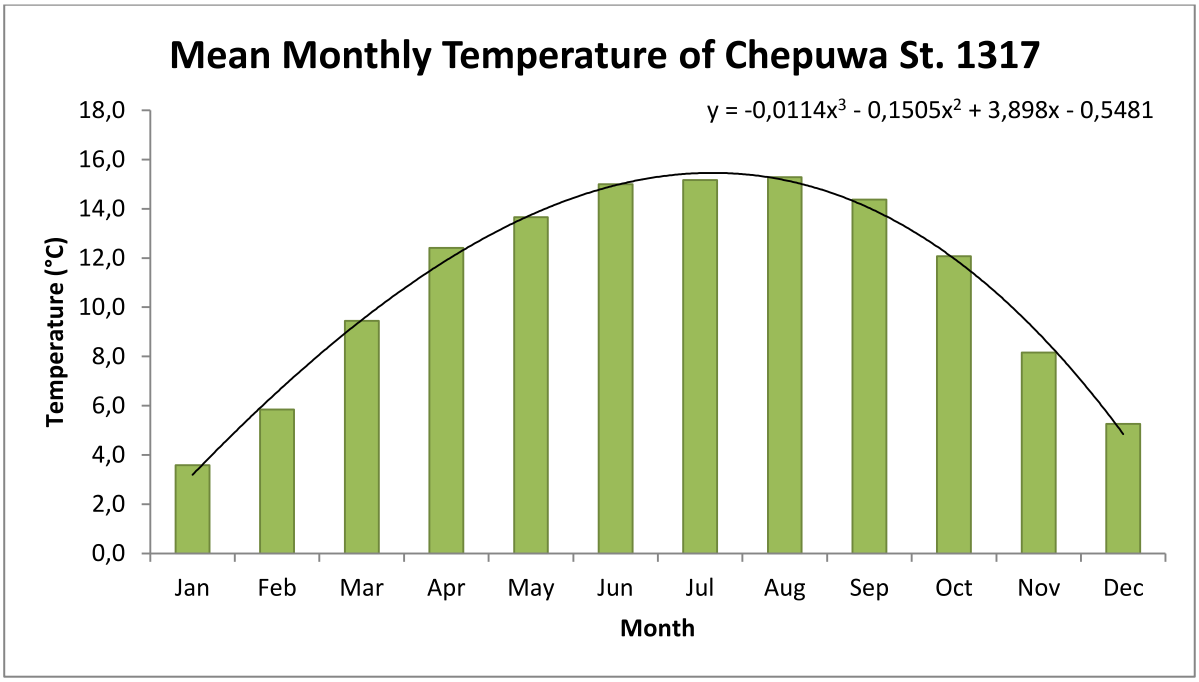
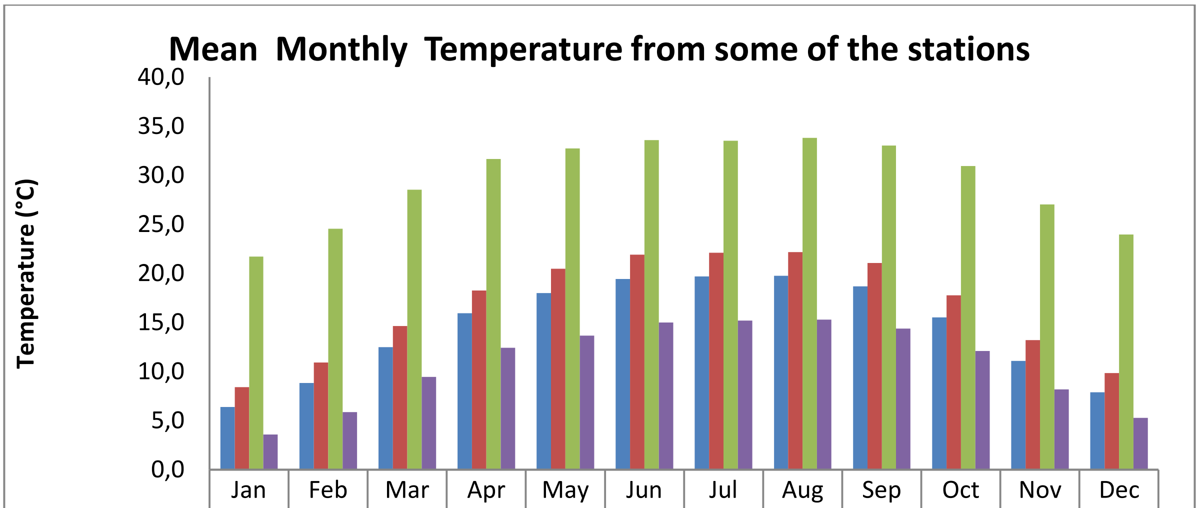


Figure 5.8: Mean monthly temperature at station Chepuwa (1999-2008)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GUMTHANG	6,4	8,8	12,5	15,9	18,0	19,4	19,7	19,7	18,7	15,5	11,1	7,9
NAWALPUR	8,4	10,9	14,6	18,3	20,5	21,9	22,1	22,2	21,0	17,7	13,2	9,8
CHATARA	21,7	24,5	28,5	31,7	32,7	33,6	33,5	33,8	33,0	30,9	27,0	24,0
CHEPUWA	3,6	5,8	9,4	12,4	13,7	15,0	15,2	15,3	14,4	12,1	8,2	5,3

Figure 5.9: Comparison of mean monthly temperature (1999-2000) of some of the stations

5.2.4 Evaporation

There are very few evaporation stations in Nepal. Three evaporation stations are found in the Saptakoshi basin and 10 years data are collected from these stations for model simulation. The evaporation stations are shown in Figure 5.10 and Table 5.4 below.

Table 5.4: Detail description of evaporation stations in the Saptakoshi basin

STNR	Point ID	Station name	Longitude	Latitude	Elevation (m)
1103	1	JIRI	86.23	27.63	2003
1304	2	PAKHRIBAS	87.28	27.05	1680
1320	3	TARAHARA	87.27	26.70	200

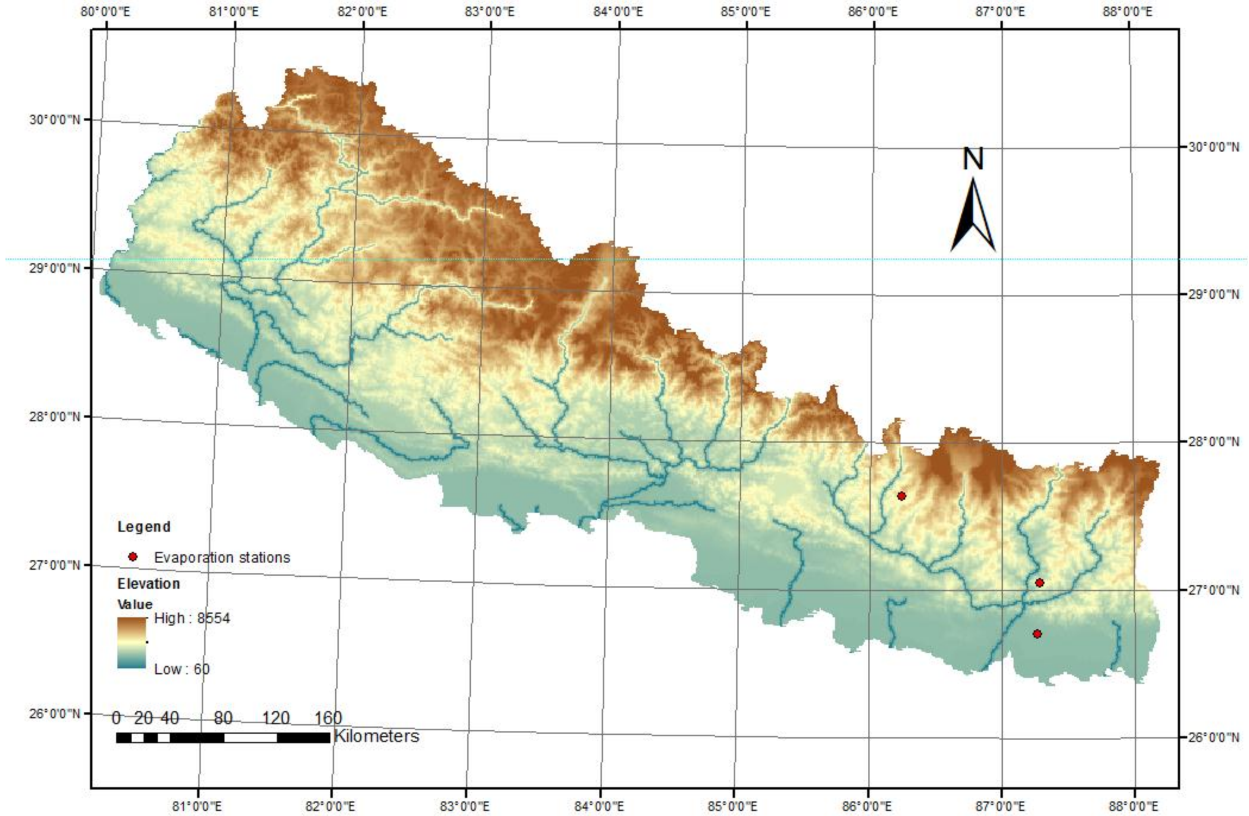


Figure 5.10: Evaporation stations in the Saptakoshi basin

5.2.4.1 Missing data Interpolation

The specific method of finding missing values of evaporation data is not available. But there are large numbers of empirical formulae available for estimation of potential evapotranspiration (PET) such as Blaney-Criddle formula, Thornthwaite formula and some are theoretical concepts like Penman's equation. The missing values are filled by using Thornthwaite formula because here only mean air temperature data are available; other data like relative humidity, wind speed are not available for application of Penman's equation. This formula is greatly influenced by air temperature only. This formula was developed from data of eastern USA and uses only the mean monthly temperature together with an adjustment for day-lenghts [25]. The PET is given by this formula as

$$PE_m = 16N_m\left(\frac{10\bar{T}_m}{I}\right)^a \quad \text{(mm)}$$

where m is the months 1, 2, 3…12, PEm is monthly PET in mm, Nm is the monthly adjustment factor related to hours of daylight, Tm is the monthly mean temperature (C), I is the heat index or the year, given by:

$$I = \sum i_m = \sum\left(\frac{\bar{T}_m}{5}\right)^{1.5} \quad \text{for m = 1, 2…12}$$

And: a = 6.7*10-7*I3 - 7.7*10-5*I2 + 1.8*10-2*I + 0.49

The estimated monthly evaporation values are equally divided for each day and filled for respective day of the year.

5.3 HYDROLOGICAL DATA

5.3.1 Runoff

The recorded daily discharges in the rivers at different gauge stations are also collected from DHM, Nepal. There are altogether 16 gauge stations in the Koshi basins. The daily data from 1999 to 2003 are used for model calibrations and rest 5 years data are applied for the model validations. The details of these gauge stations are tabulated in Table 2.1 and sub catchments are shown in Figure 2.3.

5.3.1.1 Missing data Interpolation

The missing data break the continuity of the data series. Unfortunately, records of hydrological processes are usually short and often have missing observations. The existence of data gaps might be attributed to a number of factors such as interruption of measurements because of equipment failure, effects of extreme natural phenomena such as hurricanes or landslides or of human-induced factors such as wars and civil unrest, mishandling of observed records by field personnel, or accidental loss of data files in the computer system.

Researchers have been tackling the problem of missing data in different ways and from different perspectives as well. There are different methods of filling missing data for examples Regression analysis, Time series analysis, Interpolation approach etc. Here, no any specific method is used for filling missing data and filled by simply scaling of the neighboring gauge stations.

5.3.1.2 Data Quality Check

The most challenging task is to get the good quality data of the runoff. There will be the great probability of missing data during flooding time. The 1000 years or more than return period flood data is also not reliable for simulation because it will attempt to estimate high discharge.

The quality of runoff data is simply checked by calculating runoff of local catchment at downstream gauge station. The local catchment is the separate area of the whole catchment between two gauge stations. The runoff of local catchment at downstream gauge should be positive value. If there are some errors in data collections or some large canals or diversion works across the upstream of the river then this value will be negative i.e. the runoff will lesser in downstream than in upstream site.

There are nine independent catchments in the Saptakoshi basins and they are Majhitar, Uwa Gaon, Pipletar, Tumlingtar, Rabuwa Bazar, Rasnalu Village, Busti, Jalbire and Helambu. For these stations, above method of data quality check could not be able to apply. In the remaining stations, the total catchment runoff and local catchment runoff are shown in below. The runoff of local catchment at the stations Simle, Hampuachuwar and Chatara-Kothu are almost all negative values during monsoon period. These may be due to error in data collections or maybe there are some diversion works in these rivers. So there is high degree of uncertainty in data of these stations. These negative runoff values are filled by scaling with neighboring gauge stations.

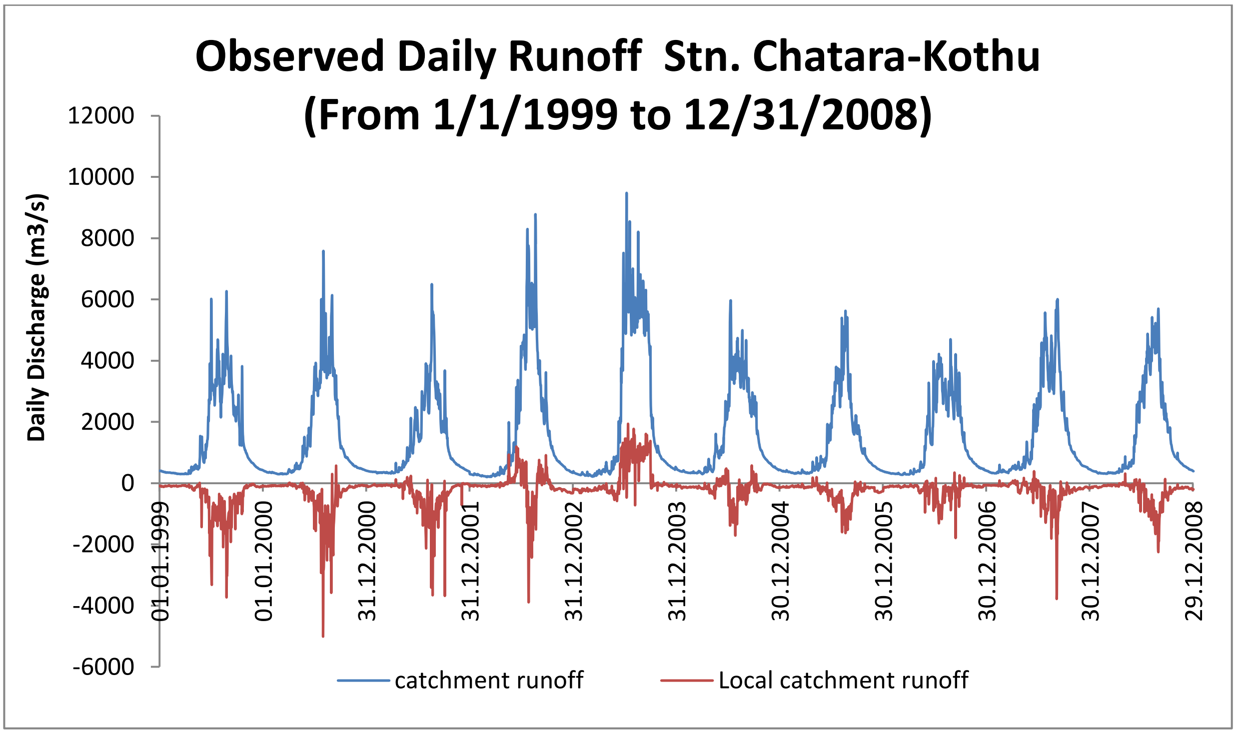


Figure 5.11: Observed daily total catchment runoff and local runoff at Chatara-Kothu

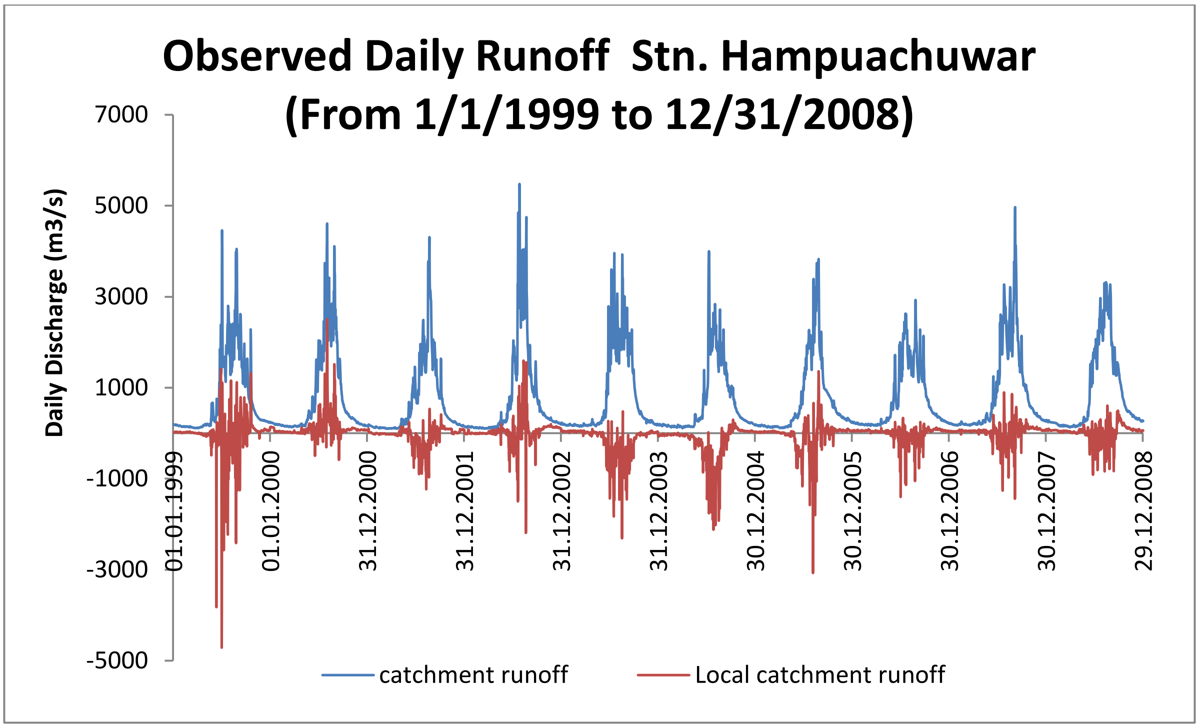


Figure 5.12: Observed daily total catchment runoff and local runoff at Hampuachuwar

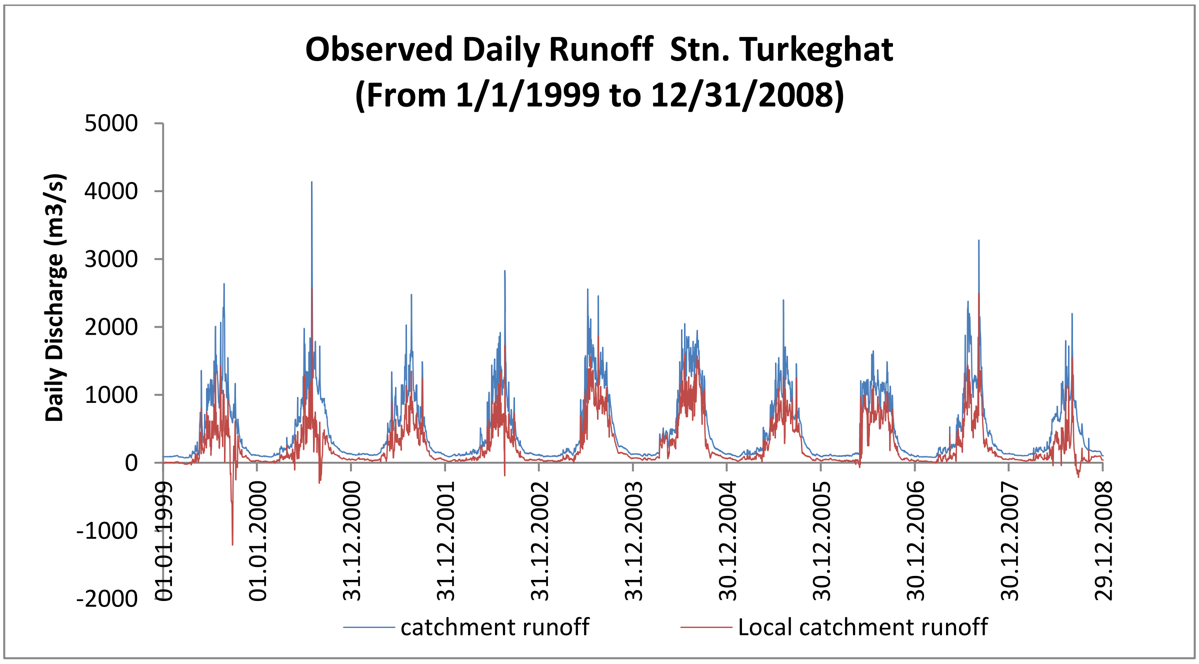


Figure 5.13:Observed daily total catchment runoff and local runoff at Turkeghat

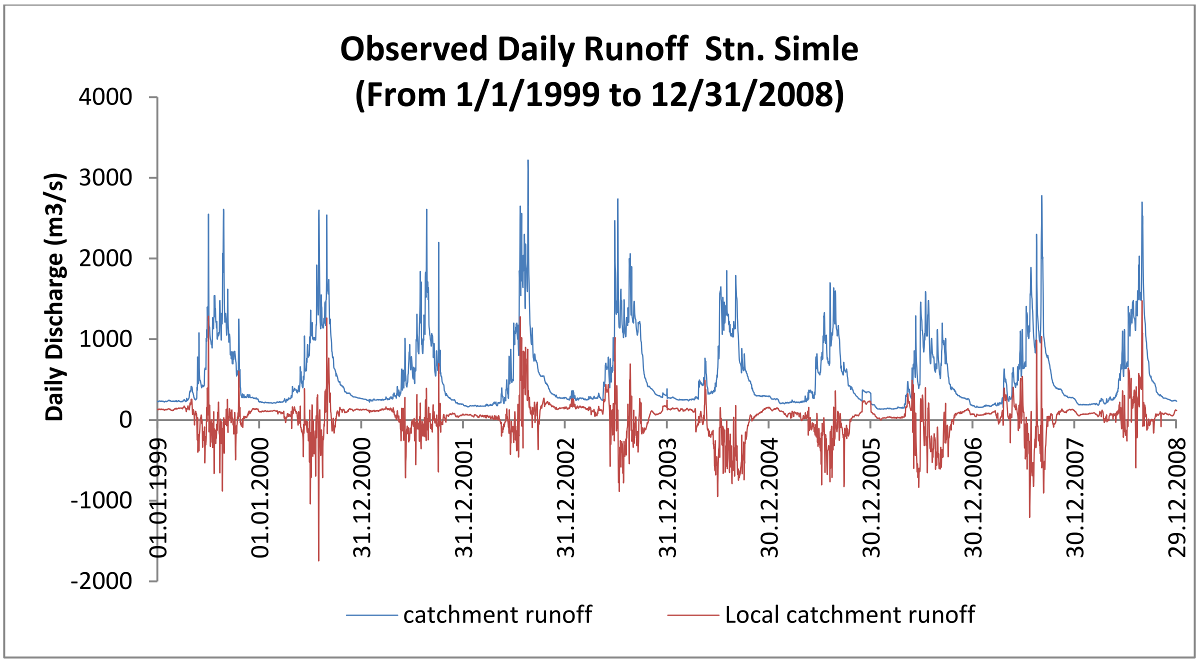


Figure 5.14: Observed daily total catchment runoff and local runoff at Simle

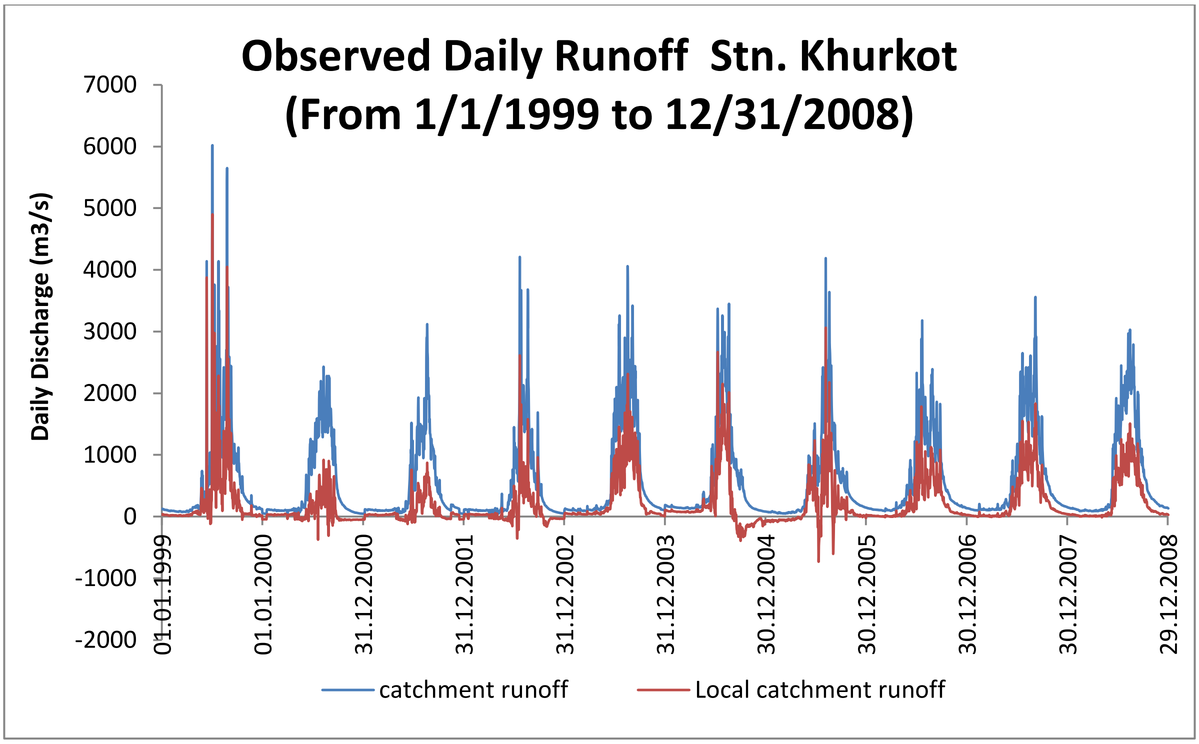


Figure 5.15: Observed daily total catchment runoff and local runoff at Khurkot

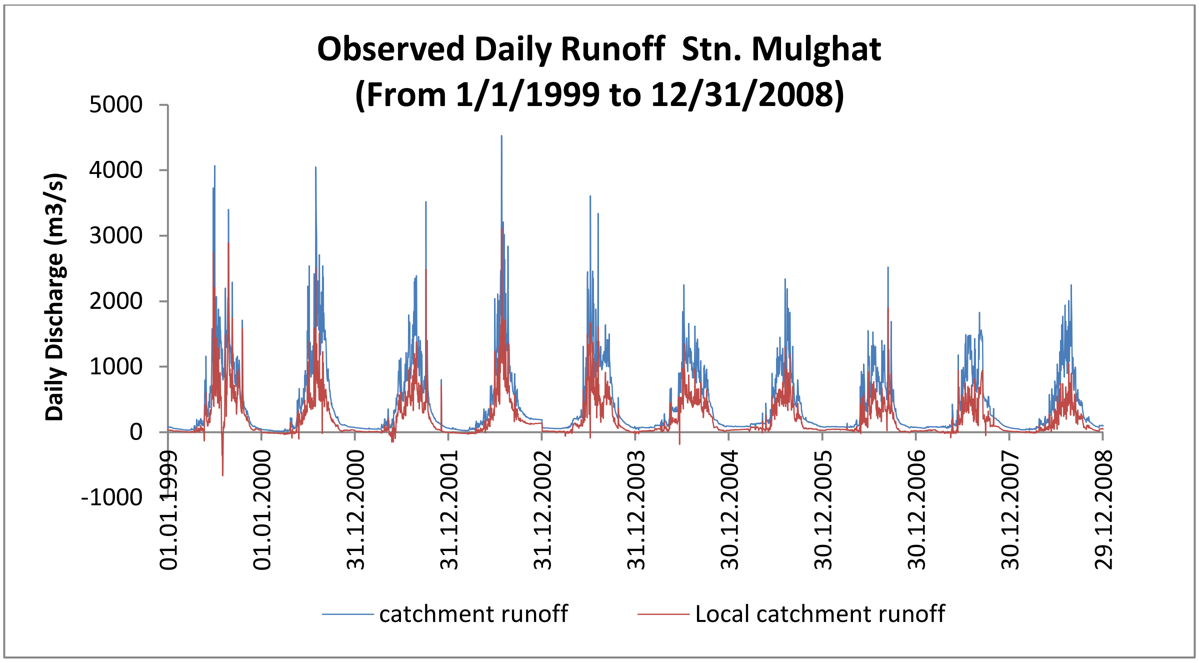


Figure 5.16: Observed daily total catchment runoff and local runoff at Mulghat

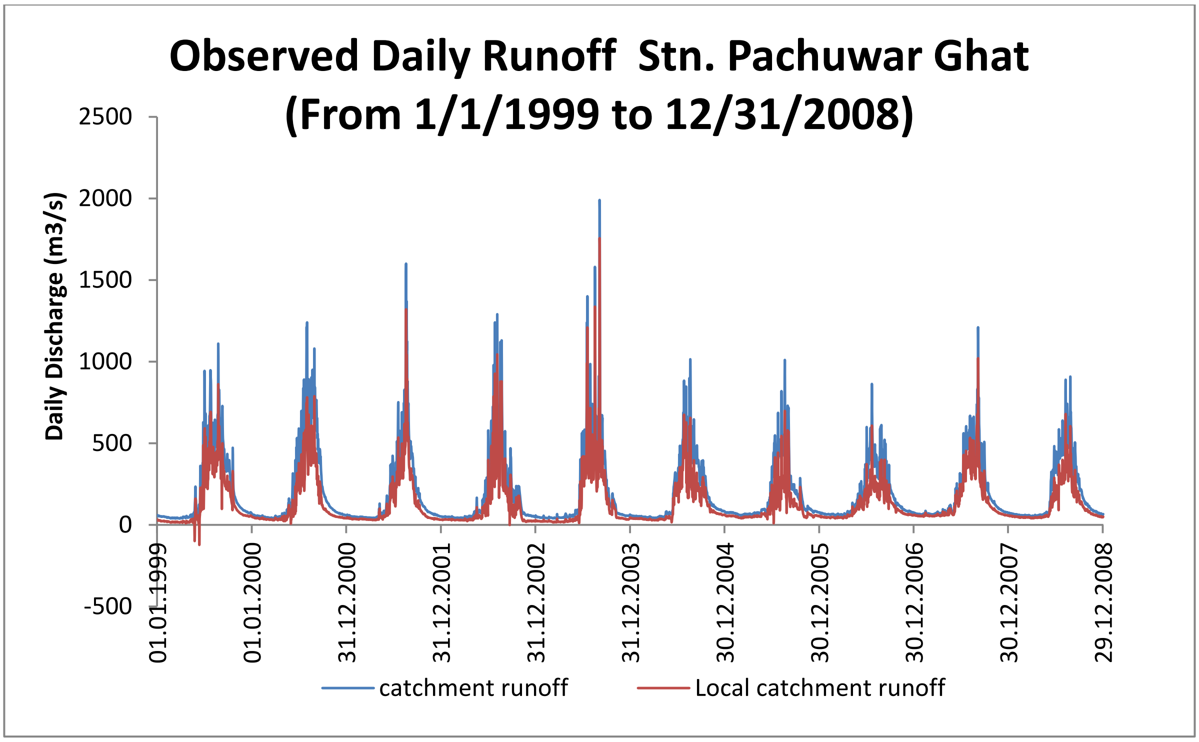


Figure 5.17: Observed daily total catchment runoff and local runoff at Pachuwar Ghat

5.4 SUMMARY OF HYDRO-METEOROLOGICAL DATA

The summary of hydro-meteorological data is described by following table:

Table 5.5: The summary of hydro-meteorological data

Data Type	No. of stations			Time series
	Data collected	Data interpolated	Total stations	
Precipitation	67	-	67	1999-2008
Temperature	18	49	67	1999-2008
Evaporation	3	-	3	1999-2008
Runoff	16	-	16	1999-2008

5.5 GIS DATA

The main applications of GIS in the hydrological models are delineating watersheds and streams, and defining slope, aspect, area, flow direction and flow length of catchment. The GIS data used for this study are mainly shape file of point networks (precipitation, temperature, evaporation and runoff), catchment area, DEM of catchment and land use of the study area. The shape files of Nepal and rivers of Nepal and Asia are collected from the DHM.

5.5.1 Point Networks

The locations of the meteorological and hydrological stations are the main input data which give the information of x, y and z coordinates. The shape files of all the stations in Nepal are available in DHM but these files are not really useful for this study. Hence, the shape files of essential hydro-meteorological stations are prepared from GIS tools. The collected information of stations, longitude, latitude and elevation were shorted in Excel and these points are added to GIS system. Nepal lies in the projected coordinate system in WGS 84 / UTM zone 44N and UTM zone 45N. WGS 84 / UTM zone 45N is a projected CRS last revised on 06/02/1995 and is suitable for use in Between 84°E and 90°E, northern hemisphere between equator and 84°N, onshore and offshore [10]. The Saptakoshi basin lies within the longitude 85°E to 87°E so that the points are projected in WGS 84 / UTM zone 45N coordinate system which are shown in Figure 2.1 below.

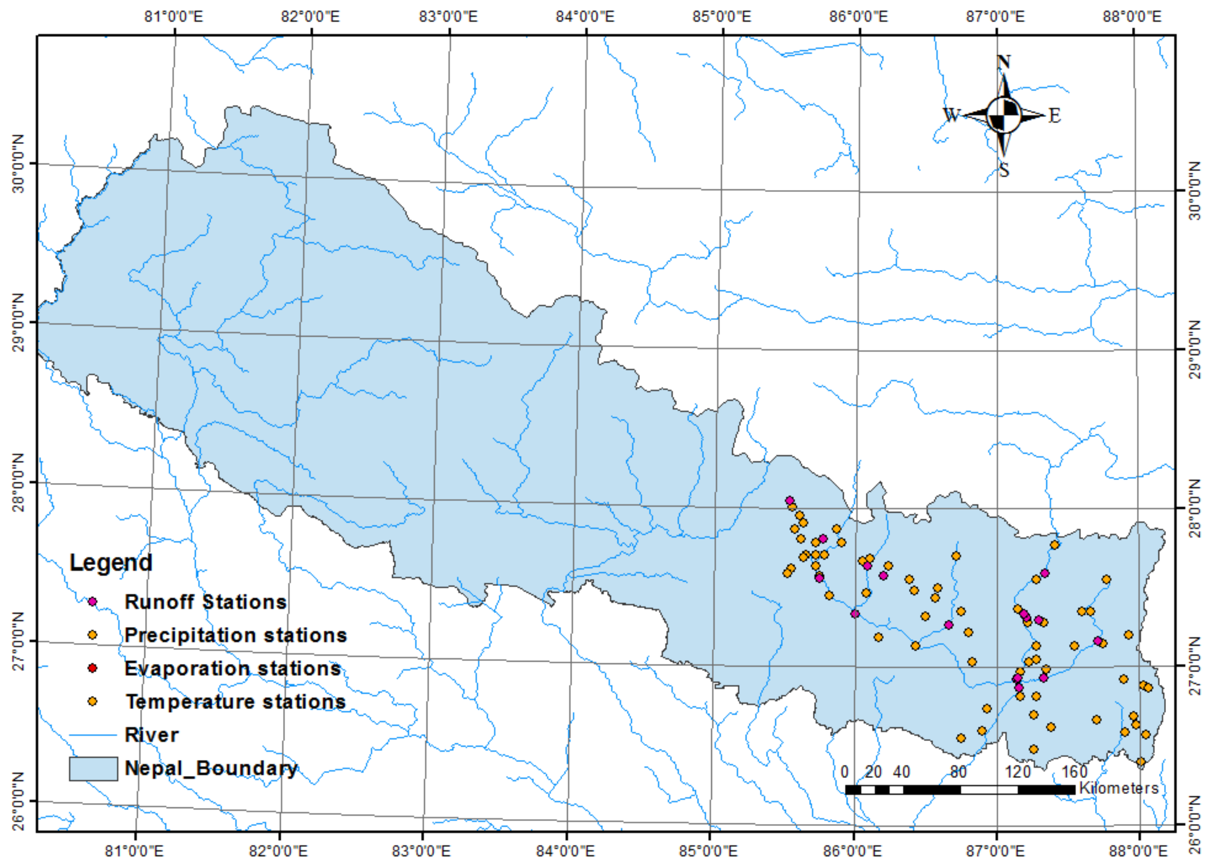


Figure 5.18: Projected map of Nepal with runoff and Hydro-meteorological stations

5.5.2 Watershed Delineation

The watershed is the region draining into a river, river system, or body of water. Watersheds are always physically delineated by the area upstream from a given outlet point. This generally means that for a stream network, the contributing area upstream to a ridge line. Ridgelines separate watersheds from each other. As traditionally, it was done by manually using topographic maps. But application of GIS Arc-hydro tools and Digital Elevation Model (DEM) simplified the creation of catchment area.

5.5.2.1 Digital Elevation Model (DEM)

A digital elevation model (DEM) is the main dataset required for watersheds delineation. The DEM is a digital model or 3-D representation of a terrain's surface created from terrain elevation data [23]. The DEM datasets of 1 degree × 1 degree resolution are downloaded from http://www.gdem.aster.ersdac.or.jp/search.jsp in the form of tile files of Nepal region. These tiles are merged by using Data management tool- Raster-Raster dataset-Mosaic to new raster of ArcGIS tools.

5.5.2.2 Procedure in delineating watersheds

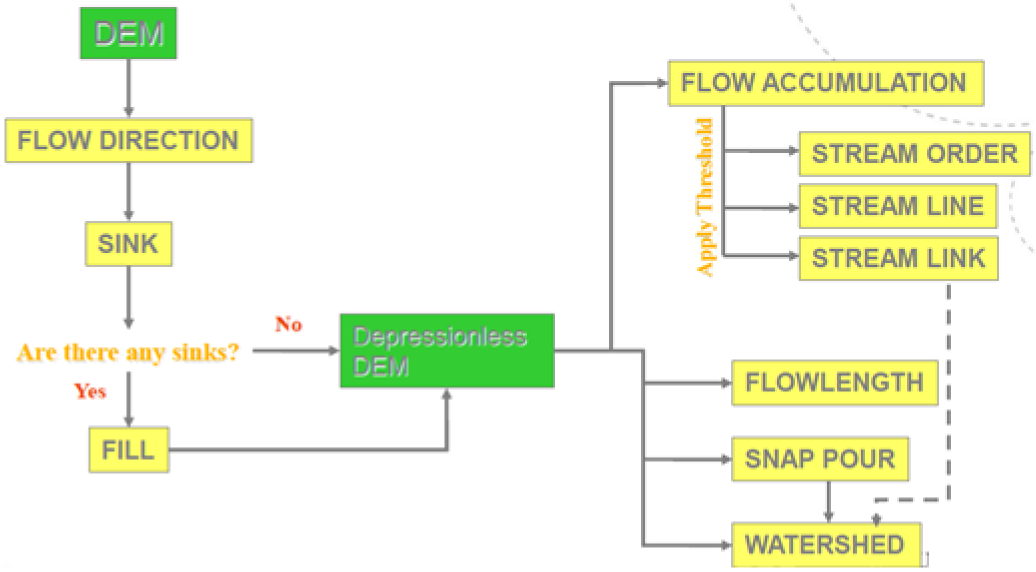


Figure 5.19: Procedure in delineating watersheds [26]

- DEM Reconditioning:

The reconditioning system adjusts the surface elevation of the DEM to be consistent with vector coverage. The vector coverage can be a stream or ridge line coverage. This function modifies a DEM by imposing linear features onto it (burning/fencing). This process can be carried out by Arc-Hydro Tools; the Arc-Hydro Tools is installed separately into the ArcGIS 10. The function needs as input a raw DEM and a linear feature class (e.g. river to burn in) that both have to be present in the map document. The reconditioned DEM is shown in Figure 5.20. The steps are as follows:

• Select **Terrain Preprocessing | DEM Manipulation | DEM Reconditioning.**

• Select the appropriate input DEM and linear feature (streams to burn in). The output is a reconditioned Agree DEM (default name AgreeDEM).

• Enter a Stream buffer: this is the number of cells around the linear feature for which the smoothing will occur.

• Enter the Smooth drop/raise value: this is the amount (in vertical units) that the linear feature will be dropped (if the number is positive) or the fence extruded (if the number is negative). This value will be used to interpolate the DEM into the buffered area (between the boundary of the buffer and the dropped /raised vector feature).

• Enter the Sharp drop/raise value: this is the additional amount (in vertical units) that the linear feature will be dropped (if the number is positive) or the fence extruded (if the number is negative). This results in additional burning/fencing on top of the smooth buffer interpolation and needs to be performed to preserve the linear features used for burning/fencing.

• Click OK. Upon successful completion of the process, the “AgreeDEM” layer is added to the map [27].

These steps are repeated by hit and trial until the desired DEM is not generated.

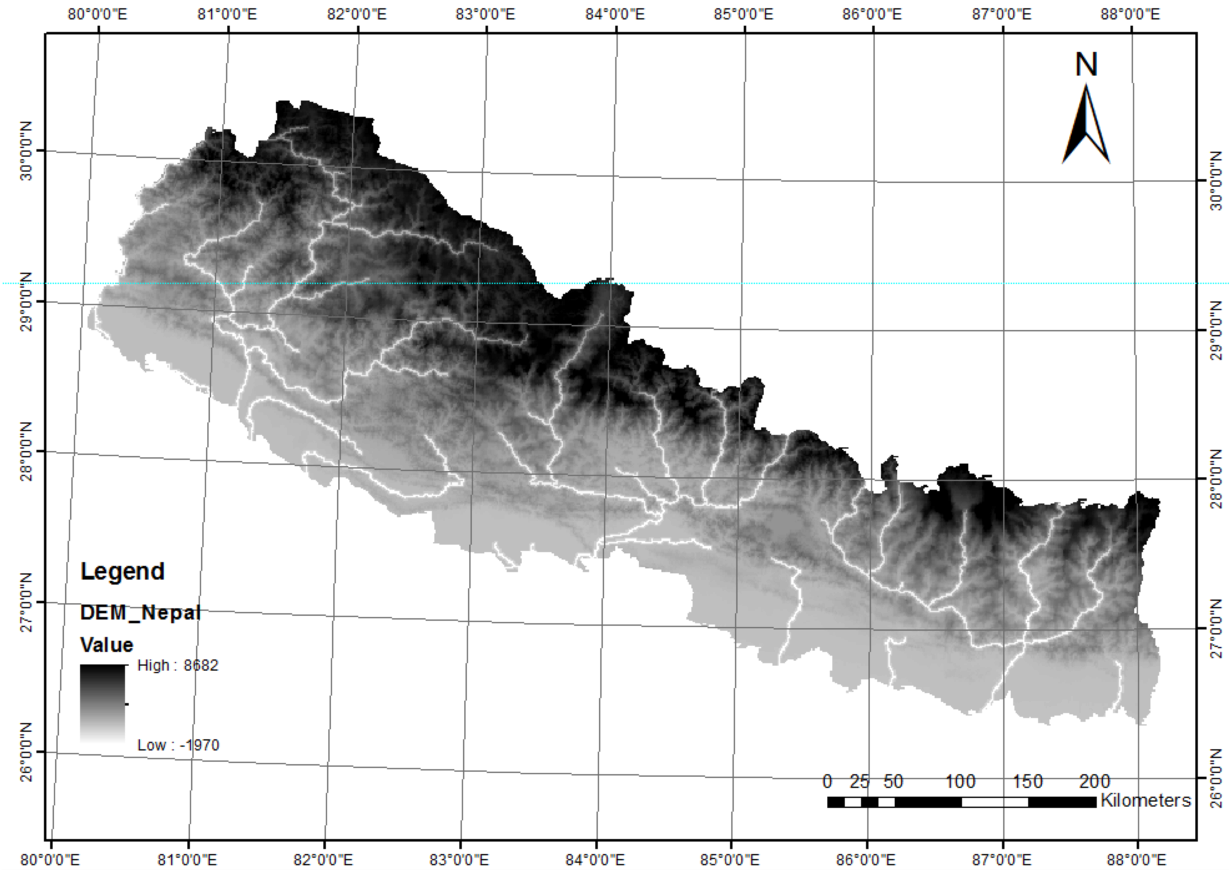


Figure 5.20: Clipped DEM of Nepal

- Fill Sinks

This function fills the sinks in a grid. If a cell is surrounded by higher elevation cells, the water is trapped in that cell and cannot flow. The Fill Sinks function modifies the elevation value to eliminate these problems.

• Select **Terrain Preprocessing | DEM Reconditioning | Fill Sinks.**

- Flow Direction

This function computes the flow direction for a given grid. The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell. The function Flow Direction with Sinks may be used instead to process a DEM with known sinks.

• Select **Terrain Preprocessing | Flow Direction.**

- Flow Accumulation

This function computes the flow accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid.

• Select **Terrain Preprocessing | Flow Accumulation.**

- Snap Pour Point

This function snaps pour points to the cell of highest flow accumulation within a specified distance.

• Select **Arc Toolbox | Spatial Analyst Tools | Hydrology |Snap Pour Point.**

- Watershed

This function determines the contributing area above a set of cells in a raster.

• Select **Arc Toolbox | Spatial Analyst Tools | Hydrology |Watershed.**

If there is only one pour point then there will be one single catchment. But in case of here, 16 pour points are available so there are 16 sub catchments in the Saptakoshi basin.

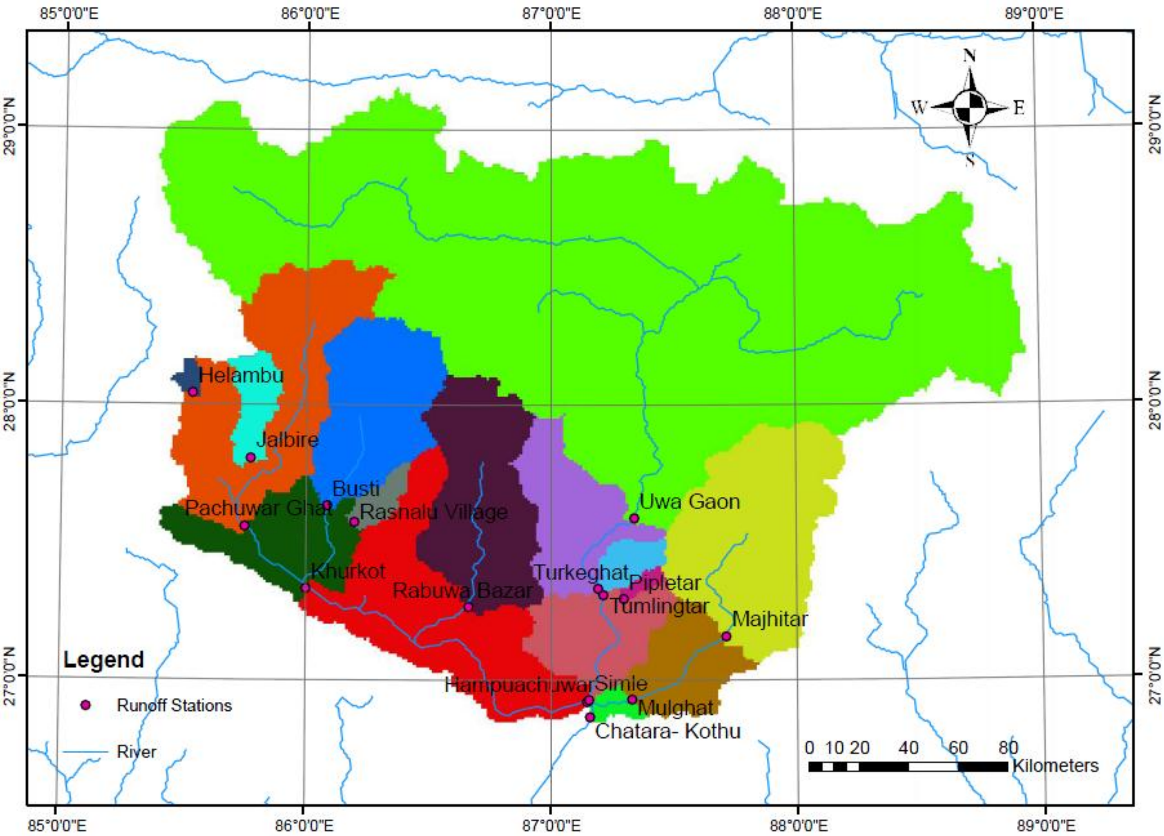


Figure 5.21:Sub-catchments of the Saptakoshi basin

- Extract by Mask

This function extracts the cells of a raster that correspond to the areas defined by a mask.

• Select **Arc Toolbox | Spatial Analyst Tools | Extraction| Extract by Mask.**

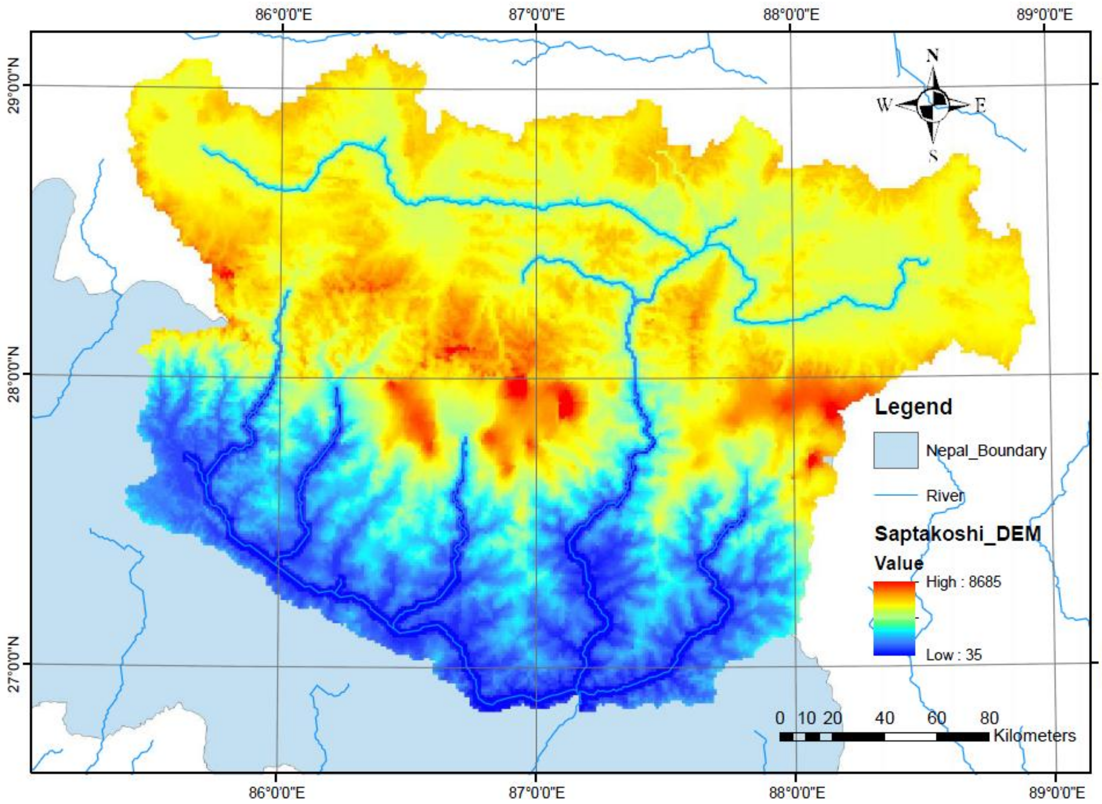


Figure 5.22: Digital Elevation Model of the Saptakoshi basin

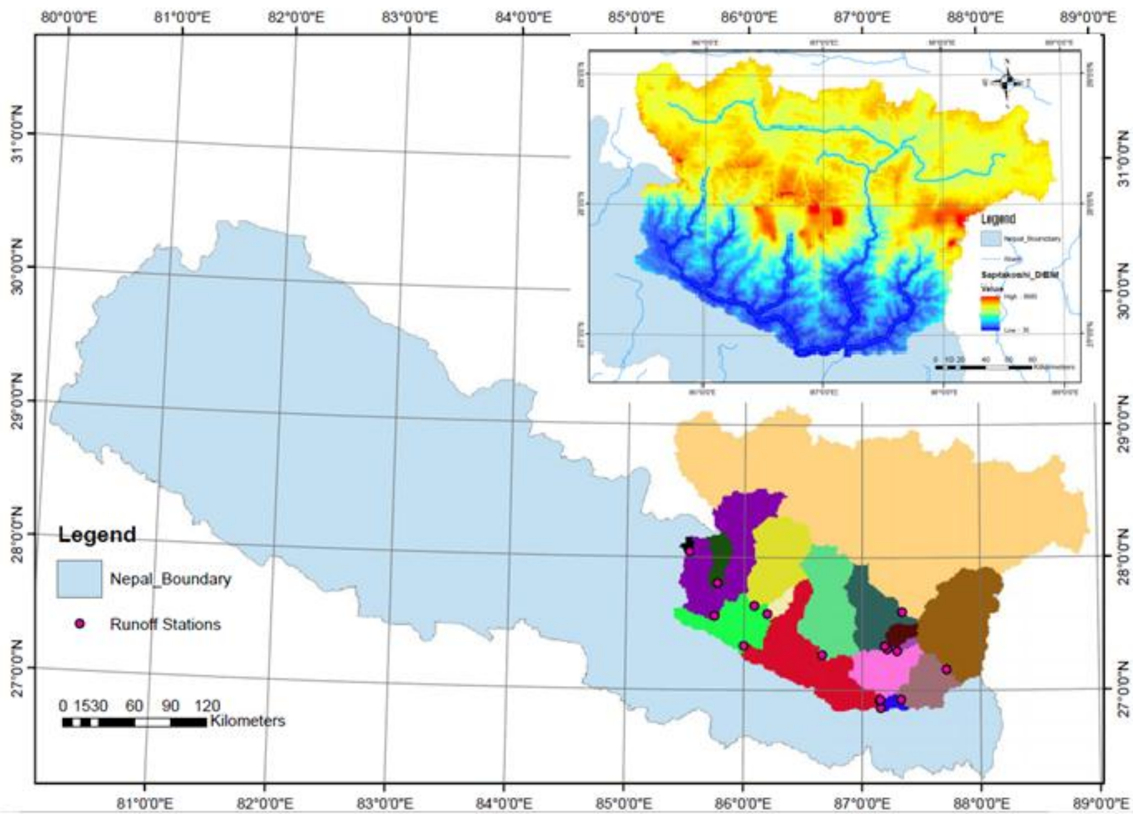


Figure 5.23: The Saptakoshi basin and its DEM

5.5.3 Land use

The simplified dataset of land use is entered into the ENKI model system. This can be achieved by reclassifying extracted catchment DEM. The reclass value of 2 is used for land and 0 for no data. The steps in ArcGIS are described below and the input raster for this process is extracted catchment.

Reclassify

This function reclassifies (or changes) the values in a raster.

• Select **Arc Toolbox | Spatial Analyst Tools | Reclass | Reclassify.**

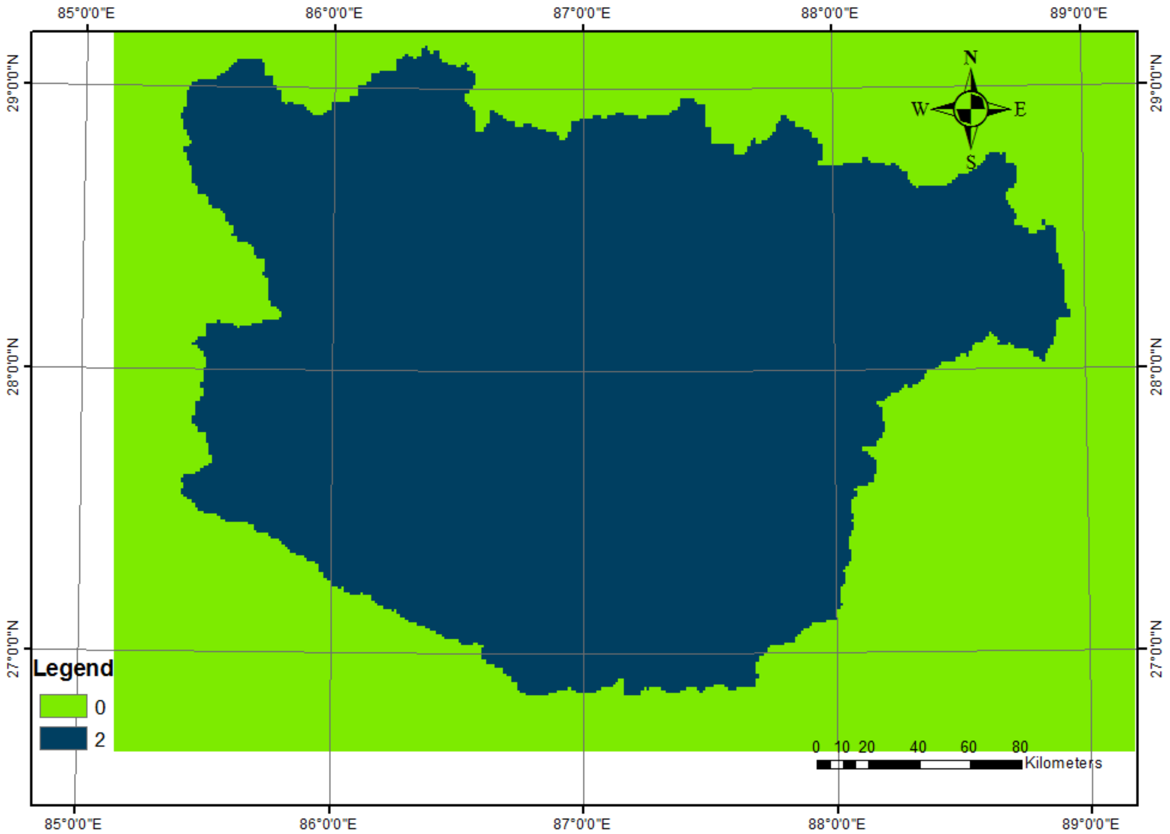


Figure 5.24: Land use map of the Saptakoshi basin for ENKI system

5.6 INPUT DATA FORMAT FOR ENKI MODEL SYSTEM

As every hydrological model has its own input data formats and system, so the ENKI model has also its own unique input data formats. The errors in input data formats will produce more problems while doing setup model and region of the ENKI model system. The model will crash if there is a tiny error in the input data. So the input data formats are explained detail in below.

5.6.1 Hydro-meteorological Input Data

The hydro-meteorological data (precipitation, temperature, evaporation and runoff) were arranged in chronological order in Microsoft Office -Excel 2007. These data files are saved as in Tab-delimited text files as shown in table below:

Owner	DHM	DHM	DHM
STNR	1006	1008	1009
Point ID	1	2	3
HOH	2000	1592	1660
Name	GUMTHANG	NAWALPUR	CHAUTARA
Missing	-99	-99	-99
Refsystem	utm-45n	utm-45n	utm-45n
xcoord	388427	363730	373562
ycoord	3082949	3075815	3073862
Network	Temperature	Temperature	Temperature
1/1/1999	6.6664	8.4184	8.0809
1/2/1999	6.7488	8.5587	8.1987
1/3/1999	7.3835	9.0692	8.6861
…………………………………………………….			
…………………………………………………….			
…………………………………………………….			
12/29/2008	5.3688	5.8575	5.5455
12/30/2008	5.5937	6.6835	6.3008
12/31/2008	5.3866	6.2392	5.8814

Any missing columns or wrong alphabets will make conflicts while creating the model and region in ENKI system.

Note: The ENKI system calculates the local catchment runoff so that the observed runoff also entered in the form of local catchment.

5.6.2 GIS Data

5.6.2.1 Point Networks

The shape files of point networks of stations (precipitation, temperature, evaporation and runoff), prepared in Arc Map, are converted into ENKI readable file format by Idrisi Taiga. The procedure as follows:

• Open **Idrisi Taiga | Help | ESRI Quick Start | SHAPEIDER (Import Export shape files)**

Note: Reference system is utm-45n, Reference Unit is meters and Unit Distance is taken as 1.

5.6.2.2 Catchment and Sub-catchment Area

The raster files of local sub-catchment area delineated by Arc Map and elevation distribution of the Saptakoshi basin extracted by mask from Filled DEM are first converted into ASCII files. The steps for converting Raster files to ASCII files in arc Map are as follows:

• Select **Arc Toolbox | Conversion Tools | From Raster| Raster to ASCII.**

These ASCII files are finally converted by Idrisi Taiga into ENKI readable file formats as explained below:

• Open **Idrisi Taiga | Help | ESRI Quick Start | ARCRASTER (Import Export grid files)**

5.6.2.3 Land use

Similarly, the land use ASCII raster file is converted into an Idrisi file as catchment files.

Summary of input file formats into ENKI systemTable 5.6 shows the summary of input files to the ENKI System

Table 5.6: The summary of input files to the ENKI system

S.N.	Data Type	Processing File	Input to ENKI System	
			File Format	File Extension
1	Hydro-meteorological data	MS Office-Excel	Text (Tab-delimited)	.txt
2	Point Networks	Arc Map 10 (Shape files)	Idrisi Files	.adc, .mdb, .vct, .vdc, .vlx
3	Catchment Area	Arc Map 10 (Raster files)	Idrisi Files	.RDC, .rst
4	Elevation Distribution of catchment	Arc Map 10 (Raster files)	Idrisi Files	.RDC, .rst
5	Landuse	Arc Map 10 (Raster files)	Idrisi Files	.RDC, .rst

6 METHODOLOGY AND PROCEDURE IN ENKI

"To err is human, but to really foul things up requires a computer."

-Paul Ehrlich

6.1 ENKI MODEL SETUP

6.1.1 Introduction

The DEMLab creates a framework to implement the hydrological models, like HBV model, in temporal and special variation. The framework contains the administrative and user interfaces. The model and the region can be created in this framework and linked to each other. The model is a process simulator and the region contains all the process data in IDRISI format. All the data are stored in this location- C:\ENKI_ntnu\Data\SentralReg. This linked model is initialized and parameters are set. The model can be run for simulation with these manually set parameters or by auto calibration. The simulated results can be stored in NetCDF files in DEMLab. The detail process and methodology is explained in step by step below.

6.1.2 New Region Creation

The region, a collection of GIS data, is created first. The "Create new region" tab is opened when following steps processed:

- **Menu | Region | New Region**

The Name of region is given such as Koshi_reg and coordinate system is selected as utm-45n. The Default raster geometry is copied such as elevation distribution of catchment and default network geometry as Precipitation network. The GIS variables are filled later when model has built. It is tedious to fill all the variables in this stage but easier from Link Model-Region because all variables are listed in model tab.

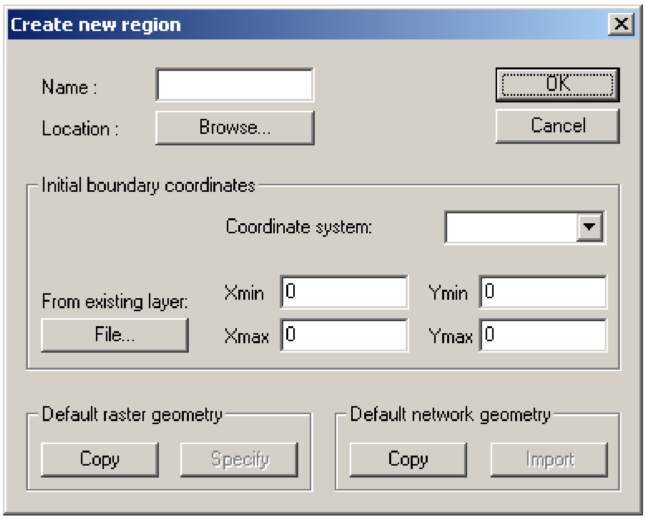


Figure 6.1: Creating a new region

6.1.3 Creating the input database

Input database are time series of climatic variables like precipitation, temperature, evaporation and runoff. These time series are associated with the network or grid in the region. This association is made during the input of time series data from the file. Either one can create a new input database in the main menu or modify the existing selecting 'Input Database' in the regional dialogue. The following steps create the location where input database file is saved in NetCDF (.nc) format.

- **Menu | Input | New database**

When clicking 'Input Database' in the regional dialogue, the 'Time series database' dialog opened as shown in Figure 6.2.

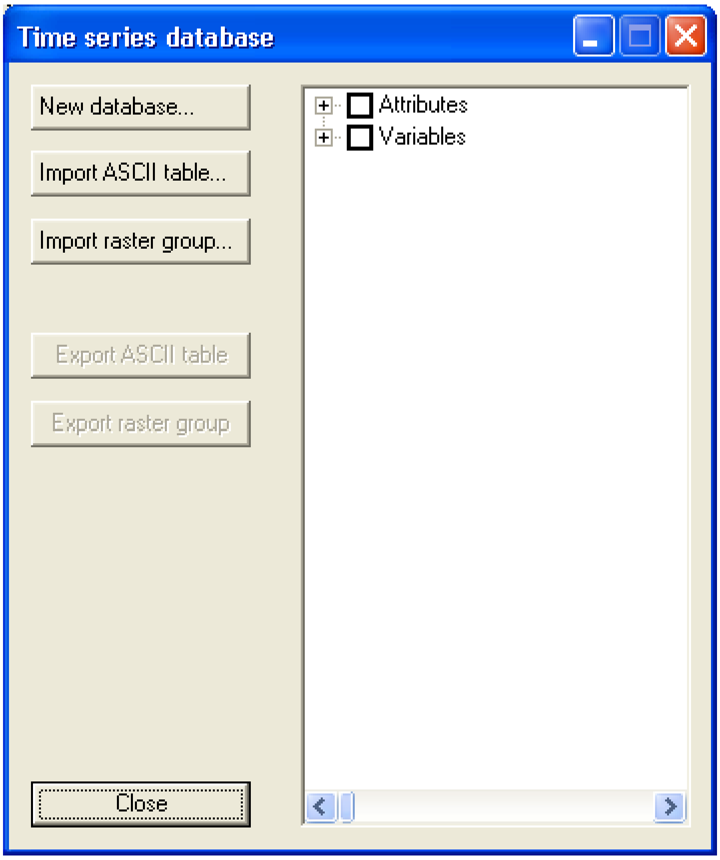


Figure 6.2: Importing time series database into input database

Then ASCII files are imported from 'Import ASCII table' tab. After importing the database, it automatically generates _elev, _stddev and_reldev variables in the Region dialog. These stddev and reldev use setfiles command to assign network name and these files can be deleted. Also write data commands is used to create .avl files for _elev (which gives the elevation information of the meta-stations).

6.1.4 Building New Model

The model is the sequential order of subroutines and subroutines are chosen as per hydrological models. The steps for building a new model are:

- **Menu | Model | New | Add subroutines**

The available subroutines can be browsed in the DLL files (from C:\ENKI_ntnu\DEMLab\bin) and added in sequential order as per requirement. The same method can be repeated by giving different name. The model is saved and routines are valid but not connected massage will be displayed simultaneously. Then, the following dialog box appeared and each tab represents the subroutines as shown in Figure 6.3.

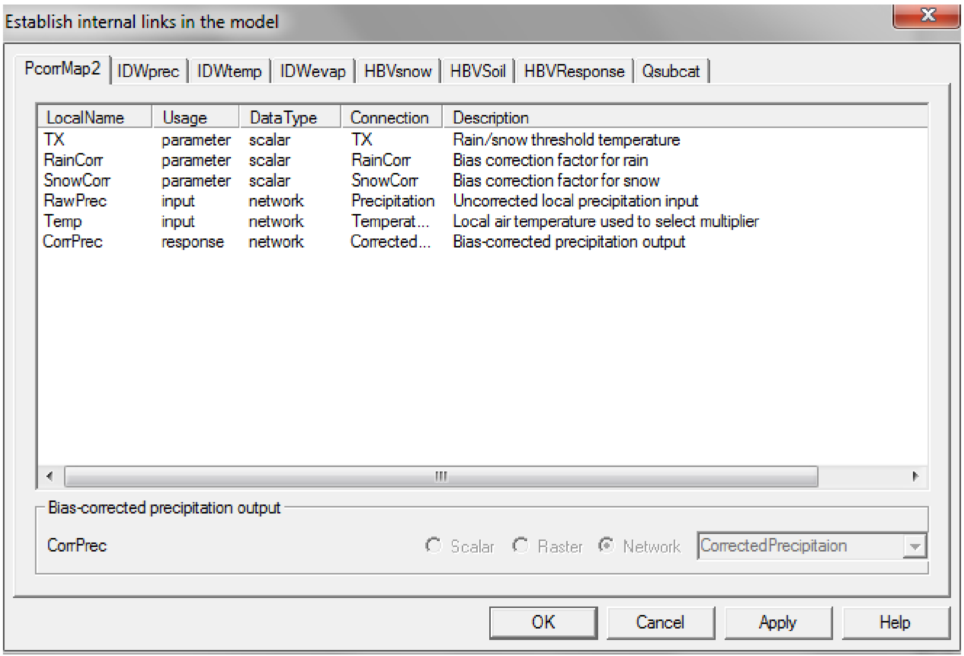


Figure 6.3: Establishing internal links in the model

This dialog box can also be opened by following step:

- **Menu | Model | Build model**

All variables will be listed with their local name under the heading "Local Name", as given in the DLL code. All the variables in each subroutine are defined connection name that may be same as local name or may not be and data types (scalar, raster or network) are selected. One can feel free to copy the original name, but one must observe the following:

- Variable names are not case-sensitive.
- One must have a defined region to get connected model. For each variable can either choose from the region's data set (after selecting the type), or create a new dataset then included in the region.

- Variable that will be output from the routine and input to another must be given the same name in the two procedures.
- Variable not to be confused must be different name, especially for generic routines should name as the input, Target Values etc are avoided.
- From time to choose whether the two methods using the same parameter. For example, different desired maximum interpolation distances for temperature and precipitation, or for convenience, use the same. Again, only the naming that determines this.

If the variables name and data type are incompletely filled then following dialog box appeared.

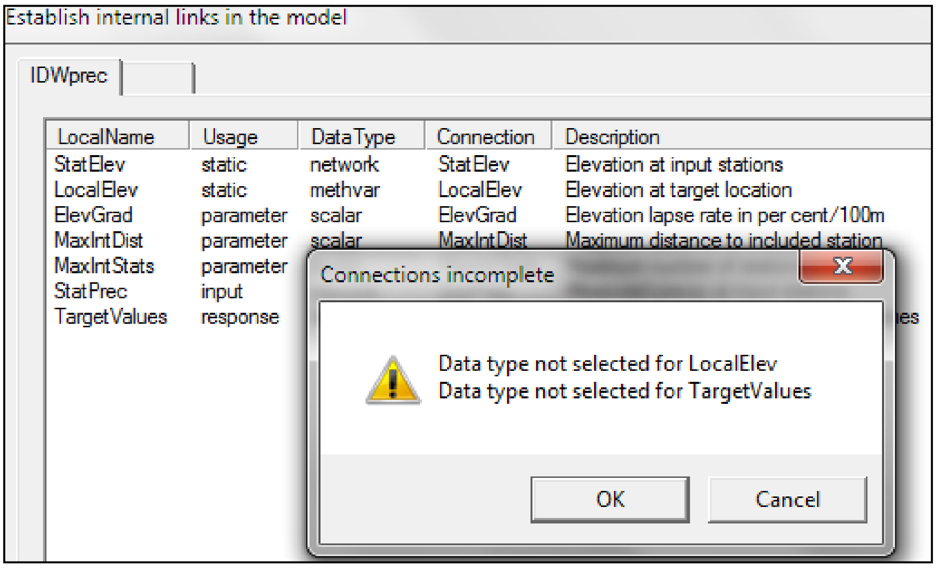


Figure 6.4: Error message screen

6.1.5 Link Model-Region

The linking of the model and the region is the process of associating the variables in the model with the variables in the region. The procedure as follows:

- **Menu | Model | Link Model-Region**

After this step, all the variables which are in the model can be filled in the region by clicking "Create New". Hence all the variables in the model linked with regional variables creating new. On the same time, there is opportunity to correct the error if there are different names of the same variable. The successful completion of link model-region opened the RunModel dialog as given Figure 6.5.

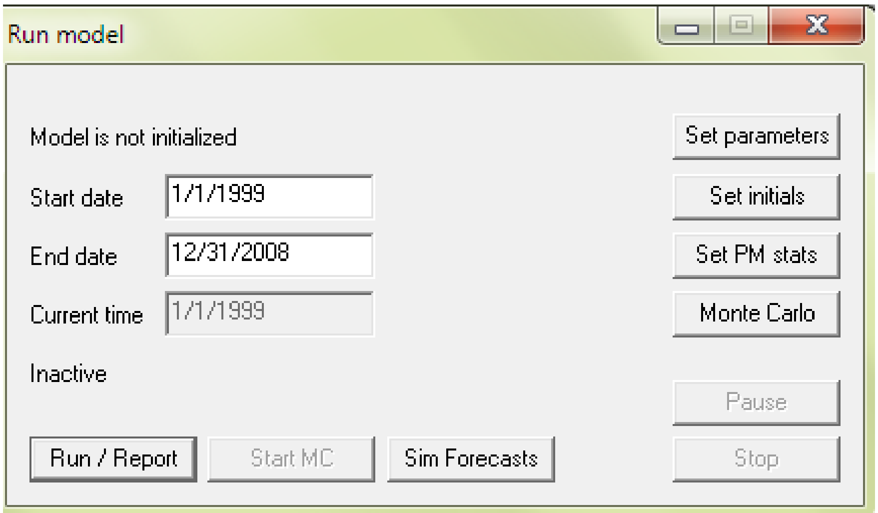


Figure 6.5: Run model dialog

6.1.6 Run Model

The RunModel dialog is the main dialog to run the model, from which parameters are set, initial conditions are set and MC setup is selected, simulation period is fixed and model is started and stopped.

6.1.6.1 Set parameters

The distributed parameters are set from browsing C:\ENKI_ntnu\Data\SentralReg, .avl file for network and .rst for raster. The scalar parameters are set as per value requirements.

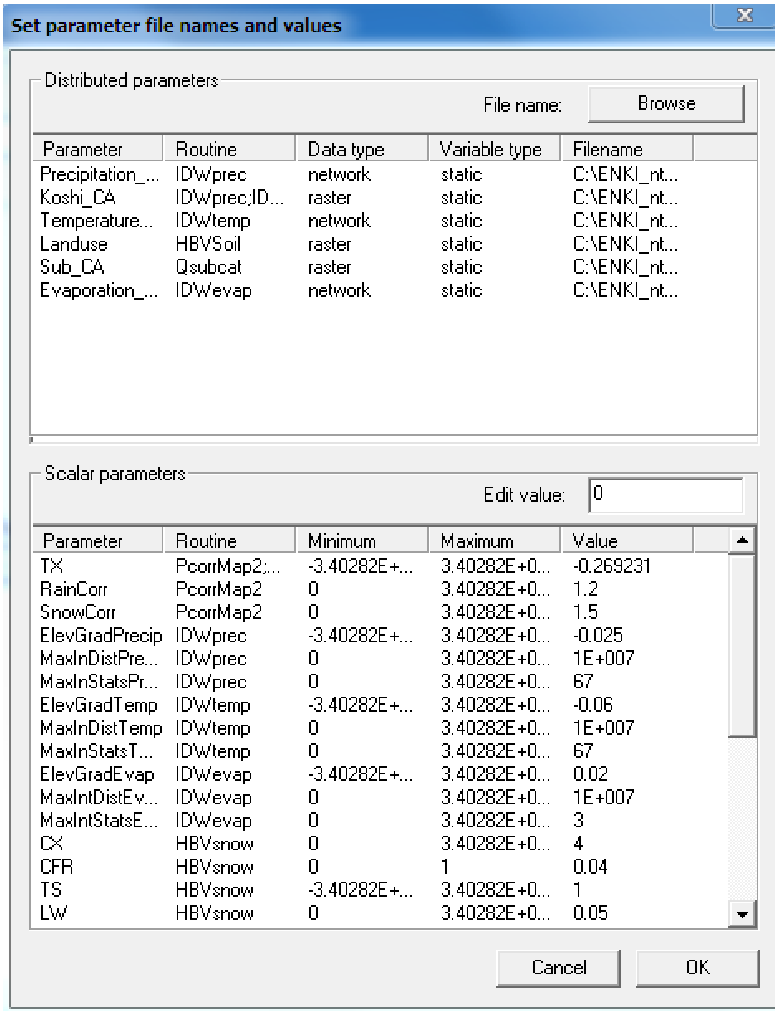


Figure 6.6: Parameters setting dialog box

6.1.6.2 Set initials

The state is initialized with specific start date/time. For any scalar state variables must be a numeric value, whereas for a distributed variable should be selected a file name. These files must exist and contain the values which required to be started with, whether results from a previous run or blind values.

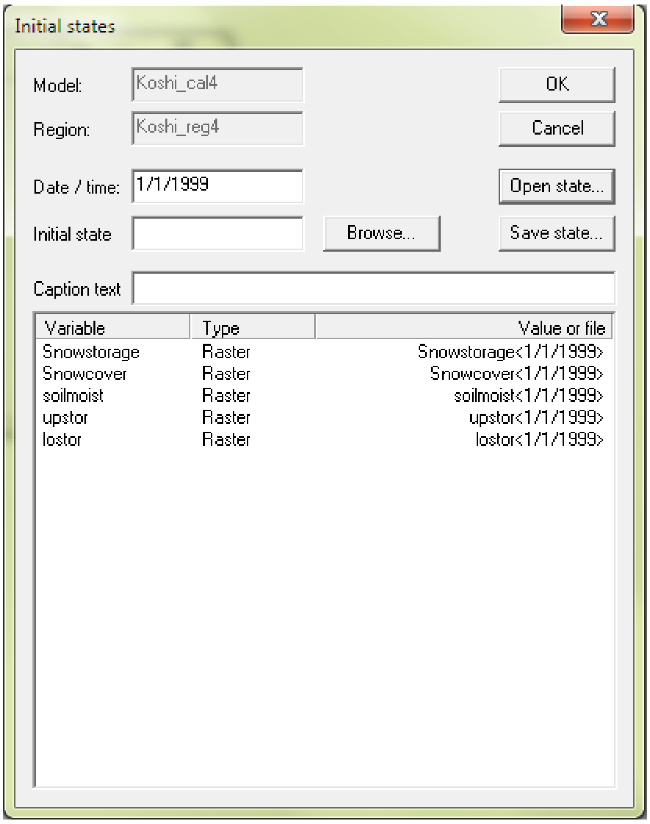


Figure 6.7: Set initials dialog

6.1.6.3 Performance specification

DEMLab has a number of objectives functions, all in the temporal and spatial release. A temporary objective function calculates the correlation between two time series, and calculates a spatial correlation between two variables distributed at a given time. The calibration of a regional model will provide a temporary objective one result for each spatial unit (e.g. subfield), in other words, it will provide a spatial vector.

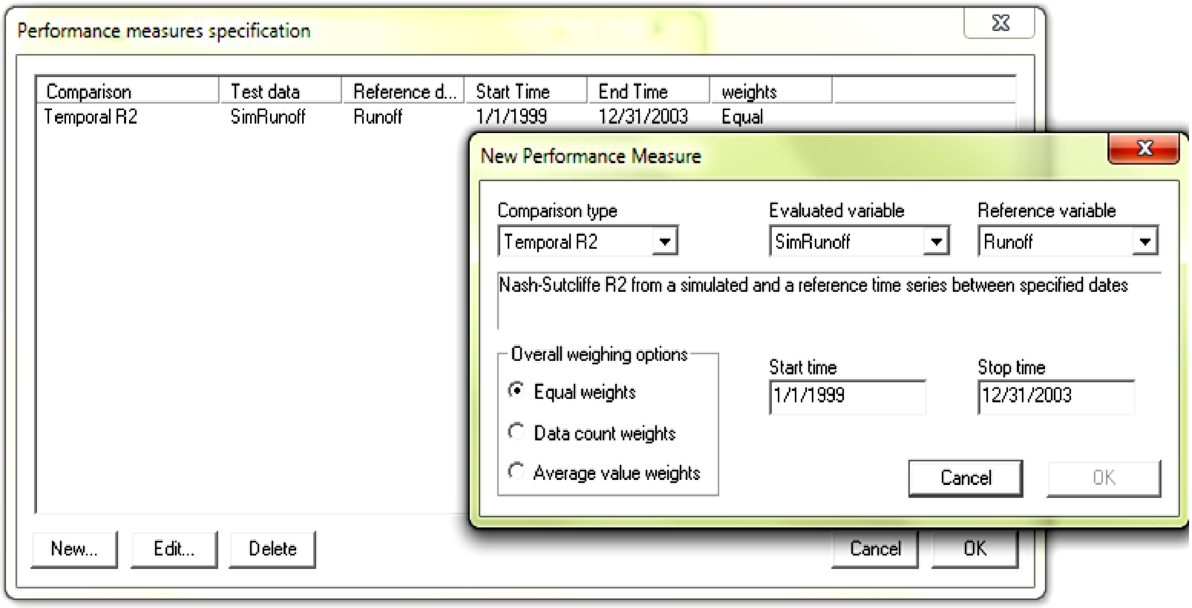


Figure 6.8: Perfomance measure specification and new performance measure dialog

Here, the evaluated variable is selected as SimRunoff, is the point network where simulation is carried out and reference variable is the observed runoff. The simulated and observed runoff values are compared by Temporal R2 (Nash-Sutcliff R^2) in equal weighs.

6.1.6.4 Starting simulation and storing results

The simulation can be run after initialization. The output time series databases are stored in NetCDF format. The stored output time series databases can be opened from:

- **Menu | Region | Output database |Variables | Select SimRunoff | Export ASCII table**

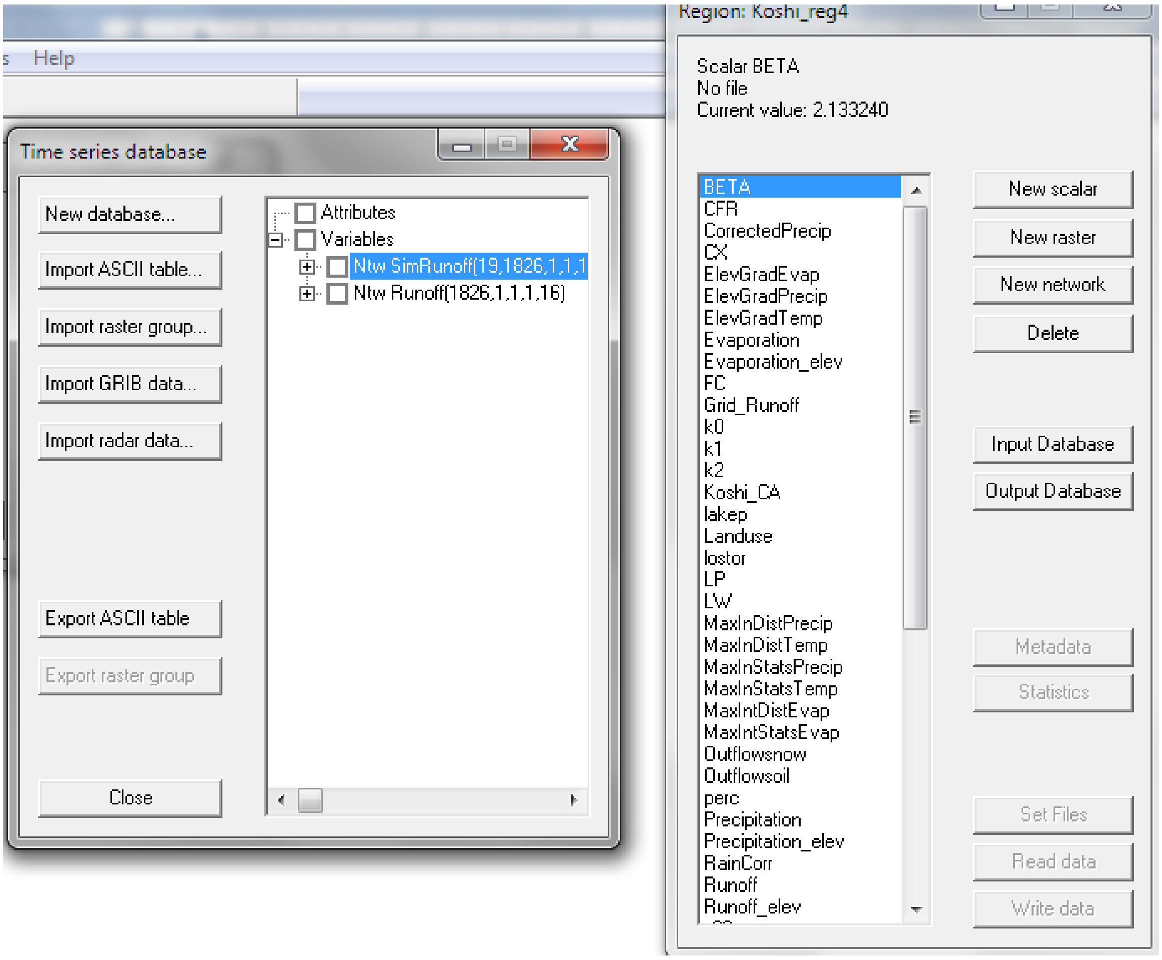


Figure 6.9: Exporting Results

The results are exported in the Excel and other process can be carried out into this.

6.2 HANDLING OF ERRORS WHEN SETUP THE ENKI

Any errors in procedure of setup ENKI or mistyping in variables may lead to crash the program. If the setup of ENKI is not in the sequential order then there will always appear a screen with message of errors. These messages indicate the direction of solutions. Some errors and the messages are described below while set up the new model and region.

Table 6.1: Handling of errors when setup the ENKI

Message of errors in screen	Handling of errors
Data type not selected for LocalElev	Select data type for LocalElev like scalar, raster or network.
Bad input time series connection for Evaporation. Please re-link. Model not properly linked to region, possibly due to missing input database.	Check input data base or make a input database of evaporation.
Input Network does not coincide.	Check the coordinates of database and networks.
Test variables and reference variable do not coincide spatially.	The simulated and observed variables should be same point networks.
No CModstate object supplied to Sent Inits Dialog [28].	Close the window and re-open.
Geometry mismatch. Selected data does not match selected files, Reload data set from disk file (YES) or cancel file linkage (NO).	The database and its corresponding network should be similar.
Increase MaxIntStats Temp for IDWtemp, Some target location are beyond range of all stations.	Increase the distance in parameter setting.
Variable temperature_elev has no map linked.	Link with _elev.avl file,in distributed parameters settings in set parameters.
New parameter value is below minimum value.	Increase the value of parameter.
Increase MaxIntStats Precfor prec, Some target location are beyond range of all precipitation stations.	Increase the distance in parameters setting.
Encountered an improper argument [28].	Select variable before editing in Performance measure specification.
Flag value missing.	Flag value should be -99.

7 SIMULATION AND VALIDATION

"The simulacrum is never that which conceals the truth--it is the truth which conceals that there is none. The simulacrum is true."

-Jean Baudrillard

7.1 INTRODUCTION

Model calibration consists of changing values of model input parameters in an attempt to match the observed variables and simulated variables such as runoff within some acceptable criteria. So, the calibration is the process which determines a set of free parameters that gives the best simulation compared to observed runoff.

There are mainly two types of parameters are used in HBV-model, confined and free parameters. The confined parameters are determined from the maps, field surveys or by direct measurements and free parameters should be determined from model calibration. Some examples of confined parameters are catchment area, elevation distribution and lake percentage and they are never changed once they have been determined. The main objective of model calibration is the determination of free parameters which gives the best fit of the simulation. The degree day factor, threshold temperature, and field capacity in soil are some of the free parameters in HBV model.

The calibration can be carried out by trial and error manually or by automatic numerical optimization. In automatic calibration, parameters are adjusted automatically according to a specific search scheme for optimisation of certain calibration criteria (objective functions). The process is repeated until a specified stopping criterion is satisfied, e.g. maximum number of model evaluations, convergence of the objective functions, or convergence of the parameter set [29].

7.2 CALIBRATION PROCESS

Model calibration is a critical phase in the modelling process, and the need for a well-established calibration strategy is obvious [30]. Therefore a systematic approach for model calibration is proposed which is guided by the intended model use, and which is supported by adequate techniques, prior knowledge and expert judgment. A general method for model calibration process is shown in flowchart in given below:

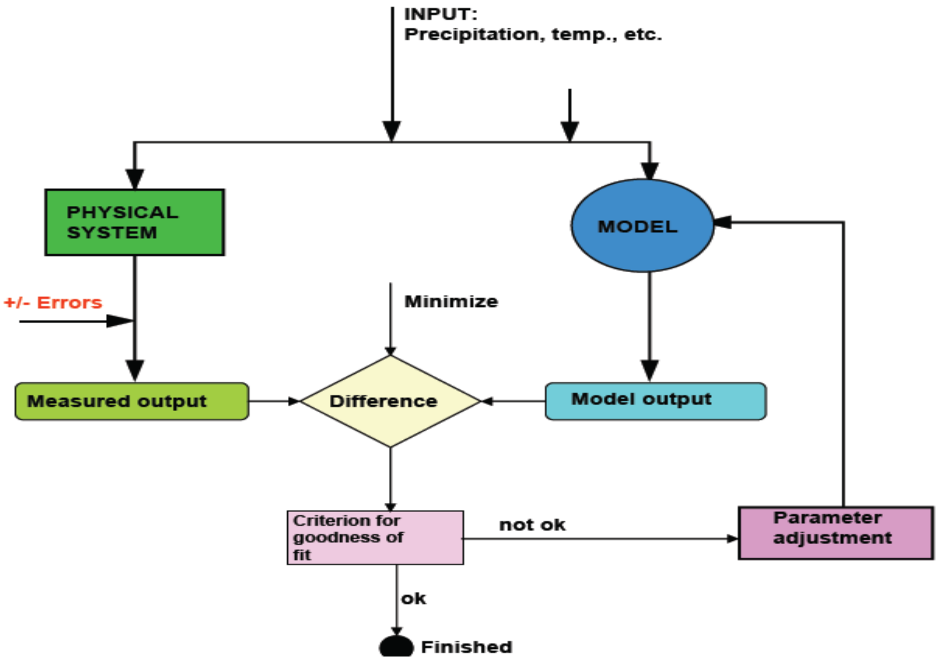


Figure 7.1: Model calibration process [18]

7.2.1 Criterion for goodness for fit

The most difficult part of the calibration process is the evaluation of the difference between observed and simulated runoff and to decide the changing of which parameters should lead better fit of the model. The Nash–Sutcliffe efficiency index (R^2) is widely used in water resources sector to assess the performance of a hydrologic model [31] and which is given by following equation.

$$R^2 = 1 - \frac{\sum(Q_s - Q_0)^2}{\sum(Q_0 - \bar{Q}_0)^2}$$

$where,$

$Q_0 = Observed\ runoff$

$Q_s = Simulated\ runoff$

$\bar{Q}_0 = Average\ bserved\ runoff$

The R^2 can vary from - ∞ to 1, the 1 is the perfect fit of model.

In addition to the R^2 criterion, the cumulative difference $\sum(Q_s - Q_0)$ is also the other error function which determines the goodness of fit.

7.3 CALIBRATION USING THE EKNI SYSTEM

The calibration of the model can be carried out in two ways in the ENKI system, one is manual calibration by setting all the parameters in the Set Parameter dialog and another is Monte Carlo-based procedure for automatic calibration. There are currently five different methods implemented, with varying degree of random sampling and targeted search in Monte Carlo (MC) setup. They are as follows:

- Marqardt-Levenberg

  Multi-surface gradient search using the Jacobian matrix (PEST algorithm)

- SCE-UA

  Global shuffled complex evolution. Slow and robust for difficult cases.
- Random MC (GLUE)

  Random drawing from specified distributions.
- DREAM MCMC

  Adaptive Metropolis sampler, best used with likelihood-based PMs.
- Conditional Univariate

  Univariate sampling around an existing optimum, n trials per parameter dimension.
- External list

  Parameter sets read from file.

Among these methods the SCE-UA method is used for this study.

SCE-UA method

A global optimization method known as the SCE-UA (shuffled complex evolution method developed at The University of Arizona) has shown promise as an effective and efficient optimization technique for calibrating watershed models [32]. This method is based on a synthesis of the best features from several existing methods, including the genetic algorithm, and introduces the new concept of complex shuffling. SCE-UA method is capable of handling high parameter dimensionality and it does not rely on the availability of an explicit expression for the objective function or the derivatives. The method has been used in various fields for optimization and reported exact results. The successful application of a conceptual rainfall-runoff model depends on how well it is calibrated. This method appears to be capable of efficiently and effectively solving the conceptual rainfall-runoff model optimization problem [33].

The model was run with three cases: in the first case, all sub-catchments are considered and in second case the Uwa Gaon sub-catchment is not taken for calibration because almost whole area of that sub-catchment lies in Tibet. In the third case, the model is setup to calibrate eight different independent catchments and validate for remaining seven catchments excluding the catchment Uwa Gaon. The models are iterated more than 1000 times by using SCE-UA method to achieve as possible as good fit of Nash efficiency R^2 value.

7.3.1 Calibration: Case I

In this case, the model was run for overall Saptakoshi basin. The calibration was carried out for all the 16 gauge stations from year 1999 to 2003. The input sub-catchment is shown in Figure 5.21. The range of the parameter values are adjusted with an attempt to achieve parameter sets those represent the behavior of the catchment as closely as possible. The ranges of parameter sets are fixed from the literature and previous reports, and calibrated values are tabulated in Table 7.1. Some parameters are set as constant values which are less sensitive the simulation results. There are some glaciers and lakes in the basin but due to lack of data, the lake percentage is taken as 0%.

7.3.1.1 Results of calibration: Case I

The simulated runoff obtained from ENKI modelling system and observed runoff is plotted against the date/time. The calibrated parameters are tabulated in Table 7.1 and the R^2 values in Table 7.2. The maximum R^2 value is 0.58 of the catchment Busti and minimum value of Uwa Gaon is -27.76. The simulated discharge of Uwa Gaon is very higher than observed data as shown in Figure 7.2. When the model is calibrated including the catchment Uwa Gaon in order to get the good average R^2 value of the model, the R^2 values of other catchments can be stretched in wrong direction. The reason may be due to missing precipitation data of Tibetan area as the catchment lies in Tibet and the precipitation pattern is different in Tibet than in Nepal. The average R^2 value is -1.57 which is very unsatisfactory so that the calibration results of case I is not further used for validation and only some these results are presented here to comparison.

The hydrograph of the catchment Helambu is shown in Figure 7.3 and R^2 value is about 0.22. The simulated discharge and observed discharge is somehow similar pattern in year 1999, 2001, 2002 and 2003 but the observed runoff is very high in year 2000. If the year 2000 is excluded for simulation, better value of R^2 can be obtained. The observed peak discharge in the year 2000 is very high for a small catchment (177 km^2) like Helambu. Again, the neighboring catchments like Jalbire, Pachuwar Ghat and Busti have not the similar pattern of observed runoff from year 1999 to 2003 (the detail hydrographs will present in case II). In case of catchment Busti, the simulated and observed discharge is relatively in good fit. The simulated base flow is lower than observed base flow. The observed peak of hydrograph is exaggerated but in similar pattern with simulated hydrograph.

Table 7.1: Calibration of parameters in ENKI system for Saptakoshi basin for Case I & II

Parameters	Description	Routine	Distribution	Value Range	Calibrated Value	
					Case I	Case II
TX	Threshold Rain/Snow	PcorrMap2; HBVsnow	Uniform	-3 to 3	**0.319**	**-0.090**
RainCorr	Rain correction	PcorrMap2	Uniform	1 to 1.5	**1.060**	**1.276**
SnowCorr	Snow correction	PcorrMap2	Uniform	1 to 1.5	**1.270**	**1.235**
ElevGradPrecip	Elevation lapse rate in %/100m	IDWprec	Uniform	-1 to 1	**-0.025**	**-0.025**
MaxInDistPrecip	Maximum Distance to included stations	IDWprec	Constant	10000000	**10000000**	**10000000**
MaxInStatsPrecip	Maximum no. of stations included	IDWprec	Constant	67	**67**	**67**
ElevGradTemp	Elevation lapse rate in %/100m	IDWtemp	Constant	-0.6	**-0.60**	**-0.60**
MaxInDistTemp	Maximum Distance to included stations	IDWtemp	Constant	10000000	**10000000**	**10000000**
MaxInStatsTemp	Maximum no. of stations included	IDWtemp	Constant	67	**67**	**67**
ElevGradEvap	Elevation lapse rate in %/100m	IDWevap	Constant	0.02	**0.020**	**0.020**
MaxIntDistEvap	Maximum Distance to included stations	IDWevap	Constant	10000000	**10000000**	**10000000**
MaxIntStatsEvap	Maximum no. of stations included	IDWevap	Constant	3	**3**	**3**
CX	Degree-day factor	HBVsnow	Uniform	0.001 to 10	**7.551**	**7.183**
CFR	Refreezing Coefficient	HBVsnow	Uniform	0 to 1	**0.542**	**0.007**
TS	Threshold Snow-melt	HBVsnow	Uniform	-2 to 2	**0.538**	**0.239**
LW	Maximum Liquid Water content	HBVsnow	Uniform	0.001 to 0.1	**0.036**	**0.049**
s00	Snow redistribution low limit	HBVsnow	Uniform	0.2 to 0.7	**0.415**	**0.477**
s25	Snow redistribution 25% quartile	HBVsnow	Uniform	0.1 to 0.5	**0.233**	**0.308**
s50	Snow redistribution median	HBVsnow	Uniform	0.5 to 0.95	**0.737**	**0.726**
s75	Snow redistribution 75% quartile	HBVsnow	Uniform	0.05 to 0.25	**0.146**	**0.126**
s100	Snow redistribution high limit	HBVsnow	Uniform	0.3 to 0.5	**0.362**	**0.365**
FC	Field capacity	HBVSoil	Uniform	100 to 2000	**1016.24**	**635.575**
LP	Threshold Evaporation SM/FC	HBVSoil	Uniform	0.001 to 0.999	**0.690**	**0.424**
BETA	Beta	HBVSoil	Uniform	1 to 6	**3.915**	**3.775**
k2	Fast drainage coefficeint	HBVResponse	Uniform	0.1 to 0.5	**0.301**	**0.231**
k1	Slow drainage coefficeint	HBVResponse	Uniform	0.05 to 0.15	**0.110**	**0.089**
k0	Drainage coefficient	HBVResponse	Uniform	0.001 to 0.01	**0.009**	**0.007**
perc	Percolation	HBVResponse	Uniform	1.2 to 2	**1.470**	**1.533**
tresh	Threshold	HBVResponse	Uniform	10 to 40	**21.62**	**23.15**
lakep	Lake percentage	HBVResponse	Constant	0	**0**	**0**

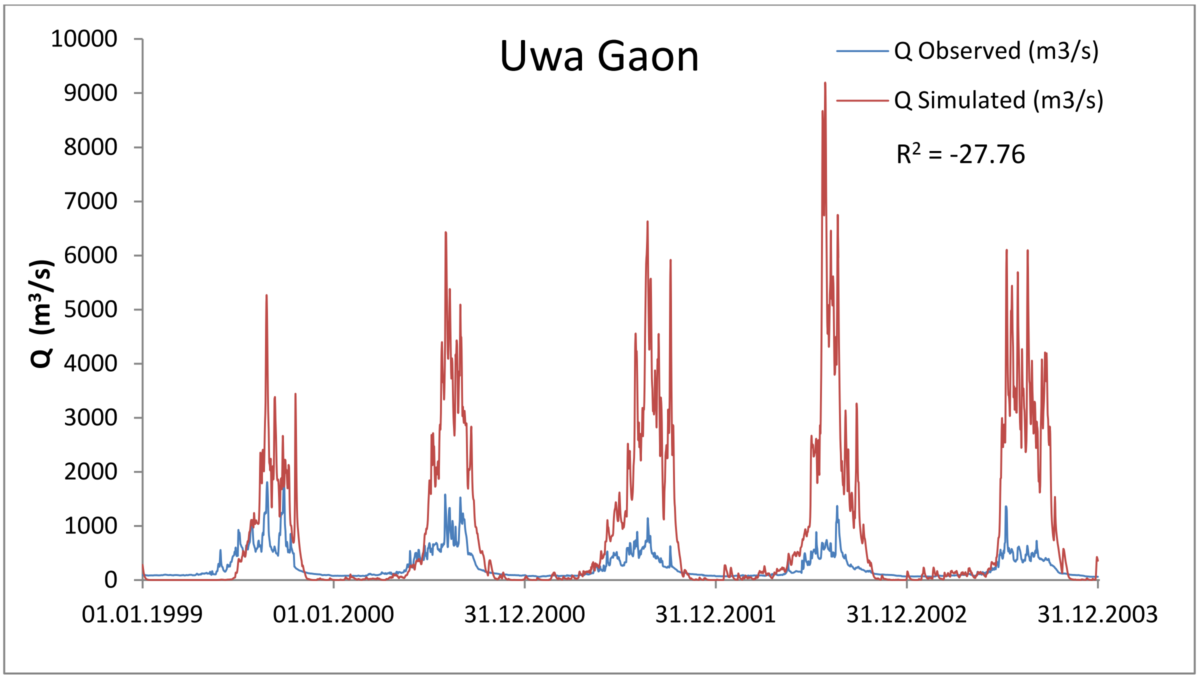


Figure 7.2: Calibration of sub-catchment Uwa Gaon for Case I

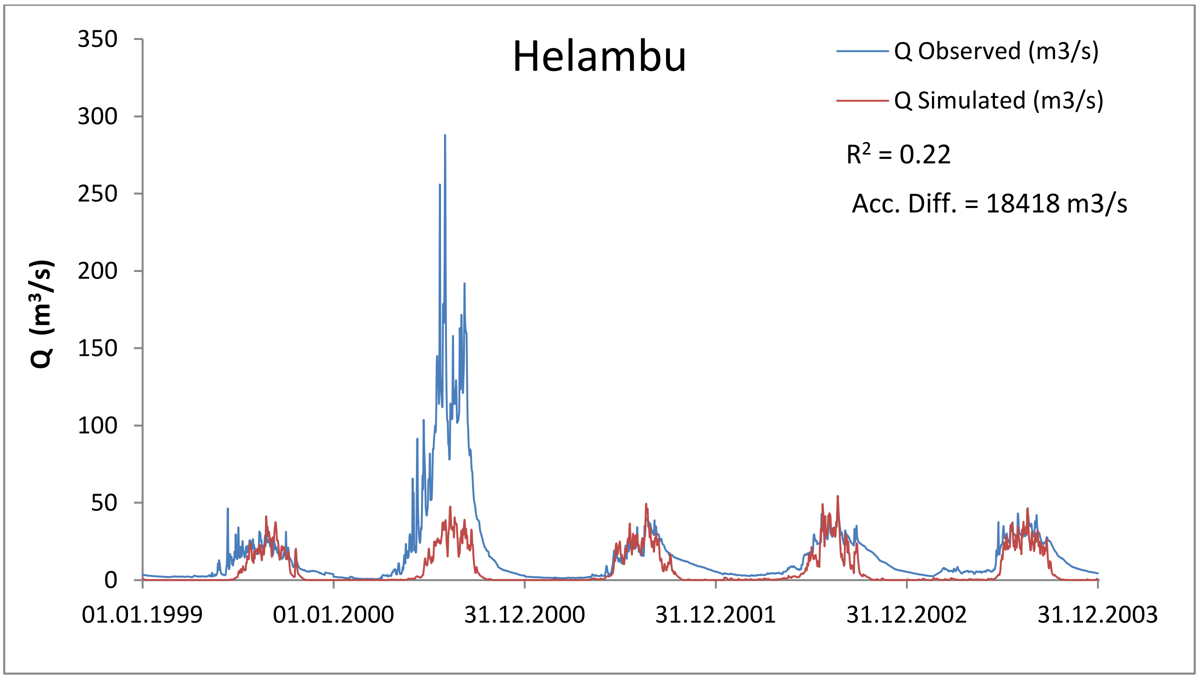


Figure 7.3: Calibration of sub-catchment Helambu for Case I

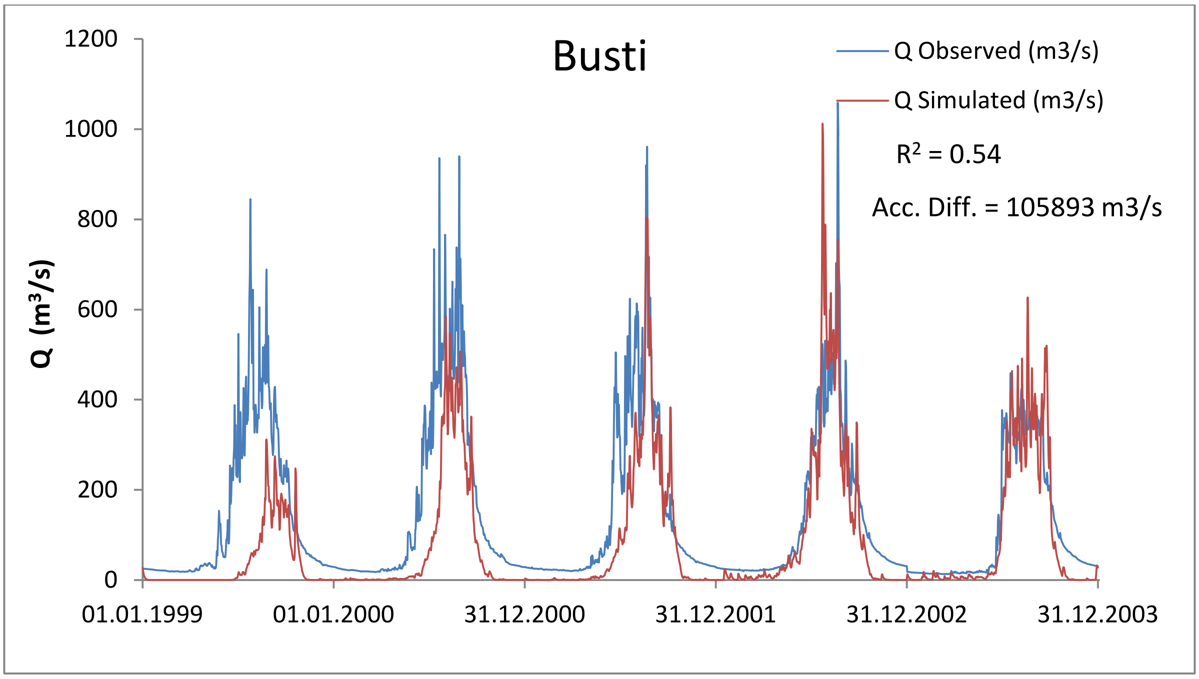


Figure 7.4: Calibration of sub-catchment Busti for Case I

7.3.2 Calibration: Case II

In this case, the Uwa Gaon sub-catchment is not considered for the calibration as shown in Figure 7.5. The main reason for this calibration is that the precipitation and air temperature data are not available for that part of the catchment. The most of the area of this sub catchment lies in Tibet. The annual precipitation is relatively low in Tibet than in Nepal and climate is cold and dry. All the inputs in the ENKI system are similar as in case I but the sub-catchment delineation and runoff data entered deleting the values of Uwa Gaon. The calibration results are shown in Table 7.1. Hence the unavailability of Tibetan region data could be the reason of result of high discharge simulation.

Figure 7.5: Sub-catchments of the Saptakoshi basin for calibration case II

7.3.2.1 Results of calibration: Case II

The hydrographs of simulated and observed runoff are plotted for five years period to compare the results as shown in given figures. The average Nash-Sutcliffe efficiency is 0.31 and the maximum is about 0.74 and minimum is -0.82.

When comparing the hydrographs of catchment Turkeghat, the simulated hydrographs for year 1999, 2001 and 2002 have good fit with observed. But in year 2000 and 2003, the simulation results are lower than observed. In case of Simle, the rising limbs of simulated hydrographs have shifted some days. The R^2 values of catchments Tumlingtar and Rasnalu Village have 0.37 and 0.39 respectively but accumulation difference of observed and simulated runoff is very high in case of Rasnalu Village. The performance measurement of catchment Rabuwa Bazar is better than other catchments and well fitted with observed runoff.

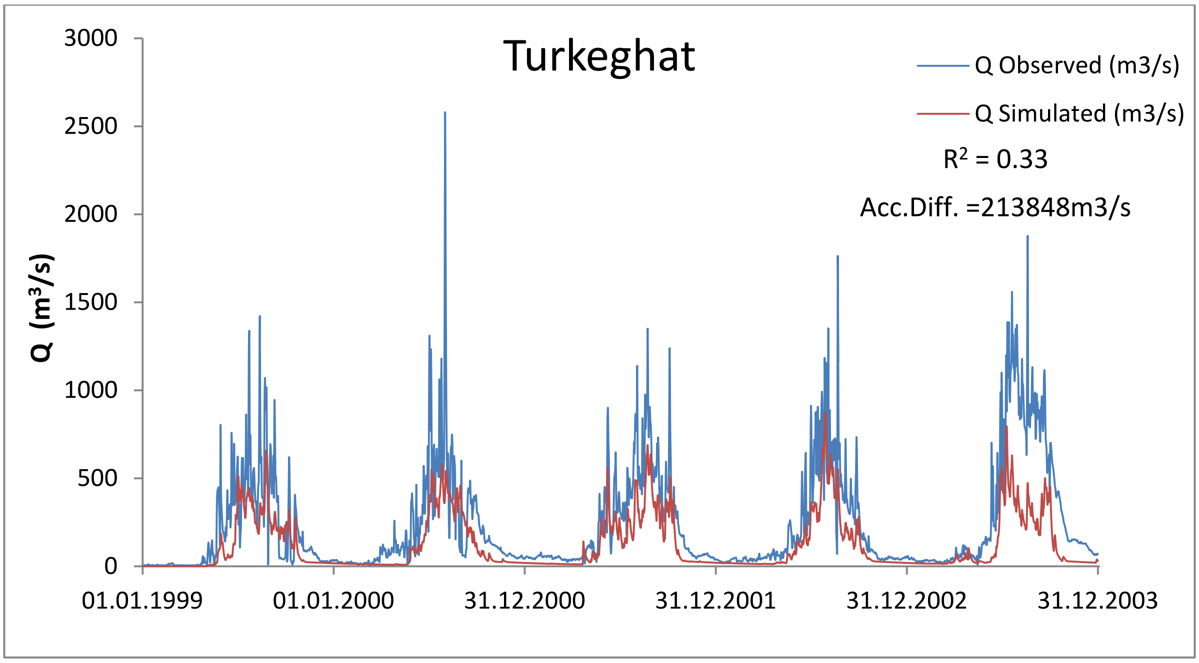


Figure 7.6: Calibration of sub-catchment Turkeghat for Case II

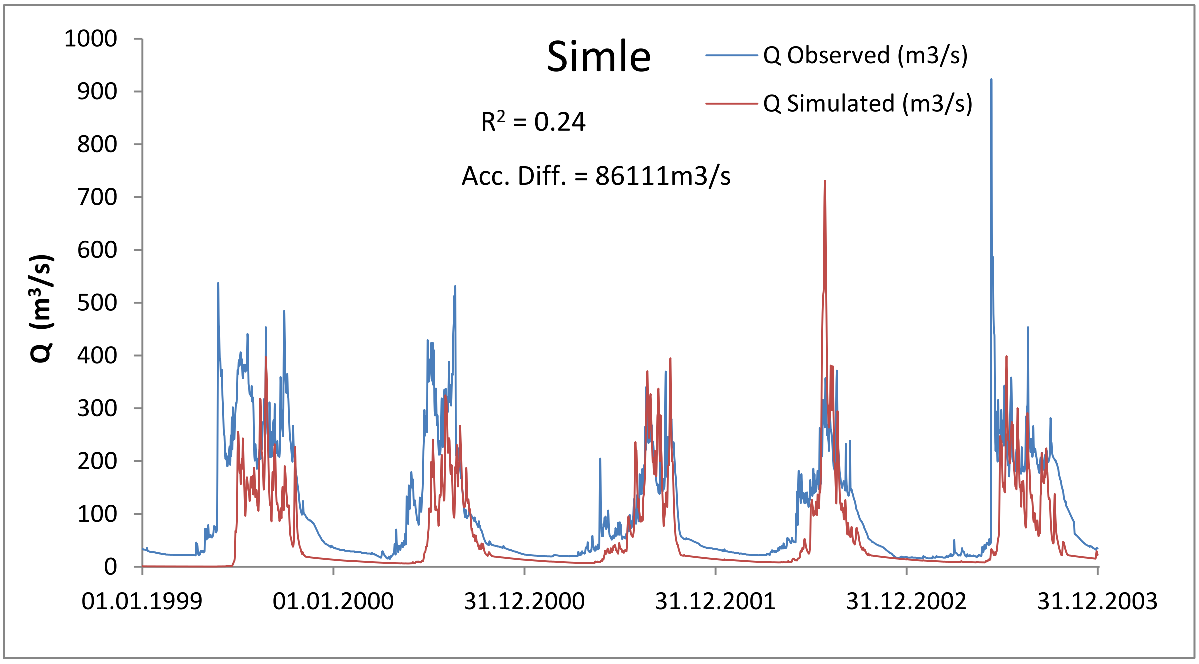


Figure 7.7: Calibration of sub-catchment Simle for Case II

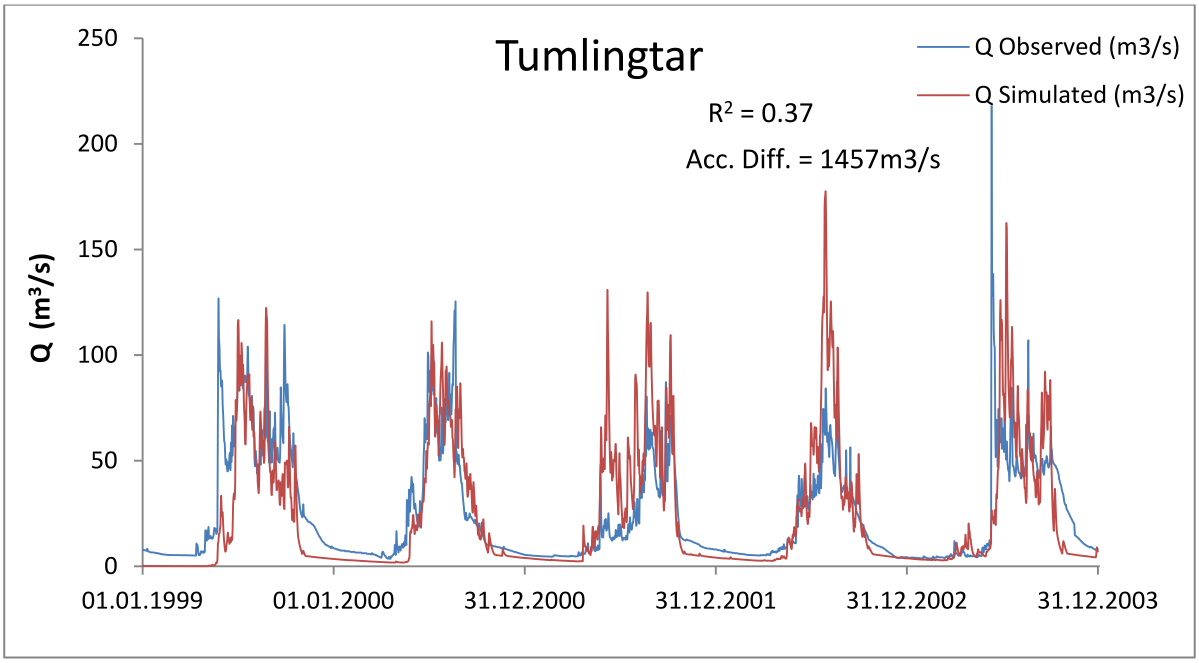


Figure 7.8: Calibration of sub-catchment Tumlingtar for Case II

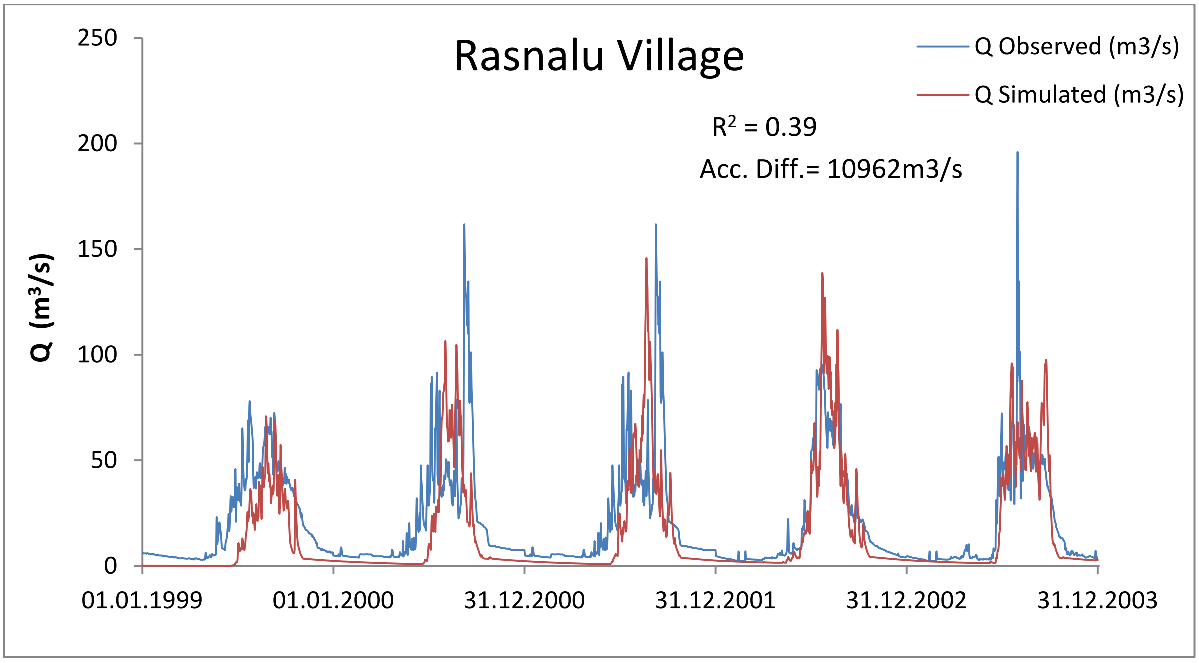


Figure 7.9: Calibration of sub-catchment Rasnalu Village for Case II

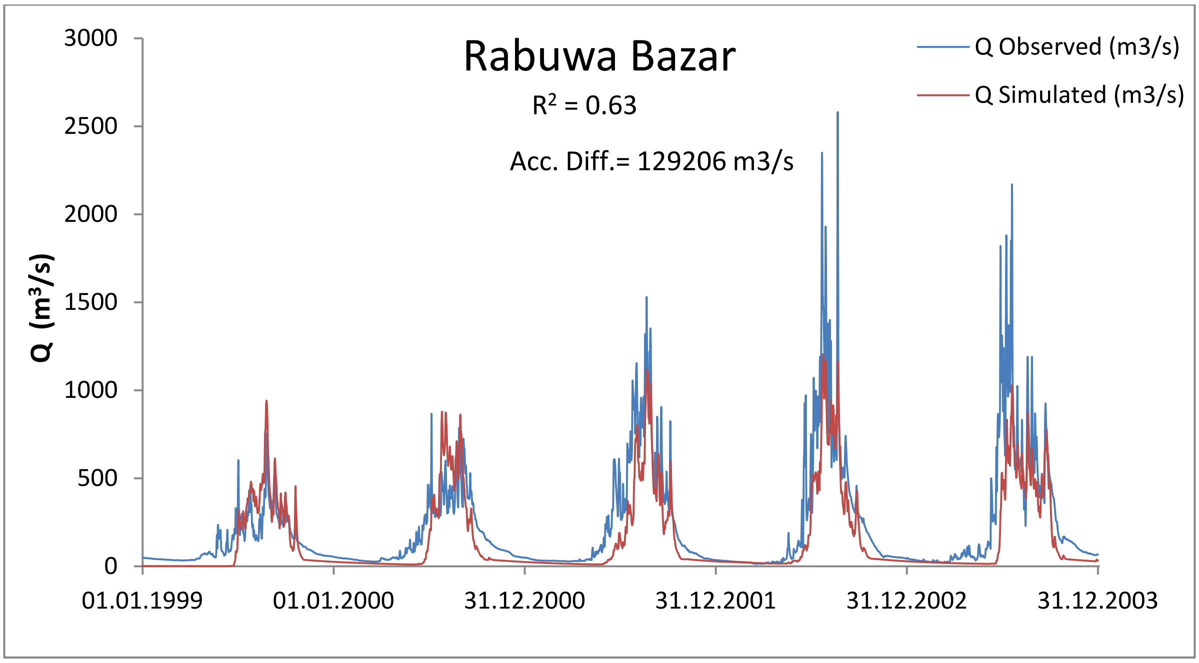


Figure 7.10: Calibration of sub-catchment Rabuwa Bazar for Case II

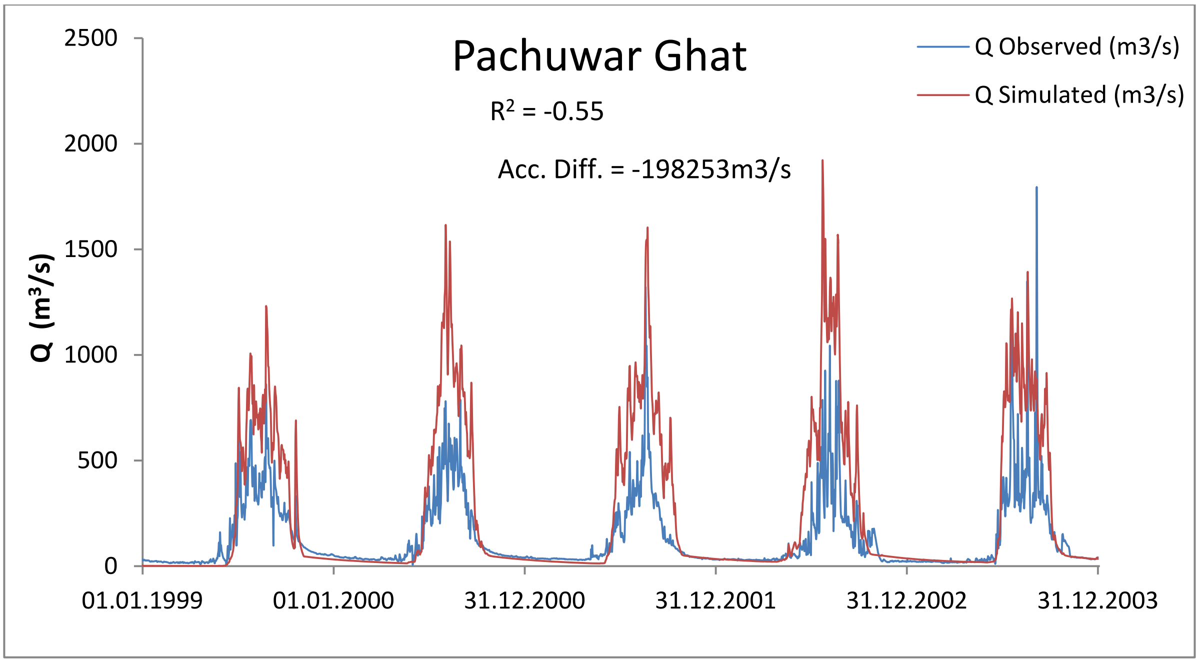


Figure 7.11: Calibration of sub-catchment Pachuwar Ghat for Case II

In case of Pachuwar Ghat, the value of simulation runoff is very high. The peaks of simulated hydrographs are higher than observed runoff but the base flows are relatively equal. But the simulated result of downstream catchment Khurkot is very low compare to observed discharge. In year 1999, the observed peak runoff is more than 10 times its mean flow. The large accumulated difference of runoff may be the impact of this. But the observed runoff of further downstream catchment Hampuachuwar is less than Khurkot as already mentioned in Figure 5.15. So the scaled runoff data is used to compare simulation and the R^2 of 0.46 is obtained which is better than other upstream catchments.

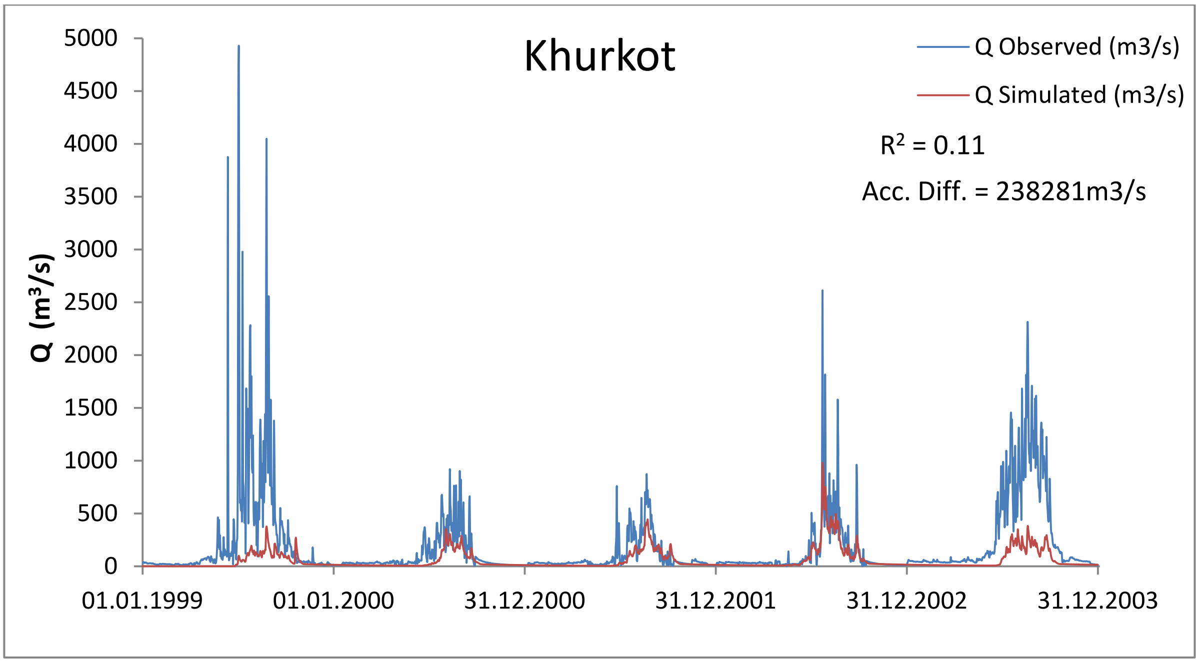


Figure 7.12: Calibration of sub-catchment Khurkot for Case II

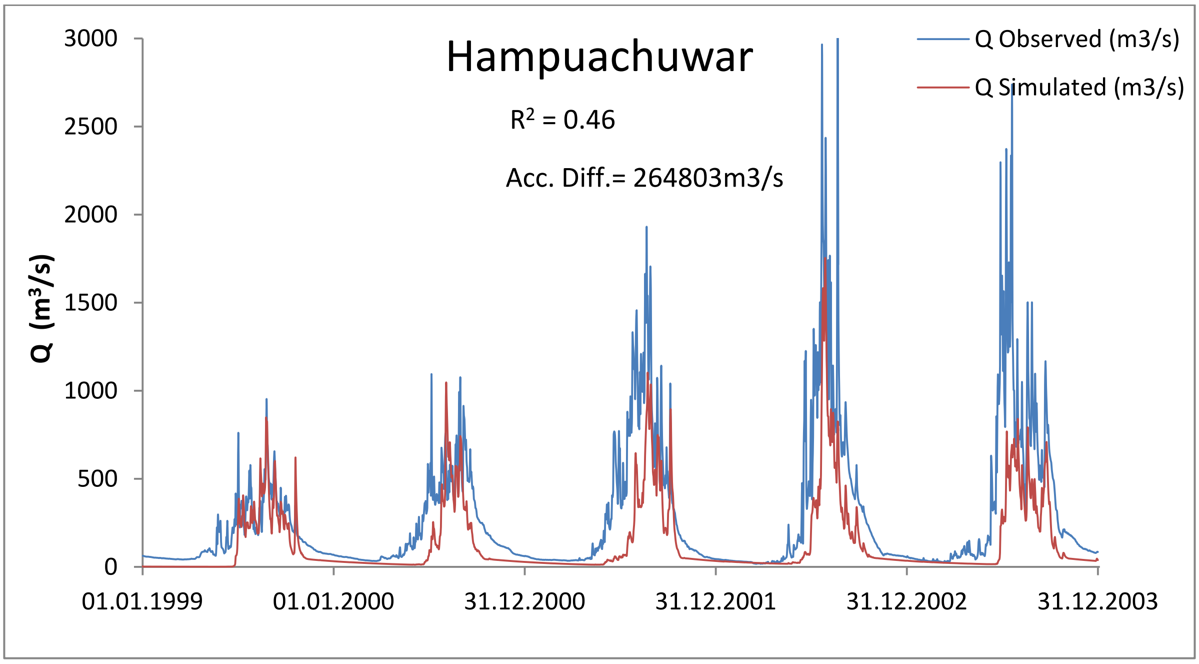


Figure 7.13: Calibration of sub-catchment Hampuachuwar for Case II

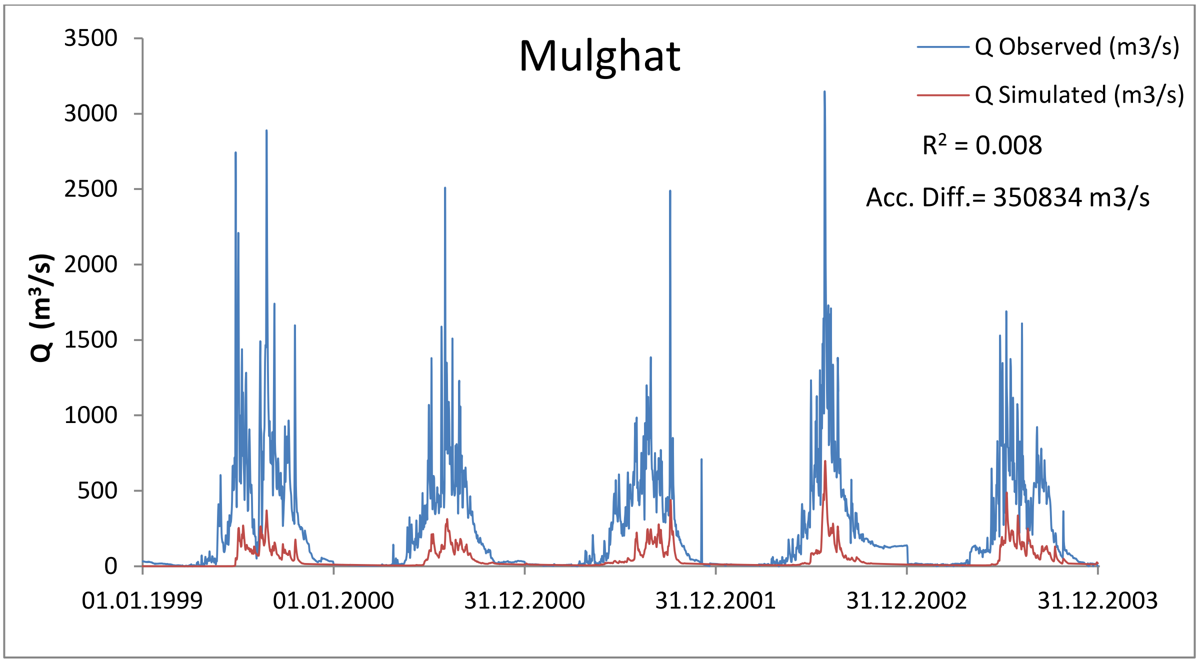


Figure 7.14: Calibration of sub-catchment Mulghat for Case II

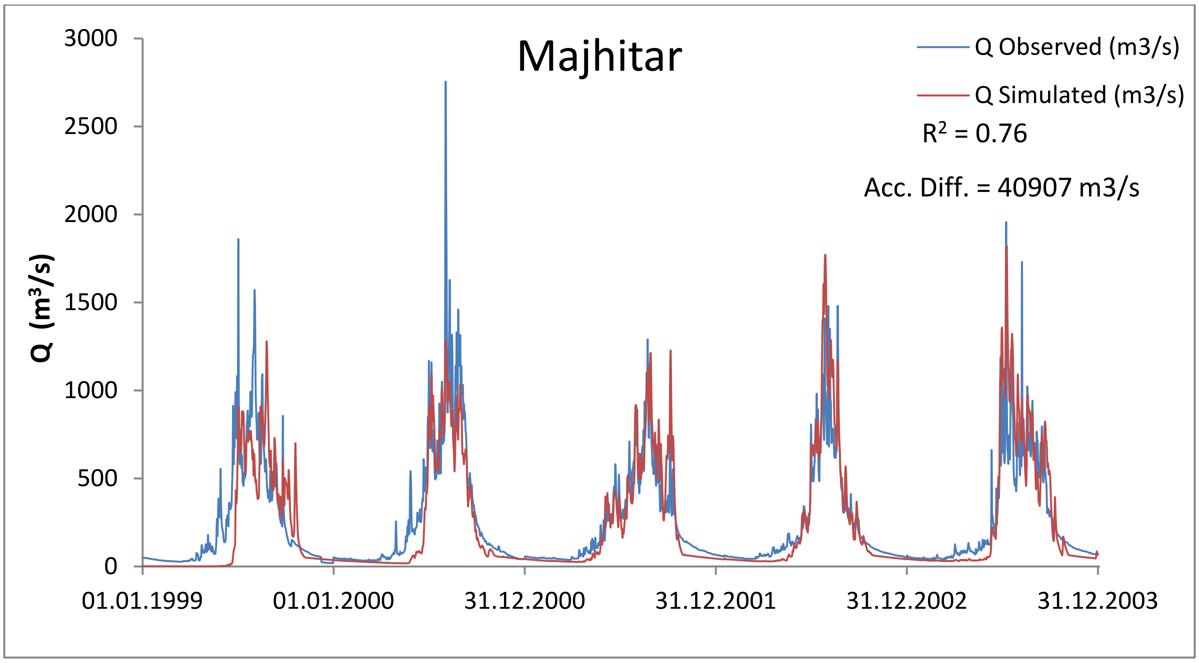


Figure 7.15: Calibration of sub-catchment Maghitar for Case II

The simulated runoff is very low in Mulghat with compared to observed flow. However, the simulated values shows quiet a good estimation of discharge values for the upper basin-Majhitar and the model is able to achieve satisfactory R^2 value of 0.76.

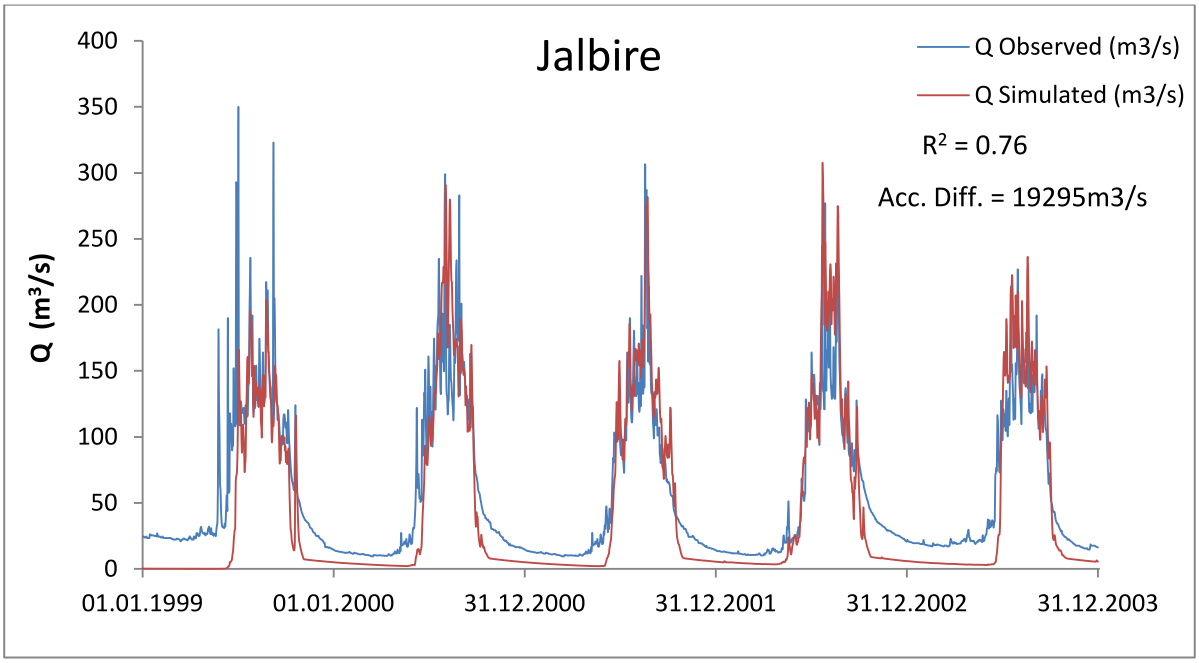


Figure 7.16: Calibration of sub-catchment Jalbire for Case II

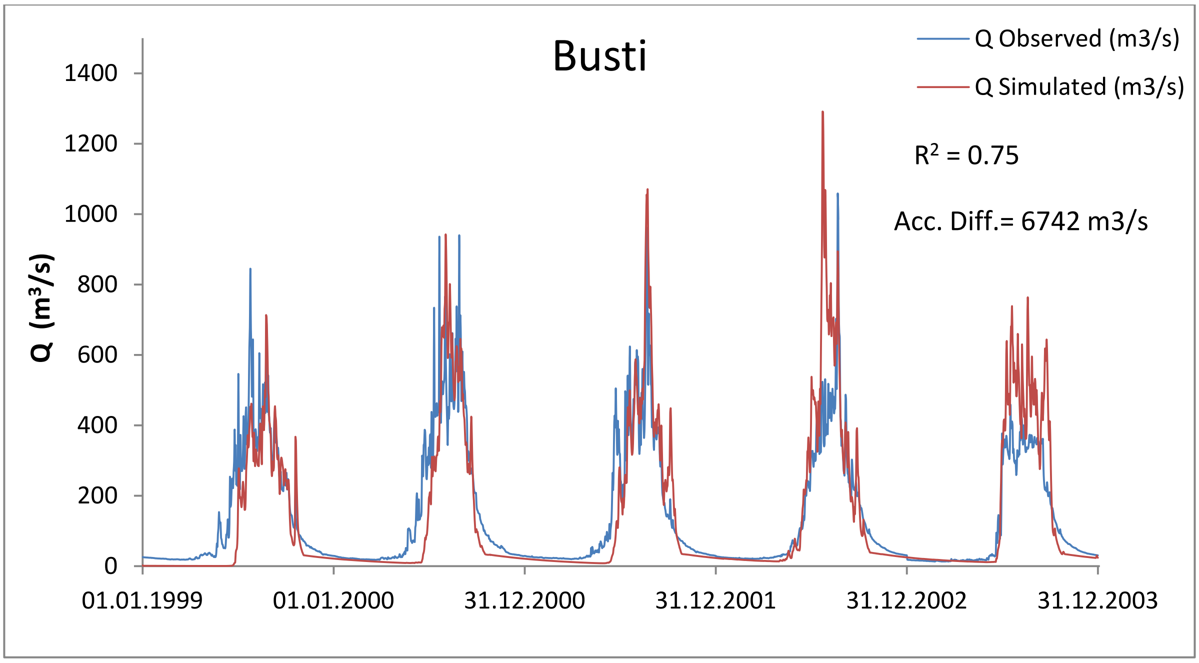


Figure 7.17: Calibration of sub-catchment Busti for Case II

It can be seen from the Figure 7.16 and Figure 7.17 that the simulation results are quiet good for sub-basins Jalbire and Busti.

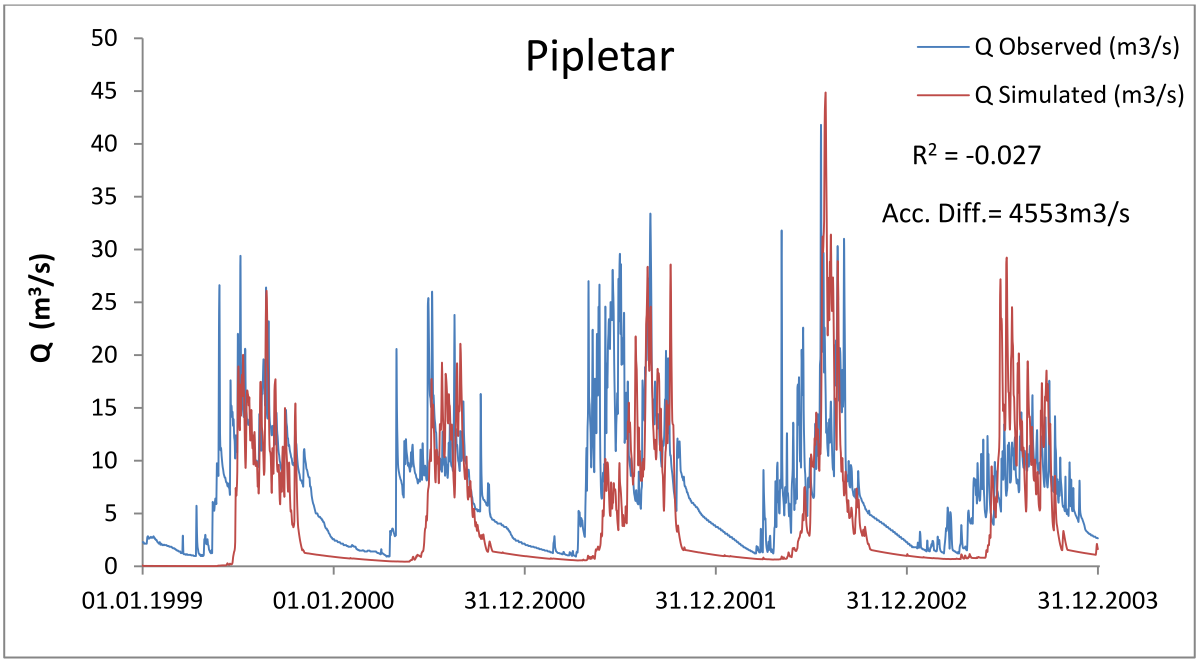


Figure 7.18: Calibration of sub-catchment Pipletar for Case II

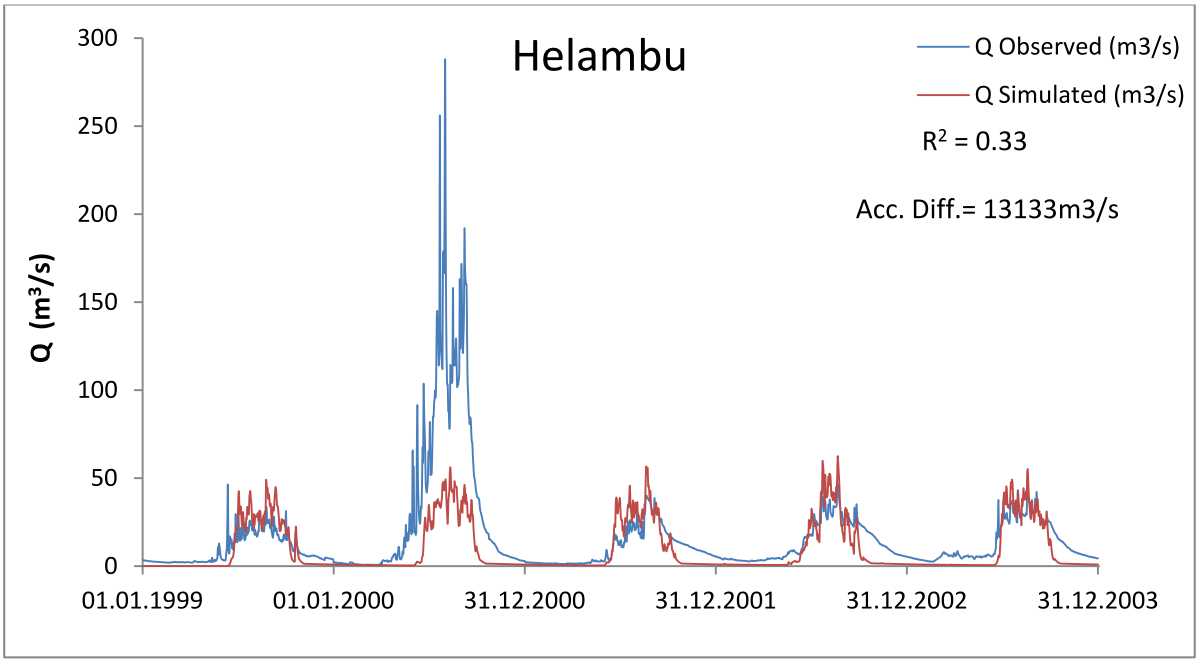


Figure 7.19: Calibration of sub-catchment Helambu for Case II

The model is not able to generate similar pattern of hydrograph of small sub-basin Pipltar. The reason may be due to a small basin has fast response time of runoff and this effect the daily measurement data. The result of simulation for Helambu is similar as in case I. The model cannot able to estimate the peak flow for year 2000 but in other years the flow seems in good pattern. In case of sub-catchment Chatara-Kothu, the outlet of the Saptakoshi basin, the result appears tentatively reasonable.

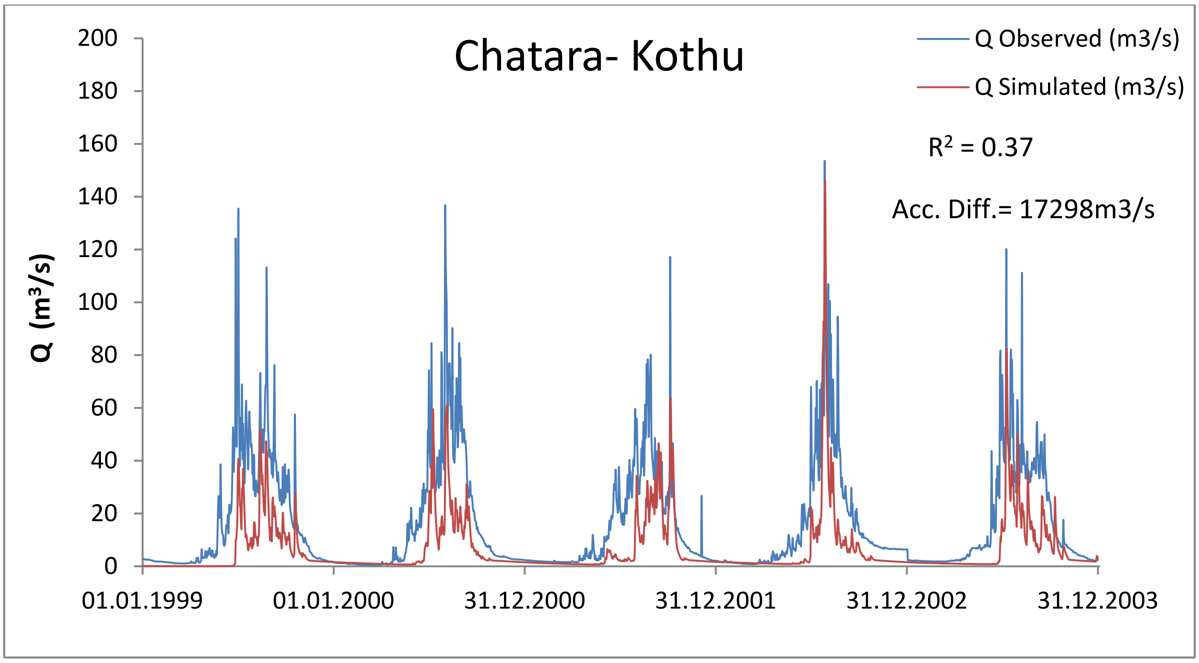


Figure 7.20: Calibration of sub-catchment Chatar- Kothu for Case II

7.3.3 Comparison of calibration results between Case I & II

The summary of the calibration results, R^2 and accumulated difference of observed and simulated runoff, are shown in Table 7.2 below. The calibration results from the 2nd case are much better than 1st case. But the calibrated best values of parameters for case II are not high deviated from the case I. In another words, most of the calibrated parameter values for case II are same as case I which are shown in above Table 7.1. But there is large difference between average R^2 values of case I and case II. The simulated runoff for Uwa Gaon basin is higher than measured data. As already mentioned in above chapters, the suspected reason is that missing climatic data of Tibetan area. So the comparison of simulation result case I is meaningless.

The average Nash-Sutcliffe efficiency R^2 of case II is satisfactorily improved after removing Uwa Gaon sub-basin from analysis. It can be concluded that the independent sub-basins showed the good results like Busti, Jalbire, Majhitar, Rabuwa Bazar, Rasnalu Village and Tumlingtar watersheds. So the further simulation is setup for only those independent sub basins in case III.

Table 7.2: Summary and comparison of calibration results

Sub-catchments	R^2		Acc. Diff. (m^3/s)	
	Case I	Case II	Case I	Case II
Uwa Gaon	-27.76	-	-1156565	-
Busti	0.54	0.75	105893	6742
Chatara- Kothu	0.10	0.37	299446	17298
Hampuachuwar	0.15	0.46	382379	264803
Helambu	0.22	0.33	18418	13133
Pipletar	-0.25	-0.03	7905	4553
Jalbire	0.56	0.76	46462	19295
Khurkot	-0.05	0.11	290486	238281
Majhitar	0.58	0.76	195456	40907
Mulghat	-0.18	0.01	389146	350834
Pachuwar Ghat	0.40	-0.55	-40373	-198253
Rabuwa Bazar	0.45	0.63	239812	129206
Rasnalu Village	0.20	0.39	21924	10962
Tumlingtar	0.33	0.37	16060	1457
Simle	-0.63	0.24	131470	86111
Turkeghat	0.20	0.33	289412	213848
Average	**-1.57**	**0.33**		

7.3.4 Validation of the model for case II

The validation of the model is done for period from year 2004 to 2008. The calibrated best parameter values are set in the ENKI system for validation. The hydrographs of runoff from validation results are plotted and summary of goodness of fit Nash efficiency R^2 and accumulated difference of observed and validated data are shown in below. The average R^2 for validation is decreased to 0.14. For most of the basins the validation results are comparatively similar with calibration. However, the R^2 value of Pachuwar Ghat is achieved -2.530 which is less than the calibration result. Again, the R^2 of independent basin Helambu has also reduced to 0.02. But R^2values of Busti, Jalbire, Rasnalu Village, Majhitar and Turkeghat basins are increased in some degree.

The detail observation of hydrographs of Turkeghat and Simle basins clarify that the model is able to generate the realistic pattern and shape of simulation runoff but peaks are lower than the observed hydrographs.

Table 7.3: The summary of validation result for case II

Sub-catchments	R^2	Acc. Diff. (m^3/s)
Busti	0.70	69673
Chatara- Kothu	0.20	12923
Hampuachuwar	0.41	260581
Helambu	0.02	1708
Pipletar	0.13	7353
Jalbire	0.77	23684
Khurkot	-0.04	363442
Majhitar	0.82	37612
Mulghat	-0.08	244193
Pachuwar Ghat	-2.53	-169898
Rabuwa Bazar	0.46	165754
Rasnalu Village	0.61	16364
Tumlingtar	0.51	10005
Simle	0.01	131171
Turkeghat	0.14	304868
Average	**0.14**	

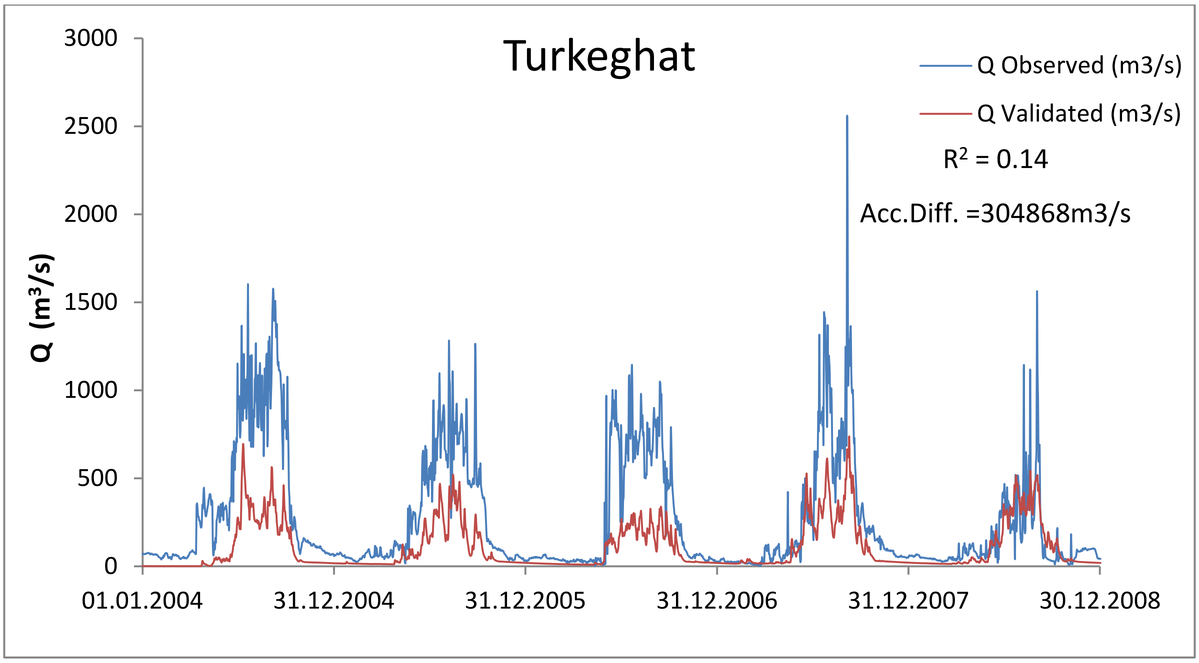


Figure 7.21: Validation of sub-catchment Tukeghat for Case II

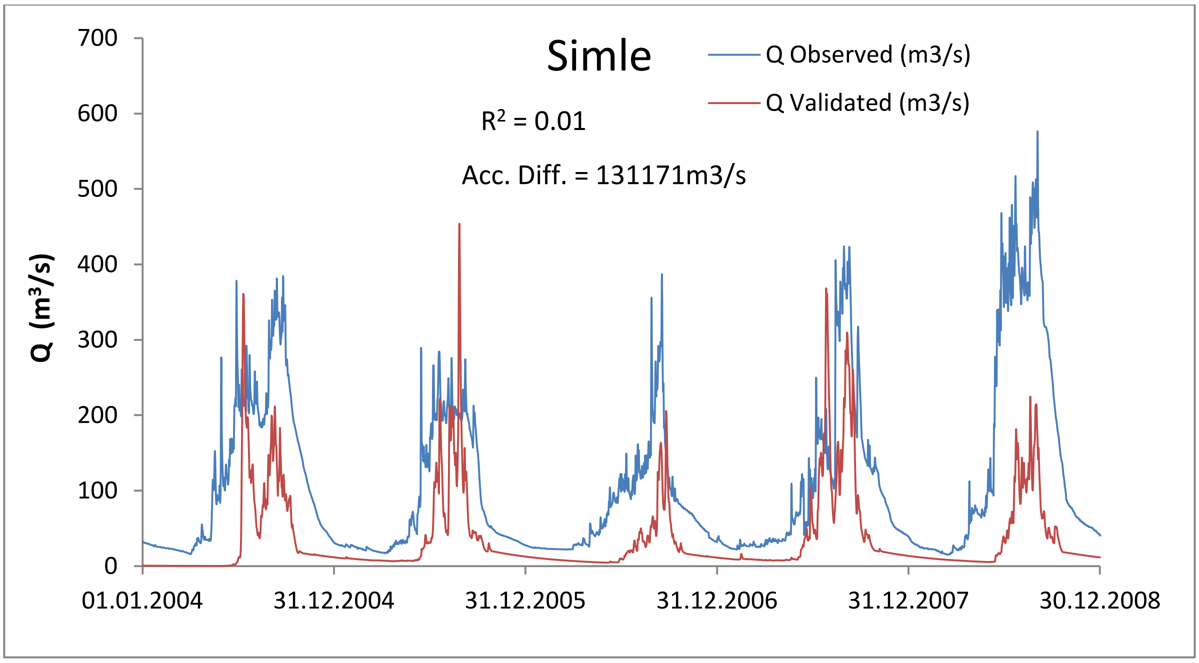


Figure 7.22: Validation of sub-catchment Simle for Case II

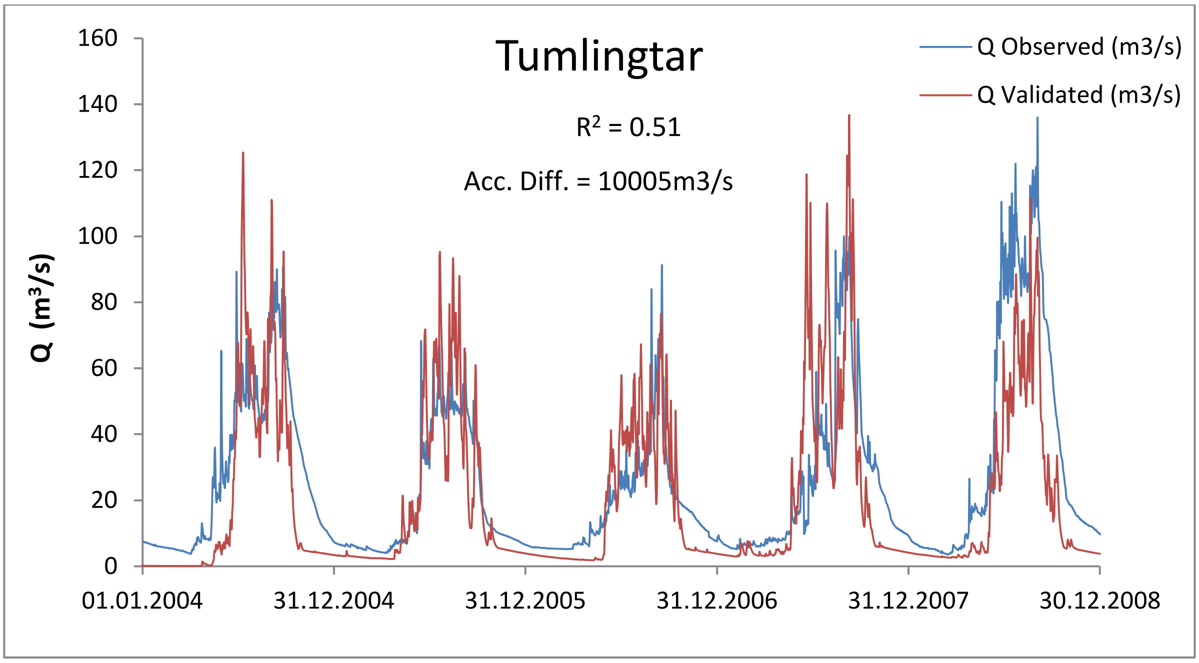


Figure 7.23: Validation of sub-catchment Tumlingtar for Case II

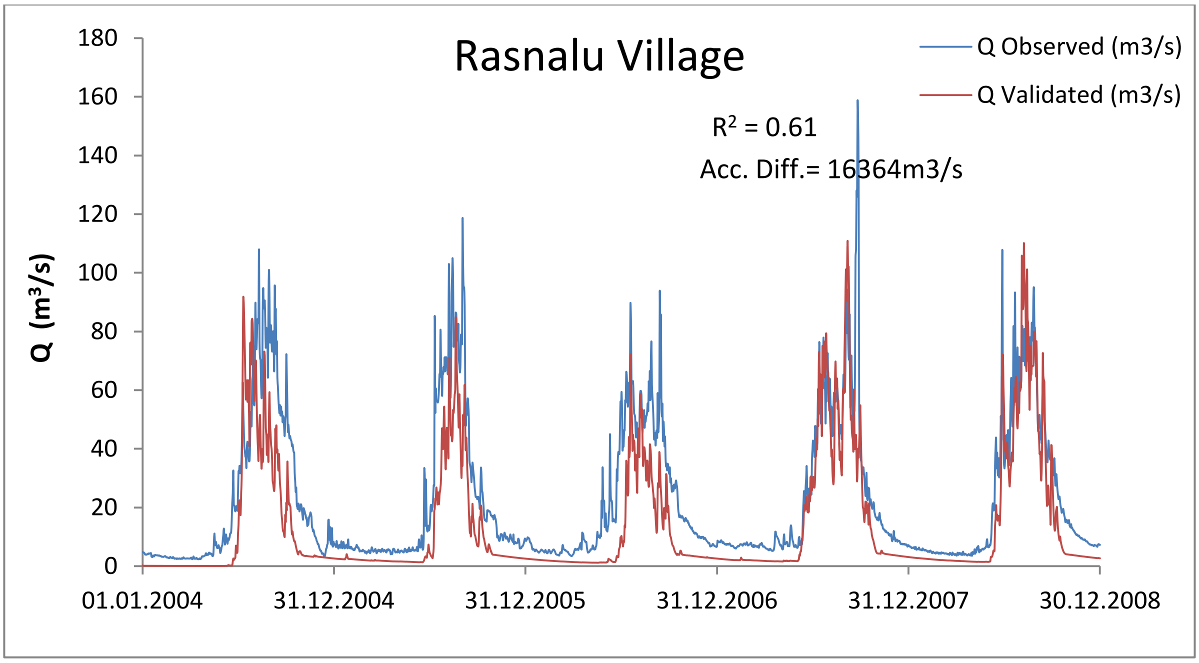


Figure 7.24: Validation of sub-catchment Rasnalu village for Case II

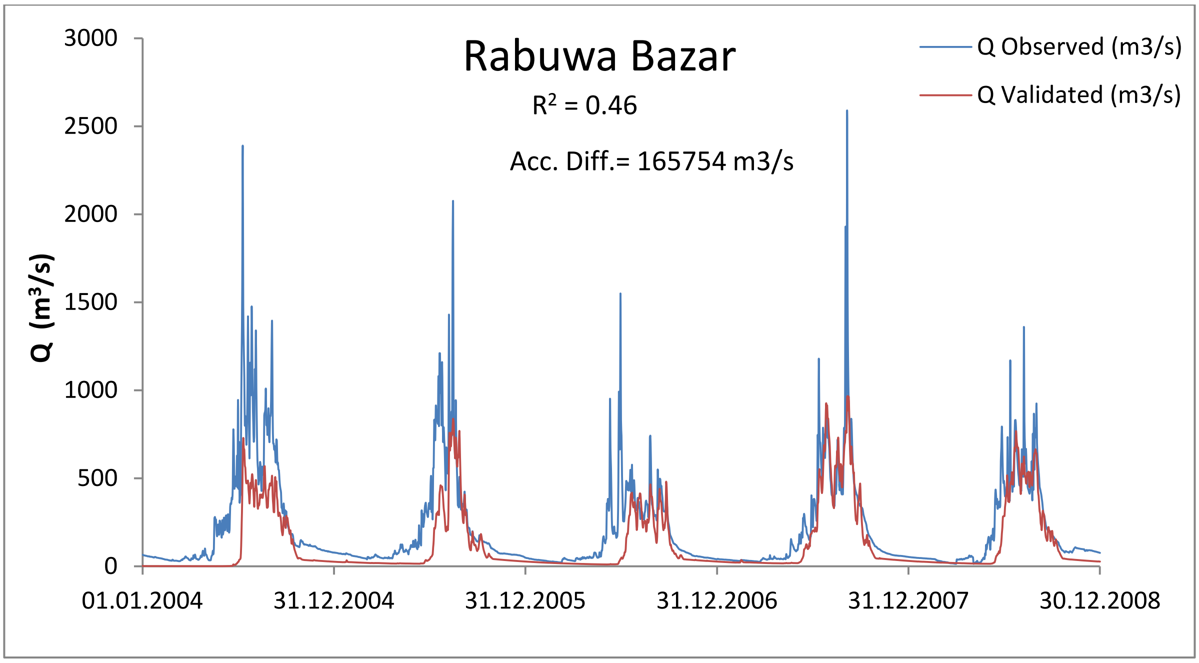


Figure 7.25: Validation of sub-catchment Rabuwa Bazar for Case II

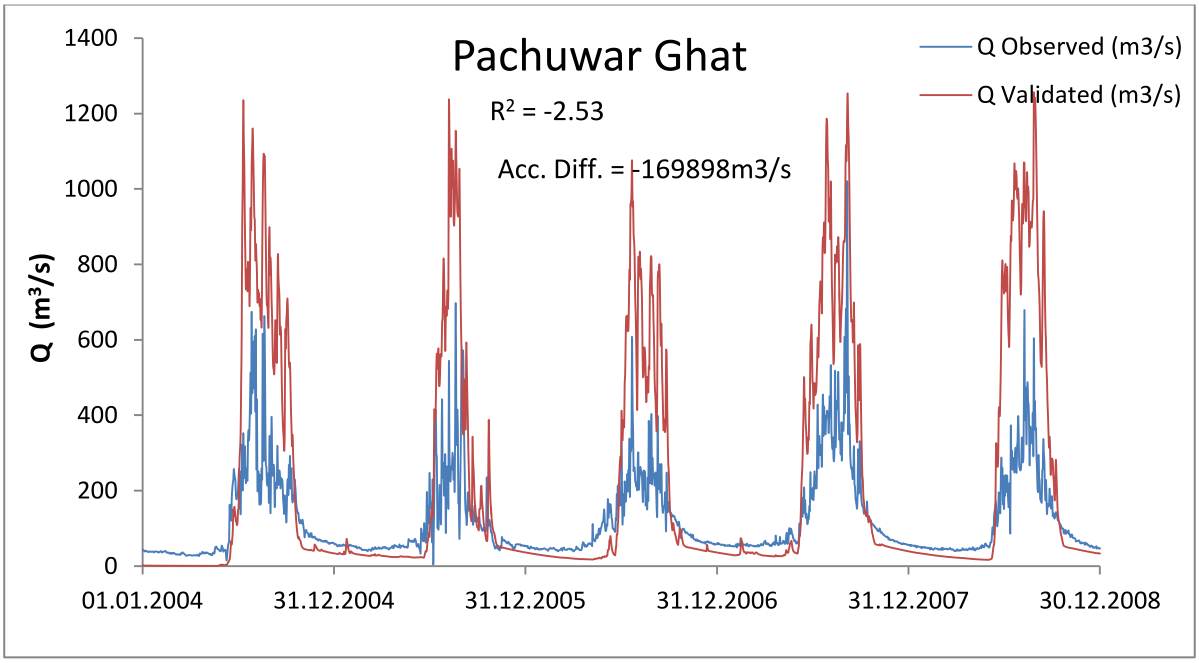


Figure 7.26: Validation of sub-catchment Pachuwar Ghat for Case II

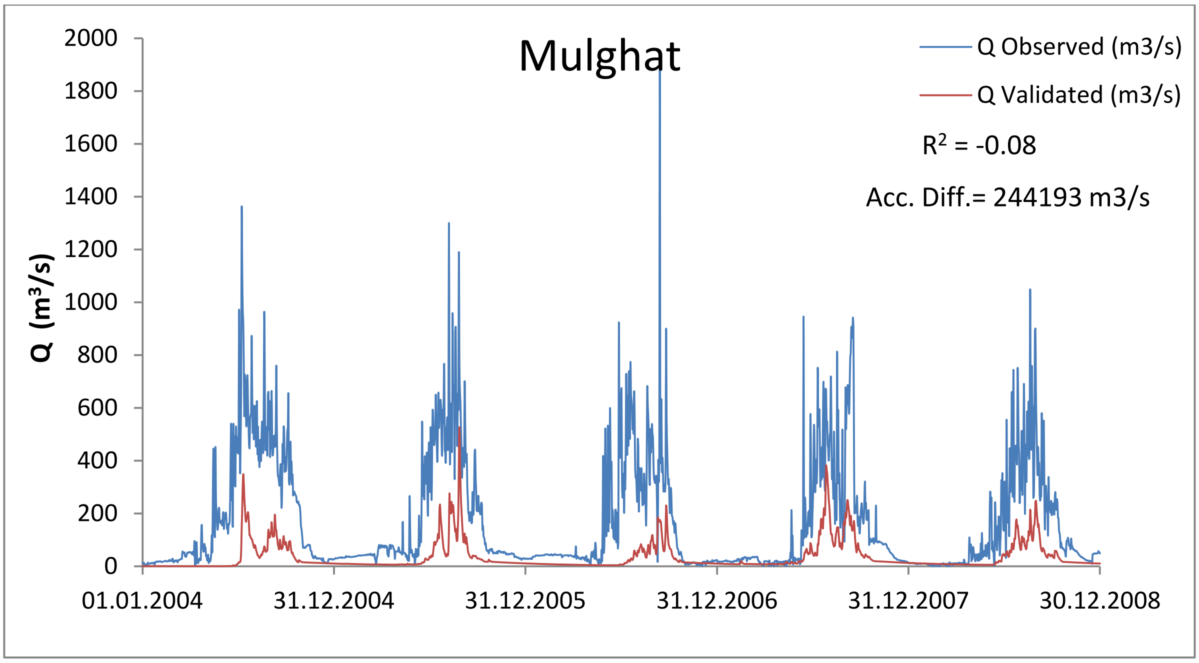


Figure 7.27: Validation of sub-catchment Mulghat for Case II

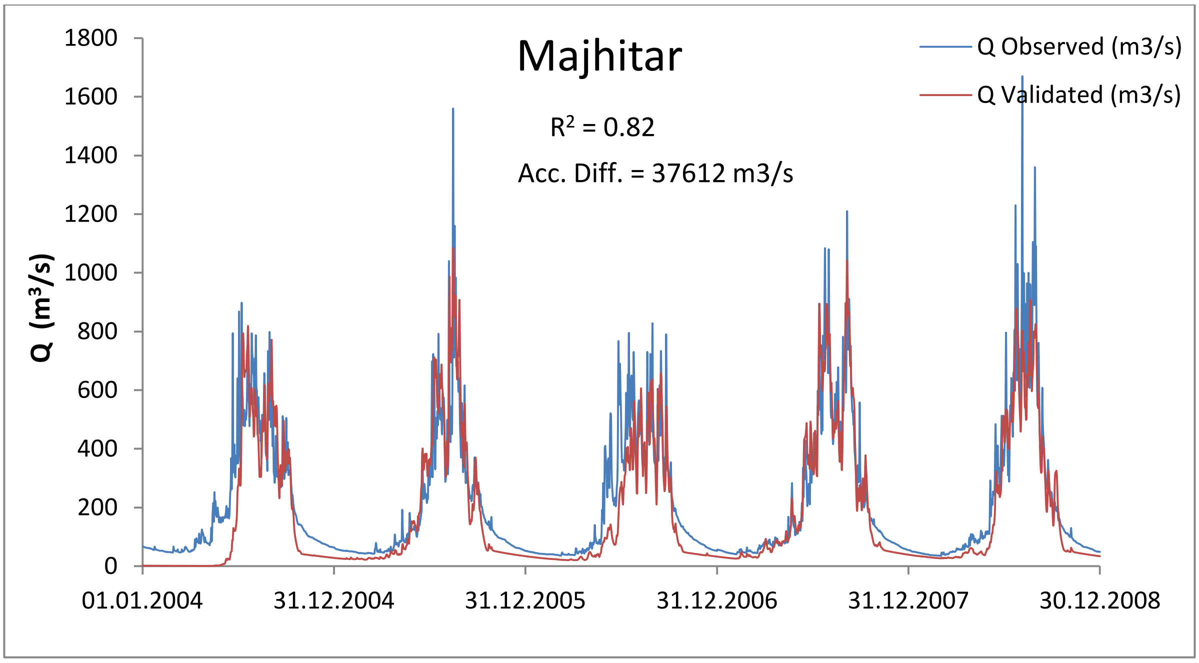


Figure 7.28: Validation of sub-catchment Majhitar for Case II

In case of Majhitar catchment, the simulated runoff is well fitted with the measured data and able to achieve R^2 of 0.82.

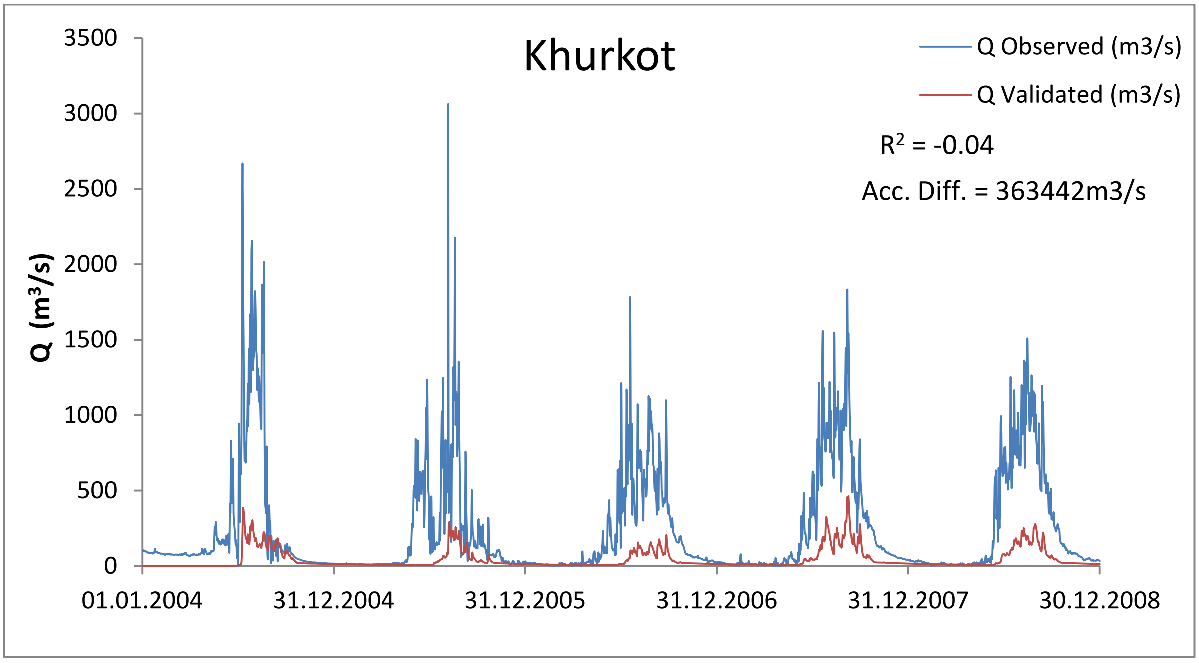


Figure 7.29: Validation of sub-catchment Khurkot for Case II

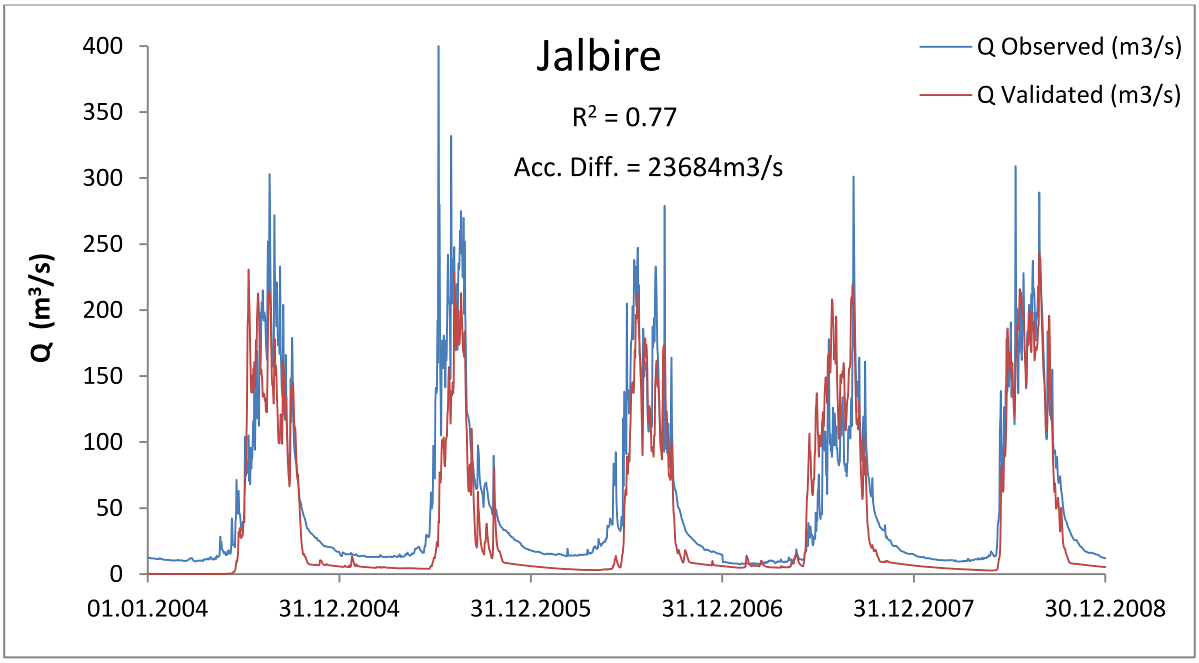


Figure 7.30: Validation of sub-catchment Jalbire for Case II

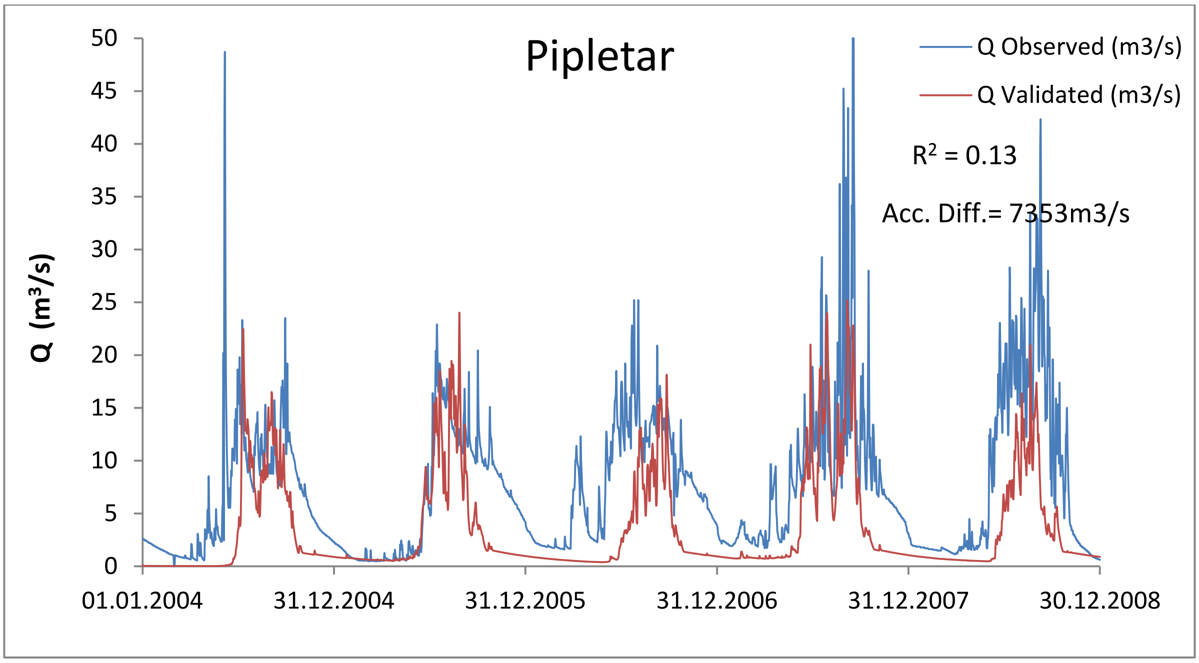


Figure 7.31: Validation of sub-catchment Pipletar for Case II

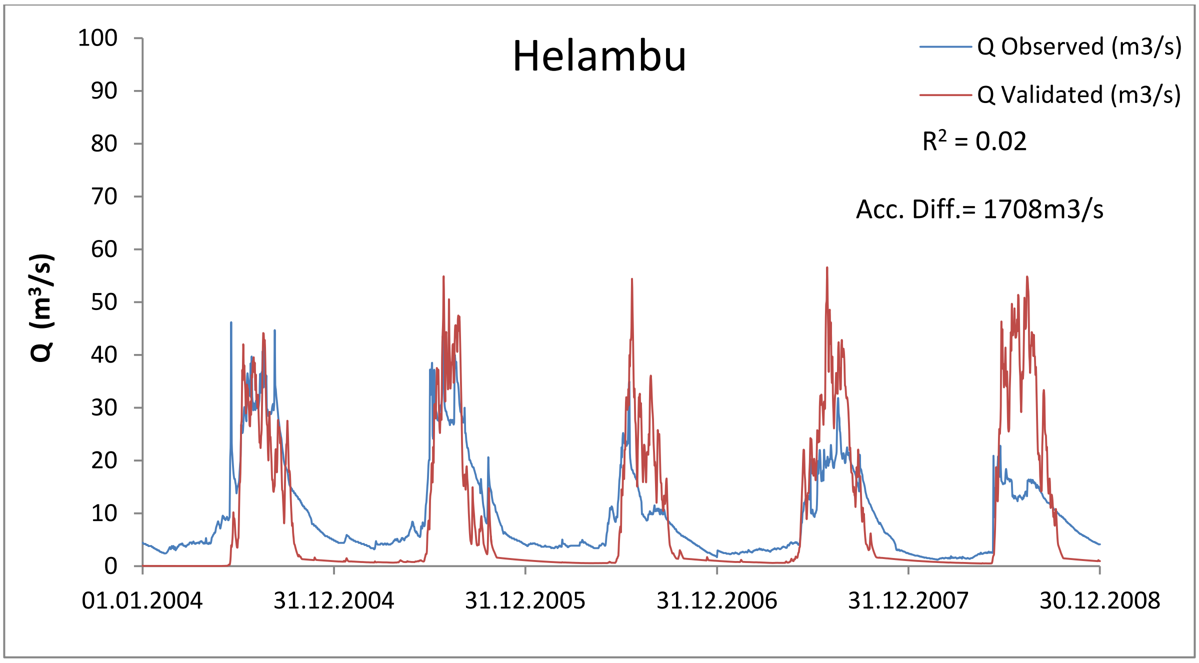


Figure 7.32: Validation of sub-catchment Helambu for Case II

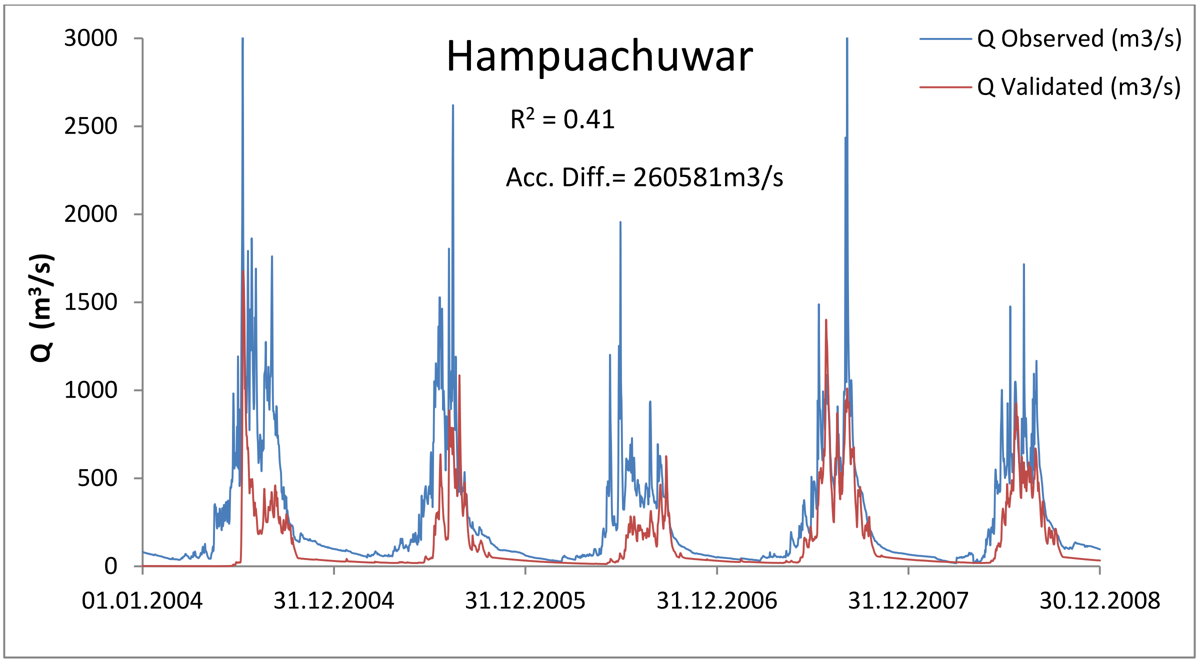


Figure 7.33: Validation of sub-catchment Hampuachuwar for Case II

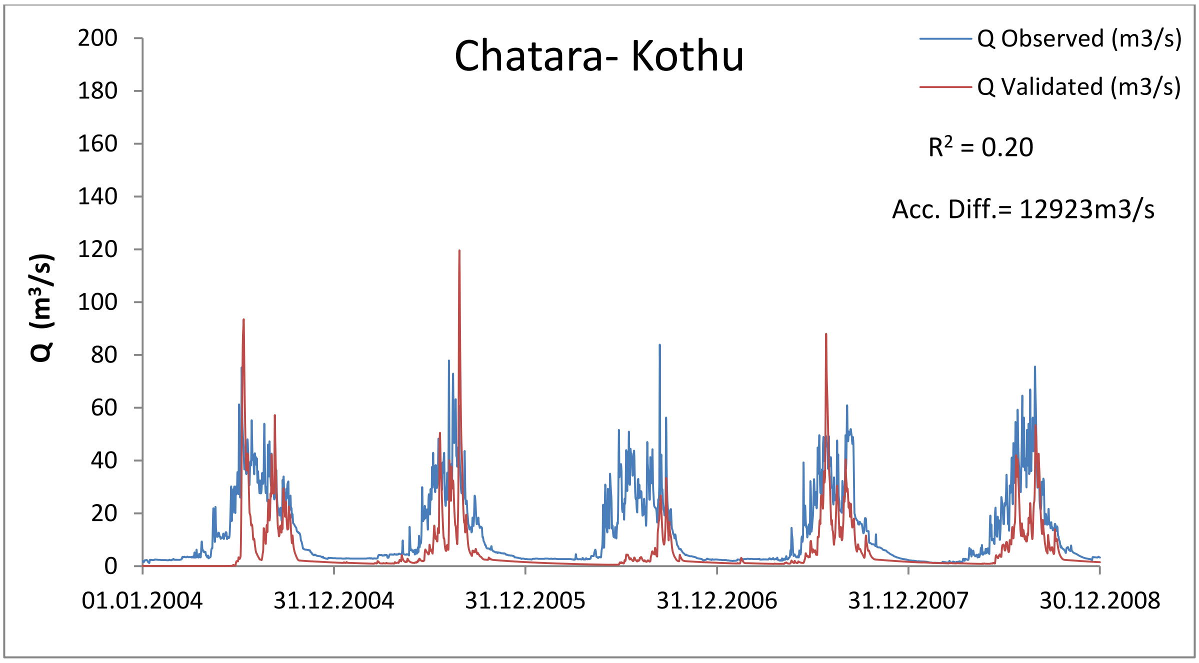


Figure 7.34: Validation of sub-catchment Chatara-Kothu for Case II

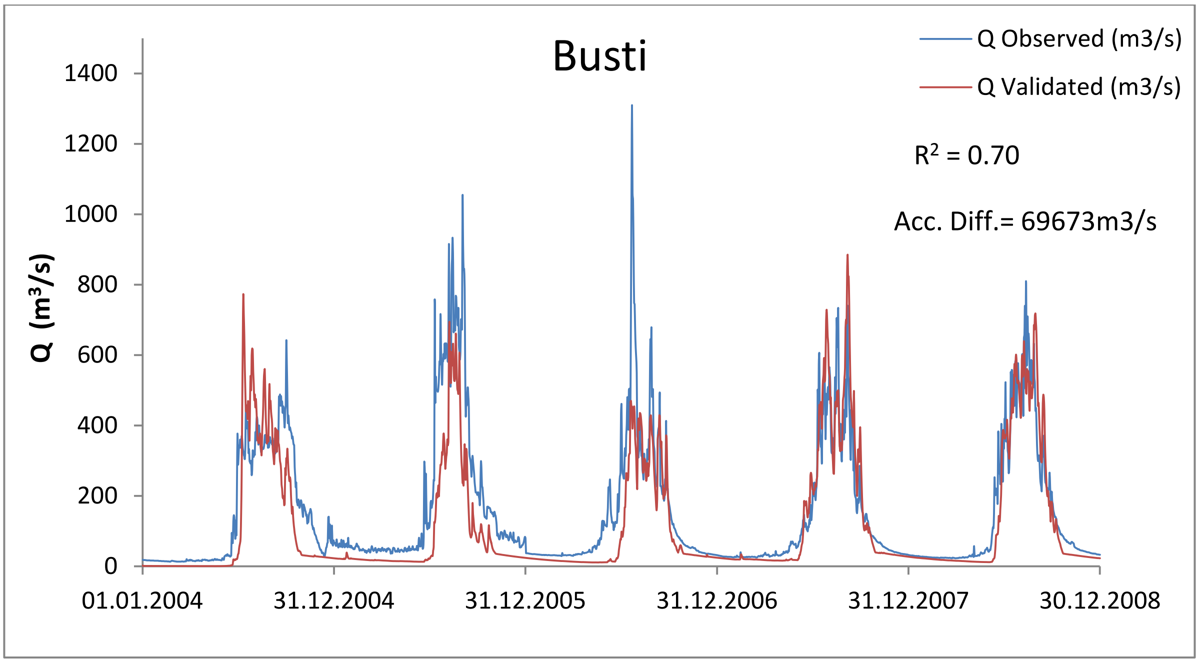


Figure 7.35: Validation of sub-catchment Busti for Case II

It can be noticed from detail observations of all 15 hydrographs that the simulated hydrographs for years 2005, 2007 and 2008 are similar pattern with observed hydrographs even in the worst conditions of R^2. For years 2004 and 2006, the time bases of the simulated hydrographs are shorter than the observed hydrographs i.e. the width of peak of simulated hydrographs are short.

7.3.5 Calibration: Case III

In the calibration case III, only independent sub-catchments of the Saptakoshi basin are considered for analysis. There are altogether 9 independent catchments but Uwa Gaon is already excluded for analysis so that the study is limited to only 8 catchments. The most of these catchments have high variation of altitude and include the elevation of 8848 m to 300m. Some catchments are very small and some are large. The one benefit of simulating independent catchments is that it reduces the accumulation of errors when calculating runoff of local catchments. Another advantage of choosing less numbers of catchments for calibration is that it reduces the dimensionality of multi-objective problem [20].

The input GIS data of catchment delineation for ENKI system is shown in Figure 7.36. The calibration is done in similar process like above cases. All the ranges of the parameters are carried out same as above cases, the detail of calibration parameters and their best values are shown in Appendix 4.The calibration is carried out for the period of year 1999 to 2003 and validation is done for the same period but for the remaining catchments of the Saptakoshi basin.

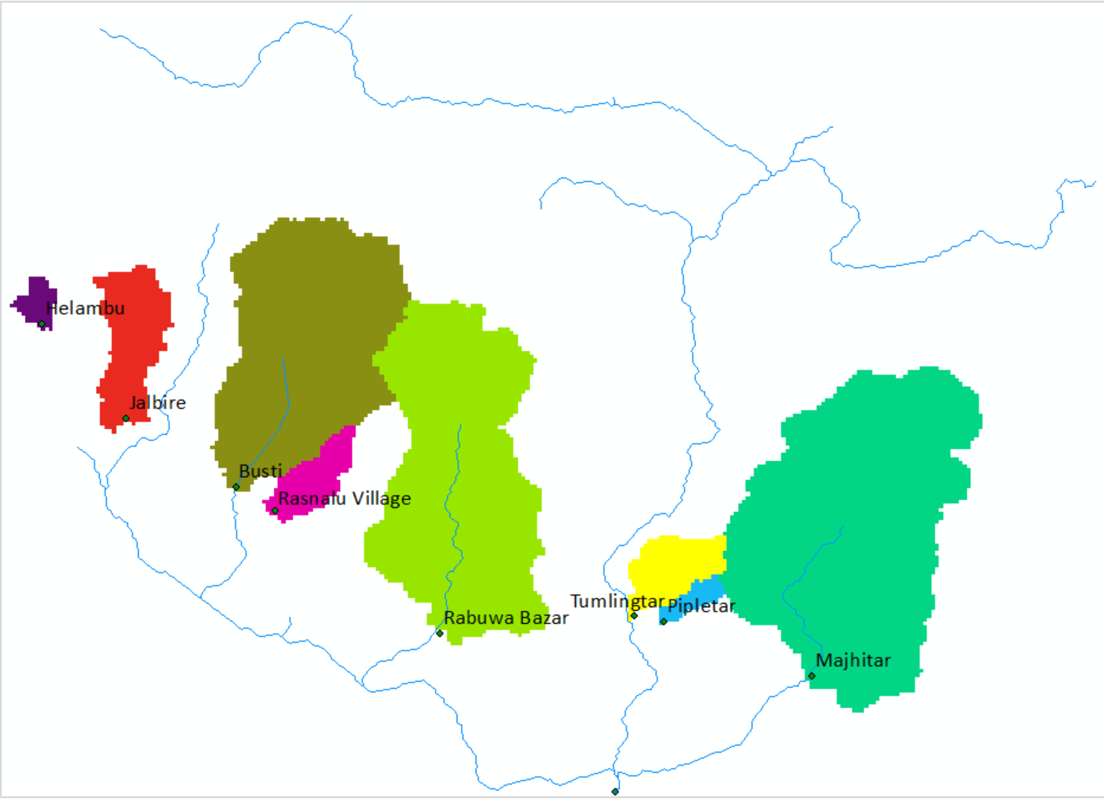


Figure 7.36: Sub-catchments of the Saptakoshi basin for calibration case III

7.3.5.1 Results of calibration: Case III

The SCE-UA calibration method is applied to achieve as possible as good fit of Nash efficiency R^2 values and the model is run less than 500 iterations to 8 catchments. It can be clarified from the Table 7.4 that the goodness of fit R^2 has been considerably improved. The average R^2 value is 0.59 for this calibration.

Table 7.4: Summary of results of case III

Sub-catchments	R^2	Acc. Diff. (m^3/s)
Busti	0.76	-14455
Helambu	0.35	11822.00
Pipletar	0.29	3916
Jalbire	0.78	12826
Majhitar	0.74	9158
Rabuwa Bazar	0.68	106232
Rasnalu Village	0.54	8743
Tumlingtar	0.54	-1687
Average	**0.59**	

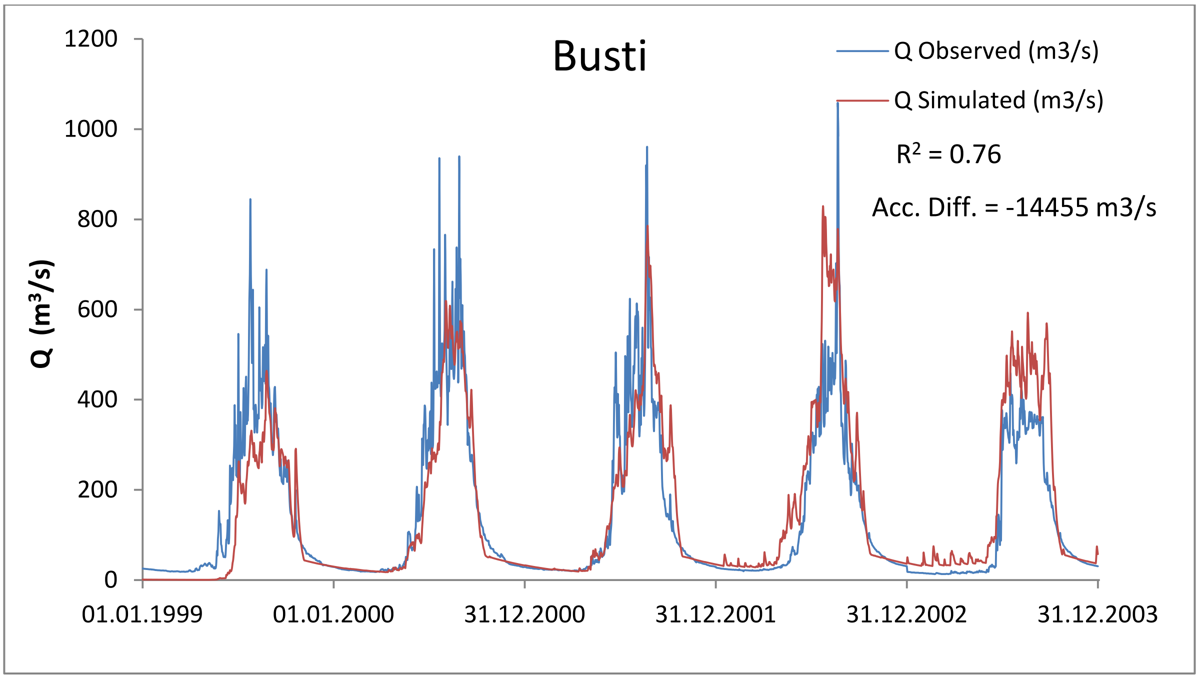


Figure 7.37: Calibration of sub-catchment Busti for Case III

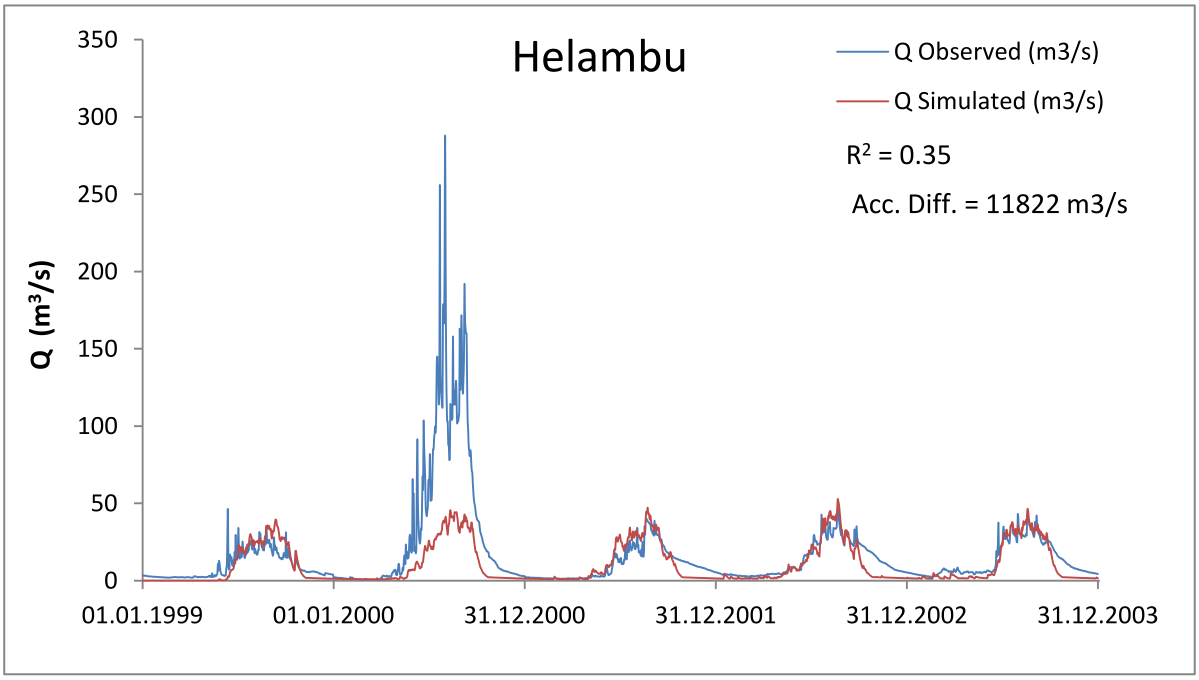


Figure 7.38: Calibration of sub-catchment Helambu for Case III

The R^2 of 0.76 is achieved for Busti basin and the model is able to estimate well fitted hydrograph. In case of Helambu, the R^2 is 0.35 and the simulated runoff is well fitted in years 1999, 2001, 2002 and 2003 but in year 2000 the observed runoff is very high. The result in case II also showed same pattern.

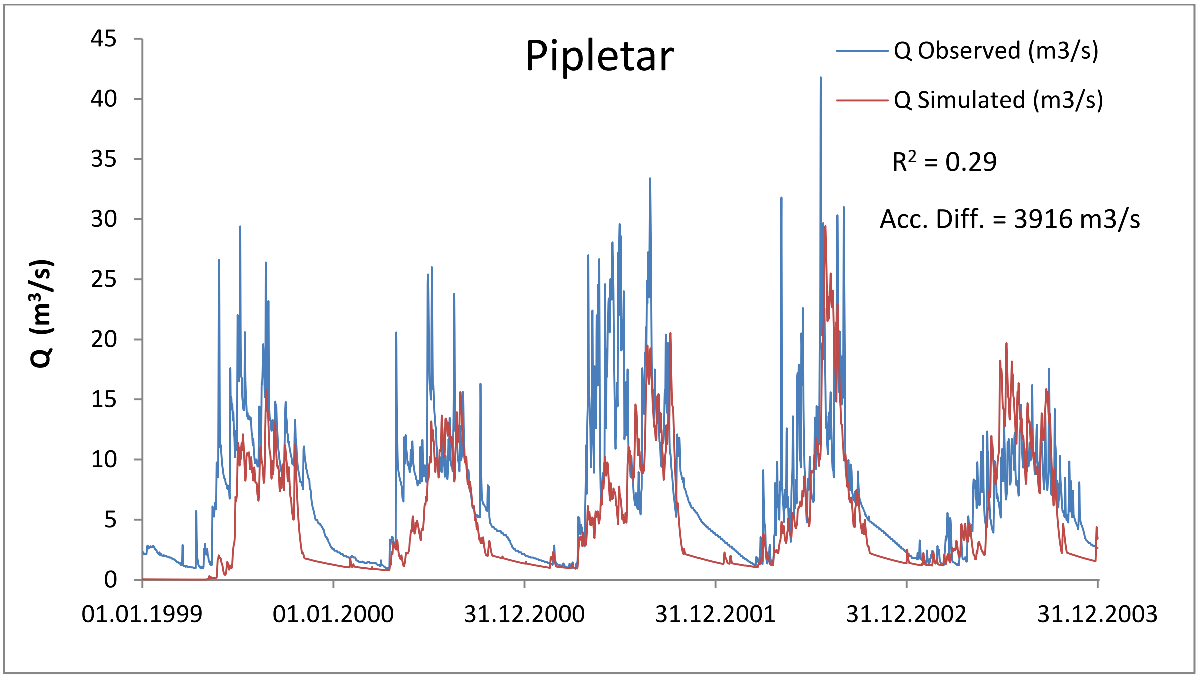


Figure 7.39: Calibration of sub-catchment Pipletar for Case III

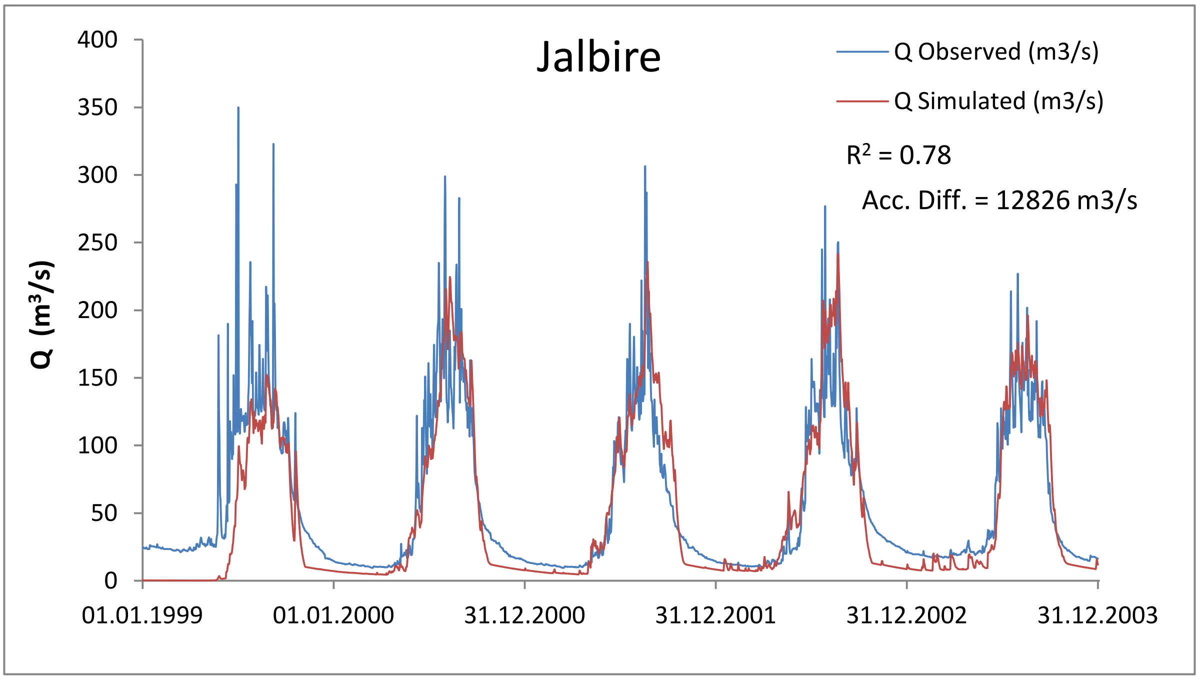


Figure 7.40: Calibration of sub-catchment Jalbire for Case III

The R^2 of small catchment Pipletar is increased than in Case II. The simulated runoff for Jalbire catchment is considerably good and the model has a goodness of fit of 0.78.

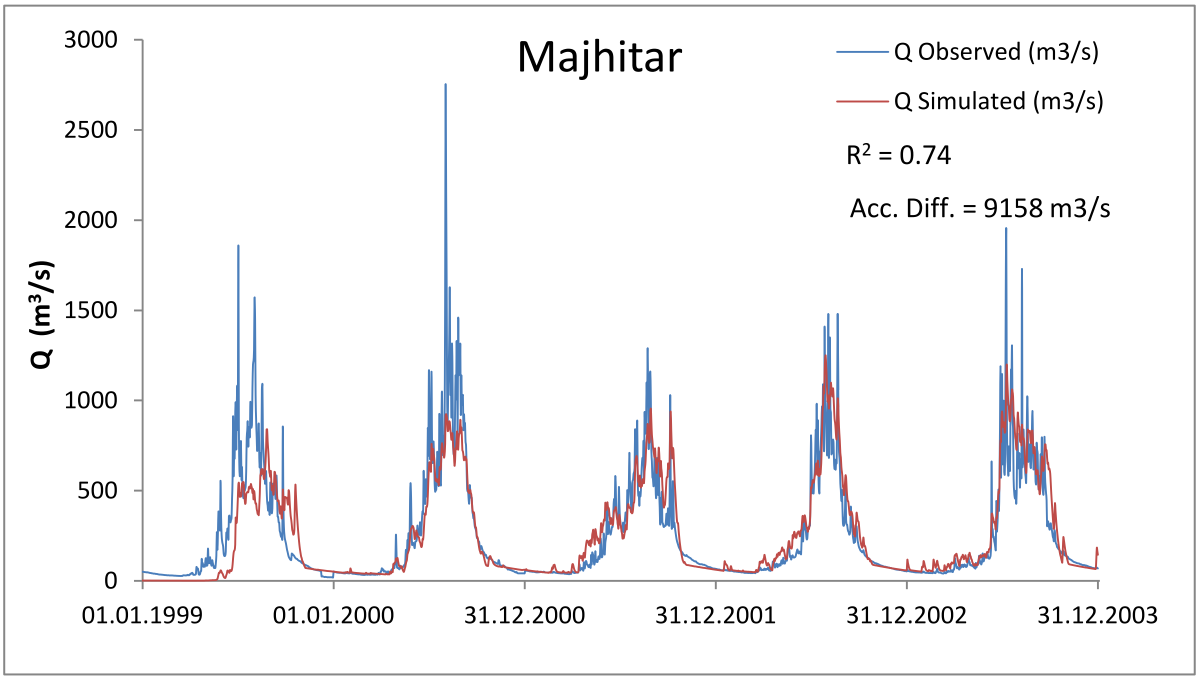


Figure 7.41: Calibration of sub-catchment Majhitar for Case III

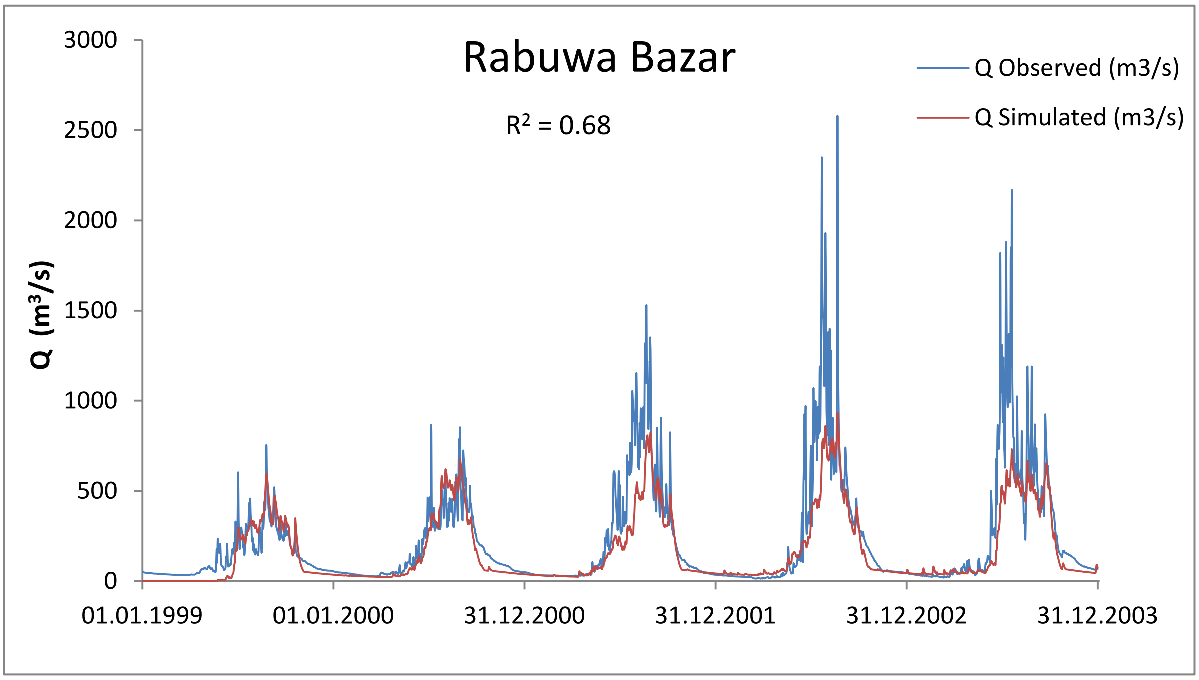


Figure 7.42: Calibration of sub-catchment Rabuwa Bazar for Case III

The model is found very well calibrated and simulated values are very well fitted for basins Majhitar and Rabuwa Bazar.

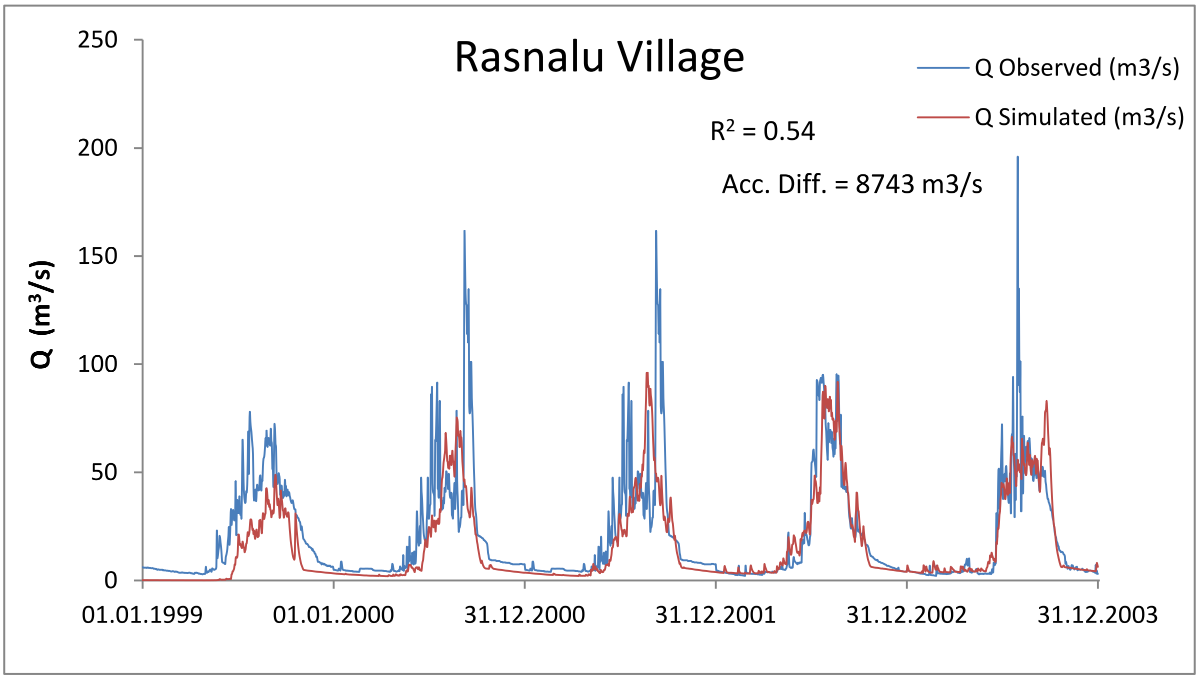


Figure 7.43: Calibration of sub-catchment Rasnalu Village for Case III

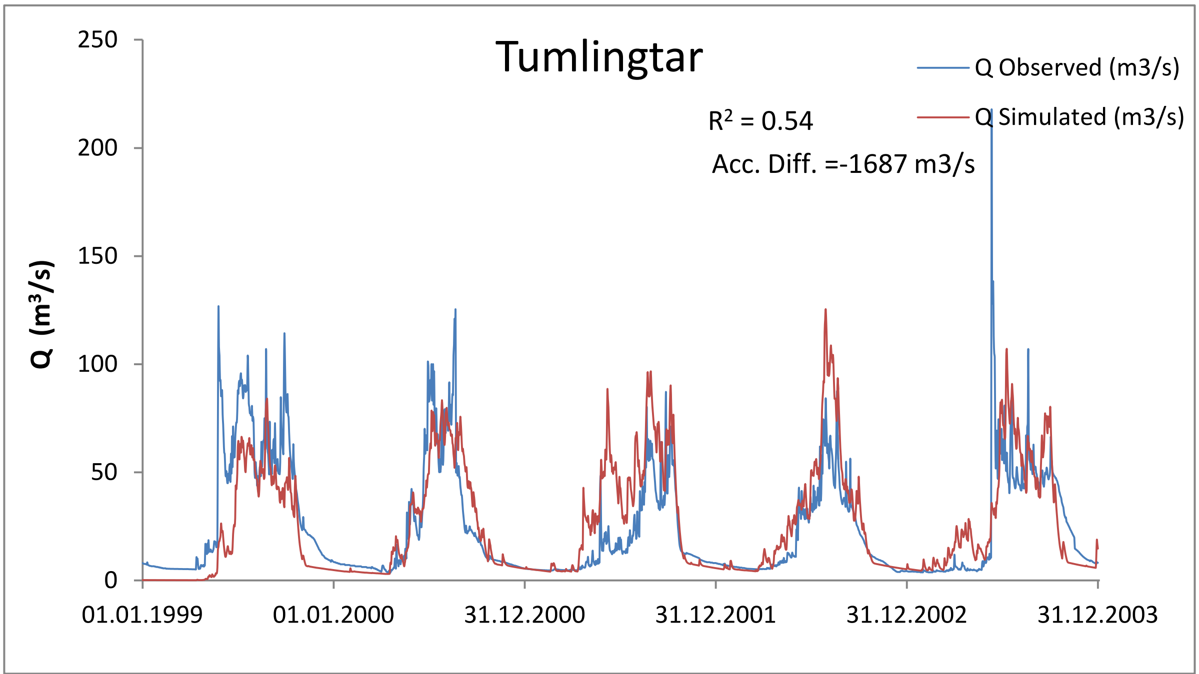


Figure 7.44: Calibration of sub-catchment Tumlingtar for Case III

It can be concluded from above results of hydrographs that the model is able to estimate the well fitted streamflows for large catchments. For small catchments Pipletar and Helambu the R^2 values are very low but higher than in case II. This may be due to flashy variations in observed runoff.

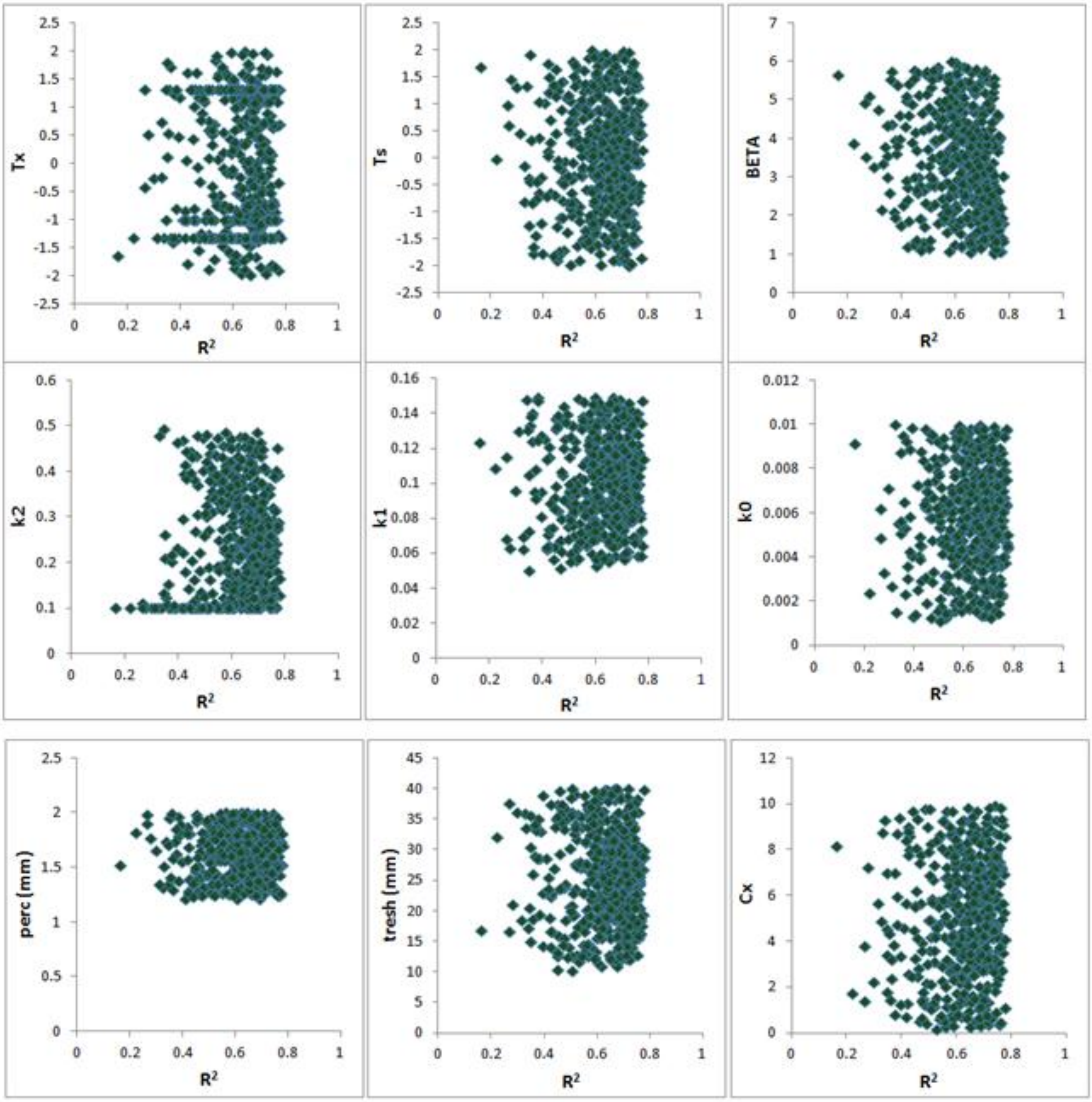


Figure 7.45: Scattered plots of different calibrated parameters vs. R^2 for catchment Majhitar

The scattered plots of different parameter with respect to R^2 are shown in Figure 7.45 for Majhitar catchment. It can be visualized from these figures that the variations of these parameter values impact the R^2. The 30 parameter values are obtained and among these some are less sensitive to the output results such as maximum distance between stations and numbers of stations which are kept constant. From above plots, it can be seen that how the variations of the different parameters deviate the performance of the model.

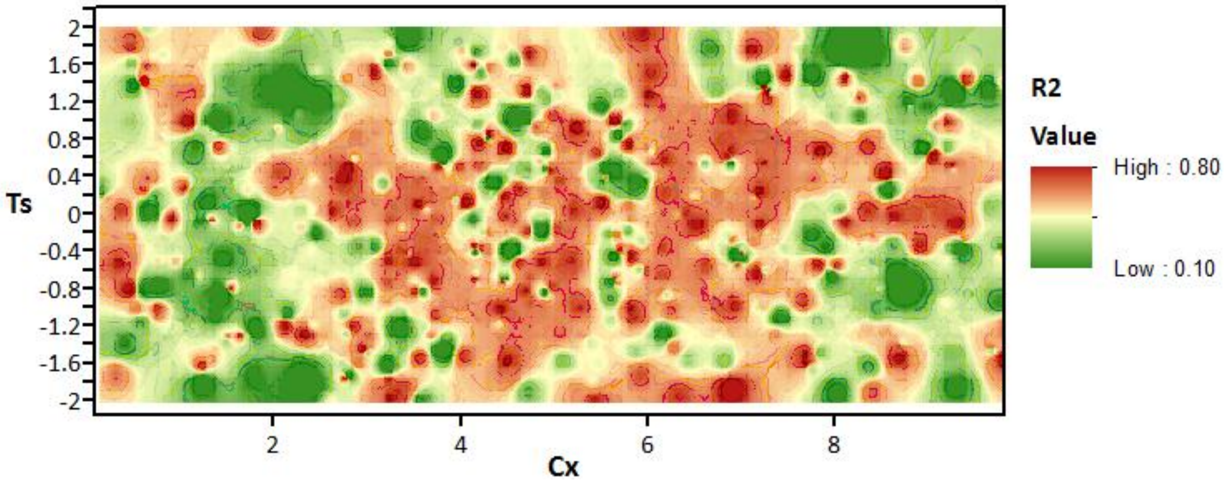


Figure 7.46: Variation of Nash-Sutcliffe efficiency (R^2) with respect to different combinations of parameter values Ts (threshold temperature for snow melt) and Cx (degree-day factor) for Majhitar catchment.

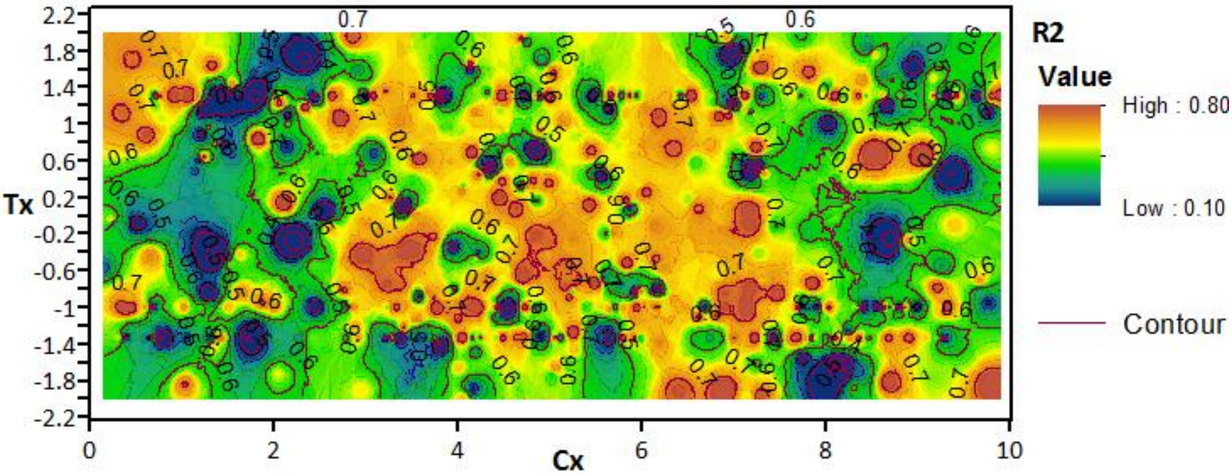


Figure 7.47: Variation and contours of Nash-Sutcliffe efficiency (R^2) with respect to different combinations of parameter values Tx (threshold temperature for rain/snow) and Cx (degree-day factor) for Majhitar catchment.

The other way of showing deviations of R^2 is the effect of combinations of two or more than two parameters. In Figure 7.46, it can be seen how the R^2 varies when the combination of Ts and Cx deviates. The model gives the best value of R^2 at the range of -0.4 to 0.8°C of Ts and 4 to 8 of Cx. The optimization concept of parameters by SCE-UA method can be visualized from Figure 7.47. The model searches the peak of R^2 value with one combination of parameters and then again leads to reach other peaks with another combination of parameters and it continues until best combinations of parameters not achieved.

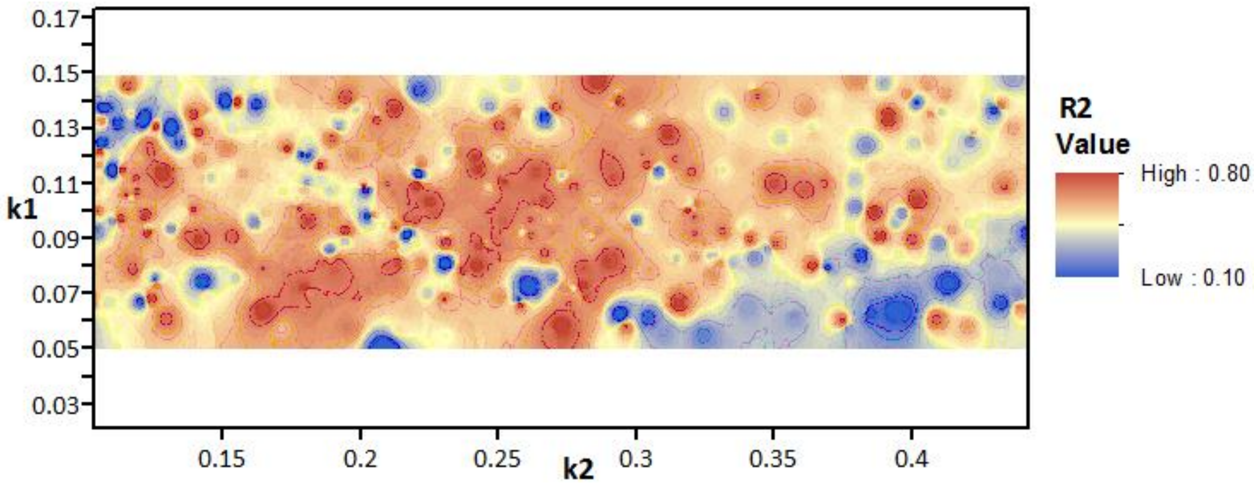


Figure 7.48: Variation of Nash-Sutcliffe efficiency (R^2) with respect to different combinations of parameter values k2 (fast discharge coefficient for upper tank) and k1 (slow discharge coefficient for upper tank) for Majhitar catchment.

The Figure 7.48 shows the combinations of the upper tank drainage coefficients k1 and k2. The k1 within range from 0.05 to .12 and k2 in the range of 0.15 to 0.3 give the good fit of calibration of the model for Majhitar catchment.

7.3.6 Validation of the model for case III

In this case, the model is validated for rest of seven catchments for same period of year 1999 to 2003. The validation result of case III is better than the result of case II when comparing summary tables of case II and III. The model is able to achieve the average R^2 of 0.15 and the individual R^2 values are closed to case II.

Table 7.5: Summary of model validation for case III

Sub-catchments	R^2	Acc. Diff. (m^3/s)
Chatara- Kothu	0.35	16227
Hampuachuwar	0.46	240275
Khurkot	0.10	227330
Mulghat	-0.04	343488
Pachuwar Ghat	-0.61	-244944
Simle	0.35	167522
Turkeghat	0.41	197031
Average	**0.15**	

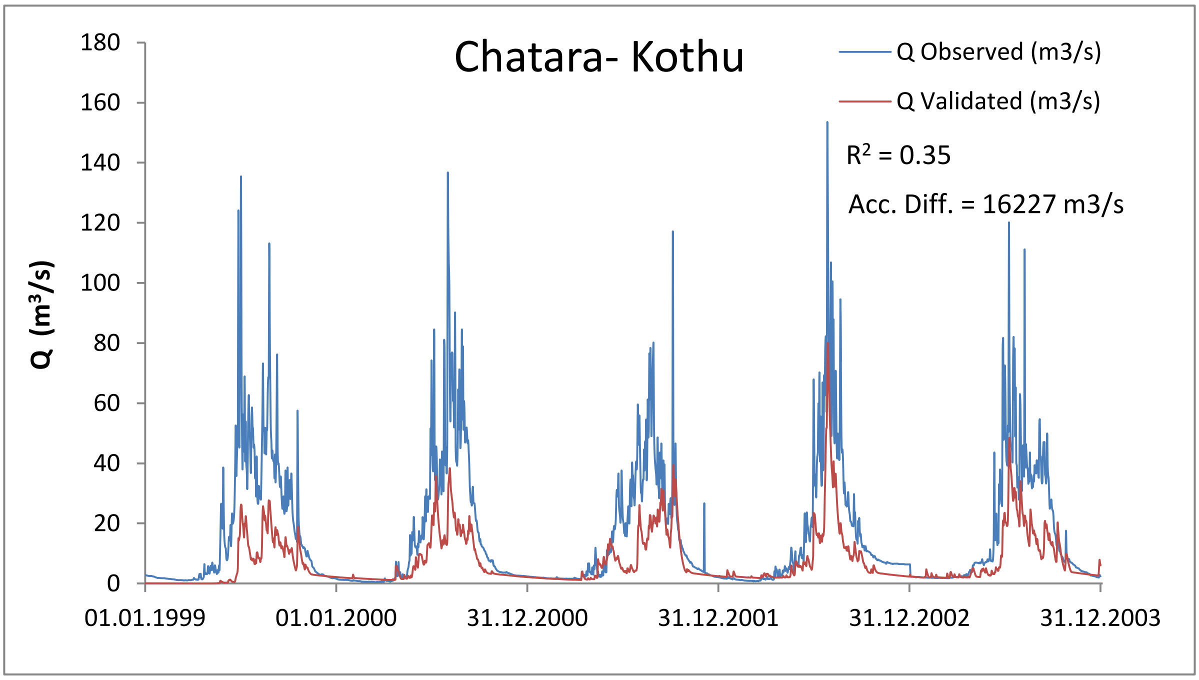


Figure 7.49: Validation for catchment Chatara-Kothu for case III

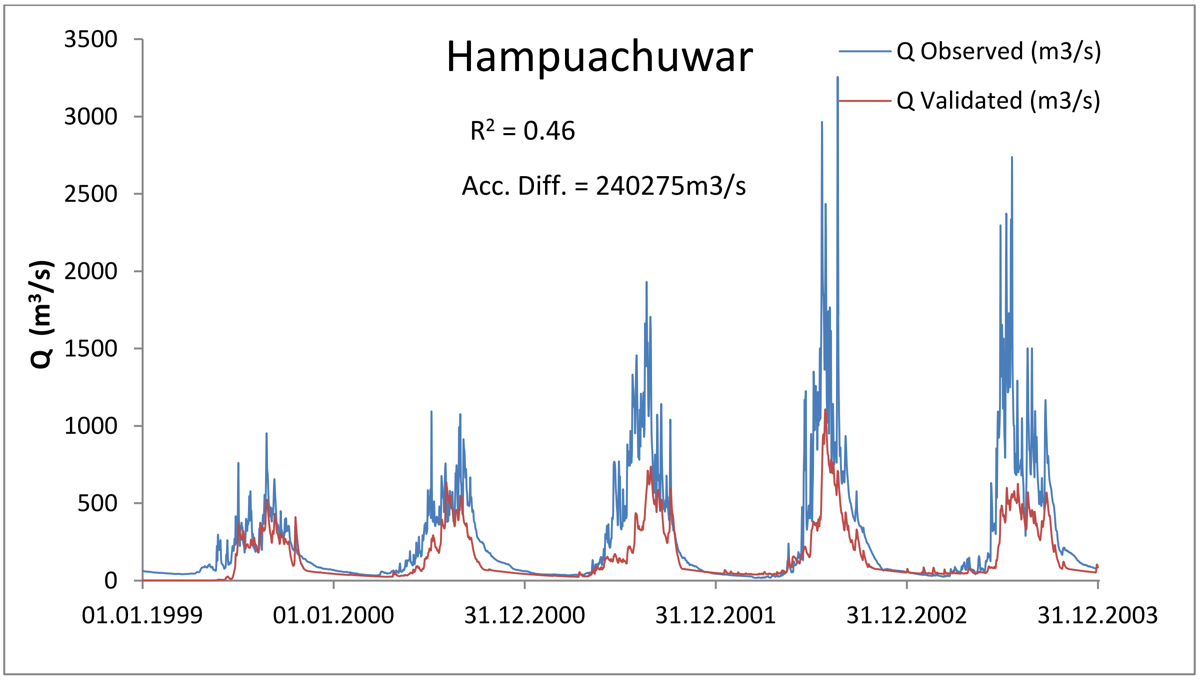


Figure 7.50: Validation for catchment Hampuachuwar for case III

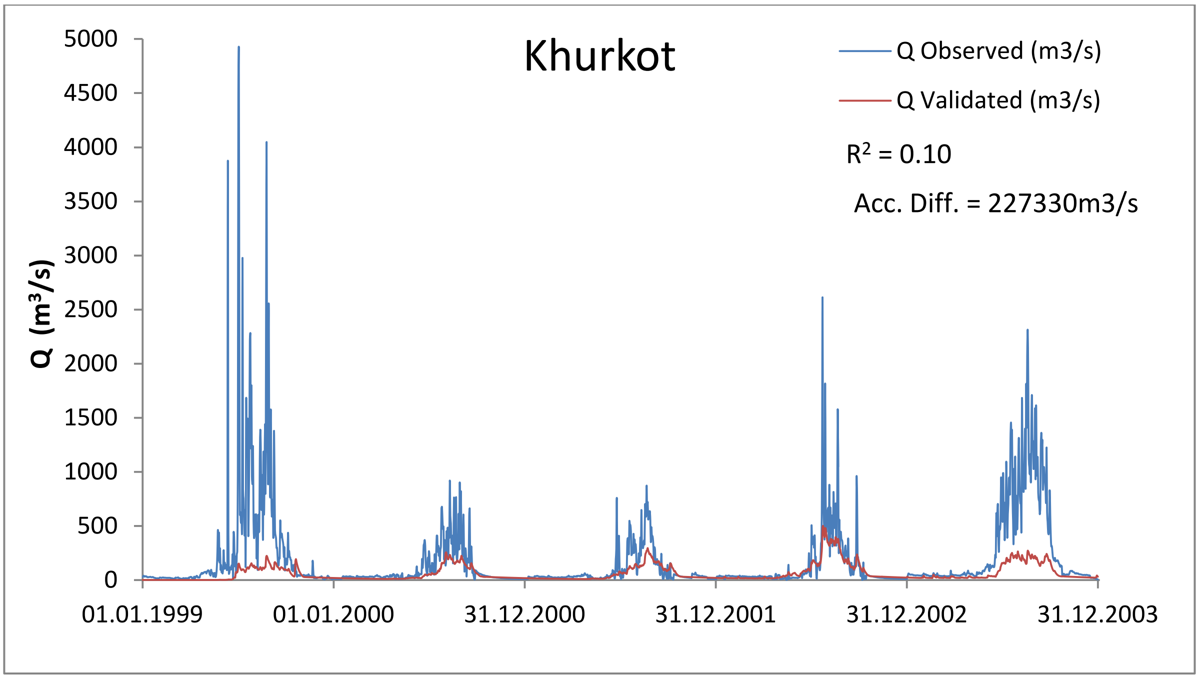


Figure 7.51: Validation for catchment Khurkot for case III

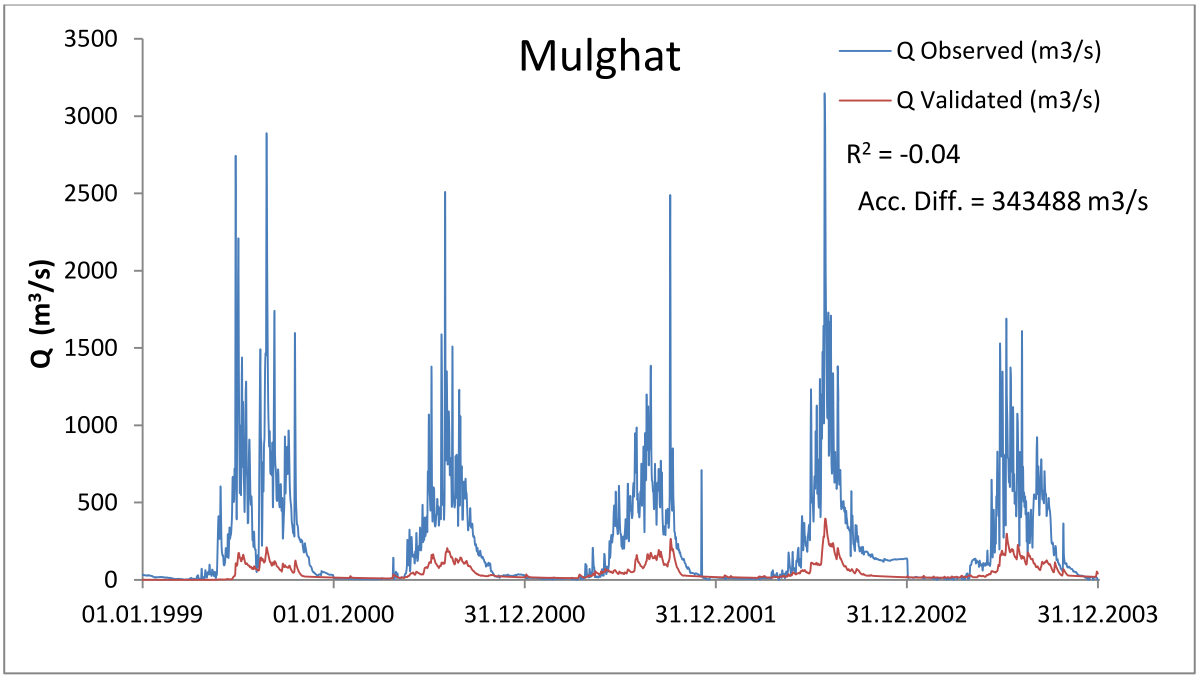


Figure 7.52: Validation for catchment Mulghat for case III

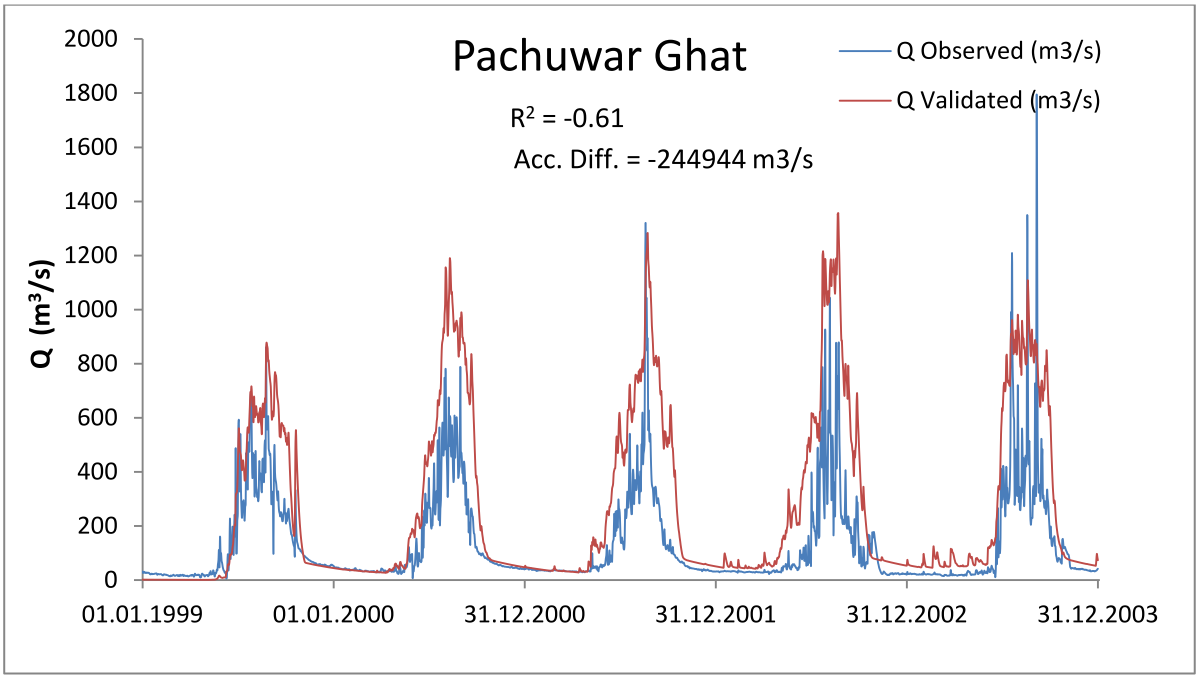


Figure 7.53: Validation for catchment Pachuwar Ghat for case III

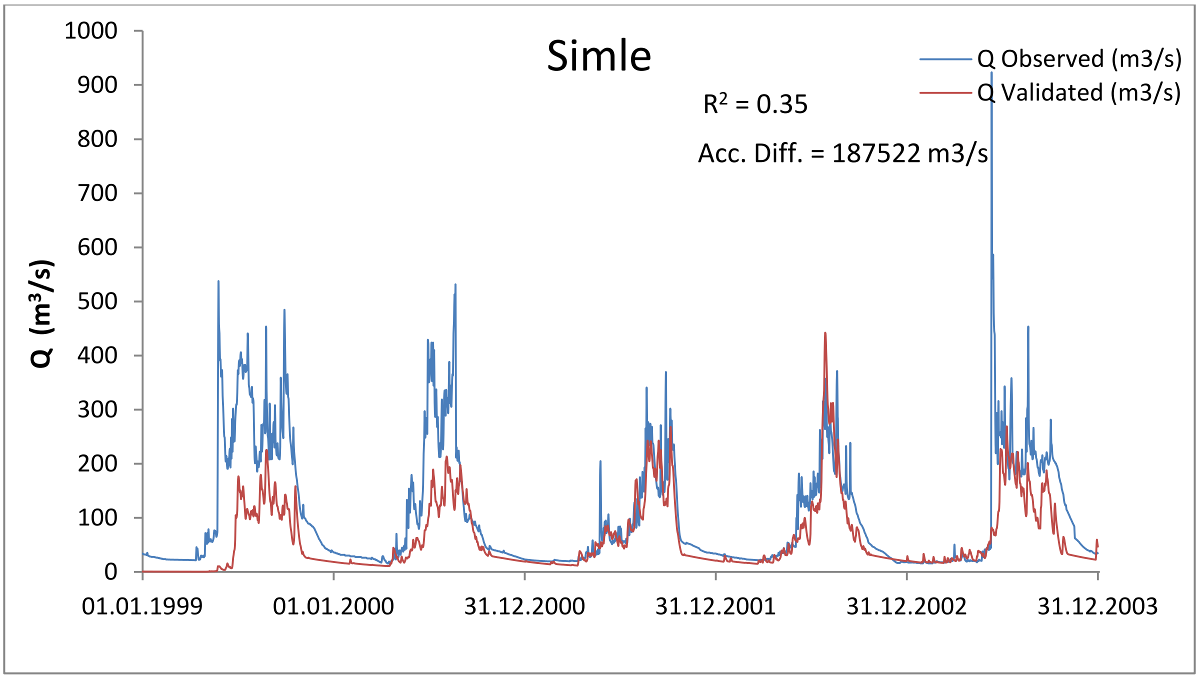


Figure 7.54: Validation for catchment Simle for case III

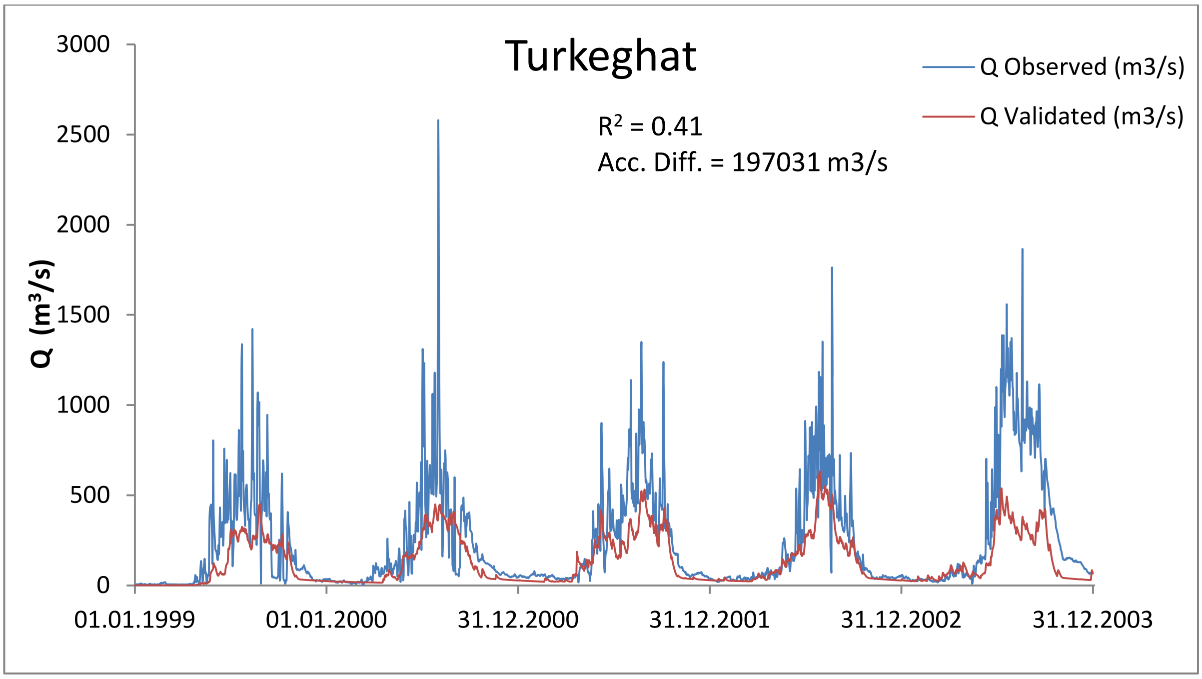


Figure 7.55: Validation for catchment Turkeghat for case III

Hence, the simulation of case III improved the overall Nash efficiency and also reduces the calibration time and iteration numbers.

7.4 EXTRACTION OF RUNOFF FROM INTAKE SITE: TAMOR

The main application of regional modelling is to extract runoff data from ungauged sites. The intake sites situated at high altitude have no measured data for long periods. The data can be extracted for these ungauged intake sites by transferring regional parameter set of that region to specific catchments. The calibrated parameter values from simulation case II are used to extract the runoff data from the intake site of Tamor hydropower project.

7.4.1 Intake location

The intake of Tamor hydropower project is located at 27°29'40"N and 87°46'59"E and altitude of 1348.5m. The capacity of project is 204MW. The detail description of project is available in Sanima Hydro and Engineering (SHE) P. Ltd. and the scaling factor used to calculate the runoff is 0.31 with the Majhitar gauge station [34]. The location of Tamor catchment is shown in Figure 7.56.

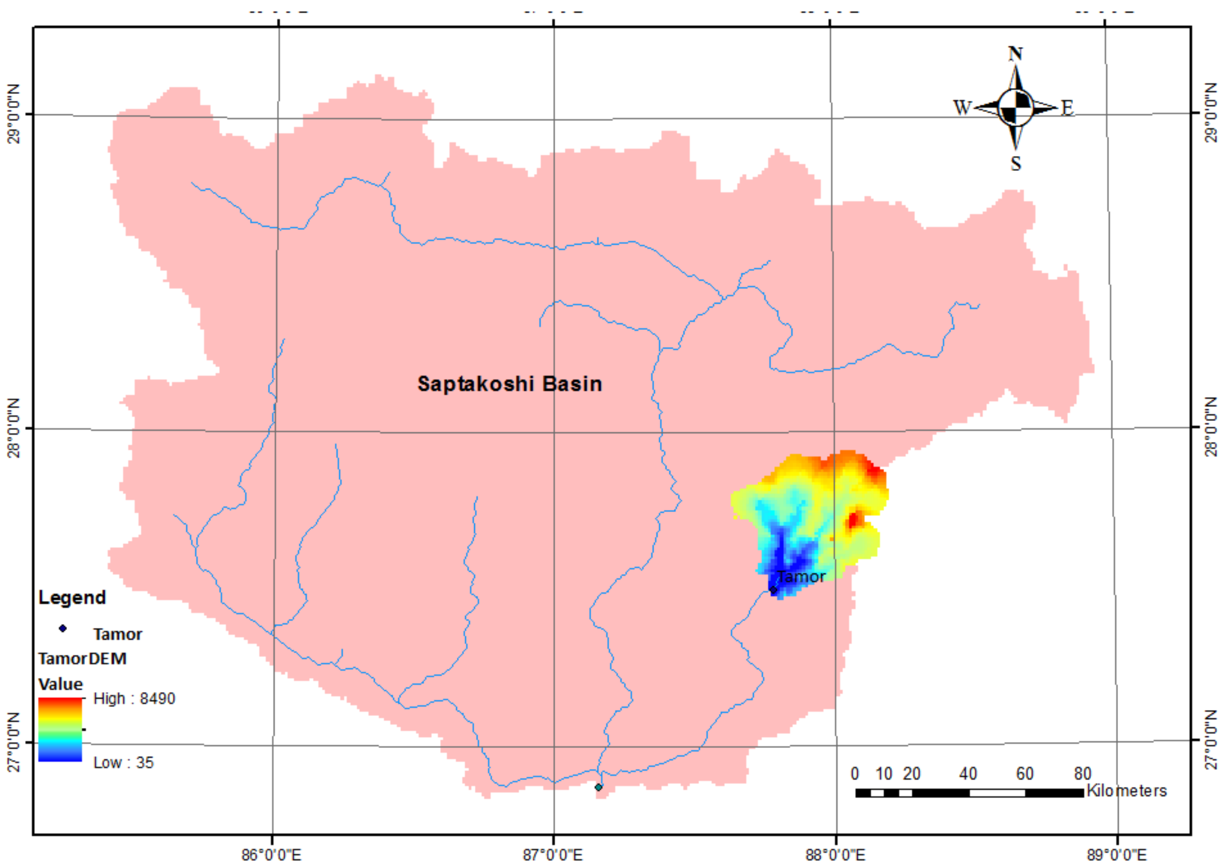


Figure 7.56: Location map and DEM of Tamor catchment

7.4.2 Input data and model setup of ENKI for extraction

The input data like precipitation, air temperature, and evaporation are same as above models. The GIS data like catchment area delineation, land use and DEM are separately prepared as shown in Figure 7.56. All the parameters, which are obtained from calibration case III as described in Table 7.1, are used to run the model. The only difference in setup of ENKI model is that when setting the performance measure specification the comparison is chosen as “only simulated values”.

7.4.3 Result of extraction of runoff data for Tamor hydropower project

The actual scaled runoff data used in planning of the project is calculated by scaling runoff data of Majhitar gauge station with scaling factor of 0.31 and this data is applied to compare with extracted data. The hydrograph of extracted runoff and scaled runoff of 10 years period from 1999 to 2008 is shown in Figure 7.57.

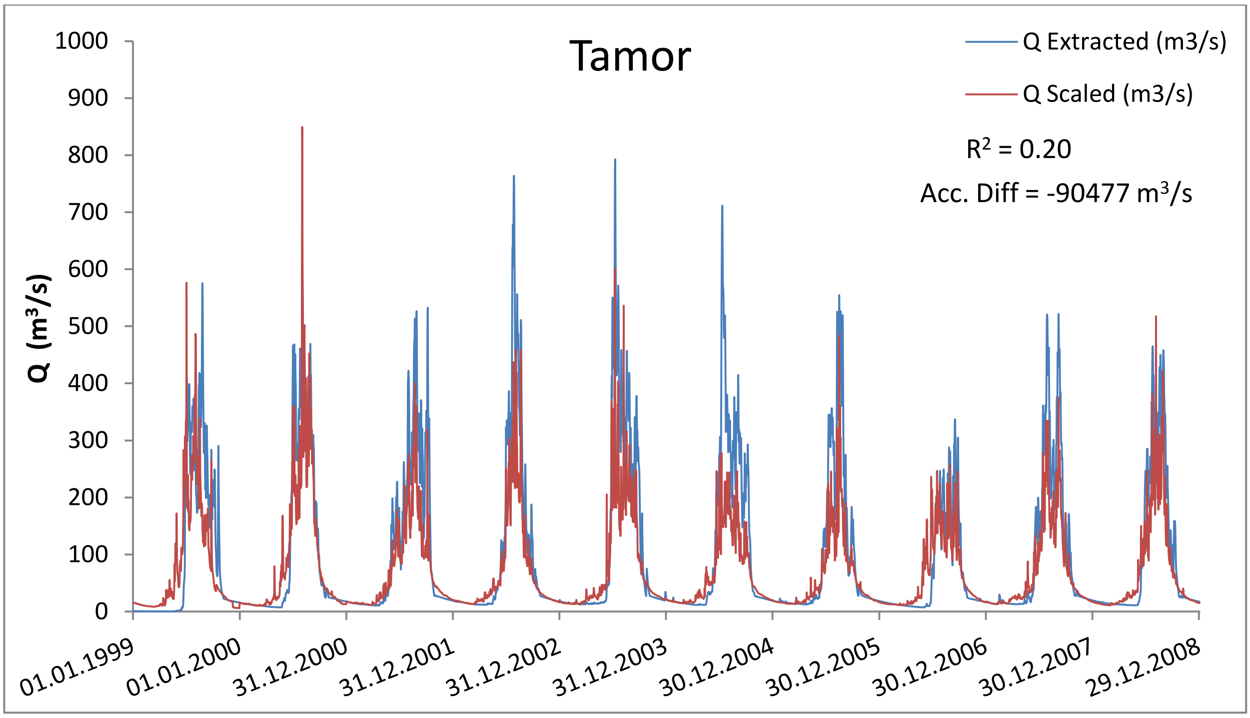


Figure 7.57: Hydrographs of extracted and scaled runoff for Tamor

The extracted runoff data and scaled runoff data is comparatively similar except the peaks of flow. The base flow is somehow lower than scaled data. The goodness of fit R^2 between these two hydrographs is 0.20 and accumulated difference between scaled and extracted streamflow for 10 years is -90477m^3/s. There are great uncertainties in comparing with these results because the actual data are not available. However, this catchment is the upper part of Majhitar catchment and the simulation results of Majhitar for both cases (II & III) are better than other catchments. Hence the extracted runoff should also be good fit with actual runoff at the intake site.

8 CONCLUSION AND DISCUSSION

"As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality."

-Albert Einstein

8.1 CONCLUSION AND DISCUSSION

The Regional rainfall runoff model is calibrated in the Saptakoshi basin of Nepal in order to get a good fit between observed and simulated runoff. The main aim of regional calibration is to obtain the regional parameter sets for ENKI model applied to the Saptakoshi basin and extract the reliable runoff data from ungauged sites.

The study river basin is the largest basin of Nepal, having the total catchment area of 54100 km^2 and high variation of the altitude from 140 m to 8848 m. The good quality of observed data and availability of enough data govern the best simulation of the model and best value of the Nash efficiency R^2.

The input climatic data such as precipitation, air temperature, evaporation and runoff from 1999 to 2008 are collected from DHM. All these data are processed for the ENKI model setup. The missing precipitation data are interpolated by Normal ratio method. The air temperature data are not available at all corresponding precipitation stations. The unavailable temperature data at corresponding stations are interpolated by applying Inverse-Distance Weighting method with the help of VBA code. The missing data of evaporation are filled by calculation of Thonthwaite formula. The main uncertainty of basin is due to unavailability of precipitation data of Tibet since the half of basin area lies in Tibet. The consistency and continuity of data are checked by different methods before use in models. The missing data of runoff are filled by scaling with neighbor gauge stations. In some gauge stations like Simle, Hampuwarchuwar and Chatara-Kothu showed less runoff than their respective upstream gauge stations. Hence, there are high errors in collected data and applying these data in simulation causes the uncertainty in results.

The GIS data like watershed delineations, DEM of catchment and landuse are prepared separately in ArcGIS 10. And, the shape files of point networks of all climatic stations are prepared in same coordinate system UTM-45N.

The input data to the ENKI model system are point networks, raster and scalars which should be in ENKI readable formats. These data are converted into ENKI readable formats by IDRISI Taiga.

The ENKI modelling system is equipped with tools for regional model setup and calibration. The models are setup for different three cases i.e. Case I, II & III for calibration. In case I, all the 16 catchments are included for calibration for the period of 1999 to 2003. The average Nash-Sutcliffe efficiency obtained from this calibration is -1.57 which is comparatively very low. The R^2 value of Uwa Gaon is -27.76 which shows that the simulated runoff is greater than observed runoff. Almost whole area of this basin lies in Tibet and due to missing data of Tibet there is high degree of uncertainty in calibration. The pattern and intensity of rainfall around Tibetan area is different than in Nepal. The annual rainfall of some stations in Tibet shows very low like 285mm and 615mm in Tingri and Nyalam stations respectively[3]. In this way, the large quantity of streamflow from simulation obtained by the model is reasonable. Hence, the further analysis and comparison of result from case I is meaningless and not carried out to further study.

In case II, Uwa Gaon catchment is removed for calibration and the average R^2 is improved to 0.33. When Uwa Gaon basin is included in calibration, the model tries to force the calibration in wrong direction to achieve good average R^2 value. Then the R^2 value of Uwa Gaon may be good but the simulations of other catchments may not be reasonable with observed runoff. Hence excluding this basin from calibration reduces this kind of problem. The model performed very well in the independent catchments such as Jalbire, Busti, Majhitar, Rabuwa Bazar, Tumlingtar and Rasnalu Village. But the model is not able to perform well in small catchments like Pipletar and Helambu and other downstream catchments. The results show that the R^2 of Mulghat and Pachuwar Ghat are extremely low but the R^2 values of respective upstream catchments are good. The runoff from simulation is within the range of corresponding catchment area ratio. And, the errors in collected data have been already suspected. The hydrographs of simulated runoff seem in good shape and pattern. So it is very difficult to conclude the simulation result from unfair runoff data. The validation of simulation is carried out for the period from 2004 to 2008. The average R^2 of the validation is 0.14 which is less than calibration results. The individual R^2 value of the catchments is nearly equal with calibration results except of Pachuwar Ghat catchment.

The R^2 values of simulations of independent catchments are superior in both cases. That's why in case III, only 8 independent catchments are selected for calibration and rest catchments are applied for validation from 1999 to 2003. It helps to reduce the accumulation of errors when calculating runoff of local catchments and also decrease the dimensionality of multi-objective problem. The average R^2 of 0.59 is achieved from calibration case III which is the best result among the 3 cases. The Nash Sutcliffe Efficiency is found at the range of 0.54 to 0.78 for most of the catchments. The R^2 of small catchments like Pipletar and Helambu are obtained 0.29 and 0.35 respectively, which seems to be quiet acceptable comparing with calibration case II. Similarly, the validation of the model seems also reliable. The average R^2 of validation is found 0.15 which is greater than calibration case II. Hence the application of regional parameters to the ungauged basins will generate the reliable runoff data.

Finally, the obtained regional parameter sets from the calibration case III are applied to extract the runoff data for planning process. The streamflow at the intake site of Tamor Hydropower Project is extracted by the application of regional parameter sets of the Saptakoshi basin and the result is compared with scaled data used in planning process. The goodness of fit R^2 is equal to 0.20. There are great uncertainties in comparing with these results because the actual data are not available. However, this catchment is the upper part of Majhitar catchment and the simulation results of Majhitar for both cases (II & III) are better than other catchments. Hence the extracted runoff should also be good fit with actual runoff at the intake site.

The overall conclusion of the study is that the regional model is very helpful tool to predict the hydrological variables at the ungauged basins in the mountainous country like Nepal. The ENKI modelling system on regional calibration is applied to the Saptakoshi basin in Nepal at the first time. The calibrated regional parameter sets of the Saptakoshi basin can be applied to extract runoff data for planning projects. Even though the quality of the observed runoff data is not satisfactory, the simulation result of the model seems reliable and reasonable. It can be concluded that if the quality of observed data is reliable and good then it reduces the uncertainty of simulation results.

8.2 DISCUSSION AND COMPARISON BETWEEN REGIONAL MODEL AND HBV MODEL

The traditional one-catchment approach by using HBV-model calibration has been tested for many single basins in Nepal and other countries. The reliability of calibration results from these models has been already proved. The HBV model was able to obtained Nash-Sutcliffe efficiency criterion more than 0.80 for many basins in Nepal [3, 34]. Hence the HBV-model itself is very applicable in the tropical area like Nepal even though it was developed for temperate regions.

The ENKI model system also uses the same subroutines of the HBV-model for calibrating regional model i.e. the HBV-model is used for calibration of many sub-catchments of the region at the same time. The best parameter sets of the region, obtained by the model calibration, are fit for all the sub-catchments of the region. But in case of traditional one-catchment approach HBV model, the calibrated parameters can be applied for only on that basin. The regional hydrological modelling implies a repeated use of a model everywhere within a region using a regional set of parameters. As the best parameter sets are converged after multi combinations of parameters and sub-basins in the regional modelling, the application of regional modelling in the ungauged basins is more reliable than traditional approach even though the R^2 value of regional model is lower than the traditional HBV model.

8.3 RECOMMENDATIONS FOR FUTURE RESEARCH

At early stage of thesis work, it was supposed that only case I simulation is enough to calibration of the model. When the work moved ahead it was realized that the enough data were not available for model calibration. So the model is calibrated removing sub-catchment lying in Tibet in cases II and III. Hence there is always some incompleteness in every work and it can be improved further. Some recommendations are explained below to improve for future research.

- The reliable and good quality of runoff data at gauge stations are required to compare with simulated runoff.
- The precipitation data at the Tibetan region is necessary to analyze and location should be evenly distributed.
- The air temperature at the corresponding precipitation stations are needed to the model for computation of type of precipitation (rain or snow).
- The percentage of lakes and glaciers in the region is needed to determine the direct runoff in the model which is not available in this study.
- The high resolution of GIS data provides the accurate watershed delineation and DEM of the catchments.

Further improvement of simulation results can be achieved with good quality of data and thus uncertainties in parameters can be reduced.

REFERENCES

[1] Å. Killingtveit, "Class Lecture Notes on TVM5135 PLANNING HYDRO HØST 2010," ed, 2010.

[2] Wikipedia. *Geography of Nepal*. Available: http://en.wikipedia.org/wiki/File:Nepal_topo_en.jpg

[3] N. P. Timilsina, "Hydrological Modelling of the Upper Trishuli 3A Catchment in Nepal. Comparison of Lumped and Distributed Models," M.Sc., NTNU, Trondheim, 2008.

[4] B. Tamrakar and "Evaluation of Precipitation distribution over Nepal using satellite data and its applications in Hydrological modeling," M.Sc., NTNU, 2011.

[5] M. C. P. Ltd. Available: http://www.nepalnews.com

[6] A. Dixit, M. Upadhya, K. Dixit, A. Pokhrel, and D. R. Rai, "Living with Water Stress in the Hills of the Koshi Basin, Nepal," Institute for Social and Environmental Transition-Nepal (ISET-N), ICIMOD2009.

[7] I. Kadel, "Statistical Prediction of Seasonal Rainfall in Nepal," APEC Climate Center, Kathmandu, Nepal2012.

[8] Department of Hydrology and Meteorolgy and Nepal. (2011). Available: www.dhm.org.np

[9] K. P. Sharma, "Role of Meltwater in Major River Systems of Nepal," International Association of Hydrological Sciences, Snow and Glacier Hydrology.

[10] Available: http://georepository.com/crs_32645/WGS-84-UTM-zone-45N.html

[11] ICIMOD. Available: http://118.91.160.238/NepalForestFire/index.html#

[12] M. K. Shukla, "Soil hydrology, land use and agriculture : measurement and modelling."

[13] S. L. Dingman, *Physical Hydrology*: Waveland Press, 2008.

[14] K. J. Beven, *Rainfall-Runoff Modelling: The Primer*: John Wiley & Sons, 2012.

[15] Z. Yu, "HYDROLOGY | Modeling and Prediction," in *Encyclopedia of Atmospheric Sciences*, R. H. Editor-in-Chief: James, Ed., ed Oxford: Academic Press, 2003, pp. 980-987.

[16] V. T. Chow, Maidment, D.R. & Mays, L.W, *Applied Hydrology*.

[17] ESRI. Available: http://proceedings.esri.com/library/userconf/proc01/professional/papers/pap443/p443.htm

[18] Å. Killingtveit and N. R. Sæalthun, *Hydrology*: Norwegian Institute of Technology, Division of Hydraulic Engineering.

[19] Å. Killingtveit, "Class Lecture Notes on TVM4106 HYDRO MODELLERING HØST 2011," ed, 2011.

[20] K. Engeland, I. Braud, L. Gottschalk, and E. Leblois, "Multi-objective regional modelling," *Journal of Hydrology,* vol. 327, pp. 339-351, 2006.

[21] K. Engeland, L. Gottschalk, and L. Tallaksen, "ESTIMATION OF REGIONAL PARAMETERS IN A MACRO SCALE HYDROLOGICAL MODEL."

[22] K. J. Beven, Rainfall-Runoff modelling, The Primer, 2000.

[23] Wikipedia. Available: http://en.wikipedia.org/wiki/Enki

[24] "DEMLab - a platform for the implementation and evaluation of distributed hydrological models," SINTEF Energy Research2008.

[25] K. Subramanya, *Engineering Hydrology*, 2nd ed.

[26] S. Kopp, D. Djokic, and A. Rea, "Introduction to GIS and Hydrology," ESRI.

[27] V. Merwade, "Watershed and Stream Network Delineation," School of Civil Engineering, Purdue University2011.

[28] S. Tiwari, "Regional Modelling for Estimation of Runoff from Ungauged Catchment, Case Study of the Narayani Basin, Nepal," M.Sc., NTNU, 2011.

[29] H. Madsen, "Parameter estimation in distributed hydrological catchment modelling using automatic calibration with multiple objectives," *Advances in Water Resources,* vol. 26, pp. 205-216, 2003.

[30] P. H. M. Janssen and P. S. C. Heuberger, "Calibration of process-oriented models," *Ecological Modelling,* vol. 83, pp. 55-66, 1995.

[31] S. K. Jain and K. P. Sudheer, "Fitting of Hydrologic Models: A Close Look at the Nash--Sutcliffe Index," *Journal of Hydrologic Engineering,* vol. 13, pp. 981-986, 2008.

[32] Q. Duan, S. Sorooshian, and V. K. Gupta, "Optimal use of the SCE-UA global optimization method for calibrating watershed models," *Journal of Hydrology,* vol. 158, pp. 265-284, 1994.

[33] Q. Duan, S. Sorooshian, and V. Gupta, "Effective and efficient global optimization for conceptual rainfall-runoff models," *Water Resour. Res.,* vol. 28, pp. 1015-1031, 1992.

[34] B. R. Paudel, "Hydrological modelling of the Tamor hydropower Project," M.Sc., NTNU, 2010.

APPENDICES

Appendix1: VBA Codes

Appendix 1.1: VBA code to interpolate missing precipitation data

```
 Const row = 3663
Const col = 68
Private Sub CommandButton1_DblClick(ByVal Cancel As MSForms.ReturnBoolean)
Dim i As Integer, j As Integer, k As Integer
Dim x As Single, y As Single, z As Single
x = 0
y = 0
z = 0
i = 0
j = 0
k = 0
For k = 2 To col
   For i = 11 To row
    If (Sheet1.Cells(i, k).Value) = "DNA" Then
      y = Sheet1.Cells(row + 1, k).Value
      For j = 2 To col
          'get average value for column and sum up ratio with current row and check for next
DNA
          If Sheet1.Cells(i, j).Value <> "DNA" Then
             x = x + 1
             z = z + (Sheet1.Cells(i, j).Value / Sheet1.Cells(row + 1, j).Value)
          End If
      Next j
      'y1 = Sheet1.Cells(3664, 2).Value ' 2 to 19
      'If Sheet1.Cells(i, 3).Value = "DNA" Then
      'x2 = 0
      'e = 0
      'Else: e = Sheet1.Cells(i, 3).Value
```

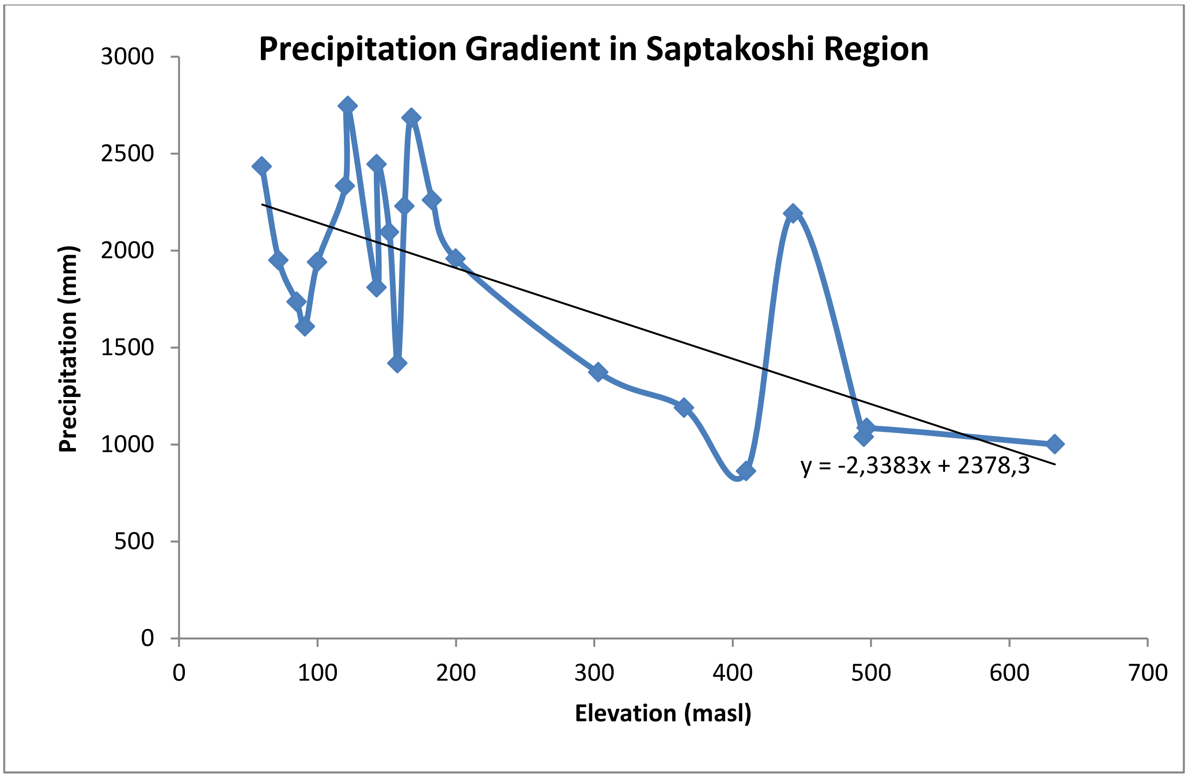
```
        'x2 = 1
        'End If
        'x = x2 + x3 + x4 + x5 + x6 + x7 + x8 + x9 + x10 + x11 + x12 + x13 + x14 + x15 + x16 + x17 + x18
        'Sheet1.Cells(i, 8).Value = y7 * (e / y2 + f / y3 + g / y4 + h / y5 + l / y6 + m / y1 + n / y8 + o / y9 + p / y10 + q / y11 + r / y12 + s / y13 + t / y14 + u / y15 + v / y16 + w / y17 + z / y18) / x
        Sheet1.Cells(i, k).Value = y * (z / x)
        Sheet1.Cells(i, k).Font.Bold = True
        End If
        x = 0
        y = 0
        z = 0
    Next i
Next k
End Sub
```

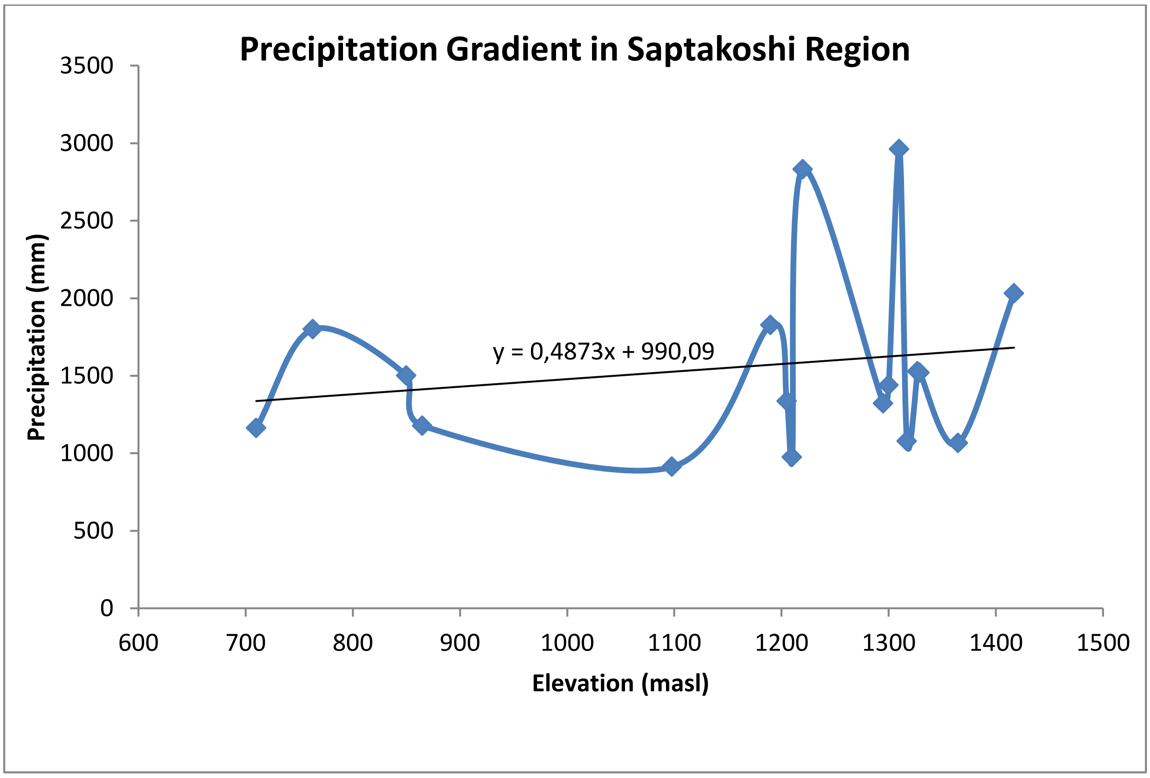
Appendix 1.2: VBA code to interpolate missing temperature data

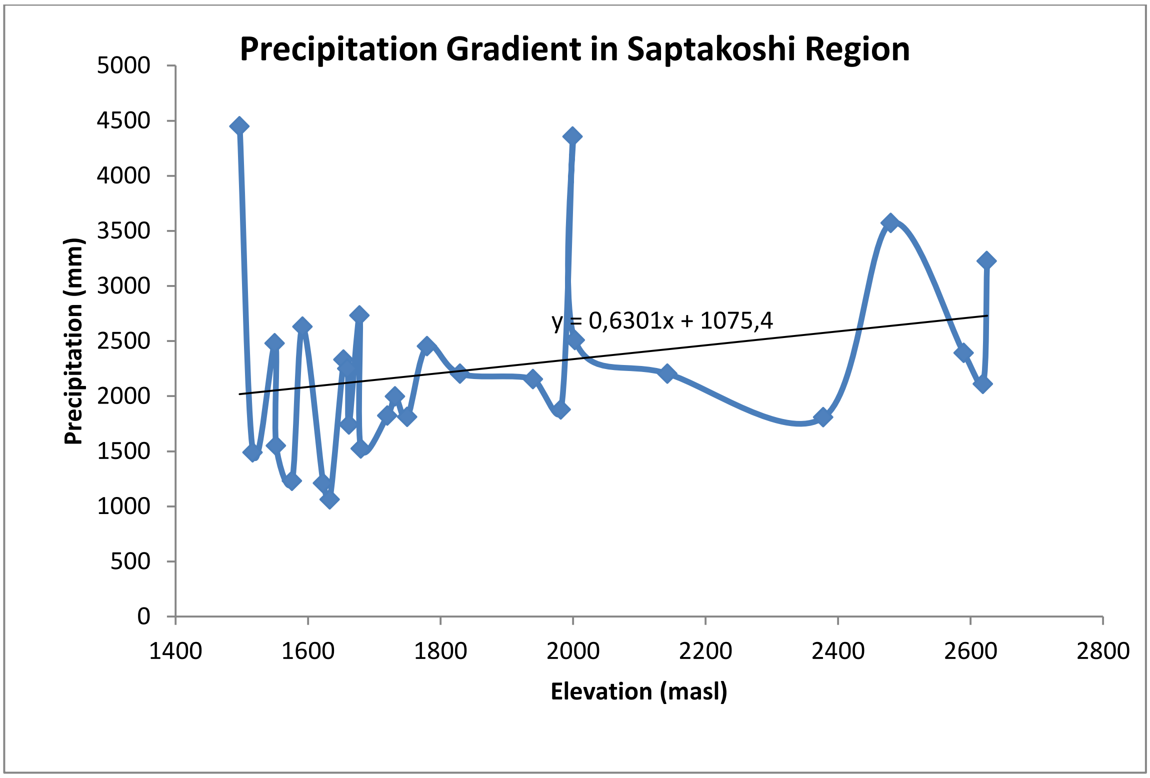
```
Private Sub CommandButton2_DblClick(ByVal Cancel As MSForms.ReturnBoolean)
Dim i As Integer, j As Integer, k As Integer
Dim x As Single, y As Single, z As Single
x = 0
y = 0
z = 0
i = 0
j = 0
k = 0
For k = 2 To col
  For i = 11 To row
    If Sheet1.Cells(i, k).Font.Bold = True Then
      Sheet1.Cells(i, k).Value = "DNA"
      Sheet1.Cells(i, k).Font.Bold = False
    End If
  Next i
Next k
End Sub
Private Sub CommandButton1_Click()
Dim i, j, k, l As Integer
Dim D, T, y, variables
Dim x As Double
D = 0
T = 0
For i = 12 To 3664 'row
For k = 21 To 38  'col

x = (((Sheet1.Cells(9, k).Value - Sheet1.Cells(9, 20).Value) ^ 2 + (Sheet1.Cells(10, k).Value - Sheet1.Cells(10, 20).Value) ^ 2) ^ 0.5) ^ (-2)
```

```
y = (Sheet1.Cells(i, k).Value) * x
D = D + x
T = T + y
Sheet1.Cells(i, 39).Value = T / D
Next k
D = 0
T = 0
Next i
End Sub
```

Appendix 2: Precipitation Gradient in Saptakoshi Region







Precipitation Gradient in Saptakoshi Region
Precipitation (mm)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1400
1600
1800
2000
2200
2400
2600
2800
Elevation (masl)
y = 0,6301x + 1075,4

Appendix 3: ENKI Model Simulation Results

Monte Carlo parameter values and performance measures

Model: Koshi_cal4

Region: Koshi_reg4

Parameter:	TX	RainCorr	SnowCorr	ElevGrad Precip	MaxInDist Precip	MaxInStats Precip	ElevGrad Temp	MaxInDist Temp	MaxInStatsTemp
Routine:	PcorrMap2;HBVsnow	PcorrMap2	PcorrMap2	IDWprec	IDWprec	IDWprec	IDWtemp	IDWtemp	IDWtemp
Distr:	Uniform	Uniform	Uniform	Constant	Constant	Constant	Constant	Constant	Constant
Par 1:	-3	1	1	-3.40E+38	0	0	-3.40E+38	0	0
Par 2:	3	1.5	1.5	3.40E+38	3.40E+38	3.40E+38	3.40E+38	3.40E+38	3.40E+38
Par 3:	-3	1	1	-3.40E+38	0	0	-3.40E+38	0	0
Par 4:	3	1.5	1.5	3.40E+38	3.40E+38	3.40E+38	3.40E+38	3.40E+38	3.40E+38
1	-0.09	1.28	1.24	-0.03	1.00E+07	67	-0.06	1.00E+07	67
2	0.34	1.45	1.12	-0.03	1.00E+07	67	-0.06	1.00E+07	67
3	1.71	1.36	1.05	-0.03	1.00E+07	67	-0.06	1.00E+07	67
4	0.72	1.15	1.50	-0.03	1.00E+07	67	-0.06	1.00E+07	67
5	0.35	1.35	1.04	-0.03	1.00E+07	67	-0.06	1.00E+07	67
6	1.15	1.48	1.08	-0.03	1.00E+07	67	-0.06	1.00E+07	67
7	0.69	1.08	1.46	-0.03	1.00E+07	67	-0.06	1.00E+07	67
8	-1.21	1.15	1.41	-0.03	1.00E+07	67	-0.06	1.00E+07	67
9	0.18	1.31	1.44	-0.03	1.00E+07	67	-0.06	1.00E+07	67
10	-1.81	1.37	1.29	-0.03	1.00E+07	67	-0.06	1.00E+07	67
11	-0.86	1.14	1.45	-0.03	1.00E+07	67	-0.06	1.00E+07	67
12	0.72	1.02	1.40	-0.03	1.00E+07	67	-0.06	1.00E+07	67
13	-0.67	1.27	1.34	-0.03	1.00E+07	67	-0.06	1.00E+07	67

ElevGradTemp	MaxInDistTemp	MaxInStatsTemp	ElevGradEvap	MaxIntDistEvap	MaxIntStatsEvap
IDWtemp	IDWtemp	IDWtemp	IDWevap	IDWevap	IDWevap
Constant	Constant	Constant	Constant	Constant	Constant
-3.40E+38	0	0	-3.40E+38	0	0
3.40E+38	3.40E+38	3.40E+38	3.40E+38	3.40E+38	3.40E+38
-3.40E+38	0	0	-3.40E+38	0	0
3.40E+38	3.40E+38	3.40E+38	3.40E+38	3.40E+38	3.40E+38
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3
-0.6	1.00E+07	67	0.02	1.00E+07	3

CX	CFR	TS	LW	s00	s25	s50	s75	s100
HBVsnow	HBVsnow	HBVsnow	HBVsnow	HBVsnow	HBVsnow	HBVsnow	HBVsnow	HBVsnow
Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform
0.001	0	-2	0.001	0.2	0.1	0.5	0.05	0.3
10	1	2	0.1	0.7	0.5	0.95	0.25	0.5
0.001	0	-2	0.001	0.2	0.1	0.5	0.05	0.3
10	1	2	0.1	0.7	0.5	0.95	0.25	0.5
7.18	0.01	0.24	0.05	0.50	0.30	0.73	0.15	0.40
4.70	0.07	0.47	0.04	0.67	0.21	0.65	0.17	0.37
7.25	0.48	0.56	0.08	0.46	0.16	0.58	0.24	0.30
6.35	0.73	-1.95	0.07	0.39	0.43	0.62	0.16	0.30
2.30	0.47	-0.15	0.04	0.36	0.13	0.87	0.07	0.33
4.45	0.20	1.79	0.10	0.36	0.49	0.84	0.13	0.38
1.54	0.44	1.41	0.04	0.37	0.10	0.79	0.08	0.30
0.45	0.35	0.99	0.08	0.60	0.39	0.76	0.12	0.32
6.51	0.54	0.19	0.08	0.23	0.49	0.69	0.14	0.41
8.69	0.37	-1.54	0.06	0.37	0.38	0.82	0.17	0.31
7.47	0.01	1.50	0.02	0.22	0.32	0.63	0.15	0.36
4.85	0.11	-0.15	0.06	0.26	0.42	0.59	0.07	0.37
5.60	0.91	-0.91	0.00	0.46	0.49	0.86	0.13	0.36

FC	LP	BETA	k2	k1	k0	perc	tresh	lakep
HBVSoil	HBVSoil	HBVSoil	HBVResponse	HBVResponse	HBVResponse	HBVResponse	HBVResponse	HBVResponse
Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Constant
100	0.001	1	0.1	0.05	0.001	1.2	10	-3.40E+38
2000	0.999	6	0.5	0.15	0.01	2	40	3.40E+38
100	0.001	1	0.1	0.05	0.001	1.2	10	-3.40E+38
2000	0.999	6	0.5	0.15	0.01	2	40	3.40E+38
635.00	0.40	3.77	0.23	0.09	0.01	1.53	23.15	0
319.06	0.48	2.74	0.38	0.12	0.00	1.40	12.72	0
709.34	0.23	5.70	0.31	0.10	0.00	1.25	12.86	0
601.17	0.77	5.55	0.25	0.10	0.01	1.63	24.19	0
1048.66	0.43	5.83	0.37	0.08	0.01	1.29	17.55	0
1206.78	0.53	3.92	0.17	0.10	0.01	1.75	36.24	0
1071.82	0.16	3.93	0.31	0.06	0.00	1.88	35.75	0
1752.19	0.75	1.57	0.45	0.14	0.01	1.89	35.95	0
1620.46	0.09	3.51	0.21	0.13	0.00	1.40	21.35	0
665.81	0.61	1.96	0.27	0.10	0.00	1.60	15.98	0
354.82	0.32	2.29	0.27	0.06	0.01	1.83	15.47	0
1803.48	0.37	2.13	0.10	0.06	0.01	1.31	35.82	0
966.50	0.00	4.93	0.3	0.10	0.00	1.67	35.39	0

PerfMeasure:	Temporal R2	Temporal R2	Temporal R2	Temporal R2	Temporal R2	Temporal R2	Temporal R2	Temporal R2
Test Data:	SimRunoff	SimRunoff	SimRunoff	SimRunoff	SimRunoff	SimRunoff	SimRunoff	SimRunoff
Reference:	Runoff	Runoff	Runoff	Runoff	Runoff	Runoff	Runoff	Runoff
time/loc:	Busti	Helambu	Pipletar	Jalbire	Majhitar	Rabuwa Bazar	Rasnalu Village	Tumlingtar
Num Obs:	1826	1826	1826	1826	1826	1826	1826	1826
Start:	01.01.1999	01.01.1999	01.01.1999	01.01.1999	01.01.1999	01.01.1999	01.01.1999	01.01.1999
End:	31.12.2003	31.12.2003	31.12.2003	31.12.2003	31.12.2003	31.12.2003	31.12.2003	31.12.2003
	0.660	0.329	-0.027	0.732	0.745	0.682	0.368	0.372
	0.161	0.342	-0.432	0.493	0.523	0.713	0.117	-0.178
	0.488	0.337	-0.237	0.637	0.662	0.733	0.254	0.120
	0.658	0.277	-0.103	0.703	0.719	0.593	0.301	0.408
	0.448	0.338	-0.259	0.615	0.635	0.731	0.213	0.084
	0.443	0.396	-0.001	0.600	0.627	0.750	0.345	0.164
	0.458	0.215	-0.308	0.533	0.530	0.406	0.136	0.279
	0.547	0.221	-0.123	0.585	0.572	0.494	0.238	0.294
	0.563	0.326	-0.096	0.634	0.626	0.644	0.304	0.272
	0.620	0.357	0.024	0.724	0.748	0.738	0.383	0.309
	0.769	0.283	-0.031	0.763	0.760	0.618	0.388	0.479
	0.309	0.136	-0.372	0.344	0.328	0.214	0.072	0.207
	0.550	0.272	0.069	0.568	0.540	0.467	0.429	0.430
	0.622	0.336	-0.007	0.697	0.695	0.679	0.339	0.332
	0.549	0.345	-0.099	0.689	0.714	0.735	0.328	0.199
	0.409	0.358	-0.219	0.594	0.621	0.756	0.210	0.021
	0.623	0.341	-0.053	0.714	0.720	0.703	0.382	0.333
	0.600	0.310	-0.128	0.679	0.692	0.653	0.290	0.318
	0.433	0.162	-0.307	0.474	0.475	0.314	0.104	0.288

Appendix 4: Calibration of parameters in ENKI system for Saptakoshi basin

Parameters	Description	Routine	Distribution	Value Range	Calibrated Value		
					Case I	Case II	Case III
TX	Threshold Rain/Snow	PcorrMap2; HBVsnow	Uniform	-3 to 3	0.319	-0.090	1.311
RainCorr	Rain correction	PcorrMap2	Uniform	1 to 1.5	1.060	1.276	1.376
SnowCorr	Snow correction	PcorrMap2	Uniform	1 to 1.5	1.270	1.235	1.313
ElevGradPrecip	Elevation lapse rate in %/100m	IDWprec	Constant	-0.025	-0.025	-0.025	-0.025
MaxInDistPrecip	Maximum Distance to included stations	IDWprec	Constant	1.00E+07	10000000	10000000	10000000
MaxInStatsPrecip	Maximum no. of stations included	IDWprec	Constant	67	67	67	67
ElevGradTemp	Elevation lapse rate in %/100m	IDWtemp	Constant	-0.60	-0.60	-0.60	-0.60
MaxInDistTemp	Maximum Distance to included stations	IDWtemp	Constant	1.00E+07	10000000	10000000	10000000
MaxInStatsTemp	Maximum no. of stations included	IDWtemp	Constant	67	67	67	67
ElevGradEvap	Elevation lapse rate in %/100m	IDWevap	Constant	0.02	0.020	0.020	0.020
MaxIntDistEvap	Maximum Distance to included stations	IDWevap	Constant	1.00E+07	10000000	10000000	10000000
MaxIntStatsEvap	Maximum no. of stations included	IDWevap	Constant	3	3	3	3
CX	Degree-day factor	HBVsnow	Uniform	0.001 to 10	7.551	7.183	9.897
CFR	Refreezing Coefficient	HBVsnow	Uniform	0 to 1	0.542	0.007	0.902
TS	Threshold Snow-melt	HBVsnow	Uniform	-2 to 2	0.538	0.239	-1.245
LW	Maximum Liquid Water content	HBVsnow	Uniform	0.001 to 0.1	0.036	0.049	0.007
s00	Snow redistribution low limit	HBVsnow	Uniform	0.2 to 0.7	0.415	0.477	0.613
s25	Snow redistribution 25% quartile	HBVsnow	Uniform	0.1 to 0.5	0.233	0.308	0.321
s50	Snow redistribution median	HBVsnow	Uniform	0.5 to 0.95	0.737	0.726	0.607
s75	Snow redistribution 75% quartile	HBVsnow	Uniform	0.05 to 0.25	0.146	0.126	0.216
s100	Snow redistribution high limit	HBVsnow	Uniform	0.3 to 0.5	0.362	0.365	0.493

FC	Field capacity	HBVSoil	Uniform	100 to 2000	1016.24	635.575	1260.760
LP	Threshold Evaporation	HBVSoil	Uniform	0.001 to 0.999	0.690	0.424	0.038
BETA	Beta	HBVSoil	Uniform	1 to 6	3.915	3.775	1.060
k2	Fast drainage coefficeint	HBVResponse	Uniform	0.1 to 0.5	0.301	0.231	0.113
k1	Slow drainage coefficeint	HBVResponse	Uniform	0.05 to 0.15	0.110	0.089	0.097
k0	Drainage coefficient	HBVResponse	Uniform	0.001 to 0.01	0.007	0.007	0.007
perc	Percolation	HBVResponse	Uniform	1.2 to 2	1.470	1.533	1.958
tresh	Threshold	HBVResponse	Uniform	10 to 40	21.620	23.156	23.754
lakep	Lake percentage	HBVResponse	Constant	0	0	0	0