Hydrological Modeling of Bhagirathi River Basin Up to Tehri Dam Using ArcSWAT

A

Thesis Report

Submitted in Partial Fulfilment of the Requirements for the Award of Degree

of

Master of Technology

in

Hydraulics & Water Resources Engineering

Submitted by

Noopur Awasthi

(Roll No. 2K19/HFE/07)

Under the Guidance of

Dr. Munendra Kumar

June 2021

DEPARTMENT OF CIVIL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

New Delhi, India – 110042

DELHI TECHNOLOGICAL UNIVERSITY

Formerly Delhi College of Engineering

New Delhi - 110042

BONAFIDE CERTIFICATE

This is to certify that the project report entitled "**Hydrological Modeling of Bhagirathi River Basin Up to Tehri Dam Using ArcSWAT**" is a record of the bonafide dissertation work carried out by me, **Noopur Awasthi**, towards the partial fulfillment of requirements for the award of the degree **of Master of Technology** in **Hydraulics & Water Resources Engineering**.

Also, I do hereby state that I have not submitted the matter embodied in this thesis to any other University/Institute for the award of any degree as per my knowledge and belief.

Noopur Awasthi

Roll No: 2K19/HFE/07

Delhi Technological University

This is to certify that the above-made statements made by the candidate are correct to the best of my knowledge

Dr. Munendra Kumar

Professor

Department of Civil Engineering

Delhi Technological University

New Delhi, India

ACKNOWLEDGMENT

I take this opportunity to express my gratitude in its most sincere and deepest sense to my thesis supervisor **Dr. Munendra Kumar,** Professor, Department of Civil Engineering, Delhi Technological University, New Delhi for his invaluable encouragement and guidance throughout the dissertation work. I am thankful to him for giving his precious time and shall remain indebted to my thesis supervisor throughout my life.

I am thankful **to Prof. V. K. Minocha**, Head of the department, Department of Civil Engineering. I also express a deep sense of appreciation to **Mr. Deepak Singh**, PhD. scholar and the whole staff of the Department of Civil Engineering for their cooperation and support throughout the dissertation.

The blessings and unconditional support of my loving parents, **Mr. R.C. Awasthi** and **Mrs. Suman Awasthi** gave me active support and helped me throughout my thesis work without which it would have been impossible to undertake and complete dissertation work.

I am also thankful to my sisters **Dr. Shilpi Awasthi, Shikha Awasthi, Ananya Awasthi**, and all other friends who helped me during the entire thesis work. Finally, I would like to thank all those who directly or indirectly helped me during the period of this work.

Last but not the least, my thanks to the almighty God without whom nothing would have been possible for me to achieve in this world.

Noopur Awasthi
Delhi Technological University
New Delhi, India
May 2021

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AWD	Automatic Watershed Delineation
CN	Curve Number
CWC	Central Water Commission
DEM	Digital Elevation Model
HRU	Hydrological Response Units
LULC	Land Use/Land Cover
NSE	Nash Sutcliffe Efficiency
SRTM	Shuttle Radar Topography Mission
SUFI-2	Sequential Uncertainty Fitting version 2
SWAT	Soil and Water Assessment Tool
WRIS	Water Resources Information System

ABSTRACT

Gaumukh Glacier is the origin of the Bhagirathi River, from there it flows about 193 km up to the Devprayag and merged with the Alaknanda river to form the River Ganga. The Bhagirathi river basin, a major river basin in Northern India and requires proactive management of water resources due to flood severity in this region. The Soil and Water Assessment Tool (ArcSWAT) was used in this study for setting up a watershed model for the simulation of streamflow in the basin. SWAT-CUP (SWAT-Calibration and Uncertainty Program) that allows calibration and global sensitivity analysis with the Sequential Uncertainty Fitting (SUFI-2) technique was used in this study.

The SWAT model was calibrated from 2000–2010 with two years warm-up period (2000–2001) and validated from 2011-2013. The feasibility of the model was reported based on R^2 and NSE (Nash Sutcliffe efficiency**)**. These parameters together indicate the strength of the calibration-uncertainty analysis of the SWAT model. During calibration, the R^2 and NSE values were obtained as 0.87 and 0.83, respectively, while during validation, the R^2 and NSE were found as 0.76 and 0.71. After the calibration and validation, global sensitivity analysis was done to find the most sensitive parameters of the basin. The result shows the CN2 (Curve number) was found most sensitive parameter. As per the statistical parameters of this study, the SWAT model can be efficiently used in the Bhagirathi river basin for managing droughts and floods, water management for agriculture, and planning for soil & water conservation structures.

Keywords: Hydrological modeling, calibration, validation, sensitivity

Chapter 1

INTRODUCTION

1.1 General

Water and land are two crucial natural resources; as the entire life system is dependent on them. Water resources on earth cannot be modified, but they can be controlled. The impacts and distribution of water issues may be minimized by handling supplies in two ways: by increasing the available supply and reducing the excessive demands and eliminating the losses. But this control isn't as simple as it seems and involves numerous factors together with environment (temperature, precipitation), population, settlements, use, economic factors, and much more. From a hydrological viewpoint, the various stages of the hydrological cycle in the river basin/watershed depend on the various natural factors and human influences. The river basin or a watershed apart from being a hydrological unit but also a socio-political-ecological unit that plays a key role in deciding the health, social and economic protection thereby providing life support services to rural citizens (Wani et al., 2008).

The population of India is 16% of the world's population and it covers approximately 2% land area of the world whereas it has only 4% of the total available water in the world. The availability of surface water in India, during 1991 and 2001 was 2309 and 1902m^3 per capita respectively. However, it has been projected that per capita surface water availability is likely to be reduced further to 1401 m^3 and 1140 m^3 by the years 2025 and 2050, respectively. The per capita water availability in 2010 was 1545 m^3 against the 6042 m^3 available in 1951 (Rakesh Kumar et al.,2005).

The presence of ancient civilizations on the banks of broad rivers shows the significance of water as a tool for farming, manufacturing, transport, and domestic needs, including financial, leisure, and aesthetic pleasures. Over time, several of these ancient sites also developed with rich human life, growing into modern-day settlements and mega-cities. Owing to the large population migration to these cities, a multitude of water problems are currently confronting these cities. Each area has its specific problems of water quality and quantity, depending on its climatic, geographical, geological, and social situation. Climate change and global warming are expected to change the trend of weather across the globe. Modeling research undertaken for the 2050s has estimated that the global flow of fresh water is expected to witness a paradigm change (Alcamo et al., 2007). Surface water and groundwater are two of the major reservoirs of water storage. Over-exploitation of these water storages has exacerbated resource degradation. Managing demand and supply with the guarantee of good water quality is a great deal today. The increased water demands can have a considerable effect on future water supplies unless there are some strategies to control the overexploitation of the resource (Castilla et al., 2019) Water resource management is therefore essential for the integration of all environmental, social, and economic concerns within the river basin or a watershed for maintaining the optimum balance of sustainable benefits for future generations and societies.

The understanding of the hydrological cycle is important in planning the water resources management in any river basin. The hydrological cycle explains the concentration and circulation of water between the biosphere, atmosphere, lithosphere, and hydrosphere. Water travels from one source to another by phenomena such as evaporation, condensation, precipitation, absorption, drainage, infiltration, sublimation, transpiration, melting, and groundwater movement (Moustafa T., 1992). About 91% of the evaporated water is transferred back to the ocean basins through precipitation. The remaining 9% is distributed across landmasses to regions where precipitation is caused by climatological causes. The schematic showing the various processes of the hydrological cycle is given in Figure 1.1.

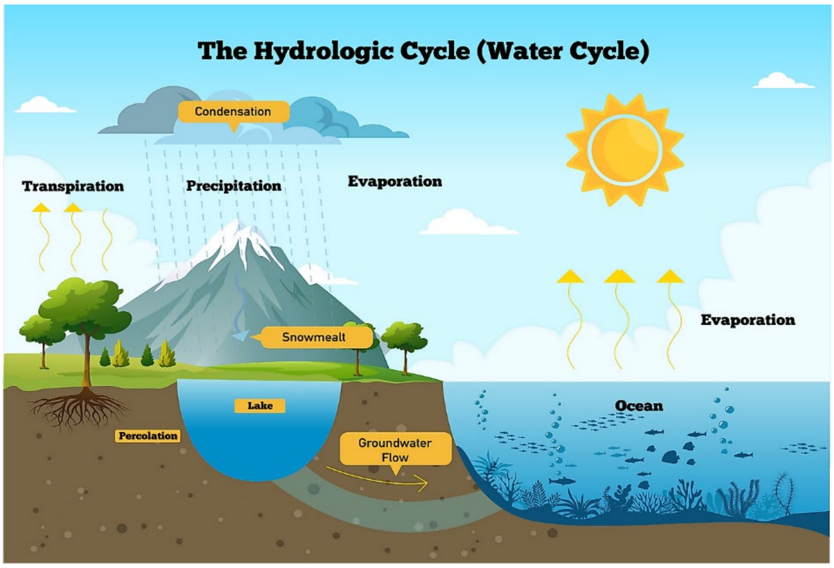


Figure 1: Process of the hydrological cycle

1.2 Need of Study

Proactive management of all the natural resources is the requirement of time in the wake of the development and rising need of the population. Water resources are generally managed by a watershed area as an initial component. A natural hydrogeological unit restricted by a ridgeline consist of a one outlet is known as the watershed. River runoff is very important factor of water resource management. Offline uses and real-time operational both processes are included for planning. Corresponding runoff generation and rainfall are the most significant hydrological progressions that depend on various factors i.e., climatic, physiographic and biotic. The Rainfall-runoff (R-R) modeling of any river basin is a very challenging job for engineers and experts. The Rainfall-runoff (R-R) modeling is nonlinear composite results of various hydrological constraints, i.e., rainfall, infiltration rate, geomorphology of basin, evaporation, depression storage, surface water and groundwater flows which are very problematic.

Hydrological modeling may play a substantial role to overcome the above stated problems. All the hydrological models are shortened mathematical depictions of the physical world had been working, with numerous enhancements, to achieve precise runoff estimations. The main fundamental of hydrological modeling is the relation between model and input data. The current advancement in technology provides powerful pre and post hydrological models

Various pre and post hydrological models are developed through the advancement in the technology by GIS data connecting with spatial or non-spatial data which brings a comprehensible modeling atmosphere.

1.3 Objective of the study

The main aim of the study was to develop a hydrological model for the simulation of streamflow of the Bhagirathi river up to the tehri dam by using ArcSWAT. To fulfill this aim, the following objectives were accomplished.

- To prepare the input database required by ArcSWAT using ArcMAP.
- To set up an ArcSWAT hydrological model for the Bhagirathi river basin.
- To check simulated swat output by SWAT OUPUT VIEWER.
- Calibration, validation, and sensitivity analysis of the model by using SUFI-2 in SWATCUP.

1.4 Thesis Organization

Chapter 1: Introduction

This chapter presents a short discussion of the study and also deals with the need for study, objectives, and scope of the study to accomplish the aim of research work**.**

Chapter 2: Literature Review

This chapter presents the details about hydrological modeling and the various methods and usage of hydrological modeling. The last section of this chapter deals with previous studies on hydrological modeling.

Chapter 3: Study Area

This chapter deals with the characterization of physiological and climatological conditions and the effects the land and soil conditions have on the watershed.

Chapter 4: Methodology and SWAT Input

This chapter describes the entire procedure carried out for the hydrological modeling. The data requirements and acquisition; step by step use of input data in the SWAT model.

Chapter 4: SWAT Output Analysis

This chapter presents the detailed analysis of swat outputs and the results are presented in the form of charts and graphs. This chapter also deals with key findings during analysis.

Chapter 5: Conclusions and Future Recommendations

This chapter presents major conclusions arising from the study. Recommendations and future scope of work are also discussed.

Chapter 2

LITERATURE REVIEW

This chapter to commence with introductory information about hydrological modelling. Secondly, Brief description about SWAT and its advantages and limitations are described. Finally, former studies concerning the subjects are summarized.

2.1 Hydrological Modeling

A simplified definition of the hydrological cycle which represents the natural system is used for hydrological modelling (Jain et al., 2017). The rainfall-runoff model is a statistical representation of the rainfall-runoff relationship for a catchment area. More specifically, using the rainfall runoff models, the surface runoff hydrograph can be generated as a response to rainfall input. The surface runoff depends on different factors, such as the size of the catchment, the length of the catchment, the slope of the catchment and the time of concentration. The rainfall-runoff cycle is a complicated process as it is affected by a variety of factors such as rainfall distribution, evaporation, transpiration, abstraction, topography and soil conditions. When rainfall occurs on the surface of the earth, it starts to flow depending on the soil conditions, the topography and the humidity. It is seen that infiltration is a very critical factor responsible for the translation of rainfall to runoff (K.J. Beven, 2011) When the river basin comprises of plain areas, the infiltration tends to rise resulting in lower runoff and vice versa for catchments with steep slopes.

Early hydrologists computed the surface runoff with basic computational techniques using minimal data. The first commonly used runoff method was the Logical Method published by Thomas Mulvaney in 1851, which used the precipitation rate, the drain zone and the runoff coefficient to evaluate the maximum discharge in the river basin (Beven, 2012; Xu, 2002). More recently, the unit hydrograph concept was developed to conceptualize the response of the catchment to a rain event based on the superposition theory. (Beven, 2012; Todini1988; Xu, 2002). The unit hydrograph has made it possible to differentiate baseflow and direct runoff from streamflow. Most of the watersheds and river basins in India are ungauged and minimal data are available from the state and central departments concerned. Under this situation, the rainfall-runoff model must be established for a river basin in order to model the hydrological processes which can eventually be used to predict runoff from the basin as well as its sub-basins. The construction and management of water resources in the river basin can be planned using a relevant hydrological model. All hydrological models are the idealization of the real-world structure into models. It is an effective tool for predicting runoff from the amount of rainfall in the watershed. Many researchers have developed a variety of rainfall-runoff models. The well-known rainfall-runoff models include Rational Formula (Armitage et al., 1969), Soil Conservation Service-Curve Number Method (SCS CN) (Maidment, 1993) and Green & Ampt Model (Green and Ampt, 1911).

People have established a distinctive capability to recognize and evade places wherever water will flow or collect when it rains. This capability has focused to a sense of competence which is very useful but also on other hand infrequently mistaken with terrible penalties. Numerical approximation of the possibility and amount of blizzard is a more modern-day responsibility and the forecasting of forthcoming hydrologic conditions is what at this time will be called *computational hydrologic modeling*.

The hydrological models predict flux, flow, or variation of water storage over the time inside one or more parameters of the usual hydrological cycle. Whereas the ultimate equations which governs the water flow are well understood, these flows are naturally complex as they arise in an environment which is practically collectively confronts modest explanation (Jain and Singh, 2017). This is mainly because of conglomerations which occur transversely a extensive series of time and space scales. These conglomerations are significant since they greatly affect the various factors i.e., velocity, flow path, residence time, and also can make response thresholds which also be subject to velocity and flow path. Meanwhile mathematical inventions are intended to forecast the state velocity, pressure, density, etc. at each point of the study area. The entire flow field can be solved by means of sophisticated but well described mathematical equations. The Hydrological models can be classified as:

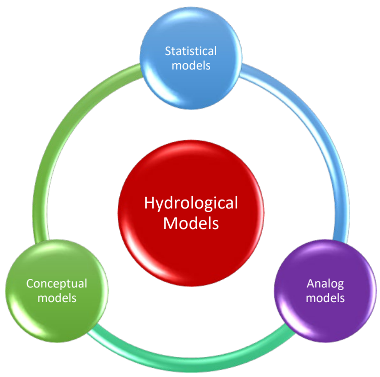


Figure 2: Types of hydrological models

2.1.1 Conceptual model

Conceptual models, which are often used to characterize the important components such as , events, processes and feature which narrate hydrological inputs to outputs. These parameters designate the momentous functions of the system of interest, and are frequently built using units (stores of water) and relations amid these units i.e., flow or flux. The conceptual models are attached with the scenarios to designate precise actions.

2.1.2 Analog model

Prior to the invention of computerized models, hydrological modeling was done by analog models to simulate flow and transport systems. Contrasting to mathematical models which uses calculations and equations to define, forecast, and accomplish hydrological models, analog models use non-mathematical methods to predict the hydrological factors.

2.1.3 Statistical model

Statistical model is also a mathematical model which is often used in hydrological modeling to define the data and relationships between data. Many researchers developed empirical relation among observed variables and also find trends in historical data which helps in forecasting possible storm or drought by using statistical methods,

2.2 Most Popular Hydrological Models

- **MODFLOW**

MODFLOW is USGS's developed hydrologic model. It is a block centered finite difference code for steady state and transient simulation of two dimensional, quasi three dimensional, and fully three dimensional saturated, constant density flow problems in combinations of confined and unconfined aquitard aquifer systems above an impermeable base.

- **SWAT**

The Soil Water Assessment Tool commonly known as SWAT, first launched in the 1990's. SWAT is a river basin-scale model that simulates surface and groundwater quality and quantity and also simulate the impacts on environmental of land use change, land use management, and climate change of small watersheds. In the processing of hydrological modeling, the SWAT model first splits the watershed into sub-basins, and then further into HRU's (hydrologic response units). HRU classification is based on land use/ land cover, soils distribution in the basin. Total runoff of the whole watershed is simulated by accumulation of each HRU's runoff which is calculated separately. The SWAT model is very popular for regional hydrological studies, impact of climate change studies, and in water quality studies of various resources. The SWAT model is widely used due to its capability to perform on numerous GIS platforms like including Map windows, ArcMAP or QSWAT. SWAT model can also be combined with the MODFLOW which is a groundwater modeling software.

- **WEAP**

WEAP (Water Evaluation and Planning) is a software tool that uses an integrated approach to water resources planning. Allocation of limited water resources between municipal, agricultural and environmental uses, now requires the full integration of demand, supply water quality and ecological considerations. WEAP aims to include these issues into a practical yet sturdy tool for integrated water resources planning.

- **MIKE HYDRO BASIN**

MIKE HYDRO Basin is a highly versatile, map-based decision support tool for integrated water resources analysis, planning and management of river drainage basins. It is designed to study water sharing issues at interstate or international level and between various competing groups of water users. It is a simple product for investigating options and making reliable decisions.

2.3 The SWAT Model

The SWAT model is a physically-based, semi-distributed catchment model developed to quantify impacts of land management practices on surface waters by simulating, infiltration, percolation, plant growth, runoff , and nutrient loads (Neitsch et al., 2011). This model is capable of continuous simulation over a long period. In the SWAT catchment processes are demonstrated in two phases. First stage is the land phase which covers the loadings of sediments, water, pesticides and nutrients from all sub-basins to the main stream, and covers all the processes in the main channel to the catchment outlet **(Neitsch et al., 2011).** In the SWAT model catchment area is further separated into sub-basins and HRUs (Hydrologic Response Units). In the present study SWAT, 2012 was used for modeling. There are two methods in SWAT for estimating surface runoff (i) Modified SCS curve number (CN) and (ii) Green-Ampt infiltration method. SCS-CN method for estimating surface runoff volume was used in the present study. SWAT model has three methods for estimating potential evapotranspiration, Penman-Monteith (PM), Hargreaves meth, Priestley-Taylor method . We used the Hargreaves methods method for estimating evapotranspiration. Kinematic storage model is used for simulation of the lateral flow. The return flow is simulated by making a shallow aquifer (Arnold et al., 1998). In this model, water balance Eq., which governs the hydrological balance is expressed as (Neitsch et al., 2005):

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{sweep} - W_{gw}\right)$$

Where:

- SW_t: Final soil water content (mm)
- SW_0: Initial soil water content on day i (mm)
- Q_{surf}: Surface runoff on day i (mm)
- R_{day}: Precipitation on day i (mm)
- E_a: Evapotranspiration (E_T) on day i (mm)
- W_{gw}: Return flow on day i (mm)
- W_{seep}: Water entering the vadose zone from the soil profile on day i (mm)

The SCS curve number is defined with the subsequent equation:

$$Q = \frac{(P - I_a)^2}{\left(P - I_a\right) + S}$$

Where:

- Q: Depth of runoff (mm)
- P: Effective precipitation (mm)
- S: Maximum potential retention
- I_a: Initial abstraction of water in (mm),
- I_a is the function of S.

Therefore,

$$I_a = \lambda S$$

Where:

λ=0.2. Therefore, I_a=0.2 S

Hence, by integrating both Eqs. we have;

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

The runoff occurs when the value of P is greater than 0.5 S. Maximum retention potential of S is associated to the dimensionless parameter SCS curve number (CN) using the following equation.

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

The SCS curve number (CN) is subjected with permeability of soil, land use, soil–water conditions and infiltration. The SCS curve number value can be described by the three conditions (wet, moist, and dry). The SWAT output develop and validate various parameters i.e., streamflow, surface runoff, evapotranspiration, reservoir water balance, deep aquifer, interception storage and infiltration.

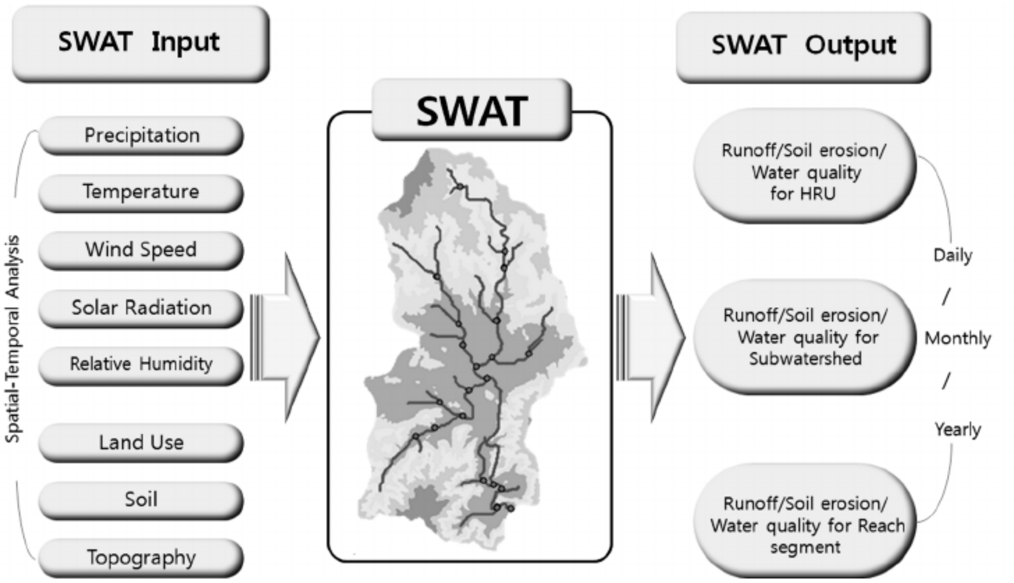


Figure 3: SWAT Model Input and Output

2.3.1 Calibration and uncertainty analysis:

Calibration is mainly subjective and therefore confidently accompanies the uncertainty of the model output. When estimating parameters through calibration, problems arise when extrapolating the measured output variables of the model (such as river flow, sediment concentration, nitrate content, etc.) to the physical system. This is striking because the straight quantity of parameters describing the physical system is time consuming, expensive, tedious, and often has inadequate applicability. Main objective of calibration is to characterize model, mainly through uncertainties to the parameters that fit the data to satisfy our assumptions as well as other prior information (Abbaspour et al.).

Uncertainty analysis is carried out statistically, because almost all predictions will have small errors. Hydrological models are interpretations of authenticity, and the inferences are usually statistical in nature. Moreover, since one can only simulate a limited number of data and because physical systems are usually modeled by continuum equations, no calibration can lead to a single parameter set or a single output.

Uncertainty analysis refers to the circulation of all the model input uncertainties to the model outputs. Input uncertainties can arise due to the deficiency of knowledge about model inputs such as climate data, soil data, and land-use land-cover. Identification of all acceptable model solutions in the face of all input uncertainties can, therefore, provide us with model uncertainty expressed in SWAT-CUP as 95% prediction uncertainty (95PPU) which is standard deviation of the measured data. It signifies the width of the uncertainty interval and it must be as low as possible. The p-factor is the proportion of data associated by the 95PPU band. The value of p-factor fluctuates from 0 to 1. P factor value nearer to 1 indicating a very decent model performance and excellent efficiency. The r-factor is the ratio of average width of the 95PPU band and the standard deviation of the measured variable, it fluctuates in the range 0– infinity (Abbaspour et al., 2007; Yang et al., 2008). The p- and r-factors both are strictly connected to each other.

2.3.2 SWAT Applications

The Soil and Water Assessment Tool (SWAT) model has emerged as one of the most widely used water quality watershed- and river basin-scale models worldwide, applied extensively for a broad range of hydrologic and/or environmental problems. SWAT has been used for a number of applications in the last decade. Many of the applications have been driven by the needs of various government agencies that require direct assessments of anthropogenic, climate change, and other influences on a wide range of water resources or exploratory assessments of model capabilities for potential future applications. One of the first major applications performed with SWAT was within the Hydrologic Unit Model of the U.S. (HUMUS) modelling system, which was carried out to support the USDA analyses of the Resources Conservation Act Assessment of 1997 (Gassman et. al., 2007). The system was used to simulate the hydrologic and/or pollutant loss impacts within each of the 2,149 U.S. Geological Survey (USGS) 8-digit Hydrologic Cataloging Unit (HCU) watersheds. Other applications in the US are reported by Mausbach and Dedrick (2004), Borah et. al. (2006), Shirmohammadi et. al. (2006), Benham et. al. (2006), etc.

2.4 Previous studies using SWAT Model

V. Pisinaras et al. (2010) proposed a methodology to apply SWAT in combination with GIS technology and used it as a management tool for Mediterranean basin in Northeast Greece. The study aims to evaluate ability of the model to simulate management scenarios for the region. The study area is the Kosynthos river basin which is located in Thrace District in north eastern Greece. Data collected includes river flow and concentration of nitrates and soluble phosphorus. The river flow was measured using flowmeter while spectrophotometry was used to measure concentrations of nitrate and phosphorus.

In this study AVSWATX was used which is a version of the SWAT model and it is the integration of the latest version of Soil Water Assessment tool (SWAT 2005) with ArcView. Pre processing of the data is done by applying ArcView GIS functions which comprises of creation of river network, sub basins and basin area. In this study a 50* 50m resolution was used. The calibration of the model was done using field measurements collected at four monitoring stations. The accuracy of the predictions from verification was determined with NOF Computation equation, NSC equation, ¥ and R^2 values for verification period.

The study concluded that the application of SWAT model with GIS technology proved to be very effective in the evaluation of management alternatives for land use change as well as crop management in rural basins.

Sisay et al. (2017) carried out a study to test and assess the capabilities, performance and limitations of SWAT model in an ungauged urban watershed of Vadodara city of Gujarat. A regionalization approach because the watershed is ungauged. The calibration and validation of the model was done by SUFI-2 algorism using SWATCUP2012. The calibration and validation of model is done by comparing the observed and simulated flow rates at the basin outlet for the time periods 1979–2001 and 2002–2013 respectively. The hydrological model's parameters for ungauged basins are predicted using regionalization method. The ArcSWAT interface requires spatially distributed data (GIS input) which includes Digital Elevation Model (DEM), land use land cover, soil data, and climate data and for calibrating and validating of the SWAT model, data of river discharge and climate was required.

The study concluded that the river discharge and peak flow in ungauged watershed is best predicted by using the regionalization method and for Vadodara ungauged watershed Ratio method of regionalization was used. The outcome of the model indicates good agreement between observed and simulated flow. Therefore, the model is applicable and has strong foretelling ability for the ungauged watershed of Vadodara city.

Uniyal et al. (2015) conducted a study to assess the impact of climate change on the water balance components of a data-starved Upper Baitarani River basin of Eastern India using ArcSWAT model. The study was conducted in Upper Baitarani River basin (1776.6 km^2). The basin is in Eastern India, Odisha (21 to 22.5° N latitude and 85 to 86° E longitude). The study area has varied topography having elevation from 330 to 1120 m and an avg. rainfall of 1534 mm per year most of which occurs during monsoon from June to October. The max. average temperature is in the month of May which reaches up to 34°C and January is the coldest month having average temperature 11°C. The basin was divided in 15 subbasins and 271 HRUs.

This study uses SWAT 2009, which is commonly known as ArcSWAT. The ArcSWAT model was calibrated in SWAT CUP which uses SUFI-2 technique. Daily streamflow data from 1998 to 2003 was used for calibration and two years 2004–2005 were used for validation period. The calibration results show the NSE (Nash-Sutcliffe efficiency) and mean absolute error value of (MAE) of 0.88 and 9.70 m3 /s respectively which is within the acceptable limits. The validation was also done for two years. Then anticipation of climate change was done by using calibrated data. 12 independents and 28 combined area specific climatic scenarios were considered during the study for the climate change assessment on the hydrological parameters of the basin.

L. Singh & S. Saravanan (2020) conducted a study to simulate the streamflow and predict the water balance components using SWAT model for watershed in Mahanadi River basin. This study is important for understanding hydrological responses of watershed that drains into Hirakud dam indirectly and which is the main source of water supply irrigation. The model was developed from 1993 to 2011 using Tropical Rainfall Measuring Mission daily rainfall data and monthly streamflow data. The monthly observed streamflow data for year 1993 to 2003 was used for calibration and for year 2004 to 2011 was used for validation. In this study calibration showed better response than validation. For the study area temporal and spatial variability of water balance components were determined.

The study concluded that there was good treaty between simulated and observed streamflow data. The temporal variability indicates 26% to 50% rainfall loss by evapotranspiration, 13% to 18% rainfall loss by groundwater flow and 15% to 21% loss by percolation. The spatial variability indicates higher surface runoff on southern region because of agricultural land and hilly region and lower groundwater because of tile drainage. The results of this study establish a quantities approach to assess the response of water balance component in watershed which will help in water resource management and in efficient watershed management.

V.K. Bhatt et al. (2016) conducted the study for simulating runoff in micro watersheds of lower Himalayan region of India using SWAT model. The two micro watersheds are Choe with 21ha area and W3B with 70.5ha area. For both the watersheds SWAT model was setup using Arc View-SWAT interface. The model was calibrated by SWAT-CUP 2009 version using Sequential uncertainty fitting. The calibration of the model was done for the period

1973-1978 and 1971-1980.The validation of the model is done for the period of 1979-1981 and 1982-1984 for study area.

The study concluded that the sensitive parameters for Choe watershed were bank storage and saturated hydraulic conductivity and for W3B watershed sensitive parameters were base flow parameters and manning's roughness coefficient. The monthly runoff for both the watersheds shows that observed data matched well with the simulated data. The study indicates reliable estimate of monthly runoff even for micro sheds can be produced using SWAT model.

A.G. Adeogun et al. (2014) conducted a study on the applicability and feasibility of SWAT model interfaced with GIS software (Map Window) to predict the streamflow of watershed located in the upstream of jebba reservoir in Nigeria. The selection of the watershed area was based on the input data availability and predominant role in national energy supply. SWAT model was selected based on its efficiency in predicting different hydrological processes as reported in previous studies. The model inputs include digital elevation map, land use land cover, soil data, and meteorological data. The model was calibrated for time period 1990 to 1992 and validated for 1993 to 1995. To calibrate the model PARASOL (Parameter Solution) method is used which is auto calibration method.

The study concluded that most sensitive parameters for watershed are curve number (CN2), soil evaporation compensation factor (ESCO), threshold water depth aquifer (GWQMN), and soil available water capacity (SOL_AWC). The result shows good correlation with observed data (NSE = 0.72 & R2 = 0.76) for calibration period and for validation period (NSE = .71 & R2= .78). The result shows that if the SWAT model is properly calibrated then it is ideal modeling tool for water resources management policies and watershed level decisions.

Mohd M. S. F. et al. (2015) studied impact of climate change on streamflow in Kuantan watershed by coupling SWAT hydrological model with statistical climate downscaling tools. The performance of the SWAT in assessing the streamflow trend in current and future climate was also evaluated. The model was calibrated for data from 1978 to 1985 and validated for data from 2000 to 2006. SWAT model was calibrated with an R2 value of 0.84 and validated with an R2 value of 0.59.

The study concluded that there is a expected increase in the streamflow by the end of the century predominantly in the month of August & September, the increment percentage will be up to 106% under the RCP 8.5 scenario and almost more than 50% increment in the month of August during the middle term period under both the RCP4.5 and RCP8.5 scenarios. No decreasing trend was found. The study recommended dynamic downscaling technique to address uncertainties that comes from the downscaling techniques and SWAT for planning and management of watersheds.

Ismail Adal Guiamel & Han Soo Lee (2020) conducted a study for simulating watershed of the Mindanao river basin for enhancing the water resource management for hydropower application in Mindanao. SWAT model was used in this study. The input data includes geospatial datasets and weather records at four stations. In this study due to the lack of precipitation data in MRB the precipitation records with global gridded precipitation datasets from NCDC-CPC and GPCC are compared. The study finds that the performance of the model was relatively low for Libungan and Pulangi rivers because of lack of the datasets on dam and water withdrawal in the MRB. Moreover this study highlights the issue of data quality for data scarcity and precipitation for river flow and water resource management in MRB and shows how the data quality and scarcity can be overcome.

Narsimlu et al. (2013) carried out a study to evaluate the impacts of future climate change on water resources of upper Sind River Basin using SWAT. For uncertainty analysis and calibration of model Sequential uncertainty fitting (SUFI-2) algorithm was applied. The studies are conducted in The Upper Sind river catchment which is one of the main sub basins of the Sind River and it becomes one of the tributaries of Yamuna River. The study area falls into semi-arid to humid climate zone. The annual rainfall varies from 800 mm to 1,100 mm. The evapotranspiration was 482 mm and mean annual temperature was 21 degree. In the study region the main land use was agriculture.

In this study climate projections are used which are based on PRECIS (Providing Regional Climates for Impacts Studies). PRECIS was developed in UK Meteorological Office by the Hadley Centre. The PRECIS RCM was based on HadCM3 climate model's atmospheric component. The SWAR 2009 was used in the study.

This study predicts that the average annual streamflow may upsurge significantly in future midcentury phase and end century period. It was also predicted that there will be increase in both baseflow and surface runoff. The paper also indicated that there would be increase in average annual streamflow in monsoon season by 16.4% and 93.5% in midcentury and end century respectively. Lower streamflow circumstances might arise due to climate change during the off-season in future. Due to projected climate change in future the water balance of the Upper Sind River basin would alter considerably, and further it would affect the accessibility the patterns of streamflow and water resources. The study concluded that there will be drastic rise in streamflow during monsoon season, but due to the projected future climate change this will decrease during non-monsoon season.

Abbaspour et al. (2009) analyzed the impact of climate change on water resources in Iran. Hydrological model of Iran was used to predict the impacts of future climate change on the water resources of the country. The study was done in Iran which is located between 25 and 40 north latitude and 44– 63 east longitude and it is a country where there is large variation of climatic from north to south. The southern part was dry with large water scarcity, frequent droughts, and a large reliance on dwindling groundwater resources and the northern part of was quite wet with frequent floods. The effect of climate change was studied at a subbasin level integrated hydrological Soil and Water Assessment Tool (SWAT) model was used. The changes in SEVERAL components of the water balance including evapotranspiration and precipitation distribution, , soil moisture, river discharge and aquifer recharge were considered and then these variables were used to calculate the changes in water resources w.r.t blue water i.e., river discharge plus aquifer recharge and green water i.e., soil moisture plus evapotranspiration.

In this study the hydrologic model was produced using SWAT MODEL (Soil and Water Assessment Tool) and calibration was done from year 1980 to 2002 by using daily river discharge and annual wheat yield data at a subbasin level. For time period of 2010–2040 and 2070–2100 future climate scenarios were created from the Canadian Global Coupled Model (CGCM 3.1) by downscaling 37 climate stations across the country for scenarios A1B, B1, and A2. To study the effect of future climate on precipitation, green water, blue water, and yield of wheat across the country the hydrologic model was applied to this time period.

From the studies it was found that for future scenarios the wet regions of the country will receive more rainfall while dry regions will receive less. It was predicted that more frequent and larger-intensity floods will occur in the wet regions and more prolonged droughts will occur in the dry regions. The crop yield analysis shows insignificant rise in winter wheat yield for most provinces. By running SWAT model for 506 sub basins across the country impact of change in climate on numerous hydrological components was provided and these analyses are very valuable in judicious planning of water resources management and crop production for future.

Middelkoop et al. (2001) studied the result of climate change impact on hydrological regime and water resources management in the Rhine basin. In this study various detailed hydrological models with daily and hourly time steps are developed for sub-catchments of the Rhine basin along bottom-up line and a water balance model for the whole Rhine basin has been developed all along a top-down line. This will calculate monthly discharges and was tested on the size of the main tributaries of the Rhine. The results of UKHI and XCCC GCM-experiments were used to calculate the effect of climate change on the discharge regime in various parts of the Rhine river basin using the set of models. The study area covers an area of 185,000 km^2 and this area was subdivided into three main hydrological area which consist of the Lowland area, Alpine area, and the German Middle Mountain area.

The RHINEFLOW model and the sub-catchment models are developed using a comprehensive database which d contains the meteorological, topographical, hydrological and land use conditions of the whole Rhine river basin on a very detailed scale using a GIS (Geographic Information System). WaSiM-ETH Model was used for the Catchment, which is a distributed model with an hourly time step. Runoff was calculated using the WaSiM-ETH model. The IRMB model (Integrated Runoff Model – F. Bultot) which was developed by the Hydrology Section of the Royal Meteorological Institute of Belgium for simulating the components of the water cycle in medium sized catchments area was used. For calculating snow accumulation and snow melt processes Saar model was used and Flood routing was done using the modified pulse method. Vecht Model, a lowland model is used which describes processes that are directly and indirectly influenced by climate. The construction of climate change scenarios is based on two General Circulation Models (GCM), the Hadley center's high-resolution 11-layer atmospheric GCM (UKHI), and the Canadian CCC model.

The study shows that same trend was indicated by all the models, higher winter discharge was observed due to increased snow-melt and intensified winter precipitation, and lesser discharge in summer was observed as a result of reduced winter snow storage and increased evapotranspiration. There will be high flood risk during winter because of hydrological changes, while inland navigation and water availability for agriculture and industry will be adversely affected due to low flows during summer. The study also found that change in climate impacts various socio-economic sectors as winter tourism in the lower winter sport areas maybe threatened due to higher temperature. The policy of no regret and flexibility was suggested in water management planning and design where preventive measures in response to impacts of climate change are undertaken in combination with ongoing activities.

R. Singh et al. (2016) conducted a study in Roorkee, to analyze the "Potential Impact of Climate Change on Rainfall Intensity-Duration-Frequency Curves. The study area is located in state of Uttarakhand in Haridwar district. Extreme variation of temperature in summer and winter is observed in this area. Precipitation data used for various models includes GCM output data and previously observed data.

The previous year's data was obtained from Department of Hydrology in Indian Institute of Technology Roorkee where self-recording rain gauge are used to record data. For projection period and baseline period, the GCM data was obtained by downscaling the selected models of GCM and all four scenarios from CIMP5 portal. The selection of model depends on the availableness of grid resolution and four scenarios of models. In this study five models were adopted which includes MRI-CGCM3, MIROC5, CCSM4, CSIRO-Mk3.6.0, and NorESM1-M. From the observed sub daily rainfall series IDF curves were prepared by assuming Gumbel distribution to fit the series. For GCM simulations under four RCP scenarios, the future sub daily rainfall series was developed using equidistant quantile matching. The change in the intensities of rainfall was assessed by comparing intensities corresponding to return period and duration of interest from the historical observations and future created sub daily precipitation series. It was found that the future intensities constantly increasing with magnifying RCP scenario for every GCM model. It was observed that for all models there is increase in precipitation intensity for all return period and durations.

For determining performance of models split sample analysis was carried out. On the basis of values of R2 the performance order of various models is CSIRO-Mk3.6.0, MIROC5, MRI-CGCM3, NorESM1-M AND CCSM4. CSIRO-Mk3.6.0 includes all forcing which is the reason for best performance in validation. In all the models CCSM4 showed highest changes but its performance is lower as compared to other models. The study concluded that future intensities will rise with higher percentage for lower return periods. It was also predicted that there will be increase in intensities in future corresponding to all durations but for lower duration intensities the percentage increase would be higher as compared to higher duration intensities. It concluded that in future there will be increase in intensity of more frequent events than rare events.

Chapter 3

STUDY AREA

3.1 Bhagirathi River Basin

3.1.1 Location

Gaumukh Glacier is the origin of the Bhagirathi River, from there it flows about 193 km up to the Devprayag and merged with the Alaknanda river to form the River Ganga. It lies in the state of Uttarakhand and is 205 km long. The basin lies between 78° 28' to 78° 98' east longitudes and 30° 43' to 31° 47' north latitudes. The total area of the watershed is 2514.254 km^2.

Figure 4: Location of Bhagirathi River Basin

3.1.2 River System

The Bhagirathi river's headwaters formed at the Gaumukh, which is allocated at 3892m above mean sea level, at the bottom of Khatling and Gangotri glaciers in the Garhwal region of the Himalayas. Numerous tributaries joinis the Bhagirathi river i.e., Kedar Ganga at Gangotri, Jadh Ganga at Bhaironghati, kakora Gad and Jalandhari Gad near Harshil, Siyan Gad near Jhala, Asi Ganga near Uttarkashi and Bhilangna River near Old Tehri.

3.1.3 Topography

The basin lies on the southern slope of the Himalaya range. Major Northern portion of the river basin are part of Greater Himalayan ranges also known as Himadri, which is covered by the high Himalayan peaks and glaciers, while the southern parts of the basin is densely forested with varying elevation from 3700m to 4100m. The elevation of the area where Bhagirathi rises is around 3892 m.

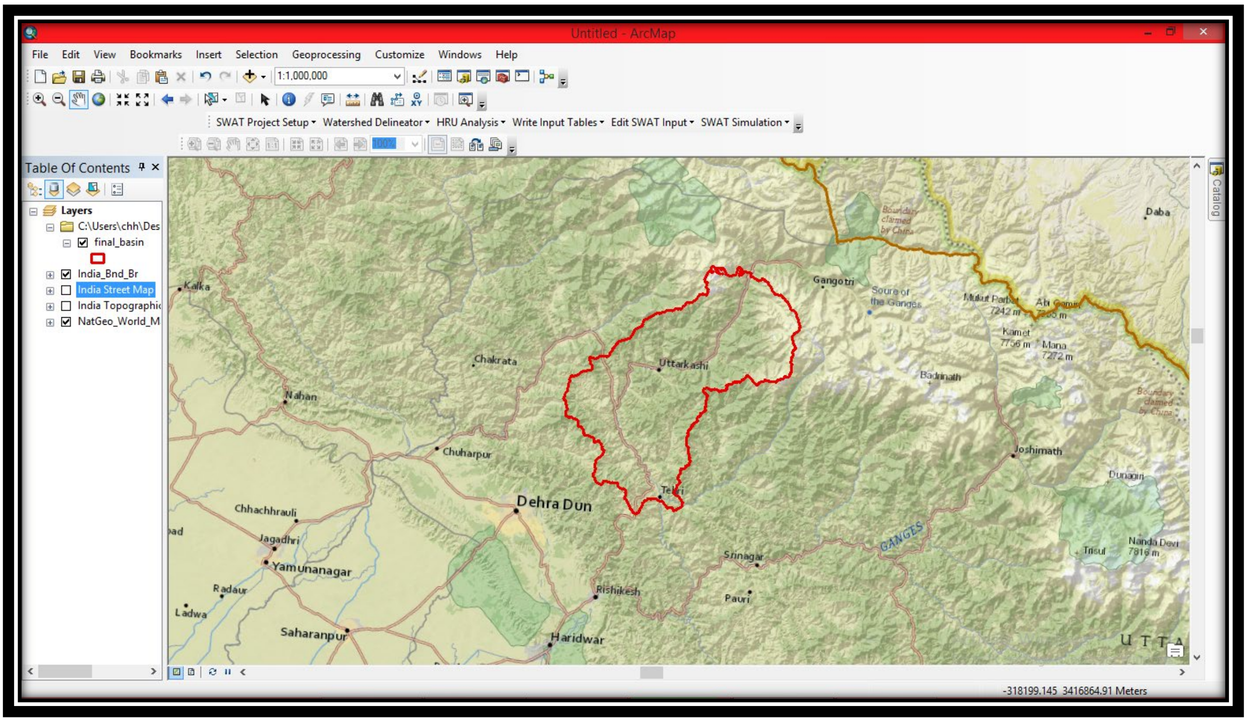


Figure 5: Shape File of Bhagirathi River Basin

3.1.4 Climate

The weather of Uttarakhand, northern state of India is moderate, noticeable seasonal dissimilarities in temperature but also affected by tropical monsoons. Like other northern states coldest month of the year in January and July is the hottest month. In the southeast parts of state, May is the warmest month, with daily temperatures about 38 °C from a low around 27 °C. Most of the basin's approx. 1,500 mm of annual precipitation is brought by the southwest monsoon, which blows from July through September. In the northern portion of basin, 10 to 15 feet (3 to 5 meters) of snowfall is very common between December and March.

3.1.5 Soil and Land use

The basin mainly consists of two types of soil in which both are vulnerable to soil erosion. Northern part of basin has the soil ranges from gravel to stiff clay. Southeastern part of consit of the soils which are very rich, clayey loams, mixed to varying degrees with fine sand and humus. Basin has a extremely diverse topography, glaciers, with snow-covered peaks, a number of large and small valleys, river streams, evergreen forests, and a few areas of dusty plains in the south.

Figure 6: Typical View of Bhagirathi River

Chapter 4

METHODOLOGY AND SWAT INPUT

4.1 The SWAT Model

SWAT model mainly requires four types of data: a digital elevation model (DEM) of the study area, land use data, soil data, climate data. DEM, land use, soil, weather and hydrology database. All the collected data was used in swat model set up process. After the successful execution of swat model, the model was calibrated and validated in SWAT-CUP.

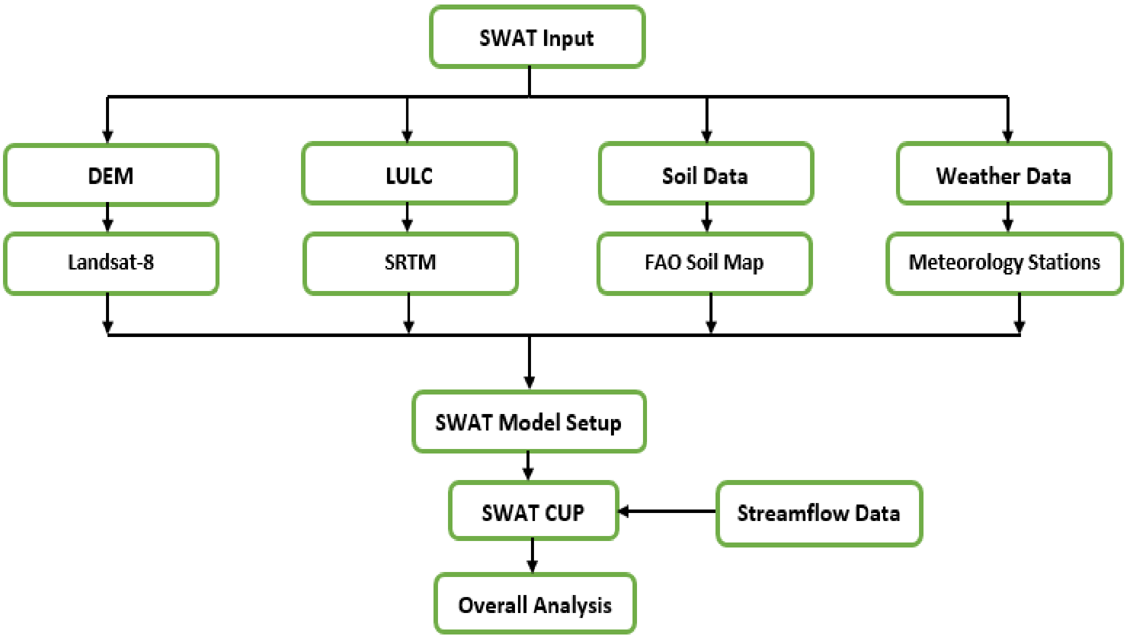


Figure 7: Project Methodology

4.2 Input Data

The utmost significant phase of hydrological modelling is the data collection. Since enormous amount of data is required, the study area was chosen consequently with the availability of data.

4.2.1 Digital Elevation Model (DEM)

Digital Elevation Model is the raster data contains an array of pixels which comprising the elevation values. The topography of the basin is described by the digital elevation model which labels the elevation of the definite area at a precise spatial resolution. For the present study, a DEM of resolution of 90*90 m was obtained from SRTM website presented in figure 8. WGS 1984 UTM Zone 43 N was used for coordinate projection and further processed in ArcMAP to accomplish the actual basin DEM.

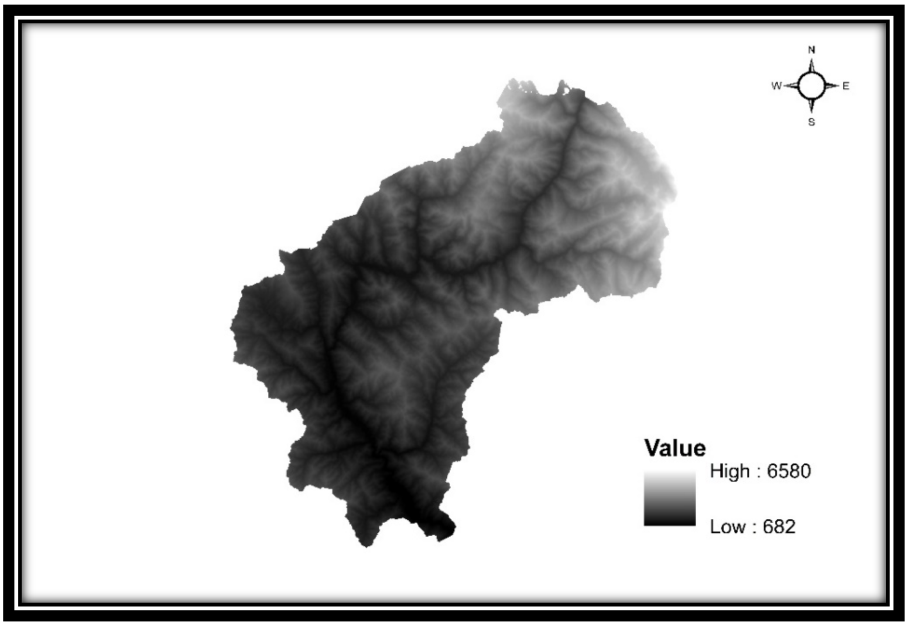


Figure 8:Digital Elevation Model of Study Area

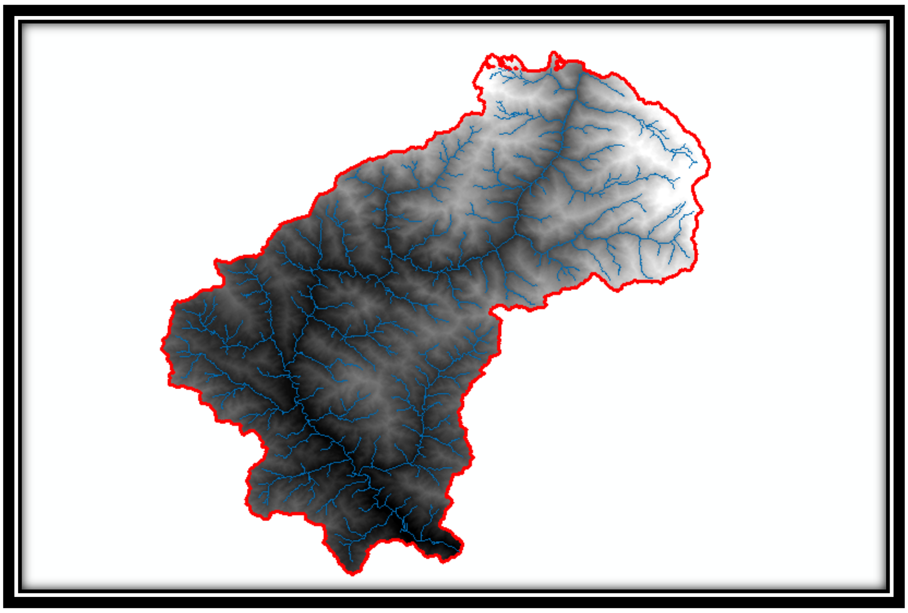


Figure 9: Stream Network Map of Study Area

4.2.2 Land use/land cover (LULC)

Land use/land cover is one of the most substantial parameters that distress various factors i.e., runoff, soil erosion, and evapotranspiration in the basin. The LULC use map is obtained from the processing of satellite images of Landsat 8 of 2020 in ArcMap of spatial resolution of 30 m. Reclassification of the LULC of the area was done by unsupervised classification and it is shown in Fig.10. LULC classes were recognized and reclassified to match the SWAT LULC database which are; snow cover, forest cover (mixed), barren land, built-up area (low density), and water body.

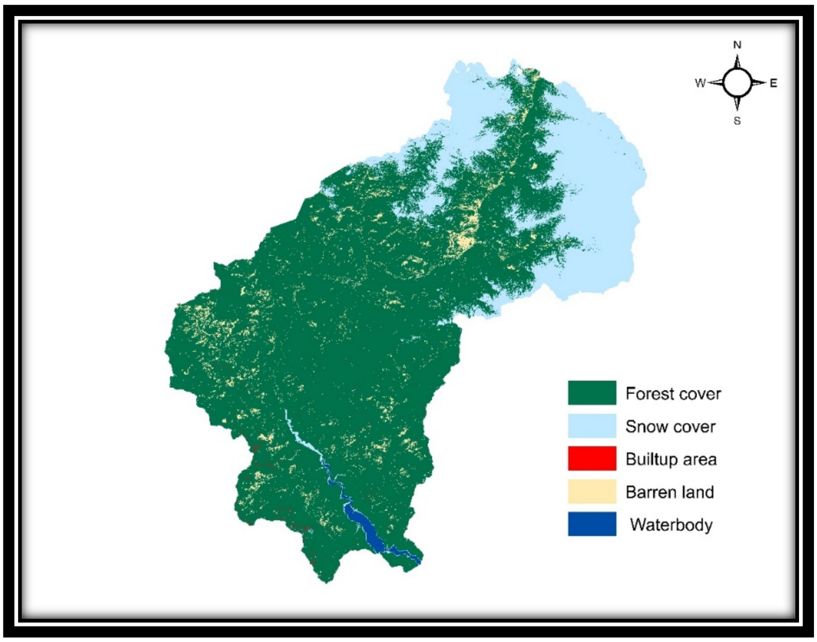


Figure 10: LULC Map of Study Area

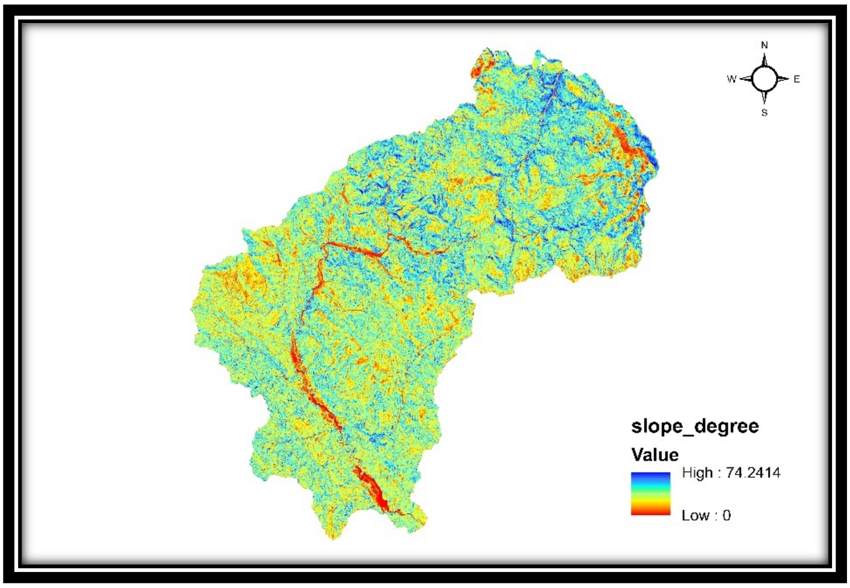


Figure 11: Slope Map of Study Area

4.2.3 Soil data

The soil map of the basin was acquired from the World Soil Database which was developed by the Food and Agriculture Organization of the United Nations (FAO-UN). This Database provides the soil map of the world. The soil map of the study area was clipped and processed. This study identified two different soil classes in the study area that have been shown in Fig. 12.

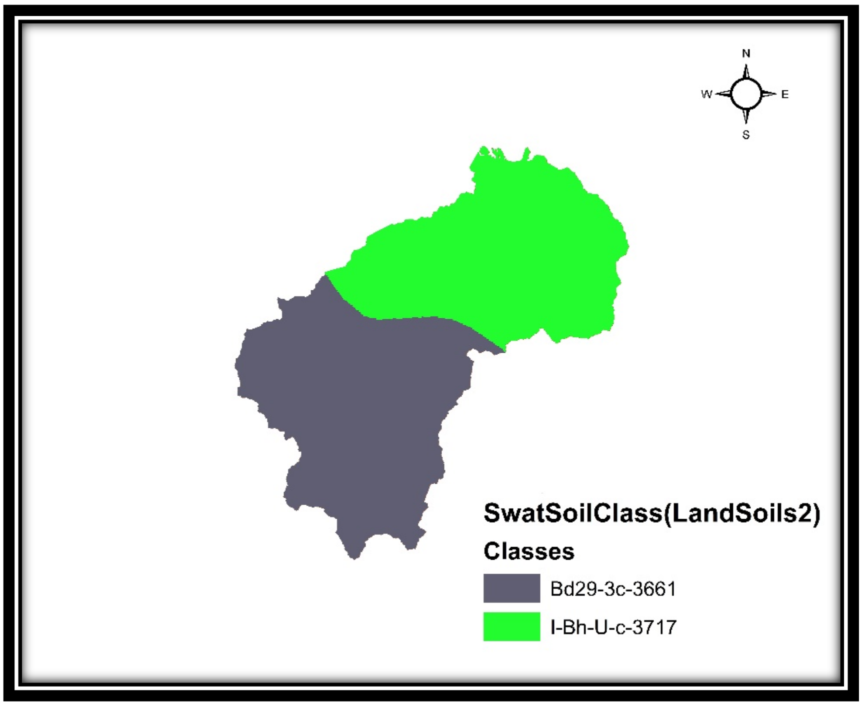


Figure 12: Soil Map of Study Area

4.2.4 Weather data

SWAT requires daily and monthly meteorological data that can either be acquired from a measured data set or generated by a weather generator model. Precipitation, min. and max. temperature, relative humidity, solar radiation and wind speed are climate variables used in this study for the period 2000–2014. All this data was found from the NCEP and CFSR website. https://globalweather.tamu.edu/#pubs

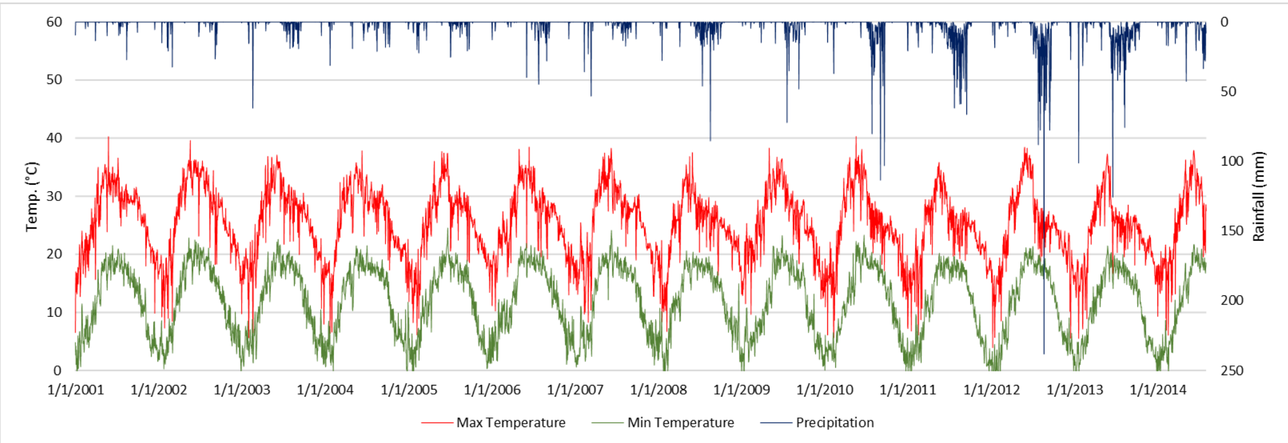


Figure 13: Daily variation of Temperature and Rainfall at Tehri Station

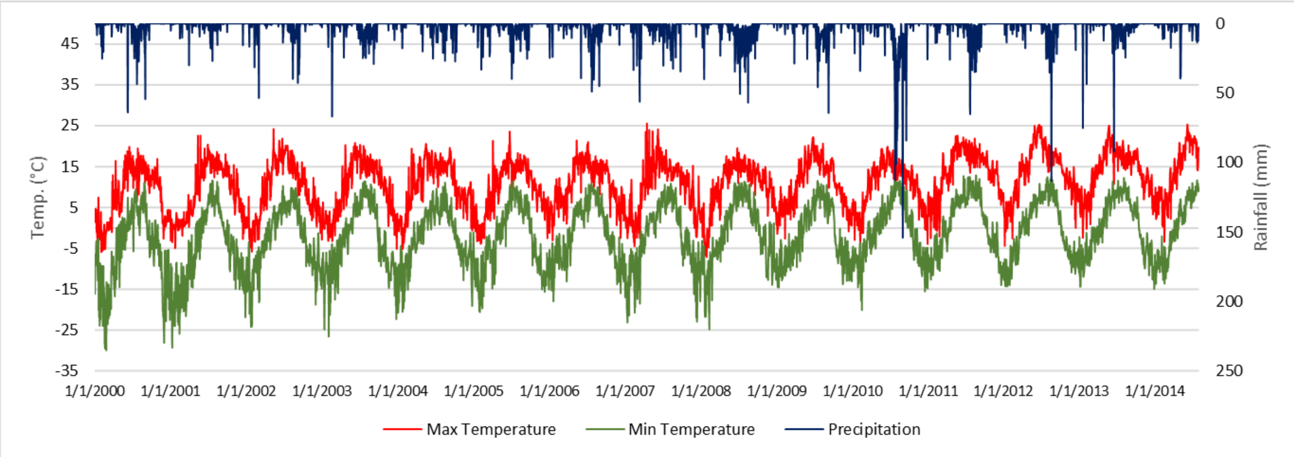


Figure 14: Daily variation of Temperature and Rainfall at Uttarkashi Station

4.3 The SWAT Model Setup

The SWAT project was setup using ArcSWAT2012 GIS interface. While setting up a SWAT project the most important step is to project the input files to an adequate projection. WGS 1984 zone 43 Northern Hemisphere from Geographic Coordinate System was used to process the raster images. The entire SWAT model setup in classified into four parts.

- Watershed delineation
- HRU Analysis
- Write Input Tables
- SWAT simulation

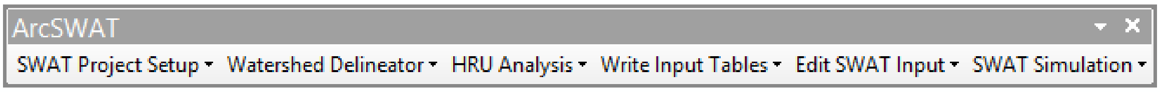


Figure 15: ArcSWAT Window in ArcMAP

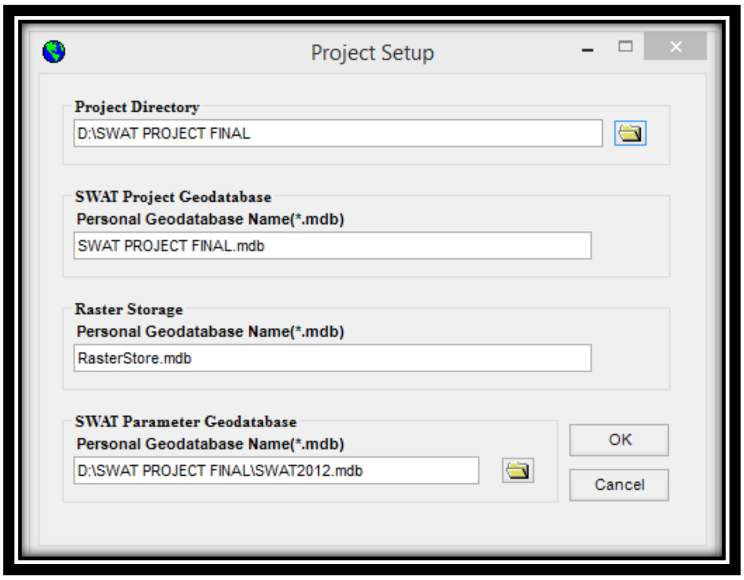


Figure 16: Project Setup window of SWAT Model

4.3.1 Watershed Delineation

The watershed delineator tool incorporated in the SWAT toolbar permits for the delineation of the watershed. It uses an automatic procedure to delineate sub-basins by calculating the flow direction and flow accumulation using the Digital Elevation Model (DEM) data and stream network data. The maximum value where the flow is directed from a cell gives the direction of the stream. The threshold value for the stream defines the minimum amount of flow in the stream for which the sub-basins will be delineated. The watershed delineation has five parts:

- DEM Setup
- Stream Definition
- Outlet and Inlet Definition
- Watershed Outlet(s) Selection and Definition
- Calculation of Subbasin Parameters.

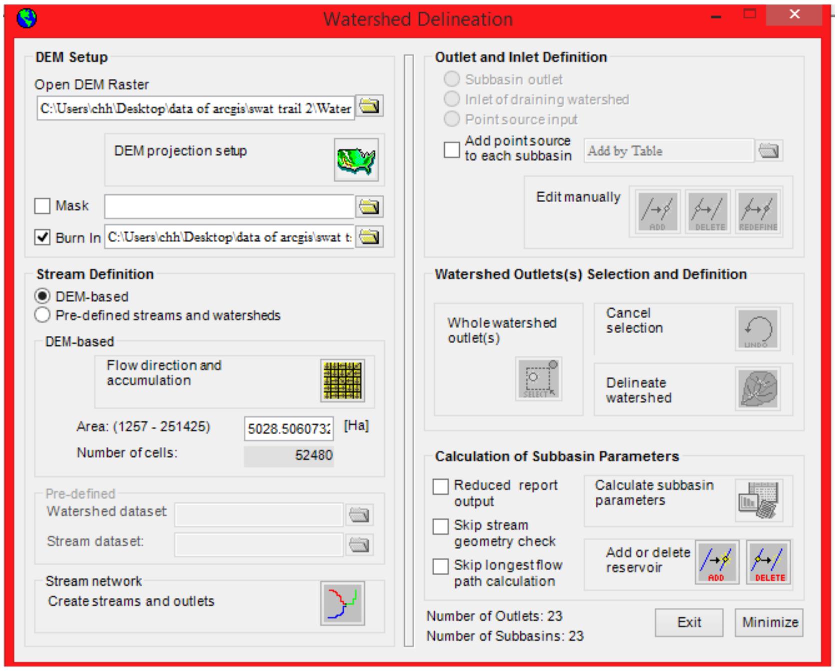


Figure 17: Watershed Delineation window in SWAT Model

4.3.2 HRU Creation

The foundation for hydrological modelling in SWAT is the formulation of Hydrologic Response Units (HRUs). HRUs are the divisions or units that perform similarly and have identical land use, soil and slope characteristics. There may be numerous HRUs created in a single subbasin depending upon the combination of land use, soil and slope in the watershed. The first step for HRU Analysis is the Land Use/ Soil/ Slope Definition and Overlay. This tool permits the user to upload soil and land use maps for the watershed for which the basin is reclassified into smaller units. Each land use and soil class have different properties which give different characteristic responses for the same rainfall. The LULC map utilized in this study was changed into SWAT LULC map by reclassification by looking up values from the land use lookup table. These lookup tables provide a common ID (value) for a particular land use class in SWAT database which make the land use map for the watershed.

After the land use reclassification, a similar procedure is adopted for the reclassification of soil data. The grid file for soil map and the database made for soil vales and their characteristic responses is added. Around 5000 soil attributes are recorded in the Global Soils database. The soil lookup table links the table grid vales into soil attributes which ultimately when reclassified give the soil map for the basin. Slope Definition for the basin is the next step in HRU analysis. It is carried out by slope discretization into multiple slopes classes. The upper and lower limits for the different slope classes were given and the basin was classified according to the percentage slope. After reclassification, the Overlay button gives the land use, soil and slope maps for the basin. The basin was divided into 102 HRUs and 23 sub basins and overlay report for the HRUs was generated. The report shows the classified HRUs and the area distribution among them.

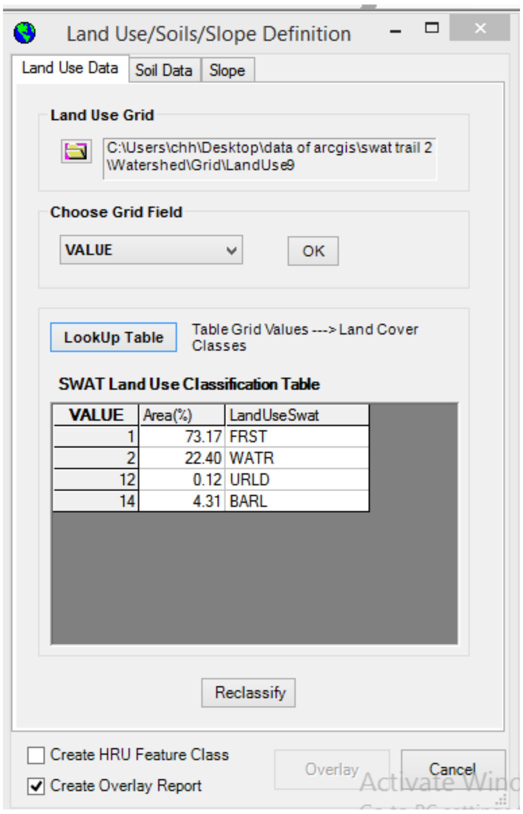


Figure 18: HRU Creation Window in SWAT Model

4.3.3 Write Input Tables

This step comprises reading the weather data and writing of input tables. The weather data definition for the basin is done by selecting the weather station files like rainfall data, temperature data and the weather generator file. The rainfall data definition tab is showing the rain gauge locations being uploaded. Rain gauge locations were selected and data was organized in the SWAT acceptable format. The temperature locations table was uploaded similarly in the temperature data tab. Total 6 weather stations were identified in the watershed the location and data availability details are given in table.

Table 1: Weather Stations Details of Watershed

Station	Longitude	Latitude	Elevation	From	To	Frequency
Tehri	78.4375	30.4423008	762	1979	2014	Daily
Sangrali	78.4375	30.75449944	1664	1979	2014	Daily
Sarun May Bandiyar	78.75	30.4423008	1929	1979	2014	Daily
Uttarkashi	78.75	30.75449944	3550	1979	2014	Daily
Gangotri	78.75	31.06679916	3714	1979	2014	Daily
Sankari Range	78.4375	31.06679916	4144	1979	2014	Daily

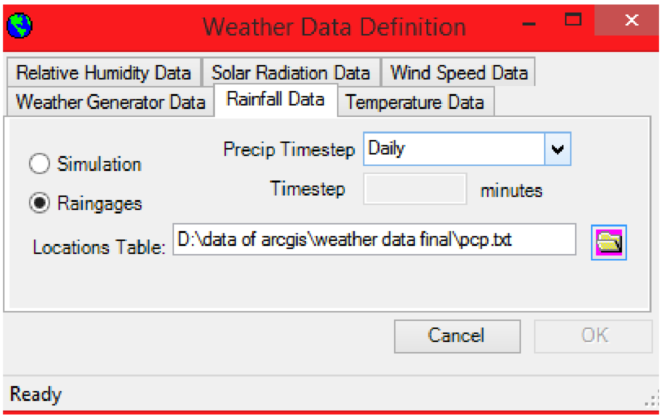


Figure 19: Weather Data Definition Window in SWAT Model

4.3.4 SWAT Simulation

The ultimate phase is the setup and run SWAT model simulation. The period of simulation was taken for 15 years from January 2000 to July 2014 for which the observed data was sufficiently available. Two years of warm up period was given to the model so that it could better simulate the results. The model is run for the complete extent of 15 years but the warm up period is not shown in the results. The setup of SWAT Run is necessary before the final SWAT Run could be made. The setup generates the final input files for the period of simulation.

After the successful SWAT Setup, the Run SWAT button becomes active. The final SWAT run is allowed which takes time in processing all the information.

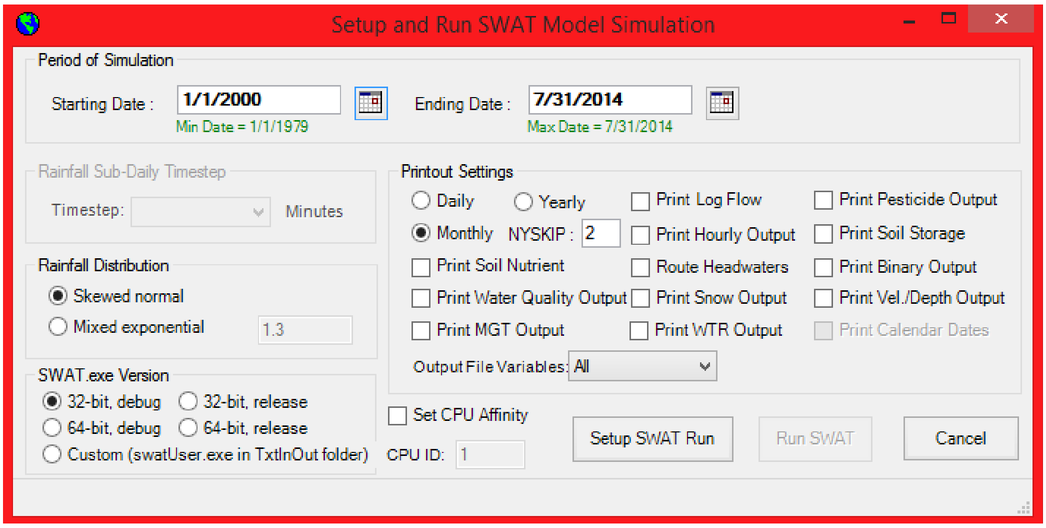


Figure 20: SWAT Setup and Run Window in SWAT Model

4.4 SWAT Output

The output of the SWAT model is in the format of database files which need to be imported to the main SWAToutput.mdb file in the SWAT database. For this purpose, SWAT OUTPUT VIEWER was used. DB Browser was used to read the .mdb files. Part of the output file imported is shown in Appendix. These output files can be exported into a excel sheets for further analysis and plotting. For the analysis of the entire basin flow, the sub-basin at the outlet is identified and the flow output from that sub-basin is plotted and checked with the observed flows of the basin.

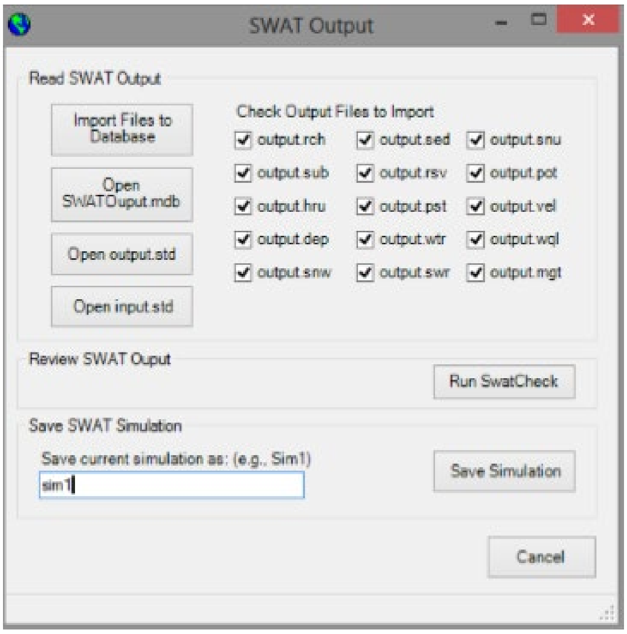


Figure 21: SWAT Output Tab in SWAT Model

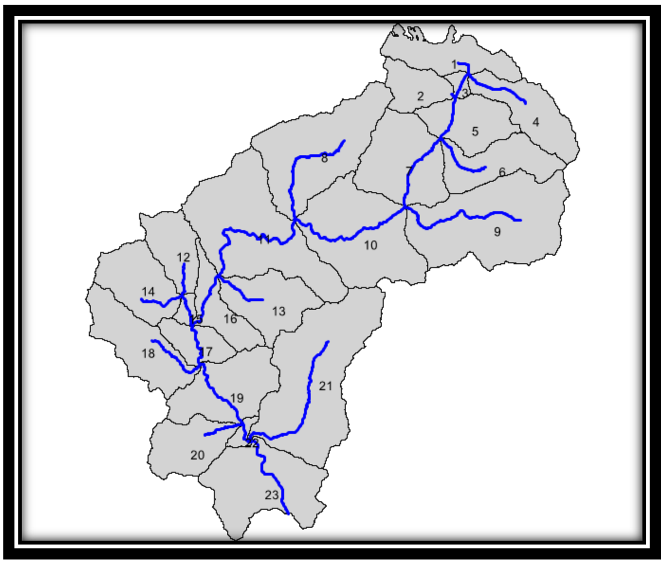


Figure 22: Subbasins of the Watershed

4.5 Calibration and Validation of SWAT Output

The calibration of data is an important factor in SWAT modeling. The available data is generally divided in two sets: calibration data and validation data. For stream flow calibration, the data from 2000-2010 and 2011-2013 are taken as calibration and validation data respectively. First two years (2000-2001) were taken as warm-up period for the SWAT run. The runoff has been simulated with the SWAT setup and the required input data and default parameters. Then the simulated runoff has been taken into SWAT-CUP for calibration and validation and sensitivity analysis of the parameters and optimization of the most sensitive selected parameters. The calibration has been done by using SUFI-2 algorithm (Sequential Uncertainty Fitting version 2). SUFI-2 is a comprehensive optimization and gradient search method able to simultaneously calibrate multiple parameters and with a global search function. It also considers the uncertainty of the input data, model parameters, and model structure.

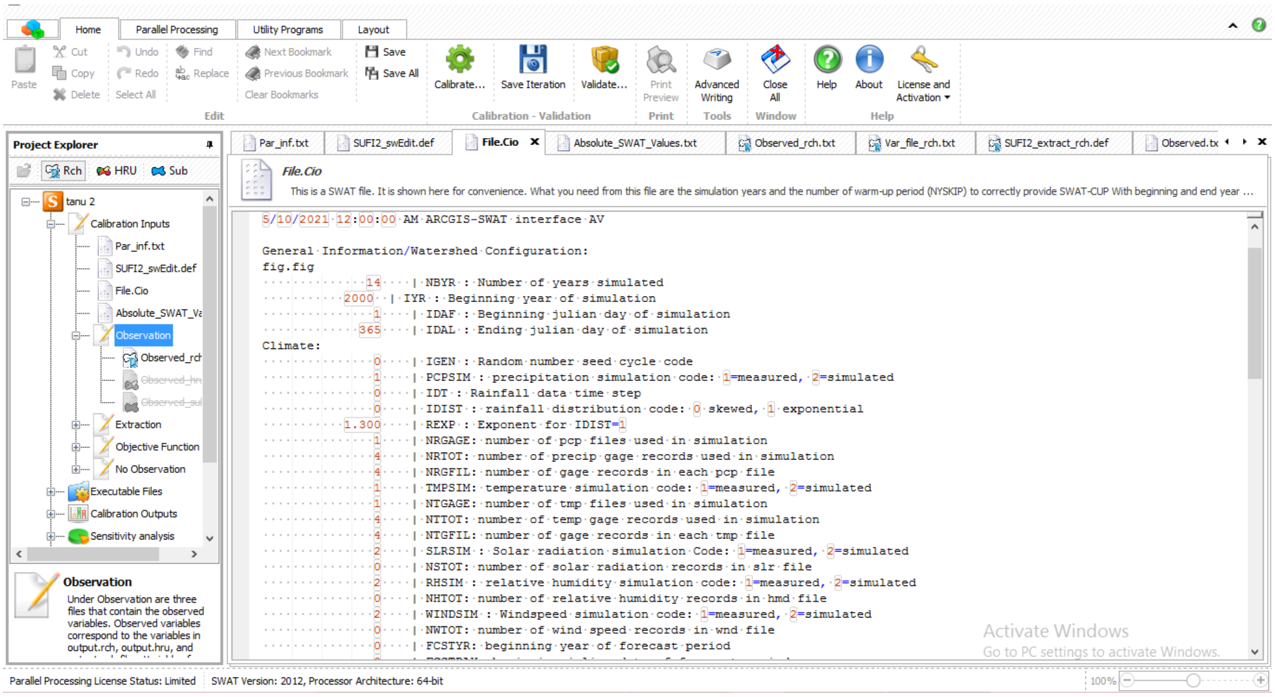


Figure 23: SWAT-CUP SUFI-2 Calibration Window

Chapter 5

SWAT OUTPUT ANALYSIS

5.1 Genral

This chapter presents the analysis of the results from the SWAT modelling. Output results are presented in various derived graphs and tables which give the necessary information of the watershed like the discharge and sediment at outlets and HRUs formed according to different land classes, soil classes and slope.

5.2 Standard SWAT Output

Standard SWAT output gives average annual information of watershed which includes various hydrological and water quality parameters. Some important factors of the basin are presented in table. Detailed output of SWAT model is presented in Appendix I.

Table 2: Standard SWAT Output

Name	Value
Total Area (Sq.Km)	2514.254
Water Stress Days	28.64
Temperature Stress Days	71.15
Precipitation (mm)	1018.44
Snow Fall (mm)	55.08
Snow Melt (mm)	54.72
Sublimation (mm)	0.53
Surface Runoff Q (mm)	130.78
Lateral Soil Q (mm)	167.11
Groundwater (Shal Aq) Q (mm)	133.69
Groundwater (Deep Aq) Q (mm)	7.90
Deep Aq Recharge (mm)	7.96
Total Aq Recharge (mm)	159.16
Total Water Yld (mm)	439.49
Percolation Out of Soil (mm)	160.68

5.3 Calibration and Validation of SWAT Output

The effective application of a hydrological model depends on the calibration (Gupta et al. 1999). In this study, SWAT CUP calibration was performed for the Bhagirathi River basin for the years 2000–2010. The first two years (2000,2001) were taken as warm-up period in order to make a model to realistically set-up the states of its internal hydrological compartments, i.e., groundwater store, soil moisture content, etc. The input parameters used for model calibration were: CN, ALPHA_BF, GW_DELAY and GW_QMN. The SCS curve number is one of the dominating factors for land use, soil permeability and soil moisture conditions. It is observed that increasing CN decreases infiltration and baseflow and thus increases hydrograph spikes. The baseflow recession constant (ALPHA_BF) is a direct index of groundwater flow response to changes in recharge (Smedema and Rycroft 1983). Groundwater delay time (GW_DELAY) is the time lag between water exiting the soil profile and entering the shallow aquifer. It depends on depth to the water table and the hydraulic properties of the geologic formations in the vadose and groundwater zones.

The calibration results (Figure 24) revealed that the observed peak value in years 2008 and 2010 were have significant difference in observed and simulated streamflow peaks. The over prediction seen during these years could be attributed to the fact that SWAT is unable to simulate extreme events accurately and over predicts or under predicts large flows in the basin (Tolson and Shoemaker, 2007). Past studies have also related over predictions and under predictions to spatial variability within a watershed (Santhi et al., 2001; Srinivasan et al., 1998).

The validation results are shown in Figure 24. During the calibration period from 2011 to 2013, as mentioned above SWAT is not capable to predict the extreme events can be seen in validation period also except that simulation is well synchronized with the observed values.

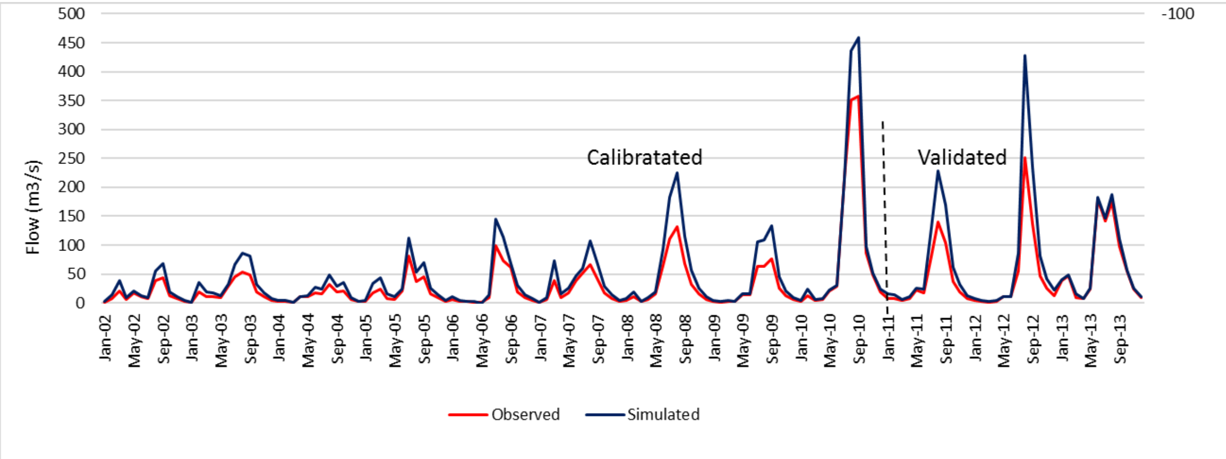


Figure 24: Observed and Simulated Flow for Calibrated and Validated Period

Figure 25 shows the graph between observed and simulated values vs. precipitation. And it can be seen that rainfall peaks are very well synchronized with observed and simulated values. Figure 25 and 26 represents the linear regression graph between observed and simulated streamflow values. Which are showing R^2 values 0.87 and 0.76 corresponding to calibration and validation periods.

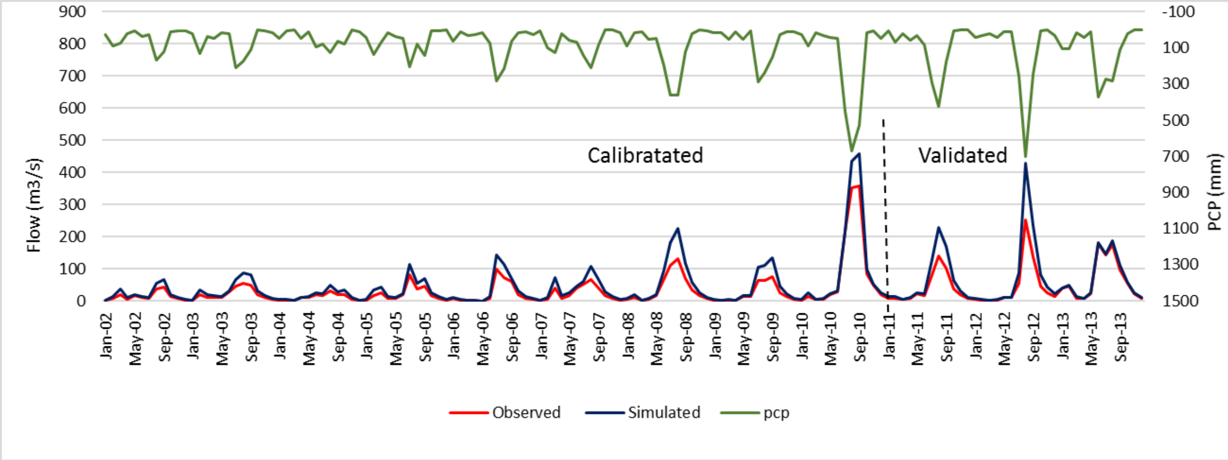


Figure 25:Observed and Simulated Flow including Precipitation for Calibrated and Validated Period

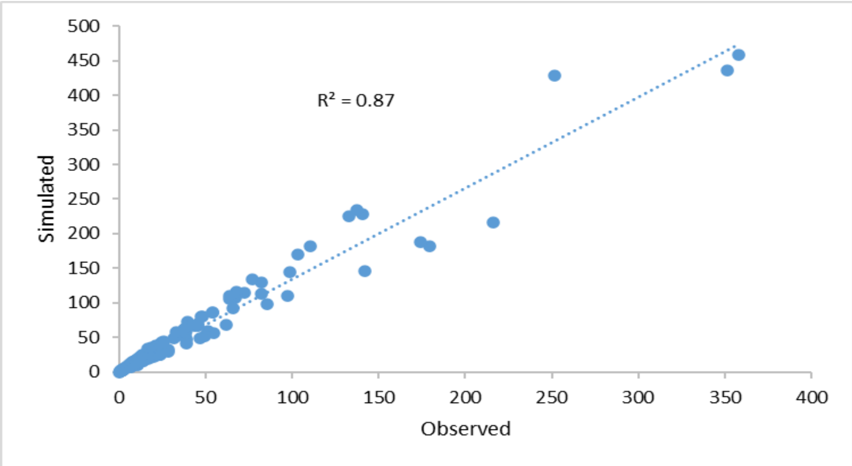


Figure 26: Linear Regression Graph of Calibration Period

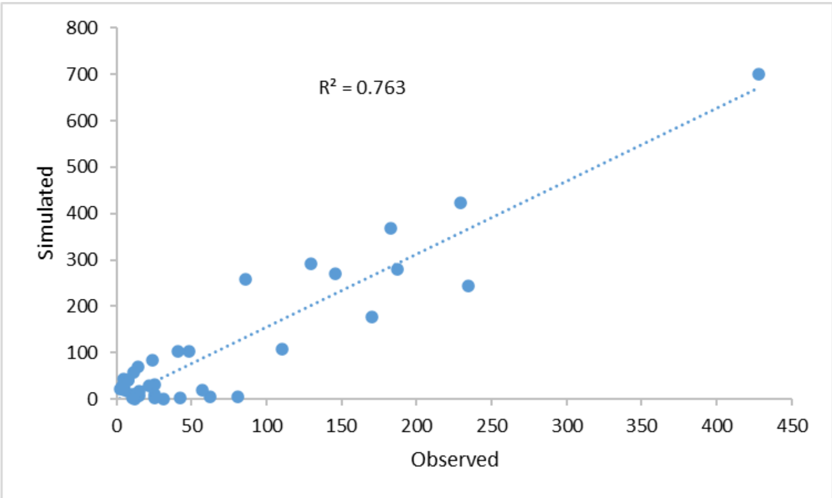


Figure 27: Linear Regression Graph of Validation Period

After calibration and validation, the R^2 value was found to be 0.87 and 0.76 for calibration and validation period respectively that shows a very good link between simulated and observed streamflow data. NSE (Nash Sutcliffe efficiency) was 0.83 for calibration and 0.71 for validation period. The NSE values are less compared to R^2 but it is more than satisfactory according to Moriasi et al., 2007 (NSE > 0.50). The lesser NSE values signifies that it was considered as the main objective function during the simulation of observed data, whereas high R^2 indicates that both are strongly correlated, while their magnitudes that varies greatly (Meng et al., 2010).

The percent of bias (PBIAS) was also computed for the calibration and validation periods.It was found 6.4 during calibration and 15.7 during validation. The PBIAS value signifies that the validation period was more overestimated than calibration period, and both values are falls within satisfactory limits (PBIAS <20) (Moriasi et al., 2007). The statistical value of NSE, R^2, PBIAS p-factor and mean values are shown in Table 3. Results indicate that calibration period had less uncertainty rather than validation it is because of lesser duration of validation period. The overall forecasting of monthly surface runoff by using the SWAT model for the calibration and validation period was very good.

Table 3: Model Performance Statistics Results

S.No.	Statistical parameters	Calibration (2000-2010)	Validation (2011-13)
1	R^2	0.87	0.76
2	p-factor	0.88	0.68
3	NSE	0.83	0.71
4	PBAIS	6.4	15.7
5	Mean (Simulated)	33.01	42.60
6	Mean (Observed)	35.26	50.56

Table 4: Statistics of Sensitivity Analysis

S.No.	Parameter	Description	Fitted Value	Min. value	Max. value

1	CN2.mgt	Curve number	-0.17	-0.2	0.2
2	ALPHA_BF.gw	Base flow alpha factor	0.125	0	1
3	GW_DELAY.gw	Ground water delay time	355.5	30	450
4	GWQMN.gw	A threshold minimum depth of water in the shallow evaporation coefficient	1.45	0	2

Table 5: Ranking of Most Sensitive Parameters

Rank	Parameter Name	P-Value	t-Stat
1	CN2.mgt	0.672	0.4315
2	GWQMN.gw	0.624	-0.4998
3	ALPHA_BF.gw	0.2	-2.3398
4	GW_DELAY.gw	0.072	-1.9315

Global sensitivity analysis was done after the successful validation and calibration. The sensitivity parameters considered and their fitted value are presented in table 4. The result of sensitivity analysis is shown in Table 5. The order of sensitive parameters to streamflow were, CN2, GWQMN, ALPHA_BF and GW_DELAY with corresponding p-values 0.672,0.624,0.2, 0.072. The p-value nearer to 1 indicates more sensitivity. The sensitivity of CN2 indicates the rapid changes in land use classes. It is due to the seasonal variation and snowfall in the basin. The sensitivity of ALPHA_BF shows that the water flow in this lowland region is predominated by percolation, infilteration and baseflow due to shallow groundwater. The sensitivity of ALPHA_BF indicates the quick response and movement to the groundwater recharge and it is because of the basin belongs to the hilly region. Whereas the p-value of GW_DELAY is approximately 0 so it has no noticeable significance.

Chapter 6

CONCLUSIONS AND FUTURE RECOMMENDATIONS

6.1 Conclusions

The aim of this study was to develop a hydrological model to simulate the streamflow for Bhagirathi river basin up to tehri dam using ArcSWAT. On the basis of observations following conclusions can be drawn from the study:

1. It is found that the parameters CN2, GWQMN, ALPHA_BF and GW_DELAY are the sensitive parameters for Bhagirathi river basin. Out of which, CN2 the parameter is the most sensitive parameters.
2. The R^2 value was 0.83 during calibration and during validation 0.76, which indicates a good performance of the model. Remarkably, the NSE value was 0.83 and 0.71 for calibration and validation, which is again a good indicator for model's applicability.
3. The SWAT model underestimates or overestimates the extreme events.
4. Due to major variation in temperature from summers to winter a rapid change can be seen in land use/land cover of the basin which depicts in results as CN2 is most sensitive parameter.
5. The results of global sensitivity analysis using SUFI-2 reflects that the SWAT model is appropriate for prediction of streamflow in the Bhagirathi river basin.

6.2 Future Recommendations

Since this model is only calibrated for flow, it can further be calibrated and validated for other hydrological and water quality parameters i.e., nutrients and sediments which can make it more useful for prediction of land use and land cover change impacts on water quality in the Bhagirathi river basin. It also can be useful for future climate scenarios analysis using the model which can help in risk assessment of floods and droughts.

References

1. Alcamo, Joseph, Martina Flörke, and Michael Märker. "Future long-term changes in global water resources driven by socio-economic and climatic changes." *Hydrological Sciences Journal* 52.2 (2007): 247-275. https://doi.org/10.1623/hysj.52.2.247

2. Armitage, Peter, C. K. McPherson, and B. C. Rowe. "Repeated significance tests on accumulating data." *Journal of the Royal Statistical Society: Series A (General)* 132.2 (1969): 235-244.

3. Arnold, Jeffrey G., et al. "Large area hydrologic modeling and assessment part I: model development 1." *JAWRA Journal of the American Water Resources Association* 34.1 (1998): 73-89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

4. Baymani-Nezhad, M., and D. Han. "Hydrological modeling using effective rainfall routed by the Muskingum method (ERM)." *Journal of Hydroinformatics* 15.4 (2013): 1437-1455. https://doi.org/10.2166/hydro.2013.007

5. Benham, Brian L., et al. "Modeling bacteria fate and transport in watersheds to support TMDLs." *Transactions of the ASABE* 49.4 (2006): 987-1002.

6. Beven, Keith J. *Rainfall-runoff modelling: the primer*. John Wiley & Sons, 2011.

7. Beven, Keith. "Causal models as multiple working hypotheses about environmental processes." *Comptes rendus geoscience* 344.2 (2012): 77-88. https://doi.org/10.1016/j.crte.2012.01.005

8. Borah, D. K., et al. "Sediment and nutrient modeling for TMDL development and implementation." *Transactions of the ASABE* 49.4 (2006): 967-986.

9. Castilla-Rho, Juan Carlos, et al. "Sustainable groundwater management: How long and what will it take?" *Global Environmental Change* 58 (2019): 101972. https://doi.org/10.1016/j.gloenvcha.2019.101972

10. Chahine, Moustafa T. "The hydrological cycle and its influence on climate." *Nature* 359.6394 (1992): 373-380. https://doi.org/10.1038/359373a0

11. Chambel-Leitão, P., et al. "Coupling SWAT and tempQsim Mohid River Network." *Geophysical Research Abstracts*. Vol. 8. 2006.

12. Chow, Ven Te. "Determination of hydrologic frequency factor." *Journal of the Hydraulics Division* 85.7 (1959): 93-98. https://doi.org/10.1061/JYCEAJ.0000327

13. Gassman, Philip W., et al. "The soil and water assessment tool: historical development, applications, and future research directions." *Transactions of the ASABE* 50.4 (2007): 1211-1250.

14. Green, W. Heber, and G. A. Ampt. "Studies on Soil Phyics." *The Journal of Agricultural Science* 4.1 (1911): 1-24. https://doi.org/10.1017/S0021859600001441

15. Hargreaves, George H., and Zohrab A. Samani. "Reference crop evapotranspiration from temperature." *Applied engineering in agriculture* 1.2 (1985): 96-99.

16. Jain, Sharad K., and V. P. Singh. "Hydrological cycles, models and applications to forecasting." *Handbook of Hydrometeorological Ensemble Forecasting* (2017). https://doi.org/10.1007/978-3-642-40457-3_20-1

17. Jain, Sharad K., and V. P. Singh. "Hydrological cycles, models and applications to forecasting." *Handbook of Hydrometeorological Ensemble Forecasting* (2017). https://doi.org/10.1007/978-3-642-40457-3_20-1

18. Kumar, Rakesh, R. D. Singh, and K. D. Sharma. "Water resources of India." *Current science* (2005): 794-811. https://www.jstor.org/stable/24111024

19. Maidment, David R. *Handbook of hydrology*. Vol. 9780070. New York: McGraw-Hill, 1993.

20. Mausbach, Maurice J., and Allen R. Dedrick. "The length we go measuring environmental benefits of conservation practices." (2004).

21. Monteith, John L. "Evaporation and environment." *Symposia of the society for experimental biology*. Vol. 19. Cambridge University Press (CUP) Cambridge, 1965.

22. Neitsch, Susan L. "Soil and water assessment tool." *User's Manual Version 2005* 476 (2005).

23. Priestley, Charles Henry Brian, and Robert Joseph TAYLOR. "On the assessment of surface heat flux and evaporation using large-scale parameters." *Monthly weather review* 100.2 (1972): 81-92. https://doi.org/10.1175/1520-0493(1972)100%3C0081:OTAOSH%3E2.3.CO;2

24. Shirmohammadi, A., et al. "Uncertainty in TMDL models." *Transactions of the ASABE* 49.4 (2006): 1033-1049.

25. Todini, E. "Rainfall-runoff modeling—Past, present and future." *Journal of hydrology* 100.1-3 (1988): 341-352. https://doi.org/10.1016/0022-1694(88)90191-6

26. Volk, Tina, Miroslav Rednak, and Emil Erjavec. "The agri-food sector in Slovenia after European Union accession." *in the Food Sector after the Enlargement of the EU* (2007): 244.

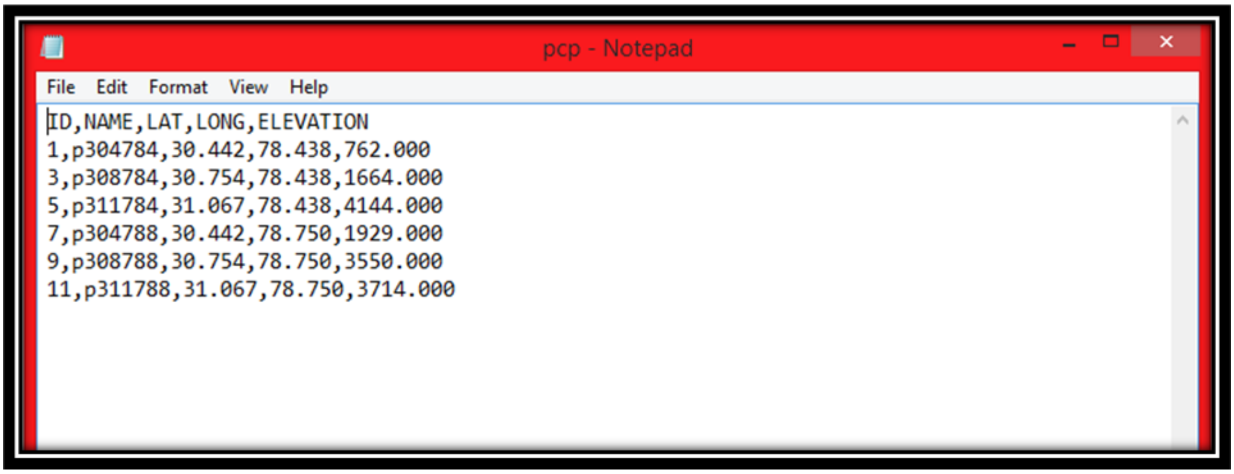
27. Wani, Suhas P., and Kaushal K. Garg. "Watershed management concept and principles." (2009): 1-11. https://doi.org/10.1038/359373a0

28. Williams, Peter F., and Brian R. Rust. "The sedimentology of a braided river." *Journal of Sedimentary Research* 39.2 (1969): 649-679. https://doi.org/10.1306/74D71CF3-2B21-11D7-8648000102C1865D

29. Xu, Jianhua, et al. "Climate change and its effects on runoff of Kaidu River, Xinjiang, China: a multiple time-scale analysis." *Chinese Geographical Science* 18.4 (2008): 331-339. https://doi.org/10.1016/j.gloplacha.2010.07.002

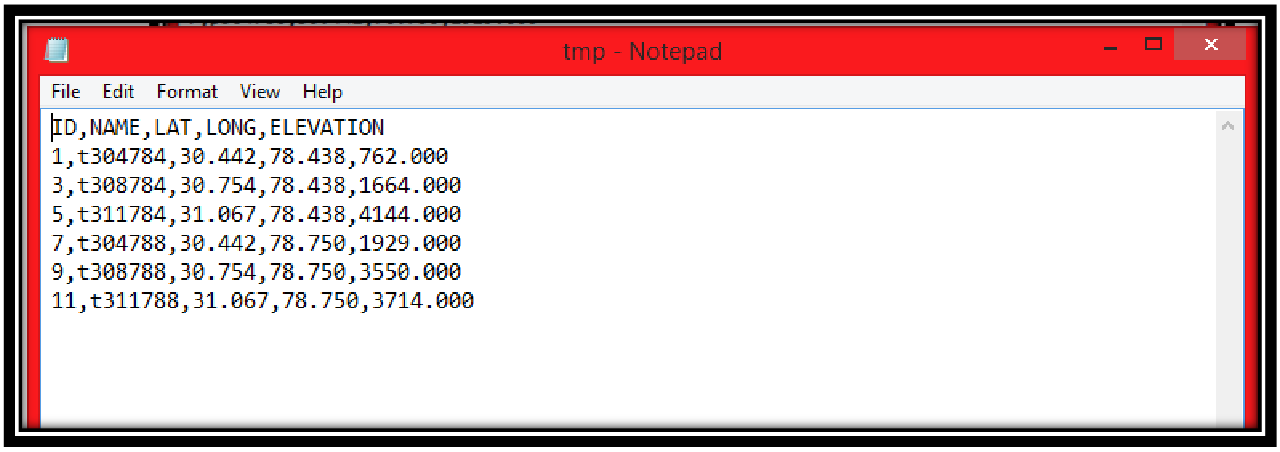
Appendix

1. Precipitation data input file




```
ID,NAME,LAT,LONG,ELEVATION
1,p304784,30.442,78.438,762.000
3,p308784,30.754,78.438,1664.000
5,p311784,31.067,78.438,4144.000
7,p304788,30.442,78.750,1929.000
9,p308788,30.754,78.750,3550.000
11,p311788,31.067,78.750,3714.000
```

2. Tepreature data input file




```
ID,NAME,LAT,LONG,ELEVATION
1,t304784,30.442,78.438,762.000
3,t308784,30.754,78.438,1664.000
5,t311784,31.067,78.438,4144.000
7,t304788,30.442,78.750,1929.000
9,t308788,30.754,78.750,3550.000
11,t311788,31.067,78.750,3714.000
```

3. Average monthly basin

Month	Rain mm	Snow mm	surfQ mm	latQ mm	Watery mm	ET mm	Sedy (t ha)	PET mm
1	38.71	14.47	1.70	3.80	7.32	12.73	0.46	43.23
2	63.35	20.63	3.38	8.63	13.49	19.33	2.56	45.46
3	40.28	7.41	3.88	6.12	13.18	29.99	4.86	94.21
4	33.25	2.73	0.51	2.24	5.96	34.03	1.59	109.36
5	34.01	2.02	2.04	4.57	8.79	38.75	6.87	131.40
6	84.53	0.32	9.93	12.66	24.98	44.10	11.10	128.71
7	232.38	0.00	29.65	38.00	75.48	55.72	26.58	98.10
8	303.36	0.00	51.13	56.29	134.04	57.32	30.11	82.53
9	159.22	0.18	29.92	32.70	102.70	49.42	17.98	85.67
10	17.05	1.00	0.60	3.03	37.19	36.29	0.67	91.52
11	3.55	0.91	0.00	0.12	17.32	19.32	0.00	68.34
12	13.61	3.91	0.09	0.64	7.75	12.28	0.00	49.58

4. Channel Dimensions

RCH	DEPTH_M	WIDTH_M	SLOPE_M_M
1	0.768	18.523	0.108
2	0.630	13.762	0.162
3	1.047	29.474	0.044
4	0.785	19.128	0.182
5	1.302	40.871	0.021
6	0.781	18.984	0.114
7	1.611	56.258	0.028
8	1.065	30.250	0.065
9	1.158	34.312	0.084
10	2.035	79.919	0.014
11	2.358	99.637	0.008
12	0.695	15.955	0.035
13	0.798	19.603	0.040
14	0.796	19.531	0.029
15	1.013	28.059	0.030
16	2.458	106.067	0.012
17	2.589	114.624	0.007
18	0.859	21.905	0.038
19	2.718	123.343	0.001
20	0.752	17.956	0.027
21	1.211	36.664	0.032
22	2.767	126.664	0.012
23	2.979	141.526	0.001

5. HRU's Land Use and Soil Report

____

```
SWAT   model   simulation   Date: 5/6/2021 12:00:00 AM   Time:
00:00:00
MULTIPLE HRUs  LandUse/Soil/Slope OPTION            THRESHOLDS :
10 / 5 / 5 [%]
Number of HRUs: 35
Number of Subbasins: 23
```

____

```
                                                                    Area
[ha]          Area[acres]

Watershed
251425.3995         621284.7334

______________________________________________________________________
________________________________________________________
                                                                    Area
[ha]          Area[acres] %Wat.Area
LANDUSE:
                                 Forest-Mixed --> FRST
195960.7610         484228.8386     77.94

SOILS:
                                         I-Bh-U-c-3717
119114.8243         294338.6865     47.38
                                          Bd29-3c-3661
132310.5752         326946.0469     52.62

SLOPE:
                                                0-9999
251425.3995         621284.7334    100.00
______________________________________________________________________
________________________________________________________
______________________________________________________________________
________________________________________________________
                                                                    Area
[ha]          Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                                   1
8482.5540          20960.8151      3.37

LANDUSE:
                                 Forest-Mixed --> FRST
2250.2341           5560.4409      0.89     26.53
                                 Forest-Mixed --> FRST
2250.2341           5560.4409      0.89     26.53
6206.4904          15336.5481      2.47     73.17

SOILS:
                                         I-Bh-U-c-3717
8456.7245          20896.9890      3.36     99.70

SLOPE:
                                                0-9999
8456.7245          20896.9890      3.36     99.70
HRUs
 1         Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
2250.2341           5560.4409      0.89     26.53    1
 2  1         Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
2250.2341           5560.4409      0.89     26.53    1/I-Bh-U-c-
3717/0-9999          6206.4904           15336.5481      2.47
73.17    2
______________________________________________________________________
________________________________________________________
```

```
_____________________________________________________________________
_______________________________________________________
                                                                 Area
[ha]          Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                                  2
5169.9427           12775.1868      2.06

LANDUSE:
                                Forest-Mixed --> FRST
951.5644            2351.3632      0.38     18.41
                                Forest-Mixed --> FRST
951.5644            2351.3632      0.38     18.41
4213.8612           10412.6616      1.68     81.51

SOILS:
                                        I-Bh-U-c-3717
5165.4256           12764.0248      2.05     99.91

SLOPE:
                                               0-9999
5165.4256           12764.0248      2.05     99.91
HRUs
 3         Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
951.5644            2351.3632      0.38     18.41    1
 4  3        Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
951.5644            2351.3632      0.38     18.41    1/I-Bh-U-c-
3717/0-9999           4213.8612          10412.6616      1.68
81.51    2
_____________________________________________________________________
_______________________________________________________
_____________________________________________________________________
_______________________________________________________
                                                                 Area
[ha]          Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                                  3
964.9806            2384.5153      0.38

LANDUSE:
                                Forest-Mixed --> FRST
725.1251            1791.8203      0.29     75.14
                                Forest-Mixed --> FRST
725.1251            1791.8203      0.29     75.14
109.1091             269.6141      0.04     11.31
                              Transportation --> UTRN
131.3528             324.5794      0.05     13.61

SOILS:
                                        I-Bh-U-c-3717
965.5870            2386.0138      0.38    100.06

SLOPE:
                                               0-9999
965.5870            2386.0138      0.38    100.06
HRUs
```

```
 5         Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
725.1251           1791.8203      0.29     75.14    1
 6  5        Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
725.1251           1791.8203      0.29     75.14    1/I-Bh-U-c-
3717/0-9999           109.1091             269.6141      0.04
11.31    2
 7       Transportation --> UTRN/I-Bh-U-c-3717/0-9999
131.3528            324.5794      0.05     13.61    3
____________________________________________________________________
______________________________________________________
____________________________________________________________________
______________________________________________________
                                                                Area
[ha]          Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                                4
8949.6655          22115.0710      3.56

LANDUSE:
LANDUSE:          8938.9907          22088.6929      3.56
99.88

SOILS:
                                            I-Bh-U-c-3717
8938.9907          22088.6929      3.56     99.88

SLOPE:
                                                   0-9999
8938.9907          22088.6929      3.56     99.88
HRUs
 8                           HRUs/I-Bh-U-c-3717/0-9999
8938.9907          22088.6929      3.56     99.88    1
____________________________________________________________________
______________________________________________________
____________________________________________________________________
______________________________________________________
                                                                Area
[ha]          Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                                5
8155.8155          20153.4278      3.24

LANDUSE:
                                Forest-Mixed --> FRST
4491.0776          11097.6773      1.79     55.07
                                Forest-Mixed --> FRST
4491.0776          11097.6773      1.79     55.07
3669.8633           9068.4158      1.46     45.00

SOILS:
                                            I-Bh-U-c-3717
8160.9409          20166.0931      3.25    100.06

SLOPE:
                                                   0-9999
8160.9409          20166.0931      3.25    100.06
```

```
HRUs
 9         Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
4491.0776          11097.6773      1.79     55.07    1
 10  9        Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
4491.0776          11097.6773      1.79     55.07    1/I-Bh-U-c-
3717/0-9999          3669.8633            9068.4158      1.46
45.00    2
____________________________________________________________________
______________________________________________________
____________________________________________________________________
______________________________________________________
                                                               Area
[ha]           Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                                   6
8837.5588          21838.0496      3.51

LANDUSE:
                                Forest-Mixed --> FRST
2974.3503           7349.7682      1.18     33.66
                                Forest-Mixed --> FRST
2974.3503           7349.7682      1.18     33.66
5868.7624          14502.0054      2.33     66.41

SOILS:
                                        I-Bh-U-c-3717
8843.1127          21851.7736      3.52    100.06

SLOPE:
                                               0-9999
8843.1127          21851.7736      3.52    100.06
HRUs
 11        Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
2974.3503           7349.7682      1.18     33.66    1
 12  11       Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
2974.3503           7349.7682      1.18     33.66    1/I-Bh-U-c-
3717/0-9999          5868.7624           14502.0054      2.33
66.41    2
____________________________________________________________________
______________________________________________________
____________________________________________________________________
______________________________________________________
                                                               Area
[ha]           Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                                   7
13471.9760          33289.9263      5.36

LANDUSE:
                                Forest-Mixed --> FRST
10187.6649          25174.2293      4.05     75.62
                                Forest-Mixed --> FRST
10187.6649          25174.2293      4.05     75.62
3292.7775           8136.6179      1.31     24.44

SOILS:
```

I-Bh-U-c-3717
13480.4424 33310.8472 5.36 100.06

SLOPE:
0-9999
13480.4424 33310.8472 5.36 100.06
HRUs
13 Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
10187.6649 25174.2293 4.05 75.62 1
14 13 Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
10187.6649 25174.2293 4.05 75.62 1/I-Bh-U-c-3717/0-9999 3292.7775 8136.6179 1.31
24.44 2

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

SUBBASIN # 8
19211.4594 47472.4767 7.64

LANDUSE:
Forest-Mixed --> FRST
13618.8376 33652.8286 5.42 70.89
Forest-Mixed --> FRST
13618.8376 33652.8286 5.42 70.89
5578.1369 13783.8553 2.22 29.04

SOILS:
I-Bh-U-c-3717
19196.9745 47436.6839 7.64 99.92

SLOPE:
0-9999
19196.9745 47436.6839 7.64 99.92
HRUs
15 Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
13618.8376 33652.8286 5.42 70.89 1
16 15 Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
13618.8376 33652.8286 5.42 70.89 1/I-Bh-U-c-3717/0-9999 5578.1369 13783.8553 2.22
29.04 2

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

SUBBASIN # 9
23700.7127 58565.6462 9.43

LANDUSE:

Forest-Mixed --> FRST
7467.7294 18453.1328 2.97 31.51
Forest-Mixed --> FRST
7467.7294 18453.1328 2.97 31.51
16247.8779 40149.3186 6.46 68.55

SOILS:
I-Bh-U-c-3717
23715.6073 58602.4515 9.43 100.06

SLOPE:
0-9999
23715.6073 58602.4515 9.43 100.06
HRUs
17 Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
7467.7294 18453.1328 2.97 31.51 1
18 17 Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
7467.7294 18453.1328 2.97 31.51 1/I-Bh-U-c-3717/0-9999 16247.8779 40149.3186 6.46
68.55 2

____
____

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

SUBBASIN # 10
19265.3090 47605.5418 7.66

LANDUSE:
Forest-Mixed --> FRST
19277.4161 47635.4592 7.67 100.06

SOILS:
Bd29-3c-3661
6815.1387 16840.5485 2.71 35.38
I-Bh-U-c-3717
12462.2774 30794.9107 4.96 64.69

SLOPE:
0-9999
19277.4161 47635.4592 7.67 100.06
HRUs
19 Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
6815.1387 16840.5485 2.71 35.38 1
20 Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
12462.2774 30794.9107 4.96 64.69 2

____
____

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

SUBBASIN # 11
23872.7056 58990.6491 9.49

LANDUSE:

Forest-Mixed --> FRST
23878.3122 59004.5034 9.50 100.02

SOILS:

Bd29-3c-3661
14149.5710 34964.2975 5.63 59.27
I-Bh-U-c-3717
9728.7412 24040.2060 3.87 40.75

SLOPE:

0-9999
23878.3122 59004.5034 9.50 100.02
HRUs
21 Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
14149.5710 34964.2975 5.63 59.27 1
22 Forest-Mixed --> FRST/I-Bh-U-c-3717/0-9999
9728.7412 24040.2060 3.87 40.75 2

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

SUBBASIN # 12
6614.4911 16344.7382 2.63

LANDUSE:

Forest-Mixed --> FRST
6614.0458 16343.6379 2.63 99.99

SOILS:

Bd29-3c-3661
6614.0458 16343.6379 2.63 99.99

SLOPE:

0-9999
6614.0458 16343.6379 2.63 99.99
HRUs
23 Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
6614.0458 16343.6379 2.63 99.99 1

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

SUBBASIN # 13
9323.1631 23038.0023 3.71

LANDUSE:

```
                              Forest-Mixed --> FRST
9329.0222          23052.4804      3.71    100.06

SOILS:
                                       Bd29-3c-3661
9329.0222          23052.4804      3.71    100.06

SLOPE:
                                             0-9999
9329.0222          23052.4804      3.71    100.06
HRUs
 24         Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
9329.0222          23052.4804      3.71    100.06    1
____________________________________________________________________
______________________________________________________
____________________________________________________________________
______________________________________________________
                                                                Area
[ha]          Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                         14
9266.3432          22897.5974      3.69

LANDUSE:
                              Forest-Mixed --> FRST
8050.0811          19892.1529      3.20     86.87
                            Transportation --> UTRN
1207.4162           2983.5857      0.48     13.03

SOILS:
                                       Bd29-3c-3661
9257.4973          22875.7386      3.68     99.90

SLOPE:
                                             0-9999
9257.4973          22875.7386      3.68     99.90
HRUs
 25         Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
8050.0811          19892.1529      3.20     86.87    1
 26       Transportation --> UTRN/Bd29-3c-3661/0-9999
1207.4162           2983.5857      0.48     13.03    2
____________________________________________________________________
______________________________________________________
____________________________________________________________________
______________________________________________________
                                                                Area
[ha]          Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                         15
1068.2721           2639.7538      0.42

LANDUSE:
                              Forest-Mixed --> FRST
1068.9435           2641.4128      0.43    100.06

SOILS:
```

Bd29-3c-3661
1068.9435 2641.4128 0.43 100.06

SLOPE:
0-9999
1068.9435 2641.4128 0.43 100.06
HRUs
27 Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
1068.9435 2641.4128 0.43 100.06 1

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

SUBBASIN # 16
6066.5094 14990.6480 2.41

LANDUSE:
Forest-Mixed --> FRST
6070.3218 15000.0688 2.41 100.06

SOILS:
Bd29-3c-3661
6070.3218 15000.0688 2.41 100.06

SLOPE:
0-9999
6070.3218 15000.0688 2.41 100.06
HRUs
28 Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
6070.3218 15000.0688 2.41 100.06 1

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

SUBBASIN # 17
4512.6329 11150.9415 1.79

LANDUSE:
Forest-Mixed --> FRST
4515.4688 11157.9492 1.80 100.06

SOILS:
Bd29-3c-3661
4515.4688 11157.9492 1.80 100.06

SLOPE:
0-9999
4515.4688 11157.9492 1.80 100.06
HRUs

29 Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
4515.4688 11157.9492 1.80 100.06 1

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

SUBBASIN # 18
11218.3425 27721.0852 4.46

LANDUSE:
Forest-Mixed --> FRST
11194.8075 27662.9291 4.45 99.79

SOILS:
Bd29-3c-3661
11194.8075 27662.9291 4.45 99.79

SLOPE:
0-9999
11194.8075 27662.9291 4.45 99.79
HRUs
30 Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
11194.8075 27662.9291 4.45 99.79 1

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

SUBBASIN # 19
11777.2474 29102.1672 4.68

LANDUSE:
Forest-Mixed --> FRST
11780.5260 29110.2688 4.69 100.03

SOILS:
Bd29-3c-3661
11780.5260 29110.2688 4.69 100.03

SLOPE:
0-9999
11780.5260 29110.2688 4.69 100.03
HRUs
31 Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
11780.5260 29110.2688 4.69 100.03 1

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

SUBBASIN # 20
8054.7277 19903.6350 3.20

LANDUSE:
Forest-Mixed --> FRST
8046.9420 19884.3961 3.20 99.90

SOILS:
Bd29-3c-3661
8046.9420 19884.3961 3.20 99.90

SLOPE:
0-9999
8046.9420 19884.3961 3.20 99.90
HRUs
32 Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
8046.9420 19884.3961 3.20 99.90 1

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

SUBBASIN # 21
26469.4625 65407.3654 10.53

LANDUSE:
Forest-Mixed --> FRST
26486.0971 65448.4702 10.53 100.06

SOILS:
Bd29-3c-3661
26486.0971 65448.4702 10.53 100.06

SLOPE:
0-9999
26486.0971 65448.4702 10.53 100.06
HRUs
33 Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
26486.0971 65448.4702 10.53 100.06 1

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

SUBBASIN # 22
994.9715 2458.6244 0.40

LANDUSE:
Forest-Mixed --> FRST
995.5968 2460.1695 0.40 100.06

```
SOILS:
                                        Bd29-3c-3661
995.5968            2460.1695      0.40    100.06

SLOPE:
                                              0-9999
995.5968            2460.1695      0.40    100.06
HRUs
 34          Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
995.5968            2460.1695      0.40    100.06    1
____________________________________________________________________
______________________________________________________
____________________________________________________________________
______________________________________________________
                                                                Area
[ha]             Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                          23
15976.5563           39478.8693      6.35

LANDUSE:
                                Forest-Mixed --> FRST
15986.5966           39503.6796      6.36    100.06

SOILS:
                                        Bd29-3c-3661
15986.5966           39503.6796      6.36    100.06

SLOPE:
                                              0-9999
15986.5966           39503.6796      6.36    100.06
HRUs
 35          Forest-Mixed --> FRST/Bd29-3c-3661/0-9999
15986.5966           39503.6796      6.36    100.06    1
```