ANALYSIS OF CLIMATE CHANGE IMPACTS IN MARSHYANGDI RIVER BASIN, NEPAL

A DISSERTATION

Submitted in partial fulfilment of the

Requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

HYDROLOGY

by

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Candidate's Declaration

I hereby certify that the work which is being presented in this dissertation report entitled **"Analysis of Climate Change Impacts in Marshyangdi River Basin, Nepal"** in the partial fulfilment for the award of the Degree of Master of Technology in Hydrology, submitted in the Department of Hydrology of the Indian Institute of Technology, Roorkee, is an authentic record of my work done under the guidance of **Dr. D S Arya, Professor & Head Department of Hydrology, IIT Roorkee.**

Date:

Place:

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Certificate

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

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Pankaj Karna

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Abbreviations

amsl: Above Mean Sea Level

CN: Curve Number

CO_2: Carbon dioxide

COD: Coefficient of determination

DEM: Digital Elevation Model

DHM: Department of Hydrology and Meteorology of Nepal

FAO: Food and Agriculture organization

HRUs: Hydrologic Response Units

ICIMOD: International Centre for Integrated Mountain Development

i.e.: “that is”

IPCC: Intergovernmental Panel on Climate Change

LH: Latin Hypercube

LULC: Land use Land cover

m: meter

MK: Mann-Kendall

mm: millimetre

MMK: Modified Mann-Kendall

MoPE: Ministry of population and Environment, Nepal

MRB: Marshyangdi River Basin

NSE: Nash-Sutcliffe Efficiency

OAT: One-factor-At-a-Time

PBIAS: Percentage bias

PMW: Pettitt-Mann-Whitney

r^2: Coefficient of determination

RCP: Representative Concentration Pathways

SCS: Soil Conservation Service

SOTER: Soil and Terrain

SRTM: Shuttle Radar Topography Mission

SWAT: Soil Water Assessment Tool

SWAT-WB: Soil Water Assessment Tool- Soil and Water Lab

TM: Thematic Mapper

USGS: United State Geological Survey

viz: "that is to say"

Abstract

Climate change is impacting Nepal's economy, health and communities in diverse ways. Rising temperatures are responsible for the glacier melt as well as shift in precipitation pattern. Changes in the climatology of precipitation lead also to changes in runoff and streamflow. The other effects include increase in the prevalence of severe events like floods and drought along with erratic rainfalls. The present study analysed the change in climatic condition i.e. on Precipitation and Temperature in Marshyangdi River Basin (MRB) and its impact on the streamflow.

Observed streamflow data is available from 2000-2009 for a duration of 10 years at Bakhundebesi station, outlet of the MRB. Hydrological modelling was used to construct streamflow series of about 30 years' at Bakhundebesi station to perform a trend analysis in order to study the impact of climate change. Hydrological modelling was attempted to construct the streamflow series of around 30 years. Soil Water Assessment Tool (SWAT) model was calibrated and validated with SWAT Cup program using SUFI2 algorithm. During calibration period, values of Nash-Sutcliffe Efficiency (NSE), Percentage Bias (PBIAS) and Coefficient of Determination (r^2) were found to be 0.75, 12.64 and 0.77 respectively for daily data. Similarly, for monthly data these parameters were estimated to be 0.84, 12.21 and 0.89. During validation phase NSE, PBIAS and r^2 were estimated to be 0.69, 10.21 and 0.70 for daily data and 0.84, 10.10 and 0.86 for monthly data. At the end, streamflows were generated from 1977, the year where from the observed precipitation data was available.

Climate change impacts analysis was carried out through trend analysis of meteorological parameters viz: precipitation, minimum and maximum temperature. Mann-Kendall (MK) and Sen's slope estimator test were used. Maximum temperature is showing significant increasing trend in the basin at both the stations and in all seasons. At Khudibazar station minimum temperature is also showing significant increasing trend while at Chame station in minimum temperature series no significant trend is observed. In precipitation series no significant trend is observed in any season in the basin, with varying changes across the seasons. In the basin precipitation, -17.18% and -54.77% changes are observed in pre-monsoon and winter season while in monsoon and post-monsoon season 12.08% and 27.19% changes are observed in the basin, with a net increase of 5.07%.

The trend analysis of streamflow was also performed and showed the increasing trend with the significant variation in the percentage change to the corresponding seasons. Trend analysis of annual streamflow determine a significant increasing trend in the basin with a 3.19% increase in mean annual flow comparing with the Basin average annual rainfall, these changes are attributed to 5.07% increase in rain fall during this period

Chapter 1

1. Introduction

1.1 General

Climate and weather plays significant role on life existing on earth surface. These are the part of the regular understanding of human beings and vital for food and health (IPCC, 2001c). Weather is defined as the instable form of the atmosphere, which is characterized by the clouds, precipitation, temperature, wind, air pressure, humidity and solar radiation (IPCC, 2001c). Whereas climate is the average measurements of meteorological conditions (Graedel and Crutzen, 1993). Also, it denotes the regular weather in relationships with its variability and its mean over an era of time extending from several months to billions of years. Climatic condition on the earth differs in time and space due to natural and anthropogenic forcing issues (IPCC, 2001c). Some transformation in any of the imposing issues and their interfaces may outcome in climate deviations giving rise to possible impacts on living beings on the earth. According to Intergovernmental Panel on Climate Change (IPCC, 2001c) the conventional period used as recent dealings of climate is 30 years.

The average weather measured in the form of mean and variability over a very long period refers as climate. Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer (IPCC 2013). Climate change has spatial and temporal variability. The driving force behind climate change as attributed by IPCC (2001c) is both natural as well as anthropogenic. Climate change can be measured by the change of temperature, Precipitation, wind, sea level and snow cover. The global temperature rises by 0.74°C by the end of 20^{th} century has more than half of this rise 0.44°C in the last three decades (ICIMOD 2009). According to the fifth assessment report by IPCC (2013), increased level of carbon dioxide, Methane, Ozone, hydrocarbons and Nitrous oxides contribute to the global warming and for much of this warming it concluding that human activities are responsible for the present climate change. The IPCC (2013) assessment report has mentioned considerably more climate change in the tropical and subtropical regions compared to that in the mid altitudes. The report has also cautioned relative to 1850–1900, the global surface temperature changes for the end of the 21st century (2081–2100) is projected to likely exceed 1.5°C for RCP4.5, RCP6.0 and RCP8.5 scenarios (high confidence) and to exceed 2°C for RCP6.0 and RCP8.5 scenarios (high confidence).

Climate Change has enormous effect on hydrology and hydrological cycle and poses challenge on future water availability. Circulation and distribution of available water under climate projection has become more complex (Pachauri, 1992). Scientific community believes that climate change will result in change of the global hydrological cycle inducing higher occurrence of extremes (Hisdal et al., 2001).

1.2 Rationale and Scope of the Study

Nepal is very rich in water resources. Over 6000 small and large rivers originating from the Himalayas flow across the hills and reaches the plains. The country has highly roughed terrain with huge difference in the lowest and the highest altitudes within a very short horizontal distance. The country has numerous snowy mountains in the northern region. Climatic condition of the country plays dynamic role on the hydrology of these rivers which is a part of global climate. Most of these rivers continuously flow in dry season because they are snow or glacier-fed and generally fulfil all the water requirements of water supply schemes, irrigation canals and hydropower plants to the downstream. Nepal's one of the major source of income is agriculture. However, according to FAO (2004a) about 63% of the agriculture land is still deprived of modern irrigation facilities. The lands where irrigation facility is not available, mainly depend upon rainfall to meet the crop water requirements. Therefore, changes in rainfall pattern is a major concern for cultivation in these lands which may cause food scarcity for the population. Due to the impact of climate change, even the agriculture lands having irrigation facility may face water shortage or completely run out of water during the dry seasons.

As compared to other developed countries, very few research studies have been carried in Nepal regarding impact of climate change on social and economic condition of the country. The varying patterns of various hydrological phenomenon and their probable impacts on environment, sociology aspects and economy is very difficult to understand and analyse. As hydropower could play a vital role in economic development of Nepal, more focus should be given to study, understand and analyse the impact of climate change on the water resources of the country. Therefore, study of probable impacts becomes very important to design the policies to delay, avoid and/or minimize the magnitude of potential damages caused by the changing climate.

1.3 Objectives of the Study

The key objective of the study is to investigate the changes in climatic conditions and its impact on the streamflow of Marshyangdi River.

The specific objectives are

i. To determine the changes in climatic parameters through the trend analysis of hydrometeorological parameters of Marshyangdi River Basin.

ii. To analyse impact of changing hydrometeorological parameters on streamflows using SWAT Model during last four decades.

1.4 Organization of the Thesis

The thesis is divided into six chapters. Chapter one is the introduction that explains the basics of the whole study. It includes the brief introductions and findings about the various terminologies and activities occurred in the thesis. Chapter two is the literature review that includes the detailed review of various aspects of the study. Mainly, the previous findings on climate change and its impact on various sectors globally as well as for Nepal are discussed. Chapter three discusses in detail about the study area, data availability & collection and methodology used which include data pre-processing and analysis, Hydrological modelling and all the working procedure required for the study. Chapter four is the construction of streamflow Series using SWAT Model, model setup, calibration and validation process and its results and generation of streamflow series. Chapter five is the climate change impact analysis of hydro-meteorological variables which describe in detail about analysis of trends in different variables in the basin. Chapter six summarizes the general and specific conclusions of the present study its limitation and future scope of the study.

Chapter 2

2. Literature Review

2.1 General

Climate change and global warming are one of the most pronounced topic among the scientist and the engineers these days. Many of the things happening around us may be a consequences of climate change. This climate change has affected the whole world. The present chapter aims to briefly summaries the comprehensive review on the climate change and its current and future impacts globally and in Nepalese context.

2.2 Global Climate Change

Land, atmosphere, cryosphere, biosphere and hydrosphere are the five major components of the climate system. Among these, the most unstable and the rapidly changing part is the atmosphere (IPCC, 2001c). The earth has witnessed considerable change in its climate due to the natural or anthropogenic forcing components. Especially the 20th century observed the higher rate of climate change than that ever in the history (IPCC, 2001a). For example, the global temperature during the 20th century, on an average raised by about 0.6 ± 0.20°C, which tends to be greater than in the last few centuries (IPCC, 2001a). The rate of warming was found to be even more noticeable during the last few decades. This rise in temperature was mostly because of the high emissions of greenhouse gases in the atmosphere through anthropogenic sources (IPCC, 2001a).

IPCC (2013) concluded that the rise in temperature, reduction in snow extend and rise in sea level in northern hemisphere during 1850 to the present based on direct observation, establishes beyond doubt the fact of global warming. Since 1750, the CO_2 concentration in the atmosphere has increased by 31% and the present CO_2 concentration has not been exceeded during the past 420000 years. Reports says that during the year 1880 to 2012, the temperature averaged over all land and ocean surface has increased by 1.53°F (0.85ºC). By virtue of water getting warmed and cooled slower than land, the continents temperature has raised the most. The northern hemisphere of the earth constitutes most of the land and hence it holds the record of warmer continent than the southern. Of the last 1400 years, the last three decades (1983-2012) in the northern hemisphere was the warmest 30 years.

Figure 2.1 from NOAA shows the trend of annual average global air temperature from 1880 to 2013. The figure shows the long term temperature variability at various time scales (yearly and decadal). The grey vertical bars indicate the range of uncertainty for every year. Similarly, the change in the trend over time is tracked by the blue line.

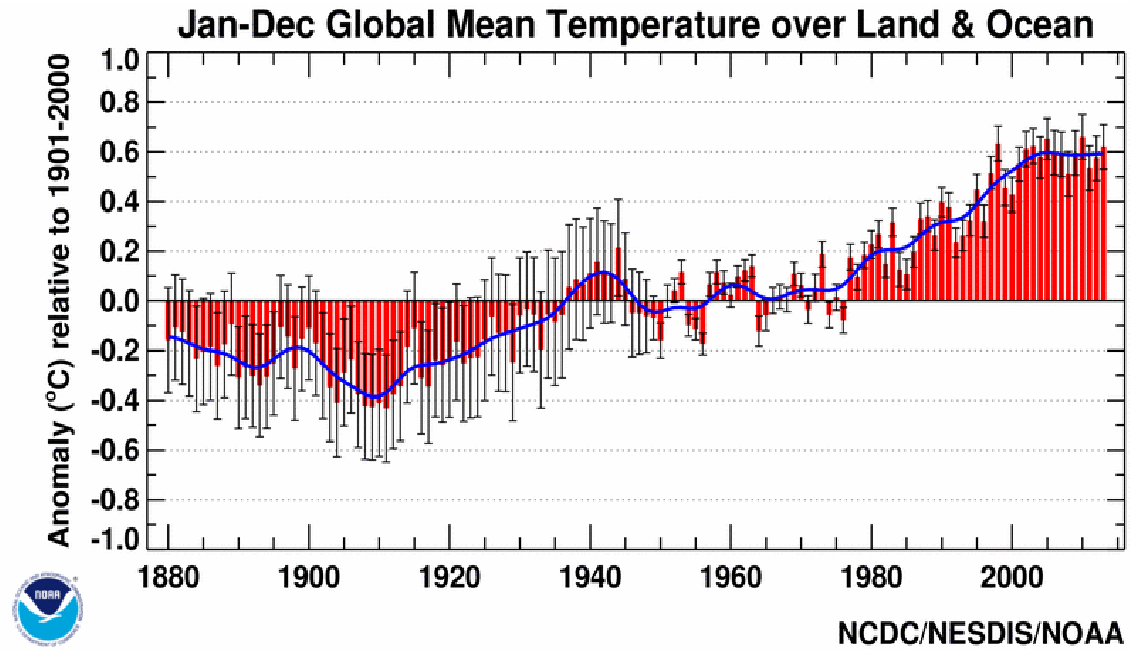

Figure 2.1 Global average temperature since 1880

(Image courtesy NOAA's National Climatic Data Centre.)

IPCC (2001 b & c) reported that the water holding capacity of the atmosphere increases with the increase in the temperature, the result of which is the increase in atmospheric moisture and reduction in rainfall. The increasing temperature has changed the atmospheric circulation; leading to more active hydrological cycle. Since the beginning of the 20th century, the global land precipitation has increased by 2%, but mostly varied in space and time. Continued aridity has been observed in North Africa since 1961. The number of rainy days across the Southeast Asia and South Pacific has significantly decreased. On the contrary, the annual average precipitation has increased. Between zones 30ºN to 85ºN the annual average precipitation increased by 7 to 12% and between zones 0ºS to 55ºS, it has increased by about 2%.

IPCC (2013) assessment report stated that South East Asia and Africa received less and less precipitation throughout the 20th century, whereas Americas and Europe experienced more. The North West coast of Australia has got wetter but the South and East coasts have got drier. This change in precipitation will have a very large impact both negative and positive on societies across the world.

Figure 2.2 shows the change in precipitation over two periods in the last 110 years. By comparing the two figures as shown above, we can see that there are fewer white gaps in the map which clearly shows that we are more confident in our values for the second half of the 20th century.

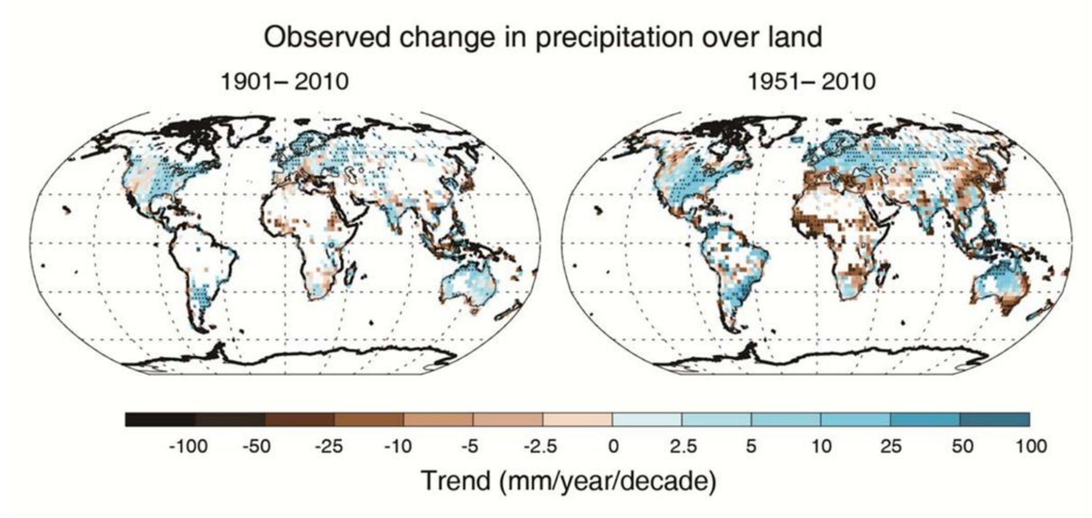

Figure 2.2 Maps of observed precipitation change from 1901 to 2010 and from 1951 to 2010

(Source: https://muchadoaboutclimate.wordpress.com)

2.3 Climate Change in the Himalayan Region

ICIMOD (2008) reported that the Himalayan Mountains constitute about 24% of the global surface area and one of the major source of fresh water that sustains 12% of the world’s population. The deposition and melting of snow and glaciers are part of the mountain hydrological cycle (Immerzeel et al., 2009). Therefore, the current change in the temperature and precipitation are predicted to be adversely affecting the complete mountain hydrological process (Barnett et al., 2005). Especially the temperature in the Himalayas has been observed to be increasing at faster rate than the global average. A significant increase is observed in the winter season at higher altitudes (Beniston, 2003)

Shrestha (2005) studied that the summer monsoon originating from the Bay of Bengal mainly influences the climate of Himalayan Mountains. Melting of the snow and glacier reaches at its peak during the summer monsoon. Therefore, intense monsoon or intense melting increases the summer runoff that would result in significant change in mountain hydrology such as flood disaster.

Schickhoff (2005) observed a range of heterogeneity or diversity in geographical features of Hindu Kush-Himalayan ranges. He found that the vegetation over Himalayan region shows a gradual change from northwest region having subtropical semi-desert and thorn steppe formations to the southeast constituting tropical evergreen rainforests. Himalaya region contains large biodiversity, often with sharp transitions (ecotones) in vegetation sequences. Also changes are observed in soil, snow and ice also (Messerli and Ives 2004).

Du et al. (2004) Observation is similar to that of Beniston, 2003 which says that Himalayas is warming up much faster than the global average of 0.74°C over last 100 years. Shrestha et al. 1999; Liu and Chen 2000; New et al. 2002 mentioned that due to the climate change the ecosystem at the higher altitude is under more threat.

Goswami et al. (2006) found that the frequency and magnitude of high intensity rainfall events are increasing rapidly in Himalayan region which has a negative impact on long term soil moisture, infiltration and groundwater recharge.
Ramesh and Goswami (2007) found that the timing and length of monsoon period changes i.e. dry period in Himalayan region is becoming drier and water scarcity is also becoming more critical.

2.4 Climate Change Trends over Nepal

There is very distinct range of climate in a country like Nepal since it lies close to the northern regime of the tropics. The climate varies from the summer tropical heat in Terai to the dry continental winter in the northern mountainous sections. Due to the rugged terrain, the range of temperature and amount of precipitation vary considerably.

In Nepal About 70–80% of annual precipitation falls during summer. The eastern Himalayas receive the brunt of the monsoon, which loses its effect as it moves west along the mountains. Consequently, there is a distinct moisture gradient from east to west. In winter, western Nepal experiences a reverse monsoon caused by a shift in the jet stream.

This phenomenon, which drags weather patterns from the west of the Arabian Sea, brings moisture to the region in the form of snow and is essential for agriculture.

World Bank (2009b) studies done over Nepal on climate change trends propose that there was no significant rise in annual temperature from 1960-2003. But in a recent year's study shows that there is small but significant increase in frequency of hot nights by 2.5% (Mc Sweeney et al. 2008) with more pronounced warming at higher altitudes.

Shrestha (2001) mentioned that warming rate in the southern plains (low elevation areas) is relatively slower than that in the high altitudes areas in north. The rate of increase of average annual temperature in the southern plain is about 0.04ºC/year and that in the middle mountain in north is about 0.08ºC /year. Similarly difference in the warming rate is observed in the pre monsoon and post monsoon season as well. The lowest warming rate of 0.03ºC/year is observed during the pre-monsoon (March- May). Almost twice double i.e. 0.08ºC/year warming rate during the post monsoon (Oct – Nov) is observed.

Findings of MoPE (Ministry of population and Environment), 2004 demonstrate that total annual rainfall in Nepal is increasing at the rate of 13.6 mm/year (0.7% annually). However, average number of rainy days is gradually decreasing at an average annual rate of 0.82 days. More detailed analysis of the rainfall pattern in Nepal has revealed that number of days with rainfall intensity less than 1 mm in a day (24 hours) is decreasing annually at the rate of approximately 0.67 days whereas the number of days with rainfall intensity more than 50 mm in a day is increasing annually at the rate of 0.14 days.
The conclusion of this finding is that despite the fact that the total absolute amount of rainfall has increased over a year, its temporal variation is not uniform. A significant concentration of rainfall is taking place within relatively shorter period. The trend shows that the average annual precipitation of Nepal is decreasing at the rate of about 9.8 mm/decade.

2.5 Hydrological Modelling

Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle, which solve the complex interaction between different components of hydrological cycle. Hydrological modelling is normally used for estimation/ prediction of hydrologic parameters and understanding various components of the hydrological system which can help to understand hydrologic phenomena affects the hydrology operating in a catchment. The recent trend in hydrological modelling is to follow the global approach for better understanding and analysis of the entire hydrological system. This approach helps in better prediction of the future scenario and also helps in dealing with major water resources management challenges.

Kirchner (2006) Mentioned that to have better understanding of the effects of changes in the system (climate, land use, population dynamics), it is of utmost important to have models in hand. Such models through sufficient representation of key processes can deliver right solution for the right reason under defined conditions. The deliverable can thus be a reliable estimate as well as solution for the future scenario.

Weingartner et al., (2007) found that, Modelling and simulation of hydrological models for mountainous catchment is a tough task; the reason for which is attributed to the highly variable morphology, vegetation, soil and climate. Mountain discharge regime at various locations and elevations are influenced by the rainfall, glacial melt, snow melt and their temporal and spatial superposition. They further said that the quality of simulation of any hydrological model depends on how well an underlying model can accurately represent and describe the complexity and heterogeneity of various components of hydrological system both in spatial and temporal scale.

Arnold et al., (2009) mentioned that Soil and Water Assessment tool (SWAT) has been recognized as one of the most powerful hydrological model being employed in the various parts of the globe including Europe, US, South Asia, China, Africa etc. Beyond hydrology, SWAT applicability in the past decade has been extended to many more studies including sediment transport, climate change, pollutant transport, nutrient loss, pesticides, agriculture management (Gassman et al., 2007).

2.6 Trend Analysis

Dore (2005) carried out a trend analysis study on precipitation pattern at a global scale. He found a global increase in the variance of precipitation and a falling trend or decreasing trend in Russia, Kazakhstan, Thailand and China. Similar trend analysis study was carried out by various investigators in many basins of India. Regional analysis has revealed that increasing rainfall trends were observed in Indus, Ganga, Krishna and Brahmaputra basins (Singh et al. 2005), Delhi (Rao et al. 2004) and Coastal Odisha. Decreasing or falling trend was observed in central basins of India such as Sabarmati, Tapti, Godavari and Mahanadi, east Madhya Pradesh and nearby north east areas.

Jhajharia et al. (2013) carried out an investigation to analyse temperature trend on 35 stations of Godavari river basin. Initially, serial correlation in the data was removed by pre-whitening procedure and then Mann-Kendall (MK) test was applied to find trends in minimum, maximum and mean temperature. No trend was observed in any stations for any of the four seasons, except post-monsoon for maximum temperature and monsoon in minimum temperature. Homogeneity of these trends were tested by applying Van Belle and Hughes method and it was concluded that the temperature data was not homogeneous for various methods and also over various stations over Godavari basin.

Basistha et al. (2009) carried out a trend analysis study using 80 years' data of Himalayan region obtained from Indian Meteorological Department (IMD) during 20th century. They used MK, Modified Mann-Kendall (MMK) and Pettitt-Mann-Whitney (PMW) tests to detect any possible shift present in the data set. An increasing trend was found to present up-to 1964 followed by a decreasing trend during the period 1965-1980.

Various studies were carried out all over the world to analyse trends over different river basins such as; a decreasing trend was observed over Greece, no annual trend over Japan (Xu et al. 2003), Iberian Peninsula (Serrano et al., 1999) and a positive or increasing trend was observed Mainland Spain (Mosmann et al., 2004), North Carolina (Boyles and Raman, 2003).

Singh et al. (2005) carried out a study to analyze trend in annual rainfall and relative humidity over north Indian River basins. He found an increasing trend in the region but no such trend was observed for monsoon rainfall.

Martinez et al. (2012) applied non parametric MK test and Sen's slope estimator test in the data set of Florida USA for the time period 1895-2009 and 1979-2009 to analyse annual, monthly and seasonal trend pattern. Seasonal rainfall showed significant trend during March-May and June-August for both the time period. However, a decreasing trend was found in monthly rainfall in May and October for both the above mentioned time period. Trends observed in minimum, maximum and mean temperature was positive or increasing with a larger portion of positive trend in the second time period i.e. 1970-2009.

Kahya and Kalayci (2004) analysed trends in Turkey for 31 years of monthly discharge record observed from 26 basins. They applied four non parametric tests such as MK, Spearman's Rho, Sen's slope and Seasonal Kendall test. It was observed that the basins located in western Turkey had a decreasing trend however eastern Turkey basins had no trend. Homogeneity of trends were analysed by applying the procedure developed by Van Belle and Hughes.

Jain and Kumar (2012) observed that even if a number of non-parametric tests such as Sen's slope, MK test etc. have been used for trend analysis in various studied, but still there are differences in results of every method. A clear and consistent picture of rainfall trend has not yet emerged.

2.7 Overall Summary

The highlight of the literature review is summarized below:

- Climate change is impacting our water resources, but the large image of this impacts is still not clear due to heterogeneous nature of these changes. Therefore, climate change impact assessment studies are necessary at basin scale.
- Hydrological models are the promising tool to study the impact of climate change on water resources. SWAT is widely used hydrological model to simulate hydrology of a basin and has been used throughout the world by the researchers to study the impact of climate change.
- To study the significance and magnitude of change in hydrometeorological variables MK test and Sen's slope estimator test are most widely used tests.

Chapter 3

3. Study Area, Data Used and Methodology

3.1 General

The present chapter discusses in detail about the study area its location on map and different physiographic region, and in data collection the sources of data, data availability, data analysis and processes and the various types of model input data preparation required to perform the hydrological model. The chapter also describe about the methodology adopted to achieve the objectives of the study.

3.2 Study Area

3.2.1 Location

The Marshyangdi River Basin (MRB) lies between latitude 28.1° N and 28.9° N and longitude 83.8° E and 84.6° E. The Basin located in western part of Nepal (Figure 3.1) with an area of about 3000 km^2. MRB is a sub-basin of the Narayani River Basin, the largest river basin of Nepal and a tributary of the Ganges River System.

3.2.2 Topography

The elevation of the basin ranges from 641m to over 8055m above mean sea level (amsl) with most of the area between 4000m to 6000m amsl. The uppermost elevation occurs at the peaks of the Annapurna Mountain which is a large Himalaya Mountain peaks with an elevation greater than 8055m, possibly highly influencing orographic precipitation patterns. The dominant soils found in the basin include Molli-Leptic Cambisol, Gleyi-Fluvic Cambisol, Humic Umbrisol, Eutri-Chromic Cambisol, Glacier, Lithtic Cryosols, and Eutri-Skeletic Regosol. The Marshyangdi River Basin varies climatically corresponding to elevation changes.

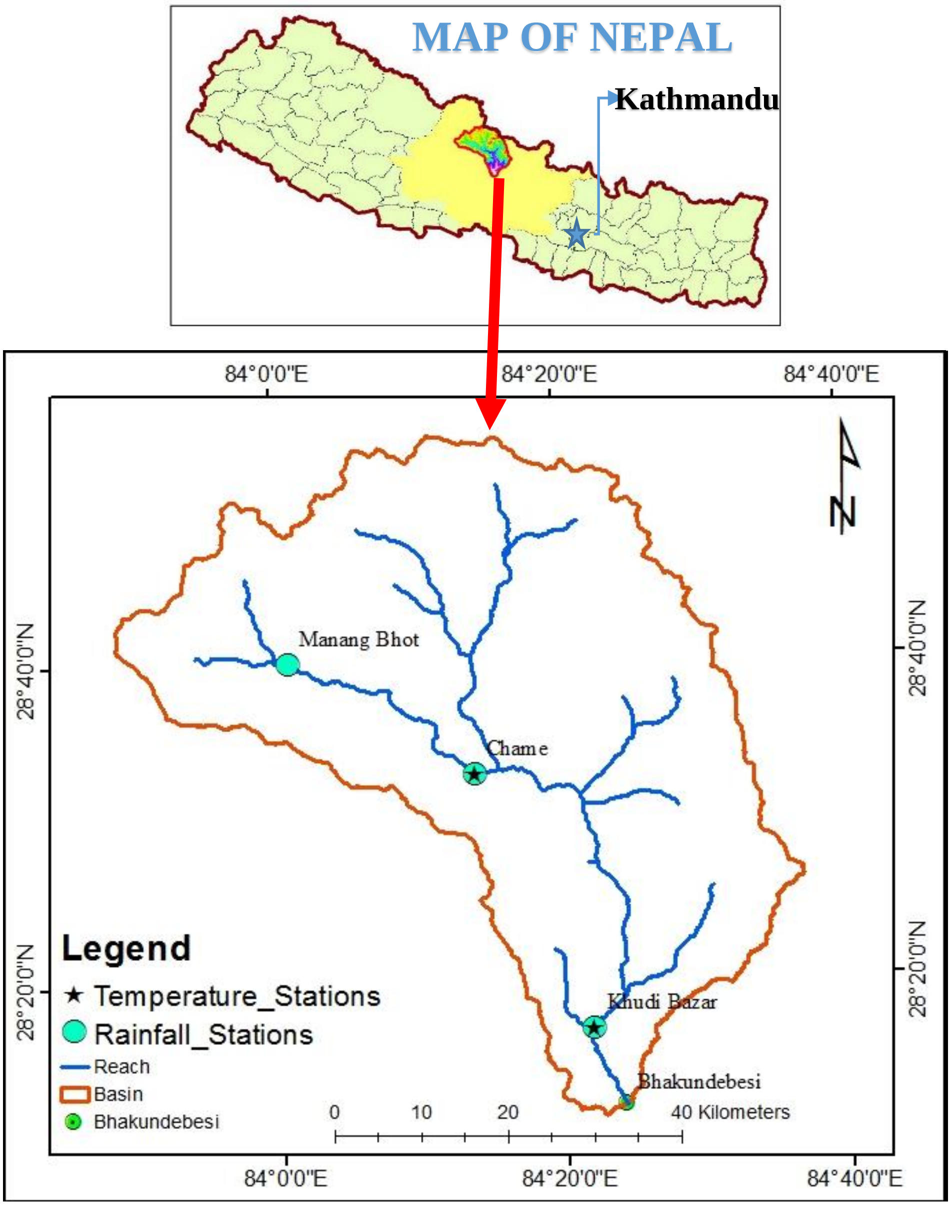

Figure 3.1 Location of climate stations and stream network in MRB

3.2.3 Climate

The basin has three distinct climatic zones ranges from cold high alpine type to humid tropical type which is sub-tropical zone (elevation less than 1800 m); temperate zone (elevation ranges from 1800m to 4000 m); and alpine zone (elevation greater than 4000 m) (Polunin and Stainton, 2000). The lower elevation is considered with total annual rainfall of 1500mm to 2000 mm and average maximum temperature of 40 °C during summer season (Ichiyanagi et al., 2007). Whereas at higher elevations, dry and cold conditions persist with the average temperature of 11 °C and precipitation of 257 mm (Pohle, 1991). During winter season, the basin is affected by westerly winds which can influence snowfall at higher elevations.

3.3 Data Availability and Collection

Daily maximum and minimum temperature, precipitation data were acquired from the Department of Hydrology and Meteorology (DHM) Nepal. There is one discharge site, three precipitation and two temperature stations located in the study area as shown in figure 3.1. The precipitation and the temperature data covers last 41 years' data from the year 1970 to 2010 with some missing data. As all data series were not of equal length, a common period (1977 – 2009) was selected for analysis. Daily discharge data at Bhakundebesi station starting from the year 2000 to 2009 were also collected from DHM Nepal.

The topographical data was extracted from Shuttle Radar Topography Mission (SRTM), Digital Elevation Model (DEM) with spatial resolution of 30 m. For Land use Land cover (LULC) map, Landsat 5 (Thematic Mapper) Sensor data was downloaded from the USGS (United State Geological Survey) Archive, i.e. http://glovis.usgs.gov/. Similarly, the soil map of the basin was obtained from the Soil and Terrain (SOTER) database for Nepal, based on ISRIC World Soil Information.

3.4 Methodology

The sequential step of the adopted study procedure are presented in the schematic diagram shown below in Figure 3.2

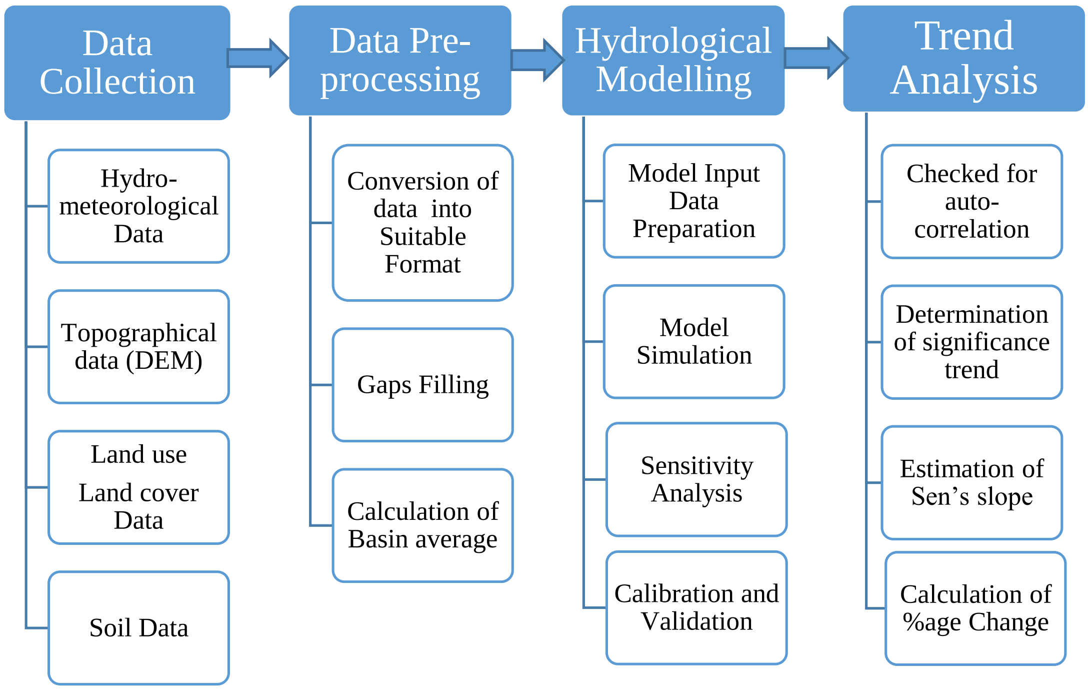

Figure 3.2 Step by step working procedure of the study

3.5 Data Pre-Processing and Gap Filling

The daily observed Precipitation and the Temperature data collected from the DHM was in the text format with some missing data and gaps, it is converted in excel format by using some simple excel macros and again converted into monthly, seasonally and annual basis, the completeness of the data was examined for the available three stations of precipitation and two stations of temperature in the basin and categorized them according to the fraction of missing data, for the temperature data set some gaps were found during analysis, and for filling these gaps monthly laps rate method was used. To calculate the laps rate for that region two temperatures at two different altitudes (heights) i.e. Temperature of station Khudibazar (832) and station Chame (2680) was taken, the rate of temperature change between these two points is assumed to be constant (straight line slope) and calculated by using given formula.

$$Laps\ Rate = \frac{(T2 - T1)}{(H2 - H1)}$$

Where T is temperature and H is height.

Lapse rate between two temperature stations was computed for each day and then average for each month.

For the computation of basin average precipitation and temperature Thiessen polygon method was used. The precipitation is never being uniform over the entire area of the basin with the high variation in intensity and duration from one place to place. Thus the rainfall recorded by each rain gauge station should be weighted according to the area, it represents. Then the average precipitation over the catchment was computed. The same process was used for computation of basin average temperature.

3.6 Hydrological Modelling (SWAT Model)

SWAT is a widely used physically – based, semi distributed continuous time hydrological model running on daily time step developed by United States Department of Agriculture-Agricultural Research Services (Neitsch et al., 2011), to simulate quantity and quality of ground and surface water and to predict the environmental impact of land management practices, land use and climate change (Gassman et al. 2007). SWAT predicts water budget dynamics as well as crop yields in different Hydrological Response Units (HRUs) identified within the river basin.

The main components of SWAT include weather, hydrology, sedimentation, crop growth, nutrients, pesticides, agricultural management, and stream routing. SWAT divides the total basin area into a number of sub-basins according to the topography depending on the number of reach outlets (generally, tributaries). Further the sub-basins are divided into several homogeneous HRUs using the landuse, soil type and slope classification. An integral part of SWAT is the general water balance equation

$$SW_t = SW_o + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{sep} - Q_{gw}\right)$$

Where,

SW_t	is the final soil water content (mm water),
SW_0	is the initial soil water content on day i (mm water),
t	is the time (days),
R_{day}	is the amount of precipitation on day i (mm water),
Q_{surf}	is the amount of surface runoff on day i (mm water),
E_a	is the amount of evapotranspiration on day i (mm water),
w_{sep}	is the amount of water entering the vadose zone from the soil profile on day i (mm water), and
Q_{gw}	is the amount of return flow on day i (mm water).

The present study is concentrated on the Climate Change Impacts on the MRB taking into account the sensitivity considerations of the SWAT model parameters. To estimate surface runoff an empirical model, SCS curve number procedure (USDA Soil Conservation Service, 1972) can be used. This method provides a consistent basis for the estimation of runoff under varying land use and soil types. The curve number equation is:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)}$$

Where,

Q_{surf}	is the accumulated runoff or rainfall excess (mm Water),
R_{day}	is the rainfall depth for the day (mm Water),
I_a	is the initial abstraction which include surface storage, interception and infiltration prior to runoff (mm Water), and
S	is the retention parameter (mm Water).

The retention parameter varies spatially due to changes in soil, land use management and slope and temporarily due to diversity in soil water content. The retention parameter is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right)$$

Where,

CN is the curve number for the day and is a function of the soil's permeability, land use and antecedent soil moisture conditions.

The initial abstractions, I_a is commonly approximated as 0.2 S. Runoff will only occur when $R_{day} > I_a$.

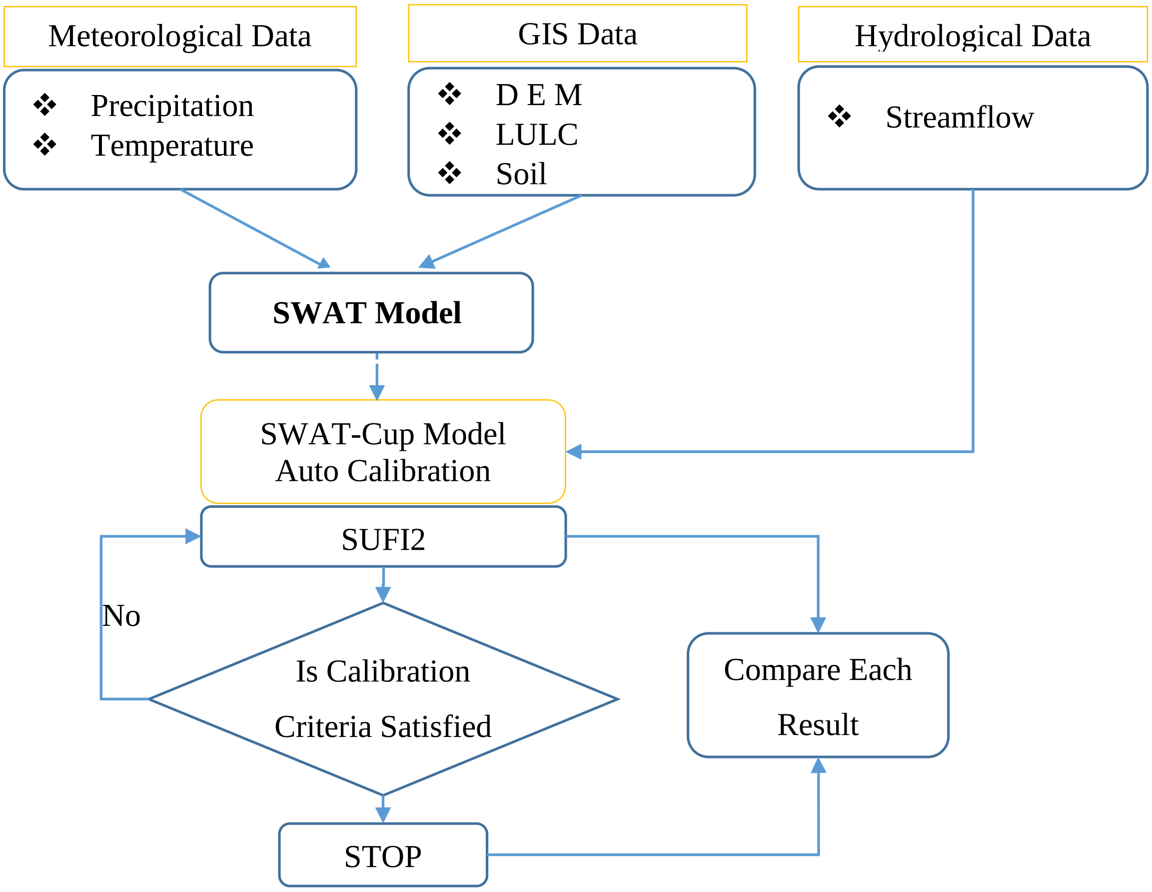

Figure 3.3 Schematic diagram of model procedure

3.7 Model Efficiency Functions

Both the daily and monthly model results were judged by three objective functions Percent Bias (PBIAS), Nash-Sutcliffe efficiency (NSE) and coefficient of determination (r^2). The formula for computing PBIAS, NSE and r^2 are given below.

PBIAS is given by,

$$\text{PBIAS} = \frac{\sum(Q_{obs}-Q_{sim})}{\sum Q_{sim}} \times 100$$

Where Q_{obs} is the observed data and Q_{sim} is the model simulated data.

Value of NSE ranges between −∞ and 1.0, with NSE = 1 being the optimal value. NSE is given by

$$\text{NSE} = 1- \frac{\sum(Q_{obs}-Q_{sim})^2}{\sum(Q_{obs}-Q_{mean})^2}$$

Where Q_{mean} is the mean of observed data.

r^2: It ranges from 0.0 (poor model) to 1.0 (perfect model) and is given by

$$r^2 = \left\{ \frac{\sum_{i=1}^{N}(Q_{obs,i}-\overline{Q_{obs}})\ (Q_{sim,i}-\overline{Q_{sim}})}{\sqrt{\sum_{i=1}^{N}(Q_{obs,i}-\overline{Q_{obs}})^2}\sqrt{\sum_{i=1}^{N}(Q_{sim,i}-\overline{Q_{sim}})^2}} \right\}$$

Where $Q_{sim,i}$ is the monthly modelled streamflow for month i, Q_{obs} is the monthly observed streamflow for month i, N is the number of months, and $\overline{Q_{sim}}$ and $\overline{Q_{obs}}$ are the mean of the monthly modelled and observed streamflow's, respectively. Higher the value of r^2, less is the error and better performance is considered.

3.8 Data Analysis

At first all the data series of precipitation, temperature and streamflow of different station are checked for auto-correlation by using Anderson's Correlogram Test at 5% significance level. The following data analysis methods which included

(1) MK test was performed in which data series are found not to be auto correlated and MMK (Hamad and Rao, 1998) test was performed in which data series are found to be autocorrelated to determine the significance of the temporal trend of precipitation and temperature.

(2) Sen’s slope estimator to detect the magnitude and direction of the trend of precipitation and temperature changes.

(3) Percentage change over the average data series were computed.

Details of the tests used are given in Appendix**.** Excel Based software XLSTAT has been used for the MK/MMK test and for the estimation of Sen’s Slope. Based on the MK test, the trends were analysed at a 95% confidence levels. The seasons considered for the analysis were from pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to November) and winter (December to February).

Chapter 4

4. Construction of Streamflow Series using SWAT Model

4.1 General

Observed streamflow data is available from 2000-2009 for a duration of 10 years at Bakhundebesi station, outlet of the MRB. Hydrological modelling was used to construct streamflow series of about 30 years' at Bakhundebesi station to perform a trend analysis in order to study the impact of climate change. SWAT model has been used to simulate streamflow at Bakhundebesi station using methodology as described in section 3.6. Hence, this chapter presents in detail the generation of streamflow series using SWAT model in the sub-basin. The chapter discusses in detail about model calibration and validation and its performance analysis. The chapter also describe the sensitivity analysis of different hydrological parameters and their rank and adopted value.

4.2 Pre-processing of Input Data for SWAT Model

The input data for SWAT-model was prepared in GIS environment to improve the representation of the distributional geographic features of the basin to be modelled. The ArcSWAT-GIS-software, available for this purpose, allows an easy integration of all relevant hydrological components of the entire watershed. For delineation of watershed and to digitize the stream network, DEM was downloaded from SRTM website and used as input. In order to analyse the impacts of climate change on hydrology and on the streamflow in the basin, daily observed climatic input data of maximum and minimum temperature and precipitation, obtained from the DHM Nepal were used.

Landsat TM image were downloaded from USGS website and were classified (supervised Classification) using ERDAS imagine (2015). Major LULC classes includes Forest Evergreen, Forest Deciduous, Range Brush, Range Grasses, Agriculture Land Generic, Barren Land, Urban area, and Snow. Table 4.1 describes all the eight LULC classes along with SWAT landuse code and percentage coverage. The land use map of the basin is shown in Figure 4.2.

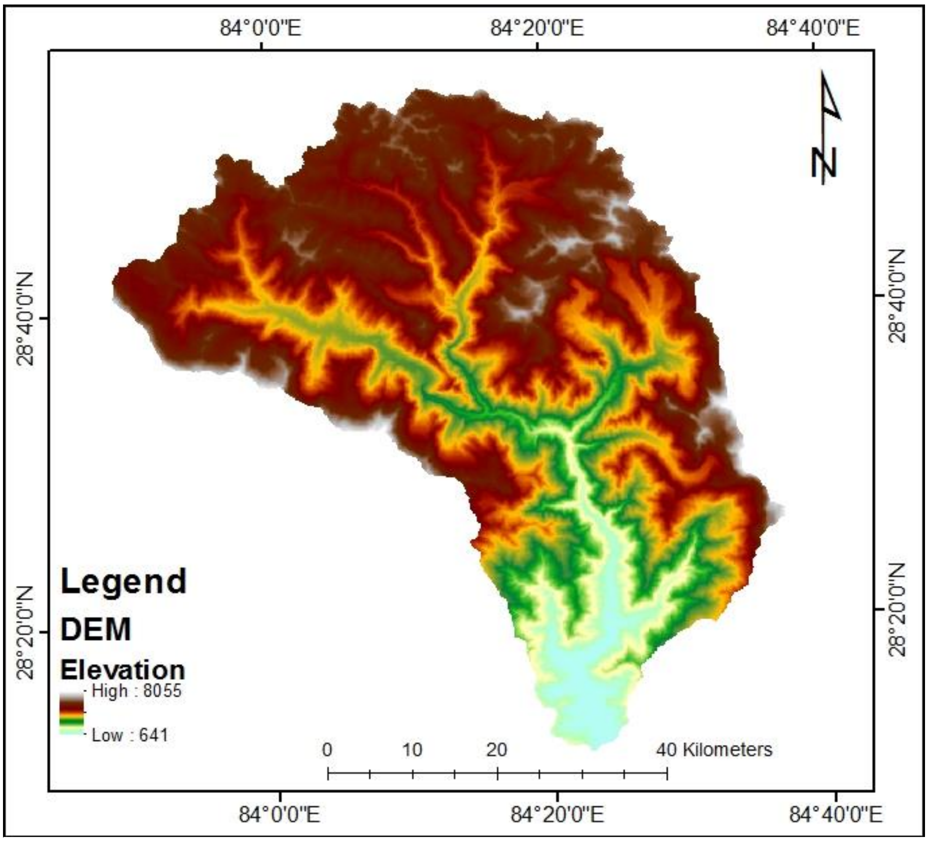

Figure 4.1 DEM of Mashyangdi River Basin

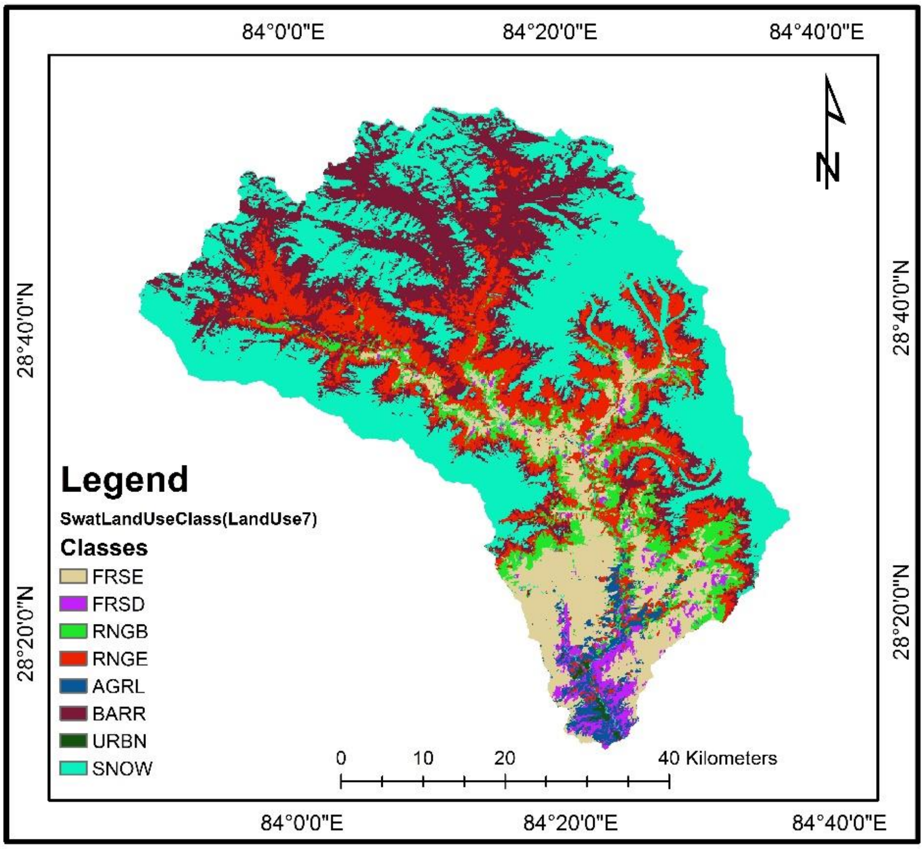

Figure 4.2 Land use Map of Marshyangdi River Basin

Table 4.1 Detail Description of Marshyangdi River Basin Land Cover

SN	Description	Landuse Code	Coverage (%)
1	Forest Ever Green	FRSE	11.17
2	Forest Deciduous	FRSD	2.24
3	Range Brush	RNGB	6.29
4	Range Grasses	RNGE	15.93
5	Agriculture Land Generic	AGRL	2.07
6	Barren Land	BARR	23.57
7	Urban area	URBN	0.17
8	Snow	WATR	38.58

Similarly, the soil map derived from the SOTER dataset, was reclassified into different categories as shown in Figure 4.3. The detailed classification consists of eight different soil classes Molli-Leptic Cambisol, Gleyi-Fluvic Cambisol, Humic Umbrisol, Eutri-Chromic Cambisol, Glacier, Lithtic Cryosols, and Eutri-Skeletic Regosol. Percentage coverage of each class alongwith FAO classification are given in Table 4.2.

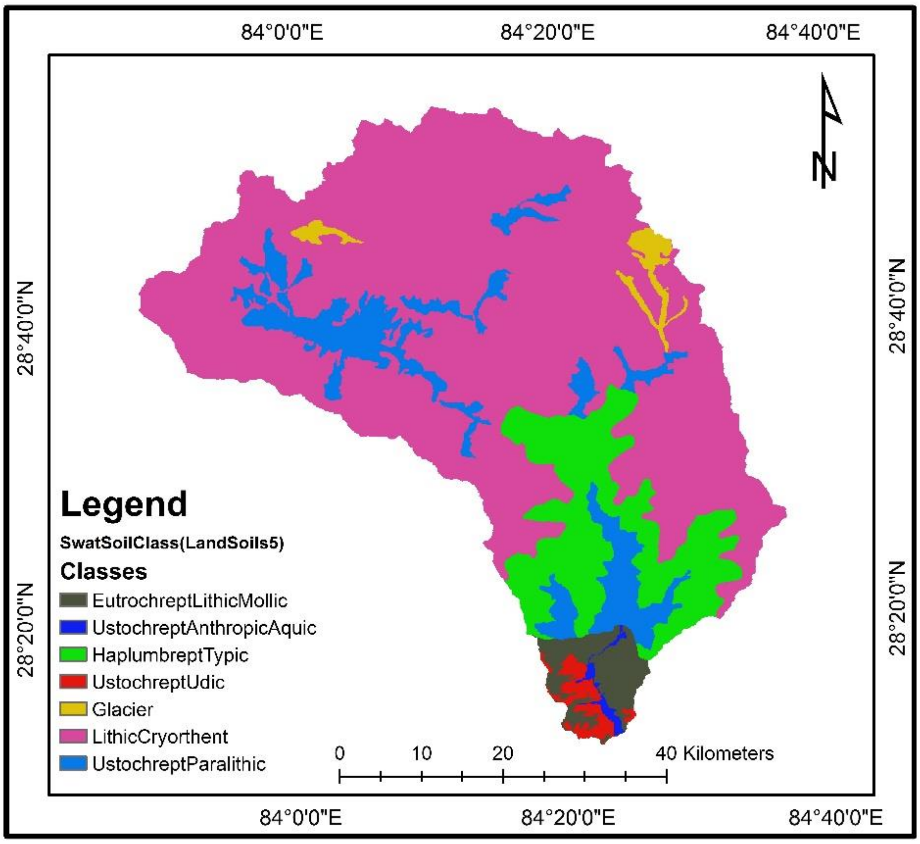

Figure 4.3 Soil Map of Marshyangdi River Basin

Table 4.2 Detail Description of Marshyangdi Basin Soil type

SN	WRBC	Soil Taxonomy	FAO Code	Coverage (%)
1	Eutrochrept Lithic Mollic	Molli-Leptic Cambisol	CMe	2.91
2	Ustochrept Anthropic Aquic	Gleyi-Fluvic Cambisol	CMg	0.35
3	Haplumbrept Typic	Humic Umbrisol	CMu	13.05
4	Ustochrept Udic	Eutri-Chromic Cambisol	CMx	1.14
5	Glacier	Glacier	GG	1.47
6	Lithic Cryorthent	Lithtic Cryosols	LPi	70.47
7	Ustochrept Paralithic	Eutri-Skeletic Regosol	RGe	10.60

Daily streamflow data observed (2000 to 2010) at Bhakundebesi gauging station were used for calibration and validation of the SWAT model.

4.3 SWAT Model Setup Process

The major steps of model setup process were used in this study:

- Delineation of watershed
- Sub-basin discretization
- HRU definition
- Calibration and validation process
- Parameter sensitivity analysis

In the present study, for watershed and stream network delineation DEM was used as input. The LULC data and the soil data were reclassified into SWAT input format. The user lookup tables were prepared to identify the SWAT code for the different categories of LULC and soil on the map as per the required format and the datasets were then imported, overlaid and linked with the SWAT2012 databases.

The watershed was then discretized spatially into 25 number of sub basins based on the topographic features of the watershed which were further divided into multiple HRUs. The HRUs depends on the size of the watershed, spatial detail of the available input data and the amount of detail required to meet the objective of the study. To define the HRU distribution, a threshold value of 5% land use, 10% soil and 10% slope were used. After the elimination processes the area of the land use, soil or slope were reallocated so that hundred percent of the land area, soil or slope in the sub basin is included in the simulation.

4.4 Model Calibration, Validation and Sensitivity Analysis

Model calibration is the process of choosing suitable values of model parameters in such a way that the hydrological behaviour of the catchment can be simulated closely with the observed one (Wagener et al., 2005; Moore and Doherty, 2005). At discharge site Bhakundebesi, 10 years (2000-2009) data was available. Out of 10 years' data, 6 years (2000-2005) was used for calibration and 4 years (2006-2009) for validation. Model was run at daily and monthly time step. For Calibration, the initial one-year data was skipped in the analysis and used as spin-up period for simulation. Model was initially run for 1500 times with SUFI2 algorithm in SWAT-CUP program. Then based on the sensitivity of the parameters, the model was again run for 1500 times for five most sensitive parameters (as described in subsequent sections) in SWAT-CUP program.

Sensitivity analysis is the analysis to identify and rank with the most sensitive parameters that have significant impact on specific model output results of interest (Saltelli et al., 2000). It establishes the impact to an individual input parameter change on the model response and can be accomplished using different methods (Veith and Ghebremichael, 2009). Sensitivity analysis was conducted to determine the sensitivity in the parameters which stimulus the flow for the sub basin outlet at Bhakundebesi. Parameters were selected for sensitivity analysis by studying previously used calibration parameters and documentation from the SWAT manuals. Optimal values of parameters were derived from trial and error process during calibration for the both daily as well as monthly simulation; generally, one input parameter was changed once to analyse the corresponding output. Sensitivity of modelled stream discharge of 10 years were compared with individual simulations in which selected parameters were changed ± 20% and expressed as 'Relative sensitivity'. The results of sensitivity analysis of the present study with the proper rank of the different parameters is presented in Table 4.3. Total twenty number of parameters were tested, out of which 5 parameters were found significantly influencing the simulated stream flow discharge of the watershed i.e. SMTMP.bsn, SFTMP.bsn, ALPHA_BF.gw, CH_N2.rte and CH_K1.sub (shown in bold in Table 4.3).

Table 4.3 Result of sensitivity analysis with ranking of SWAT Parameter for streamflow in MRB including t-Stat and P-Value

Parameter Name	Description	t-Stat	P-Value	Rank
SMTMP.bsn	**Snow melt base temperature**	**-14.57**	**0**	**1**
SFTMP.bsn	**Snowfall temperature**	**-10.69**	**0**	**2**
ALPHA_BF.gw	**Base flow alpha factor (days)**	**5.33**	**<0.05**	**3**
CH_N2.rte	**Manning's "n" value for the main channel**	**5.23**	**<0.05**	**4**
CH_K1.sub	**Effective hydraulic conductivity in tributary channel alluvium**	**-3.64**	**<0.05**	**5**
SOL_BD.sol	Moist bulk density.	-1.51	0.13	6
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium.	-1.45	0.14	7
CN2.mgt	runoff curve number	-1.43	0.15	8
PLAPS.sub	Precipitation lapse rate.	0.75	0.45	9
SMFMN.bsn	Minimum melt rate for snow during the year (occurs on winter solstice)	0.70	0.48	10
SURLAG.bsn	Surface runoff lag time	0.68	0.49	11
ESCO.bsn	Soil evaporation compensation factor	-0.55	0.58	12
TIMP.bsn	Snow pack temperature lag factor	-0.52	0.60	13
SNO50COV.bsn	Snow water equivalent that corresponds to 50% snow cover	-0.44	0.65	14
REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	-0.39	0.69	15
GW_DELAY.gw	Groundwater delay (days)	0.34	0.73	16
TLAPS.sub	Temperature lapse rate	0.26	0.79	17
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm).	-0.25	0.79	18
SOL_ALB.sol	Moist soil albedo	-0.13	0.89	19
RCHRG_DP.gw	Deep aquifer percolation fraction	-0.05	0.95	20

4.5 Results and Analysis

The model was calibrated for 20 parameters affecting the snowmelt and baseflow component. After calibration it was observed that the model was underestimating systematically. To correct the systematic error, a bias of 15 cumec was added to the simulated streamflow. Observed and simulated flows in the calibration phase are shown in figures 4.4 and 4.5 for daily and monthly time period respectively. The three major statistical performance ratings during the calibration phase is presented in Table 4.4. During calibration period, values of NSE, PBIAS and r^2 were found to be 0.75, 12.64 and 0.77 respectively for daily time scale. Similarly, for monthly time scale these parameters were estimated as 0.84, 12.21 and 0.89. Figure 4.6 and figure 4.7 represents the Scatter plot & correlation between observed and simulated streamflow during model calibration for daily as well as monthly time period.

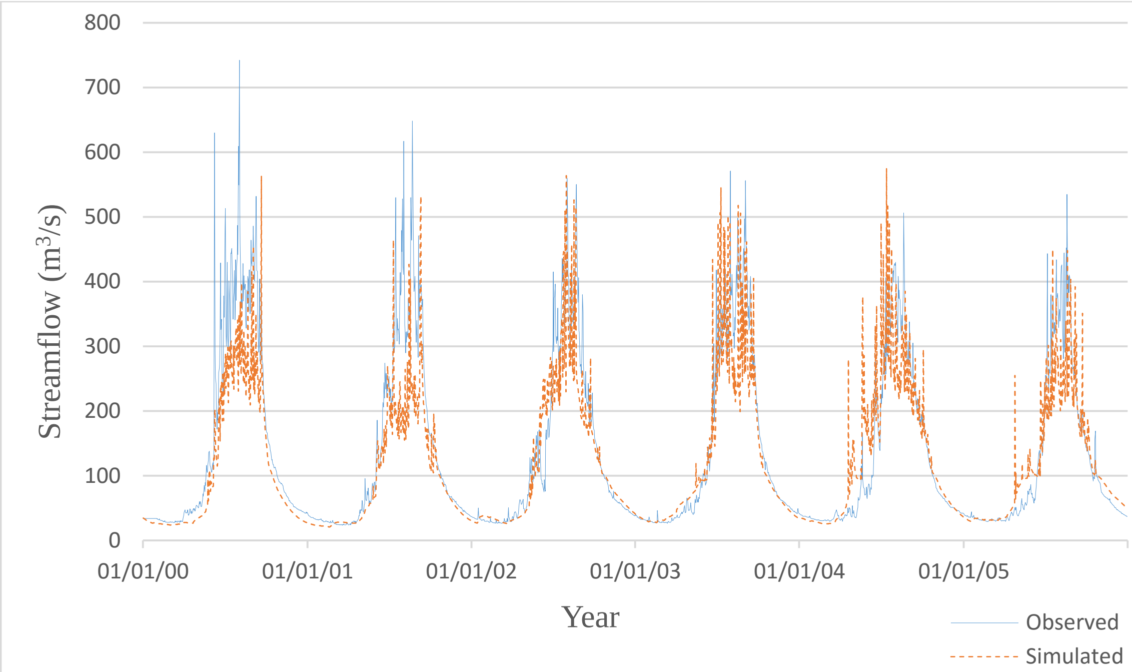

Figure 4.4 Hydrographs obtained during model calibration for daily, time period

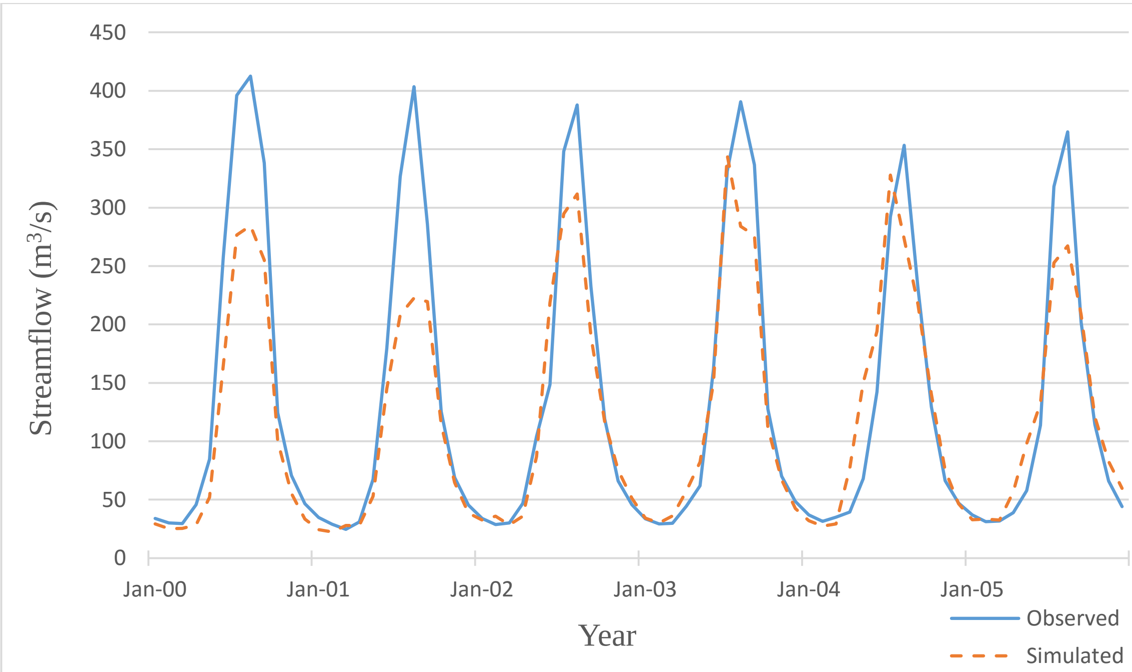

Figure 4.5 Hydrographs obtained during model calibration for monthly time period

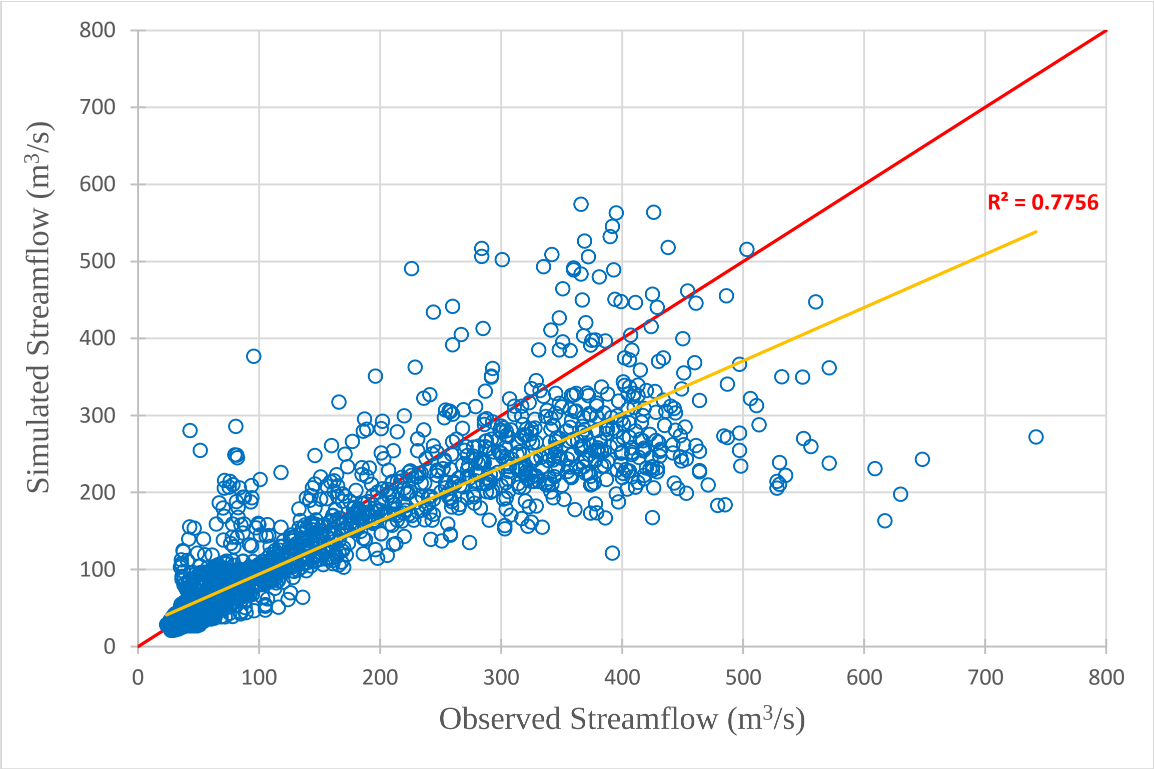

Figure 4.6 Scatter plot & correlation between observed and simulated streamflow during model calibration for daily time period

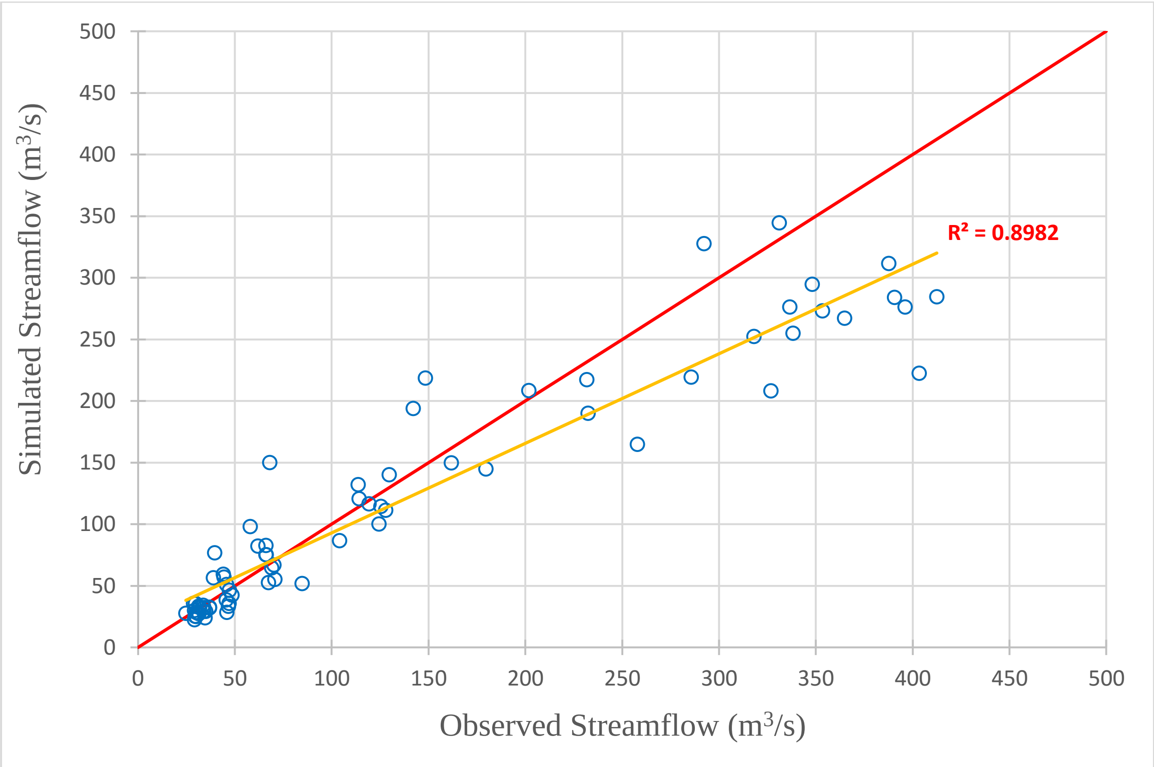

Figure 4.7 Scatter plot & correlation between observed and simulated streamflow during model calibration for monthly time period

Table 4.4 Model performance statistics for calibration period

Time	Calibration	NSE	PBIAS (%)	r^2
Daily	Without Bias addition	0.71	23.7	0.78
	With bias addition	0.75	12.64	0.77
Monthly	Without Bias addition	0.80	23.4	0.90
	With bias addition	0.84	12.21	0.89

During calibration the regression lines in above (Figures 4.6 & 4.7) indicate a good model performance.

Figure 4.8 and Figure 4.9 represents the model validation result for daily and monthly time period respectively. During the validation phase, NSE, PBIAS and r^2 were estimated to be 0.69, 10.21 and 0.70 for daily time scale and 0.84, 10.10 and 0.86 for monthly time step respectively. Better model accuracy for simulated stream discharge during the validation period was found at monthly time scale. Finally, simulated mean daily stream discharge was found to be 114.95 m^3/sec which agreed well with the observed data 128.02 m^3/sec. Figure 4.10 and figure 4.11 represents the scatter plot and correlation between observed and simulated streamflow during model validation for daily time period as well as monthly time period.

Table 4.5 Model performance statistics for validation period

Time	Validation	NSE	PBIAS (%)	r^2
Daily	Without Bias addition	0.65	21.9	0.71
	With bias addition	0.69	10.21	0.70
Monthly	Without Bias addition	0.80	21.9	0.86
	With bias addition	0.84	10.1	0.86

During validation the regression lines in (Figures 4.10 & 4.11) indicate a good model performance.

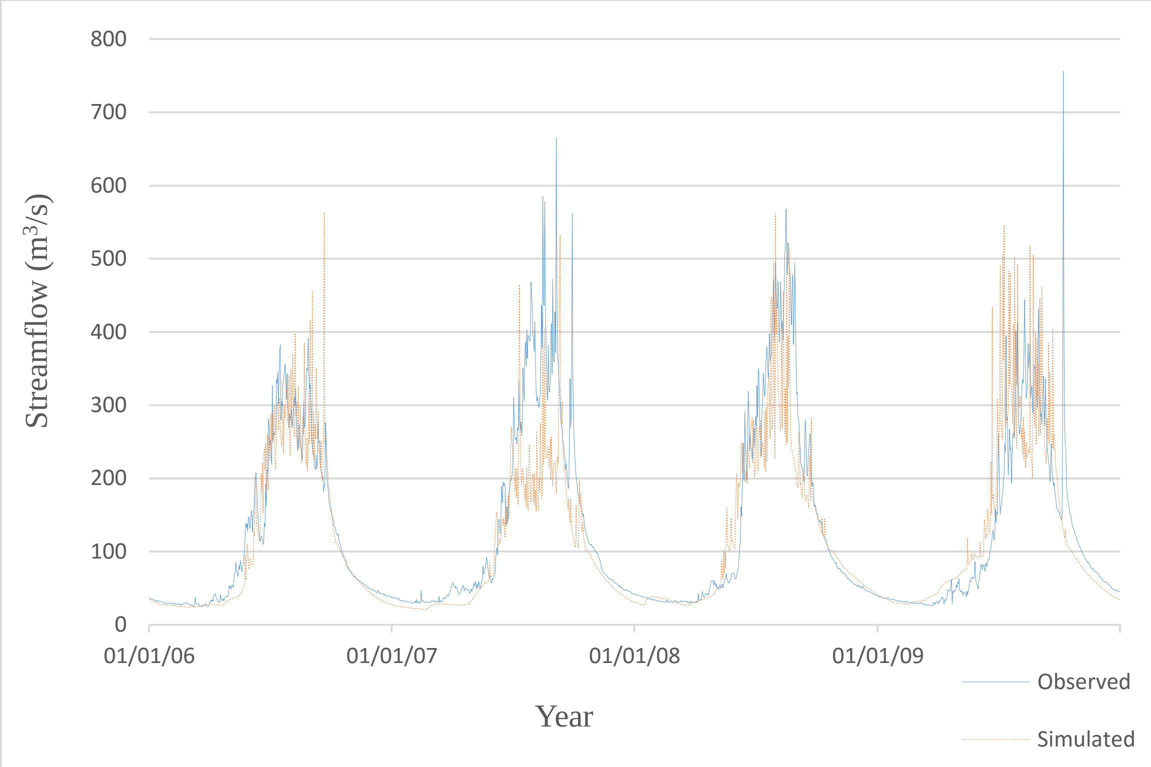

Figure 4.8 Hydrographs obtained during model validation for daily time period

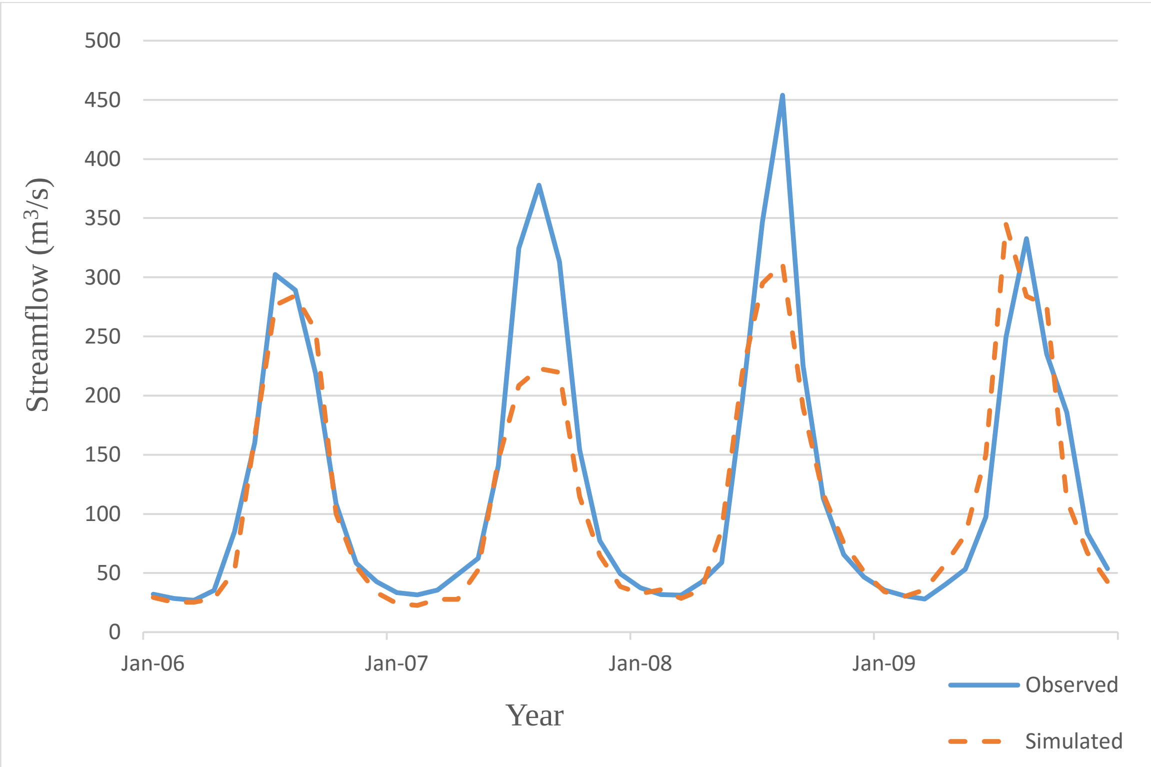

Figure 4.9 Hydrographs obtained during model validation for monthly time period

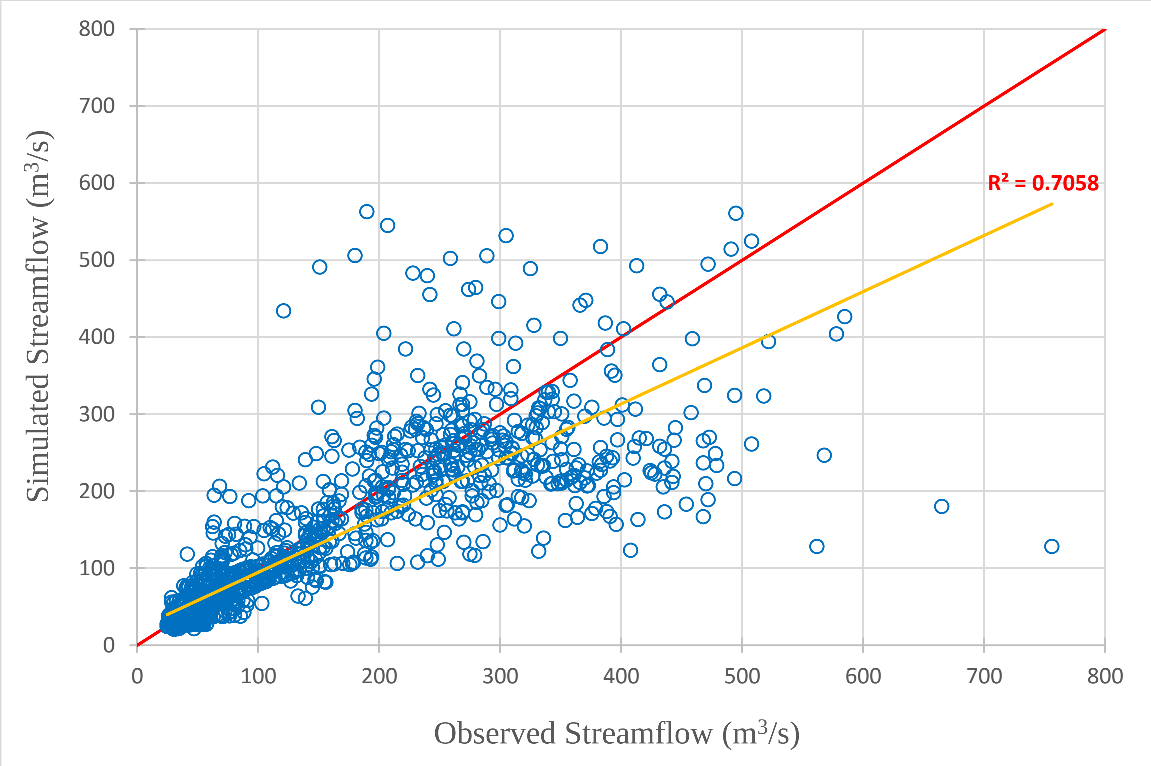

Figure 4.10 Scatter plot & correlation between observed and simulated streamflow during model validation for daily time period

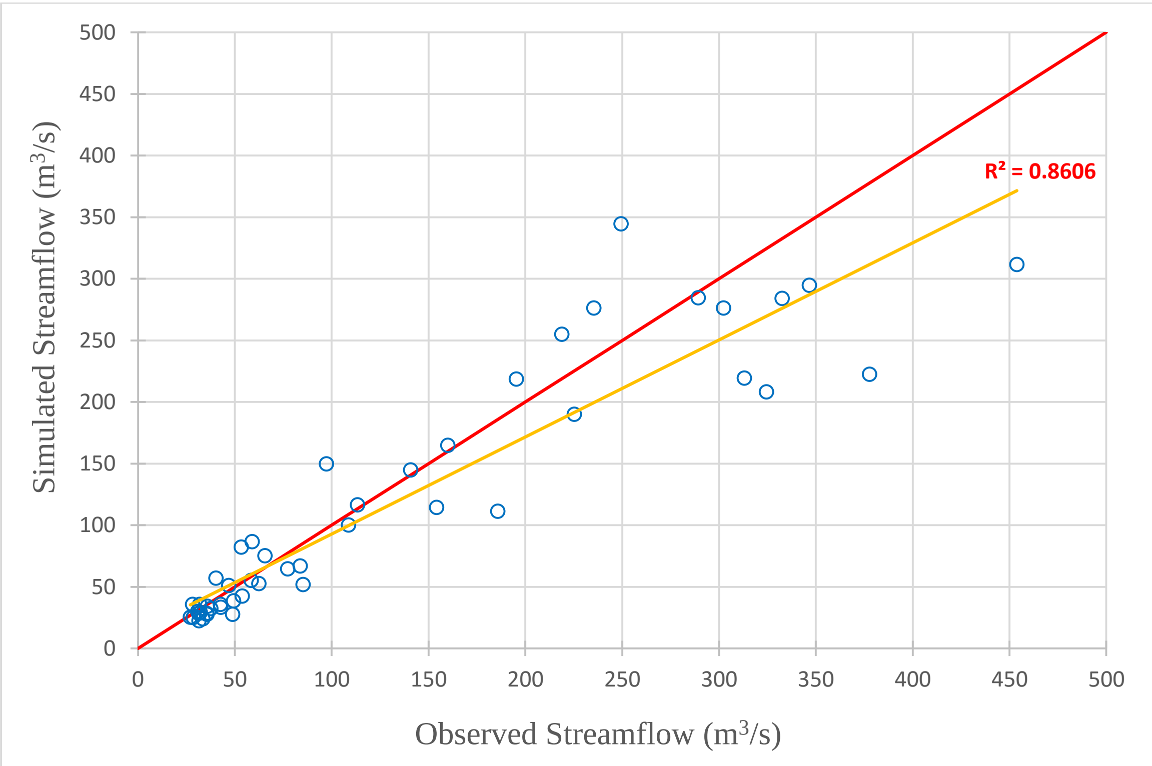

Figure 4.11 Scatter plot & correlation between observed and simulated streamflow during model validation for monthly time period

4.6 Streamflow Data Generation

After model calibration and validation, SWAT model was run for full length of study period i.e. from 1977-2009 with calibrated model parameters. The generated daily streamflow hydrograph is shown in figure 4.12 and monthly in figure 4.13. Monthly generated streamflow data are given in Appendix IV.

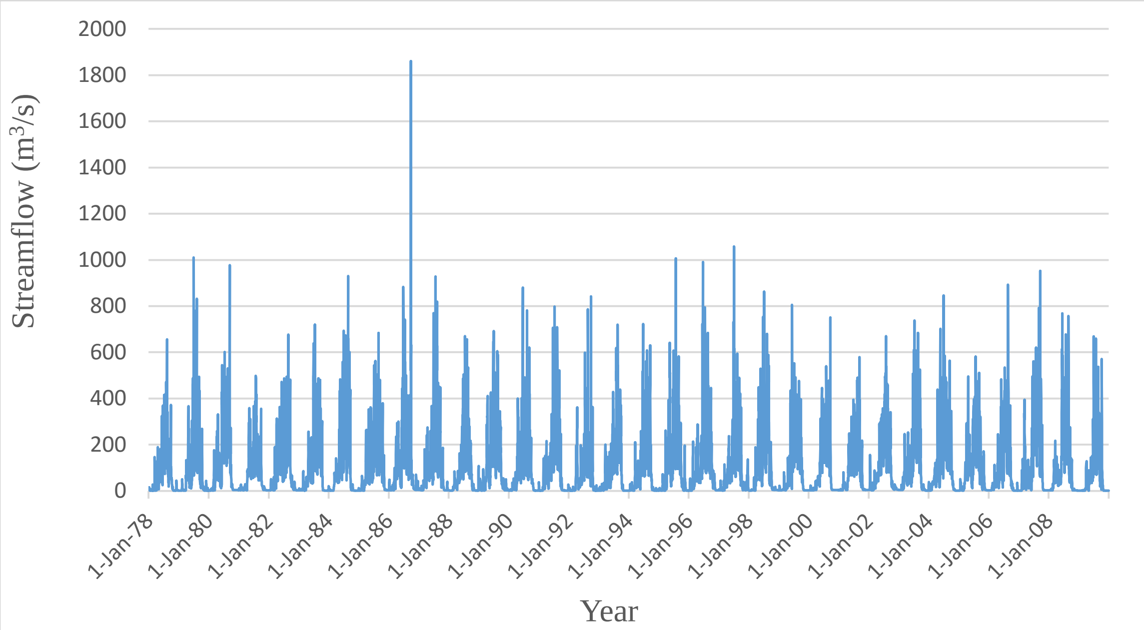

Figure 4.12 Generated daily streamflow hydrograph from 1978-2009 for daily time period

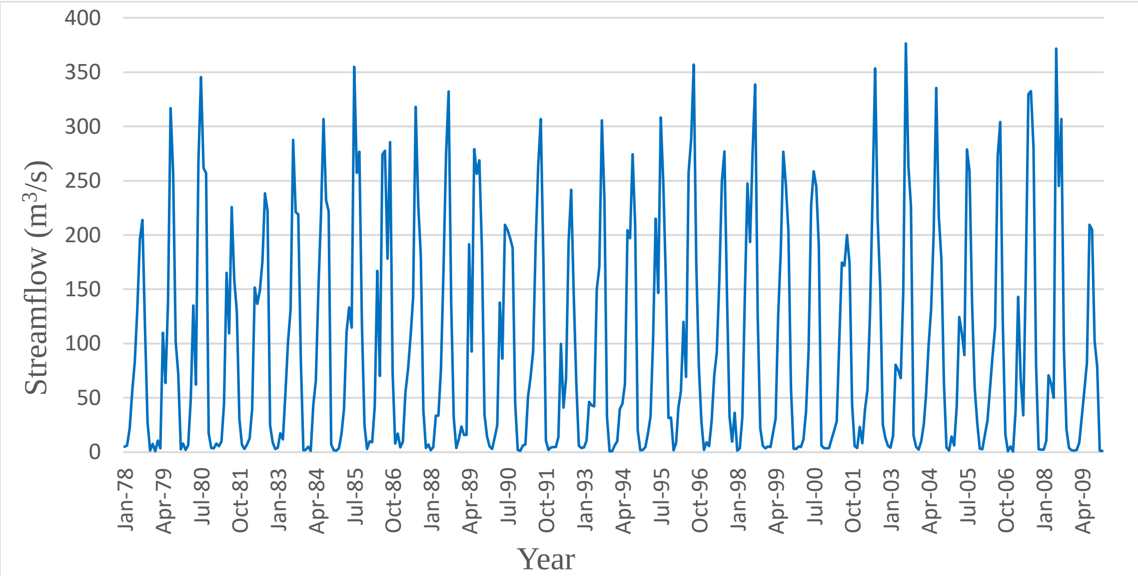

Figure 4.13 Generated daily streamflow hydrograph from 1978-2009 for monthly time period

Chapter 5

5. Climate Change Impact Analysis on Hydrometeorological Variables

5.1 Analysis of Temperature Trends (1977-2009)

The results of MK test and Sen's slope estimator test and the percentage change of seasonal temperature series at two stations Khudibazar and Chame the year 1977-2009 are presented in Table 5.1. A significant autocorrelation was found in minimum and maximum temperature series; therefore, MMK test was applied for these series.

Increasing trends were found for the minimum and maximum temperatures at both the stations. A significant trend was observed at station Khudibazar for all seasons as well as annually; in minimum temperature at Khudibazar the percentage change in the monsoon season i.e. 9.63% has been significantly increased to 26.05% in the post monsoon. Percentage change variation in maximum temperature was found less as compare to minimum temperature for all the seasons. But, at station Chame, it can be seen that in minimum temperature there is more season wise variation in the percentage change in all the seasons. Table 5.1 shows that change in percentage at Khudibazar station is significantly lower than percentage change at Chame.

Overall basin series were prepared using Thiessen weights. An increasing trend was found in both the minimum and maximum temperature except in the pre monsoon and post monsoon season in the minimum temperature. Significant change in both minimum and maximum temperature trends were observed during the winter season. Among temperatures, minimum temperature is showing more increase than maximum temperature at all the stations for all the seasons and annual data series.

Figures 5.1 and 5.2 shows the pattern of annual average temperature at stations Khudibazar and Chame respectively. From the figure it can be clearly observed that there is an increasing trend in both the data series, but the increasing trend is considerably lesser at station Chame as compare to the Khudibazar.

Table 5.1 Result of Mann-Kendall test (at 5% significance level) and percentage change for temperature over year 1977 to 2009.

Khudibazar

Seasons	Minimum Temperature			Maximum Temperature		
	MK "P" Value	Sen's Slope	%age Change	MK "P" Value	Sen's Slope	%age Change
Pre Monsoon	0.049*	0.058	12.754	0.104	0.032	3.71
Monsoon	**0.040***	0.060	9.631	**0.012***	0.058	6.38
Post Monsoon	**0.000***	0.107	26.056	**0.000***	0.101	12.65
Winter	0.024*	0.055	23.999	**0.000***	0.079	12.48
Annual	**0.004***	0.059	13.087	**0.000***	0.065	8.06

Chame

Seasons	Minimum Temperature			Maximum Temperature		
	MK "P" Value	Sen's Slope	%age Change	MK "P" Value	Sen's Slope	%age Change
Pre Monsoon	0.466	0.021	14.268	**0.001***	0.095	17.70
Monsoon	**0.432**	-0.087	-29.340	0.039*	0.031	4.97
Post Monsoon	0.525	-0.021	-16.255	**0.000***	0.127	25.64
Winter	0.355	-0.016	33.004	**0.048***	0.151	44.55
Annual	**0.077**	-0.039	-26.892	**0.007***	0.095	18.69

Basin Overall

Seasons	Minimum Temperature			Maximum Temperature		
	MK "P" Value	Sen's Slope	%age Change	MK "P" Value	Sen's Slope	%age Change
Pre Monsoon	0.034*	0.060	19.218	**0.000***	0.072	10.17
Monsoon	**0.735**	-0.018	-3.857	**0.004***	0.046	6.07
Post Monsoon	0.914	-0.002	-0.702	**0.000***	0.092	14.45
Winter	0.355	0.018	19.414	**0.000***	0.125	25.65
Annual	**0.588**	0.015	5.206	**0.000***	0.081	12.28

MMK values in bold represent presence of autocorrelation in the series.

* Represents significant trend

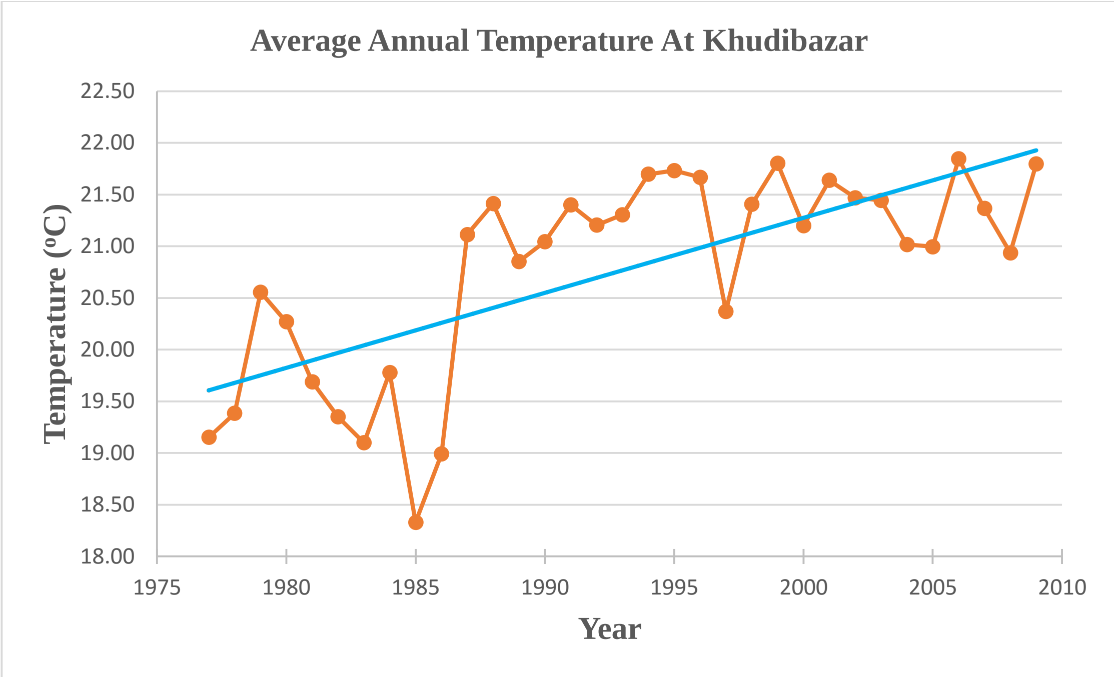

Figure 5.1 Annual Average Temperature at Station Khudibazar

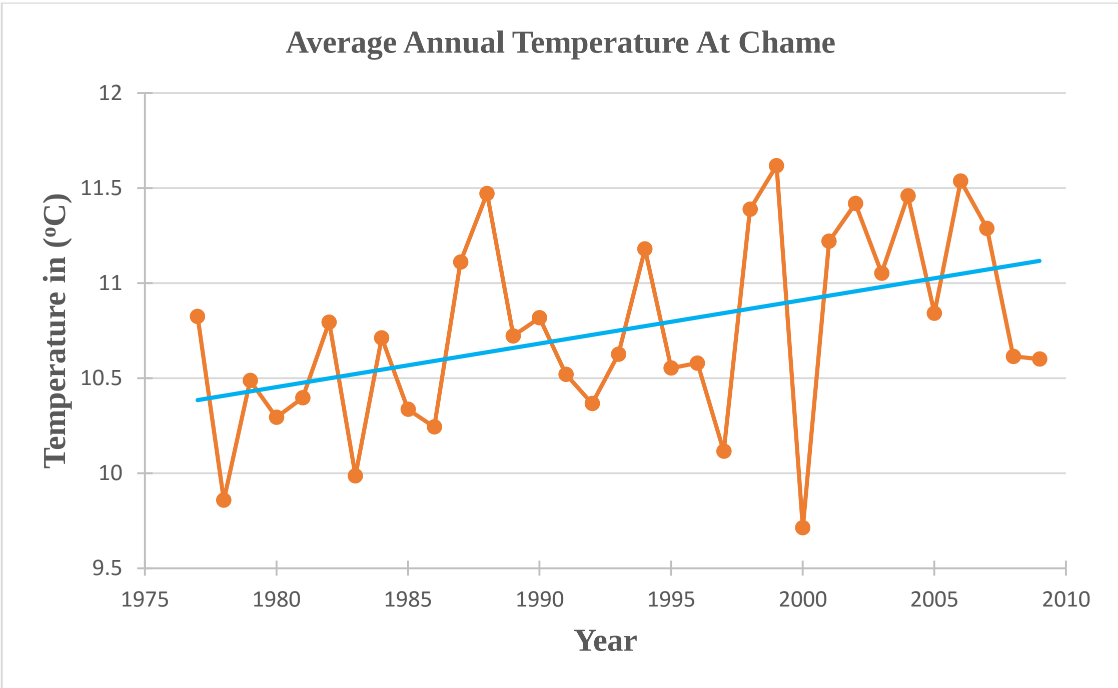

Figure 5.2 Annual Average Temperature at Station Chame

5.2 Analysis of Precipitation Trends (1977-2009)

Precipitation data was available for three stations namely Chame, Manang Bhot and Khudibazar during 1977 to 2009. Station at Chame and Manang Bhot receive considerably less amount of rainfall as compared to the station at Khudibazar. Preliminary analysis of the precipitation data shows that total annual precipitation of the entire basin varies from 439.17mm at station Chame to 3341.76mm at station Khudibazar. In Figure 5.3, the total annual precipitation shows an increasing trend at all the stations and also for all the seasons except station Manang Bhot. Station Manang Bhot, however, shows a slightly decreasing linear trend.

Statistical analysis of trends (annual as well as seasonal precipitation) are presented in Table 5.2 for different stations and for the entire basin. Over the entire basin, pre-monsoon, monsoon, post-monsoon, winter and as well as annual precipitation showed an increasing trend for all the stations. At station Khudibazar a significant trend was found in the post monsoon season whereas at station Chame and Manang Bhot, pre monsoon season trends are significant. Monsoon season is the season which shows increasing trend at all the stations, although none of these trends were found statistically significant.

Table 5.2 also shows the percentage changes over mean values in annual and seasonal precipitation. From the table it can be seen that at Khudibazar station the percentage change in winter precipitation is by more than 50%, whereas at station Chame all the seasons have significant change in percentage except post monsoon. However, at station Manang Bhot and overall basin average, the significant percentage change can be seen in pre-monsoon and winter seasons only.

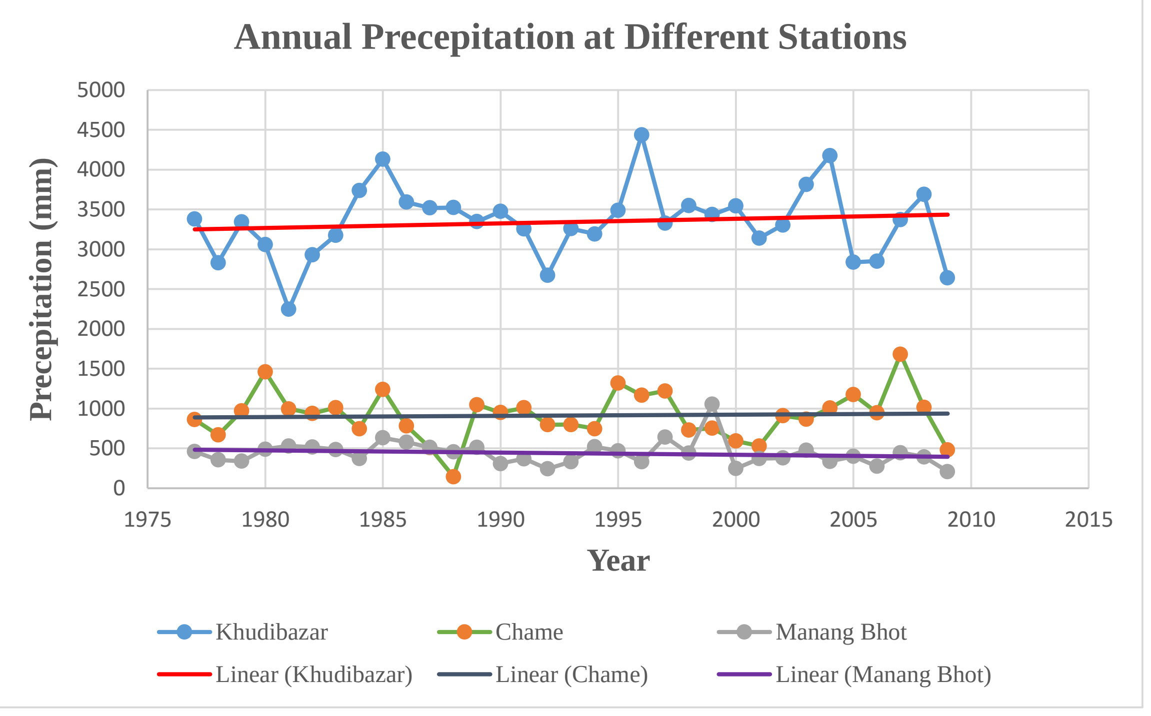

Figure 5.3 Total Annual Precipitation at different stations

Table 5.2 Result of Mann-Kendall test (at 5% significance level), Total Precipitation and percentage change for Precipitation over year 1977 to 2009.

Khudibazar				
Season	MK “P” Value	Sen's Slope	Total Precipitation (mm)	% age Change
Pre Monsoon	0.865	0.456	396.33	3.80
Monsoon	0.653	4.000	2697.34	4.89
Post Monsoon	**0.037***	1.691	157.09	35.53
Winter	0.116	-1.420	90.15	-51.98
Annual	0.588	4.348	3341.76	4.29
Chame				
Season	MK “P” Value	Sen's Slope	Total Precipitation (mm)	% age Change
Pre Monsoon	**0.049***	-1.700	84.08	-66.72
Monsoon	0.141	-2.653	242.73	-36.06
Post Monsoon	0.448	0.483	57.29	27.85
Winter	0.083	-0.897	52.65	-56.22
Annual	0.097	-3.714	439.17	-27.91
Manang Bhot				
Season	MK “P” Value	Sen's Slope	Total Precipitation (mm)	% age Change
Pre Monsoon	**0.121**	-1.269	178.24	-23.49
Monsoon	0.271	4.296	575.74	24.62
Post Monsoon	0.901	0.048	74.92	2.12
Winter	0.545	-0.913	81.83	-36.82
Annual	0.889	0.413	911.38	1.49
Basin Overall				
Season	MK “P” Value	Sen's Slope	Total Precipitation (mm)	% age Change
Pre Monsoon	0.361	-1.034	198.53	-17.18
Monsoon	0.285	3.478	950.35	12.08
Post Monsoon	0.486	0.725	87.99	27.19
Winter	0.188	-1.242	74.82	-54.77
Annual	0.631	2.017	1312.96	5.07

MMK values in bold represents presence of autocorrelation in the series.

* Represents significant trend

5.3 Trend Analysis of Streamflow Data (1978-2009)

Trend analysis was performed on stream flow series obtained in Chapter 4. The series was divided into four seasons such as pre-monsoon, monsoon, post monsoon and winter for the analysis purpose. The data of the year 1977 was not used in the analysis because this year was used as spin up period. The results of above MK test are presented in Table 5.3.

Table 5.3 Result of Mann-Kendall test (at 5% significance level), average streamflow and percentage change over year 1978 to 2009

Season	Q*(m^3/s)	% of Annual	MK "P" Value	Sen's Slope	% age Change
Pre-monsoon	221.44	18.82	0.775	-0.931	-13.45
Monsoon	882.07	74.97	0.265	2.325	8.43
Post Monsoon	50.24	4.27	0.405	0.168	10.70
Winter	22.38	1.90	0.532	-0.007	-1.00
Annual	1176.50	100.00	0.430	1.173	3.19

**Average stream flow of 32 years*

Analysis of annual streamflow demonstrate a non-significant increasing trend in the basin with a 3.19% increase in mean annual flow. Stream flows have also been increased in all the seasons but the statistics shows that there is a variation in these trends. In monsoon and post monsoon season, the stream flow has increased by 8.43% and 10.7% respectively, whereas in pre-monsoon and winter season streamflow has decreased by -13.45% and -1% respectively.

Figure 5.4 is the yearly average annual discharge of MRB over the year 1978- 2009. From figure it can also be clearly seen that there is a slightly increasing trend in the average annual flow.

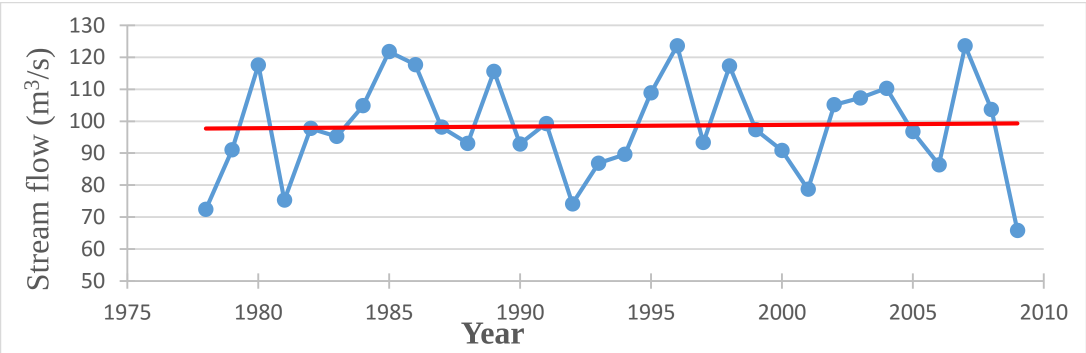

Figure 5.4 Annual Average Discharge of MRB over the year 1978-2009

The rainfall within the basin is the principal source for the stream discharge of the basin. Approximately about 76% of the total stream discharge flowing through MRB is dependent on the rainfall comprising the stream discharge of the entire basin which is presented in figure 5.5, which suggest that the changes in rainfall pattern have definite effect on streamflow.

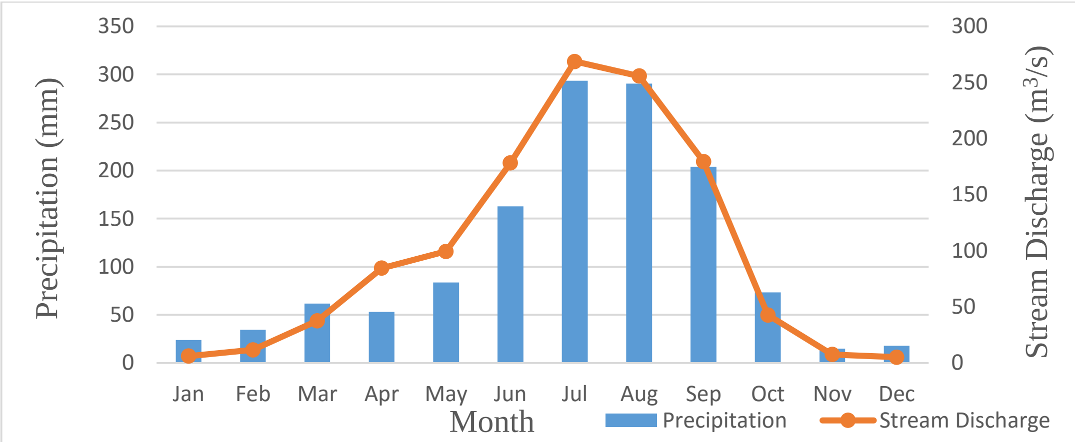

Figure 5.5 Average monthly precipitation and stream discharge of MRB

Average precipitation and streamflow in the MRB in each month is shown in figure 5.5. The graph of streamflow is closely following the pattern of precipitation in each month, except in summer months. It is due to melting of snow in pre-monsoon season, which was accumulated during winter season. The decrease in streamflow in pre-monsoon season is -13.45% which is lower than decrease in precipitation -17.18%. One possible explanation for that can be increased snowmelt component due to increasing temperatures in pre-monsoon season. Similarly, in winter season the decrease in precipitation is very high, -54.77% while the streamflow only decreased by -1%. The possible explanation for this is change in the precipitation pattern (rainfall/snow). Due to increasing temperatures in the MRB, now more precipitation is falling as rainfall than snow, that's why in spite of very high decrease in precipitation, the streamflow doesn't change much.

During the monsoon and post monsoon season the increase in streamflow (8.43% and 10.7%) is lower than increase in precipitation (12.08% and 27.19%). The increasing temperatures in the MRB are increasing the losses in the form of evapotranspiration, thereby offsetting the increased precipitation.

Chapter 6

6. Conclusion

One of the undisputed fact of these days is the climate change due to the global rise in temperature. Year 2015 is observed the hottest year ever and 2016 is predicted to be even warmer. The consequences of the global climate change are evident everywhere in the form of temperature rise, unpredicted severe flood and droughts, change in weather pattern etc. Every corner of the globe is affected with the climate change.

Nepal, though not responsible for the current situation, is at the receiving end of the resulting consequences. Nepal, being a Himalayan country is highly susceptible to climate change. Fast depleting snows in the Nepal Himalayas has a potential threat on the water availability in the Nepal's major rivers. MRB feeds the major rivers in Nepal. Its climate characteristics varies with the altitude.

Observed streamflow data is available from 2000-2009 for a duration of 10 years at Bakhundebesi station, outlet of the MRB. Hydrological modelling was used to construct streamflow series of about 30 years' at Bakhundebesi station to perform a trend analysis in order to study the impact of climate change. Hydrological modelling was attempted to construct the streamflow series of around 30 years. SWAT model calibration and validation gave significant results of three major statistical performance measures. During calibration period, values of NSE, PBIAS and r^2 were found to be 0.75, 12.64 and 0.77 respectively for daily time scale. Similarly, for monthly time scale these parameters were estimated to be 0.84, 12.21 and 0.89. While for validation values of NSE, PBIAS and r^2 were estimated to be 0.69, 10.21 and 0.70 at daily and 0.84, 10.10 and 0.86 at monthly time scale. A high correspondence in r^2 and NSE value was observed at monthly time scale for both calibration and validation. Out of total twenty numbers of model parameters five were found to be most significantly influencing the simulated stream discharge of the watershed.

Trend analysis of temperature data by applying MK test showed a significant increasing trend in temperature pattern. The temperature data was analysed by dividing the data set into four seasons such as pre monsoon, monsoon, post monsoon and winter as well as annually. The maximum temperature at all the stations was observed to be increasingly invariably, while the minimum temperature was found to have a monotonic increasing trend significantly at both stations at Khudibazar and Chame. The analysis of the precipitation in the basin showed huge difference in the total annual precipitation. Precipitation at two stations Khudibazar and Manang Bhot, is showing an increasing trend while at Chame station it is showing decreasing trend. Overall precipitation has increased by 5.07% in the MRB. Winter precipitation has decreased in all stations and post monsoon season precipitation has increased at all three stations. At Chame, each season showed a negative percentage change except post monsoon which had 27.85% of positive change in annual value. Manang Bhot station and the basin averaged value showed a decrease in percentage change in total annual precipitation during pre-monsoon and winter season.

Analysis of annual streamflow demonstrate a non-significant increasing trend in the basin with a 3.19% increase in mean annual flow. Changes in streamflow in MRB are controlled by precipitation and temperature both. Precipitation being a direct input to streamflow generation process is affecting the streamflow, while increasing temperatures are increasing the losses (evapotranspiration), changing the dynamics of precipitation by changing the rainfall/snowfall distribution and increasing the snowmelt.

6.1 Limitations and Scope for Future work

The limitations of present work are mentioned below:

- Peaks of the simulated streamflow does not match with the observed peak values therefore analysis of extremes should not be done.
- The analysis is performed on simulated streamflow. Thought, the results are in acceptable range, but these must be used keeping in mind the limitations of hydrological modelling.
- Only two meteorological variables were used to simulate streamflow.

Following are the areas where this work can be improved and enhanced in future:

- LULC change impact on streamflow may be carried out to understand its role.
- Calibrated model may be used to study other hydrological processes under changing climate.
- Future climate change scenarios can be used to study the future water availability.

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Appendix I

Autocorrelation

Presence of positive or negative autocorrelation affects the detection of trend in a series (Hamed and Rao, 1998; Serrano et al., 1999; Yue et al., 2002b, 2003; Cunderlik and Burn, 2004; Novotny and Stefan, 2007). With a positively autocorrelated series, there are more chances of a series being detected as having trend while there may be actually none. The case is reverse for negatively autocorrelated series, where a trend fails to get detected. The autocorrelation coefficient ρ_k of a discrete time series for lag-k is estimated as

$$\rho_k = \frac{\sum_{i=1}^{N-k}(x_i-\overline{x_i})(x_{i+1}-\overline{x_{i+k}})}{\sqrt{\sum_{i=1}^{N-k}(x_i-\overline{x_i})^2 * \sum_{i=1}^{N-k}(x_{i+k}-\overline{x_{i+k}})^2}}$$

Where, x_i and Var (x_i) are the sample mean and sample variance of the first (n − k) terms, and x_{i+k} and Var (x_{i+k}) are the sample mean and sample variance of the last (n − k) terms. The hypothesis of serial independence is then tested by the lag-1 autocorrelation coefficient as H0: $\rho 1 = 0$ against H1: $|\rho 1| > 0$ using

$$t = |\rho_1| \sqrt{\frac{n-2}{1-\rho_1^2}}$$

Where the test statistic t has a Student's t-distribution with (n − 2) degrees of freedom (Cunderlik and Burn, 2004). If $|t| \geq t_{\alpha/2}$, the null hypothesis about serial independence is rejected at the significance level α (here10%).

Mann–Kendall Test

It is based on the test statistic *S* defined as (Yue *et al*., 2002a):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i)$$

Where, x_j are the sequential data values, *n* is the length of the data set and

$$\operatorname{sgn}(y) = \begin{Bmatrix} 1 \cdots if(y > 0) \\ 0 \cdots if(y = 0) \\ -1 \cdots if(y < 0) \end{Bmatrix}$$

It has been documented that when $n \geq 8$, the statistic S is approximately normally distributed with the mean $E(S) = 0$ and variance is

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} ti(ti-1)(2ti+5)}{18}$$

Where m is the number of tied groups and ti is the size of the ith tied group. The standardized test statistic Z is computed by

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if \quad S < 0 \end{cases}$$

Modified Mann–Kendall Test

Pre-whitening has been used to detect a trend in a time series in presence of autocorrelation (Cunderlik and Burn, 2004). However, pre-whitening is reported to reduce the detection rate of significant trend in the MK test (Yue *et al*., 2003). Therefore, the MMK test (Hamed and Rao, 1998; Rao *et al*., 2003) has been employed for trend detection of an autocorrelated series. In this, the autocorrelation between ranks of the observations ρ_k are evaluated after subtracting a non-parametric trend estimate such as Theil and Sen's median slope from the data. Only significant values of ρ_k are used to calculate the variance correction factor $n/n{*}S$, as the variance of S is underestimated when the data are positively autocorrelated:

$$\frac{n}{n_S^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2)\rho_k$$

Where n is the actual number of observations, $n{*}s$ is considered as an 'effective' number of observations to account for autocorrelation in the data and ρ_k is the autocorrelation function of the ranks of the observations. To account only for significant autocorrelation in data, number of lags can be limited to 3 (Rao *et al*., 2003).

The corrected variance is then computed as

$$V^*(S) = V(S) \times \frac{n}{n_S^*}$$

Where *V (S)* is from Equation (6). The rest is as in the MK test.

Percentage Change

Some trends may not be evaluated to be statistically significant while they might be of practical interest, and vice versa (Yue and Hashino, 2003). Even if a climate change component is present, it does not need to be detected by statistical tests at a satisfactory significance level (Radziejewski and Kundzewicz, 2004). For the present study, change percentages have been computed by approximating it with a linear trend, estimating its magnitude by Theil and Sen's median slope and assessing the change over the period as percentage of mean of the period concerned, following Yue and Hashino (2003).
That is, change percentage equals median slope multiplied by the period length divided by the corresponding mean, expressed as percentage. The significance level has been set up to be 10%, the same as the level for statistical significance.

Percentage Change (%) = $\frac{Sen\ slope * Length\ of\ the\ year}{mean} * 100$

Theil and Sen's median slope estimator

This gives a robust estimate of trend (Yue *et al*., 2002b). The slope estimates of *N* pairs of data are first computed by

$$Q_i = (x_j - x_k)/(j - k) \text{ for } i = 1, \ldots N$$

Where xj and xk are data values at times *j* and *k (j > k)*, respectively. The median of these *N* values of Q_i is Sen's estimator of slope.

Appendix II

SWAT weather generator data

Khudibazar

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
TMPMX	19.75	21.97	26.27	29.72	30.34	30.70	29.96	30.15	29.45	27.56	24.54	20.97
TMPMN	6.60	8.74	12.55	15.73	18.01	20.26	20.96	20.87	19.48	15.27	11.09	7.56
TMPSTDMX	2.34	2.82	3.05	2.64	2.46	1.98	2.02	1.86	2.10	2.22	2.32	2.29
TMPSTDMN	2.63	3.01	2.95	2.74	2.54	1.98	1.64	1.63	2.06	2.90	2.45	2.30
PCP_MM	35.37	65.06	104.77	126.68	243.15	545.58	861.85	848.81	494.58	108.72	23.61	25.83
PCPSTD	4.58	7.06	8.09	9.49	13.59	24.21	27.81	27.02	23.05	9.56	4.63	4.53
PCPSKW	6.55	8.42	4.48	4.55	3.31	2.45	1.90	1.51	3.39	4.71	11.68	7.54
PR_W1	0.08	0.17	0.23	0.30	0.48	0.58	0.82	0.83	0.55	0.17	0.06	0.04
PR_W2	0.38	0.44	0.52	0.53	0.60	0.82	0.92	0.90	0.81	0.52	0.36	0.41
PCPD	3.79	6.79	10.24	12.12	17.42	23.79	29.30	28.67	23.48	8.70	2.76	2.09

Chame

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
TMPMX	9.96	11.57	15.28	18.66	20.16	20.96	20.41	20.17	19.49	17.40	14.79	11.86
TMPMN	-2.67	-0.52	2.73	5.41	7.58	9.61	10.08	10.01	9.30	5.72	2.05	-1.62
TMPSTDMX	3.53	3.82	3.56	2.49	2.10	1.85	1.68	1.85	1.81	2.16	2.62	3.38
TMPSTDMN	2.34	2.77	2.36	2.68	2.38	2.21	2.43	2.34	2.10	2.51	2.68	2.30
PCP_MM	38.01	54.51	79.51	58.38	64.54	121.15	189.94	169.52	133.51	55.90	20.67	25.88
PCPSTD	3.30	4.45	5.83	3.69	4.20	8.82	7.00	6.11	6.85	5.42	4.43	3.45
PCPSKW	4.41	4.30	4.62	2.85	4.19	8.59	2.74	1.90	2.78	4.81	17.86	7.74
PR_W1	0.09	0.16	0.20	0.18	0.25	0.30	0.47	0.46	0.28	0.10	0.04	0.04
PR_W2	0.71	0.64	0.61	0.68	0.59	0.74	0.85	0.83	0.78	0.68	0.70	0.75
PCPD	7.70	9.67	11.30	11.61	12.15	16.36	24.73	23.76	18.42	8.36	3.76	4.94

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Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
TMPMX	6.05	7.43	10.9	14.25	16.1	17.08	16.61	16.19	15.53	13.36	10.91	8.24
TMPMN	-6.37	-4.21	-1.19	1.29	3.42	5.37	5.75	5.68	5.24	1.92	-1.55	-5.27
TMPSTDMX	4.59	4.92	4.52	3.13	2.59	2.48	2.22	2.51	2.39	2.7	3.4	4.51
TMPSTDMN	3.03	3.55	2.81	3.25	3.06	2.98	3.48	3.35	2.93	3.22	3.53	3.14
PCP_MM	26.25	21.51	34.19	23.99	31.82	44.84	67.51	76.63	72.70	36.04	12.41	15.76
PCPSTD	2.90	2.46	3.53	2.38	3.18	4.48	4.13	4.56	6.65	5.57	2.85	2.35
PCPSKW	5.29	6.25	6.08	5.39	6.88	9.15	3.66	3.38	6.02	9.53	10.69	6.21
PR_W1	0.11	0.13	0.16	0.15	0.18	0.23	0.34	0.32	0.20	0.06	0.03	0.06
PR_W2	0.57	0.53	0.56	0.48	0.53	0.65	0.73	0.73	0.65	0.58	0.43	0.45
PCPD	6.61	6.64	8.58	7.06	8.91	12.27	18.12	17.64	11.79	4.52	1.76	2.91

Appendix III

Model Output Result for the Calibration (2000-2005) and Validation (2006-2009) time period

Calibration Monthly output data

Date	Observed	Simulated	Date	Observed	Simulated
Jan-00	34	29.29	Jan-03	33.58	34.22
Feb-00	30.02	25.23	Feb-03	29.17	30.08
Mar-00	29.53	25.4	Mar-03	29.72	36.01
Apr-00	45.85	28.5	Apr-03	44.37	57.26
May-00	84.76	52.11	May-03	61.87	82.31
Jun-00	257.9	165.1	Jun-03	161.76	149.9
Jul-00	396.03	276.5	Jul-03	331.1	344.8
Aug-00	412.52	284.6	Aug-03	390.68	284.1
Sep-00	338.17	255.2	Sep-03	336.5	276.4
Oct-00	124.38	100.24	Oct-03	127.8	111.56
Nov-00	70.66	55.41	Nov-03	70.12	67.17
Dec-00	46.67	33.42	Dec-03	48.49	42.52
Jan-01	34.67	24.286	Jan-04	36.91	32.12
Feb-01	29.07	22.566	Feb-04	31.53	27.47
Mar-01	24.76	27.87	Mar-04	35.01	29.36
Apr-01	31.01	27.81	Apr-04	39.49	76.9
May-01	67.29	52.77	May-04	68	150.2
Jun-01	179.62	145.1	Jun-04	142.16	194.1
Jul-01	326.81	208.4	Jul-04	292.19	327.9
Aug-01	403.45	222.7	Aug-04	353.42	273.4
Sep-01	285.57	219.5	Sep-04	231.73	217.4
Oct-01	125.42	114.6	Oct-04	129.63	140.3
Nov-01	69.03	64.78	Nov-04	66.25	75.38
Dec-01	45.51	38.63	Dec-04	47.13	46.56
Jan-02	33.97	32.62	Jan-05	36.85	32.81
Feb-02	28.61	35.76	Feb-05	31.24	33.49
Mar-02	29.99	28.5	Mar-05	31.79	32.61
Apr-02	46.96	35.91	Apr-05	38.84	56.69
May-02	104.07	86.82	May-05	57.92	98.13
Jun-02	148.41	218.7	Jun-05	113.62	132.3
Jul-02	348.13	294.8	Jul-05	318.1	252.6
Aug-02	387.74	311.7	Aug-05	364.87	267.3
Sep-02	232.3	190.1	Sep-05	201.87	208.7
Oct-02	119.22	116.7	Oct-05	114.14	120.9
Nov-02	66.01	75.42	Nov-05	65.98	82.85
Dec-02	45.7	51.19	Dec-05	44.02	59.6

Validation Monthly output data

Date	Observed	Simulated	Date	Observed	Simulated
Jan-06	32.08	29.29	Jan-09	35.71	34.22
Feb-06	28.52	25.23	Feb-09	30.77	30.08
Mar-06	26.94	25.4	Mar-09	28.1	36.01
Apr-06	35.43	28.5	Apr-09	40.27	57.26
May-06	85.15	52.11	May-09	53.32	82.31
Jun-06	160	165.1	Jun-09	97.27	149.9
Jul-06	302.35	276.5	Jul-09	249.45	344.8
Aug-06	289.23	284.6	Aug-09	332.58	284.1
Sep-06	218.77	255.2	Sep-09	235.3	276.4
Oct-06	108.68	100.24	Oct-09	185.77	111.56
Nov-06	58.46	55.41	Nov-09	83.66	67.17
Dec-06	42.78	33.42	Dec-09	53.77	42.52
Jan-07	33.49	24.286			
Feb-07	31.45	22.566			
Mar-07	35.64	27.87			
Apr-07	48.9	27.81			
May-07	62.43	52.77			
Jun-07	140.81	145.1			
Jul-07	324.55	208.4			
Aug-07	377.77	222.7			
Sep-07	313.07	219.5			
Oct-07	154.13	114.6			
Nov-07	77.27	64.78			
Dec-07	49.39	38.63			
Jan-08	37.59	32.62			
Feb-08	31.82	35.76			
Mar-08	31.37	28.5			
Apr-08	42.47	35.91			
May-08	58.86	86.82			
Jun-08	195.33	218.7			
Jul-08	346.62	294.8			
Aug-08	453.83	311.7			
Sep-08	225.29	190.1			
Oct-08	113.39	116.7			
Nov-08	65.53	75.42			
Dec-08	46.81	51.19			

Appendix IV

Model Output Result of generated streamflow (1978-2009) for monthly time period

Date	Q (m3/s)	Date	Q (m3/s)	Date	Q (m3/s)
Jan-78	5.02	Jan-81	8.05	Jan-84	4.82
Feb-78	6.11	Feb-81	5.65	Feb-84	1.16
Mar-78	21.52	Mar-81	9.70	Mar-84	43.30
Apr-78	55.37	Apr-81	44.57	Apr-84	65.71
May-78	82.95	May-81	165.20	May-84	150.20
Jun-78	131.90	Jun-81	109.40	Jun-84	218.30
Jul-78	195.90	Jul-81	225.70	Jul-84	306.80
Aug-78	214.00	Aug-81	158.80	Aug-84	232.30
Sep-78	114.30	Sep-81	129.40	Sep-84	221.70
Oct-78	27.35	Oct-81	30.64	Oct-84	6.89
Nov-78	1.42	Nov-81	6.65	Nov-84	1.61
Dec-78	7.58	Dec-81	2.89	Dec-84	1.32
Jan-79	0.81	Jan-82	7.16	Jan-85	3.49
Feb-79	10.56	Feb-82	12.48	Feb-85	16.32
Mar-79	3.45	Mar-82	39.91	Mar-85	39.71
Apr-79	110.10	Apr-82	151.70	Apr-85	110.70
May-79	63.71	May-82	136.70	May-85	133.30
Jun-79	138.50	Jun-82	148.60	Jun-85	114.60
Jul-79	316.90	Jul-82	175.60	Jul-85	355.00
Aug-79	257.30	Aug-82	238.50	Aug-85	257.10
Sep-79	101.50	Sep-82	222.00	Sep-85	276.80
Oct-79	71.59	Oct-82	24.82	Oct-85	117.80
Nov-79	2.62	Nov-82	9.19	Nov-85	25.06
Dec-79	7.86	Dec-82	2.92	Dec-85	2.92
Jan-80	1.90	Jan-83	4.15	Jan-86	10.10
Feb-80	6.45	Feb-83	17.21	Feb-86	9.16
Mar-80	48.34	Mar-83	11.72	Mar-86	41.84
Apr-80	135.20	Apr-83	54.79	Apr-86	166.80
May-80	62.28	May-83	101.30	May-86	70.05
Jun-80	267.80	Jun-83	131.10	Jun-86	274.10
Jul-80	345.40	Jul-83	287.60	Jul-86	277.50
Aug-80	261.60	Aug-83	220.90	Aug-86	178.10
Sep-80	257.00	Sep-83	219.30	Sep-86	285.60
Oct-80	17.48	Oct-83	85.10	Oct-86	72.61
Nov-80	3.75	Nov-83	1.69	Nov-86	7.76
Dec-80	3.35	Dec-83	1.91	Dec-86	17.07

Date	Q (m3/s)	Date	Q (m3/s)	Date	Q (m3/s)
Jan-87	4.48	Jan-90	2.86	Jan-93	4.29
Feb-87	9.57	Feb-90	13.65	Feb-93	10.46
Mar-87	55.16	Mar-90	24.65	Mar-93	46.38
Apr-87	75.88	Apr-90	137.80	Apr-93	42.92
May-87	106.40	May-90	85.98	May-93	42.04
Jun-87	142.30	Jun-90	209.40	Jun-93	149.80
Jul-87	317.90	Jul-90	204.60	Jul-93	170.70
Aug-87	227.70	Aug-90	197.40	Aug-93	305.50
Sep-87	181.10	Sep-90	188.30	Sep-93	231.80
Oct-87	38.53	Oct-90	45.17	Oct-93	32.50
Nov-87	3.81	Nov-90	1.86	Nov-93	0.80
Dec-87	7.13	Dec-90	1.07	Dec-93	0.73
Jan-88	1.76	Jan-91	6.24	Jan-94	6.15
Feb-88	4.55	Feb-91	7.04	Feb-94	9.92
Mar-88	33.58	Mar-91	50.79	Mar-94	39.73
Apr-88	33.44	Apr-91	68.67	Apr-94	44.43
May-88	76.48	May-91	92.67	May-94	62.75
Jun-88	168.20	Jun-91	191.90	Jun-94	204.40
Jul-88	274.90	Jul-91	263.90	Jul-94	197.00
Aug-88	332.20	Aug-91	306.70	Aug-94	274.30
Sep-88	137.70	Sep-91	179.20	Sep-94	208.80
Oct-88	31.56	Oct-91	10.69	Oct-94	20.36
Nov-88	3.67	Nov-91	2.07	Nov-94	1.56
Dec-88	12.01	Dec-91	4.50	Dec-94	1.96
Jan-89	23.53	Jan-92	4.54	Jan-95	4.70
Feb-89	15.85	Feb-92	4.60	Feb-95	17.28
Mar-89	15.83	Mar-92	13.74	Mar-95	32.77
Apr-89	191.40	Apr-92	99.62	Apr-95	103.90
May-89	92.63	May-92	40.88	May-95	214.90
Jun-89	279.00	Jun-92	68.16	Jun-95	146.60
Jul-89	256.40	Jul-92	194.00	Jul-95	308.30
Aug-89	268.70	Aug-92	241.50	Aug-95	247.30
Sep-89	187.50	Sep-92	145.20	Sep-95	157.40
Oct-89	34.72	Oct-92	64.07	Oct-95	31.60
Nov-89	14.45	Nov-92	5.77	Nov-95	31.95
Dec-89	5.11	Dec-92	3.92	Dec-95	1.60

Date	Q (m3/s)	Date	Q (m3/s)	Date	Q (m3/s)
Jan-96	8.52	Jan-99	5.28	Jan-02	23.10
Feb-96	40.78	Feb-99	4.70	Feb-02	8.14
Mar-96	56.24	Mar-99	17.81	Mar-02	38.41
Apr-96	120.10	Apr-99	31.00	Apr-02	57.35
May-96	69.27	May-99	126.00	May-02	128.10
Jun-96	257.40	Jun-99	184.80	Jun-02	237.00
Jul-96	288.20	Jul-99	276.70	Jul-02	353.50
Aug-96	357.00	Aug-99	246.30	Aug-02	213.60
Sep-96	173.90	Sep-99	202.80	Sep-02	150.90
Oct-96	79.31	Oct-99	58.69	Oct-02	25.33
Nov-96	28.24	Nov-99	3.07	Nov-02	12.87
Dec-96	2.14	Dec-99	2.81	Dec-02	5.72
Jan-97	9.15	Jan-00	5.39	Jan-03	4.14
Feb-97	5.68	Feb-00	4.69	Feb-03	14.88
Mar-97	28.65	Mar-00	11.66	Mar-03	80.39
Apr-97	70.13	Apr-00	37.20	Apr-03	75.43
May-97	91.43	May-00	93.86	May-03	68.04
Jun-97	157.90	Jun-00	227.70	Jun-03	148.50
Jul-97	249.20	Jul-00	258.80	Jul-03	376.40
Aug-97	276.90	Aug-00	244.80	Aug-03	263.30
Sep-97	143.90	Sep-00	190.10	Sep-03	226.40
Oct-97	32.82	Oct-00	6.17	Oct-03	15.23
Nov-97	9.76	Nov-00	3.88	Nov-03	4.95
Dec-97	36.22	Dec-00	3.38	Dec-03	2.41
Jan-98	1.35	Jan-01	3.74	Jan-04	10.04
Feb-98	3.53	Feb-01	11.99	Feb-04	25.31
Mar-98	32.39	Mar-01	20.04	Mar-04	52.33
Apr-98	146.90	Apr-01	28.53	Apr-04	97.80
May-98	247.50	May-01	102.90	May-04	131.90
Jun-98	193.50	Jun-01	174.50	Jun-04	202.30
Jul-98	276.20	Jul-01	171.70	Jul-04	335.50
Aug-98	338.80	Aug-01	199.90	Aug-04	216.70
Sep-98	125.30	Sep-01	174.10	Sep-04	178.10
Oct-98	21.97	Oct-01	43.94	Oct-04	63.59
Nov-98	5.71	Nov-01	5.49	Nov-04	4.28
Dec-98	3.35	Dec-01	3.78	Dec-04	1.50

Date	Q (m3/s)	Date	Q (m3/s)
Jan-05	14.39	Jan-08	2.32
Feb-05	6.26	Feb-08	10.42
Mar-05	42.38	Mar-08	70.80
Apr-05	124.50	Apr-08	63.15
May-05	109.70	May-08	50.15
Jun-05	89.37	Jun-08	371.70
Jul-05	278.70	Jul-08	245.20
Aug-05	258.80	Aug-08	306.90
Sep-05	137.20	Sep-08	94.52
Oct-05	60.24	Oct-08	21.00
Nov-05	27.44	Nov-08	3.91
Dec-05	3.08	Dec-08	1.77
Jan-06	2.73	Jan-09	1.49
Feb-06	15.95	Feb-09	1.89
Mar-06	28.86	Mar-09	8.84
Apr-06	58.47	Apr-09	32.57
May-06	88.75	May-09	57.24
Jun-06	115.30	Jun-09	82.42
Jul-06	272.50	Jul-09	209.50
Aug-06	304.30	Aug-09	205.00
Sep-06	119.30	Sep-09	102.10
Oct-06	16.56	Oct-09	78.97
Nov-06	0.85	Nov-09	1.31
Dec-06	5.21	Dec-09	1.08
Jan-07	0.51		
Feb-07	38.37		
Mar-07	143.00		
Apr-07	67.17		
May-07	33.74		
Jun-07	165.80		
Jul-07	329.90		
Aug-07	332.40		
Sep-07	280.30		
Oct-07	80.56		
Nov-07	2.62		
Dec-07	2.21		