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STREAM FLOW MODELLING IN A PART OF SATLUJ BASIN USING SWAT MODEL

Major Project Thesis

Submitted by

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DECLARATION

This is to certify that the work that forms the basis of this project "STREAM FLOW MODELLING IN A PART OF SATLUJ BASIN USING SWAT MODEL" is an original work carried out by me and has not been submitted anywhere else for the award of any degree.

I certify that all sources of information and data are fully acknowledged in the project thesis.

Shahnaz Khatun

Shahnaz Khatun

Date: 19/05/2017

CERTIFICATE

This is to certify that SHAHNAZ KHATUN has carried out her major project in partial fulfillment of the requirement for the degree of Master of Science in M.Sc. Geoinformatics on the topic "STREAM FLOW MODELLING IN A PART OF SATLUJ BASIN USING SWAT MODEL" during January 2017 to May 2017. The project was carried out at National Institute of Hydrology (NIH), Roorkee.

The thesis embodies the original work of the candidate to the best of our knowledge

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Date: (SHAHNAZKHATUN)

95PPU – Uncertainty

Arc SWAT – Arc GIS Integrated SWAT Hydrological Model

TM – Thematic Mapper

Enhanced Thematic Mapper

DEM – Digital Elevation Model

ASTER – Advanced Space borne Thermal Emission and Reflection Radiometer

LULC –

SWAT – Soil and Water Assessment tool

GIS – Geographical Information System

HRU – Hydrological Response Unit

SWAT CUP – SWAT Calibration Uncertainty Procedures

SUFI 2 – Sequential Uncertainty Fitting

NSE –

PBIAS – Percent bias

R Goodness of fit

RSR – Ratio of the root mean square

T stat – Provides a measure of sensitivity (larger absolute values)

P value – Determine the significance of the sensitivity (close to zero)

UTM – Universal Transverse Mercator

– Weather Generator

Adoption of mathematical models for evaluation of hydrology of watershed is most popular and prevailing trend. The most trending techniques in present time, to derive out the information related to watershed, are GIS and Remote Sensing. SWAT is a universal, semi distributed, mathematical river basin model that needs a number of input parameters. In the present study, the model is implemented for gaining knowledge of hydrological behavior of the study area which is lying between Suni to Kasol in the state of Himachal Pradesh, India. For model calibration, daily observed while for validation data from 1999 to 2011 have been used. The applicability of SWAT model is assessed by using various graphical and statistical methods which helped to determine the ability of the model in simulating the runoff for the study basin of Satluj river (Suni to Kasol). SWAT CUP is one of the new developments for calibration/uncertainty analysis of watershed models. It gives an effective graphical interface for depicting outputs, together with simulated data, observed data, best fit model results and 95PPU for all variables used in model calibration. SUFI 2 procedure is effective but need more iterations as well as modification of the parameter allowing users to adopt different measures and objective functions. This approach has been used in the present study. The model is calibrated by using eleven most sensitive parameters namely , ALPHA , ESCO, GW , SOL , GW . The calibration period reported the R for daily runoff was derived 0.99 with Nash the validation period. It shows the effectiveness and appropriateness of the SUFI 2 method for the study area. As per It is required to attain spatial, soil and hydro meteorological database for the study by installing the Automatic Weather Stations (AWS) to measure more accurate precipitation, temperature and other climatic variables at various locations. The results of non parametric approach indicates that during monsoon season there is rising trend in rainfall at both stations. The rainfall is found to be falling during the pre monsoon, post monsoon and winter season.

Chapter 1

1. INTRODUCTION

The major intension of study is to create an idea for the water resources development and management for the watersheds and river basins and to demonstrate the importance of using and integrated approach in spirit and reality through the strength of IT, remote sensing and GIS, Hydrology and other latest technological advancements. The integrated watershed management approach has been globally accepted as the best approach for natural resource management but very rarely or partially implemented because of the lack of required framework and technical knowledge.

1.1 General

Water is essential for livelihood from basic drinking water to food production and health, from energy production to industrial development, from sustainable management of natural resources to conservation of the environment. It is very precious natural resource and at the same time very complex to manage. There is no doubt that we as a country have performed quit well in the sector of water resources in the last fifty years which has played a very important role in the progress of the country. Most of the big rivers in the world originate from the mountains areas and are considered important sources of water for the large population of the world. Himalayas provide one of the world's largest renewable supplies of fresh water. The chain of the Himalayan mountains act as an effective barrier to the summer monsoon and westerly winter disturbances. The major river systems of India, the Ganges, Indus and Brahmaputra have their origin in the Himalayan mountain region. The availability of high runoff coupled with wide variations in elevations provides a large potential for hydroelectric power. Himalayan region is a witness of large economic source and irrigation water. The biggest issue of any water resources development project is the transportation of high sediments from the Himalayan Basin. The Indian Himalayan region, which is more than 2,800 km in length and 220-300 km wide, is situated over the states of Jammu and Kashmir, Himachal Pradesh, Sikkim, Arunachal Pradesh, Nagaland, Mizoram, Manipur, Tripura, Meghalaya, and a part of Assam, along with eight district of Uttarakhand and one district of West Bengal. The Himalayan mountain chain has an effective influence on the climatic conditions prevailing over Indian sub-continent. The region is composed both of rivers and glaciers. The entire mountain chain is occupied by river, they have cut across the various mountain ranges. Two types of river systems are exist in Himachal Pradesh, namely Indus River System, which consists of Satluj, Beas, Ravi Chenab, and Jhelum. On the other side second river system is Ganga River System, which consist of Yamuna River. The origin of the Satluj River is in the Southern slopes of the Kailas Mountain near Mansarover Lake from Rakas Lake, as Longcchen Khabab River in Tibet. It is the largest among the five rivers of Himachal Pradesh. It enters Himachal at Shipkila (6,608 m) and flows in the South-Westerly direction through Kinnaur, Shimla, Kullu, Solan, Mandi and Bilaspur districts. The human settlements that have come on the banks of Satluj River are Namgia, Rampur, Tattapani, Suni, Kasol and Bilaspur. The total length of the river is 1,448 km. Total catchment area of the intermediate basin of the Satluj River (Suni to Kasol) is 685.15 sq. km. As an end product, the hydrologic unit which is called watershed, produces water with the interaction of land surface and precipitation. The nature of the watershed management is completely based on the quality and quantity of the water, which is produced by the watershed. The management of the watershed is vary from location to location. The aim may be to harvest maximum total quality of water throughout the year for irrigation and drinking purpose, in another watershed the objective may be reduce the peak rate of runoff for minimizing soil erosion and sediment yield, some may be increase ground water recharge. For sustainable development, the modelling of runoff is necessary (Sanjay et al. 2010). The concept of watershed modeling is interrelated with geospatial techniques and hydro-meteorological data and it is represented through mathematical abstractions. The behavior of each process is controlled by its own characteristics and also by its interaction with other processes active in the catchment area. Some of the predominant hydrological processes are rainfall, evapo-transpiration, infiltration, surface runoff, percolation and subsurface flow (Khalid et al. 2014). The physical and chemical properties of water depend on the hydrology, and their interaction with people, living things and their surroundings. The demand of natural resources are increasing day by day due to the over exploitation. Excess use of water resources is a big problem now a days, it is essential to store and maintain the resource properly (Srinivas. J et al. 2016).

Hydrological model is a power full technique to management the natural resources. Models are essential tool which can be used to manage the hydrological process and evaluate the risks and benefits of Landuse and soil over various period of time (Spruill, C.A et al. 2000). The main objective of hydrological model is to extract the reliable information for managing water resources in a sustained manner to develop human welfare and protect the environment. Create awareness for sustainable use of water, among the users with respect to planning, design and management of the projects under their jurisdiction. A large number of hydrologic model are available for different aspect for water resource management. Geographic Information System (GIS) gives a convenient platform for water resource modelling. A huge number of models are interfaced with GIS. Remote Sensing and GIS techniques will provide useful information on the various problems of water and land management, up to the date. Remote Sensing is a tool which deals with spatial and temporal domain to extract useful information, with high resolution. Hydrological model can produce all the terms of water balance at a high temporal but low spatial resolution. The use of remote sensing data, with distributed hydrological model, providing a new way to extract spatially distributed time series of input variables, as well as new means for calibration and validation for the hydrological model. The application of GIS has been widely used in water resource field. GIS stored these data as 'Geodatabase', like satellite data, topographic data, thematic map and others.

The SWAT is one of the most recent models developed by United States Department of Agriculture (USDA). It's a physical based, continuous, long term simulation agricultural models. The application of SWAT in the present study provides the capabilities to assessing the stream flow based on climate data.

1.2 SWAT Model

SWAT operates on a daily time step and is designed to predict the impact of land use and management on water, sediment, and agricultural chemical yields in ungauged watersheds. The model is process based, computationally efficient, and capable of continuous simulation over long time periods. Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. In SWAT, a watershed is divided into multiple sub watersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, topographical, and soil characteristics. The HRUs are represented as a percentage of the sub watershed area and may not be contiguous or spatially identified within a SWAT simulation. Alternatively, a watershed can be subdivided into only sub watersheds that are characterized by dominant land use, soil type, and management. SWAT was introduced by the U.S. Department of Agriculture – Agricultural Research Service (USDA-ARS) primarily at the Grassland, Soil, and Water Research Laboratory in Temple, Texas (Gassman et al. 2007). The model was schemed for basin-scale applications. SWAT is able to predict water, sediment, and chemical yields in ungauged basins (Gassman et al. 2007). Major components of the SWAT model include weather generation, hydrology, sediment, crop growth, nutrients, and pesticides (Neitsch et al. 2005). The SWAT model, first released in the early 1990s. The latest version of the SWAT model is SWAT 2012. SWAT can be used in different division like hydrology, groundwater, agricultural management (SWAT theoretical documentation). Physical based input is use in SWAT model namely soil properties, elevation, weather variables. The hydrological cycle (equation no. 1) is simulated by SWAT model based on different weather datasets.

$$SW_t = SW_O + \sum_{i=1}^{t}(R - Q - E - W - G)$$

Where,

SWt = the final water content

SWo = the initial soil water content

T = time in days

R = the amount of precipitation on day

Q = the amount of surface runoff

E = the amount of evapotranspiration on day

W = the mount of percolation and bypass exiting the soil profile bottom on day

G = the amount of ground flow on day

In the water balance equation the hydrological simulation process are shown, as precipitation, surface runoff, evapotranspiration and percolation and return flow. Precipitation and the other weather parameters, in general, provide the energy and moisture inputs that controls the water balance. The daily weather data required by SWAT are precipitation, temperature (maximum and minimum), solar radiation, wind speed, and relative humidity. These data can be observed or generated using a weather generator. The weather generator is used to either generate daily weather data or fill in missing values in the input data.

For each HRU, Runoff is simulated, then it combined to get the total stream flow for the sub-basin, which further combines with other sub-basins' stream flow to contribute the total stream flow for the whole basin. According to Neitsch et al (2011), SWAT estimate surface runoff using modified SCS curve number method or the Green and Ampt infiltration method. The SCS curve number, which was used in this study, is a function of the soil permeability, land use and the antecedent moisture condition. The curve number varies non-linearly based on antecedent moisture condition. The basic equation used in the SCS curve number method is given by:

$$Q = \frac{(R-I)^2}{R-I+S}$$

Here, Q is the accumulated surface runoff or rainfall excesses (mm), R is the rain depth for the day, I is the initial abstraction, which includes surface storage, interception and infiltration prior to runoff (mm) and S is the retention parameter (mm).

1.3 SWAT-CUP Model

SWAT CALIBRATION UNCERTAINITY PROCEDURES (SWAT-CUP) is a software program for calibration, validation of SWAT model. It was created by Eawag, Swiss Fedral Institute that looks into prediction uncertainty of SWAT model. The parameters of the model can be chosen in accordance with the objectives of the study. The results obtained after using different variables and combination of variables from among water content. Pressure head and cumulative outflow on the estimation of hydraulic parameters by inverse modelling were investigated in previous study (Abbaspour et al. 1999). GLUE is included in SWAT-CUP which is defined to partly show the possible similarity, PARASOL, and SUFI-2 are the methods to give combined objective functions into a criteria which is globally optimized which uses SCE-UA algorithm.

A soil map is considered in model parameterization, in SWAT-CUP of a watershed model which can be similar soils in different parameters due to difference in climate, land use and soil management. Various calibration programs allow parameter combinations on the basis of soil, land use, hydrological group and sub-basin specification which are linked to SWAT (Abbaspour et al. 1999).

X_<parname>.<ext>_<hydrogrp>_<soltext>_<landuse>_<subbsn>

Where, x = indicate the type of change to be applied to the parameter

<parname> = SWAT parameter name

<ext> = SWAT file extension

<hydrogrp> = Soil hydrological group (A, B, C, D)

<soltext> = Soil texture

<landuse> = Land use category

<Subbsn> = sub-basin number

1.4 SUFI-2 (Sequential Uncertainty Fitting)

SUFI-2 can be used for calibration of model and uncertainty analysis, it is a multisite and semi-automated global search procedure. In SUFI-2 we take an account the uniform distribution to describe the uncertainty of input parameters. In this model the out uncertainty is quantified by 95% prediction uncertainty, which is calculated at 2.5% and 97.5% levels of cumulative distribution of output variables obtained through Latin hypercube sampling. The parameter uncertainty is directly proportional to uncertainty of output. In SUFI-2 p-factor is used for the assessment of uncertainty, r-factor is also a significant method that can be used, which is the average thickness of the 95PPU band divided by the standard deviation of the measured data. The value of p ranges between 0-100%, while that the r-factor ranges between 0 to infinity. The exact correspondence to measured data is p-factor of 1 and r-factor of 0. The parameter uncertainties are the desired parameter ranges after obtaining satisfactory values of r- factor and p-factor. The most reliable result can be measured by the R^2 or Nash-Sutcliff coefficient amongst the observations and the final "best" simulation.

Chapter 1

1.5 STUDY AREA

1.5.1 Location

For the current research, the data of the study area Suni to Kasol an intermediate basin of Satluj river was selected. The study area (Figure no.1) situated in the latitude range of 31° 5′ to 31° 30′ and longitude 76° 50′ to 77° 15′ with an elevation of 580 to 3200 m above mean sea level covering an area about 685.15 sq. km. It is covered by the Survey of India toposheet no 53A/15, 53A/16, 53E/3, 53E/4, located in the state of Himachal Pradesh, India.

In the current study runoff simulation of the intermediate part of Satluj River (Suni to Kasol) was calculated, which flows over Western Himalayan region. The Western Himalayans cover the hilly areas of Jammu-Kashmir, Himachal Pradesh and Uttarakhand in India. The major river systems originating from Western Himalayan region are Indus system including Indus, Jhelum, Chenab, Ravi, Beas and Satluj and Ganga system including Yamuna, Sarda, Ramganga, and Karnali. These rivers are maintained by snowmelt and rainfall during summer and groundwater flow during the winter.

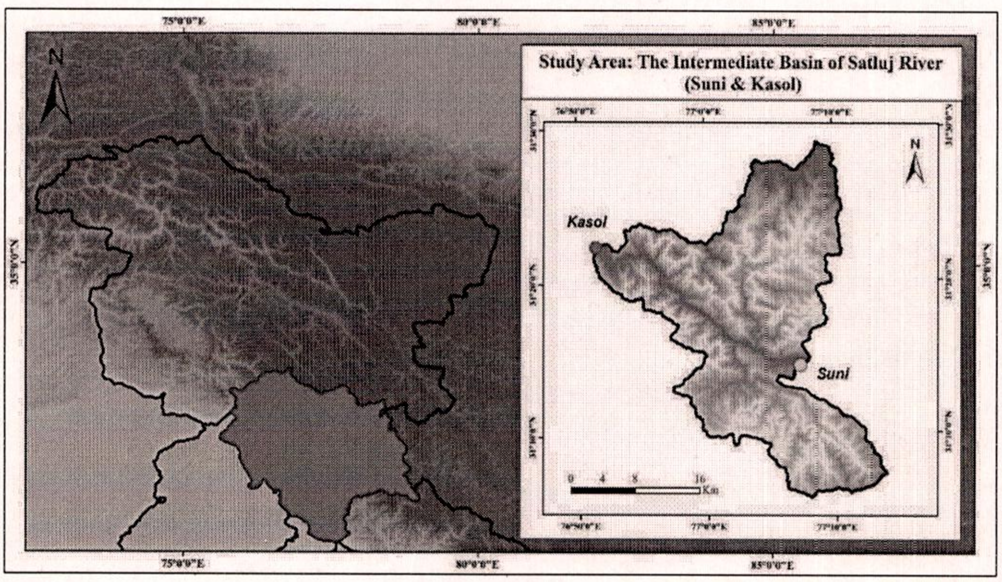


Figure 1: Showing the location of the study area

1.5.2 Satluj River System

The Himalayan mountain chain has a great impact on climatic conditions pre-dominating over Indian sub-continent. They fall in the part of rain bearing monsoon winds and thus bring rain to a large part of India. The rivers draining the Himalayas preserve life in the Northern part of the Indian sub-continent. The drainage system of Himalayan region follows a very complex pattern. It is embedded both of rivers and glaciers. Himalayan River intersect the entire mountain chain. In fact a number of rivers are older than the mountain system. It is the largest river among the five of Himachal Pradesh. It enters Himachal at Shipkila and flows in the South-Westerly direction through Kinnaur, Shimla, Kullu, Solan, Mandi, and Bilaspur districts.

The total catchment area of Satluj River up to Bhakra dam is about 56,500 km² out of which 22,305 km² falls in India consisting whole catchment of the Spiti basin. The elevation of the catchment varies from near about 500m to 7000m, above 6000m only a smaller part of these catchment are exists. The Satluj finally going out into the Indus in Pakistan. Spiti, Baspa, The Nogli Khad and Soan River are the main tributaries of the Satluj River.

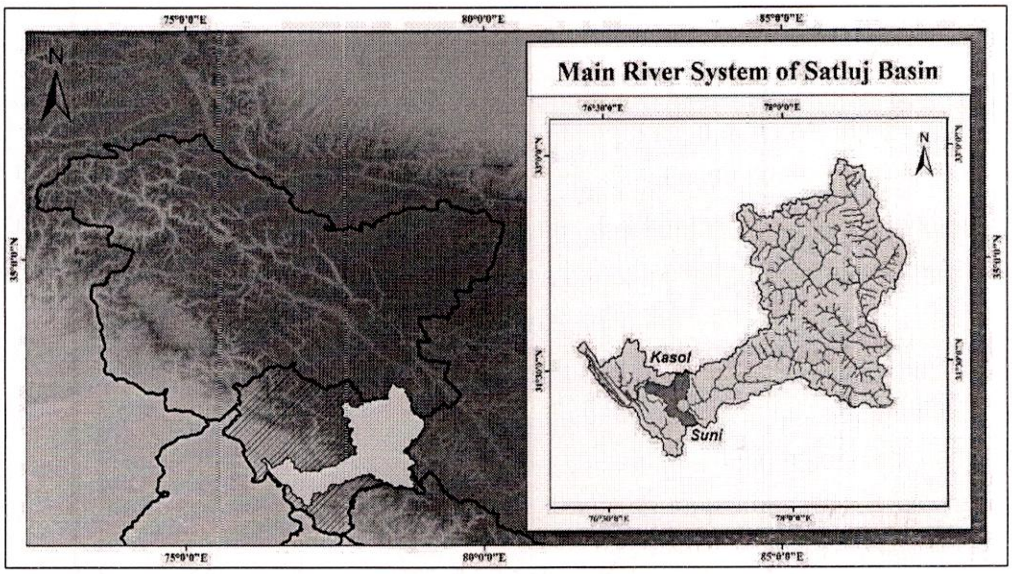


Figure 2: Map showing main river system of Satluj Basin

1.5.3 Physiological and Topographical Features

Satluj basin is one of the major basins in the Western Himalayas. The total length of the Satluj River is 1,448 km under which 54.18 km falls in the study area. This large river flows through areas having different climatic and topographic features. Near about 11% area of the satluj catchments lies under glaciers (Upadhyay et al. 1983). The catchment has high surrounding hills which is bounded by foothills of Shiwaliks near Bhakra dam. The rainfall in this region is moderate to heavy. The area is covered with scattered to dense patches of trees. There is agricultural development in several locations, mainly along the river and in the areas having moderate slopes.

1.5.4 Precipitation

Within the study area there are two rain gauges which is located at Suni and Kasol point. The rainfall distribution with altitude on the leeward side of outer Himalayas has shown that for all the seasons' rainfall increases linearly with elevation in Satluj basin.

1.5.5 Soil Quality in the Suni to Kasol

In the study area the soil is dominantly shallow in depth, but the areas having low vegetation the depth is increases gradually. In the regions above 1,500m, the soil is normally deep. Mostly the soil can be classified as podzols, humus and iron podzols which found within the study area.

1.5.6 Ecological Resources of the Region

The altitudinal variation in the area Suni to Kasol, a part of Satluj basin leads to variety on forests types. The various type of forest found in the area are as: dry mixed deciduous forests, Himalayan subtropical pine forests, Himalayan sub alpine forests, mix broad leaves coniferous forests, western mixed coniferous forests. Various important species of trees like deodar, kali, chil, oak, mohru, and kharu etc.

The altitudinal variation can also be observed in climatic and forest types. The variation in fauna of the satluj basin is observed. The most precious fauna of the upper basin is cold desert.

Chapter 2

2. AIMS & OBJECTIVES

The current study was attempted with the application of SWAT in integration with remote sensing and GIS techniques. It helps to evaluate the runoff for the focused area Suni to Kasol (an intermediate basin of Satluj river located in Western Himalayan regions in India) using multispectral and temporal satellite datasets. The main focus of the study was calibrating and validating the SWAT model. The aim & main objectives of the present study are:

2.1 OBJECTIVES

1. Assessment of stream flow for the study area using Arc-SWAT.
2. To perform SWAT-CUP for calibration, validation and global sensitivity analysis of the model.
3. To analyze the trend of rainfall and discharge of the study area.

2.2 Software Used in the Study

The following software has used to set up the model and load the input database.

Table no 1. Showing the software's description

S.No.	Software Used	Description
1	ERDAS IMAGINE 9.2	LULC Preparation Using Supervised Classification
2	Arc GIS 9.3	DEM Preparation, Co-registration, Map Preparation
3	Arc SWAT 2009	Runoff Estimation
4	Arc SWAT-CUP 2012	Calibration, Validation & Global Sensitivity Analysis
5	AUTO-MK-Sen	Trend Analysis
6	Microsoft Office Excel 2013	Data Preparation

Chapter 3

3. REVIEW OF LITERATURE

The main objective of the present work is to estimate model for an intermediate basin of Satluj river (Suni to Kasol). Most of the hydrological models requires the application of Remote Sensing & GIS techniques. It is also necessary to update information regarding advancement in remotely sensed watershed information and GIS techniques by different models. Keeping this in view, this present chapter deals with the review of significant contribution made by researchers in the field of hydrologic models, using Remote Sensing and GIS techniques for runoff estimation. A detail review is presented for various studies dealing with the application of SWAT (Soil and Water Assessment Tool) in hydrological modeling of watershed. ***Jain et al. (2010)*** carried out 'Simulation of Runoff and Sediment Yield for a Himalayan Watershed Using SWAT Model' to estimate the runoff & sediment yield for the intermediate part of Satluj river (Suni to Kasol) located in the western part of the Himalayan region. The model was calibrated on daily and monthly basis using the observed discharge data from 1993 to1994. Similarly the validation was done using three years of datasets (1995 to 1997). Statistical and graphical methods were used during calibration and validation period to evaluate the model efficiency. The coefficient of determination (R^2) of runoff for daily and monthly basis were obtained as 0.53 & 0.90 respectively during model calibration. On the other side for validation the computed values were 0.33 and 0.62 as well. According to the R^2 value, it shows that SWAT model has been proved as a reasonable and efficient model for estimate the runoff. ***Shivhare et al. (2014)*** conducted a study on 'Simulation of Surface Runoff for Upper Tapi Sub catchment Area (Burhanpur Watershed) Using SWAT', located in inter-state basin of Madhya Pradesh and Maharashtra, India. The model was performed from the year of 1992 to 1997 on daily basis. The simulated runoff at the outlet, was compared with observed datasets (1992-1993 to 1995-1996). The statistical results like coefficient of determination (R^2) was acquired as 0.82, 0.68, 0.92, and 0.69 respectively. Based on the R^2 it shows the model efficiency. ***Singh et al. (2013)*** formulated a study on 'Hydrological Stream Flow Modelling on Tungabhadra Catchment: Parameterization and Uncertainty analysis using SWAT-CUP', these study was specifically based on a methodology for calibration and parameter uncertainty analysis for distributed model based on generalized likelihood measures. SUFI-2 and GLUE two parameterization techniques were compared. The performance of both the techniques were evaluated on the basis of five statistical methods namely p-factor, r-factor, R^2, NS and bR^2 on daily and monthly basis. The simulated value shows an excellent result of goodness of fit, between observed and simulated discharge. A strong correlation was found on monthly steps. From this study it can be concluded that the model can be used for future prediction and assessment of water balance and climate change. ***Gyamfi et al. (2016)*** examined the application of SWAT on the Olifants Basin in South Africa to focus on model calibration, validation and uncertainty analysis. SUFI-2 algorithm was used to identify the most sensitive parameters to stream flow during calibration. The model efficiency was determined using some statistical methods namely NSE, PBIAS, RSR, R^2. The results during calibration period shows the following statistics NSE= 0.88, PBIAS= -11.49%, RSR= 0.34, R^2= 0.89 respectively. Statistics during validation were NSE= 0.67, PBIAS= -20.69%, RSR= 0.57, and R^2= 0.79. The results reveal that the SWAT model can be used as a Decision Support Tool (DST) for sustainable management of water resources. ***Rahman et al. (2012)*** inspected the stream flow simulation in the upper Rhone watershed located in the south western part of Switzerland using SWAT. In mountainous watershed it is very difficult to estimate the simulation because of irregular topography and complex hydrological process. In this study calibration was performed both manual and automatic. Manual calibration were done based on parameter sensitivity. Where automatic calibration was performed on the basis of model iterations. The model was run on daily time steps. The coefficient of determination (R^2) during manual calibration was 0.73, where else automatic calibration estimated 0.81. They found relatively better model performance during automatic calibration. Their result shows that SWAT can be help to take decision on water resource management in future scenario. ***Shrestha et al (2011)*** carried out the calibration and validation of SWAT model of climate introduced hydrologic changes in the Lake Winnipeg watershed. They found that the SWAT model for the Vergara basin has been proved a useful tool to make preliminary assessment of the potential impact of land use and climate change on the hydrology of this basin. ***Shawul et al (2013)*** used SWAT model to estimate the water balance components of Shaya mountainous watershed, which is located in Southeastern Ethiopia. The study was invented to evaluate the performance of these physical model. During calibration the model was performed well, the coefficient of determination (R^2) was 0.71. Based on the results it can be concluded that the model can be taken as a potential tool to estimate the water resources in a sustainable manner. ***Jain et al (2003)*** assessed sediment yield for Satluj River which flows through the western part of the Himalayan region. In this study a relationship was established between discharge and sediment yield, using three years of datasets. The model was run on daily steps. Result shows a reasonable and good performance between observed and estimated data for the intermediate basin of Satluj. ***Levesque et al (2008)*** evaluated the performance of the SWAT model under snowmelt and rainfall for two tiny watersheds, which is located in Southeastern Canadian conditions through different calibration schemes. The model was performed in seasonal base. According to the results the performance of the model was much better in winter season than summer. As per this conducted study it can be concluded that for small agricultural watersheds in Southeastern Canada, SWAT model can be used in two sets of parameters, one for the summer and other one is for winter. ***Stehr et al (2009)*** carried out a study which was focused on the application of SWAT model in Lonquimay River basin which is located in Chilean Andes, where snowmelt and snow accumulation has played an important role. Due to lack of ground data for snow coverage, remotely sensed MODIS snow product was used to validate the model as stream hydrology and spatial snow cover extent. The performance of the model was good and it gave a satisfactory representations of long-term discharge at the outlet of the basin. The MODIS information directly built into the model calibration process, is the suggestion for the future improvement of the model as per the conducted study. ***Stehr et al (2008)*** applied SWAT model on the Biobio basin, which is located in central Chile. The model was performed on daily basis for simulation and monthly basis for validation. As per the results model was performed well in most part of the study basin. SWAT can be useful tool to make a preliminary assessments of the potential impact of land use and climate changes on the basin hydrology. ***Feyereisen et al (2007)*** conducted a baseline calibration and an input parameter sensitivity analysis for simulation in the Little River Experimental Watershed (LREW) in the Coastal Plain near Tifton, Georgia. Manual calibration was done using SWAT for simulate the hydrological budget components. For local sensitivity analysis, 16 variables were used as input file. According to the result a negative influenced was found when seasonal tropical storms occurred during a dry year. For total water yield, most sensitive parameters were selected namely CN2, SOL_AWC, ESCO. On the other side for base flow selected sensitive parameters were CN2 (crop), CN2 (forest), ESCO and SOL_AWC. The identification of the sensitive parameters for the study area provides a clear knowledge to the modelers for future guidance. ***Setegn et al (2008)*** applied SWAT-2005 model on the Lake Tana Basin for estimate the hydrological water balance. The main objective of this study was to predict the stream flow in the Lake Tana Basin. Three different methods were used for model calibration likely SUFI-2, GLUE, PARASOL. SUFI-2 and GLUE gave good results as compare to PARASOL. The model can be used in future analysis for climate change and other management scenarios on stream flow as well as soil erosion. ***Fontaine et al (2002)*** carried out a study to increase the versatility of SWAT model to simulate hydrology of a non-agricultural mountainous region with a large component of snowmelt. The study area is located in Wyoming basin, Rocky Mountain region. Based on results, using elevation bands to distribute temperature and precipitation with elevation the algorithms were developed. ***Shen et al (2012)*** conducted a study on "Analysis of parameter uncertainty in hydrological and sediment modeling using GLUE method: a case study of SWAT model applied to Three Gorges Reservoir Region, China," In this study, GLUE (Generalized Likelihood Uncertainty Estimation) method was assemble with the SWAT to measure the parameter uncertainty of the stream flow and sediment simulation in the Daning River Watershed of the Three Gorges Reservoir Region (TGRA), China. According to the results, sediment simulation presented greater uncertainty than stream flow, and uncertainty was even greater in high precipitation conditions from May to September during the dry season.

Chapter 4

4. Methodology

4.1 Precipitation and Discharge Trend Analysis

Observed rainfall and discharge data for two different weather stations have been obtained for different time period such as 1983 to 2010. Only the daily rainfall and discharge data of the stations namely Suni and Kasol for the period of 1983 to 2010 have been selected for trend analysis on seasonal and annual scale. In the current study both trend analysis methods - Parametric (Simple Regression) and non-parametric (Mann-Kendall & Sen Slope) have been used.

The term 'trend' conveys the tendency or the rate of change of any long term data. Here the trend uses to denote weather data of a series increase or decrease over the time period. In statistics, trend analysis is an important aspect to find out the underlying pattern or behavior of the long term datasets. According to 'science community' statistics and probability are the major branches which play a great role (Kumar et al. 2017) because statistical tools help to estimate spatial and temporal trends for hydrological and environmental studies. Trend analysis assists to investigate the overall pattern of change over time in hydro-meteorological variables especially for water resources management on temporal and spatial scales. Trends in data can be recognized by using either parametric or non-parametric methods, and both the methods are widely used in public domain. The parametric methods are considered to be more intense than the non-parametric methods only when the data sets is normally distributed, independent and homogeneous variance. Conversely, non-parametric methods are more compatible as it does not requires normal distribution of the data; this method is less sensitive to outliers and missing values. Trend analysis of time series defines the magnitude of data and its statistical significance. In general, the magnitude of a trend extracted either using regression analysis that is parametric test or using Sen's Slope estimator method that is non-parametric test, and significance level is determined by Mann-Kendall test (non-parametric method). In the conducted study, to analyze the trends of the rainfall and discharge data of each two different station (Suni & Kasol), the popular statistical methods; simple regression method (parametric), Mann-Kendall test and Sen's estimator of slope method (non-parametric) have been applied. The systematic approach has been selected to examine the trend in three phases. Firstly, a simple linear regression method to test the long term linear trend, secondly, non-parametric Mann-Kendall test which shows the monotonic increasing or decreasing trend and Thirdly, the non-parametric Sen's Slope estimator of slope test to determine the magnitude of the trend or to identify the rate of change in the time series of meteorological parameter i.e. rainfall at the basin scale. For trend analysis of discharge data, only Kasol station has been selected. The methods are described in the following sections.

4.1.1 Regression model (Parametric Test)

One of the most efficient parametric models to extract the trend is the "Simple Linear Regression" model. For this method the basic requires the variables to be normally distributed and temporally and spatially independent. The method of linear regression requires the adoption of normality of residuals, constant variance, and true linearity of relationship (Helsel and Hirsch, 1992). The model for Y (e.g. precipitation) can be described by an equation of the form $y = m x + c$. Where, x = time (year), m = slope coefficient and c = least-squares estimate of the intercept. The slope coefficient indicates the rate of change in the hydrologic characteristic. If the slope is significantly different from zero statistically, it shows a real change occurring over time. The slope defines the direction of the trend of the variable: positive sign indicates a rising trend where negative sign indicates a falling trend.

4.1.2 Sen's Slope Estimator (Non-Parametric method)

Sen's Slope estimator is a robust trend estimator for a linear trend. The magnitude of data, extracted using a non-parametric method known as Sen's estimator (Sen 1968). This method estimate a linear trend in the time series. It has been widely used for determining the magnitude of trend in hydro-meteorological time series

(Lettenmaier et al., 1994, Yue and Hashino, 2003, Partal and Kahya, 2006). In this method, the slopes (Ti) of all data pairs are first calculated by-

$$T_i = \frac{x_j - x_k}{j - k} \quad \text{for } i = 1,2,\ldots,N$$

Where *xj* and *xk* are data values at time *j* and *k* (*j* >*k*) respectively. N represents the number of observations. Sen's estimator of slope which is calculated as

$$\beta = \begin{cases} T_{\frac{N+1}{2}} & \text{if } N \text{ is odd,} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & \text{if } N \text{ is even.} \end{cases}$$

A positive value of β indicates an upwards (increasing) trend while a negative value indicates a downwards (decreasing) trend in the datasets.

4.1.3 Mann–Kendall test (Non-parametric test)

Mann-Kendall trend test is a non-parametric way to detect a trend in long term datasets. It's commonly used to detect monotonic trends in series of hydrological data. For non-parametric test the required data to be normally distributed and containing outlier in the data (Helsel and Hirsch 1992; Birsan et al. 2005). To identify the statistical significant trend in hydrologic climatic variables such as temperature, relative humidity, precipitation and stream flow with reference to climate change, the non-parametric Mann–Kendall (MK) test has been chosen by a number of researchers (Yu et al. 1993; Douglas et al. 2000; Burn et al. 2004). The MK method finds out for a trend without specifying whether the trend is linear or non-linear. The MK test has been also applied in the present study. The MK test calculate the null hypothesis H_0 of no trend versus the alternative hypothesis H_1 of the existence of an increasing or decreasing trend. The statistic *S* is defined as (Salas 1993):

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

Where *N* is the number of observed points. Assuming (*xj*– *xi*) = *θ*, the value of sgn (*θ*) is computed as follows (4.5)

$$\text{sgn}(\theta) = \begin{cases} 1 & if \quad \theta > 0, \\ 0 & if \quad \theta = 0, \\ -1 & if \quad \theta < 0. \end{cases}$$

This statistic represents the number of positive differences minus the number of negative differences for all the differences considered. For large samples (*N*> 10), the test is conducted using a normal distribution (Helsel and Hirsch, 1992) with the mean and the variance as follows:

$$Var(S) = \frac{N(N-1)(2N+5) - \sum_{k=1}^{n} t_k(t_k - 1)(2t_k + 5)}{18}$$

Where, *n* is the number of tied (zero difference between compared values) group and *th*is the number of data points in the k^{th} tied group. The standard normal deviate (Z-statistics) is then computed as (Hirsch *et al.* 1993):

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

In our study, both trend analysis methods have been used i.e. Parametric (Regression analysis) and non-parametric (Mann-Kendall & Sen's slope) and daily precipitation and discharge records for Suni & Kasol have been collected for the period of 1983 to 2010 have been used for analysis of rainfall discharge trend on seasonal and annual scale.

4.2 Preparation of the Database for the Study Area

The study area mainly falls in the state of Himachal Pradesh, for carrying out the study various types of multispectral, multi temporal and dynamic data was collected. A hydro-metrological network was developed in Satluj River basin by BBMB, Nangal. In Satluj basin rainfall gauges is detected at 10 stations which is completely maintained by BBMB. The stations are Bhakra, Berthin, Kahu, Suni, Kasol, Rampur, Kalpa, Rackchham, Namgia, and Kaza. The meteorological data from all these sites are available from 1983 onwards. Suni and Kasol, only two stations are located within the study area in order to assess stream flow. The satellite imageries, ASTER DEM (30m) was obtained from the web (USGS) which is freely available. Meteorological data such rainfall, temperature, discharge, and relative humidity were observed from BBMB, except solar radiation and relative humidity, which is downloaded from the link http://globalweather.tamu.edu/. LULC map was prepared using supervised classification from LANDSAT-8 satellite imagery with help of the image processing software ERDAS. The soil map was prepared by using digitization from toposheet of NBSS & LUP, Nagpur. Daily stream flow data (1983-2011) was collected from BBMP, India. Source and description of the datasets are showing in Table 1.

Table no 1: Sources and Description of the input data for the study

Data Type	Source	Spatial/Temporal Resolution	Description
Topography	USGS Earth Explorer	30 m	ASTER Digital Elevation Model
Land use/Land cover	Landsat-8 satellite imagery (Earth Explorer)	30 m	Land use Classification
Soils	NBSS & LULP, Nagpur (Hardcopy of soil map was converted into digital form)	-	Soil Classification
Weather Data	BBMB, India	Daily	Rainfall, Minimum & Maximum Temperature
	http:/globalweather.tamu.edu/	Daily	Solar Radiation, Relative Humidity, Wind Speed
Stream Flow Data	BBMB, India	Daily	Daily Stream Flows measured at the gauging stations

4.2.1 SWAT-Model Inputs

To perform the model, primary steps are identification and delineation of the hydrological response units (HRUs). From ASTER DEM drainage network (Suni to Kasol) was delineated, where analytical technique of the Arc SWAT-2009 GIS interface was used. To calculate an acceptable numbers of HRUs within each sub basins, a perfect combination of land use and soil (10%, 10%, and 10%) were used. To run this process the study area from Suni to Kasol was divided into 23 sub basins and 325 HRUs. These combination establish an acceptable drainage network description as regard to the management of dominant land uses, soil types within every sub basins, and an acceptable numbers of HRUs in each sub basins.

4.2.2 ASTER Digital Elevation Model (DEM)

A DEM is an array of numbers that represent the spatial distribution of elevation above some datum, it represents a topographic surface. For the current study ASTER DEM was used. The resolution ranges from 15 to 90 m depending on the wavelength. ASTER DEM was downloaded for the study area from the USGS Earth Explorer, which has 30 m resolution onward. The basin was covered in a single tile. The study area which is Suni to Kasol was extracted from the downloaded DEM. The ASTER DEM of the study area is showing in the figure no 3.

4.2.3 Soil Map

For SWAT Model one of the main major input is the physical properties of the soil. It plays a great role for any hydrological modeling. The basic requirement of the model is soil properties like texture, hydraulic conductivity, water availability etc. For this current study soil map has been digitized using NBSS (National Bureau for Soil Survey & Land Use Planning) and LUP, Nagpur, with a scale of 1:50,000 provided by National Institute of Hydrology. According to the soil properties the study area has been classified in to four categories namely clay-loamy-loamy sand, loamy-sand-rock outcrop, fine-loam-moderate and loamy-sand-moderate (Fig no.4). 85.34% of the study area has been covered by fine loam-moderate soil.

Table no 3. Showing soil categories and their characteristics

Type	Classes	Reclassified Classes According to SWAT Geodatabase	Area (%)
Soil	Clay loamy - Loamy sand	CL-LS-D	4.98
	Loamy sand - Rock outcrop	LS-RO-D	6.55
	Fine loam - Moderate	FL-MD-C	85.34
	Loamy sand - Moderate	LS-MD-D	3.13

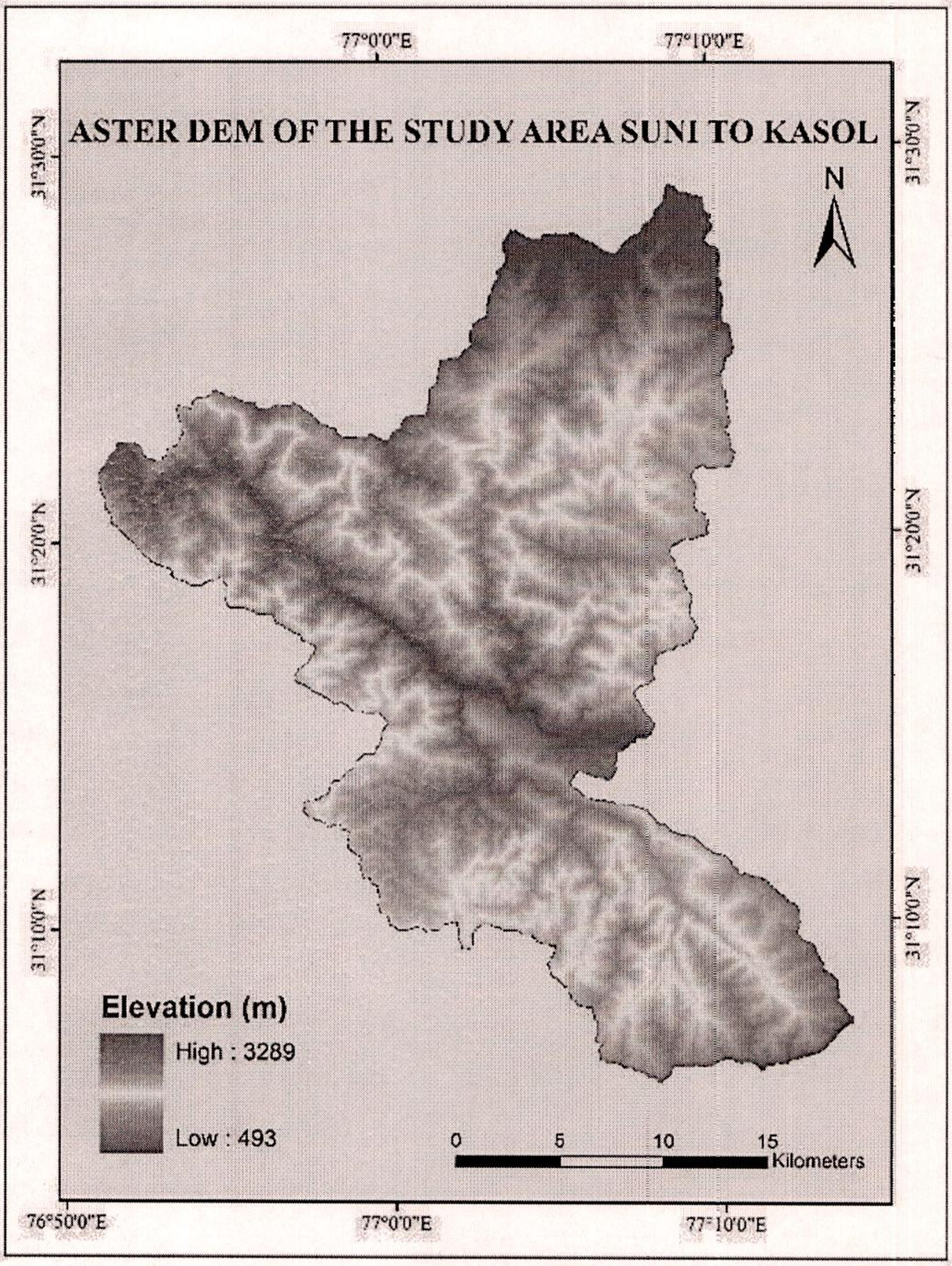


Figure 3: ASTER DEM of the study area

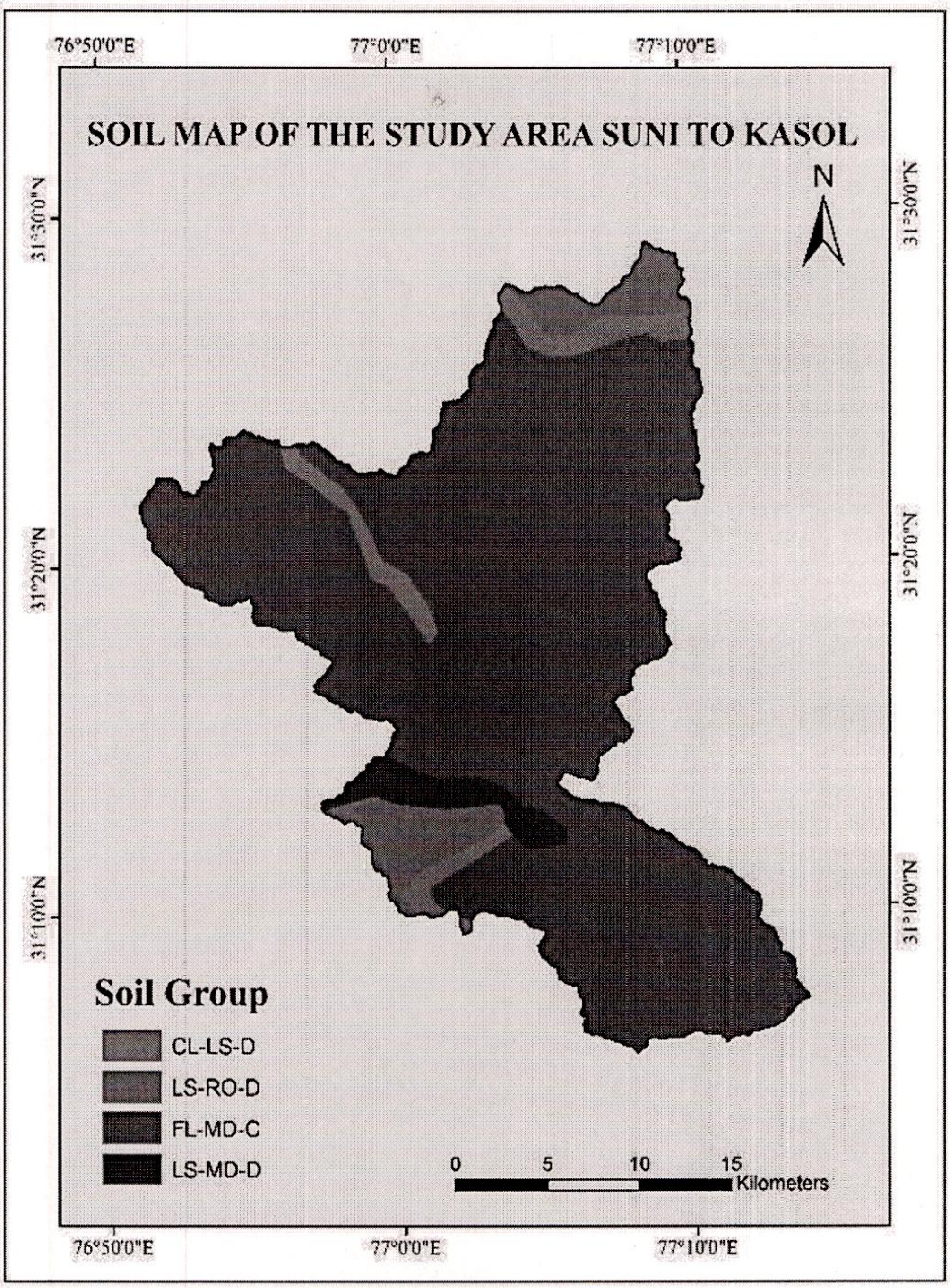


Figure 4: Soil map of the study area

4.2.4 Land Use and Land Cover map

It is necessary to prepare a proper LULC (land use land cover) map to perform the model as it is one of the most essential factor effecting the runoff, infiltration, percolation, evapotranspiration, drainage network, soil erosion in a basin. In this study a LULC map (Fig no.6) has been prepared by using remotely sensed satellite data. For this current study, LANDSAT-8 data has been used, after downloading the data from USGS Earth Explorer. The particular study area has been masked according to basin area using Arc GIS 9.3 software. There are eleven spectral bands in this sensor. Using this False Color Composition (FCC) has made (Fig no.5). There are several classification techniques which are dominantly used in the field of remote sensing. For this particular study supervised classification has done using ERDAS IMAGINE 9.2 software. According to spectral pattern four land use land cover classes have been made, those are deciduous, forest evergreen, water and barren land. Descriptions of the LULC classes are given in Table no.4

Table no 4. Characteristics of land use/ land cover types

Type	classes	Reclassified According to SWAT Geodatabase	Area (%)
Land Use/Land Cover	Forest deciduous	FRSD	6.61
	Barren land	BARN	35.57
	Forest evergreen	FRSE	56.33
	Water	WATR	1.49

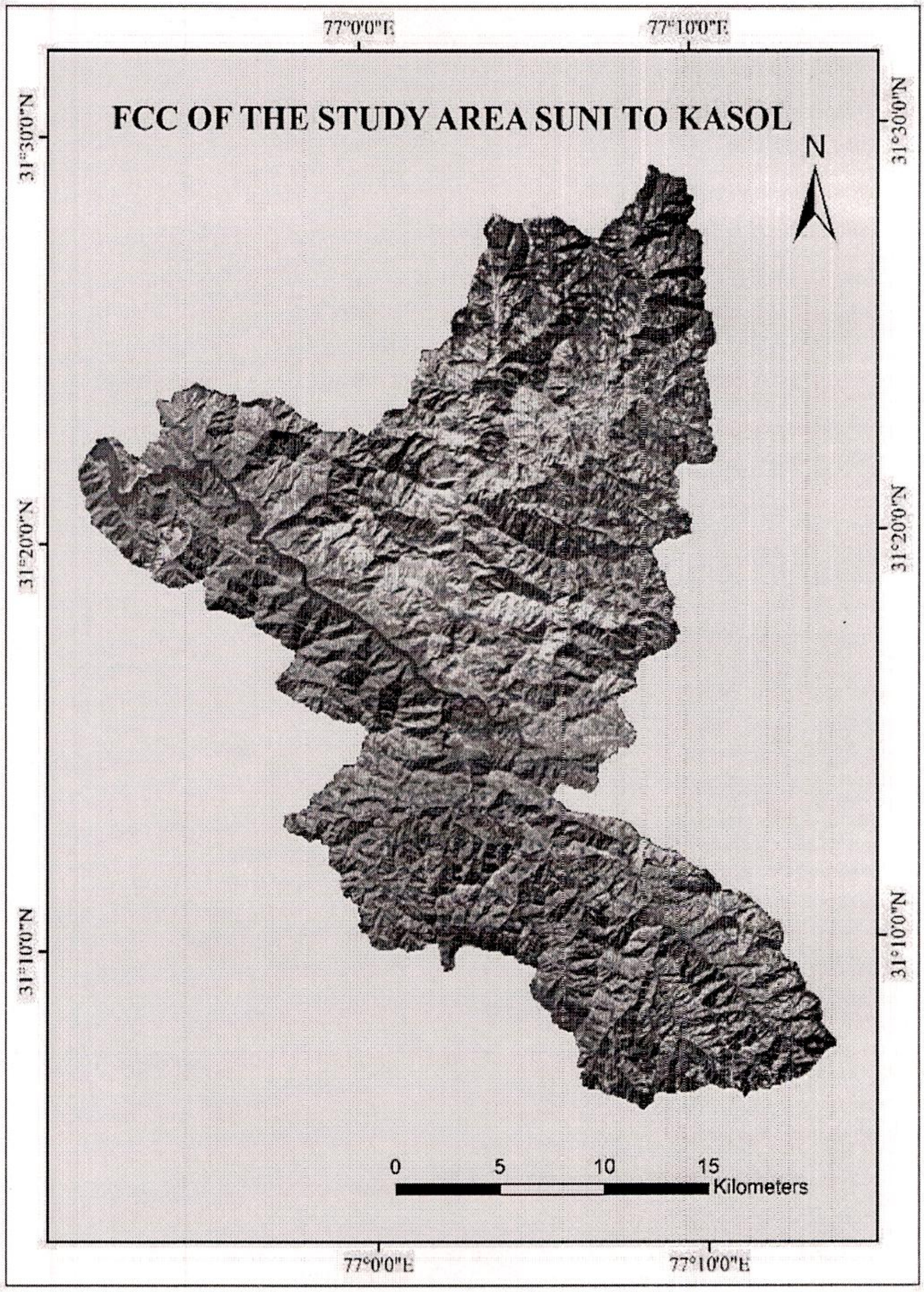


Figure 5: FCC showing the study area Suni to Kasol

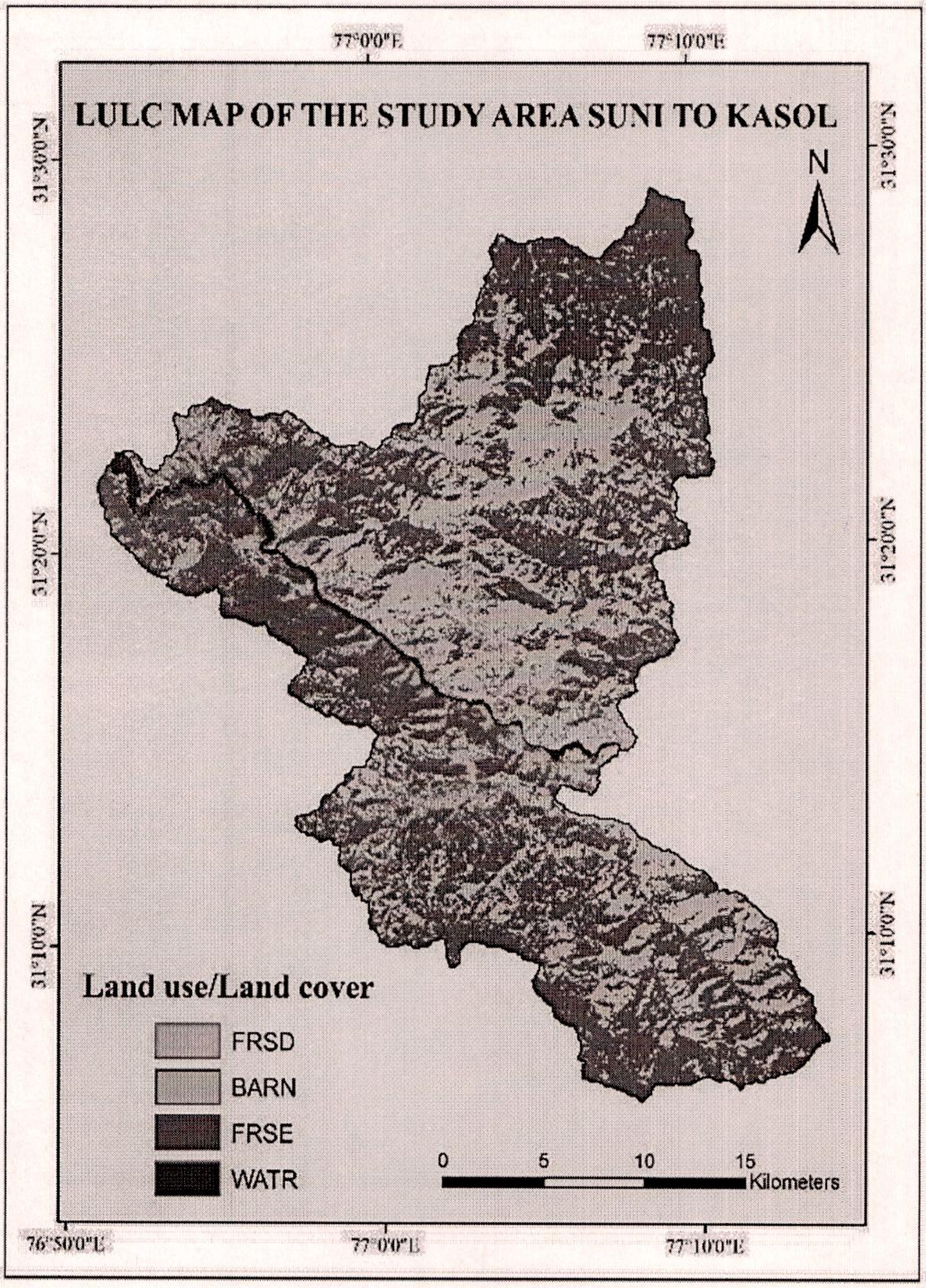


Figure 6: Showing the land use/land cover classification of the study area Suni to Kasol

4.2.5 Climate Data

To calculate the stream flow using Arc SWAT, it is necessary to prepare a required database. Some statistics were generated using WGN EXCEL MACRO Software (http://swat.tamu.edu/software/links-to-related-software/) downloaded from SWAT website. Rainfall, temperature, and discharge which are observed data in daily basis, has been processed, on other hand relative humidity, solar radiation and wind speed data are in gridded form. The model has processed at the daily time steps.

4.3 Arc SWAT Model Setup Simulation of Hydrological Process

The model has setup to establish hydrological simulation for a part of Satluj river basin (Suni to Kasol). The following steps were followed to set up the model and load the input database:

- SWAT project setup
- Automatic water shade delineation
- Land use and soil characterization (HRUs analysis)
- Climate data definition (Write input tables)
- Editing input information
- SWAT simulation

4.3.1 SWAT Project Setup

The first step of the model is to define the location of the project, and it's Geodatabase. All associated files are stored in the specified database.

4.3.2 Data Processing

To estimate the stream flow, the required database has generated, to fulfill all the objectives for the current study, required database have successfully developed. The detail steps have explained in the flow chat of the methodology, which is given in Figure no.7

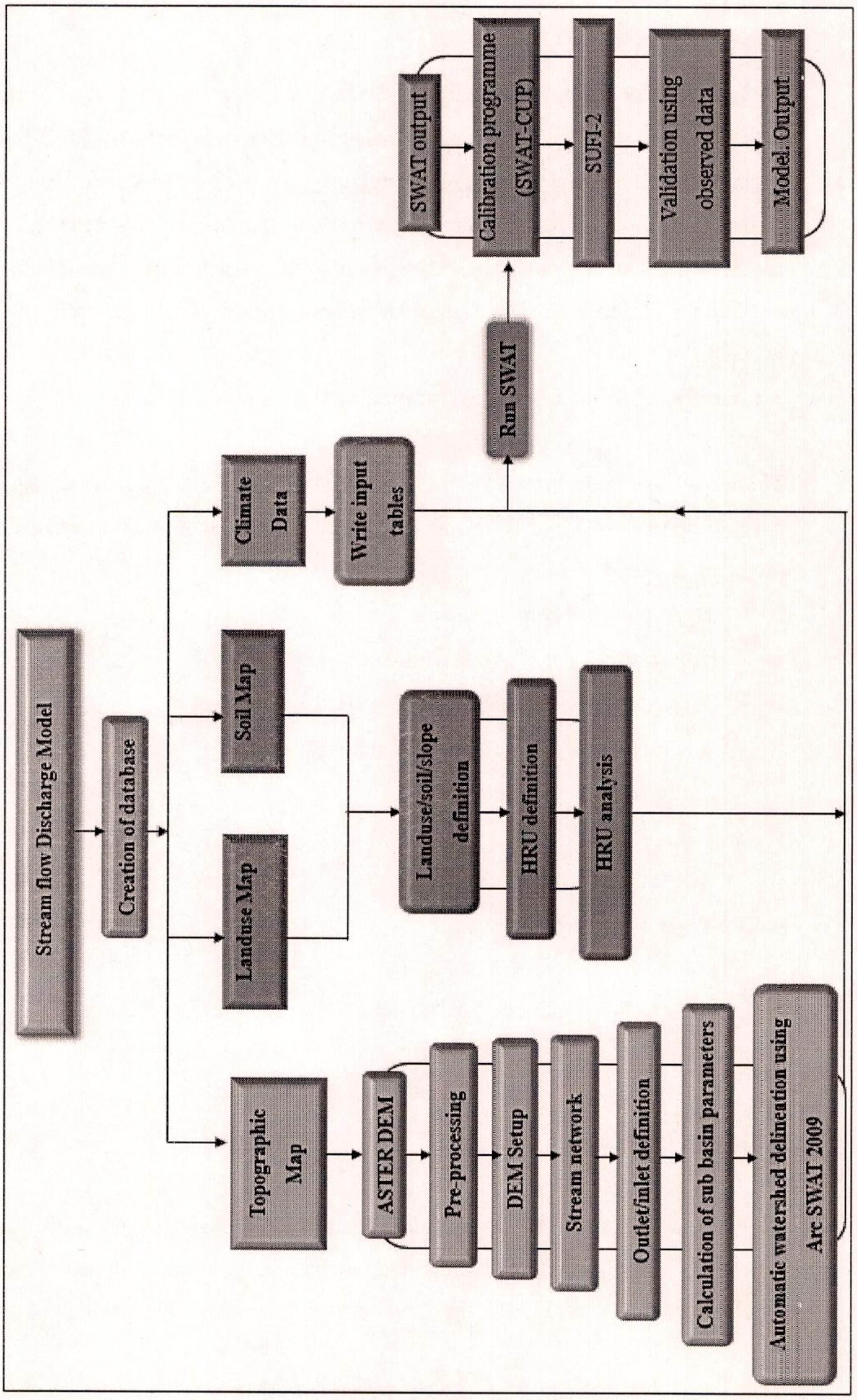


Figure.7 Flow Chart of Methodology

4.3.3 Automatic Watershed Delineation

Arc SWAT 2009 automatically delineates watershed (Figure no.8) into sub-watersheds based on DEM and drainage network. The ASTER DEM has imported in the model, a masking of polygon has created manually in Arc SWAT (grid format) which has inserted in the model in order to extract only the area of interest. The DEM has pre-processed in order to determine the size and number of sub watersheds based on the threshold area. In the current study the default threshold value area has taken to be 2500 ha which formed 23 sub basins. Once the watershed and sub-watersheds boundaries are delineated, a specific outlet of the study area has defined at Kasol (585m elevation) point to generate the whole watershed. As the study area is not a whole basin it's just a part of it so the concept of inlet became necessary to bring here. For the study area a weather station named "Suni" has been defined as inlet.

Lastly all the geometric parameters of each sub basins and stream reaches are calculated and stored as a vector file (.shp format). The geographic area delineated by the software was found to be 685.15 sq. km.

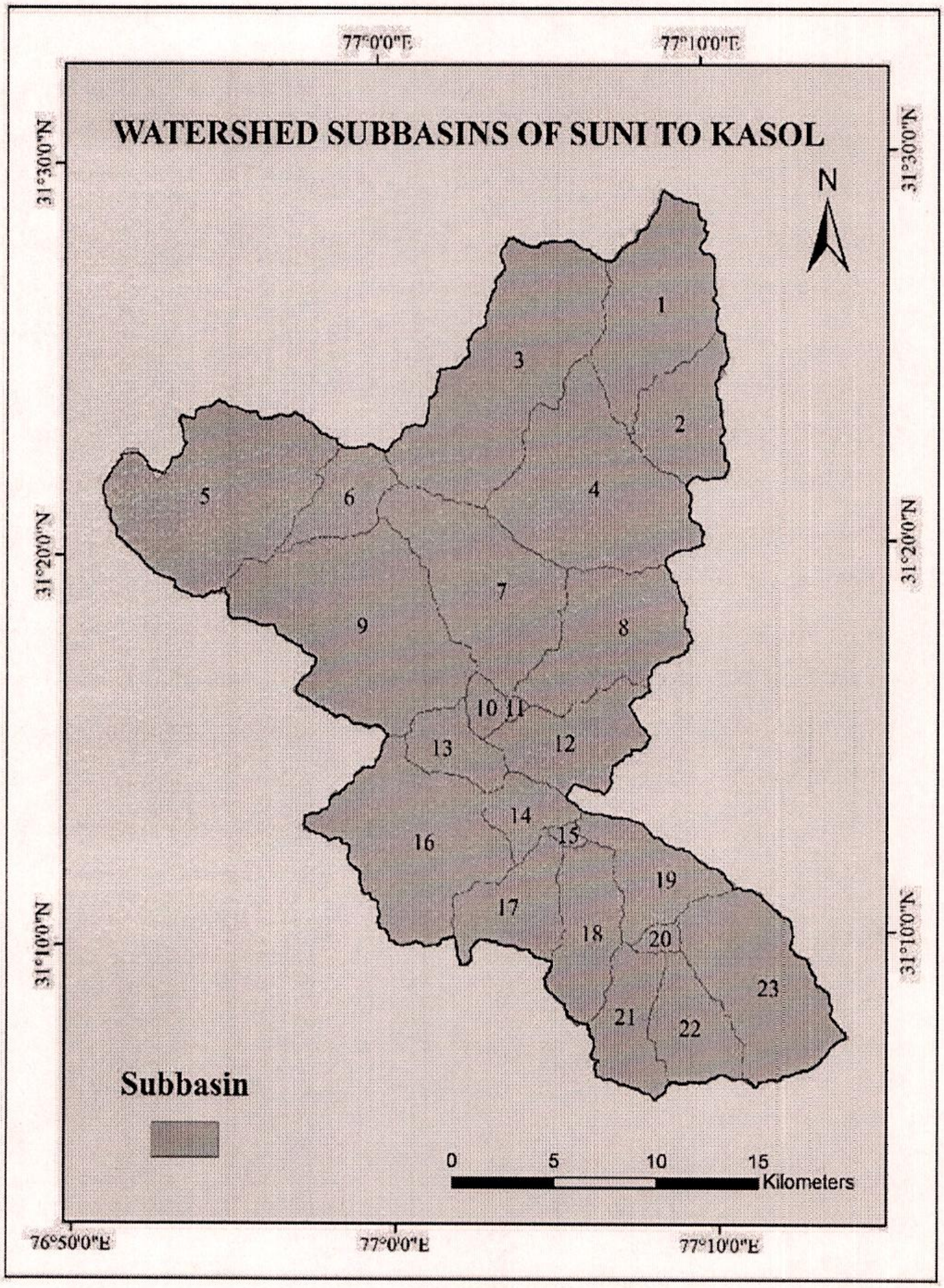


Figure 8: showing the watershed sub-basin of the study area

4.3.4 HRU Definition

The Hydrological Response Unit (HRUs) is basically which divided the whole watershed into different homogeneous unit with respect to land use, soil and slope properties at each grid. HRUs are a part of sub basin which produces a unique land use/management/soil attributes. Land use, management and soil may be scattered throughout the study area but for HRUs creation it should be put together in one group. As a general rule, a given sub basin should have 1-10 HRUs. HRU definition allows users to load land use map, soil map and also include classification of HRU in to different slope classes, which has linked to the SWAT Geodatabase to generate HRUs. The inserted datasets have reclassified according to the given codes. The slope map is classified in four different ranges, which varies from 0-25, 25-50, 50-75, 75-9999 in percentage. To calculate an acceptable numbers of HRUs within each sub basins, a perfect combination of land use and soil (10%, 10%, and 10%) were used. The associated topographic report regarding HRUs has been generated successfully which described all the statistical parameters for each sub basins like minimum elevation, maximum elevation, standard deviation, percentage of area, percentage of watershed. The land use map as well as soil map have been overlapped 100% with the delineate watershed and 325 HRUs were created for the 23 sub basins. The slope map of the study area is shown Figure no.9

4.3.5 Write Input Tables

SWAT requires daily precipitation, maximum/minimum temperature, solar radiation, wind speed and relative humidity data. Values for all these parameters may be read from records of observed data or they may be generated. Required parameters have been used in SWAT weather input database, with swat supported format and inserted into the model. Two weather stations namely Suni and Kasol has been defined across the river basin. The weather generator input file (Figure no.10) consist the statistical data, needed to generate representative daily climate data for each sub basins. Ideally, at least 20 years of records are used to calculate parameters in the .wgn file. For this current study 28 years of data has used. These statistics has been generated using

WGN EXCEL MACRO downloaded from SWAT website. The weather generated input file consists of several parameters like TITLE (the first line of the .wgn file is used for user comments), WLATITUDE (latitude of weather stations used to calculate statistical parameters), WLONGITUDE (longitude of the weather stations), WELEV (elevation of the weather stations), RAIN_YRS (the number of years of rainfall, if no value is input for RAIN_YRS, SWAT will set 10, by default), TMPMX (average or mean daily maximum air temperature), TMPMN (average or mean daily minimum temperature), TMPSTDMX (standard deviation for daily maximum air temperature), TMPSTDMN (standard deviation for daily minimum air temperature), PCPMM (average or mean total monthly precipitation), PCPSTD (standard deviation for daily precipitation in month), PCPSKW (skew coefficient for daily precipitation in month), PR_W (probability of a wet day following a wet day in the month), PCPD (average number of days of precipitation in month), RAINHHMX (maximum 0.5 hour rainfall in entire period of record for month), SOLARAV (average daily solar radiation for month), DEWPT (average daily dew point temperature for each month or relative humidity can be input), WNDAV (average daily wind speed in month).

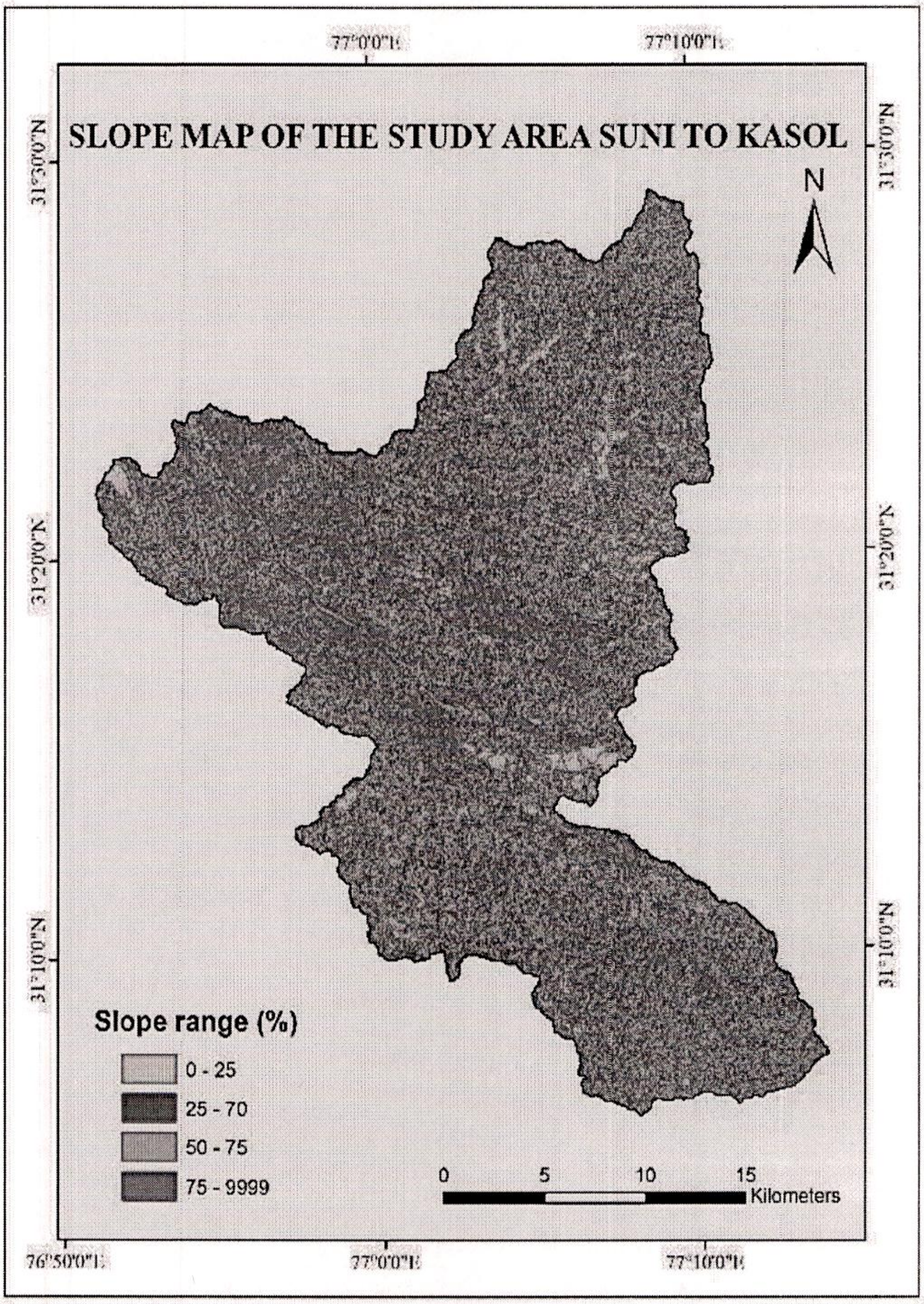


Figure 9: Slope map of the study area

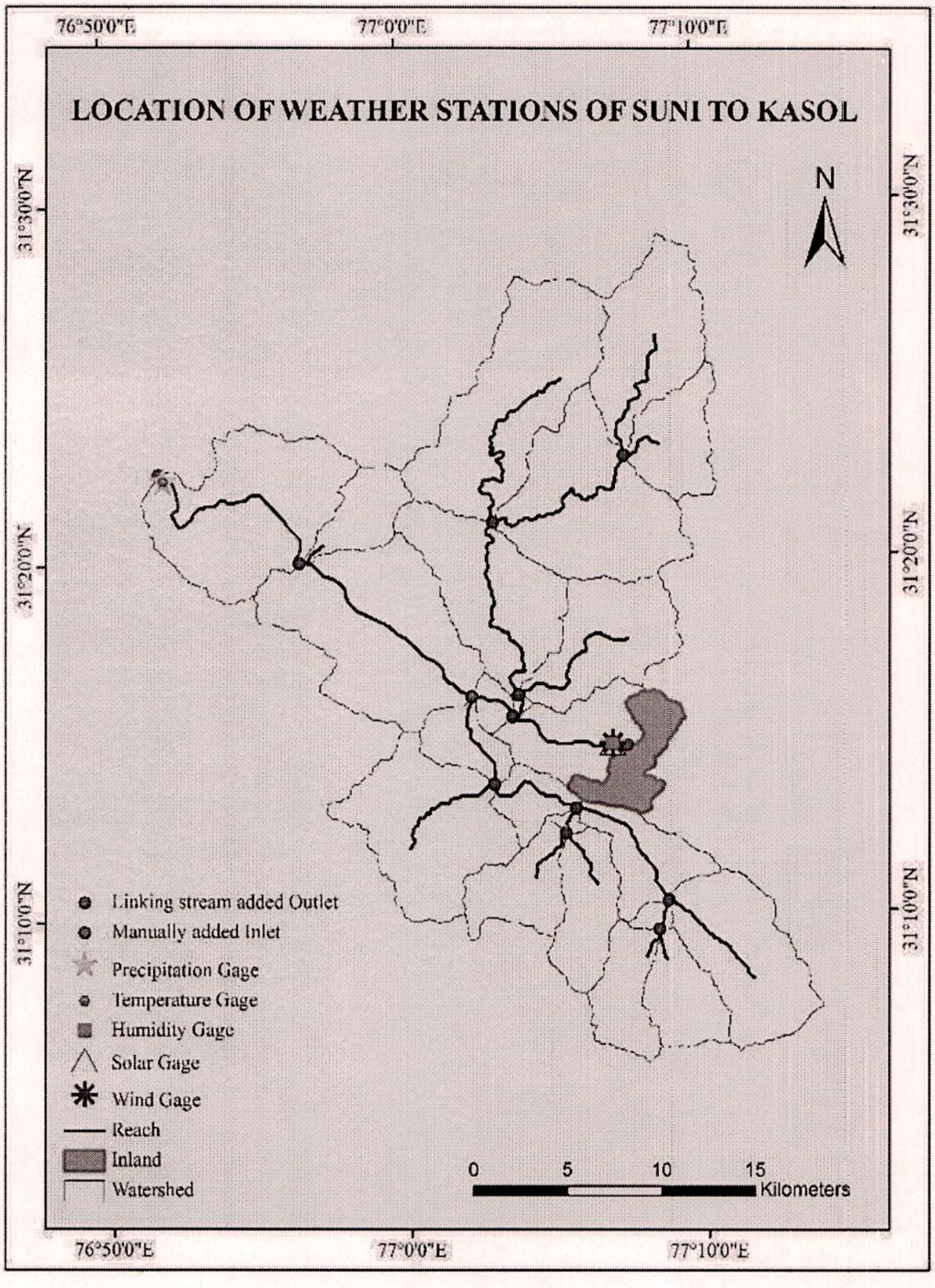


Figure 10: Location of weather stations of Suni to Kasol

4.3.6 Edit SWAT Input

The user can edit the database file in the model. The climate data like precipitation, relative humidity, solar radiation, wind speed, temperature and location of meteorological data file were used as inputs for running the SWAT model. The required files were developed as per the format given in the input/output documentation of SWAT 2009.

4.3.7 SWAT Simulation

Once all the weather parameters are inserted in the model, SWAT has been run successfully. The output of the model like HRU, RCH, and SUB was generated on the daily basis. The simulated discharge and its associated reports were generated successfully.

4.4 SWAT CUP Model (Sufi-2)

SWAT-CUP was used for calibration and validation purpose. After SWAT simulation SWAT-CUP-2012 was used to calibrate and validate the data using SUFI-2 algorithm. In the SWAT-CUP, observed stream flow and SWAT simulated data (1986-1998 for calibration) was imported to run the model, both datasets were prepared as per the required format in the SWAT-CUP. Data for the first three year (1983-1985) were conserved as 'warm-up' period for model initialization. Same methods were followed for model validation (1999-2011). The model iteration was 500 for both calibration and validation. The statistics (PBIAS, R^2, NSE, p-value, t-test) for calibration was evaluated for the period of 1986-1999.

Chapter 5

5. RAINFALL AND DISCHARGE TREND ANALYSIS

The study looks into the irregularities and the trends shown by them for all the stations. The graphs were plotted regarding the anomalies (deviation from mean) in discharge and rainfall pattern against the time (in years). The graphs show the deviation in seasonal and annual trends for all the stations. The magnitude of the seasonal and annual trend in the time series as determined using the Sen's estimator is given in Table.5.

5.1 Annual Trend

Anomalies in seasonal and annual rainfall and their trend for Suni and Kasol stations within the study area are shown graphically in figures. 10-19. the annual rainfall of Suni station is showing the rising trend whereas Kasol is showing the falling trend. The non-parametric approach depicts also shows the same nature of trend. The Suni stations indicate the rising trend with a magnitude of 0.0572 whereas Kasol indicating decreasing trend of the magnitude of -0.1733mm/year.

5.2 Seasonal Trend

From table 5, Seasonal trend for two stations by parametric method (linear regression) is described by the following table in which the magnitude of regression slope or "m" represents the rate of increase or decrease of seasonal precipitation in mm/year. Whereas the seasonal trend for two stations by non-parametric method (Mann Kendall &Sen's estimator) is described by the table no. 6 in which the value of Z statistic denotes the significance of trend. If the value of Z lies within the range -1.96<Z>+1.96 at 95% significance, then only the trend is significant, & the magnitude of Sen's Slope denotes the rate of increase or decrease in seasonal or annual precipitation in the units of mm/year. Both stations experienced an increasing trend in monsoon at the rate of 0.2124 and 0.0018 mm/year respectively. On the other side non-parametric approach, only in winter, rainfall is statistically significant (95% confidence level) at Kasol. No significant trend is observed in any of the station (as per Mann-Kendall test), but still precipitation increases at the rate of 0.18 mm in monsoon period at Suni and decreases at the rate of 0.19 mm (as per Sen's estimator).

5.3 Monsoon Season

The parametric approach shows that the rainfall trends during pre-monsoon, post-monsoon and winter are found to be decreasing at both the stations. During the monsoon season rainfall trends at both stations are found to be increasing.

Table 5: Seasonal trends in rainfall of different stations in intermedial part of Satluj (Suni and Kasol) basin

Season	Stations	Trend	Magnitude
Pre-monsoon (Mar - May)	SUNI	Falling	-0.0496
	KASOL	Falling	-0.0263
Monsoon (June - September)	SUNI	Rising	0.2124
	KASOL	Rising	0.0018
Post – Monsoon (Oct - Nov)	SUNI	Falling	-0.0175
	KASOL	Falling	-0.0712
Winter (Dec – Next Yr. Feb)	SUNI	Falling	-0.0687
	KASOL	Falling	-0.0716
Annual (Jan – Dec)	SUNI	Rising	0.0572
	KASOL	Falling	-0.1733

Table no. 6

Sl. No.	Station Name	Latitude	Longitude	Pre-monsoon		Monsoon		Post-monsoon		Winter		Annual	
				Mann-Kendall Statistics, Z	Sen's Slope	Mann-Kendall Statistics, Z	Sen's Slope	Mann-Kendall Statistics, Z	Sen's Slope	Mann-Kendall Statistics, Z	Sen's Slope	Mann-Kendall Statistics, Z	Sen's Slope
1	SUNI	31.246578	77.116979	-0.02	-0.005	1.36	0.177	0.2	0.003	-1.17	-0.063	0.02	0.019
2	KASOL	31.372102	76.866972	-0.49	-0.019	-	-0.001	-0.01	-0.014	-1.13	-0.064	-1.19	-0.193

Sl. No.	Station Name	Latitude	Longitude	Pre-monsoon		Monsoon		Post-monsoon		Winter		Annual	
				Mann-Kendall Statistics, Z	Sen's Slope	Mann-Kendall Statistics, Z	Sen's Slope	Mann-Kendall Statistics, Z	Sen's Slope	Mann-Kendall Statistics, Z	Sen's Slope	Mann-Kendall Statistics, Z	Sen's Slope
1	KASOL	31.372102	76.866972	0.06	0.523	-1.84	-22.716	-0.14	-0.167	-0.46	-0.854	-1.32	-22.942

Non-Parametric Test (Mann-Kendall) for Precipitation and Kasol Discharge Data (1983-2010)

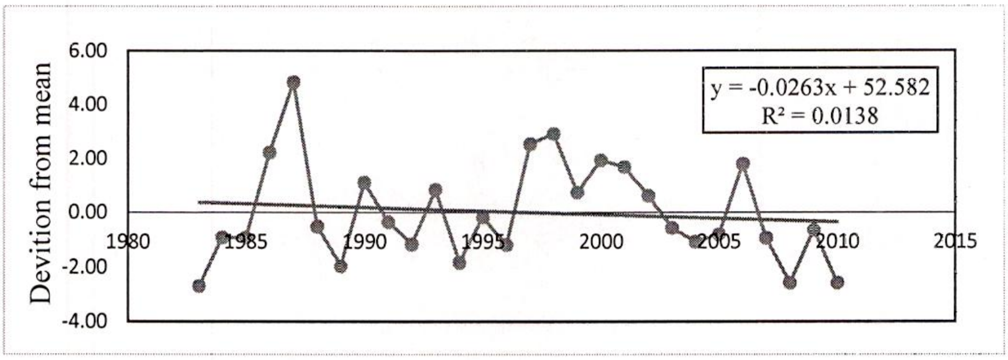


Figure 11: Trend analysis of Kasol during Pre-monsoon

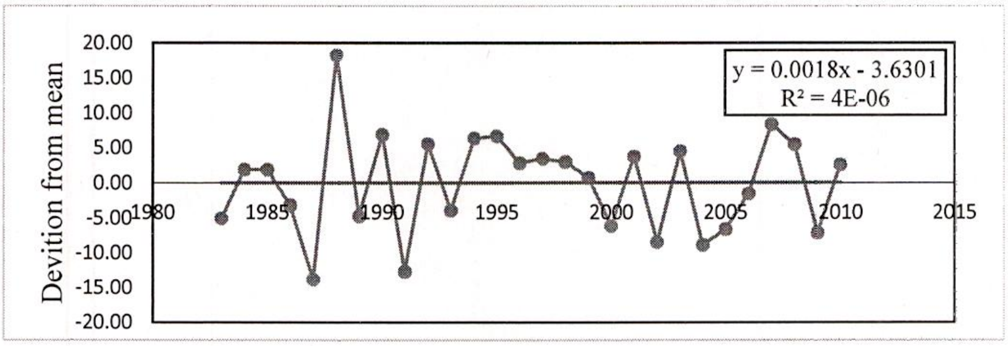


Figure 12: Trend analysis of Kasol during Monsoon

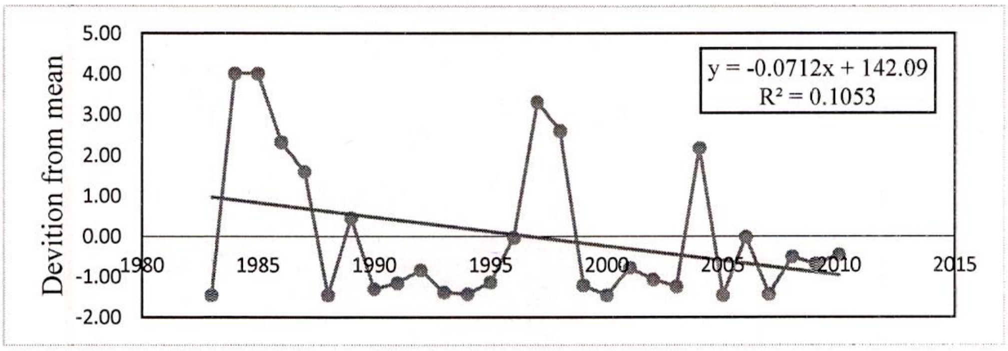


Figure 13: Trend analysis of Kasol during Post-Monsoon

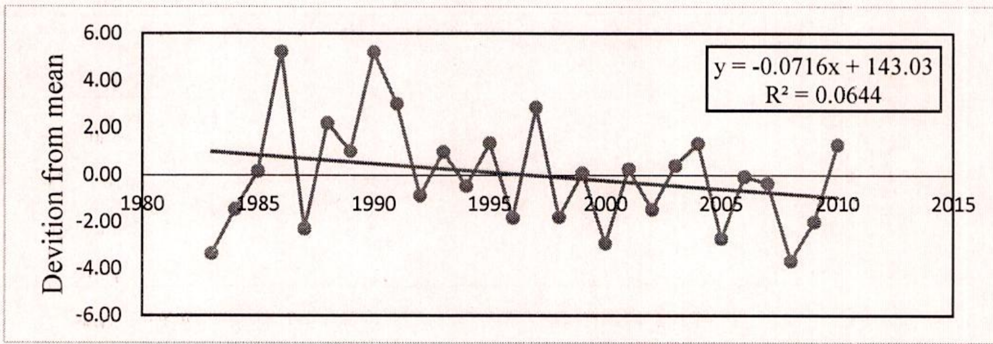


Figure 14: Trend analysis of Kasol during winter

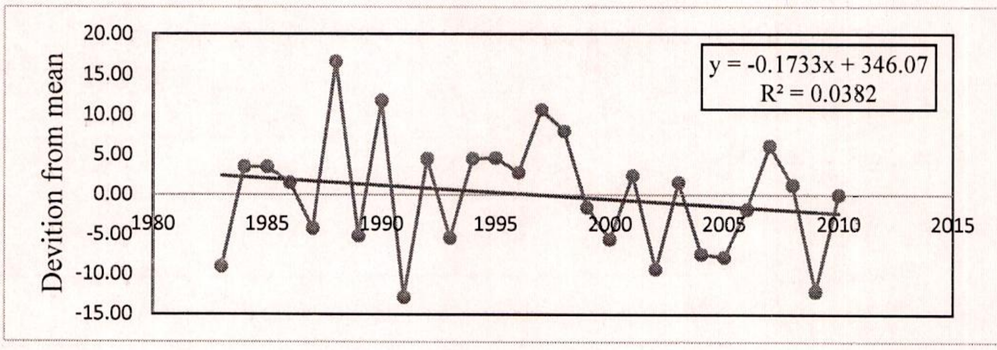


Figure 15: Trend analysis of Kasol during annual

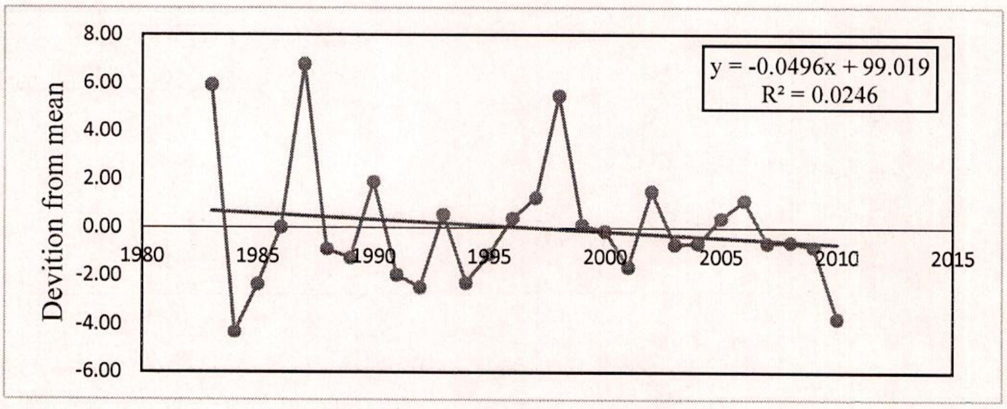


Figure 16: Trend analysis of Suni during Pre-monsoon

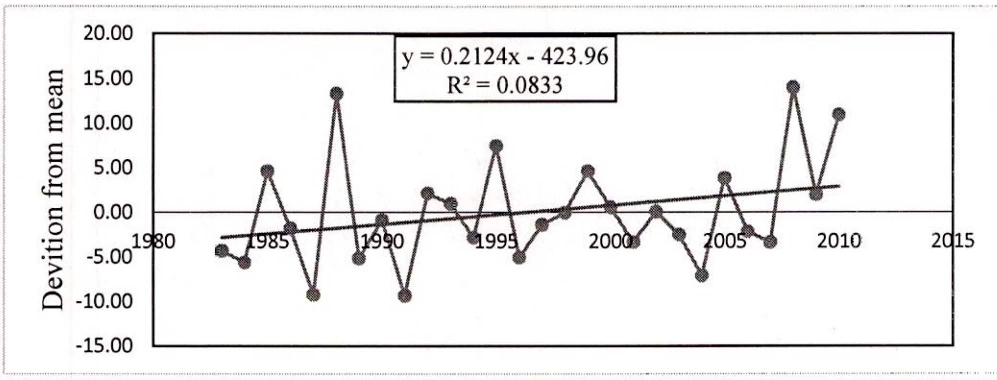


Figure 17: Trend analysis of Suni during Monsoon

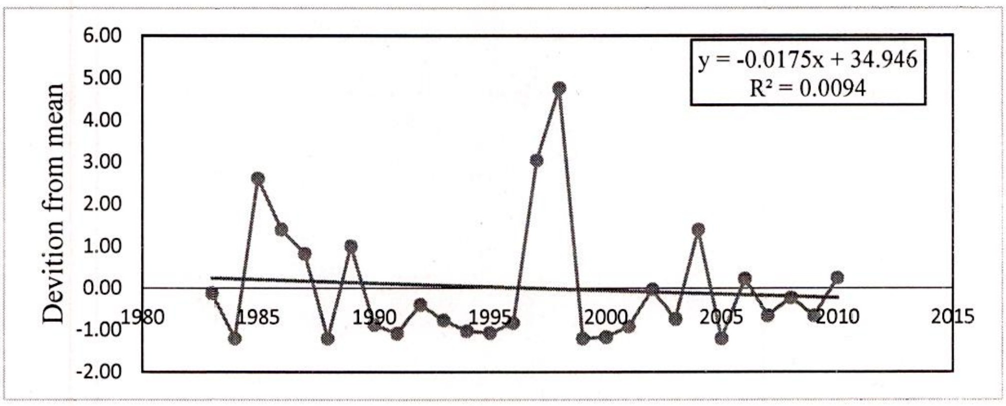


Figure 18: Trend analysis of Suni during Post-monsoon

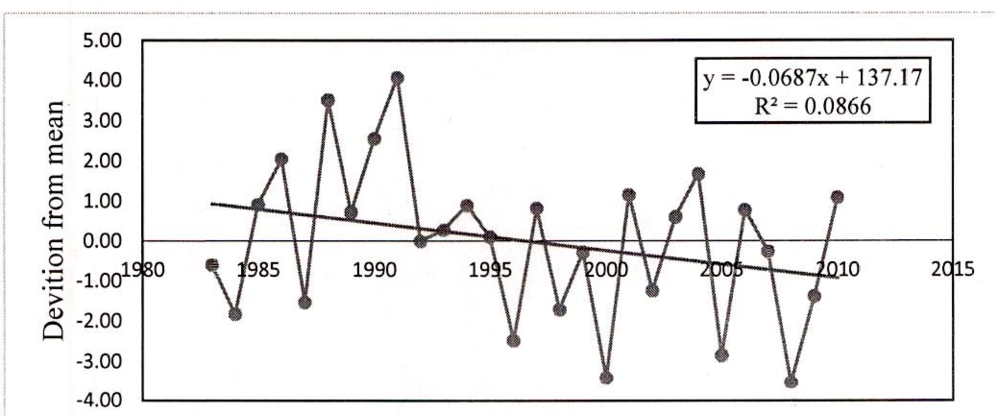


Figure 19: Trend analysis of Suni during winter

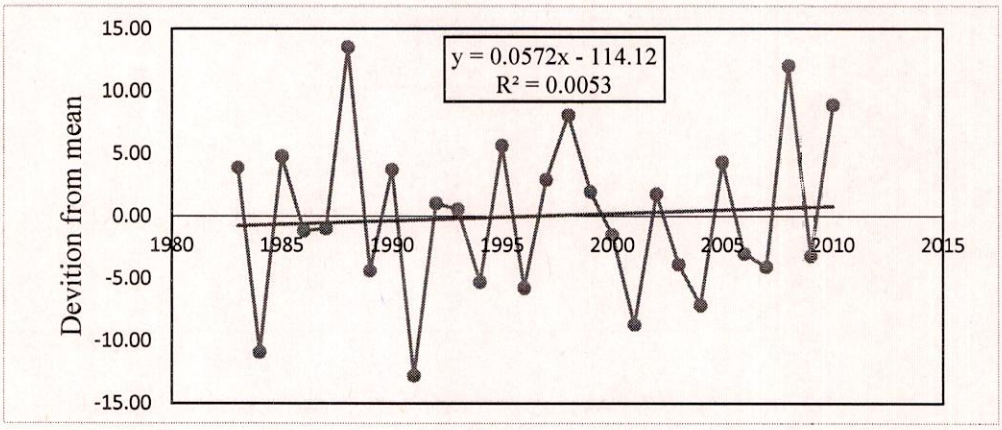


Figure 20: Trend analysis of Suni during annual

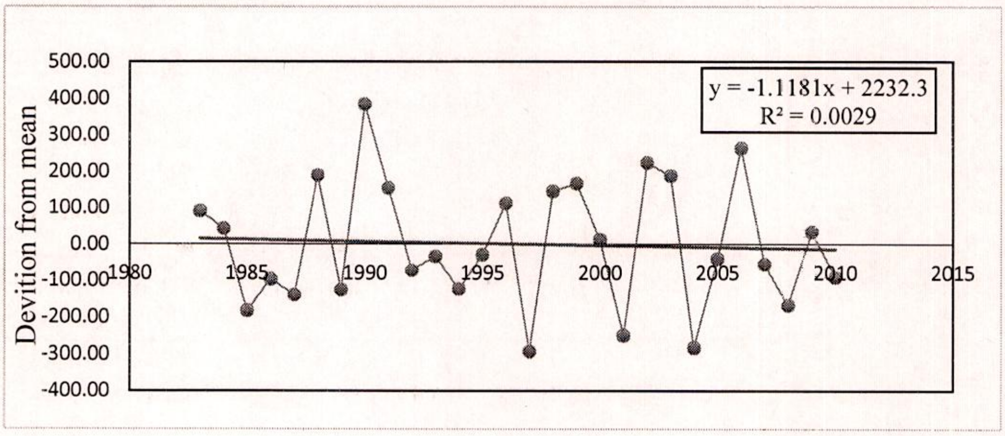


Figure 21: Trend analysis of Kasol (discharge) during Pre-monsoon

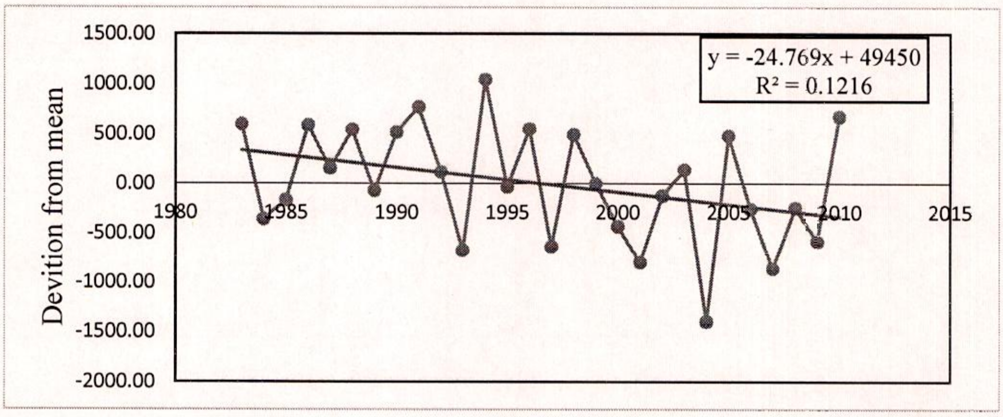


Figure 22: Trend analysis of Kasol (discharge) during monsoon

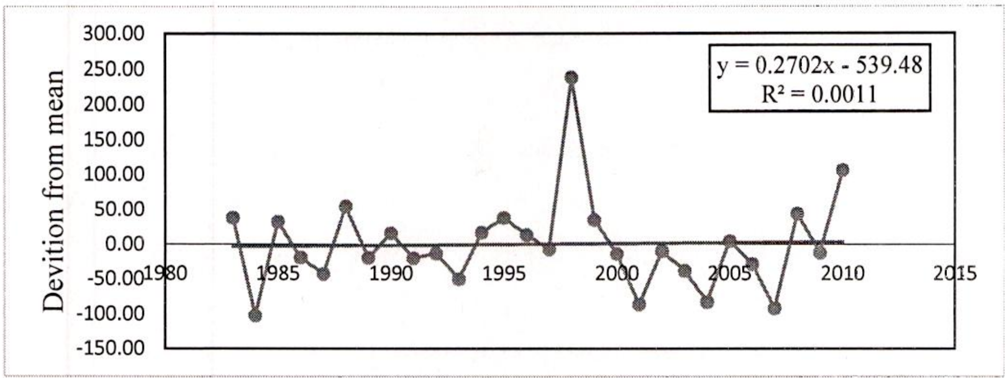


Figure 23: Trend analysis of Kasol (discharge) during Post-monsoon

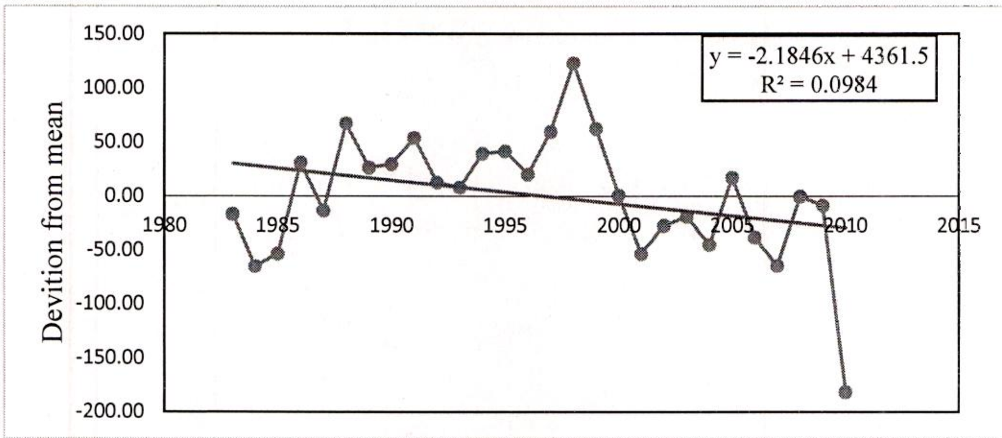


Figure 24: Trend analysis of Kasol (discharge) during winter

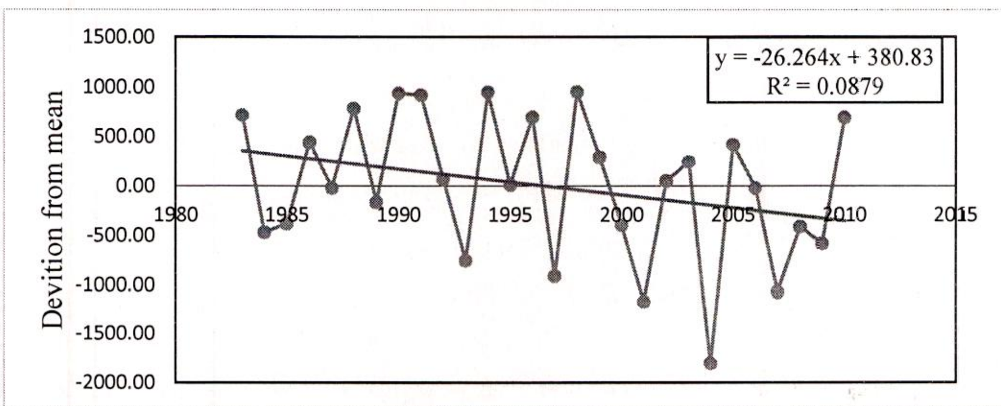


Figure 25: Trend analysis of Kasol (discharge) during annual

Chapter 6

6. RESULTS AND DISSCUSSION

As per the objectives of the project, the study area Suni to Kasol, a mountains basin of Satluj River was delineated from the Arc SWAT automatically. Various input layers have been prepared from satellite images and toposheet. Data base has been prepared as per the requirement of the Arc SWAT model. The hydrological datasets like rainfall, temperature, relative humidity, solar radiation, and wind speed have been simulated on daily basis. The model has performed on daily basis for surface run off simulation. And lastly the observed and simulated stream flow data has been compared.

6.1 Model Calibration

In the current study the Arc SWAT model has simulated on daily basis for the year of 1983 to 2011. The calibration has performed for the year of 1983 to 1998 using discharge data recorded at the outlet of the study area which is Kasol, in which three year has been cropped as a "warm-up period". The model has calibrated based on several parameters like available water content (AWC) and soil evaporation compensation factor (ESCO) and some others, in between the range of the model. Many simulations have been conducted till the time the desired simulated flow was obtained. In order to check the efficiency of the model, the simulated and observed discharge value have been compared with coefficient of determination (R^2) and Nash & Sutcliffe efficiency index (NSE) were applied.

The time series of observed and simulated discharge value have been compared graphically on the daily basis. The calibration period indicated coefficient of determination R^2 of 0.99 (Figure no.27) for daily results. On the other side Nash & Sutcliffe has been found 0.98. From the equate results obtained we can conclude that the model can be considered as best fit although inlet flow can also be observed as a great contributor. The time series of observed and simulated daily discharge are shown in figure no.26 respectively.

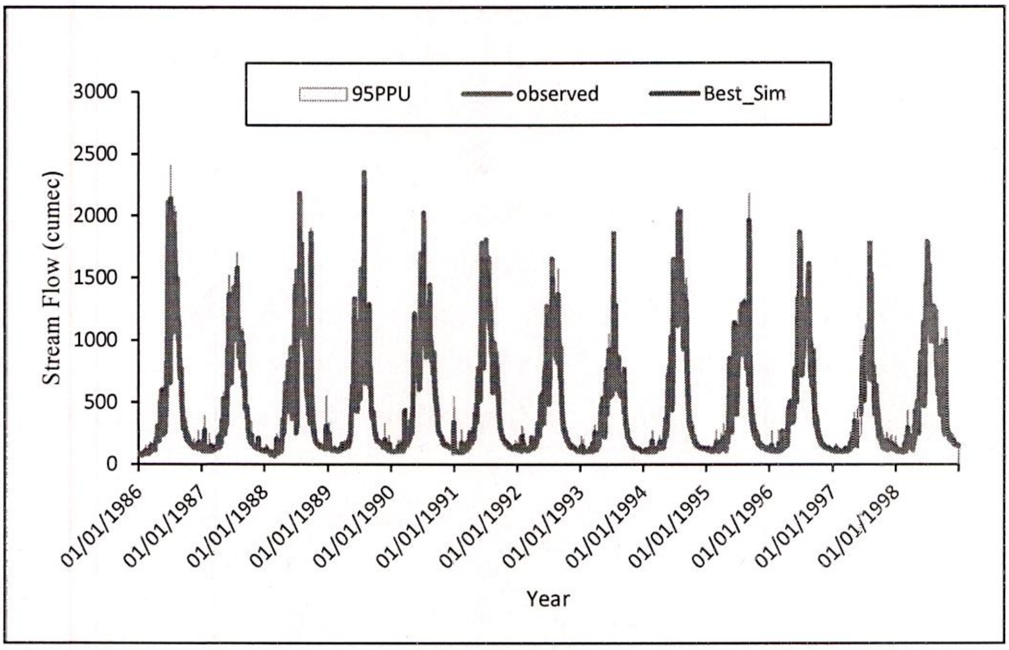


Figure 26: Daily flow calibration plot (SUFI-2) using SWAT-CUP for the period of1986-1998

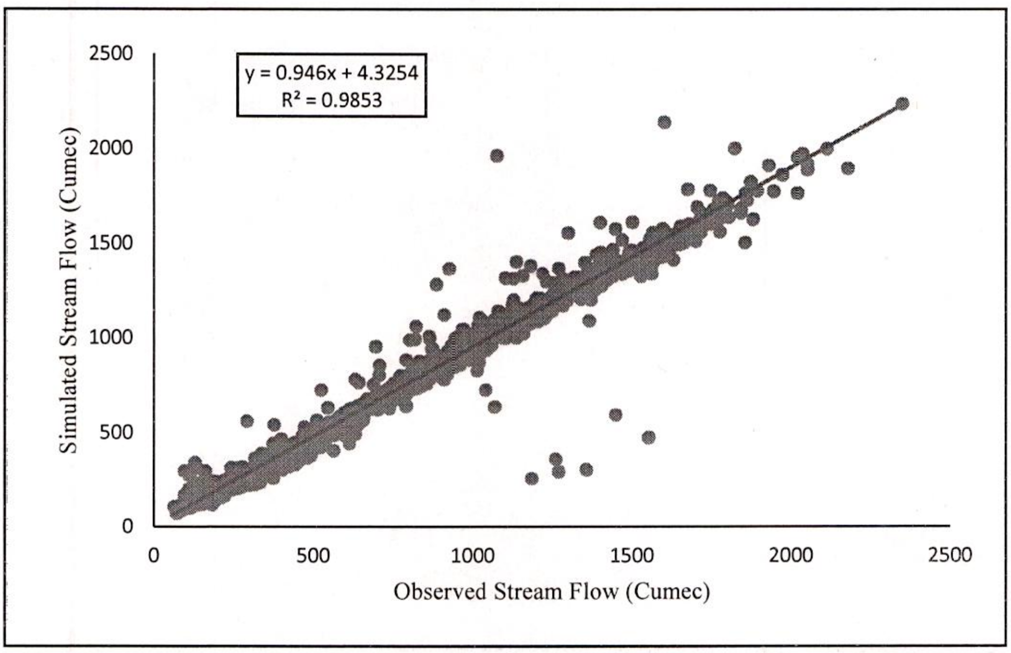


Figure 27: Correlation between daily observed and simulated stream flow measured Kasol during calibration (1986-1998)

6.2 Model Validation

After calibration, the model was validated for the daily surface runoff (Figure no.28 & 29) from 1999 to 2011. Calibration and Validation of SWAT model are two critical issues in this hydrological modeling. After achieving the objective function for calibration, validation of the model ensues. Validation process is similar to calibration procedures in that predicted and measured to determine if the objective function is met. However a dataset of measured watershed response selected for validation preferably should be different than the one used for model calibration, and the model parameters are not adjusted during validation. Validation provides a test of whether the model was calibrated to a particular datasets or the system it is to present. If the objective function is not achieved for the validation datasets, calibration and or model assumptions may be revisited (White and Chaubey, 2005). Iteration was run in several times until the calibration goal was achieved. For these current study iteration carried out 500 times. For each iteration 400-600 simulation were performed. The model was simulated at the outlet (KASOL) of the sub basin (sub-basin 5). Model validation was done for the catchment using SUFI-2 algorithm, which is available inside the SWAT-CUP software. The simulated daily flow shows an outstanding result which is best for the model as well. Table no.7 is shown the statistical performance for calibration and validation of the model.

Table no 7. Daily time step Calibration and Validation performance statistics

Model Stage	Evaluation Statistics			
	NSE	R^2	PBIAS (%)	RSR
Calibration (1986-1998)	0.98	0.99	4.2	0.13
Validation (1999-2011)	0.96	0.97	7.6	0.20

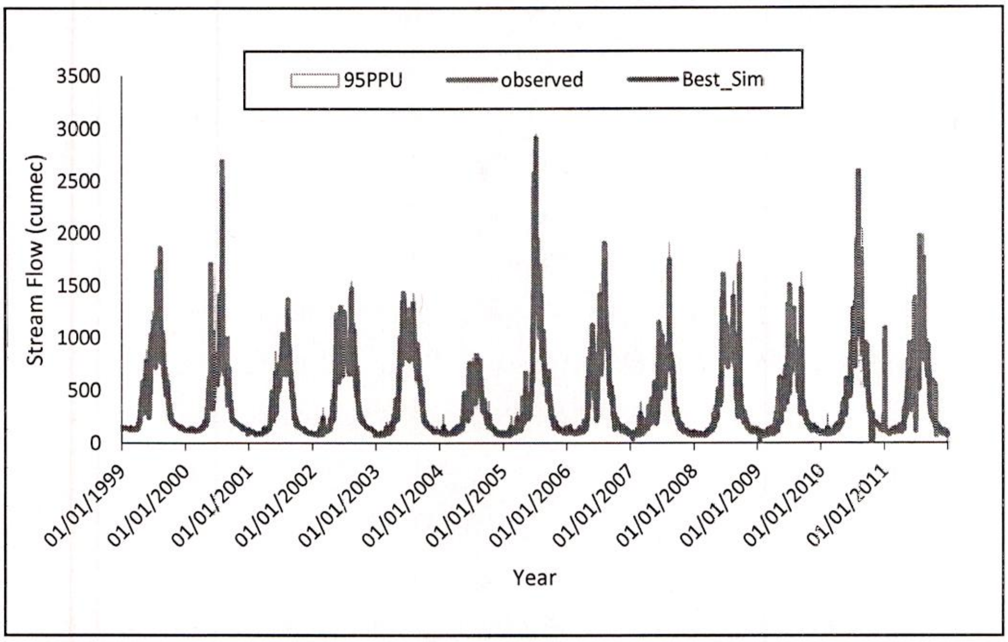


Figure 28: Daily flow validation plot (SUFI-2) using SWAT-CUP for the period of1986-1998

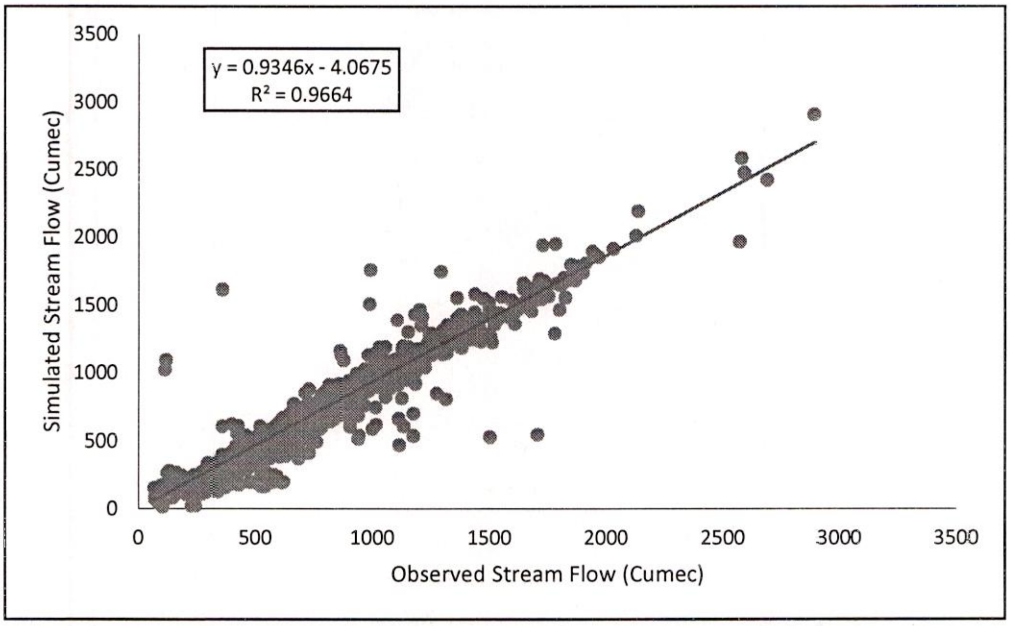


Figure 29: Correlation between daily observed and simulated stream flow measured Kasol during validation (1999-2011)

6.3 Global Sensitivity Analysis

Before calibration, a sensitivity analysis is performed for the control point, i.e., outlet of the sub-basin (Kasol in the present study) in order to find the lists of the most suitable model parameters. For watershed delineation, a large number of parameters have played a great role. In SWAT-CUP, SUFI-2 method has been selected for the current study for parameter optimization to find out the key parameters that effect the runoff during calibration. Global sensitivity analysis has been done to determine the sensitive parameters in the study. Two statistical tests have been measured to find out the sensitivity of the selected parameters namely t-test and p-value. The t-test measures the sensitivity of a parameter, on the other side p-values gives a measure of significance of sensitivity. The parameters were used to rank according to their sensitivity which influence of stream flow. The parameters are vary from one watershed to another based on their geomorphologic characteristics, therefore cannot accept any generalization status for model calibration (Gyamfi et al. 2015). In general the sensitivity analysis, the parameters listed in Table no.7 TheSUFI-2 algorithm is inbuilt within the SWAT calibration and SWAT-CUP environment. In SUFI-2 the goodness of calibration is measured on the basis of closeness of the P-factor to 0 and the R-factor to 1. The number of iteration necessary to get the best parameter ranges in the simulation result (Singh et al, 2013). In the study however the efficiency has been measured including several statistical techniques likewise Nash-Sutcliffe (NSE) [Equation number 1], the coefficient of determination (R^2) [Equation number 2], percent bias (PBIAS) [Equation number 3], and RMSE observation standard deviation ratio (RSR) [Equation number 4] have been used to evaluate the performance of the model.

1. $$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{obs,mean}\right)^2}$$

2. $$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - S_i)(S_i - \bar{S})}{\left(\sum_{i=1}^{n}(O_i - \bar{O})^2\right)^{0.5}\left(\sum_{i=1}^{n}(S_i - \bar{S})^2\right)^{0.5}}\right]^2$$

3. $$PBIAS = \frac{\sum_{i=1}^{n}(O_i - S_i)\times 100}{\sum_{i=1}^{n} O_i}$$

4. $$RSR = \frac{\sqrt{\sum_{i=1}^{n}(O_i - S_i)^2}}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

Where O_i= observed variable, S_i= simulated variable, O dash = mean of observed variable. S dash = mean of simulated variable, n = number of observation in the model. The result of relative sensitivity analysis of parameter using SUFI-2 method is shown in Table no. 8. For this current study eleven parameters have been used, five were found to be more sensitive to stream flow based on t-stat and p-value ($p < 0.00$). Sensitivity of a parameter is calculated based on t-stat and how significant the parameter is to the sensitivity analysis is measured by p-value. A parameter with larger t-stats and smaller p-value considered as most sensitive parameter on the specific variable. The sensitivity of a parameter has been ranked based on the SCS runoff curve number (CN2) on the stream flow. The sensitivity of a parameter varies with respect to land use and soil properties of the specific area. The other relative sensitive parameters ranges from 0.00 to 0.78 according to p-value, the parameters are CN2 (SCS runoff curve number), SOIL_K (Saturated hydraulic conductivity), RCHRG_DP (Deep aquifer percolation fraction), CH_K2 (Manning's n value for the main channel), ALPHA_BF (Base flow alpha factor or recession constant), ESCO (Soil evaporation compensation factor), GW_DELAY (Groundwater delay), SOL_AWC (Available soil water capacity), GW_REVAP (Groundwater "revap" coefficient), GWQMN (Threshold depths of water in the shallow aquifer required for return flow to occur), and REVAPMN (Threshold depths of water in the shallow aquifer required for "revap" to occur).

Table no 8. List of Parameters used in SWAT Model for Parameterization

Parameters	Description	Units
Parameters governing surface water response		
CN2	SCS runoff curve number	none
ESCO	Soil evaporation compensation factor	none
SOL_AWC	Available soil water capacity	mm/mm
SOL_K	Saturated hydraulic conductivity	mm/h
Parameters governing surface water response		
GW_REVAP	Groundwater "revap" coefficient	none
REVAPMN	Threshold depths of water in the shallow aquifer required for "revap" to occur	mm
GWQMN	Threshold depths of water in the shallow aquifer required for return flow to occur	mm
GW_DELAY	Groundwater delay	days
ALPHA_BF	Base flow alpha factor or recession constant	days
RCHRG_DP	Deep aquifer percolation fraction	none
Parameters governing surface basin response		
CH_K2	Manning's n value for the main channel	mm/h

The parameters ranges have been used to calibrate the model with help of SUFI-2 method. For the study area elven most sensitive parameters and their fitted value with ranking is defined in Table no. 9

Table no 9. Eleven most sensitive parameters used in calibration of SWAT model

Parameters	Rank	Maximum Value	Minimum Value	Fitted Value
CN2	1	0.01	-0.20	-0.20
SOIL_K	2	0.80	-0.80	-0.19
RCHRG_DP	3	0.40	0.00	0.10
CH_K2	4	50.00	30.00	47.50
ALPHA_BF	5	0.80	0.23	0.60
ESCO	6	1.00	0.80	0.88
GW_DELAY	7	100.00	45.00	33.56
SOL_AWC	8	0.40	0.12	0.39
GW_REVAP	9	0.20	0.02	0.09
GWQMN	10	2.00	0.89	0.99
REVAPMN	11	200.00	60.00	126.22

6.4 P-value and T-test

The degree to which all uncertainties are accounted for is quantified by a measure referred to as the p-factor, which is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU). Another measure quantifying the strength of a calibration/uncertainty analysis is the t-test, theoretically, the value for p-factor ranges between 0 and 100%, while that of t-test ranges between 0 and infinity. A p-factor of 1 and t-test of zero is a simulation that exactly corresponds to measured data. The p-value and t-test is shown in Figure no. 30 & 31. The degree to which we are away from these numbers can be used to judge the strength of our calibration. A larger p-factor can be achieved at the expense of a larger r- factor. Hence, often a balance must be reached between the two. When acceptable values of r-factor and p-factor are reached, then the parameter uncertainties are the desired parameter ranges (SWAT-CUP 2012 user manual). The sensitivity ranking of the parameters according to p-value and t-test is showing in Table no 10.

Table no 10. Sensitivity ranking of parameters for modeling stream flow in the intermedial part of satluj basin

Parameters	t-stat	p-value	Sensitivity ranking
CN2	-62.19	0.00	1
SOIL_K	-22.04	0.00	2
RCHRG_DP	-6.17	0.00	3
CH_K2	5.18	0.00	4
ALPHA_BF	-5.14	0.00	5
ESCO	-2.77	0.01	6
GW_DELAY	-2.42	0.02	7
SOL_AWC	2.28	0.02	8
GW_REVAP	-1.51	0.13	9
GWQMN	1.50	0.13	10
REVAPMN	-0.28	0.78	11

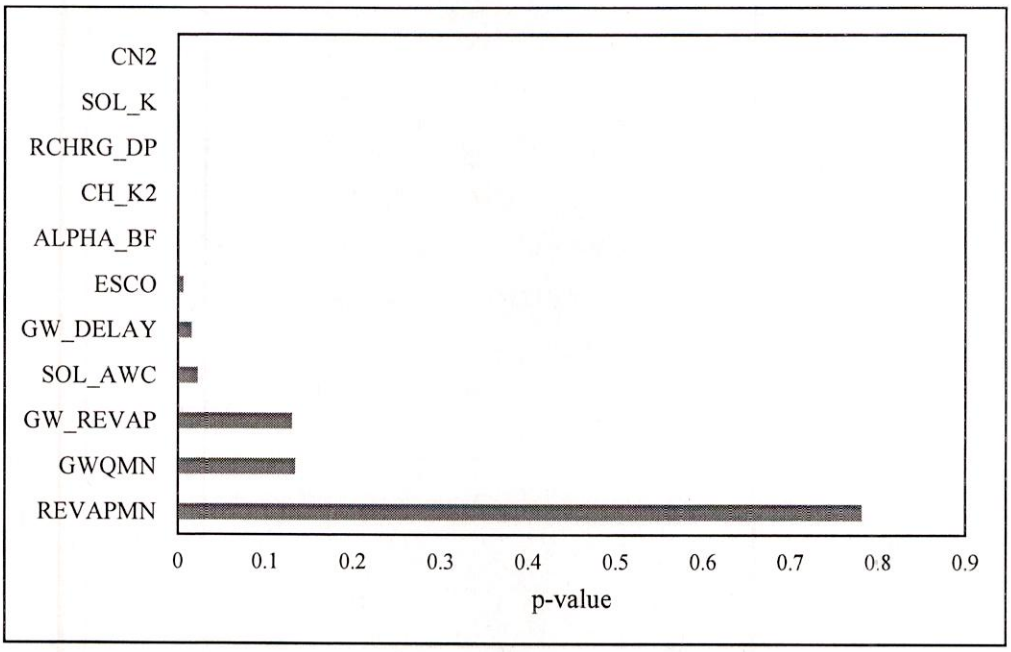


Figure 30: Graphical representation of p-value showing the sensitive parameters

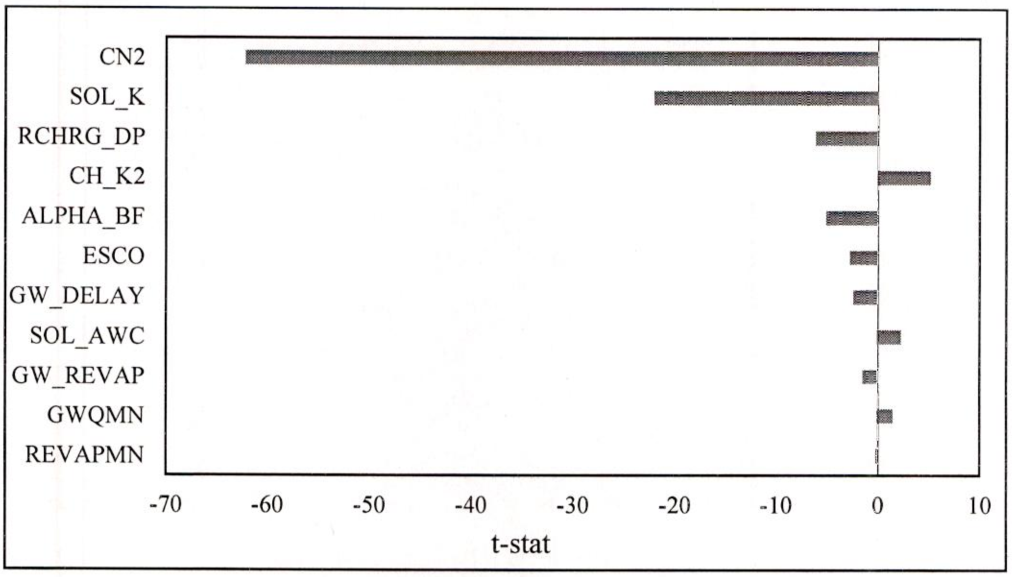
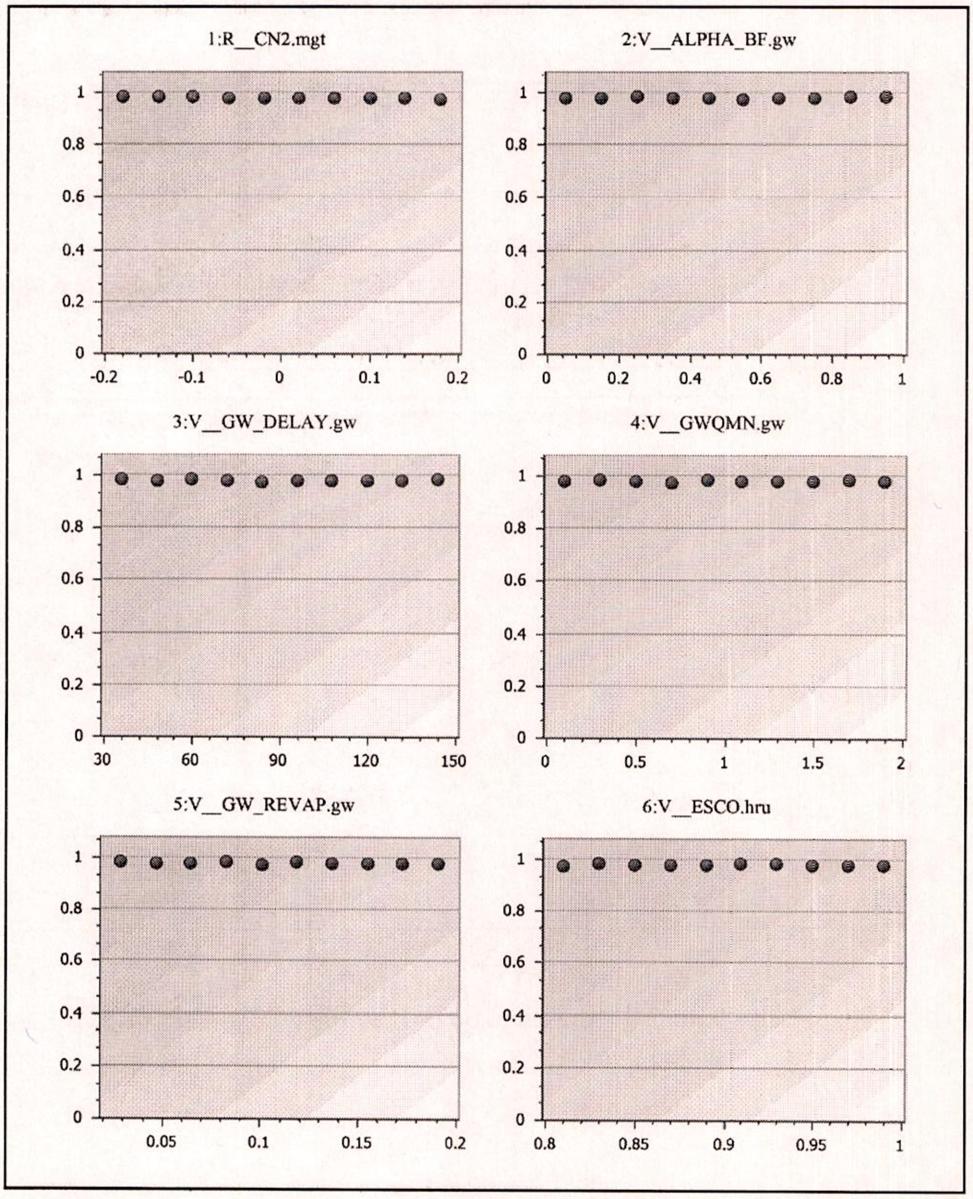


Figure 31: Graphical representation of t-test showing the sensitive parameters

6.5 Dotty Plot

The dotty plots showing the distribution of the number of simulations in the sensitivity analysis after comparing the parameters value with the objective function for daily calibration. The dotty plots for the study area are shown in Figure no.32. It can be concluded that during calibration process, maximum parameters are less uncertainty than validation period.



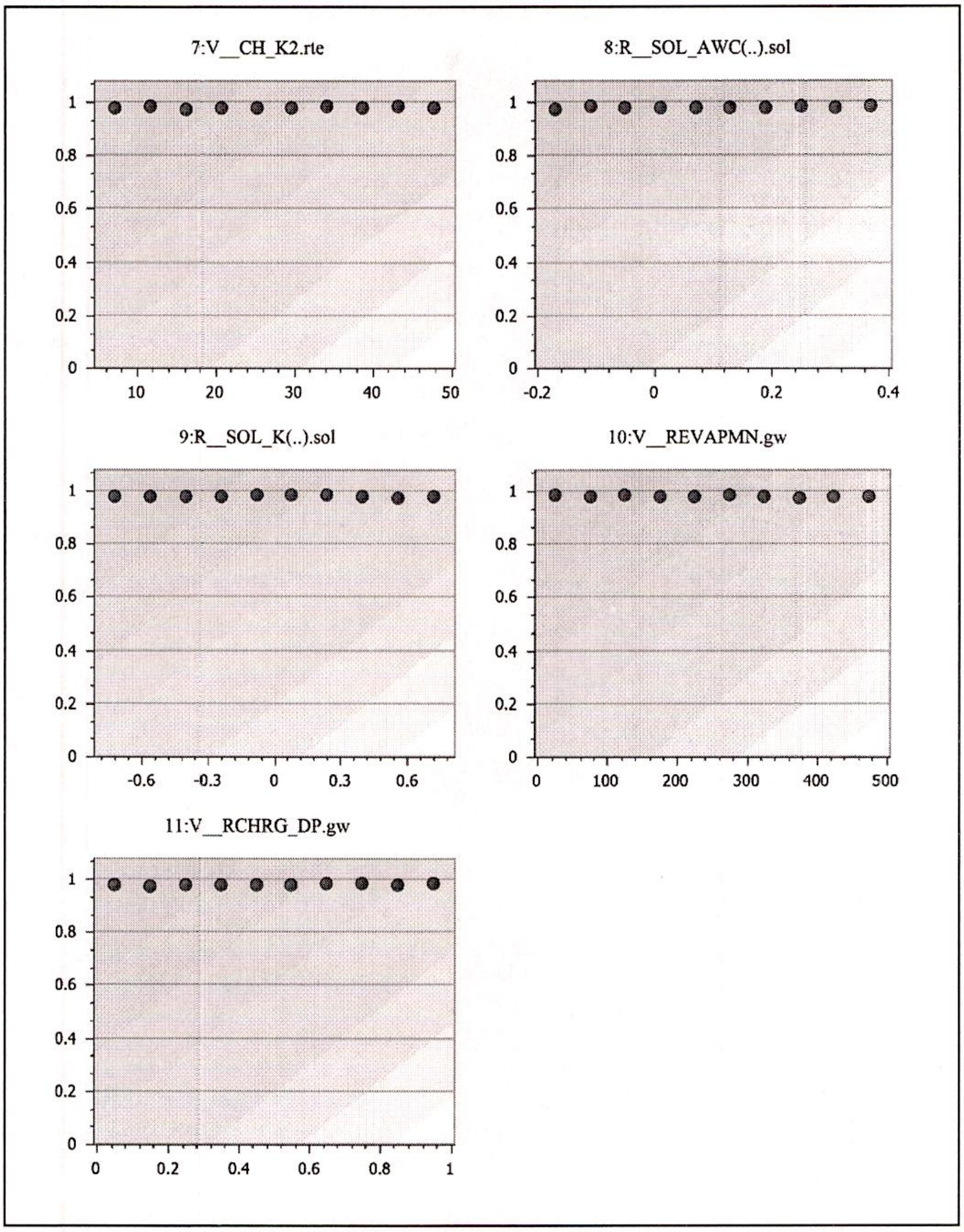


Figure 32: Dotty Plots for the study area during calibration

6.6 Estimation of water balance for the intermediate part of the Satluj Basin

By using Arc SWAT, mean annual water balance for the study area has been simulated for the year of 1986 to 2011. In 1986, the average observed discharge is 445.92 cumec where the simulated discharge comes out 431.91cumec, which is much closer to the observed one. The water balance components for calibration and validation period are shown in Table no. 11. SWAT simulation is based on water balanced equation -$SW_t = SW_o + \sum_{i=1}^{N}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})$. Where SW_t is the final soil water content (mm H_2O), $SW_o$is the initial soil water content (mm H_2O), t time in days, R_{day}amount of precipitation on day I (mm H_2O), Q_{surf} the amount of surface runoff on day i (mm H_2O), E_a the amount of evapotranspiration on day i (mm H_2O), W_{seep} the amount of percolation and bypass existing in the soil profile bottom on day i(mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O). The intermediate part of the Satluj Basin (Suni to Kasol) receives 1079.1 mm precipitation out of which 484.6 mm has lost due to evapotranspiration. The SWAT simulated mean water yield is 543.31 mm, only this water can be used for drinking as well as irrigation purposes. The water budget component and their ratio are shown Table no. 12

Table no. 11 showing the annual water balance for the study area

Annual Basin	Calibration (Parameters)	Validation (Parameters)
PRECIP	1079.1 MM	1055.5 MM
SURFACE RUNOFF Q	207.46 MM	121.03 MM
LATERAL SOIL Q	229.37 MM	346.20 MM
GROUNDWATER (SHALAQ) Q	106.66 MM	84.89 MM
DEEP AQ RECHARGE	57.45 MM	19.31 MM
TOTAL AQ RECHARGE	164.14 MM	104.27 MM
TOTAL WATER YLD	543.31 MM	552.01 MM
PERCOLATION OUT OF SOIL	163. 84 MM	106.09 MM
ET	484.6 MM	486.1 MM
PET	1052.4 MM	1038.9 MM

Table no. 12 showing the hydrological water balance ratio

Hydrological water balance ratio		
Hydrology (Water balance ratio)	Stream flow/precipitation	0.50
	Base flow/total flow	0.62
	Surface run-off/total flow	0.38
	Percolation/precipitation	0.15
	Deep recharge/precipitation	0.05
	ET/precipitation	0.45

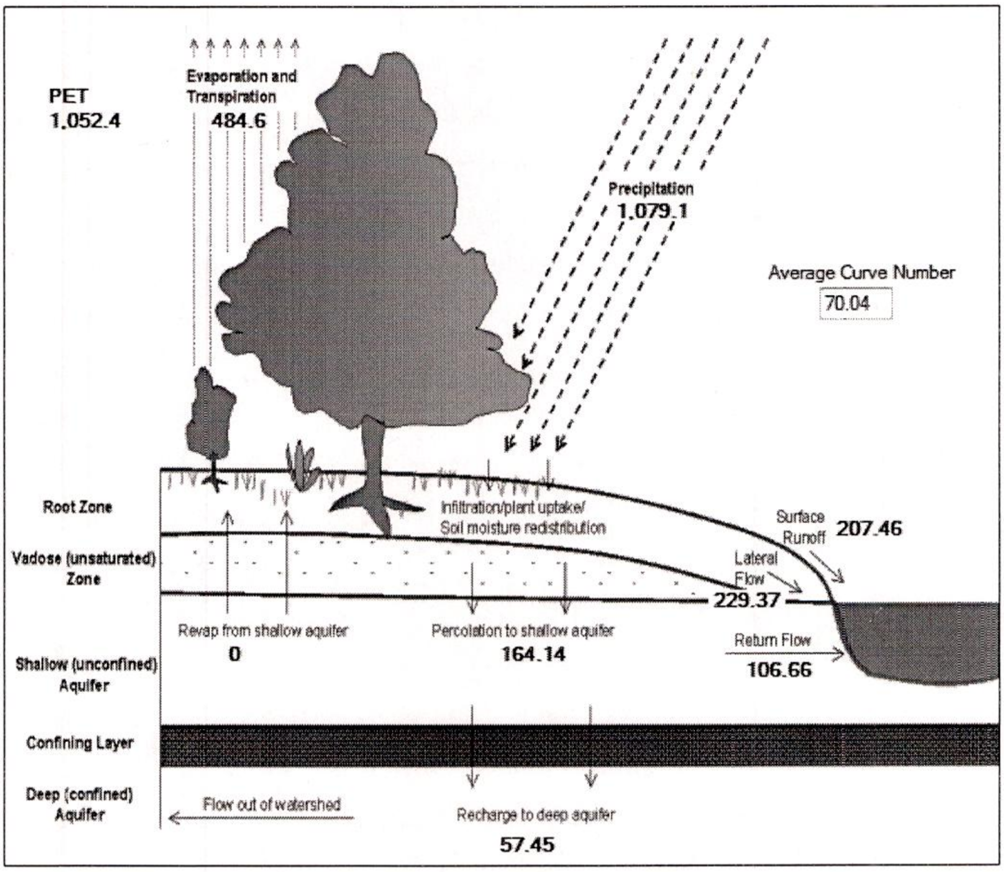


Figure 33: Pictorial diagram of water balance by SWAT Check

Chapter 7

7. SUMMARY AND CONCLUSIONS

In the present work, the main objective was to simulate stream flow for a part of Satluj basin (Suni to Kasol site) using a physical based semi-distributed model SWAT, having an interface with Arc GIS. Data base has been created in ArcGIS which took a lot of time. The automatic watershed delineation at HRU level clearly shows how the basic features like land use, soil and slope have an effect on the hydrology of the catchment. SWAT-CUP is one of the latest programs available for calibration, validation and uncertainty analysis of SWAT model. It gives an effective graphical interface for depicting outputs, together with simulated data, observed data, best-fit model results and 95PPU for all variables used in model calibration. SUFI-2 is one of the procedures in SWAT-CUP which is effective but need more iterations as well as modification of the parameter ranges for better results. These methods are flexible allowing users to adopt different measures and objective functions. SUFI-2 methods have been used in the present study. Sensitivity analysis shows the most sensitive parameters for the simulation of stream flow include CN2, SOIL_K, RCHRG_DP, CH_K2, ALPHA_BF, ESCO, GW_DELAY, SOL_AWC, GW_REVAP, and GWQMN. SWAT model was calibrated and validated to examine its applicability for simulating daily flow from the study basin. The model was set up for 28 years from 1983-2011, out of which the first 3 years were considered as the model warm up period. Out of these 28 years, 12 years (1986-1998) were used for calibration and next 13 years (1989-2011) for validation of model. The model simulation was carried out on daily basis. The coefficient of determination (R_2) and Nash–Sutcliffe efficiency (NSE) were used for performance evaluation. The model simulated the daily runoff of the catchment with a high degree of accuracy with R_2, NSE and PBIAS values as 0.99, 0.98 and 4.2% during calibration and 0.97, 0.96 and 7.6% respectively during validation. These results indicated a good performance of SWAT in simulating the runoff from the study area. The model performance and evaluation criteria showed that the model performance was good and acceptable. As per water balance study, the water yield and ET of the catchment varies from 45-50% and 40-45% of the total precipitation, respectively. It is required to attain spatial, soil and hydro meteorological database for the study by installing the Automatic Weather Stations (AWS) to measure more accurate precipitation, temperature and other climatic variables at various locations. The results of non-parametric approach indicates that during monsoon season there is rising trend in rainfall at both stations. The rainfall is found to be falling during the pre-monsoon, post-monsoon and winter season.

Limitation of the study

The limitation of SWAT model is given below:

1. The Arc SWAT interface Sensitivity Analysis/ Auto Calibration and Uncertainty tools only allow calibration at a single point within a watershed.

2. Spatial Coverage incomplete due to thresholds in HRU definition step.

3. Since the model is not easy t understand and is used nowadays by its own experts.

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Chapter 9

9. ANNEXURE (S)

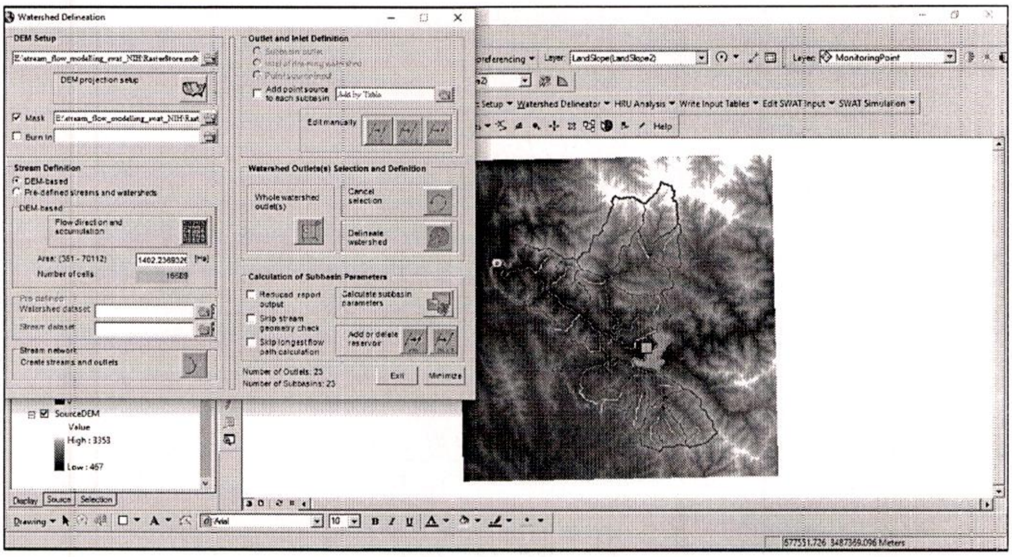
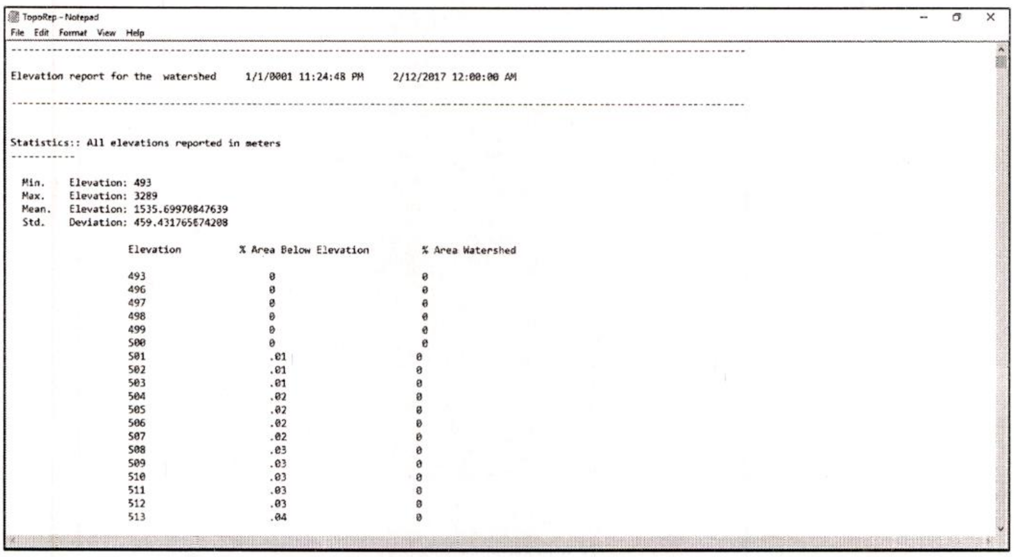


Figure 1. Watershed delineation using SWAT (Suni to Kasol)



Elevation report for the watershed 1/1/0001 11:24:48 PM 2/12/2017 12:00:00 AM

Statistics:: All elevations reported in meters

Min. Elevation: 493
Max. Elevation: 3289
Mean. Elevation: 1535.69970847639
Std. Deviation: 459.431765674208

Elevation	% Area Below Elevation	% Area Watershed
493	0	0
496	0	0
497	0	0
498	0	0
499	0	0
500	0	0
501	.01	0
502	.01	0
503	.01	0
504	.02	0
505	.02	0
506	.02	0
507	.02	0
508	.03	0
509	.03	0
510	.03	0
511	.03	0
512	.03	0
513	.04	0

Figure 2. Topographic report of the study area

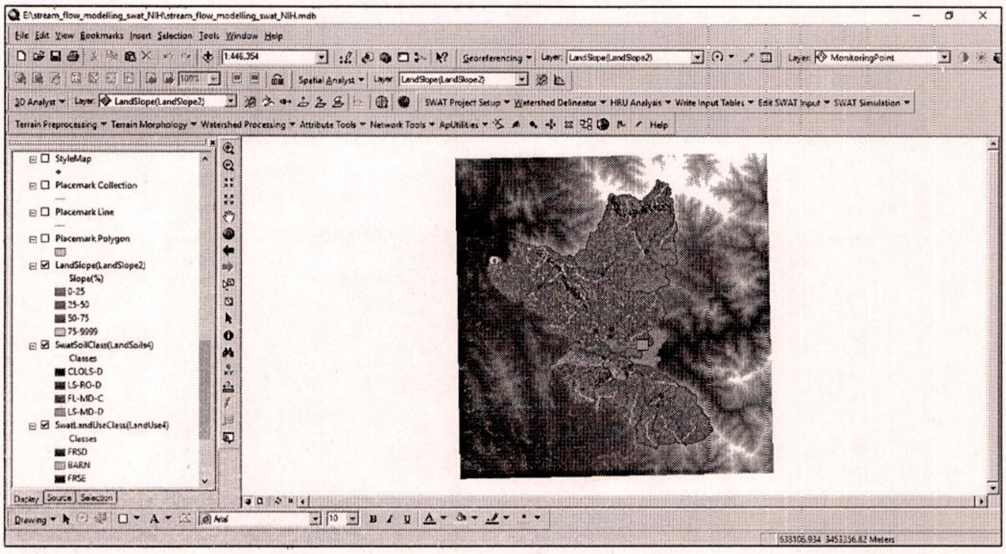
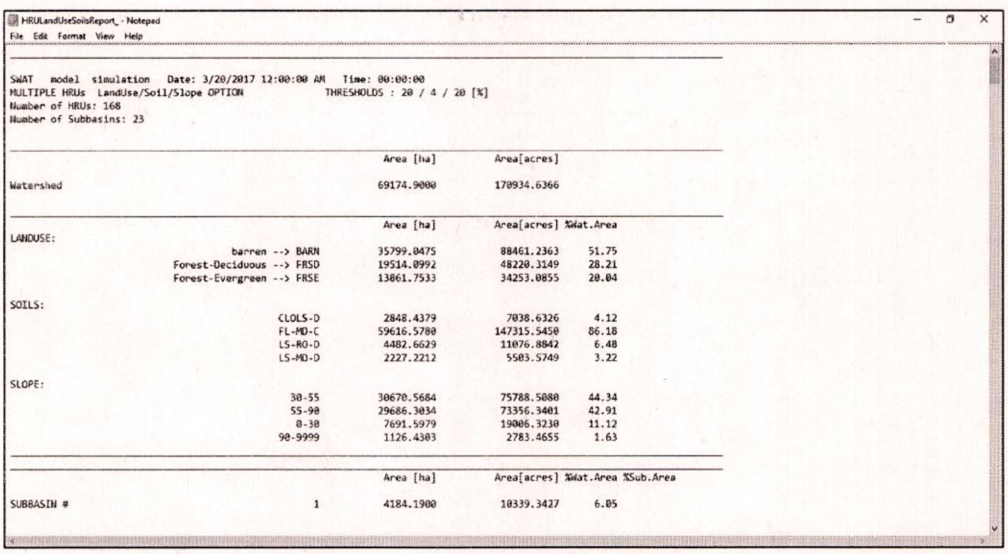


Figure 3. HRU analysis of the sub-basin



```
SWAT  model  simulation   Date: 3/20/2017 12:00:00 AM   Time: 00:00:00
MULTIPLE HRUs  LandUse/Soil/Slope OPTION            THRESHOLDS : 20 / 4 / 20 [%]
Number of HRUs: 168
Number of Subbasins: 23

                                                   Area [ha]        Area[acres]

Watershed                                         69174.9000        170934.6366

                                                   Area [ha]        Area[acres] %Wat.Area
LANDUSE:
                                barren --> BARN   35799.0475         88461.2363     51.75
                      Forest-Deciduous --> FRSD   19514.0992         48220.3149     28.21
                      Forest-Evergreen --> FRSE   13861.7533         34253.0855     20.04

SOILS:
                                        CLOLS-D    2848.4379          7038.6326      4.12
                                         FL-MD-C  59616.5780        147315.5450     86.18
                                         LS-RO-D   4482.6629         11076.8842      6.48
                                         LS-MD-D   2227.2212          5503.5749      3.22

SLOPE:
                                           30-55  30670.5684         75788.5080     44.34
                                           55-90  29686.3034         73356.3401     42.91
                                            0-30   7691.5979         19006.3230     11.12
                                         90-9999   1126.4303          2783.4655      1.63

                                                   Area [ha]        Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                     1   4184.1900         10339.3427      6.05
```

Figure 4. HRU analysis report

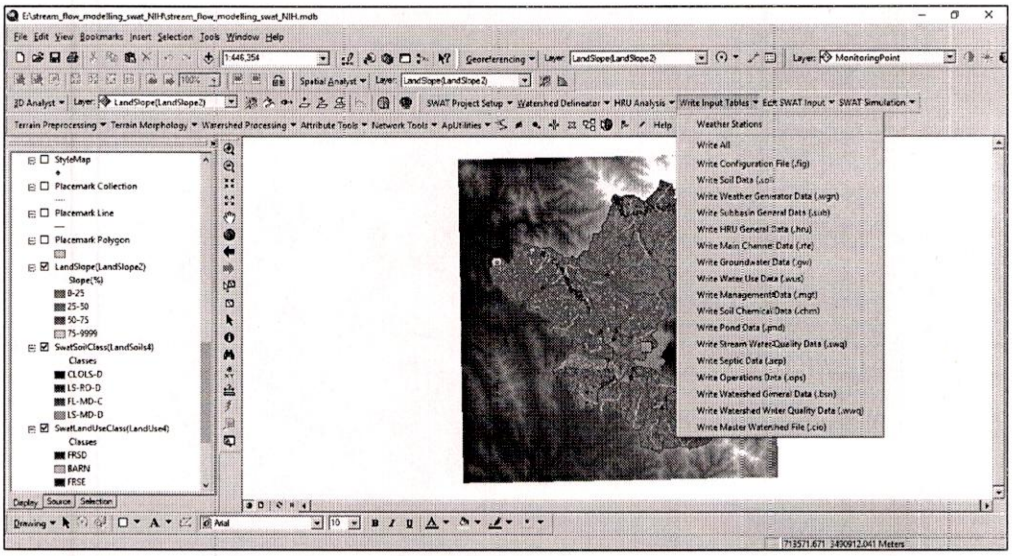


Figure 5. Write input table

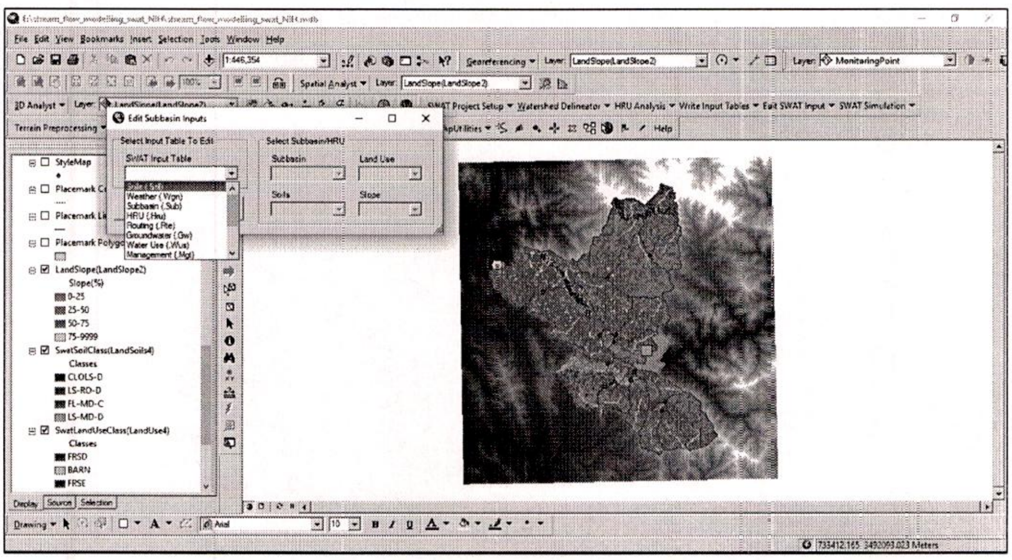


Figure 5. Edit sub-basin inputs

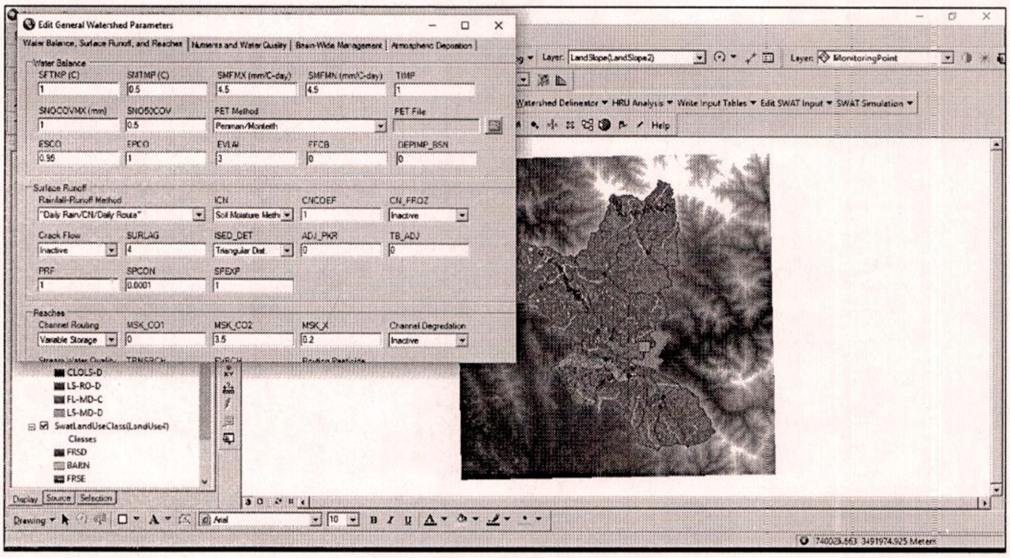


Figure 6. Edit general weather parameters

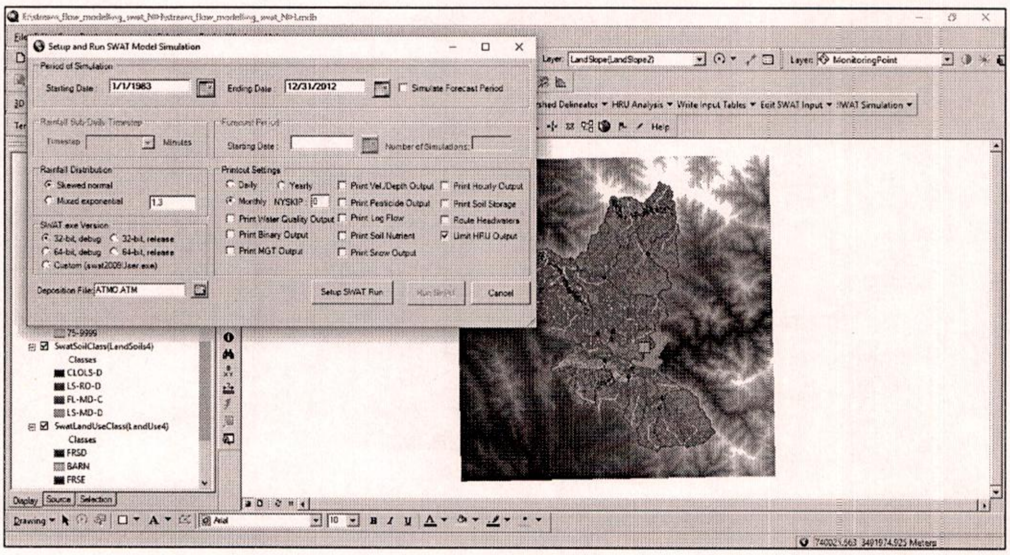


Figure 7. Setup and run SWAT model

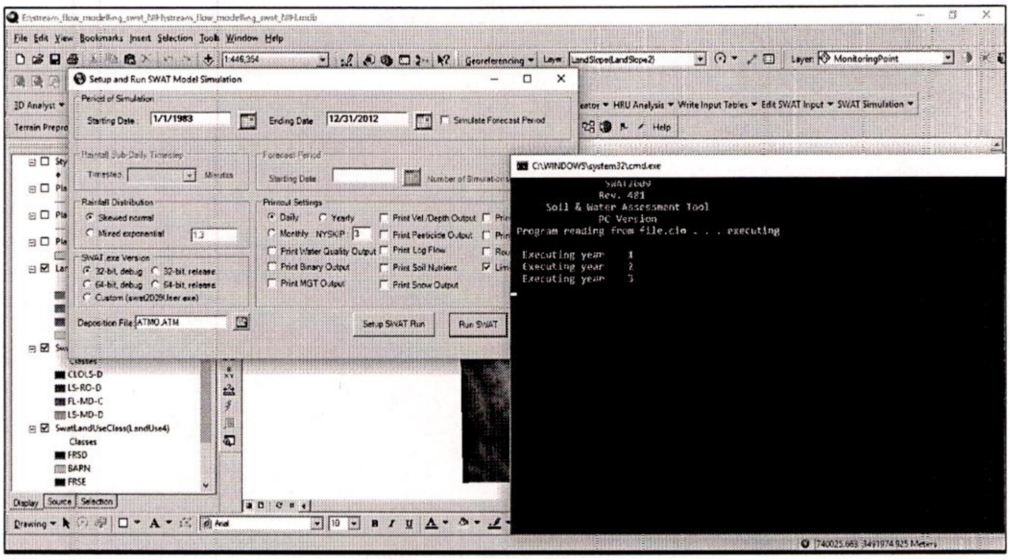


Figure 8. SWAT run

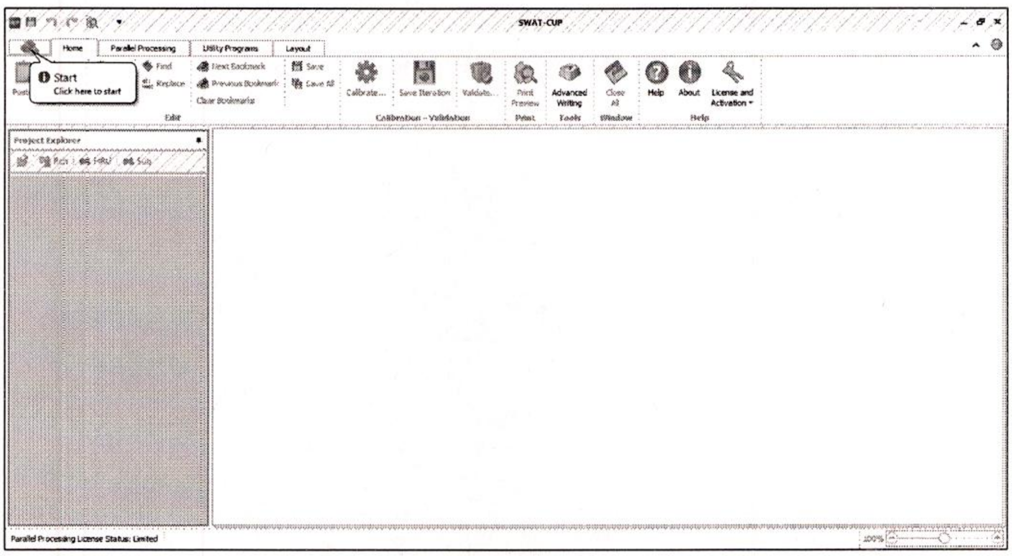


Figure 9. SWAT-CUP Model

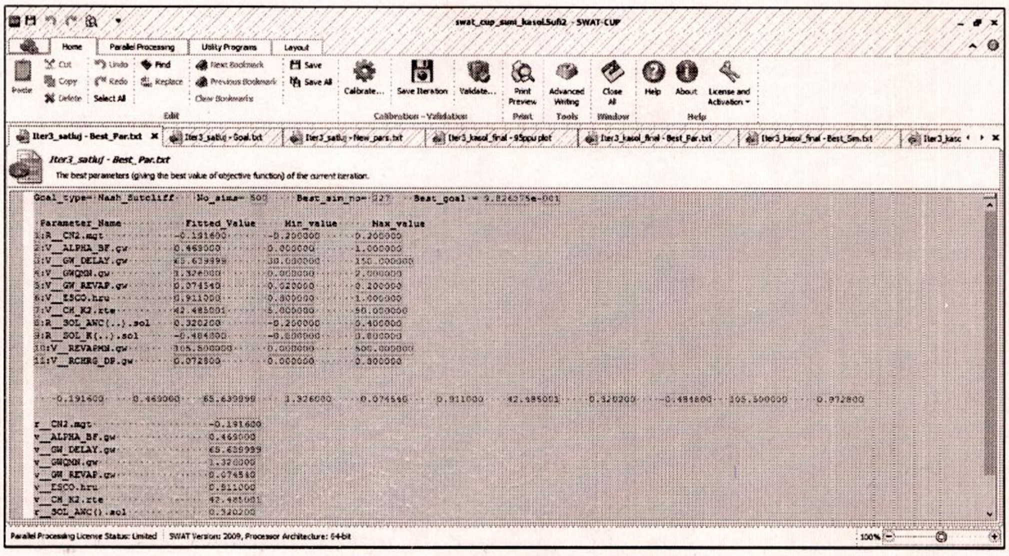


Figure 10. Parameters Editing in SWAT-CUP

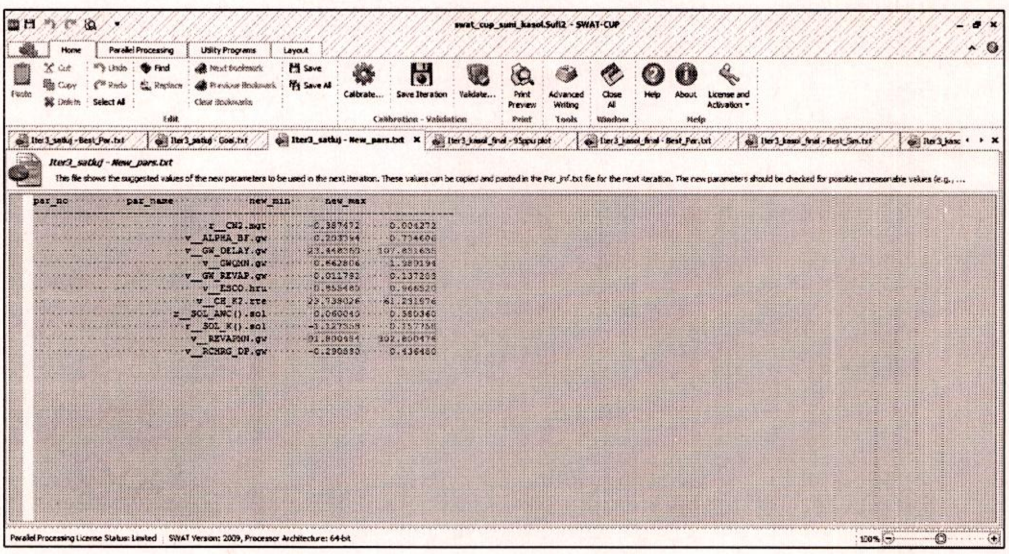


Figure 11. Eleven Parameters Editing in SWAT-CUP

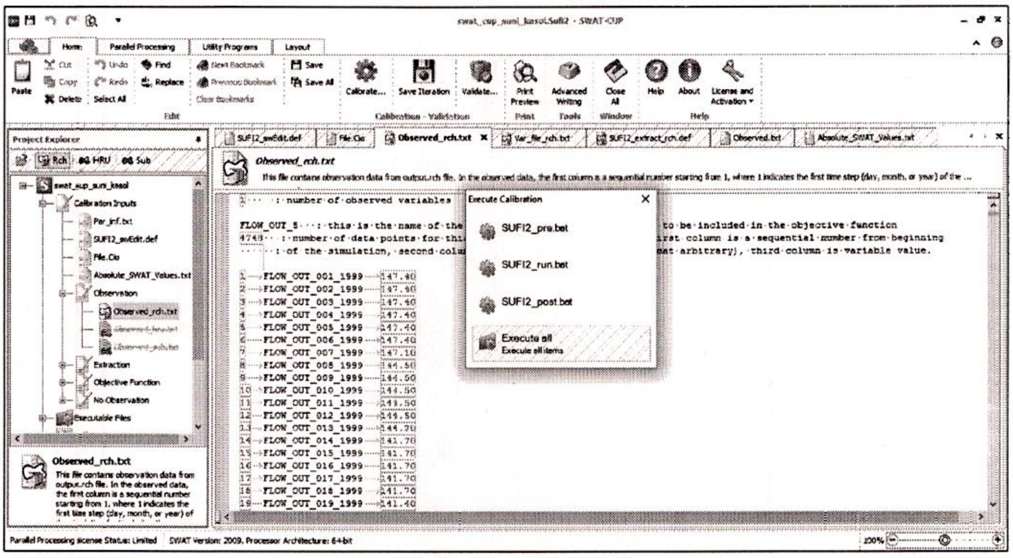


Figure 12. Calibration Process in SWAT-CUP

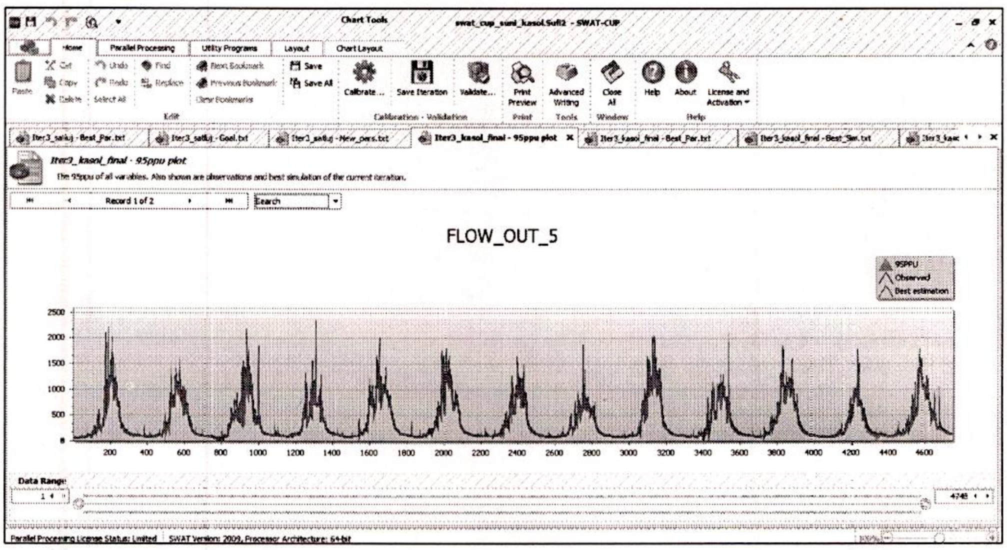


Figure 13. 95PPU Plot (Calibration Process)

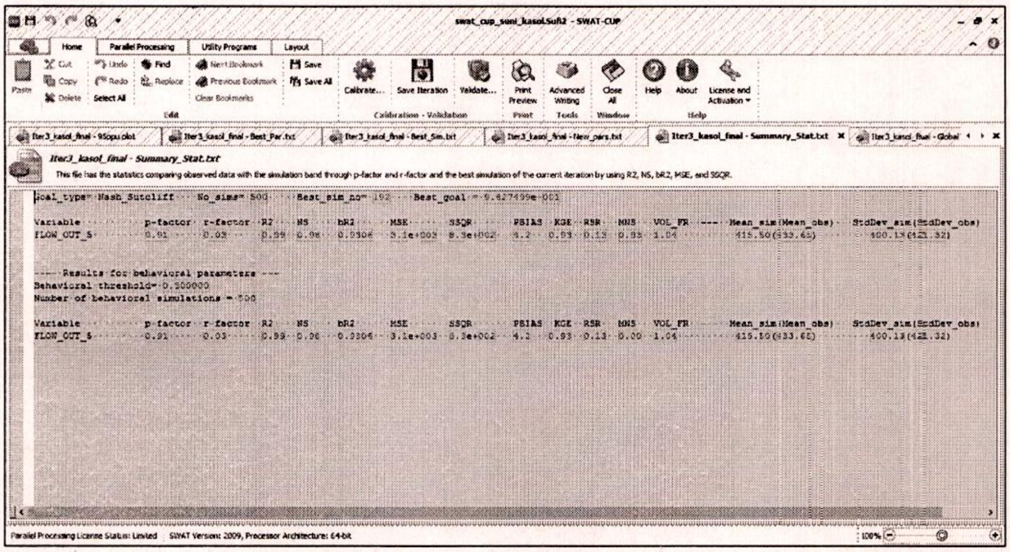


Figure 14. Summary Report for Stream Flow Calibration

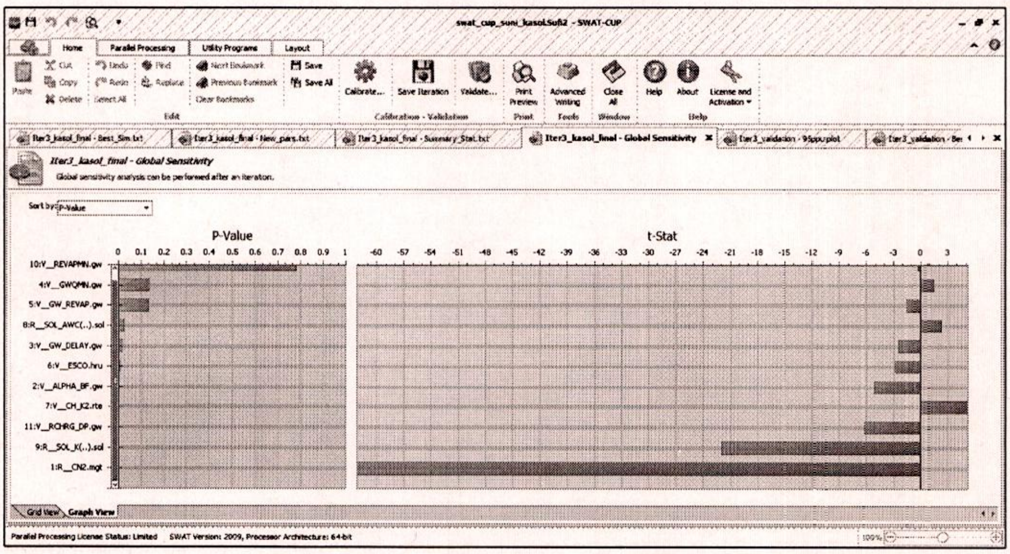


Figure 15. Sensitivity Analysis during Calibration time

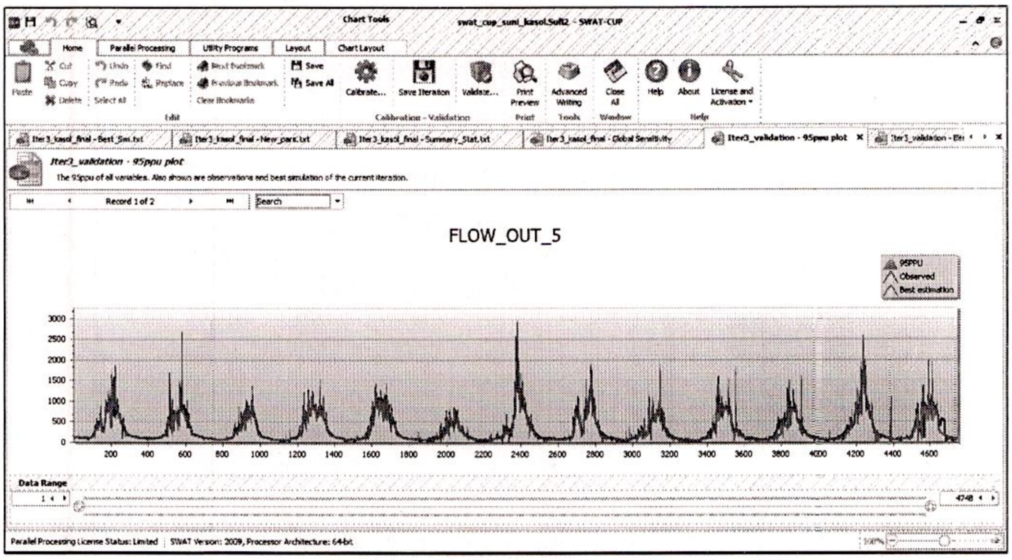


Figure 16. 95PPU Plot (Validation Process)

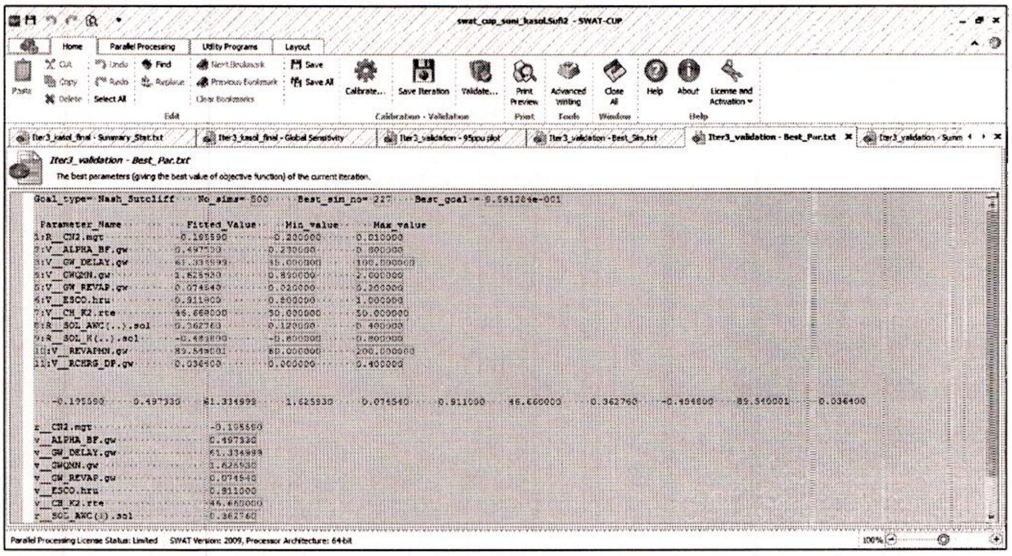


Figure 17. Parameterization (Validation Process)

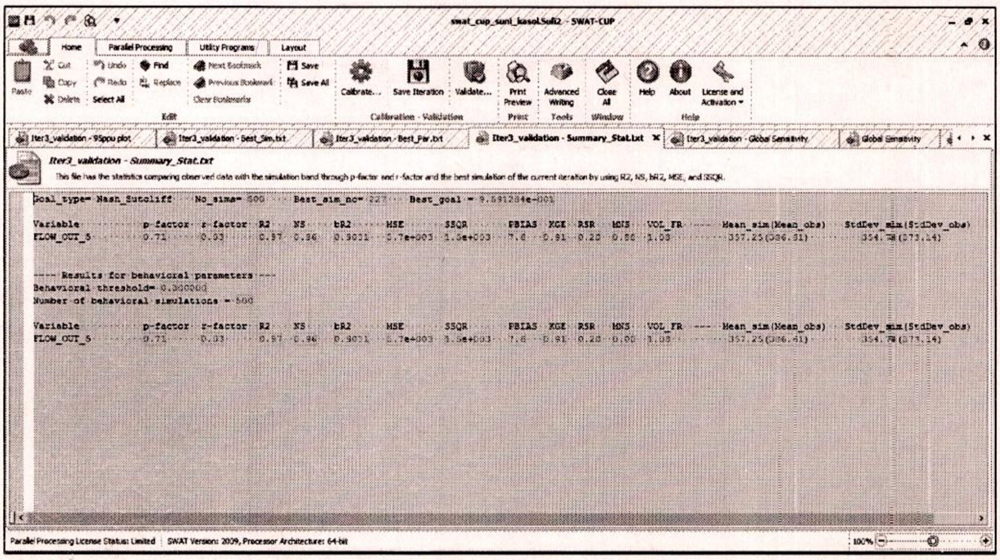


Figure 18. Summary Report for Stream Flow Validation

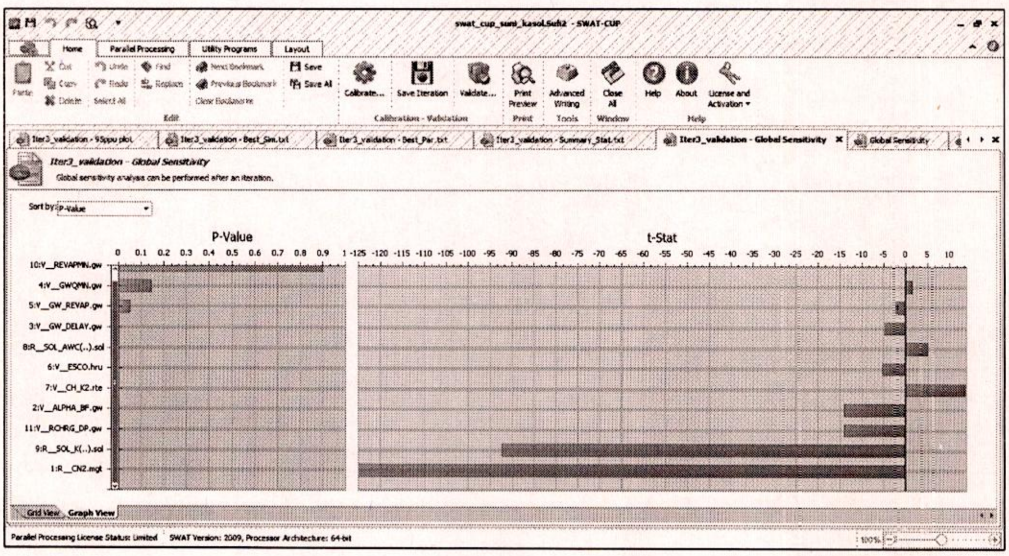


Figure 19. Sensitivity Analysis during Validation time