HYDROLOGICAL MODELLING OF DEO RIVER SUB-BASIN USING SWAT MODEL AND PERFORMANCE EVALUATION USING SWAT-CUP

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CERTIFICATE

This is to certify that this dissertation entitled ***"Hydrological Modelling of Deo River Sub-Basin Using SWAT Model and Performance Evaluation Using SWAT-CUP"*** *which has been submitted by* ***Miss Parikh Mansi Manojkumar*** *in partial fulfilment of the requirements for the award of the degree of* ***Master of Engineering (Civil) In Water Resources Engineering*** *to* ***"The Maharaja Sayajirao University Of Baroda"*** *has been carried out by her under my supervision and guidance during 2018-2019. The matter embodied in the dissertation has not been submitted for the award of any other degree of diploma.*

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TABLE OF CONTENTS

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Place: Vadodara

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ABSTRACT

Water is the main component for all living things, and it is a great force that constantly shapes the earth's surface. Understanding a basin's water balance system is the most significant aspect in water resources development and management programs. Using water balance relationships, major hydrological procedures can be quantified. Due to heterogeneities in topography, land use, soil cover and other catchment characteristics, the conversion of precipitation into stream flow is a complicated process for all catchment areas. So, understanding the connection between these physical parameters and hydrological elements for any work linked to the growth of water resources is very important. A hydrological model can thus provide the foundation for policy intervention development and the development of sound watershed management that guarantees environmental protection and economic sustainability.

The semi-distributed, continuous time step, Soil and Water Assessment Tool (SWAT) hydrological model has been employed extensively for long-term simulations of river basins. The present study analyses the runoff response during rainfall events over the sub basin of Deo River, Panch Mahal, Gujarat, India using Soil and Water Assessment Tool (SWAT). The SWAT model is configured for the Deo river sub basin having catchment area of 194.36 km^2, with 7 sub-basins comprising of 94 Hydrological Response Units (HRUs). Two rain gauge stations in the basin (viz., Deo dam and Shivrajpur) were selected to assess the model performance. Digital Elevation Model (DEM), land use map, Soil map, precipitation and climatological parameters are important inputs used for estimating runoff using SWAT Model. The watershed comprises mainly of seven land use classes namely; agriculture, water, deciduous forest, urban cover, bushes, pasture lands and barren lands and two types of soil; loam and clay.

Calibration and validation of the model were performed using the Soil and Water Assessment Tool-Calibration Uncertainty Program (SWAT-CUP) with Sequential Uncertainty Fitting (SUFI-2) algorithm. The model was run for the period from 2000 to 2017 considering 2 years (2000-2001) warm up period with a calibration period from 2002 to 2012 and a validation period from 2013 to 2017. The sensitivity of basin parameters has been analysed and found curve number as the most sensitive parameter, hence, it can be considered to improve the runoff simulation efficiency of the model. The study concluded that the model performed well with a Coefficient of Determination (R2) and Nash–Sutcliffe Efficiency (NSE) as 0.89 and 0.87 during calibration and 0.88 and 0.81 during validation respectively at daily scale. This modelling technique helps in different aspects such as analysis of watershed hydrology, identification of hydrological sensitive parameters, identification of soil characteristics and can assign the effective management practices in the basin. The findings of this study revealed that SWAT model is useful for runoff simulation and flood forecasting for extreme rainfall events in Deo River basin.

LIST OF TABLES

LIST OF FIGURES

LIST OF NOTATIONS

'	Minute
"	Second
%	Percentage
℃	Degree Centigrade
Σ	Summation
σ	Standard Deviation
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
E	East
cm	Centimetre
e.g.	For Example
et al.	And others
etc.	Etcetera
FAO	Food and Agricultural Organisation
G.I.S	Geographical Information System
i.e.	That is
Km	Kilometre
Km^2	Square kilometre
MCM	Million Cubic Metre
mm	Millimetre
m/s	Metre per second
m^3/s	Cubic metre per second
N	North
No.	Number
Sr.	Serial
SRTM	Shuttle Radar Topography Mission
USDA	United States Department of Agriculture
Viz.	Namely

CHAPTER 1

INTRODUCTION

1.1 GENERAL

This chapter gives a brief description about importance of water, water balance in watershed, hydrological processes, hydrological methods, their types and research objectives of the present study.

1.2 BACKGROUND

Water, the basic need of survival, the most important feature of planet, essential for life, is at the most threatened position today. Availability of water in the World is an emerging issue for sustainable development. India is experiencing an average annual rainfall of 1,170 millimetres, or about 1,720 cubic meters of fresh water per individual each year. Approximately 80% of its region experiences 750 millimetres or more of rain a year. Most rains happen during their monsoon seasons (June to September), with the north-east and north getting much more rains than the west and south of India. Despite the comprehensive river system, there is a shortage of secure clean drinking water and supplies of irrigation water for sustainable farming throughout India. In the current situation, there is a random reduction in the quality and quantity of water due to population growth, increased industrialization energy use, urbanization, global warming and desertification. Approximately one third of the population is projected to experience water scarcity by 2050.

Given the large-scale water scarcity that is likely to prevail in the future, water resource management's watershed strategy is the need of hour. Technically, Watershed is described as a natural integrator of all hydrological processes within its boundaries and is thus a well-accepted unit for soil and water management. A watershed's soil, water, and bio-resources, including the energy system, are extremely interrelated and require an integrated plan of management. Watershed is the perfect unit for micro-level planning in India. Water balance research is very important for the development program to preserve water by improving watershed projects planning. Creation and operation of water resources projects depends on the accessibility of water in terms of both amount and quality.

1.3 WATER BALANCE IN WATERSHED

Water balance is usually expressed as general mass conservation in any specified time span for all rain falling on a region. The water balance in a watershed states that all water entering a basin must be absorbed or stored within a defined period of time, or that it must flow as surface or subsurface water. Water balance is needed to understand the role of different leadership approaches in minimizing losses and maximizing the use of water, which is the most limiting factor in watershed crop manufacturing. Runoff is generated as the end product of the watershed with the interaction of rainfall, land use and land cover and type of soil. Therefore, hydrological runoff modelling is performed to estimate runoff, sediment yield, and soil erosion for sustainable growth. Now a days, the most significant aspect of tracking the watershed management program is the use of contemporary tools for adequate planning. Modern tools and techniques such as GIS and Remote Sensing assists to configure a watershed's water equilibrium.

Higher living standards, population shifts, land and water policies, and other external forces are increasing pressure on local, national, and regional water supplies required for irrigation, energy production, industrial, domestic, and environmental reasons. Rapid and often unexpected changes in freshwater supplies generate uncertainties for water executives. At the same moment, climate change brings a new level of uncertainty about freshwater resources and the primary water usage sectors such as agriculture and energy, which in turn will exacerbate uncertainty about future water requirements. As meeting future water demands becomes more uncertain, and water scarcity is continuously increasing, societies become more vulnerable to a wide range of risks associated with inadequate water supply in quantity and/or quality. Hydrological models are important tools for planning sustainable use of water resources to meet various demands of water.

1.4 HYDROLOGICAL PROCESS

Hydrology can be defined as a science concerned with the occurrence, distribution and circulation of the water on the earth.

Hydrological process can be defined as the natural system in which water moves between land, atmosphere and the water bodies cyclically as shown in figure 1.1.

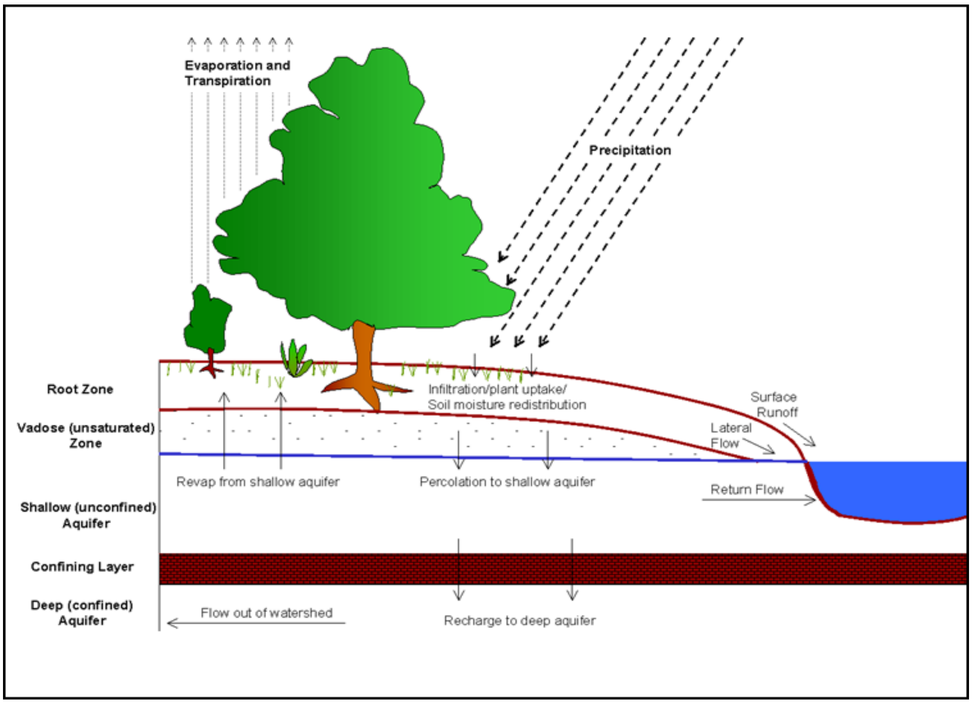


Figure 1.1 Schematic Representation of the Hydrologic Cycle

Hydrological cycle is composed of several natural processes which have interactions among themselves and they can be represented or simplified using a mathematical model. Following processes that are represented in hydrological cycle;

- Precipitation
- Water losses in from of evaporation, transpiration and seepage
- Surface flow
- Subsurface flow
- Absorption and Percolation

- Water movement from shallow to deep aquifers

1.5 HYDROLOGICAL MODELLING FOR PLANNING AND MONITORING OF WATERSHED

Hydrological modelling is generally a complicated job requiring a user-defined balance (and associated assumptions) between available inputs, necessary outputs, time constraints, computational effort, modelling experience, modelling efficiency, etc. Hydrological procedures are depicted through mathematical equations through traditional lumped, conceptual rainfall-runoff models. These equations involve a big amount of parameters, e.g. the Stanford Watershed Model IV utilizes 16 parameters and 21 parameters are used by the SACRAMENTO model. The model becomes unable to truly depict the study area due to absence of data about the different complicated phenomenon that occurs within the study region. Usually the minimum difference with high correlations in parameters within the measured and simulated value makes it hard to define the important individual parameter. This encourages researchers to develop physical based models such as the model for SHE, soil and water assessment tool (SWAT). While these models can represent the research region and different physical procedures that occur within it with very excellent precision, a big amount of input datasets are needed to operate these models. Therefore, data accessibility for model run and calibration remains the bottleneck to develop in this direction.

Several hydrological models, such as SWAT, SMAP, LASH, AnnAGNPS, among others, have been developed and implemented in the simulation. Among the hydrological models, emphasis should be placed on the conceptually distributed one, which simulates multiple procedures that make up the hydrological cycle based on spatialized empirical functions and input parameters, which is possible through model and integration of the Geographic Information System (GIS). With the advent of GIS, a big quantity of data that distributed hydrological models requires has become simpler to manage, thus allowing process simulations with higher physical base. Hydrological models, however, do not correctly depict water movement in a natural system, that is why with observed data they should be calibrated.

The current modelling philosophy requires that models are transparently described; and that calibration, validation, sensitivity and uncertainty analysis are routinely performed as part of modelling work. As calibration is ‘‘conditional’’ (i.e., conditioned on the model structure, model inputs, analyst’s assumptions, calibration algorithm, calibration data, etc.) and not uniquely determined, uncertainty analysis is essential to evaluate the strength of a calibrated model.

The Soil and Water Assessment Tool (SWAT) has demonstrated its strengths in the aspects specified above. It is an open source code with a large and growing number of model applications in various studies ranging from catchment to continental scales.

1.6 TYPES OF HYDROLOGIC MODELS

Hydrological models represent the hydrological cycle conceptually. These models are based on our knowledge of physics of hydrological process with control catchment response and use physically based equations to define these processes. The American Society of Civil Engineers (ASCE) introduced the fundamental terms like mathematical models, analytical models, deterministic models, dynamic models, empirical models, heuristic models, interactive models, linear and nonlinear models, numerical models, probabilistic (stochastic) models, simulation models of semi-empirical models and theoretical models.

A broad classification for hydrological models may emerge from the development of old-time hydrological models, but generally the models can be defined simply as black-box, conceptual or deterministic models. Figure 1.2 shows the schematic classification of hydrological models :

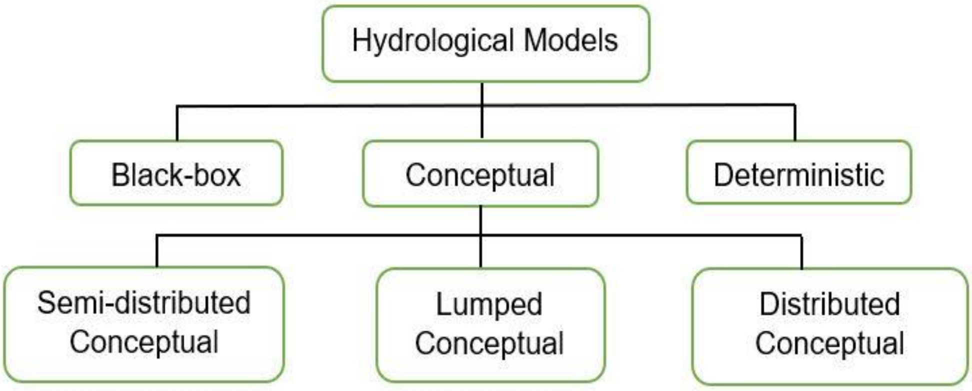


Figure 1.2 Classification of Hydrological Models

1.6.1 Black-box models

Black-box models mathematically illustrate the relationship between input and output data. Physical procedures are not usually considered in this sort of model. It is logical to say that because of their mathematical structure underlying the physical system. The prediction, however, is based completely on mathematics. Artificial Neural Network (ANN), for instance, is a type of black-box model represented by extremely complicated, multi-dimensional and non-linear relationships.

1.6.2 Deterministic models

Deterministic models have complex theory of physics and require a large amount of data and computational time. These models apply non-linear partial differential equations that describe the procedures of hydrology. One of the major benefits of deterministic models is that they show the inner perspective of a method that allows for a better understanding of the hydrological system. Soil and Water Assessment Tool (SWAT), for instance, utilizes a two-level disaggregation system; a preliminary sub-basin identification based on topographic criteria, followed by further discretization using considerations of land use and soil type.

1.6.3 Conceptual Models

Conceptual models are substitution between deterministic and black-box models. These models are generally developed with a number of conceptual components that are simple representations of a reference system. One of the benefits of conceptual models is its non-linearity that reflects the hydrological system's threshold existence.

1.7 ArcSWAT MODEL

ArcSWAT, which is embodied in ArcGIS, is a graphical user interface for SWAT (SOIL AND WATER ASSESSMENT TOOL) model. It is a river basin or watershed scale model developed by Dr. Jeff Arnold jointly for United States Department of Agriculture - Agriculture Research Services (USDA-ARS) and Agriculture Experiment Station in Temple, TEXAS (U.S.A).The model can be applied in various watershed and water quality modelling like National and regional scale watershed assessment for current and project management condition, impact assessment of global climate, simulation of land management practices, sediment contamination, poultry waste analyzation, evaluation of pesticide registration. The actual aim of developing this model is to predict the impact of land management practices on water, sediment and agriculture chemical yields in large complex watershed with varying soil, land use and management conditions over a long period of time.

1.7.1 Overview

SWAT is a continuous daily deterministic time-step model used to assess land-management procedures in basins. It is intended to forecast long-term non-point source pollution effects on water quality such as loads of sediments, nutrients and pesticides. It is a long-term simulation of hydrodynamic, physical, ongoing time model for complicated and big basins originating from an agricultural model. Model inputs include physical features of the basin and its sub-basins from variables such as precipitation, temperature, soil type, soil slope and slope, width and slope, Manning’s n values and universal soil loss equation (USLE) K factors. Either simulated or measured precipitation and temperature values can be used. The model enables statistical comparisons with model predictions of measured stream flow and sediment levels.

1.8 RESEARCH OBJECTIVES

The specific objectives of the proposed study are:

- To use GIS techniques for simulation of surface runoff and water balance study of Deo dam basin.
- DEM based watershed delineation.
- To classify HRUs using ArcSWAT tool based on spatial data Land use, soil type and slope variation.
- To analyse the watershed characteristics.
- To assess the different components of water balance for the Deo dam basin.
- To develop the model of the study area for the years 2000 to 2012 and to validate the model for the years 2013 to 2017.
- Calibration and Validation of the model using Soil and Water Assessment Tool-Calibration Uncertainty Program (SWAT-CUP) with Sequential Uncertainty Fitting 2 (SUFI-2) algorithm.
- To determine the sensitive basin parameters using Global Sensitivity Analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The review of the research works related to Rainfall-Runoff relationships using Soil and Water Assessment tool (SWAT) and Calibration and Validation using SWAT Calibration and Uncertainty Programs (SWAT-CUP) are described in this chapter.

2.2 LITERATURE REVIEW

Francos and Bidoglio *et al*. (2002) applied SWAT model to the Kwrava watershed, covering 400 km^2 area. The database prepared by temperature and precipitation records of number of meteorological stations. The model was adapted to specific conditions of catchment by adding a weather generator and snow melt sub-model calibrated for Finland. They compared the SWAT generated flows, nitrated and total phosphorous concentrations with daily and monthly based observed data for calibration and concluded that Nash and Sutcliffe efficiency coefficient was employed a good agreement with measured and predicted values.

Green and Griensven *et al*. (2008) embedded an auto- calibration sensitivity analysis procedure in SWAT version 2005 (SWAT 2005) to optimize parameter processing. The embedded procedure was applied to six small-scale watersheds (sub-watersheds) in the central Texas Blackland Prairie. The objective of this study was to evaluate the effectiveness of the auto calibration-sensitivity analysis procedures at small-scale watersheds (4.0-8.4 ha). Model simulations were completed using two data scenarios: (1) 1 year used for parameter calibration (2) 5 years used for parameter calibration. The impact of manual parameter calibration versus auto calibration with manual adjustment on model simulation results was tested. The combination of auto calibration tool parameter values and manually adjusted parameters for the 2000-2004 simulation period resulted in the highest NSE and R^2 values for discharge;

however, the same 5-year period yielded better overall NSE and R^2 and P-values for the simulation values that were manually adjusted. The disparity was not likely due to the limited number of parameters that were included in the version of the auto calibration tool (i.e Nperco, Pperco, and nitrate). Overall, SWAT2005 simulated the hydrology and the water quality constituents at the sub-watershed scale more adequately when all of the available observed data were used for model simulation as evidenced by statistical measure when both the auto calibration and manually adjusted parameters were used in the simulation.

Githui and Mutua *et al.* (2009) estimated runoff and the impacts of land-cover change on runoff using the soil and water assessment tool in Nzoia catchment in western Kenya in the Lake Victoria basin. The overall objective of this study was to estimate the impacts of land-cover change on runoff. They concluded that the changes in LULC over the period 1973–2001, have been significant and have contributed to a considerable increase in runoff. The agricultural area increased from about 39.6 to 64.3%, while the forest area decreased from 12.3 to 7.0%. The model-generated runoff increased by about 119% between 1970 and 1985. By putting climatic inputs constant the land-cover changes accounted for a difference in runoff of 55–68%.

Simic and Milivojevic *et al.* (2009) applied SWAT runoff modeling with theoretical background and numerical Procedures in complex catchment area of 20.000 km^2 on a selected part of the River Drina basin and computed total runoff on the exit profile of the catchment at the daily and hourly level of discretization and used for multiannual simulations. They found that the model reacts properly during the dry and rainy seasons and that it can be used successfully for annual and multiannual of simulations rainfall-runoff transformation. This result also indicates that the quality of simulation results during rain seasons is directly related to input data (rainfall, temperature and other).

Hosseini and Amin *et al.* (2011) applied soil and water assessment tools to model estimation of runoff. The study was done on the upper part of Taleghan dam watershed which is located in north western of Tehran, capital of Iran. They found surface runoff was 21% of the precipitation for the upper part of the catchment and 33% at the outlet. Groundwater and lateral flows took place mostly in the mountainous upper part of the catchment with contribution of 23% and 17% respectively. Evapotranspiration losses at Joestan and Galinak stations were around 38% and 49% of the precipitation. They found that high surface runoff and low interflow at Galinak station and inversely at Joestan station showed downstream of Joestan stations on need of greater soil conservation measures and concluded main reason was snowpack in the winter and good rangeland in other seasons. The study was done successfully reliable capability and high accuracy for annual and monthly water balance components of the Taleghan catchment.

Arnold and Moriasi *et al.* (2012) suggested the ideas about calibration and validation using SWAT-CUP. As SWAT required a large number of input parameters, which complicated the model parameterization and calibration so several calibration techniques were developed for SWAT, including manual calibration procedures and automated procedures using the shuffled complex evolution method and other common methods. In addition, SWAT-CUP was developed and provided a decision-making framework that incorporated a semi-automated approach (SUFI-2) using both manual and automated calibration and incorporate sensitivity and uncertainty analysis. In SWAT-CUP, users could manually adjust parameters and range iteratively between auto-calibration runs. Parameter sensitivity analysis helped to focus the calibration and uncertainty analysis and was used to provide statistics for goodness-of-fit. The user interaction or manual component of the SWAT-CUP calibration forced the user to obtain a better understanding of the overall hydrologic processes (e.g., base flow ratios, ET, sediment sources and sinks, crop yields, and nutrient balances) and of parameter sensitivity. It was important for future calibration developments to spatially account for hydrologic processes; improve model run time efficiency; include the impact of uncertainty in the conceptual model, model parameters, and measured variables used in calibration; and assist users in checking for model errors. All model input parameters were kept within a realistic uncertainty range and no automatic procedure could substitute for actual physical knowledge of the watershed.

Kaviya *et al.* (2012) estimated the runoff by using SWAT model in Brahmani and Baitarani rivers in year 2012. They executed the study using remote sensing data and other geo-spatial database, and other field data using semi-distributed hydrological models and concluded that runoff simulation SWAT performes better in all time steps and SWAT model provides 70% accuracy for daily time step for all sub-basins. The model also performed well when calibration parameters were extended to the validation year 2004-2005.

Mamo and Jain (2013) undertook the study to examine the applicability of the SWAT model in Gumera river basin upstream of Lake Tana, Ethiopia for simulating stream runoff and sediment load. The area of river basin was discretized into 24 sub- catchments using ArcSWAT interface of the model. The semi automated Sequential Uncertainty Fitting (SUFI2) and fully automated Parameter Solution (ParaSol) calibration process built in SWAT calibration and uncertainty program (SWAT-CUP) were used to calibrate the model parameters using time series of flow and sediment load data of 1994 to 2002 and validated with the observed data from years 2003 to 2006.

Narsimlu and Gosain *et al.* (2013) selected a semi-distributed model SWAT for Upper Sind River basin that effectively manages the water resources. Model calibration and uncertainty analysis were performed with Sequential Uncertainty Fitting of SWAT Calibration and Uncertainty Programme. Results showed that p-factor was 0.73 and r-factor was 0.42 in calibration period (1992-2000) while p-factor was 0.42 and r-factor was 0.36 in validation period (2001-2005). When values of p-factor and r-factor were accepted, further goodness of fit quantified by the coefficient of determination and Nash–Sutcliffe coefficient between observed and final best simulated data. Results indicated that R^2 was 0.82 and NSE was 0.80 in calibration period, while R^2 was 0.96 and NSE was 0.93 in validation period. Outcomes of calibration and uncertainty analysis were satisfactory.

Santra and *Das* (2013) estimated runoff and sedimentation with the help of runoff modelling in from an agricultural watershed of western catchment of Chilika Lake (the biggest lagoon in the Indian Eastern coast) through ArcSWAT. They observed the deposition of sediments in the lake carried through runoff water from its drainage basins may alter this wetland ecosystem in future. So implementation of appropriate soil water conservation measures might reduce the sediment load in runoff water and thus to protect this lagoon ecosystem. They applied the ArcSWAT with a purpose to estimate future runoff potential from western catchment and concluded that Nashe Sutcliffe coefficient of predicted monthly runoff was 0.72 and 0.88 during calibration and validation periods respectively and the root mean squared error of predicted monthly runoff was 54.5 and 66.1 mm for calibration and validation periods respectively. Modeling results indicated that about 60% of rainfall is partitioned to runoff water, which carry significant amount of sediment load and contributes to Chilika Lake.

Singh and Bankar *et al*. (2013) did hydrological stream flow modeling on Tungabhadra catchment and performed parameterization and uncertainty analysis using SWAT-CUP. Adequate stream flow measurement was vital for agricultural watershed management and its effect on many aspects of water balance parameters. For that reason, soil water assessment tool (SWAT) was applied for the measurement of the stream flow to the Tungabhadra catchment in India. They described a methodology for calibration and parameter uncertainty analysis for distributed model based on generalized likelihood measures. The sequential uncertainty domain parameter fitting algorithm (SUFI-2) and generalized likelihood uncertainty equation (GLUE) of SWAT-CUP worked with multiple sets of parameter values and allowed the user within the slight limitation of the model structure in boundary conditions and field observations. The performance of the SUFI-2 and GLUE techniques was evaluated using five objective functions, namely P- factor, R-factor, the coefficient of determination R^2, Nash–Sutcliffe Efficiency (NSE) and coefficient of determination divided by the coefficient of regression R^2 calculated on daily and monthly time steps. The obtained results showed that the observed and simulated discharge were not significantly different at the 95% level of confidence (95PPU). The results showed excellent correlation during monthly calibration time steps, whereas daily calibration exhibited relatively good agreement between the observed and simulated flows.

Shivhare and Goel *et al.* (2014) estimated the surface runoff for upper Tapi Subcatchment Area (Burhanpur watershed) in inter-state basin of Madhya Pradesh and Maharashtra with total geographic area of 9364 km^2 under study by using SWAT with the specified data at daily time step and the output results analyzed at monthly time step. They compared simulated flows at the basin with the observed flows for four years of record (1992-93 to 1995-96) and concluded that the coefficient of determination for the monthly runoff can be considered as a satisfactory, which indicates the performance of SWAT model is good.

Kaona and Boupha (2015) successfully calibrated and validated The SWAT2009 model in the Xebanghieng River Basin using different algorithm. It was applied to the Xebanghieng River Basin for the modeling of the hydrological water balance. The sensitivity analysis of the model to sub basin delineation and HRU definition thresholds showed that the flow is more sensitive to the HRU definition thresholds than sub basin discretization effect. Annual average discharge at the Kengdon gauging site was found to be 516.76 m3/s. The runoff depth is about 1700 mm, higher than the average annual rainfall at mouth. The monthly discharge is highest in the month of August followed by September and July. Value of the coefficient of determination (R^2) of 0.69 (daily simulation) and 0.81 (monthly simulation), Nash-Sutcliff efficiency (NSE) of 0.67 (daily simulation) and 0.79 (monthly simulation), indicates satisfactory calibration of the ArcSWAT model. For the Kengdon gauging site for model validation period (2003-2005) and Annual average discharge is 524.96 m3/s, Value of coefficient of determination (R^2) of 0.85 (daily simulation) and 0.94 (monthly simulation), Nash-Sutcliff efficiency (NSE) of 0.85 (daily simulation) and 0.94 (monthly simulation), indicates satisfactory validation of the Arc SWAT model.

Bebau and Jomaa *et al.* (2016) The objective of the study undertaken was to assess the performance and predictive uncertainty of the Soil and Water Assessment Tool (SWAT) model on the Bani River Basin, at catchment and subcatchment levels. The SWAT model was calibrated using the Generalized Likelihood Uncertainty Estimation (GLUE) approach. Potential Evapotranspiration (PET) and biomass were considered in the verification of model outputs accuracy. Global Sensitivity Analysis (GSA) was used for identifying important model parameters. Results indicated a good performance of the global model at daily as well as monthly time steps with adequate predictive uncertainty. PET was found to be overestimated but biomass was better predicted in agricultural land and forest. Surface runoff represents the dominant process on streamflow generation in that region. Individual calibration at sub catchment scale yielded better performance than when the global parameter sets were applied. These results are very useful and provide a support to further studies on regionalization to make prediction in ungauged basins.

Teshager and Gassman *et al*. (2016) The SWAT model was the calibrated/validated for Raccoon River watershed in Iowa for 2002–2010 and Big Creek River watershed in Illinois for 2000–2003. Applications of the Soil and Water Assessment Tool (SWAT) model typically involve delineation of a watershed into sub-watersheds/sub-basins that are then further subdivided into hydrologic response units (HRUs) which are homogeneous areas of aggregated soil, land use, and slope and are the smallest modelling units used within the model. In a given standard SWAT application, multiple potential HRUs (farm fields) in a sub-basin are usually aggregated into a single HRU feature. In this study, ArcGIS pre-processing procedures were developed to spatially define a one-to-one match between farm fields and HRUs (spatially unique HRUs) within a sub basin prior to SWAT simulations to facilitate input processing, input/output mapping, and further analysis at the individual farm field level. Model input data such as land use/land cover (LULC), soil, crop rotation, and other management data were processed through these HRUs. SWAT was able to replicate annual, monthly, and daily streamflow, as well as sediment, nitrate and mineral phosphorous within recommended accuracy in most cases. The one-to-one match between farm fields and HRUs created and used in this study is a first step in performing LULC change, climate change impact, and other analyses in a more spatially explicit manner.

Hosseini and Ghafouri *et al*. (2017) prepared the SWAT2012 model for estimation of hydrological budget in six subbasin of Persian Gulf watershed; Golgol, Baghan, Marghab Shekastian, Tangebirim and Daragah, which are located in south and south west of Iran during 1991–2009. The water budget components encompass surface runoff, lateral flow, groundwater flow, evapotranspiration and soil water content. Comparison of the modeled results with measured water budgets allowed comparison of the accuracy of the different components of the model. In this particular study, it demonstrates that each components of the model gives reasonable output. This should allow more realistic appraisal of various land use management practices on a large watershed. It should also better pinpoint exactly how each alternative will affect the water budget, thus allowing for more innovative management practices to test a priori and their effects traced through each hydrologic component of the watershed.

Jajarmizadeh and Sidek *et al*. (2017) selected Roodan watershed for simulation of daily flow in southern part of Iran with an area of 10,570 km^2. Three scenarios as evolution have been performed for calibration and uncertainty analysis. (1) The global method, which is adjusted for sensitive parameters globally for whole watershed; (2) discretization method, which is considered for dominant features (e.g., land use and soil type) in calibration; (3) the optimum parameters method, which is adjusted for only those sensitive parameters by considering effectiveness of their features according to SUFI-2 algorithm. According to NS coefficient, all scenarios (1, 2, and 3) are logical and satisfactory and they have a fair tendency with observed data. The result also showed that condition of parameters (parameter set) during calibration in SWATCUP program model has an important role to increase the performance of the model.

Kurbah and Jain (2017) undertook a study with an aim to test the performance of SWAT Hydrological model on Sher River at Belkheri in Narsimhpur District of Madhya Pradesh, India. For model application, the watershed area was divided into 11 sub-watersheds. They found that the accuracy and precision of the model can be improved drastically with better and high resolution gridded rainfall data or if available observed meteorological data. Therefore, SWAT can be an important tool for integrated basin management with respect to water flow and its availability where the significant factor lies with the basin dominated with Agriculture fields. This will bring the potential for irrigation and better agriculture management practices and directly and indirectly helps in improving the socio-economic life of the people.

Mehan and Neupane *et al*. (2017) coupled SWAT and SUFI 2 for improving the simulation of streamflow in an agricultural watershed of South Dakota. Simulation results showed a reasonable accuracy between measured and model simulated stream flow values. The SWATCUP improved the stream flow simulations, and reducing uncertainty among the parameters. It was observed that due to the inclusion of larger confidential interval in less sensitive parameters, the uncertainty reduction among these parameters took more time than more sensitive parameters. Moreover, during parameterization process, awareness of physical meaningful range of parameters chosen for calibration led to better simulation results. It was also observed that in order to maximize the objective function, optimum number of iterations and simulations should be performed, else the best fitted value for the parameters may go beyond acceptable range. Finally, semi-automated stochastic model, the SWAT-CUP improved the SWAT simulations of stream flow with the meaningful physical acceptable range of the key hydrologic parameters and higher statistical evaluating parameters depicting more reliability of simulated results.

Alipour and Hosseini (2018) simulated runoff in Karaj Dam basin in Iran. The main objective of this study was to develop a catchment modeling platform which translates ongoing land-use changes, soil data, precipitation and evaporation into surface runoff of the river discharging into the reservoir using Soil and Water Assessment Tool, SWAT, model along with hydro-meteorological records of 1997–2011. A variety of statistical indices were used to evaluate the simulation results for both calibration and validation periods; among them, the robust Nash–Sutcliffe coefficients were found to be 0.58 and 0.62 in the calibration and validation periods, respectively. In this study, eight sensitive parameters including CN2, ALPHA_BF, CH_K2, ESCO, CH_N2, REVAPMN, GW-REVAP and SOL-BD were used in with a successful effort to decrease uncertainty.

Tejaswini and Sathian (2018) conducted a study to calibrate the SWAT model for Kunthipuzha basin using SUFI-2 algorithm in SWAT-CUP package. Kunthipuzha River is an important tributary of Bharathapuzha river basin, the second largest river basin in Kerala. Both one-at-a time and global sensitivity analysis were conducted. Calibration was done for a period of 7 years starting from 2000 to 2006, whereas, validation was done for a 3 year period starting from 2007 to 2009. The values of statistical indices such as NSE and R^2 were 0.81, 0.82 for calibration period and 0.73, 0.88 for validation period respectively which indicates the “very good” performance of the model in simulating hydrology. The p-factor and r- factor were 0.69 and 0.47 for calibration period, 0.57 and 0.51 for validation period respectively. SUFI-2 was found to be very convenient and easy to use than the other automatic calibration techniques. The most sensitive factor was found to be ALPHA_BF followed by CH_K2, CN2, SOIL_Z and SURLAG.

Venkatesh and Chandramohan *et al*. (2018) calibrated process-based rainfall-runoff model namely Soil and Water Assessment Tool (SWAT) for Manimala River basin in Kerala, with a catchment area of 780 km^2. The optimized curve number for the catchment was reported to be 78, which is indicative of generating higher runoff. The results obtained showed that the surface runoff is influenced by the parameters such as CN, ESCO, and SOL_AWC, whereas baseflow was influenced by lower values of GW_REVAP and ALPHA_BF.

Yaduvanshi and Sharma *et al*. (2018) analyzed the runoff response during extreme rain events over the basin of Subernarekha river in India using Soil and Water Assessment Tool (SWAT). The SWAT model is configured for the Subarnarekha River basin with 32 sub-basins. Three gauging stations in the basin (viz., Adityapur, Jamshedpur and Ghatshila) were selected to assess the model performance. Calibration and validation of the model were performed using the Soil and Water Assessment Tool-Calibration Uncertainty Programs (SWAT-CUPs)with sequential uncertainty fitting (SUFI-2) algorithm. The study concluded that the model performed well in Ghatshila gauging station with a Nash–Sutcliffe efficiency (NSE) of 0.68 during calibration and 0.62 during validation at daily scale. The model, thus calibrated and validated, was then applied to evaluate the extreme monsoon rain events in recent years. Five extreme events were identified in Jamshedpur and Ghatshila sub-basins of Subarnarekha River basin. The simulation results were found to be good for the extreme events with the NSE of 0.89 at Jamshedpur and 0.96 at Ghatshila gauging stations. The findings of this study can be useful in runoff simulation and flood forecasting for extreme rainfall events in Subarnarekha River basin.

Aadhar and Swain *et al.* (2019) checked the applicability of soil and water assessment tool (SWAT) model over the Kharun River Basin, Chhattisgarh, India. The SWAT simulations generated runoff, which was auto-calibrated with the observed values through SWAT-CUP. The model was run for a period of 20 years i.e. 1994-2014 to check its performance and applicability. Generalized uncertainty likelihood estimation (GLUE) optimization approach was used for sensitivity analysis of various parameters during auto-calibration. The results revealed for a moderate correlation between the observed and modelled values at daily time scale i.e. the Nash-Sutcliffe efficiency and R^2 values are close to 0.5. This highlighted the fact that model application needs to be carried out carefully with processed and reliable data sets.

Bhattacharya and Khare *et al*. (2019) found the major problem in estimating snowmelt runoff for Beas river basin is inadequacy of observed meteorological data distributed across the basin. The snow module of ArcSWAT hydrology model has been simulated by integration of sub basin-wise elevation band files for modeling snowmelt runoff process including sediment yield due to rainfall and temperature change for different elevation bands varying from 361 to 6188 m. The gridded reanalysis (0.125° × 0.125°) dataset produces a decreased maximum and minimum temperature and increased precipitation at higher elevation in comparison with IMD gridded weather data. The outcome of this study conveys that the reanalysis data represent better snowmelt runoff (NSE = 0.76, 0.70 and R^2 = 0.80, 0.70) and sediment yield (NSE = 0.50, 0.53 and R2 = 0.72, 0.57) mechanism at Pong and Pandoh dams than IMD gridded weather data (NSE = 0.50, 0.47 and R^2 = 0.65, 0.60) for stream flow and (NSE = 0.50, 0.53 and R^2 = 0.65, 0.60) sediment yield during the period 1996–1999 and 1999–2002 for these two locations.

Das and Jain *et al*. (2019) applied SWAT model to understand the status of water resources as well as hydrological process in the Gomti river basin. The basin was calibrated through monthly discharge for the period (2002–2008) including 2 years as warm-up (2000–2001), after that model was validated on 5 years of hydrometeorological datasets (2009–2013) at two gauge sites located at Neemsar (upstream gauge) and Lucknow (downstream gauge). It was found that the most sensitive parameter for moisture condition II (CN2) was initial curve number. The p-factor and r-factor were obtained in calibration period at Neemsar 0.73 and 0.58 while at Lucknow values are 0.79 and 0.51, whereas in validation period values are 0.61, 0.45 and 1.22, 0.75, respectively. Three statistical parameters have been used to evaluate the SWAT model performance such as Coefficient of Determination (R^2), Nash–Sutcliff efficiency (NSE), percent bias (PBIAS). The NSE and R^2 values were observed as 0.85, 0.84 and 0.87, 0.86, respectively, in the time of calibration period and values is 0.76, 0.76 and 0.79, 0.83, respectively, in the time of validation period at two above said gauging stations. The PBIAS values during calibration and validation period were − 13.3, − 14.7 and − 4.0, − 15.7, respectively, at the same gauge site which indicates good model performance result.

Khayyun and Alwan *et al*. (2019) prepared hydrological model for Hemren dam reservoir catchment area at the middle River Diyala reach in Iraq using ArcSWAT model. The model was calibrated in monthly time step for the period extended from 1981 to 2000 with 2 years of warm-up period and validated with observed stream flow for years between 2001 and 2008. The model calibration and parameters sensitivity analysis were conducted using automatic calibration method within the SWAT-CUP program. Results showed that an effective runoff happens at wet seasons, and there is not continuous effective base flow from the studied catchment, and the average annual inflow volume to Hemren dam reservoir during the simulation period was 0.871 BCM, i.e., 17.42% of the overall inflow volume to Hemren dam reservoir. Furthermore, it was founded that the use of climate forecast system reanalysis of global weather station data is possible in the studied catchment area. Finally, a simple direct regression formula was determined by correlating the monthly runoff volume with monthly rainfall depth.

CHAPTER 3

TOOLS AND TECHNIQUES

3.1 GENERAL

This chapter contains details about SWAT model, its definition, basic features, SWAT Modelling, Land phase and routing phase of hydrological cycle in SWAT, description of SWAT-CUP and SUFI-2 algorithm.

3.2 SWAT MODEL

Soil and Water assessment Tool (SWAT) is River basin or watershed scale model developed Dr. Jeff Arnold in 1985 for the USDA rural Research Service. SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. Arc SWAT, a version of SWAT integrated with a Geographic Information System allows the user to prepare SWAT input and run the model within the framework of ArcGIS.

Figure 3.1 Soil & Water Assessment Tool

3.3 BASIC FEATURES OF SWAT

SWAT is a continuous time step, long-term yield spatially discrete model. Compared to other modelling techniques, SWAT has home unique features (quoted from SWAT Manual, Neitsch, 2012):

- Daily time long term simulations of model.
- Basins are subdivided based on differences in soil, land use/land cover, crops, geology, and climate, so forth.
- Few thousand square miles basins area can be examined.
- Soil profile can be isolated into ten layers.
- Basins can be sub-divided into number of sub-catchment.
- Hundreds of cells / sub-basin can be simulated in spatially shown outputs.
- Groundwater flow model.
- Nutrients and pesticide input/output.
- SWAT accepts measured data & point sources.
- Water can be transferred from channels and reservoirs.

3.4 BASIC MODELING METHOD OF SWAT

Conservation of mass is the basic principle of hydrologic modelling. Simulation of the hydrology of a watershed can be separated into two major divisions. The first division is the land phase of the hydrology cycle. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loading to the main channel in each sub-basin. The second division is the routing phase of the hydrologic cycle, which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet.

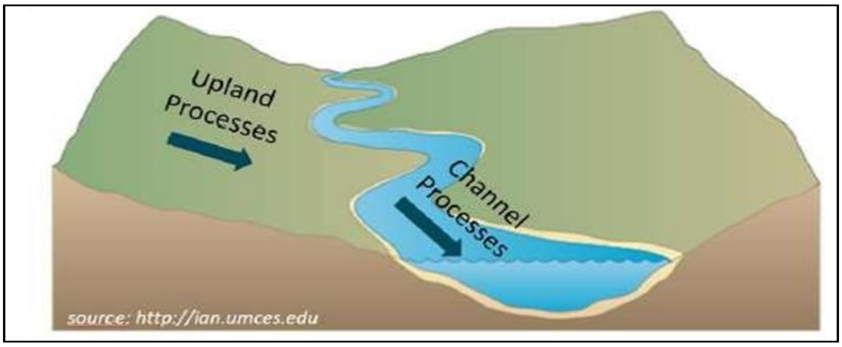


Figure 3.2 Conceptual Model of Hydrologic Simulation in the SWAT Model (Upland process and Channel process)

In SWAT, watersheds are divided into sub-basins and each sub basin is further divided into numbers of Hydrologic Response Units (HRU). The division of the sub-basins is determined by geological location and connection of the streams. The classification of HRU is determined by soil types, land used conditions, and elements related to vegetation and landscape characteristics. Each HRU is spatially independent. Water generated from HRUs contributes to reaches through the most upstream end of the main river within the sub-basin. Sub-basins are spatially connected by river reaches. Water contributed to each sub-basin is then conveyed through reaches along the stream network. The Land phase generally represents the water cycles within sub-basins and the routing phase represents the water flow among sub-basins.

3.5 MODEL PROCESSING

Modeling procedures include water balance calculations that are the driving force behind all that occurs in a basin to predict the motion of runoff, sediment or nutrients correctly. The elements of the model processing are the land phase and routing phase.

3.5.1 Land Phase of the hydrological cycle

Land phase regulates the quantity of runoff and sediment that flows into the basin's main channel so that control measures can be applied to both soil and water conservation. This stage follows the principle of equation of the fundamental water equilibrium or water balance.

$$SWt = SWo + \sum_{i=1}^{n}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad \ldots(3.1)$$

Where,

SW_t = Final soil water content (mm)

SW_o = Initial soil water content (mm)

t = Time in days.

R_{day} = Amount of precipitation on day i (mm)

Q_{surf} = Amount of surface runoff on day i (mm)

E_a = Amount of evapotranspiration on day i (mm)

W_{seep} = Amount of percolation and bypass exiting the soil profile bottom on day i (mm)

Q_{gw} = Amount of return flow on day i (mm)

The subdivision of the watershed allows the model to represent variations in evapotranspiration for different plants and soils. Runoff is anticipated individually for each HRU and routed to get the complete runoff for the watershed. This improves precision and provides a much better physical description of the water balance.

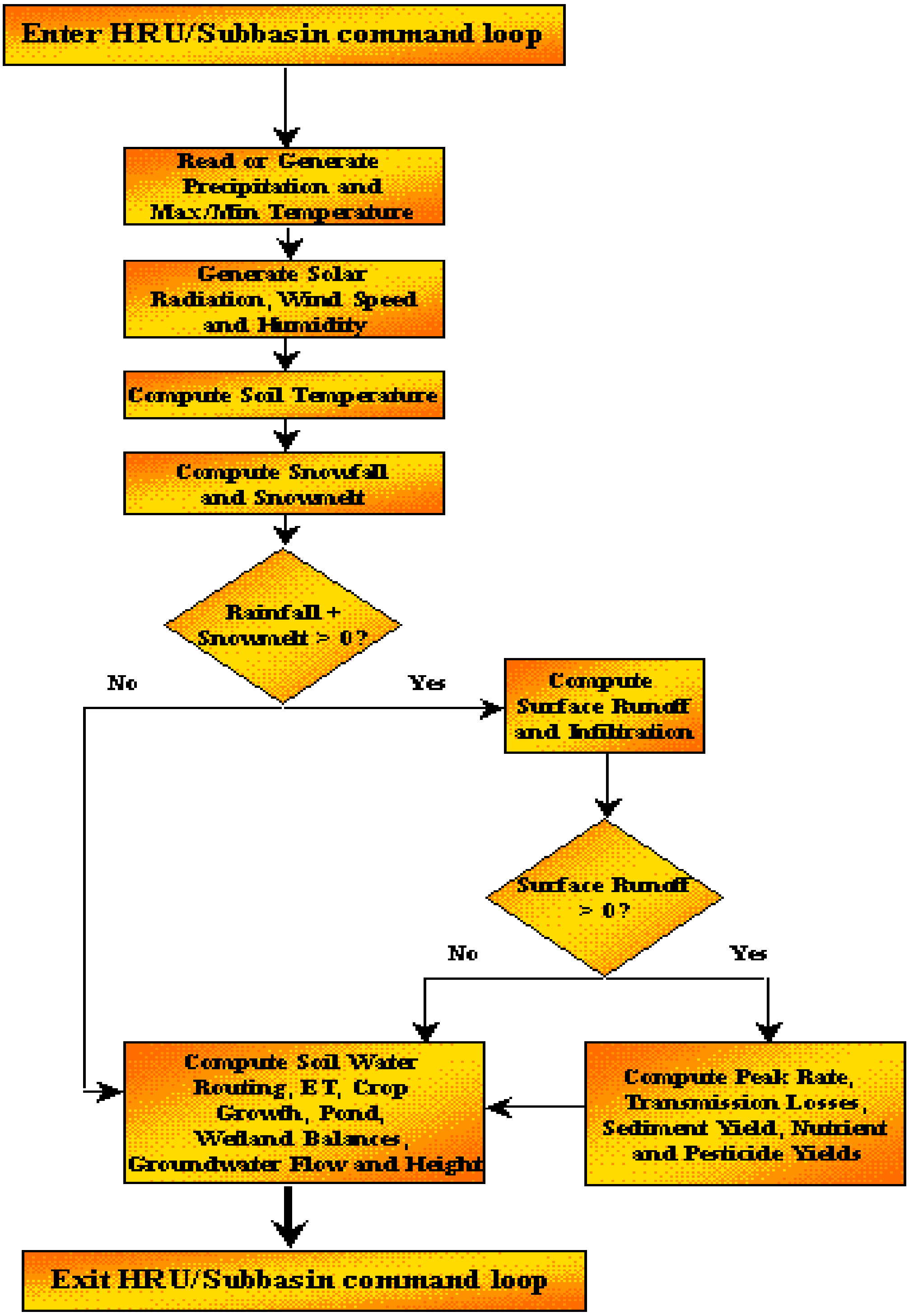


Figure 3.3 HRU/Sub-basin Command Loop

Figure 3.3 shows the general sequence of processes used by SWAT to model the land phase of the hydrologic cycle. The different inputs and processes involved in this phase of hydrologic cycle are summarized in the following sections.

3.5.1.1 Climate

The climate of a watershed offers the inputs of moisture and energy that regulate the water balance and determine the relative significance of the various parts of the hydrological cycle.

The climate variables needed by SWAT consist of daily precipitation, maximum/ minimum air temperature, solar radiation, wind speed and relative humidity. The model allows values for daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity to be input from records of observed data or produced during simulation.

- **Weather Generator**

Daily weather values are produced from average monthly values. The model produces a set of weather data for each sub-basin. The values for each sub-basin will be produced separately and there will be no spatial correlation of produced values between the distinct sub-basins. SWAT needs daily input values of precipitation, maximum and minimum temperatures, solar radiation, relative humidity and wind speed. They can be given to the model as a measured time series defined by the user or can be generated within SWAT from a monthly data and summarized over a number of years (Global Weather Database). A WXGEN climate generator model can produce the above-mentioned information or fill in gaps for measured records based on the continuous U.S. situation. It can also be introduced to local circumstances by offering a user-defined database (userwgn.dbf).

Generated Precipitation

SWAT utilizes a model created by Nicks (1974) to produce daily precipitation for simulations that do not read in measured information. The precipitation generator utilizes a first-order Markov chain model to describe a day as wet or dry by comparing a random number (0.0-1.0) produced by the model to the user's monthly wet-dry probabilities. If the day is categorized as moist, the quantity of precipitation will be produced from a skewed distribution or a modified exponential distribution.

Sub-daily rainfall patterns

If sub-daily precipitation values are required, a double exponential function is used to represent the intensity patterns within a storm.

Generated air temperature and solar radiation

From a normal distribution, maximum and minimum air temperatures and solar radiation are produced. A continuity equation is integrated into the generator to account for differences in temperature and radiation induced by dry vs. rainy conditions.

Generated wind speed

A modified exponential equation is used to generate daily mean wind speed given the mean monthly wind speed.

Generated relative humidity

The relative humidity model utilizes a triangular distribution to simulate from the monthly average the daily average relative humidity. As with temperature and radiation, the mean relative daily humidity is adapted to account for wet-and dry-day impacts.

- **Soil Temperature**

  Soil temperature affects the motion of water and the rate of residue decay in the soil. The average daily soil temperature is calculated on the soil surface and the centre of each soil layer. The temperature of a soil layer is a function of surface temperature, mean annual air temperature and soil depth at which temperature variation owing to modifications in climatic circumstances no longer happens. This depth, referred to as the damping depth, depends on the bulk density and soil water content.

3.5.1.2 Hydrology

As precipitation falls, it may be intercepted and kept in the canopy of the vegetation or drop from the surface of the soil. Water on the soil surface will infiltrate as runoff into the soil profile or overland flow. Runoff moves comparatively quickly towards a stream channel and adds to short-term stream response. Infiltrated water makes its way to the soil and then it may be used by vegetation in the form of evapotranspiration or it can slowly make its way through underground routes to the surface water system. The potential pathways of water movement simulated by SWAT in the HRU are explained as,

- **Canopy Storage**

Canopy storage is the water intercepted by vegetative surfaces (the canopy) where it is stored and made accessible for evaporation. In the surface runoff calculations, canopy storage is taken into consideration when using the curve number technique to calculate surface runoff. SWAT allows the user to input the maximum amount of water that can be stored for land cover in the canopy at the maximum leaf area index. Water is first removed from the canopy storage when evaporation is calculated.

- **Infiltration**

Infiltration relates to the entry of water from the soil surface into a soil profile. As infiltration progresses, the soil becomes progressively moist, causing the rate of infiltration to decline with time until it reaches a constant value. The original infiltration rate relies on the moisture content prior to the introduction of water on the soil surface. The final infiltration rate is equal to the saturated hydraulic conductivity of soil. Because the technique of curve number is used to calculate surface runoff works on a daily time-step, it is unable to immediately model infiltration.

- **Evapotranspiration**

Evapotranspiration is a collective term for all processes by which water in the liquid or solid phase at or near the earth's surface becomes atmospheric water vapour. Evapotranspiration includes evaporation from rivers and lakes, bare soil and vegetative surfaces; evaporation from within plant leaves (transpiration); and sublimation from ice and snow surfaces. The model independently calculates plant and soil evaporation as outlined by Ritchie (1972). Potential soil water evaporation is predicted as a function of potential evapotranspiration and leaf area index (area of plant leaves relative to the area of the HRU). The actual evaporation of soil water is estimated using exponential functions of soil depth and water content.

- **Lateral sub-surface flow**

  Lateral subsurface flow, or interflow, is streamflow contribution that originates below the surface but above the zone where rocks are saturated with water. Lateral subsurface flow in the soil profile (0-2m) is calculated concurrently with redistribution. A kinematic storage model is used to predict lateral flow in each soil layer. The model accounts for variations in conductivity, slope and soil water content.

- **Surface Runoff**

  Surface runoff volume is computed using a modified SCS curve number method (USDA Soil Conservation Service, 1972) or the Green & Ampt infiltration method (1911). In the curve number method, the curve number varies non-linearly with the water content of the soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation. The Green & Ampt method requires sub-daily precipitation data and it calculates infiltration as a function of the wetting front matric potential and effective hydraulic conductivity.

- **Return flow**

  Return flow or base flow is the volume of streamflow originating from groundwater.

  SWAT separates groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the watershed and a deep, confined aquifer which contributes return flow to streams outside the watershed.

3.5.1.3 Management

SWAT allows the user to define management practices taking place in every HRU. The user may define the beginning and the ending of the growing season, specify timing and amounts of fertilizer, pesticide and irrigation applications as well as timing of tillage operations. At the end of the growing season, the biomass may be removed from the HRU as yield or placed on the surface as residue.

3.5.2 Routing Phase of the hydrological cycle

The routing phase regulates runoff motion, sediments to the outlet through the basin channel network. Using the variable storage routing technique or Muskingum process, flow is transmitted through the channel. Storage routing is based on the continuity equation for a specified reach section in the variable storage routing technique.

$$V_{in} - V_{out} = \Delta V_{stored} \quad \ldots(3.2)$$

Where,

V_{in} = Volume of inflow during the time step (in m^3)

V_{out} = Volume of outflow during the time step (in m^3)

ΔV_{stored}= Change in volume of storage during the time step (in m^3)

Once SWAT determines the loadings of water, sediment, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed using a command structure comparable to that of HYMO. In addition to maintaining the track of mass flow in the channel, SWAT models the transformation of chemicals in the stream and streambed.

3.5.2.1 Routing in the Main channel or reach

Routing in the main channel can be divided into four parts: water, sediment, nutrients and organic chemicals.

- **Flood Routing**

Flow is routed through the channel using a variable storage coefficient method developed by Wiliams (1969) or the Muskingum routing method.

- **Sediment Routing**

The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. SWAT uses stream power to estimate deposition/degradation in the channels.

3.5.2.2 Routing in the Reservoir

The water balance for reservoirs includes inflow, outflow, rainfall on the surface, evaporation and seepage from the reservoir bottom and diversions.

- **Reservoir Outflow**

The model provides three alternatives for estimating outflow from the reservoir. The first option allows the user to input measured outflow. The second option, designed for small , uncontrolled reservoirs, requires the user to specify a water release rate. When the reservoir volume exceeds the principle storage, the extra water is released at the specified rate. Volume exceeding the emergency spill way is released within one day. The third option, designed for larger, managed reservoirs, has the user to specify monthly target volumes for the reservoir.

- **Sediment Routing**

The concentration of sediment in the reservoir is estimated using a simple continuity equation based on the volume and concentration of inflow, outflow, and the water retained in the reservoir.

3.6 PRINCIPLES OF ESTIMATION OF SURFACE RUNOFF

Surface runoff relates to the part of rainwater in interception, infiltration, and evapotranspiration that is not lost. If the precipitation rate exceeds the infiltration rate, surface runoff will occur. To calculate surface runoff, SWAT utilizes hourly and daily time measures. The Green and Ampt equation is used on an hourly basis and the daily calculation is based on an empirical SCS curve number (CN) technique. Basin is delineated into sub-basins for this runoff estimate, which are then further split into hydrological response units (HRUs). Here, the technique for estimating surface runoff adopted was SCS curve number.

3.6.1 SCS Curve Number Procedure

The SCS runoff equation is an empirical model commonly used in the 1950s. It was the result of more than 20 years of research involving interactions of rainfall-runoff from small rural basins throughout the United States. The model was created to provide a coherent foundation for estimating runoff quantities under different kinds of land use and soil. To assign different curve numbers, SWAT uses the soil classification of the U.S. Natural Resource Conservation Service.

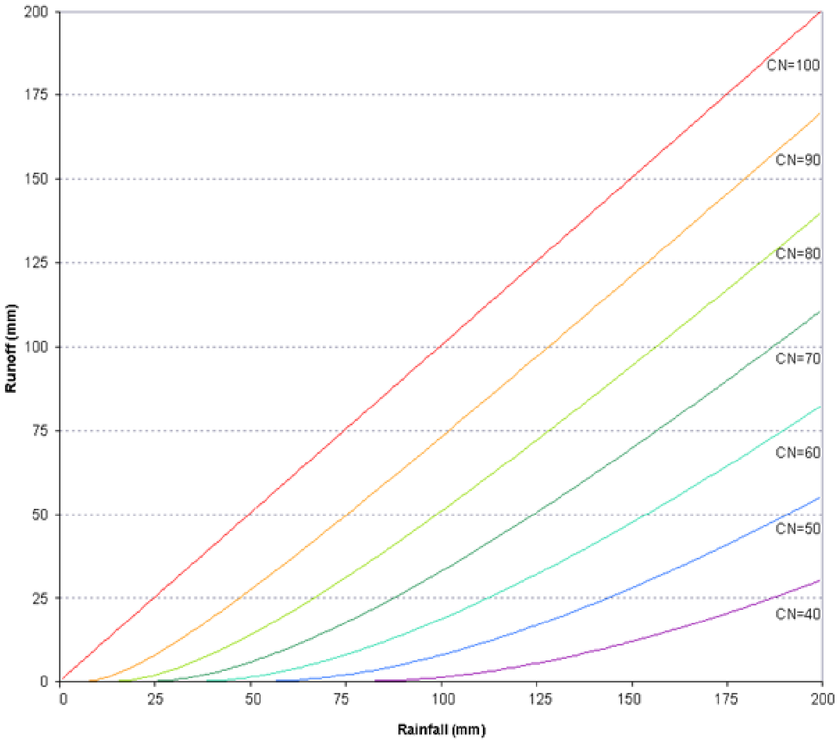


Figure 3.4 Relationship of Runoff to Rainfall in SCS Curve Number Method.

$$Q_{surf} = \frac{(R_{day}-I_a)^2}{(R_{day}-I_a+S)} \qquad \ldots(3.3)$$

Where,

Q_{surf} = Accumulated runoff or rainfall excess (mm)

R_{day} = Rainfall depth for the day (mm)

I_a = Initial abstractions, which includes surface storage, interception and infiltration (mm)

S = Retention parameter (mm)

$$S = 25.4(\frac{100}{CN} - 10) \quad \ldots(3.4)$$

Where,

CN = Curve number for the day

Finally the equation becomes,

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \quad \ldots(3.5)$$

3.6.2 Antecedent Moisture Condition

SCS describes three Antecedent Moisture Conditions, (AMC): I — dry (wilting point), II — average humidity, and III — wet (field ability). The smallest value of the daily curve number can be assumed in dry conditions for moisture condition II curve number. The equations calculate the curve numbers for moisture conditions I and III:

$$CN_1 = CN_2 - \frac{20(100 - CN_2)}{(100 - CN_2 + \exp[2.533 - 0.0636(100 - CN_2)])} \quad \ldots(3.6)$$

$$CN_3 = CN_2 * \exp(0.00673 * (100 - CN_2)) \quad \ldots(3.7)$$

Where, CN_1, CN_2 and CN_3 are curve numbers for AMC-I, II and III respectively.

3.6.3 Slope Adjustments

Williams (1995) developed an equation to adjust the curve number to a different slope.

$$CN_{2s} = \frac{(CN_3 - CN_2)}{3} * \left(1 - 2 * e^{(-13.86 * slp)}\right) + CN_2 \quad \ldots(3.8)$$

Where,

CN_{2s} = Moisture condition II curve number adjusted for slope

CN_3 = Moisture condition III curve number for the default 5% slope

CN_2 = Moisture condition II curve number for the default 5% slope.

slp = Average fraction slope of the sub-basin

The Green-Ampt infiltration technique is based on the values of Green and Ampt (1911) and Mein and Larson (1973). It says that water infiltrates as a sharp wetting front into comparatively dry soil. The technique requires information on sub-daily precipitation and it depends on the wetting capacity of the front matrix and the efficient hydraulic conductivity of the soil profile (Ksat). The Green-Ampt infiltration technique requires extensive information compared to the SCS curve number technique and is not feasible for large basins. Compared to the Green-Ampt infiltration technique, the disadvantage of the SCS curve number technique is that it lumps canopy interception in the original abstraction term and also requires a slope adjustment.

3.7 MERITS AND LIMITATIONS OF SWAT MODEL

The following are some merits of the SWAT model:

- The daily time based distributed parameter model is simple and user friendly.
- It is efficient to operate on large basins in a reasonable time.
- It is a continuous timescale model which is capable of simulating long-term effects of management changes.
- It has high potential to integrate with GIS. The output data from other simulation models can also be input to the SWAT.

The following are some limitations of the SWAT model:

- The main weakness of the SWAT model is a non-spatial representation of the HRU inside each sub-catchment.
- Wide range of different data are needed to run the model and numerous parameters are needed to be modified during the calibration which discourages modellers to use SWAT.
- It simulates only single event based flood.

3.8 SWAT-CUP

Quantifying the uncertainty inherent in the results achieved is essential in evaluating the efficiency of these modelling methods, particularly when the model outcomes could be used as a means for watershed planning and management procedures.

Automated model calibration requires that the uncertain model parameters are changed systematically, the model is run, and the required outputs (corresponding to measured data) are extracted from the model output files. The main role of an interface is to provide a link between the input/output of a calibration program and the model.

Various approaches exist for the uncertainty analysis in distributed watershed models. Popular methods for this are: Generalized Likelihood Estimation (GLUE), Parameter Solution (Parasol), Markov Chain Monte Carlo (MCMC) and Sequential Uncertainty Fitting-2 (SUFI2). To perform calibration and uncertainty analysis for SWAT the software package SWAT Calibration and Uncertainty Programme (SWAT- CUP) has been developed.

Thus, SWAT-CUP is an interface that was developed for SWAT. Using this generic interface, any calibration/uncertainty or sensitivity program can be linked easily to the SWAT. A schematic of the linkage between SWAT and five optimization programs is illustrated in the Figure 3.5.

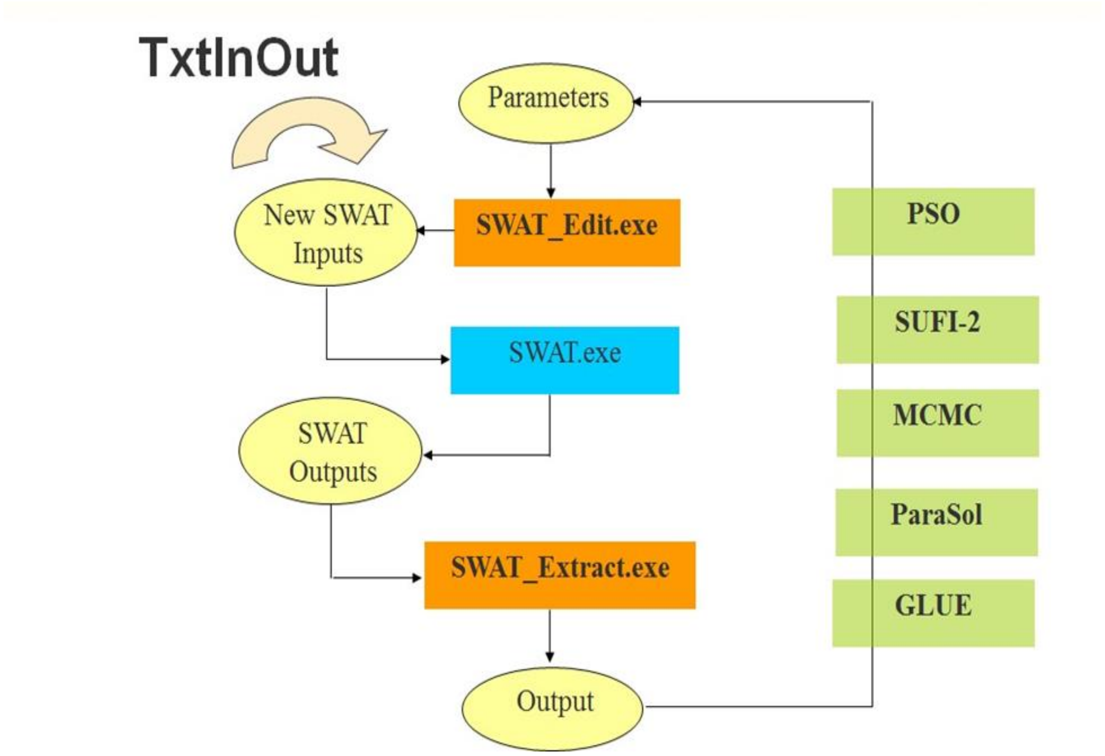


Figure 3.5 Schematic Diagram Showing Linkage Between SWAT and Five Optimization Programs

3.9 THE CONCEPTUAL BASIS OF SUFI-2

In SUFI-2, parameter uncertainty accounts for all sources of uncertainties such as uncertainty in driving variables (e.g., precipitation), conceptual model, parameters, and measured data. The degree to which all uncertainties are accounted for is quantified by a measure or factor referred to as the P-factor, which is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU). As all the processes and model inputs such as rainfall and temperature distributions are correctly manifested in the model output (which is measured with some error) - the degree to which we cannot account for the measurements - the model is in error; hence uncertain in its prediction. Therefore, the percentage of data captured or bracketed by the prediction uncertainty is a good measure to assess the strength of our uncertainty analysis. The 95PPU is calculated at 2.5 percent and 97.5 percent of the cumulative distribution of an output variable acquired through Latin hypercube sampling, disallowing 5 percent of the very poor simulations. Since all forms of uncertainties are reflected in the measured variables (e.g., discharge), the parameter uncertainties generating the 95PPU account for all uncertainties.. It is extremely interesting to break down the complete uncertainty into its multiple parts, but it is quite hard to do so, and as far as the author is conscious, no reliable procedure yet exists.

Another measure quantifying the strength of a calibration/uncertainty analysis is the R factor, which is the average thickness of 95PPU band divided by the standard deviation of the measured data. SUFI-2, hence seeks to bracket most of the measured data with the smallest possible uncertainty band. The concept behind the uncertainty analysis of the SUFI-2 algorithm is depicted graphically in Figure 3.6. This Figure illustrates that a single parameter value (shown by a point) leads to a single model response (Figure. 3.6 a), while propagation of the uncertainty in a parameter (shown by a line) leads to the 95PPU illustrated by the shaded region in Figure 3.6 b. As parameter uncertainty increases, the output uncertainty also increases (not necessarily linearly) (Figure. 3.6 c). Hence, SUFI-2 starts by assuming a large parameter uncertainty (within a meaningful range), so that the measured data initially falls within the 95PPU, then decreases this uncertainty in steps while monitoring the P-factor and the R-factor. In each step, previous parameter ranges are updated by calculating the sensitivity matrix (equivalent to Jacobian), and equivalent of a Hessian matrix, followed by the calculation of covariance matrix, 95% confidence intervals of the parameters, and correlation matrix. Parameters are then updated in such a way that the new ranges are always smaller than the previous ranges, and are centred to the best simulation.

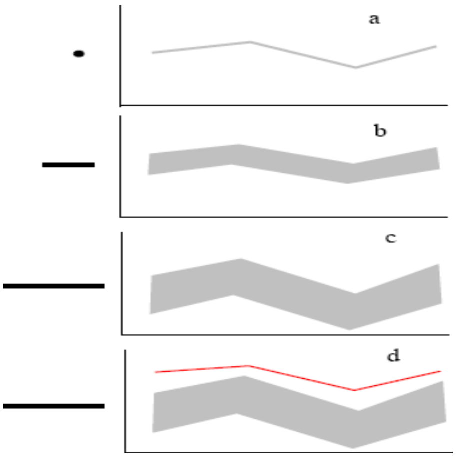


Figure 3.6 A conceptual Illustration of the Relationship Between Parameter Uncertainty and Prediction Uncertainty

The goodness of fit and the degree to which the calibrated model accounts for the uncertainties are assessed by the above two measures. Theoretically, the value for P factor ranges between 0 and 100%, while that of R-factor ranges between 0 and infinity. A P-factor of 1 and R-factor of zero is a simulation that exactly corresponds to measured data. The degree to which we are away from these numbers can be used to judge the strength of our calibration. A larger P-factor can be achieved at the expense of a larger R- factor. Hence, often a balance must be reached between the two. When acceptable values of R factor and P-factor are reached, then the parameter uncertainties are the desired parameter ranges. Further goodness of fit can be quantified by the R^2 and/or Nash- Sutcliff (NS) coefficient between the observations and the final ―best simulation. It should be noted that we do not seek the ―best simulation as in such a stochastic procedure the ―best solution‖ is actually the final parameter ranges.

If initially we set parameter ranges equal to the maximum physically meaningful ranges and still cannot find a 95PPU that brackets any or most of the data, for example, if the situation in Figure 3.6 d occurs, then the problem is not one of parameter calibration and the conceptual model must be re-examined.

CHAPTER 4

STUDY AREA AND DATA COLLECTION

4.1 GENERAL

This chapter contains details about Deo river basin or Deo dam watershed (Study area). Also this chapter gives brief description about the data used for preparation of SWAT model.

4.2 STUDY AREA

Deo river is selected for the present study which flows in Dahod, Panch Mahals and Vadodara districts of Gujarat. Deo river is the right bank tributary of the Dhadhar river in Gujarat. Its other name is Dev river in the name of God.

4.2.1 Physiography

Dhadhar river originates from Pavagadh hill and meets to the Bay of Khambhat. Its length is 142 km and catchment area 4201 sq. km. Vishvamitri and Deo are the right bank tributaries of Dhadhar river. At 26 km. distance Deo dam is located on Deo river having catchment area of 194.36 sq. km., which is selected as study area. The basin lies between 22° 22´ N to 22° 31´ N Latitude and 73° 30´ E to 73° 42´ E Longitude. Deo river sub basin covers the part of Dahod, Panch Mahals and Vadodara district. Maximum elevation in the catchment area is 761 m and minimum elevation is 66 m. Location of Deo river sub-basin is shown in figure 4.1.

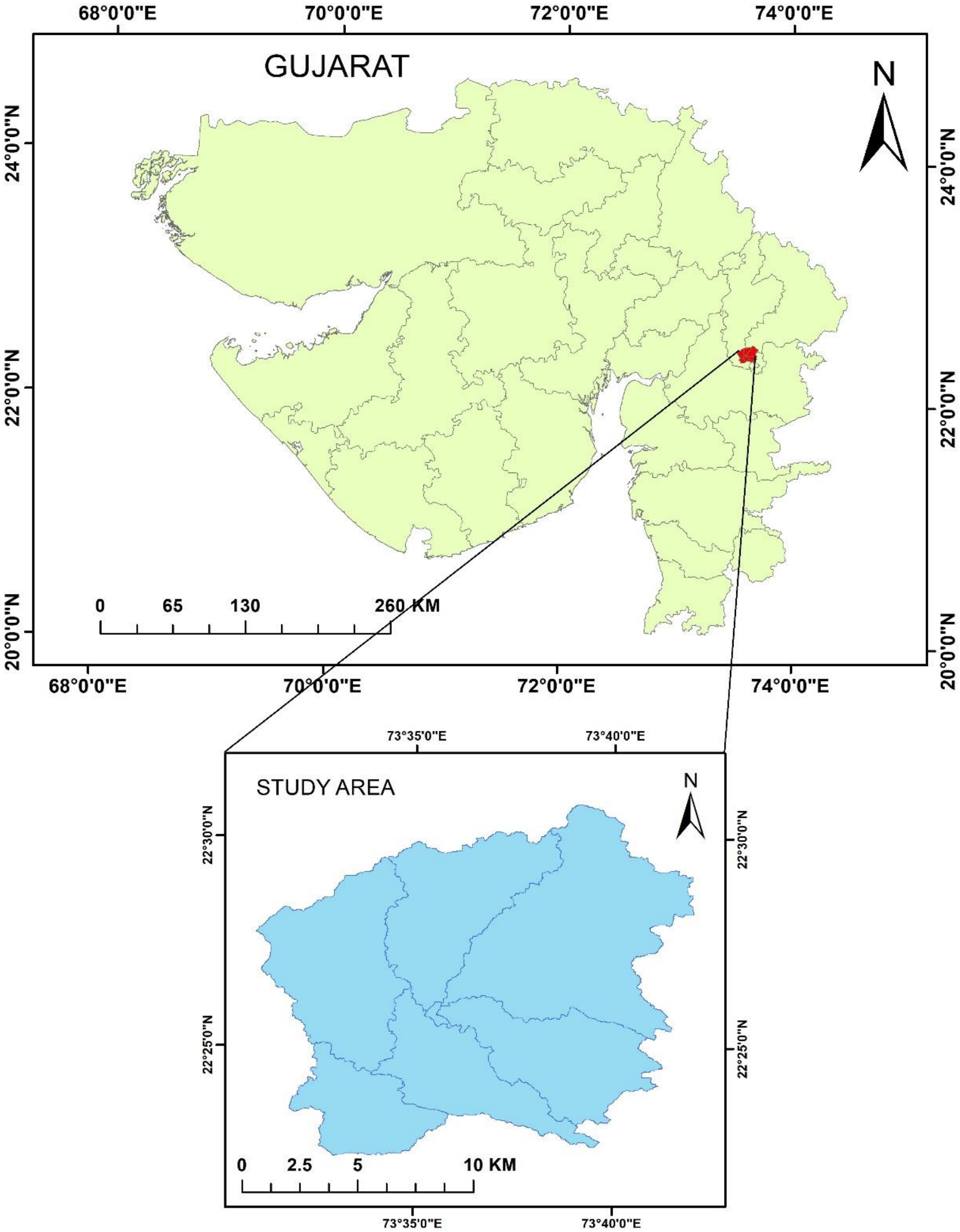


Figure 4.1 Location Map of Deo River Sub-basin

4.2.2 Climate

The climate of the basin can be characterized by a hot dry summer, a moderate winter and humid monsoon. May is the hottest month while January is the coldest month. The maximum average temperature of around 39℃ is occurred in the month of May whereas; the minimum average temperature of around 13℃ is felt during the month of February. The average annual wind speed recorded at the Deo dam weather station is 6.53 m/s and the average annual Relative humidity observed here is 0.693.

The average annual rainfall is around 1072 mm (42.21 inches) in the basin. The rainfall mainly occurs in the monsoon season that spans between June to September. March to May and October to November are considered as pre-monsoon and post-monsoon respectively during which scanty rainfall is witnessed in the basin.

4.2.3 Drainage Network

The figure 4.2 shows the drainage network of Deo river sub basin:

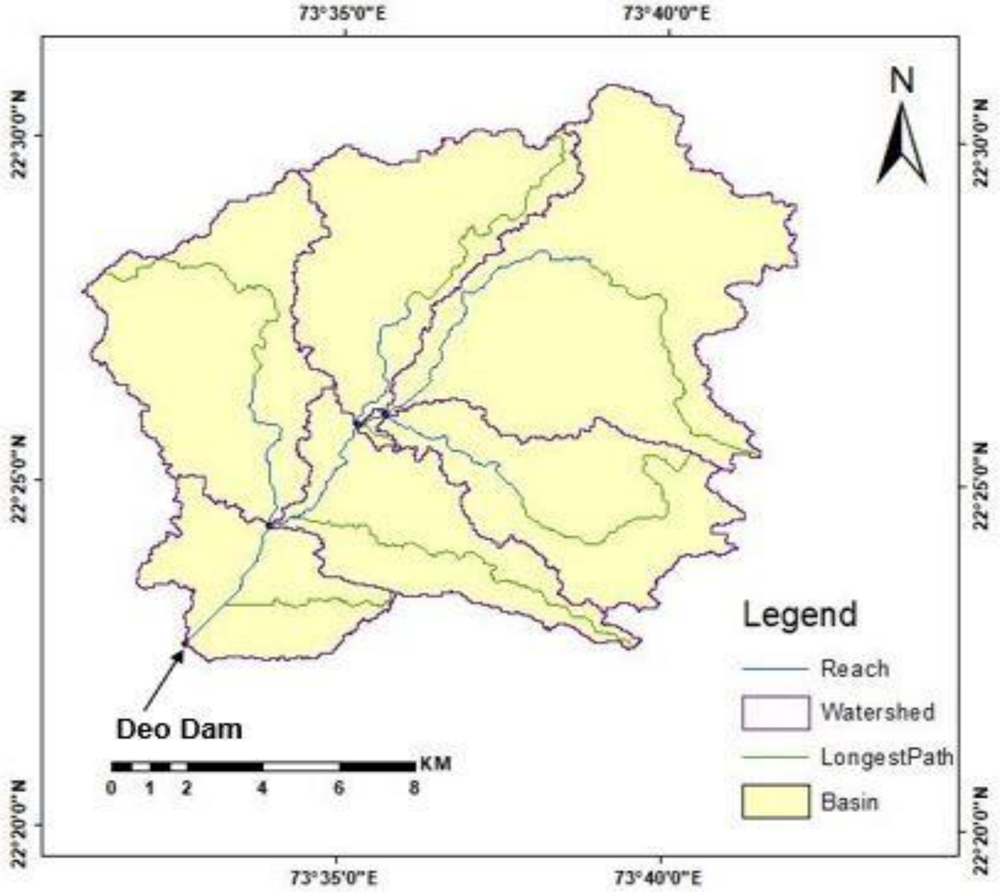


Figure 4.2 Drainage Network Map of Study Area

4.3 DATA COLLECTION

Input data required for ArcSWAT are Digital Elevation Model (DEM), Land use map, soil map and Weather data.

4.3.1 Digital Elevation Model (DEM)

A digital elevation model is a digital model or 3D representation of terrain’s surface. The different types of DEMs are available online such as ASTER (Advanced space-borne Thermal Emission and Reflection Radiometer), STRM (Shuttle Radar Topography Mission) and CARTOSAT. CARTOSAT-1 DEM (30 X 30 m resolution) was downloaded from bhuvan.nrsc.gov.in (Figure. 4.3). The highest and lowest point elevation values from DEM are 761 m and 66 m respectively. The northern and southern regions of the study area have low elevation range while eastern and western part is of higher altitude. DEM was used to derive slope, aspect, flow direction and accumulation, and stream network information.

The primary goal of CARTOSAT-1 is to generate a current, accurate and nationally consistent Digital Elevation Model (DEM) throughout the country to facilitate the user communities of remote sensing and cartography. It is anticipated that the DEM will be useful in providing an elevation reference of the existing topographic conditions. In the GIS environment, DEM will provide a terrain model to facilitate drainage network analysis, watershed demarcation, erosion mapping, contour generation and quantitative analysis like volume-area calculation. DEM will enable the generation of ortho-rectified images which can be used as raster maps to define and demarcate features such as land use, topography, roads, rivers, water-bodies, etc. They may also be used to establish accurate geographic locations of features and make measurements of altitude. Other applications of DEM and Ortho-image include scene simulation and fly through visualization for appreciation of terrain relief.

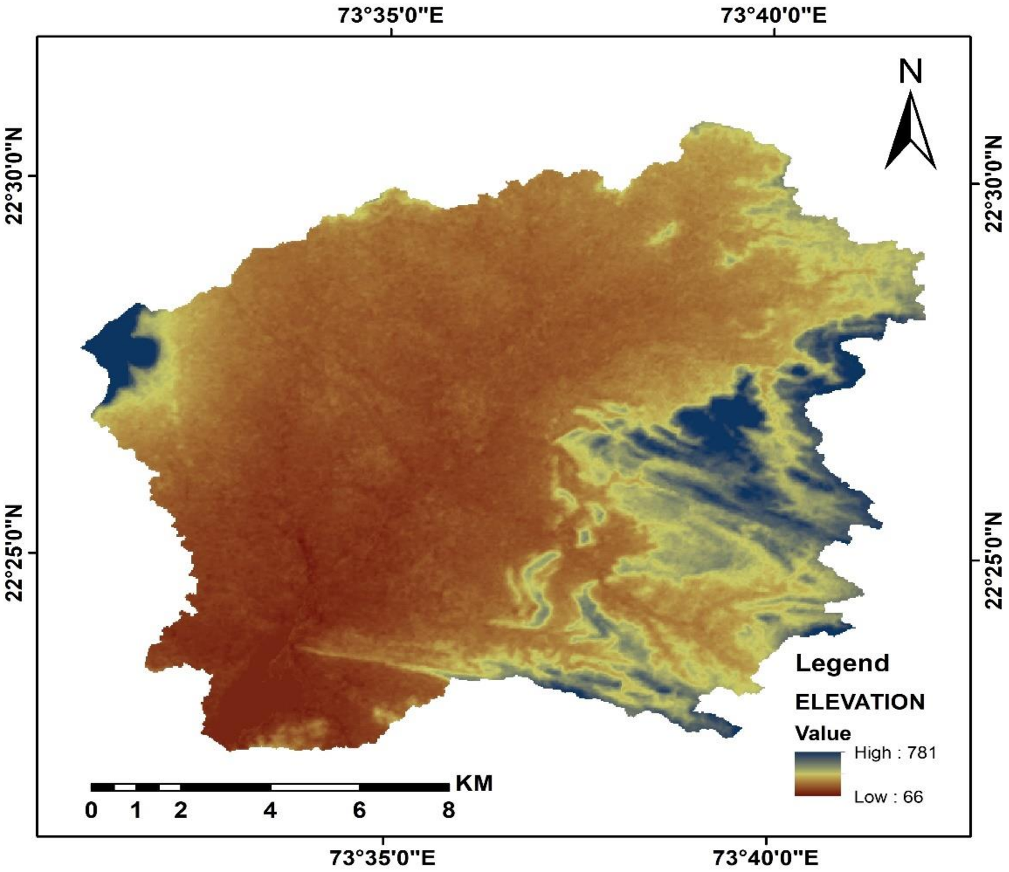


Figure 4.3 Digital Elevation Model (DEM)

4.3.2 Land Use/Land Cover Map

Land use land cover (LULC) map is a critical input for SWAT model. Land use/land cover map was prepared using remote sensing data of LandSAT-8 (Land Satellite 8) downloaded from earthexplorer.usgs.gov. Landsat 8 measures different ranges of frequencies along the electromagnetic spectrum. Each range is called a band, and Landsat 8 has 11 bands. Landsat numbers its red, green and blue sensors as 4,3 and 2, so when we combine them we get a true-colour image.

The classification of satellite data mainly follows two approaches i.e. supervised and unsupervised classification. The intent of the classification process is to categorize all pixels in a digital image to one of the several land cover classes. This categorized data are then used to produce thematic maps of the land cover present in an image. In the present study, the unsupervised classification method was used for preparation of the LULC map. The study area was classified into 7 classes at a spatial resolution of 30-meter in

WGS_1984_UTM_Zone_43N projection. They were as follows: 1) Agriculture area, 2) Deciduous forest area, 3) Pasture area, 4) Range brushes, 5) Urban area, 6) Barren area and 7) Water bodies. Land use classes for Deo river basin are shown in figure 4.4.

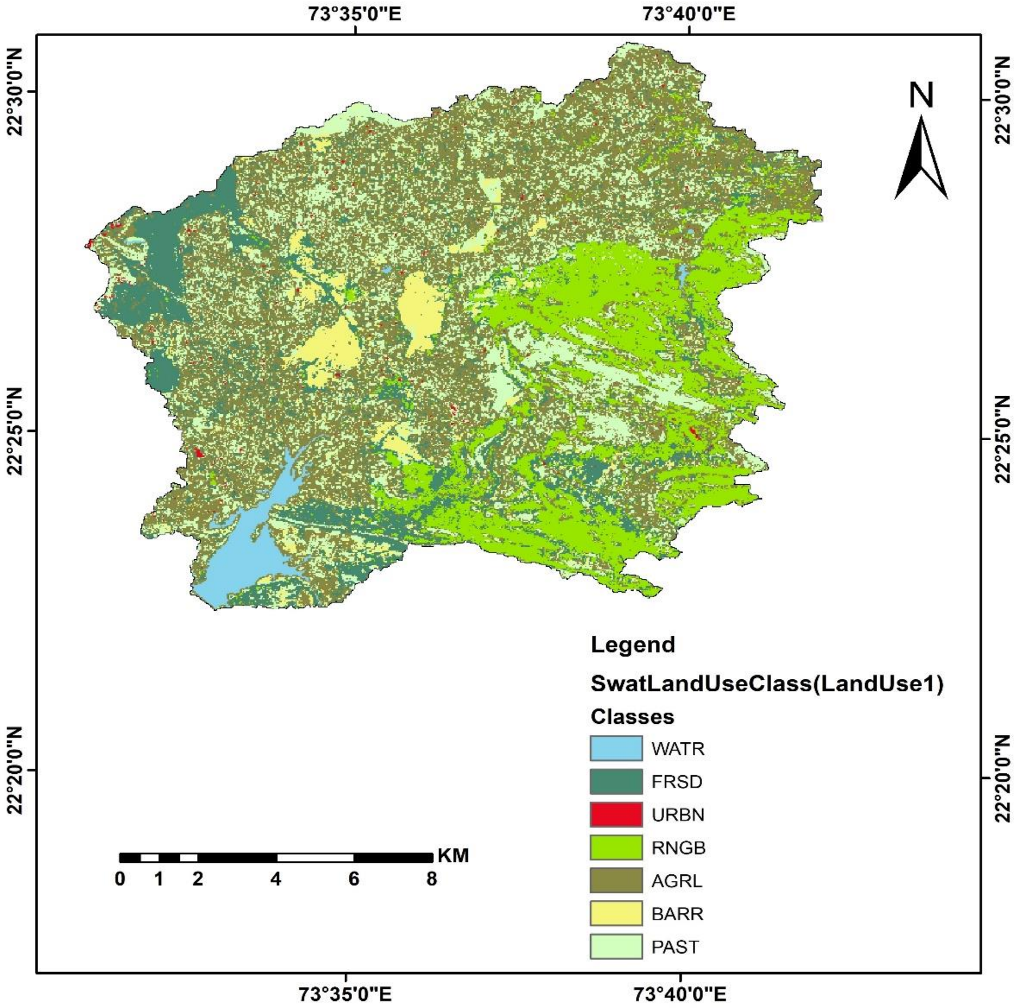


Figure 4.4 Land Use/Land Cover Map

4.3.3 Soil data

The characteristics of the soil is required to be known for the estimation of runoff, sedimentation, groundwater. It mainly depends on the percentage of sand, silt and clay particles present in the soil. Soil data were obtained from the United Nations Food and Agriculture Organization (FAO) for the study. Although SWAT model can take ten-layer soil data as input, but due to data unavailability, only two-layer information was given here. Soil properties are of great concern for the SWAT model as precipitation events and hydrology of flow are solely dependent on the composition and conditions of the soil. Soil properties such as texture, structure, chemical composition, physical properties, moisture content, hydraulic conductivity, bulk density, and organic carbon content are needed as model inputs. These properties are required for each soil type and each soil layer as they influence the movement of water above and below the soil. Using these parameters hydrologic soil group of soil was determined. Figure 4.5 shows soil map of the Deo river basin.

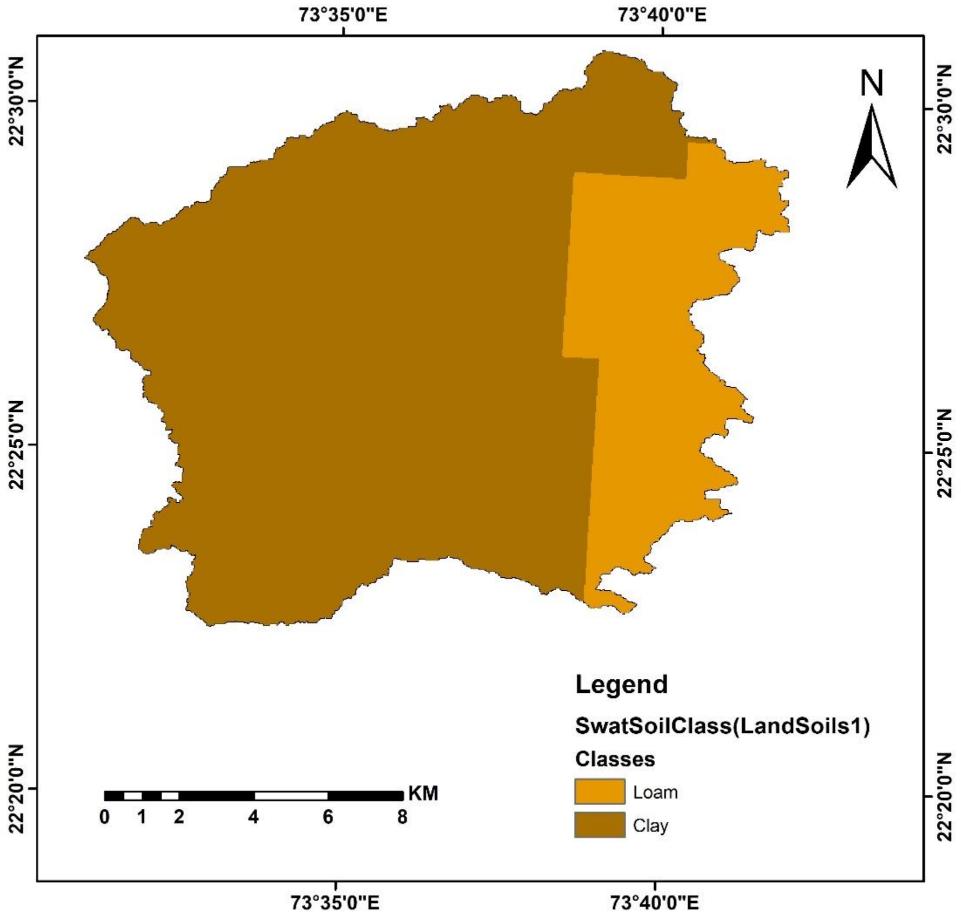


Figure 4.5 Soil Map

4.3.4 Weather data and Stream flow data

Daily observed data for precipitation (mm), minimum temperature (℃) and maximum temperature (℃) were collected from State Water Data Centre (Gandhinagar). Deo dam weather station was chosen based on the availability of 18-year datasets, from 2000 to 2017. Daily inflow data from 2002-2017 was collected from the office of Deo Dam.

CHAPTER 5

METHODOLOGY

5.1 GENERAL

This chapter is divided into two sections viz., methods used for data processing and modelling the SWAT model and the procedure used for calibration and validation of the model and various criteria used for evaluating the model performances are discussed in this chapter.

5.2 METHODOLOGY

5.2.1 Database Development for the Study Area

Spatial attribute and dynamic data were collected for the Deo river sub-basin. DEM (Digital Elevation Model) is one of the main and first input for SWAT. From DEM, flow accumulation, flow direction, streams path and outlets points are generated which is used to delineate watershed and also slope map is derived from DEM. Land use map and Soil map are critical inputs for SWAT. Various land use information like curve number, crop factors, runoff coefficient, manning's n value, etc. are needed in the database table of land use in ArcSWAT. Similarly soil information like number of layers of soil, texture of soil, their hydrologic groups, AWC, percentage of clay, sand and silt, etc of each layer should be there in the database table of ArcSWAT.

SWAT requires daily precipitation (mm) and minimum, maximum temperature (℃). Other climatic parameters like Relative humidity, Solar radiation and Wind speed can given as input or they can also be simulated by ArcSWAT. In this study these parameters are simulated.

5.2.2 Model Set-up

The main steps involved in GIS interface of ArcSWAT are Watershed delineation, HRU analysis, Write Input Tables (weather data) and SWAT run. Flow chart of SWAT model is shown in figure 5.1.

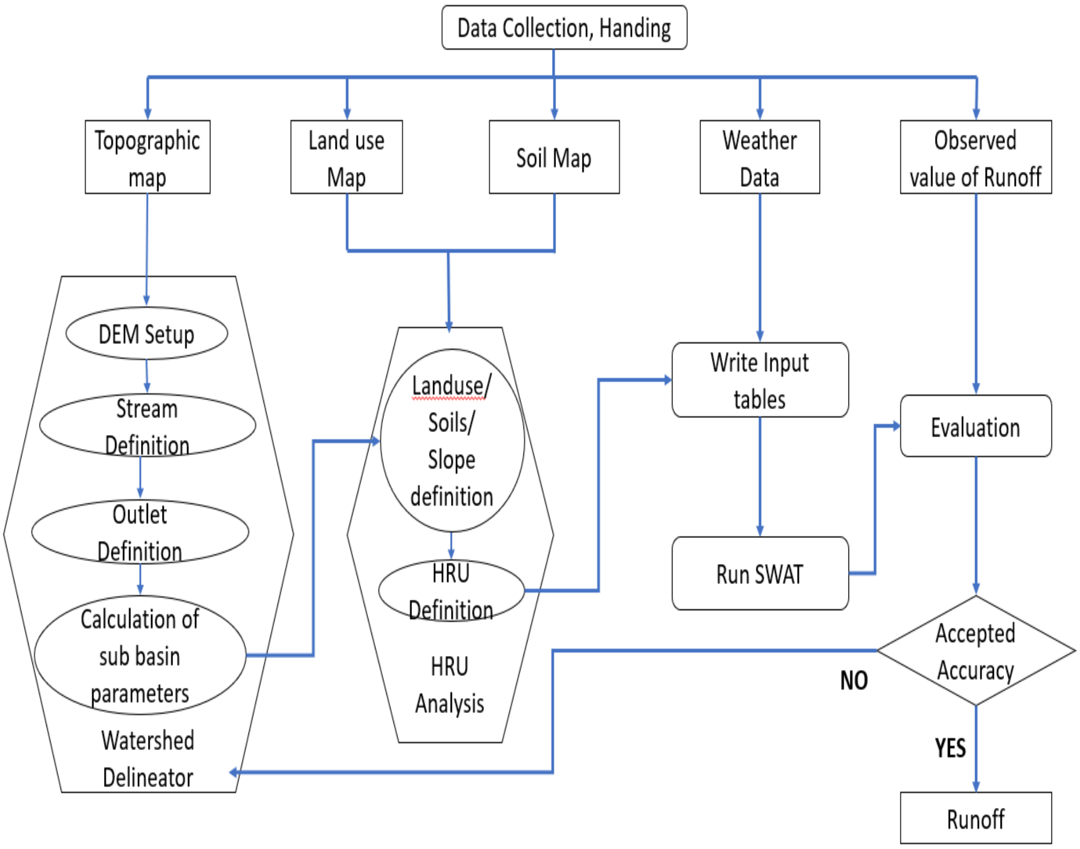


Figure 5.1 Methodology of SWAT model

Watershed is delineated with DEM as main input and Land use and soil map are required for HRU analysis. 94 HRUs were generated giving thresholds as 5% for land use, 5% for soil and 10% for slope. Then rainfall(mm) and maximum, minimum temperature (℃) were given as input for SWAT Run. At last SWAT run is performed entering the starting and ending date of simulation, Print-out setting set to daily and the number of warm up years. Finally SWAT check was run to get the details of Water balance in the Deo river sub-basin.

5.2.3 Performance Evaluation of the Model

Evaluation involves a comparison of the model’s output to corresponding measured variable. Results of the calibration and validation were evaluated using SWAT-CUP with four objective functions Coefficient of Correlation (R^2), Nash Sutcliffe Efficiency (NSE), Percent Bias and Root mean square and Standard deviation ratio (RSR).

5.3 DEVELOPMENT OF SWAT MODEL

Step by step procedure for the preparation of the input datasets for SWAT model is described under this section. In order to get a logistic output from the SWAT model, preparation of correct input data is necessary.

A basin is divided into several sub-basins in the SWAT model. There is at least one Hydrologic Response Unit (HRU) in each sub-basin, a tributary channel and a main channel or reach. Each Sub basin possess a geographical position and is spatially interconnected and flow from one sub-basin enters another. These sub-basins are further divided into HRUs, which consist of lumped land fields comprising of distinct combinations of land cover and soil. Sub-basin partitioning into HRUs improves precision and provides a much better physical depiction of the water balance. There is no interaction between the HRUs, contrary to the flow between sub-basins. So runoff is predicted separately for each HRU.

Steps involved in ArcSWAT are shown in figure 5.2.

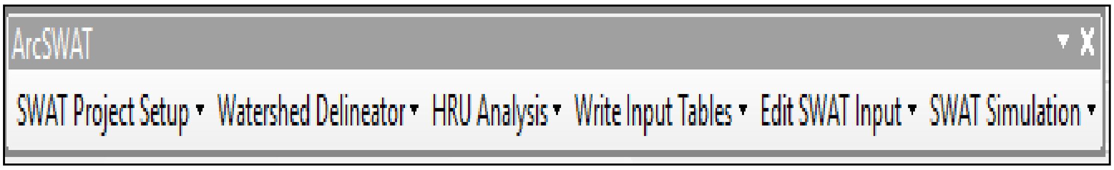
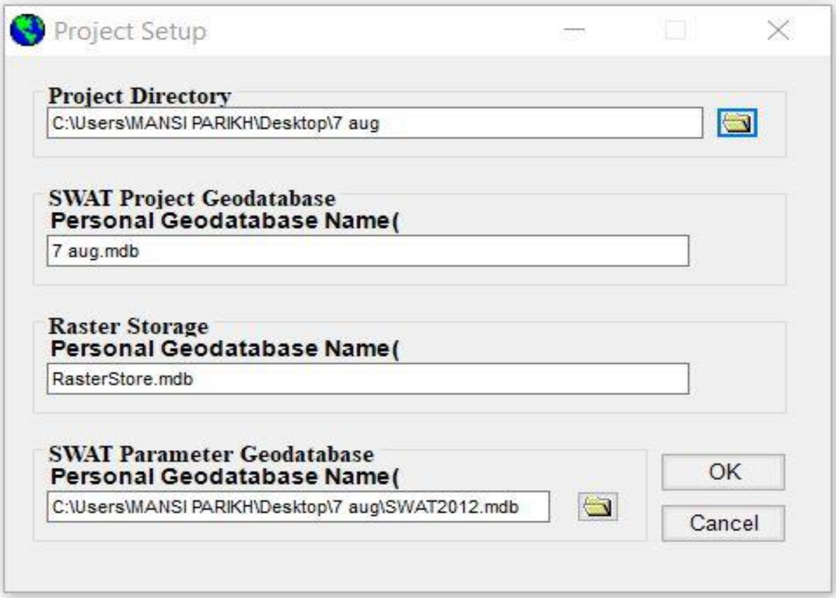


Figure 5.2 ArcSWAT Tool Menu

5.3.1 Project Setup

This is the first step to set up a project so that all necessary files, folders, databases, maps and output are stored there. Click on SWAT Project Setup >> New SWAT Project and the Project Setup Dialog box will popup. Then select the project directory and SWAT project geodatabase, raster storage geodatabase and the SWAT parameter geodatabase automatically get a name as shown in figure 5.3. Click ok and after few seconds Project Setup done message will pop up. Click ok to proceed.



Project Setup

Project Directory
C:\Users\MANSI PARIKH\Desktop\7 aug

SWAT Project Geodatabase
Personal Geodatabase Name(
7 aug.mdb

Raster Storage
Personal Geodatabase Name(
RasterStore.mdb

SWAT Parameter Geodatabase
Personal Geodatabase Name(
C:\Users\MANSI PARIKH\Desktop\7 aug\SWAT2012.mdb

Figure 5.3 Project Setup Dialog Box

5.3.2 Watershed Delineation

Watershed delineation is the first step for the development of SWAT model. Before starting the watershed delineation change the co-ordinate system of the map as “WGS 1984 UTM Zone 43N” using Data Frame Properties in ArcMAP. Also DEM should be in the same projected co-ordinate system. For creating the longest flow path, individual sub-basins, the stream networks have to be defined properly. Automatic watershed delineation is selected as shown in figure 5.4. For delineation of Deo watershed, DEM was provided and digitized stream was burnt in the automatic watershed delineation tab. To define the watershed boundary, the main outlet was selected at the Deo dam site and after that watershed delineation was processed.

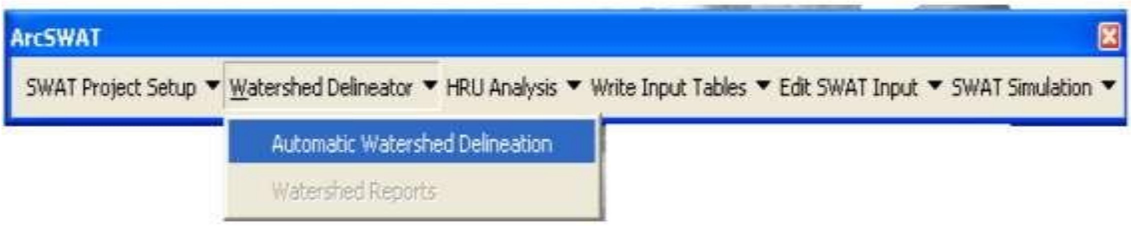
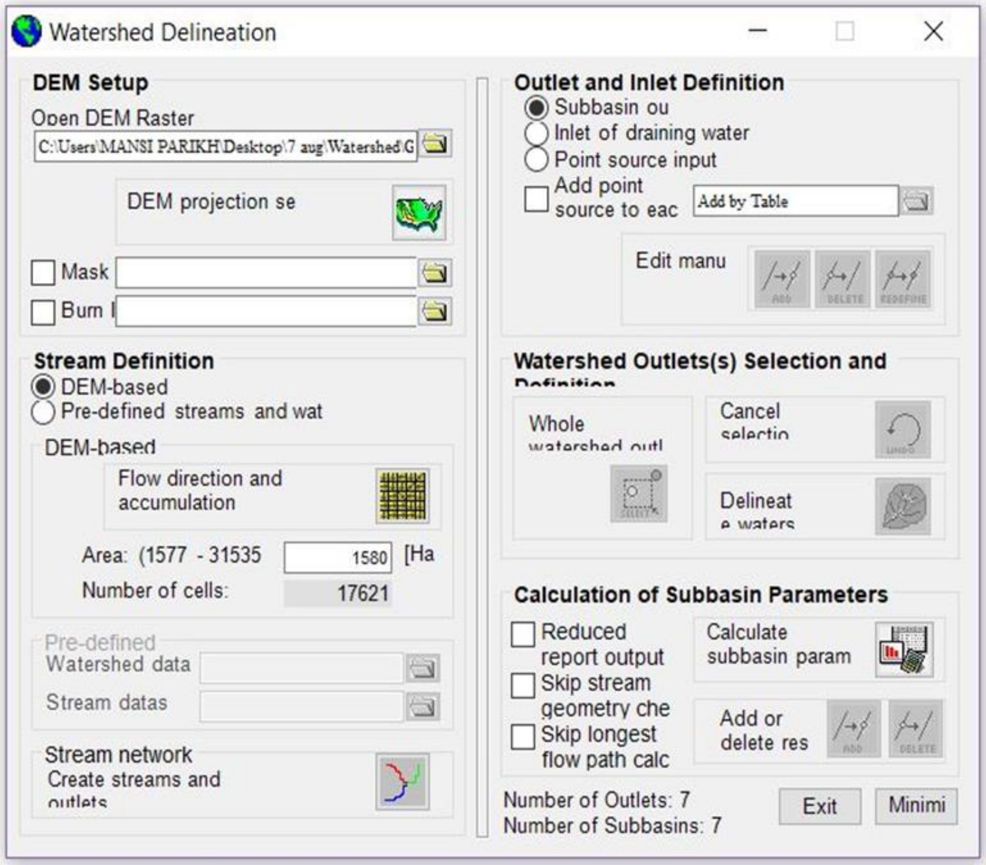


Figure 5.4 Watershed Delineator Tool Menu

Watershed Delineation is done following the steps shown in figure 5.5. First select the DEM .tif file and then keep DEM Projection setup the same as it is set. Skip the Mask and Burn in option and proceed to create Flow direction and Accumulation.


Watershed Delineation

Open DEM Raster: C:\Users\MANSI PARIKH\Desktop\7 aug\Watershed\G

● Subbasin ou

☐ Add point source to eac: Add by Table

☐ Mask

☐ Burn I

● DEM-based

Area: (1577 - 31535 1580 [Ha

Number of cells: 17621

☐ Reduced report output

☐ Skip stream geometry che

☐ Skip longest flow path calc

Number of Outlets: 7

Number of Subbasins: 7

Figure 5.5 Automatic Watershed Delineator Dialog Box

after flow direction and flow accumulation process is complete, the box will show the area of watershed in hectares and number of cells in watershed. This is the critical stream area threshold that we will use to define the stream network. Here area of cell is given as 1580 ha as watershed area is less so more accuracy will be achieved and more stream flows will be shown. Then click the create stream and outlets button to create stream network, sub basin and outlet for each of the sub-basin.

Then add the outlet using Add button in Edit manually frame at location of Deo dam on the stream line created in previous step. Next step, in the watershed outlets selection and definition, click on the select whole watershed outlet button, then select the outlet that we just added. We can use the undo button if we have mistakenly selected a wrong outlet. Then click on Delineate Watershed button to get the desired watershed. After the watershed is delineated, we will see that a polygon feature class with sub-basin is added to the map document.

As a result, 7 sub-basins with 7 outlets respectively have been defined for the watershed. Finally calculation of sub-basin parameter containing elevation data has been derived with information on the stream geometry and longest flow path calculation. After this, we can see the topographic report of the watershed generated.

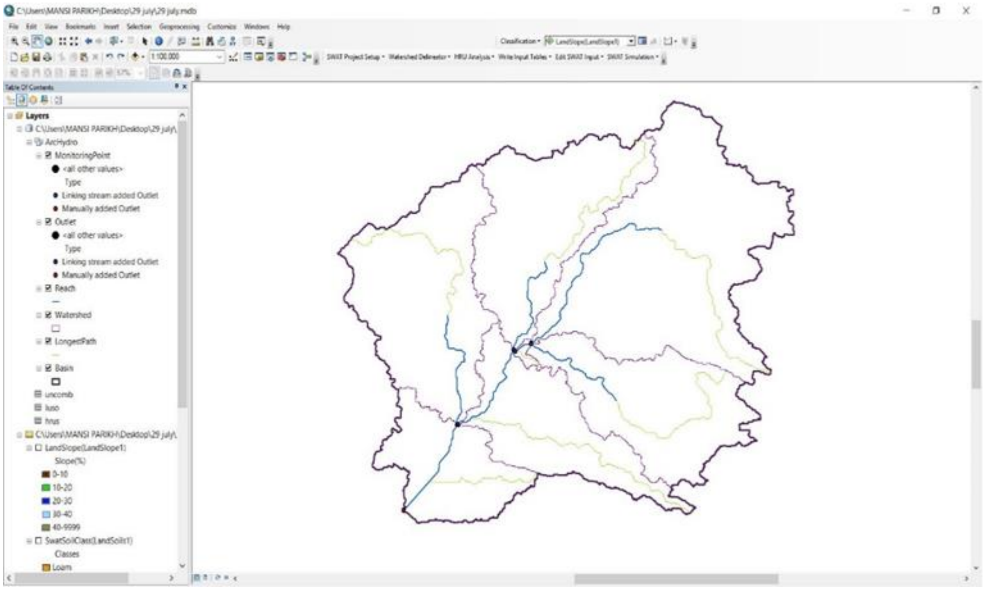


Figure 5.6 Watershed Delineation in SWAT

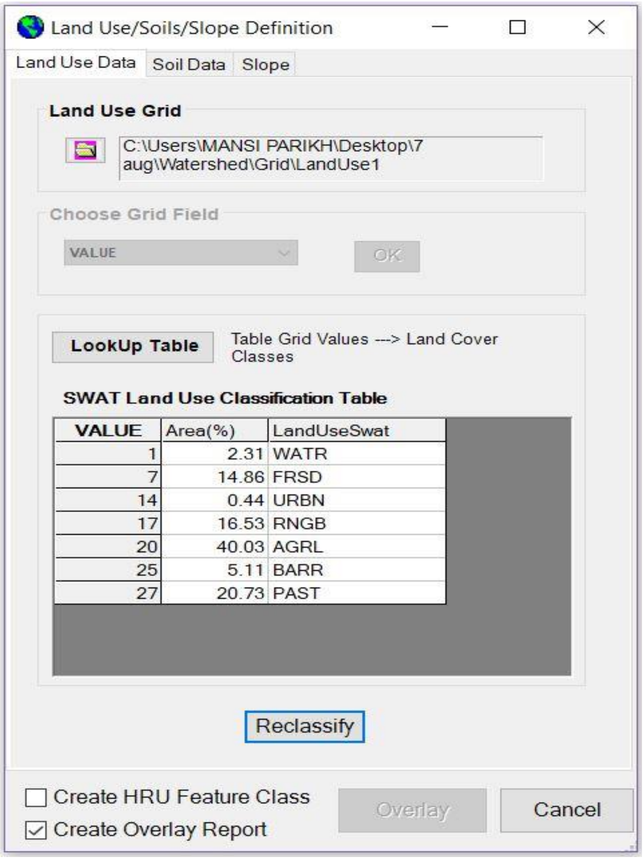
5.3.3 HRU Analysis

In this step, Land use, Soil and slope maps are defined.

First, click on Land Use/ Soils/ Slope Definition button and a window having three tabs will pop up. First classifying land use as shown in figure 5.7.

Select the land use tif file using browse button to load the land use map. After the map is loaded we will get clip window having information about overlaying area, percentage overlaying area and non-recording data. Clip should always be greater than 90%. Here we have got 100% of overlap.

Now we select value in the choose grid field, and click on Ok. Now Click on Lookup table and select Use Table option and this will create an extra column. Then select the look up table and Land use classes will be displayed in the column. Finally we click on Reclassify to finish the land use data processing portion of HRU analysis.



Land Use/Soils/Slope Definition

Land Use Data | Soil Data | Slope

Land Use Grid

C:\Users\MANSI PARIKH\Desktop\7 aug\Watershed\Grid\LandUse1

Choose Grid Field

VALUE

OK

LookUp Table

Table Grid Values ---> Land Cover Classes

SWAT Land Use Classification Table

VALUE	Area(%)	LandUseSwat
1	2.31	WATR
7	14.86	FRSD
14	0.44	URBN
17	16.53	RNGB
20	40.03	AGRL
25	5.11	BARR
27	20.73	PAST

Reclassify

☐ Create HRU Feature Class

☑ Create Overlay Report

Overlay

Cancel

Figure 5.7 Land Use/Soils/Slope Definition Dialog box

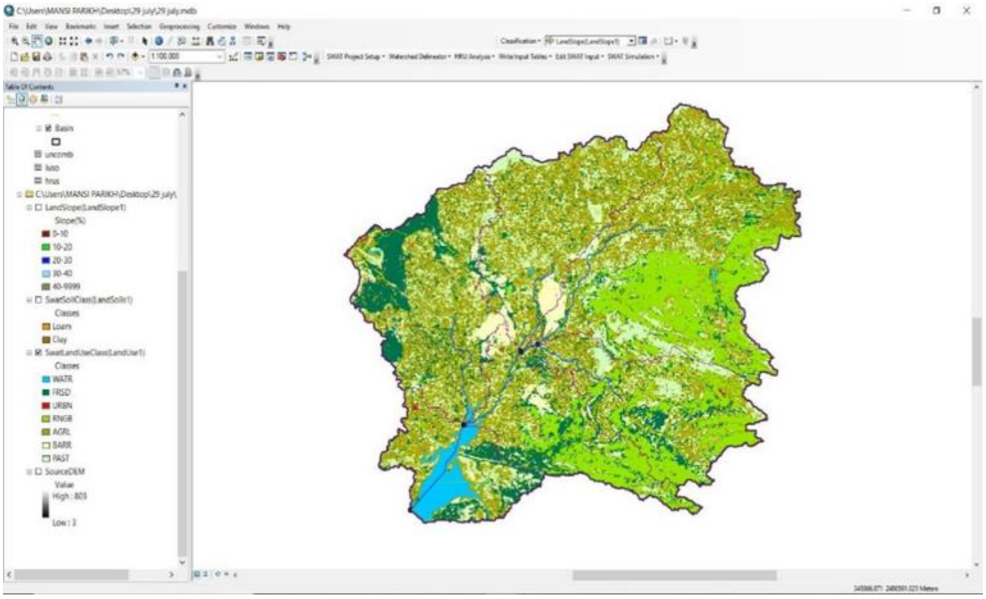
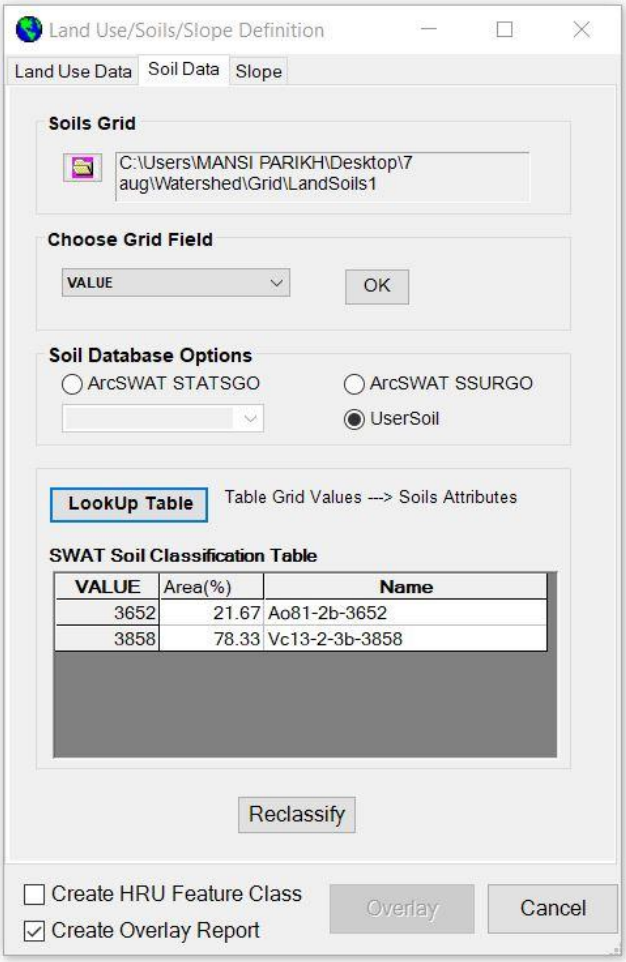


Figure 5.8 Land use/ Land Cover Map in SWAT Model

After Land use map processing, select soil data tab.

Load soil dataset from disk and using browse button. This step will take input raster and then clip that raster to the watershed area just like land use data.

After loading soil raster choose Value in Choose Grid Field. Then select the UserSoil button in Soil Database Options. This will add a name column in SWAT Soil Classification Table. Then click LookUp Table option and select the look up table for soil classification. This will fill names of the soil given in the user soil database as shown in figure 5.9. Then reclassify the soil dataset.



Soils Grid

C:\Users\MANSI PARIKH\Desktop\7 aug\Watershed\Grid\LandSoils1

Choose Grid Field

VALUE

Soil Database Options

○ ArcSWAT STATSGO
○ ArcSWAT SSURGO
● UserSoil

SWAT Soil Classification Table

VALUE	Area(%)	Name
3652	21.67	Ao81-2b-3652
3858	78.33	Vc13-2-3b-3858

☐ Create HRU Feature Class
☑ Create Overlay Report

Figure 5.9 Soils Definition Dialog Box

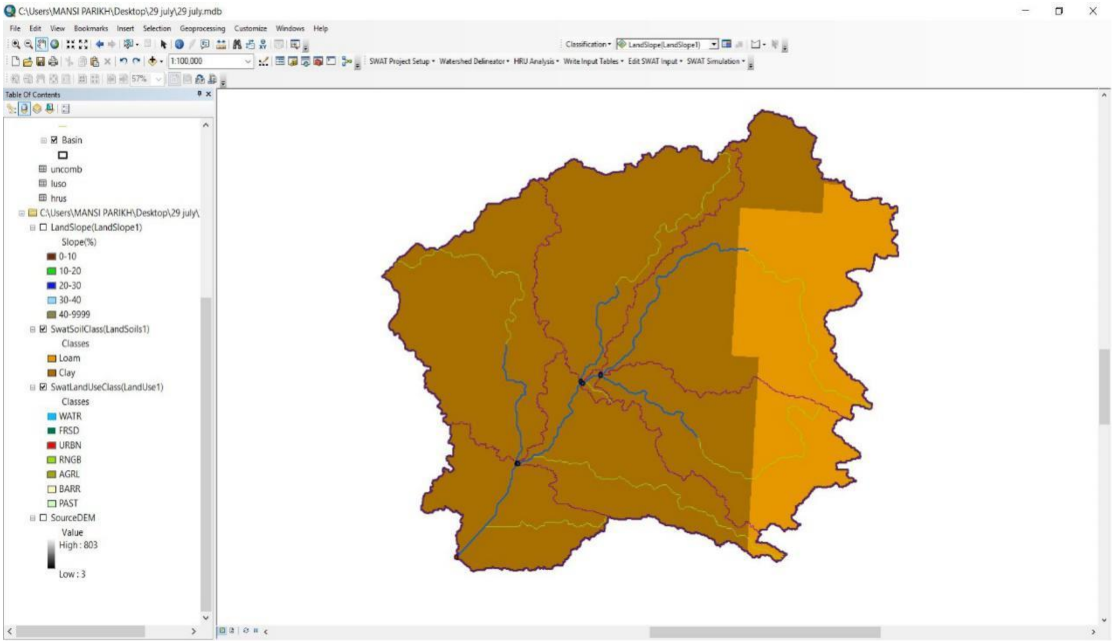
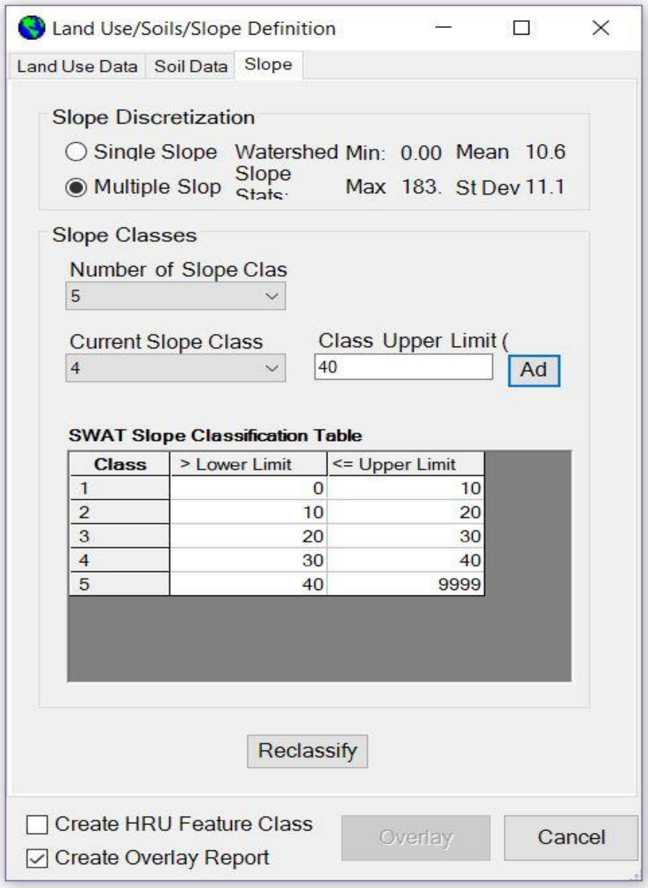


Figure 5.10 Soil Map in SWAT Model

After soil data processing, we will assign slope attributes to each HRU. So click on slope tab.



Slope Discretization

○ Single Slope

● Multiple Slop

Watershed Slope Stats: Min: 0.00 Mean 10.6 Max 183. St Dev 11.1

Slope Classes

Number of Slope Clas: 5

Current Slope Class: 4

Class Upper Limit (: 40 Ad

SWAT Slope Classification Table

Class	> Lower Limit	<= Upper Limit
1	0	10
2	10	20
3	20	30
4	30	40
5	40	9999

☐ Create HRU Feature Class

☑ Create Overlay Report

Figure 5.11 Slope Definition Dialog Box

In the slope discretization we select the multiple slope option then we select the Total number of slope classes and give the class upper limit (in %) then click on add button, after giving all value of slope classes now we click on Reclassify. After giving all the information about Land/soil/slope the overlay button will highlight now click overlay button to start the overlay process.

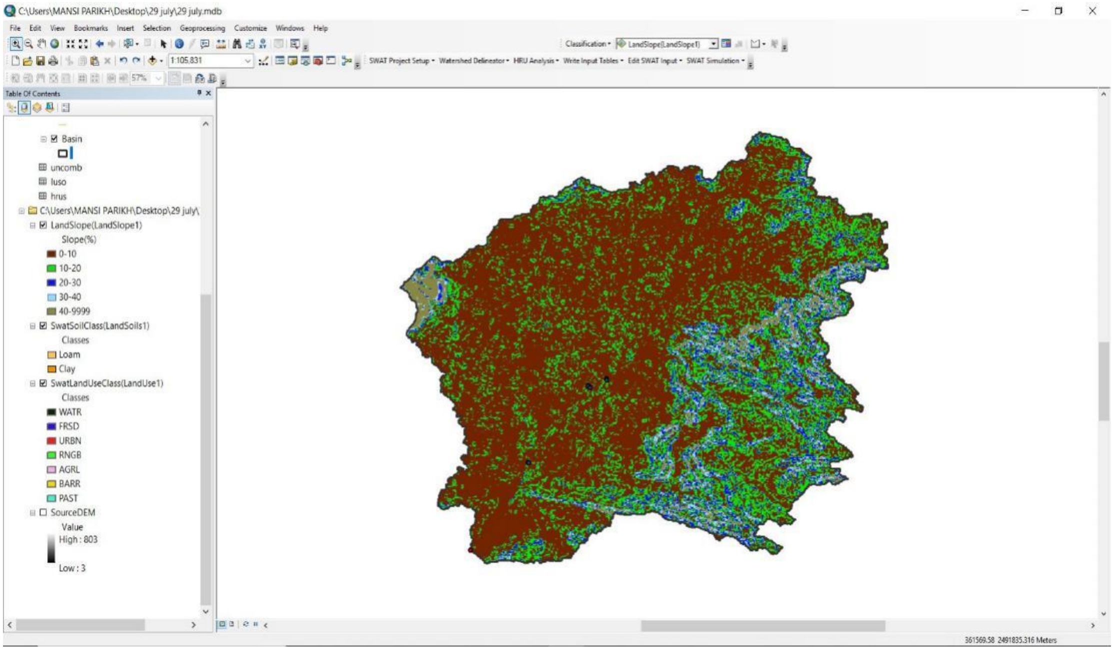


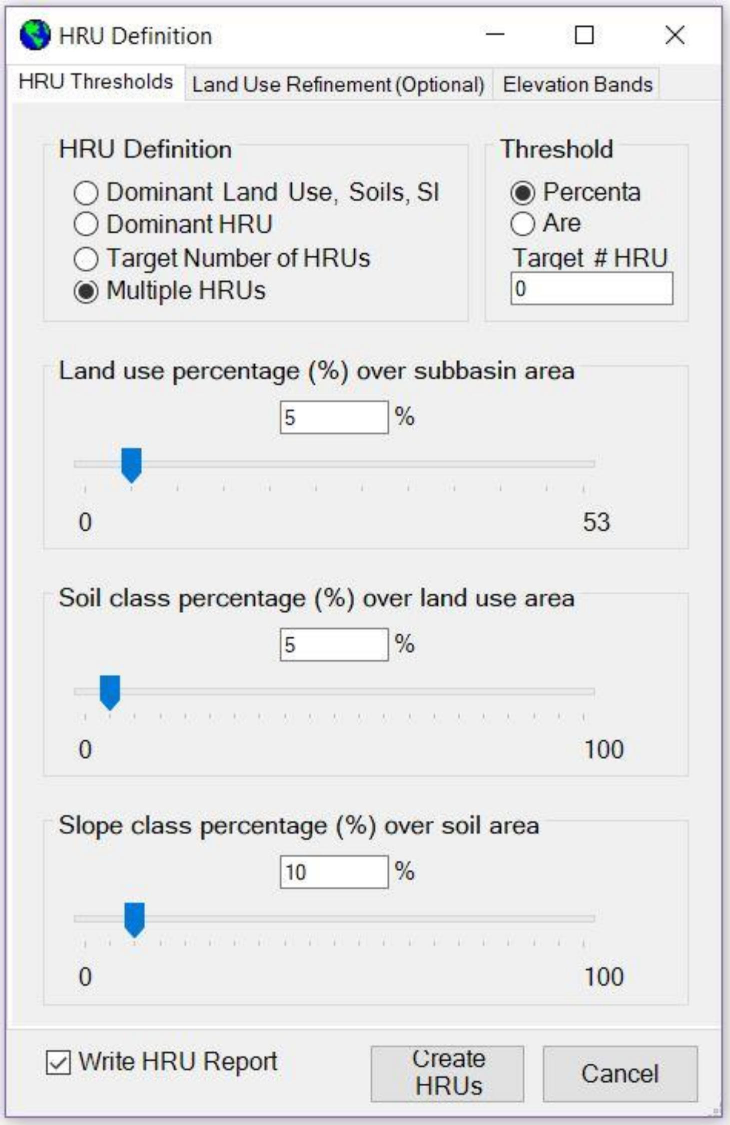
Figure 5.12 Slope Map in SWAT Model

After Land use/Soils/Slope Definition we proceed to HRU Definition.

After selecting Multiple HRUs option and percentage in the threshold frame, thresholds percentage were given as 5% for Land use, 5% for Soil and 10% for slope.

Then HRUs were created by selecting Create HRUs.

After this we can see HRU Analysis Reports, which have Land use/Soils/Slopes Distribution and Final HRUs Distribution report. Land use/Soils/Slopes Distribution report have information about each sub basin having the type of land use, soil and slope distribution and their percentage of watershed area and Final HRUs Distribution report having information about 94 HRUs.



HRU Definition

○ Dominant Land Use, Soils, Sl
○ Dominant HRU
○ Target Number of HRUs
● Multiple HRUs

Threshold

● Percenta
○ Are

Target # HRU: 0

Land use percentage (%) over subbasin area: 5 % (0 – 53)

Soil class percentage (%) over land use area: 5 % (0 – 100)

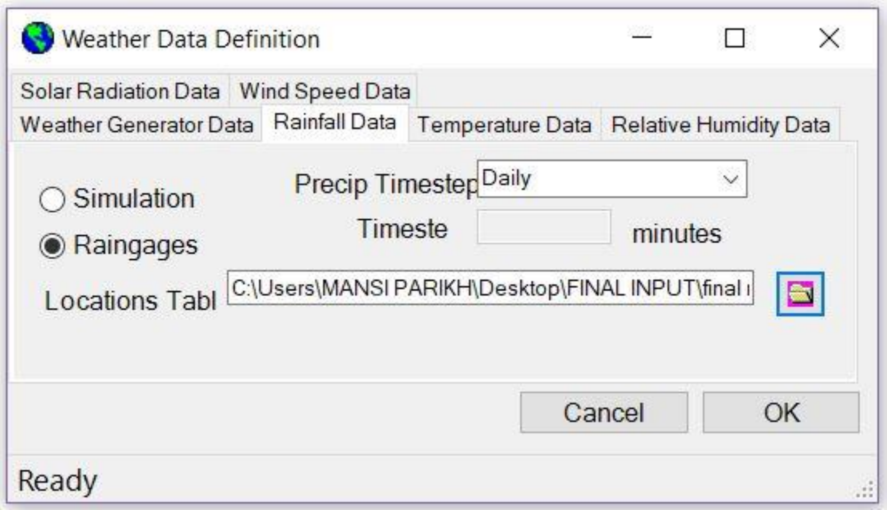
Slope class percentage (%) over soil area: 10 % (0 – 100)

☑ Write HRU Report

Figure 5.13 HRU Threshold Definition Dialog box

5.3.4 Write Input Tables

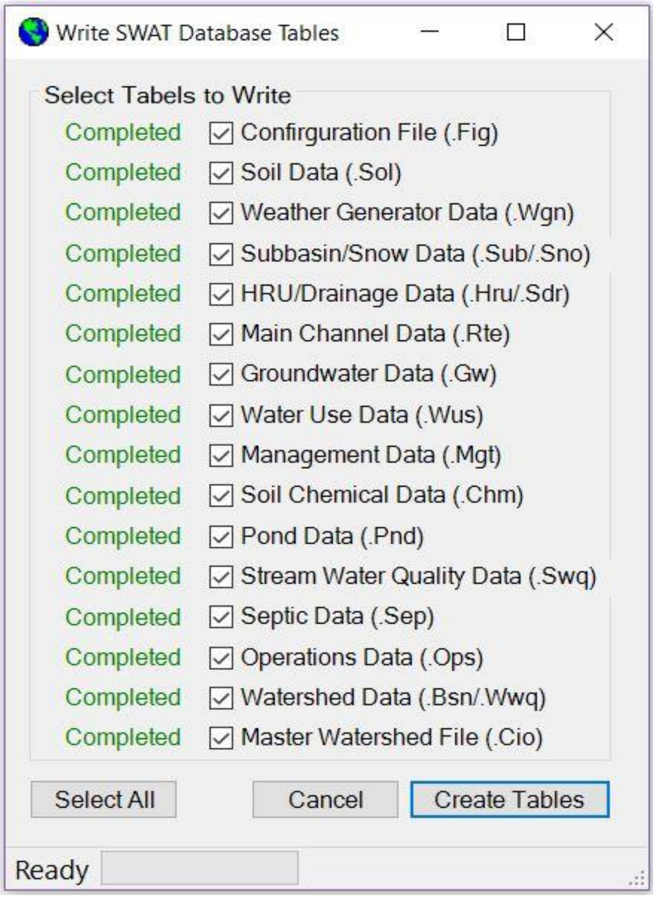
After getting all HRUs, final input for SWAT is Weather data. Selecting Weather stations option in Write Input Tables we get Weather Data Definition dialog box as shown in figure 5.14. Then WGEN_user is selected to input weather data by user. Then for rainfall data, text file is selected using location table browse button as shown in figure 5.14. Likewise temperature data is entered while for Relative Humidity Data, Solar Radiation Data and Wind Speed Data tabs simulation option is chosen which means SWAT will generate these data. So weather databases are created for study area.



○ Simulation
● Raingages
Precip Timestep Daily
Timeste minutes
Locations Tabl C:\Users\MANSI PARIKH\Desktop\FINAL INPUT\final

Figure 5.14 Weather Data Definition Dialog Box

Then select Write SWAT Input Tables in Write Input Tables and Write SWAT Database Tables Dialog box will pop up as shown in figure 5.15. Then select Select all button and click Create Tables and completing the process we will get a message box saying done writing all SWAT database tables.



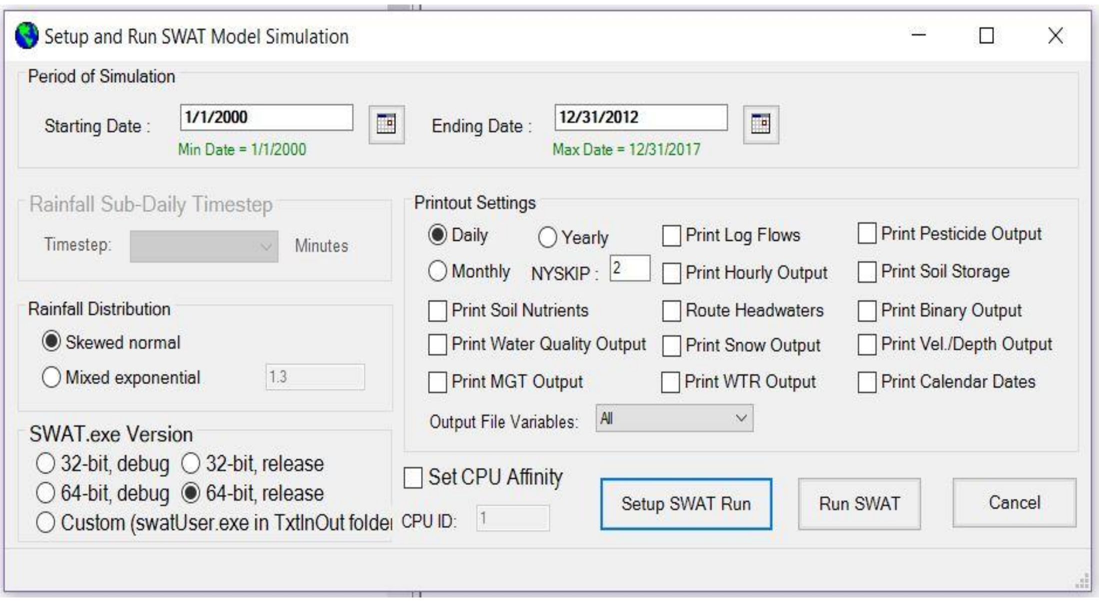
Select Tabels to Write

Completed ☑ Confrguration File (.Fig)
Completed ☑ Soil Data (.Sol)
Completed ☑ Weather Generator Data (.Wgn)
Completed ☑ Subbasin/Snow Data (.Sub/.Sno)
Completed ☑ HRU/Drainage Data (.Hru/.Sdr)
Completed ☑ Main Channel Data (.Rte)
Completed ☑ Groundwater Data (.Gw)
Completed ☑ Water Use Data (.Wus)
Completed ☑ Management Data (.Mgt)
Completed ☑ Soil Chemical Data (.Chm)
Completed ☑ Pond Data (.Pnd)
Completed ☑ Stream Water Quality Data (.Swq)
Completed ☑ Septic Data (.Sep)
Completed ☑ Operations Data (.Ops)
Completed ☑ Watershed Data (.Bsn/.Wwq)
Completed ☑ Master Watershed File (.Cio)

Figure 5.15 Write SWAT Database Table Menu

5.3.5 SWAT Simulation

In SWAT simulation menu select Run SWAT and the dialog box as shown in figure 5.16 will appear.



Setup and Run SWAT Model Simulation

Period of Simulation

Starting Date : 1/1/2000
Min Date = 1/1/2000
Ending Date : 12/31/2012
Max Date = 12/31/2017

Rainfall Sub-Daily Timestep
Timestep: Minutes

Rainfall Distribution
● Skewed normal
○ Mixed exponential 1.3

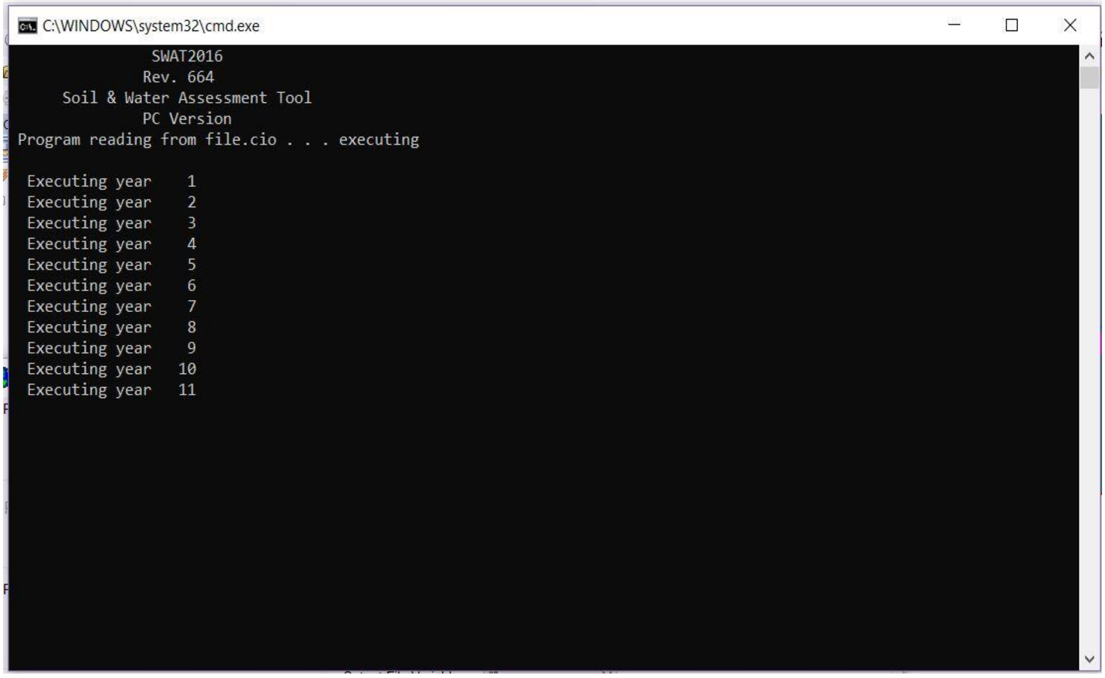
SWAT.exe Version
○ 32-bit, debug ○ 32-bit, release
○ 64-bit, debug ● 64-bit, release
○ Custom (swatUser.exe in TxtInOut folde

Printout Settings
● Daily ○ Yearly
○ Monthly NYSKIP : 2
☐ Print Log Flows
☐ Print Hourly Output
☐ Route Headwaters
☐ Print Snow Output
☐ Print WTR Output
☐ Print Soil Nutrients
☐ Print Water Quality Output
☐ Print MGT Output
☐ Print Pesticide Output
☐ Print Soil Storage
☐ Print Binary Output
☐ Print Vel./Depth Output
☐ Print Calendar Dates
Output File Variables: All

☐ Set CPU Affinity
CPU ID: 1

Figure 5.16 Setup and Run Swat Model Simulation Dialog Box

Now set the period of simulation for calibration from 01/01/2000 to 31/12/2012 and select Daily print out setting, 64-bit, release SWAT.exe Version and NYSKIP as 2 years and click Setup SWAT Run and after run the SWAT model.



C:\WINDOWS\system32\cmd.exe

```
               SWAT2016
              Rev. 664
     Soil & Water Assessment Tool
              PC Version
Program reading from file.cio . . . executing

 Executing year    1
 Executing year    2
 Executing year    3
 Executing year    4
 Executing year    5
 Executing year    6
 Executing year    7
 Executing year    8
 Executing year    9
 Executing year   10
 Executing year   11
```

Figure 5.17 Run Window of SWAT

5.3.6 Output Analysis

After SWAT run, simulation outputs were obtained in the form of Spatial and temporal results on HRU scale (hru files), Reach inflow-outflow (rch file), Reservoir Inflow- outflow and other components at reservoir location (rsv file), Total water yield from the watershed (wtr files), Various management operation (mgt files) and Summarize results of Sub-basin format (sub file) that can be seen in TextInOut folder in Scenarios folder.

5.4 MODEL CALIBRATION AND UNCERTAINTY ANALYSIS USING SWAT-CUP

Calibration is an important step in developing any hydrologic model which results in the representation of accurate and realistic physical processes occurring inside the basin. A set of parameters that are more influencing to runoff process were set for performing the calibration process like management parameters, ground water parameters, soil parameters and main channel parameters.

This set of calibrated parameters seeks to minimize the difference between simulated and observed stream flows. Calibration is regarded necessary because there may be some uncertainties in the input of the model and because the models only offer simplified depictions of the physical procedures of the catchment, working on a range of scales that are not always consistent with the catchment or grid scale. A calibration period of eleven years was considered in this study, from 2000-2012 including two years of warm-up period, i.e. 2000 and 2001. A total of 10 parameters were used to perform the calibration method. Observed discharge data of outlet station located at Deo dam site were used as inputs.

Calibration and validation are typically conducted by dividing the observed data accessible into two datasets: one for calibration and one for validation. Data are most frequently divided over time periods, ensuring that the climate data used for both calibration and validation are not significantly distinct, i.e. wet, moderate and dry years occur in both phases. Data may also be divided spatially, with all available data allocated to the calibration stage at a specified monitoring location and validated at one or more other gauges within the basin. This strategy may be essential when users face data-limited circumstances that prevent using a single gauge from performing a split-time calibration and validation. SWAT users also used calibrated watershed parameters with roughly comparable or similar climatic, soil and land use conditions for validation in their research basin, or vice versa. Split-location calibration and validation approaches have been performed in some past SWAT researches.

Step by step procedure for creating SWAT-SUFI2 Input Files is shown in figure 5.18

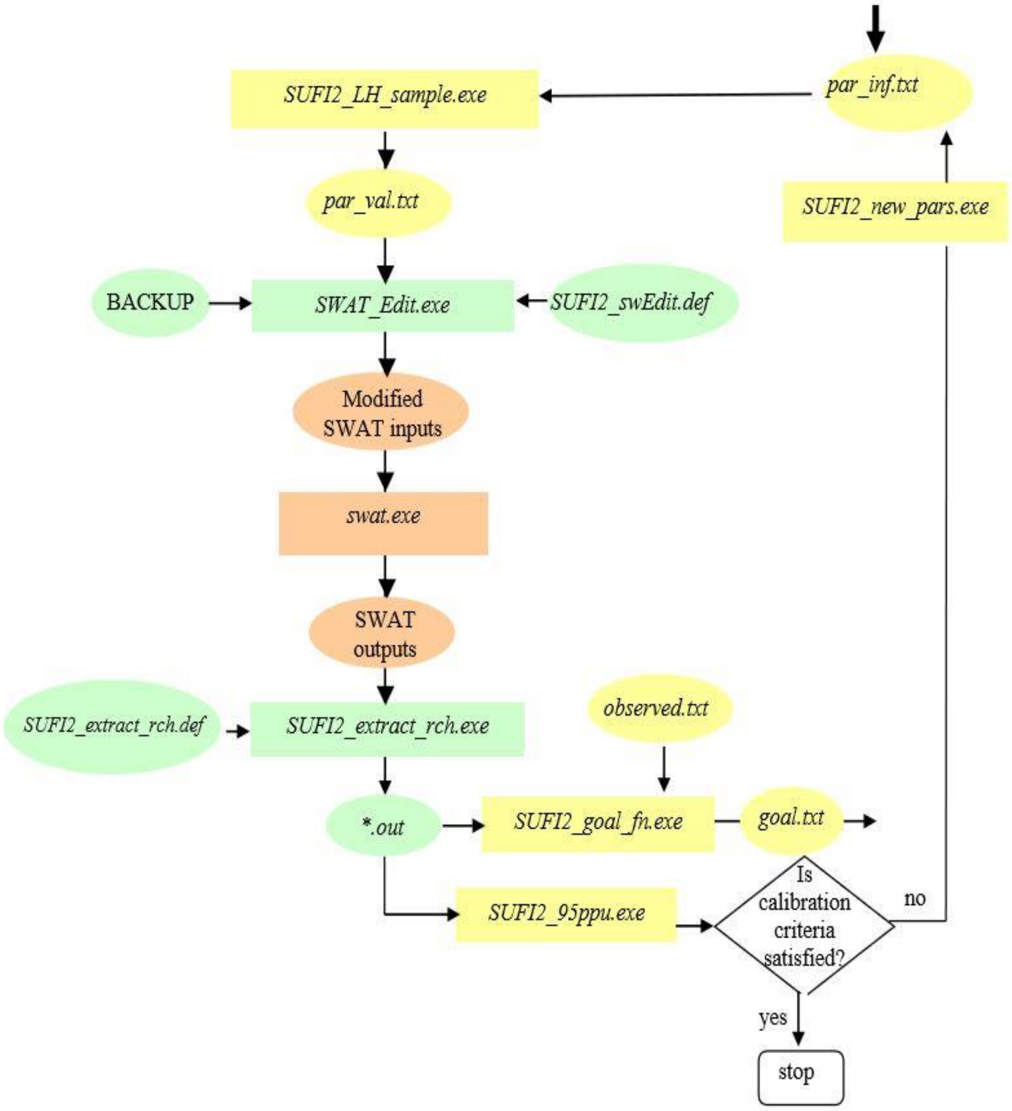


Figure 5.18 Procedure for Calibration Using SUFI2 Algorithm

The SWAT-CUP Calibration Input Files to update are shown in figure 5.19.

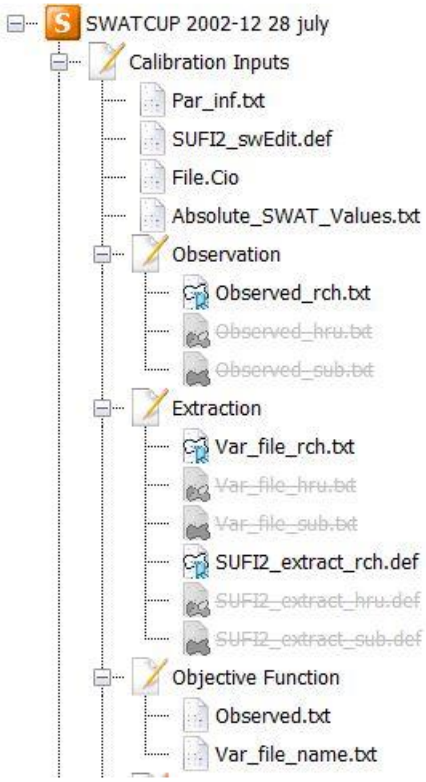
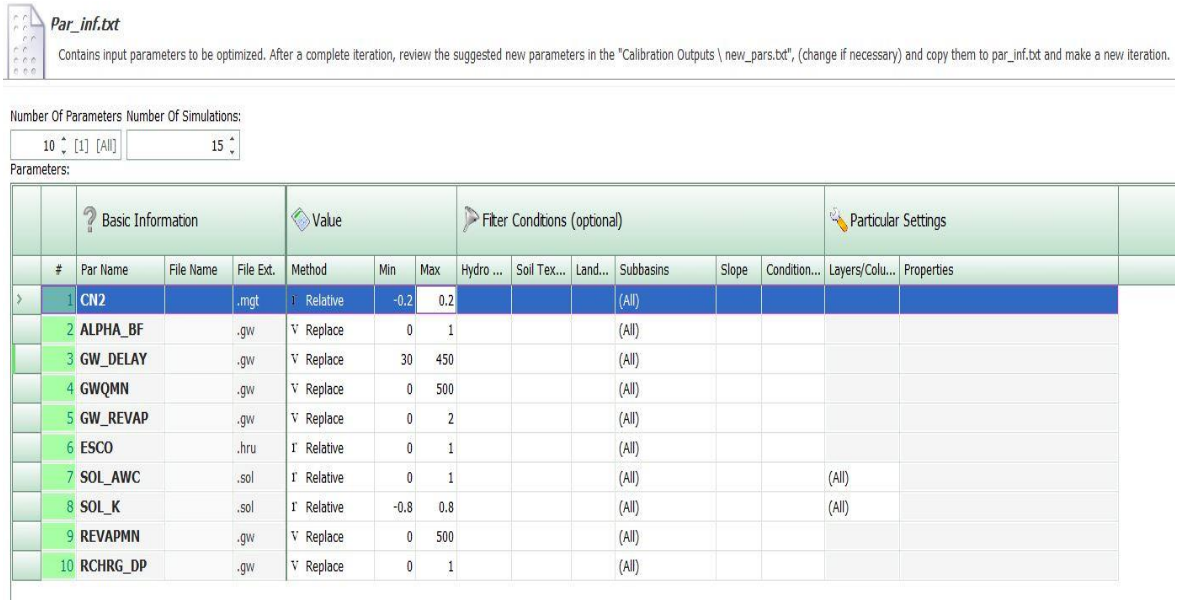


Figure 5.19 SWAT-CUP Calibration Input Files

5.4.1 Par_inf.txt

Here we have selected 10 parameters which mainly affects the Streamflow and number of simulations is set to 15. This is shown in figure 5.20.



Par_inf.txt

Contains input parameters to be optimized. After a complete iteration, review the suggested new parameters in the "Calibration Outputs \ new_pars.txt", (change if necessary) and copy them to par_inf.txt and make a new iteration.

Number Of Parameters: 10 [1] [All]
Number Of Simulations: 15

Parameters:

		Basic Information			Value			Filter Conditions (optional)						Particular Settings	
	#	Par Name	File Name	File Ext.	Method	Min	Max	Hydro ...	Soil Tex...	Land...	Subbasins	Slope	Condition...	Layers/Colu...	Properties
›	1	**CN2**		.mgt	r Relative	-0.2	0.2				(All)				
	2	**ALPHA_BF**		.gw	v Replace	0	1				(All)				
	3	**GW_DELAY**		.gw	v Replace	30	450				(All)				
	4	**GWQMN**		.gw	v Replace	0	500				(All)				
	5	**GW_REVAP**		.gw	v Replace	0	2				(All)				
	6	**ESCO**		.hru	r Relative	0	1				(All)				
	7	**SOL_AWC**		.sol	r Relative	0	1				(All)			(All)	
	8	**SOL_K**		.sol	r Relative	-0.8	0.8				(All)			(All)	
	9	**REVAPMN**		.gw	v Replace	0	500				(All)				
	10	**RCHRG_DP**		.gw	v Replace	0	1				(All)				

Figure 5.20 Parameters Input File in SWAT-CUP

5.4.1.1 Parameters Description

The parameters selected for calibration are described as,

- **Management Parameters**

The main motto of environmental modelling is to have access to the effect of human operations on a specified system. Central to this evaluation is the description of land and water management practices taking place within the system. The main files used to summarize these procedures are the HRU management file (.mgt). This file includes input data of applications for planting, harvesting, irrigation, nutrient applications, pesticide applications, and tillage operations. Data regarding tile drains and metropolitan regions is also stored in this file. Curve Number 2 management parameter is selected here.

Curve number 2 (CN2)

The initial SCS runoff curve number for antecedent moisture condition II (CN2) is a function of soil permeability, land use, and soil water condition. Curve Number 2 was developed by USDA, Natural Resources Conservation Services, also known as the Soil Conservation Service (SCS). Curve Number 2 was selected as a parameter because it represents average moisture conditions versus dry (wilting point) or wet (field capacity). It depends on the hydrologic soil groups (A, B, C or D), condition (poor, fair, good), and land-use type. It ranges from 30 to 100 with runoff potential increasing as the curve number gets higher values. Lower runoff potential is usually found where more permeable soils exist while high runoff potential is more prevalent where soils are more impervious. When curve number increases, surface runoff increases in simulation process.

- **Ground Water parameters**

Base Flow Alpha Factor (ALPHA_BF)

Base flow is the flow that occurs below the table of groundwater and discharges into a stream and later on responds to the gradients of the water table and stream. In order to contribute to stream flow, a downhill gradient is required for base flow. If the water table is below the level of the stream, then groundwater will not add to the runoff and there will be no contribution to the base flow.

The alpha base flow variable is a constant and demonstrates the groundwater flow reaction to modifications in the recharge of stream flow. The study area's topography, geology, slope, vegetation, and drainage density affects the base flow alpha factor. For this parameter, the calibration limit ranged from 0 to 1. A value close to 0 indicates a slow response where a quick response is indicated as a value close to 1.

Groundwater Delay time (GW_DELAY)

Groundwater delay time is the time it takes for water to percolate to the shallow aquifer from the bottom layer of the soil profile in days. The depth of the water table and the hydraulic characteristics of individual soil layers affect the time of transfer of water. Layers with small particle size such as sand, silt and clay will obstruct the flow of water within the soil profile resulting in low hydraulic conductivity within the saturated soil layers. Similarly, high particle size soil layers will allow more water movement within the soil to increase hydraulic conductivity. The calibration range for this parameter ranged from 30 to 450. By increasing the value of GW_DELAY, the time required for movement of water from surface to shallow aquifer increases resulting a quick response to stream flow recharge.

REVAPMN

REVAPMN can be described as the threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur. Movement of the water from the shallow aquifer to the unsaturated zone is allowed only if the volume of water in the shallow aquifer is equal to or greater than REVAPMN depth. This variable, along with GW_REVAP, is the reason a different groundwater file is created for each HRU rather than each sub-basin.

Groundwater “revap” Coefficient (GW_REVAP)

Water can migrate into the overlaying unsaturated area from the shallow aquifer. During periods of dryness of the aquifer's overlaying material, water in the capillary fringe separating the saturated and unsaturated zones will evaporate and diffused upward. As water is removed by evaporation from the capillary fringe, water from the underlying aquifer is substituted. Deep rooted crops can also remove water from the aquifer, which can uptake water directly from the aquifer.

In watersheds where the saturation zone is not much below the ground or where deep rooted crops are growing, this method is significant. Since the sort of plant cover will impact the significance of revap in the water balance, it is possible to vary the parameters governing revap by land use.

As GW REVAP approaches 0, water movement is limited from the shallow aquifer to the root zone. As the GW REVAP approaches 1, the transfer rate from the shallow aquifer to the root zone approaches the evapotranspiration rate. The value of GW_REVAP should be in between 0.0 to 0.2.

Together with REVAPMN, this variable is the reason for creating a distinct groundwater file for each HRU rather than for each sub basin.

Deep aquifer percolation fraction (RCHRG_DP)

Deep aquifer percolation fraction can be described as the portion of percolation from the root zone which recharges the deep aquifer. The value for RCHRG_DP should range between 0.0 and 1.0.

- **Soil parameters**

  The soil data used by SWAT can be split into two groups, physical characteristics and chemical characteristics. The physical properties of the soil regulate the movement of water and air through the profile and have a significant impact on the cycling of water within the HRU. While the physical properties are required, information on chemical properties is optional. For all layers in the soil, the soil input(.sol) files define the physical properties.

Available Water Capacity (SOL_AWC)

The available water capacity of the soil layer (expressed as mm water/ mm soil), is the amount of water present at field capacity minus the amount of water present at permanent wilting point available for plant growth. High water holding capacity of the soil layer helps to control runoff and sediment loss. The calibration range of this parameter ranged from 0.0 to 1.0. Available water content is mainly affected by Soil texture and its composition and is important for vegetation growth and nutrient transport.

Saturated hydraulic conductivity (SOL_K)

K_{sat}, the saturated hydraulic conductivity, relates soil water flow rate (flux density) to the hydraulic gradient and is a measure of the ease of water movement through the soil. K_{sat} i reciprocal of resistance of the siul matrix to water flow.

- **HRU general parameters**

The overall HRU input file contains information related to a diversity of the features within the HRU. Data in the HRU input file can be grouped into the following categories: topographic characteristics, water flow, erosion, land cover, and depressional storage areas.

Evapotranspiration is defined as the water lost to the atmosphere from the ground surface, evaporation from the capillary fringe of the groundwater table, and transpiration of groundwater by plants whose roots tap the capillary fringe of the groundwater table.

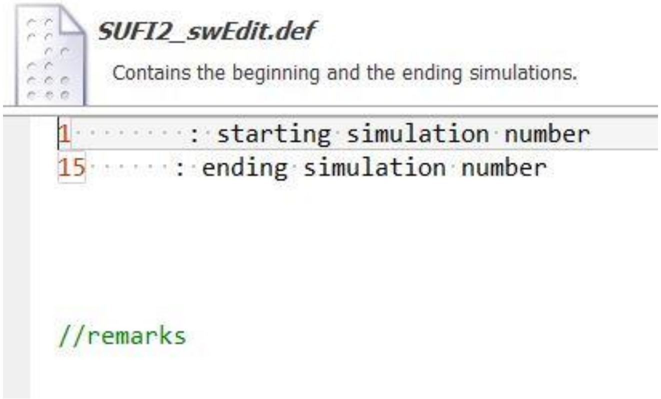
Estimates of evapotranspiration are mainly influenced by climatic variables such as temperature increases, relative humidity, wind velocity, etc. These factors therefore indirectly induce some effect on variables of hydrological flow. The use of the plant compensation factor (EPCO) and the soil evaporation compensation factor (ESCO) represented evapotranspiration in calibration. In this study, only the compensation factor for soil evaporation (ESCO) is considered.

Soil Evaporation Compensation Factor (ESCO)

ESCO is the soil evaporation compensation factor used to modify the depth of soil layers to satisfy evaporation demand. ESCO ranges from 0 to 1, as the coefficient decreases, evaporation demand in the model can be extracted from lower soil layers. The complete ESCO range was used and adapted based on graphical output simulation during calibration.

5.4.2 SUFI2_swEdit.def

In this input file we have to enter starting and ending simulation number.



SUFI2_swEdit.def

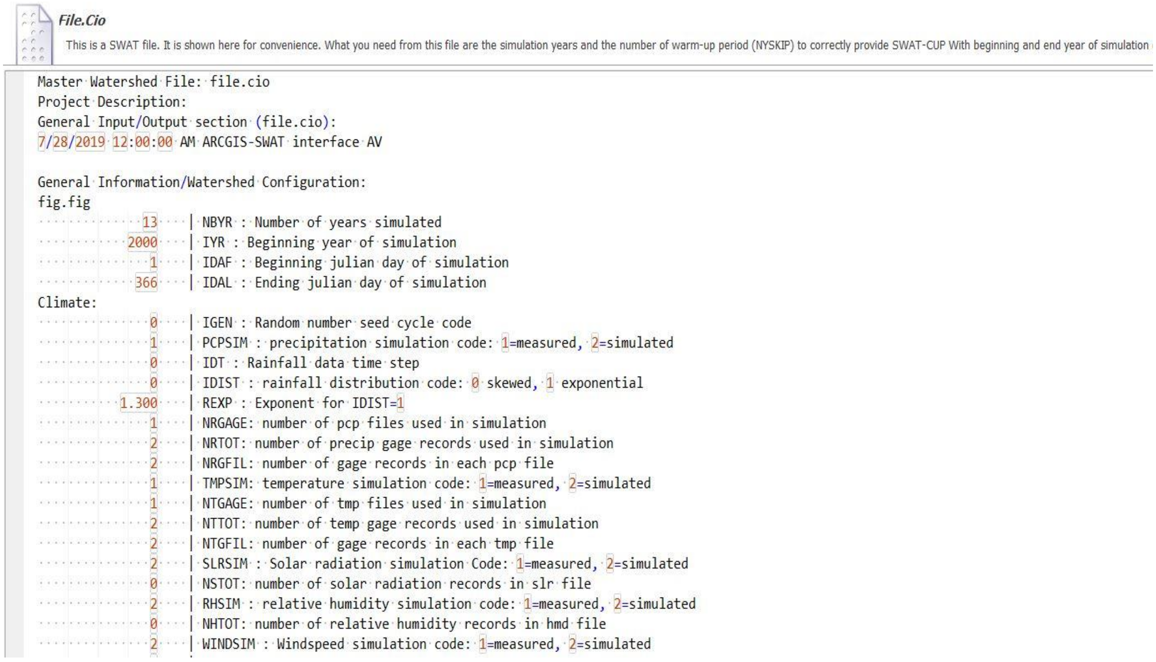
Contains the beginning and the ending simulations.

```
1        : starting simulation number
15     : ending simulation number




//remarks
```

Figure 5.21 SUFI2_swEdit.def Input File

5.4.3 File.cio

This file contains information about ArcSWAT. So there is no need to make any changes in this file. Number of years simulated, beginning year of simulation, beginning and ending julian day of simulation are there in this file as shown in figure 5.22.



File.Cio

This is a SWAT file. It is shown here for convenience. What you need from this file are the simulation years and the number of warm-up period (NYSKIP) to correctly provide SWAT-CUP With beginning and end year of simulation

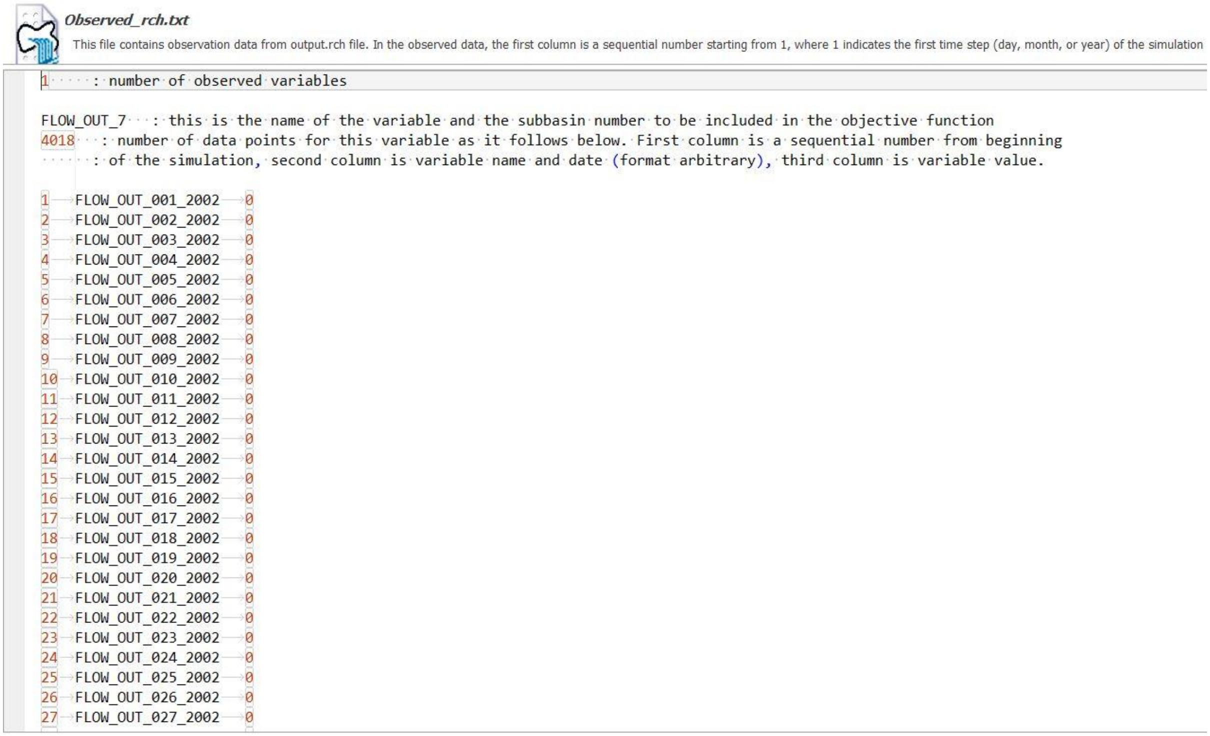
```
Master Watershed File: file.cio
Project Description:
General Input/Output section (file.cio):
7/28/2019 12:00:00 AM ARCGIS-SWAT interface AV

General Information/Watershed Configuration:
fig.fig
              13    | NBYR : Number of years simulated
            2000    | IYR : Beginning year of simulation
               1    | IDAF : Beginning julian day of simulation
             366    | IDAL : Ending julian day of simulation
Climate:
               0    | IGEN : Random number seed cycle code
               1    | PCPSIM : precipitation simulation code: 1=measured, 2=simulated
               0    | IDT : Rainfall data time step
               0    | IDIST : rainfall distribution code: 0 skewed, 1 exponential
           1.300    | REXP : Exponent for IDIST=1
               1    | NRGAGE: number of pcp files used in simulation
               2    | NRTOT: number of precip gage records used in simulation
               2    | NRGFIL: number of gage records in each pcp file
               1    | TMPSIM: temperature simulation code: 1=measured, 2=simulated
               1    | NTGAGE: number of tmp files used in simulation
               2    | NTTOT: number of temp gage records used in simulation
               2    | NTGFIL: number of gage records in each tmp file
               2    | SLRSIM : Solar radiation simulation Code: 1=measured, 2=simulated
               0    | NSTOT: number of solar radiation records in slr file
               2    | RHSIM : relative humidity simulation code: 1=measured, 2=simulated
               0    | NHTOT: number of relative humidity records in hmd file
               2    | WINDSIM : Windspeed simulation code: 1=measured, 2=simulated
```

Figure 5.22 File.cio Input File

After this comes Absolute_SWAT_Values.txt file. This file contains limits of all parameters that can be used in SWATCUP. So changes in these file are not needed.

5.4.4 Observation_rch.txt

In this input file we have to mention the number of observed variables i.e. streamflow here. Then the name of the variable and the sub-basin number to be included in the objective function (FLOW_OUT_7), total number of observed data points (number of daily observed streamflow i.e. 4018 for 2002-2012) which is shown in figure 5.23.



Observed_rch.txt

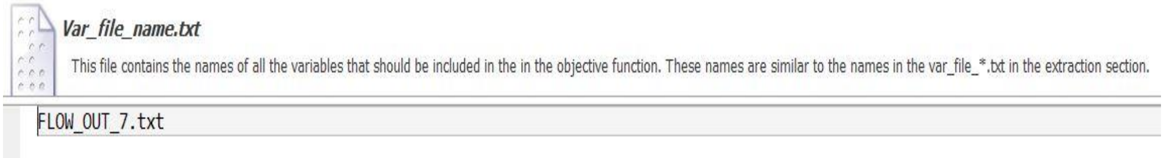
This file contains observation data from output.rch file. In the observed data, the first column is a sequential number starting from 1, where 1 indicates the first time step (day, month, or year) of the simulation

```
1     : number of observed variables

FLOW_OUT_7   : this is the name of the variable and the subbasin number to be included in the objective function
4018   : number of data points for this variable as it follows below. First column is a sequential number from beginning
      : of the simulation, second column is variable name and date (format arbitrary), third column is variable value.

1	FLOW_OUT_001_2002	0
2	FLOW_OUT_002_2002	0
3	FLOW_OUT_003_2002	0
4	FLOW_OUT_004_2002	0
5	FLOW_OUT_005_2002	0
6	FLOW_OUT_006_2002	0
7	FLOW_OUT_007_2002	0
8	FLOW_OUT_008_2002	0
9	FLOW_OUT_009_2002	0
10	FLOW_OUT_010_2002	0
11	FLOW_OUT_011_2002	0
12	FLOW_OUT_012_2002	0
13	FLOW_OUT_013_2002	0
14	FLOW_OUT_014_2002	0
15	FLOW_OUT_015_2002	0
16	FLOW_OUT_016_2002	0
17	FLOW_OUT_017_2002	0
18	FLOW_OUT_018_2002	0
19	FLOW_OUT_019_2002	0
20	FLOW_OUT_020_2002	0
21	FLOW_OUT_021_2002	0
22	FLOW_OUT_022_2002	0
23	FLOW_OUT_023_2002	0
24	FLOW_OUT_024_2002	0
25	FLOW_OUT_025_2002	0
26	FLOW_OUT_026_2002	0
27	FLOW_OUT_027_2002	0
```

Figure 5.23 Observed_rch.txt Input File

5.4.5 Var_file_rch.txt

In this file we have to mention only name of variable and the sub-basin number to be included in the objective function (FLOW_OUT_7) as shown in figure 5.24.



Var_file_name.txt

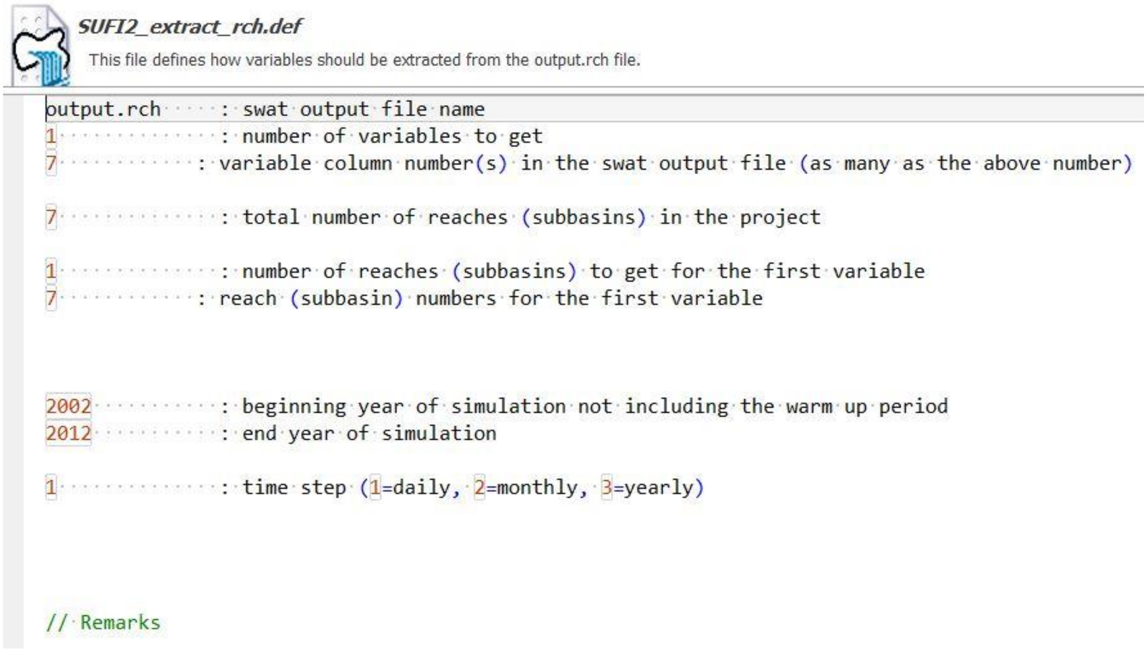
This file contains the names of all the variables that should be included in the in the objective function. These names are similar to the names in the var_file_*.txt in the extraction section.

```
FLOW_OUT_7.txt
```

Figure 5.24 Var_file_rch.txt Input File

5.4.6 SUFI2_extract_rch.def

In this input file number of variables to calculate, variable column number in the SWAT output file, total number of sub-basins, beginning year of simulation after warmup period (i.e 2002), ending year of simulation (2012) and number for daily time step (i.e 1) as shown in figure 5.25.



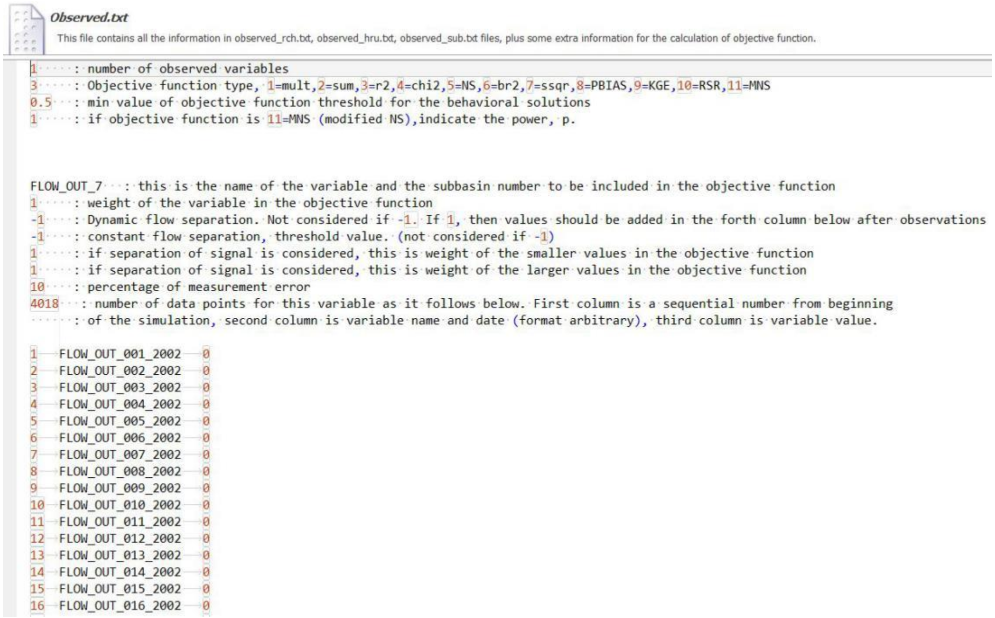
SUFI2_extract_rch.def

This file defines how variables should be extracted from the output.rch file.

```
output.rch     : swat output file name
1              : number of variables to get
7            : variable column number(s) in the swat output file (as many as the above number)

7              : total number of reaches (subbasins) in the project

1              : number of reaches (subbasins) to get for the first variable
7            : reach (subbasin) numbers for the first variable



2002           : beginning year of simulation not including the warm up period
2012           : end year of simulation

1              : time step (1=daily, 2=monthly, 3=yearly)




// Remarks
```

Figure 5.25 SUFI2_extract_rch.def Input File

5.4.7 Observed.txt



Observed.txt

This file contains all the information in observed_rch.txt, observed_hru.txt, observed_sub.txt files, plus some extra information for the calculation of objective function.

```
1     : number of observed variables
3     : Objective function type, 1=mult,2=sum,3=r2,4=chi2,5=NS,6=br2,7=ssqr,8=PBIAS,9=KGE,10=RSR,11=MNS
0.5   : min value of objective function threshold for the behavioral solutions
1     : if objective function is 11=MNS (modified NS),indicate the power, p.



FLOW_OUT_7   : this is the name of the variable and the subbasin number to be included in the objective function
1     : weight of the variable in the objective function
-1    : Dynamic flow separation. Not considered if -1. If 1, then values should be added in the forth column below after observations
-1    : constant flow separation, threshold value. (not considered if -1)
1     : if separation of signal is considered, this is weight of the smaller values in the objective function
1     : if separation of signal is considered, this is weight of the larger values in the objective function
10    : percentage of measurement error
4018   : number of data points for this variable as it follows below. First column is a sequential number from beginning
      : of the simulation, second column is variable name and date (format arbitrary), third column is variable value.

1	FLOW_OUT_001_2002	0
2	FLOW_OUT_002_2002	0
3	FLOW_OUT_003_2002	0
4	FLOW_OUT_004_2002	0
5	FLOW_OUT_005_2002	0
6	FLOW_OUT_006_2002	0
7	FLOW_OUT_007_2002	0
8	FLOW_OUT_008_2002	0
9	FLOW_OUT_009_2002	0
10	FLOW_OUT_010_2002	0
11	FLOW_OUT_011_2002	0
12	FLOW_OUT_012_2002	0
13	FLOW_OUT_013_2002	0
14	FLOW_OUT_014_2002	0
15	FLOW_OUT_015_2002	0
16	FLOW_OUT_016_2002	0
```

Figure 5.26 Observed.txt Input file

As shown in figure 5.26, this file needs information about the objective function to be used for calibration, number of flow data points, and values of all observed stream flow data.

After giving all inputs, calibration is done by executing executable files as shown in figure 5.27.

Figure 5.27 Calibration Executable Dialog Box

SUFI2_run.bat executes simulations and performs calibration for all parameters and SUFI2_post.bat calculates simulated stream flows for all data points.

5.4.8 Calibration Outputs

Calibration output gives the files as shown in figure 5.28. Here, global sensitivity analysis can be performed only after one iteration having simulation numbers 2 greater than number of parameters.

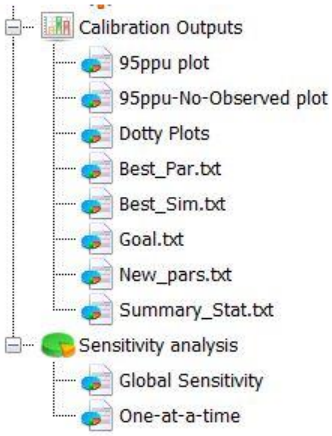


Figure 5.28 Calibration Output Files

5.5 SWAT MODEL PERFORMANCE EVALUATION

The time-series plots of measured and simulated data were evaluated by using four statistical indicators or objective functions in SWAT-CUP and are given as follows:

5.5.1 Coefficient of Determination (R^2)

The coefficient of determination (R^2) is one of the most frequently used criteria to describe the proportion of the total variance in the measured data that can be explained by the model. It ranges from 0.0 to 1.0, with higher values indicating better agreement.

Coefficient of determination is calculated by equation:

$$R^2 = \frac{\left[\sum_{i=1}^{n}(X_i+X')(Y_i-Y')\right]^2}{\sum_{i=1}^{n}(X_i-X')^2 \sum_{i=1}^{n}(Y_i-Y')^2} \qquad \ldots(5.1)$$

Where, n is the number of measured data

Xi and Yi are the measured and predicted data at time i

X' and Y' are the mean of measured and predicted data.

5.5.2 Nash-Sutcliffe Efficiency (NSE)

The effectiveness of Nash-Sutcliffe (NSE) is a standardized statistic that determines the comparative magnitude of the residual variance compared to the measured data quantity. NSE shows how well the observed vs. simulated data plot fits the 1:1 line. NSE range is between $-\infty$ and 1.0. The values between 0.0 and 1.0 are generally considered to be acceptable performance levels, whereas values < 0.0 indicate that the mean observed value is a better predictor than the simulated value, indicating unacceptable performance.

The Nash-Sutcliffe efficiency (NSE) can be calculated as:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_i-Y_i)^2}{\sum_{i=1}^{n}(X_i-X')^2} \qquad \ldots(5.2)$$

Where, n is the number of measured data

X_i and Y_i are the measured and predicted data at time i

X' is the mean of measured data.

5.5.3 Percent Bias (PBIAS)

Percent bias (PBIAS) measures the average tendency of the simulated data to be greater or lower than their observed counterparts. It is the deviation of the data being evaluated, expressed as a percentage. The optimal value of PBIAS is 0.0, with lower-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias and negative values indicate model overestimation bias.

PBIAS is calculated as:

$$PBIAS = \frac{\sum_{i=1}^{n}(X_i - Y_i)\times 100}{\sum_{i=1}^{n} X_i} \qquad \ldots(5.3)$$

Where, n is the number of measured data

X_i and Y_i are the measured and predicted data at time i.

5.5.4 Root mean square and standard deviation ratio (RSR)

Root mean square and standard deviation ratio (RSR) incorporates the advantages of error index statistics and includes a scaling/normalization factor, so the resulting statistics and recorded values can be applied to different constituents. RSR ranges from the ideal value of 0 to a high positive value, zero value shows zero RMSE or residual variation and therefore ideal simulation of the model. The lower RSR, the lower RMSE, and better the performance of model simulation. RSR is calculated as the RMSE and standard data deviation ratio.

The Root mean square and standard deviation ratio (RSR) can be calculated as:

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}(X_i - Y_i)^2}}{\sqrt{\sum_{i=1}^{n}(X_i - X')^2}} \qquad \ldots(5.4)$$

Where, n is the number of measured data

X_i and Y_i are the measured and predicted data at time i

X' is the mean of measured data.

The closer the value of NSE and R^2 to 1, the better is the model performance. NSE ranges from -∞ to 1.0, with higher values indicating better agreement of the model. Nash- Sutcliffe coefficient of efficiency (NSE) has been widely used to evaluate the performance of hydrological models. The model performance for daily basis is considered to be satisfactory when NSE, RSR, PBIAS lies between 0.5 to 0.65, 0.6 to 0.7, ±15% to ±25% respectively. The performance is considered to be good when NSE, RSR, PBIAS lies between 0.65 to 0.75, 0.5 to 0.6, ±10% to ±15% respectively and it is said to be very good when model with NSE,RSR,PBIAS lies between 0.75 to 1, 0 to 0.5, less than ±15% .The same criteria have been used for model evaluation in the present study.

Other measure of simulation precision is by plotting the 95PPU (95% prediction uncertainty) or P-factor in the simulated versus observed flow graphical representation. The 95PPU measures how well the observed data fit into an uncertainty range of 95 percent confidence range of uncertainty from the acquired simulated output.

R-factor measures the range of output uncertainty represented by the visual band. A well-calibrated model will have a small R-factor, represented as a thin 95PPU band that contains the observed measurements.

5.6 MODEL VALIDATION

Model validation was carried out after the model calibration at the same observation stations used before for calibration. All the ranges of input parameters used for calibration remain unchanged in this process. Evaluation was conducted in a similar way as in model calibration process, i.e. visual comparison of hydrographs, statistical index of NSE and with the analysis of residuals. This was used to assess whether or not the calibrated parameters were appropriate for the study area basin. For the present study a validation period of five years was considered i.e. from 2013-2017.

5.6.1 Validation in SUFI2

To perform validation in SUFI2, edit the files SUFI2_extract_rch.txt, observed_rch.txt, observed_hru.txt, observed_sub.txt, and observed.txt as necessary for the validation period. Also, the file.cio should reflect the validation period. It must be ensured that pcp.pcp and tmp.tmp files in ArcSWAT contains data for validation period. Then simply use the calibrated parameter ranges to make one complete iteration (using the calibration button) without changing the parameters further.

5.7 SENSITIVITY ANALYSIS

Sensitivity analysis is used to predict the rate of change in model outputs with respect to change in model inputs. SWAT model has many parameters due to the fact that it takes the spatial heterogeneity into consideration. The sensitivity analysis of this study was done using Global Sensitivity Analysis which uses Latin Hypercube Sampling and One-At-a-Time (LHS-OAT) method. The inputs were the observed daily flow data, the simulated daily flow (obtained from model) during the period (2002-2012) and the sensitive parameter in relation to flow with the absolute lower and upper bound and default type of change to be applied. The sensitivity analysis was performed based on the simulation results at a runoff station and sensitive parameters were identified and ranked on the basis of measure of sensitivity. 10-parameters for runoff were used for sensitivity analysis.

Parameter sensitivities are determined by calculating the multiple regression system, which regresses the Latin hypercube generated parameters against the objective function values (in file goal.txt):

$$g = \alpha + \sum_{i=1}^{m} \beta_i b_i \qquad \text{…(5.5)}$$

A t-test is then used to identify the relative significance of each parameter b_i. The t-stat is the coefficient of a parameter divided by its standard error. It is a measure of the precision with which the regression coefficient is measured. Then t-stat of a parameter are compared with the values in the Student's t-distribution table to determine the p-value. The Student's t-distribution describes how the mean of a sample with a certain number of observations is expected to behave. The lower the p-value, the more sensitive the parameter is. With a p- value of 0.05, there is only a 5% chance that results you are seeing would have come up in a random distribution, so you can say with a 95% probability of being correct that the variable is having some effect.

CHAPTER 6

RESULTS AND DISCUSSION

6.1 GENERAL

In the present chapter, results obtained from hydrological modelling utilizing ArcSWAT and SWAT-CUP are discussed. These include results from watershed delineation, HRU analysis, SWAT check, model calibration, validation, sensitivity analysis and uncertainty analysis.

6.2 SPATIAL DATA ANALYSIS OF DEO RIVER SUB-BASIN

In this section watershed characteristics, elevation range of catchment area, land use map, soil map and HRU reports generated by ArcSWAT are discussed which are important factors affecting various aspects of runoff.` Figure 6.1 shows watershed and sub-basins of Study area.

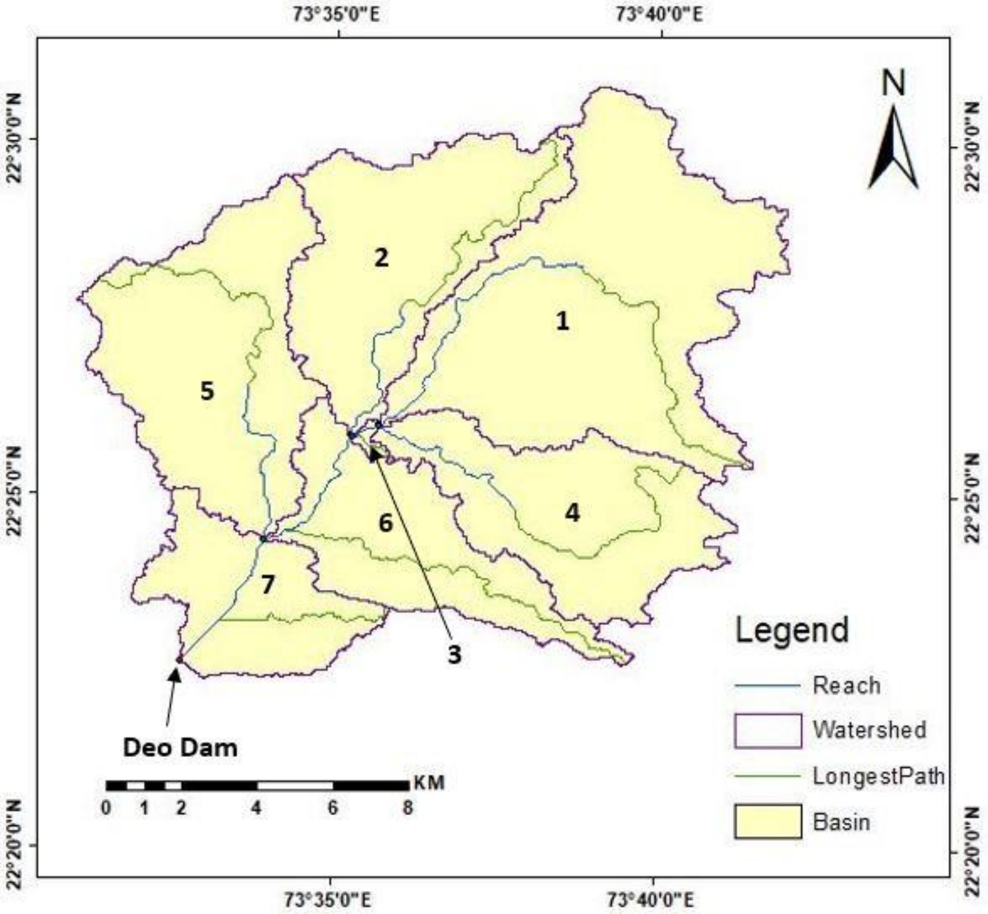


Figure 6.1 Map Showing Sub-basins of Study Area

6.2.1 Details of Topographic report generated by ArcSWAT

Area of Deo river sub-basin: 19435.80 ha

Number of sub-basins: 7

Minimum Elevation: 66 m

Maximum Elevation: 781 m

Mean Elevation: 136.91 m

Table 6.1 Topographic Report Details

Sub basin	Area(ha)	Min. Elevation(m)	Max. Elevation(m)
1	5772.35	87	310
2	3151.81	85	197
3	54.69	84	114
4	2768.03	87	313
5	3628.66	66	781
6	2281.41	74	283
7	1778.82	69	202

6.2.2 Land use/ Land cover

LULC map was prepared by using Landsat 8 image. In the present study, the supervised classification method was used for preparation of the LULC map. Seven different classes have been assigned for the study area. After classification it was found that Agriculture area was dominating with a coverage of the total basin area (40.03%). The LULC distribution for the Deo river basin is presented in Table 6.2 and Land use map is shown in Figure 6.2.

Table 6.2 Land use Distribution

Land Use	Code	Area(Ha)	%Wat. Area
Water	WATR	448.24	2.31
Forest-Deciduous	FRSD	2888.19	14.86
Urban	URBN	85.54	0.44
Range-Brush	RNGB	3212.61	16.53
Agricultural Land	AGRL	7780.36	40.03
Barren	BARR	992.35	5.11
Pasture	PAST	4028.49	20.73

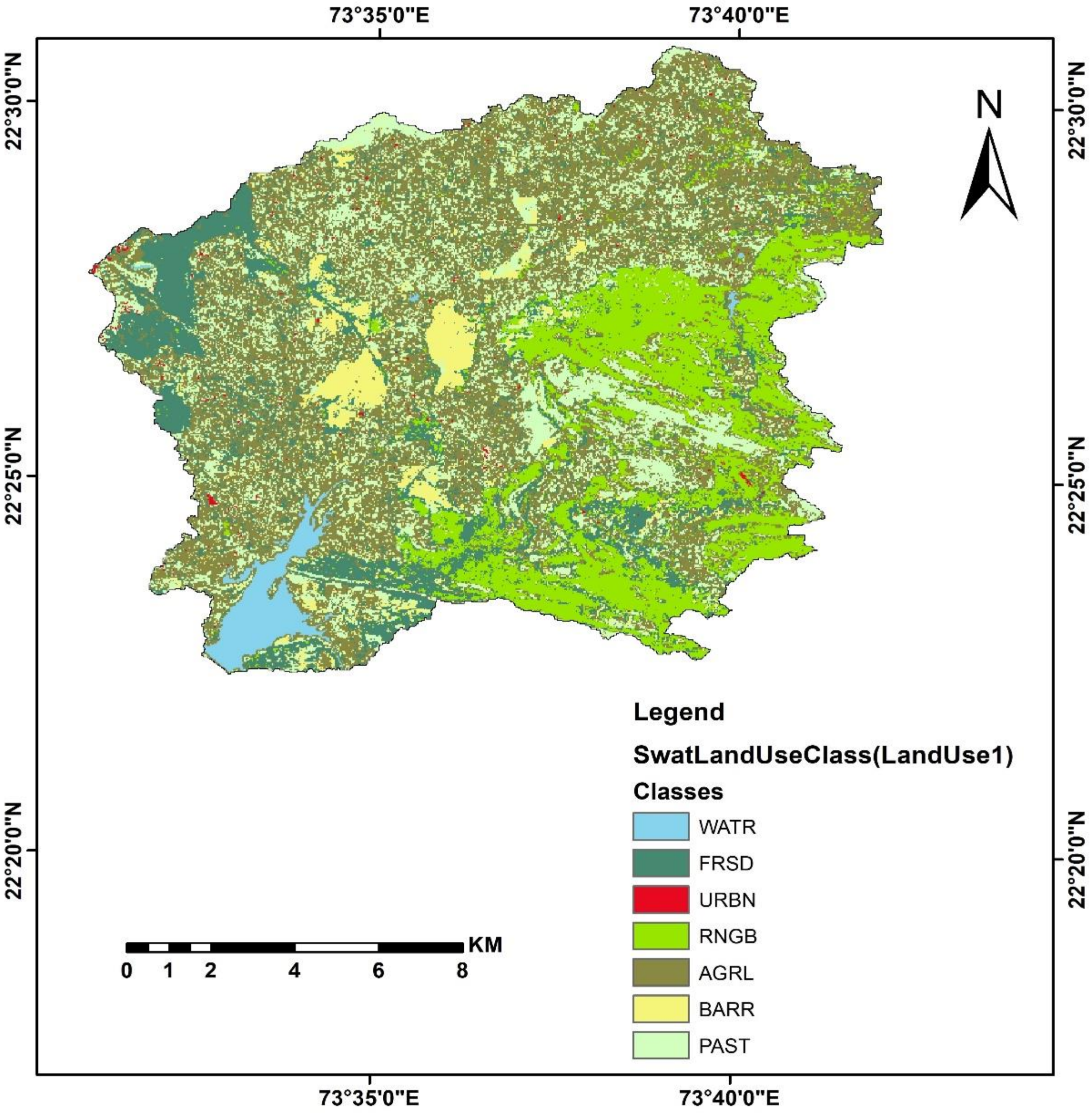


Figure 6.2 LULC Map

6.2.3 Soil Data

As per the FAO soil database two distinct soil classes have been found in the study area viz. Clay and Loam. The percentage of watershed area and the percentage of sand, silt and clay is presented in Table 6.3 and the soil map is shown in Figure 6.3.

Table 6.3 Soil data

Soil	Area(ha)	% Watershed area	% Clay	% Silt	% Sand
Loam	4210.78	21.67	28	50	22
Clay	15225.01	78.33	45	46	29

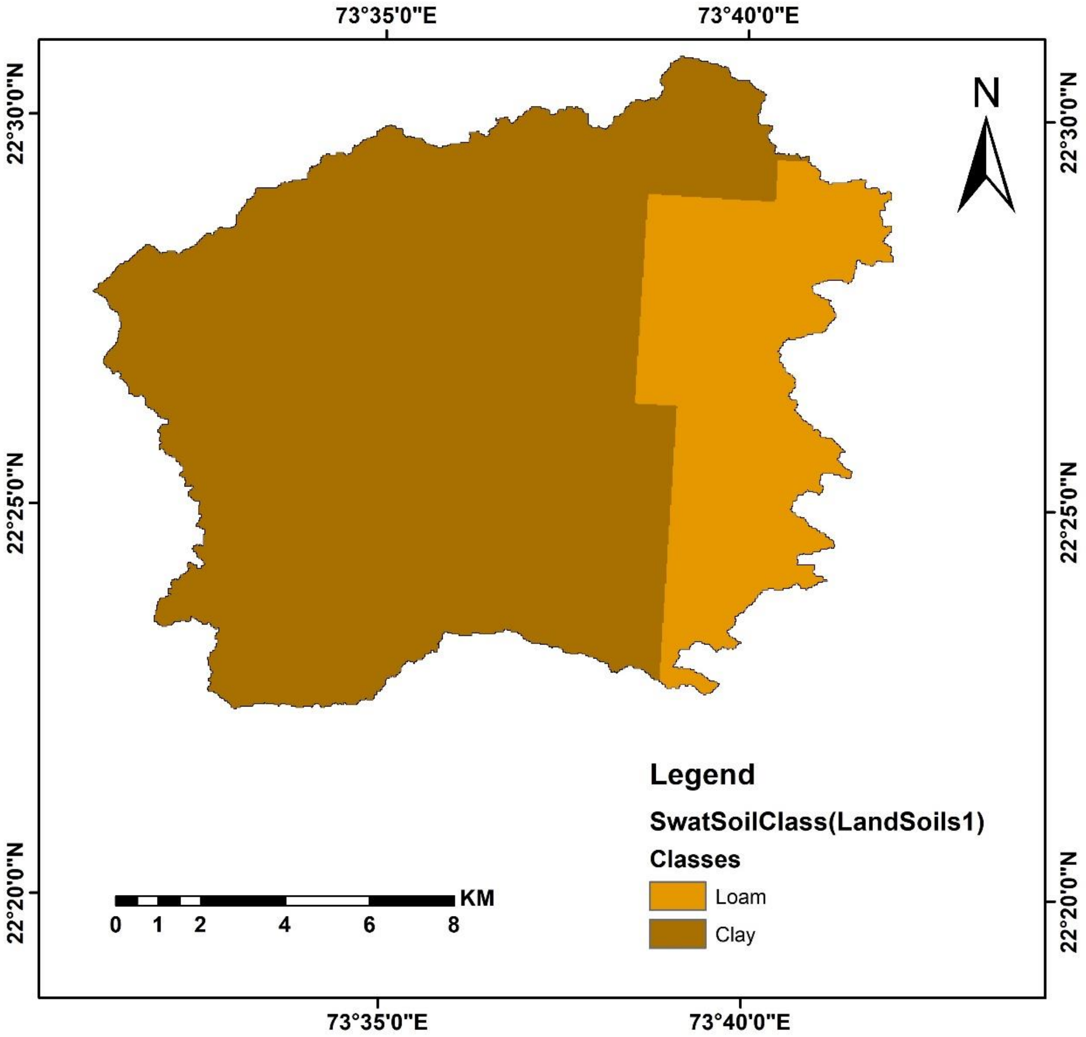


Figure 6.3 Soil Map

6.2.4 Slope Range

Flow direction, Flow accumulation and catchment area are dependent on the slope of the area. Various types of slope range categories and their coverage in Deo river sub-basin are shown in Table 6.4 and Figure 6.4. Mostly slope range 0f 0-10% is there in there Deo river sub-basin .

Table 6.4 Slope Range

Slope Range (%)	Area (ha)	% Watershed area
0-10	3177.28	55.04
10-20	1501.21	26.01
20-30	587.50	10.18
30-40	272.05	4.71
40-9999	234.30	4.06

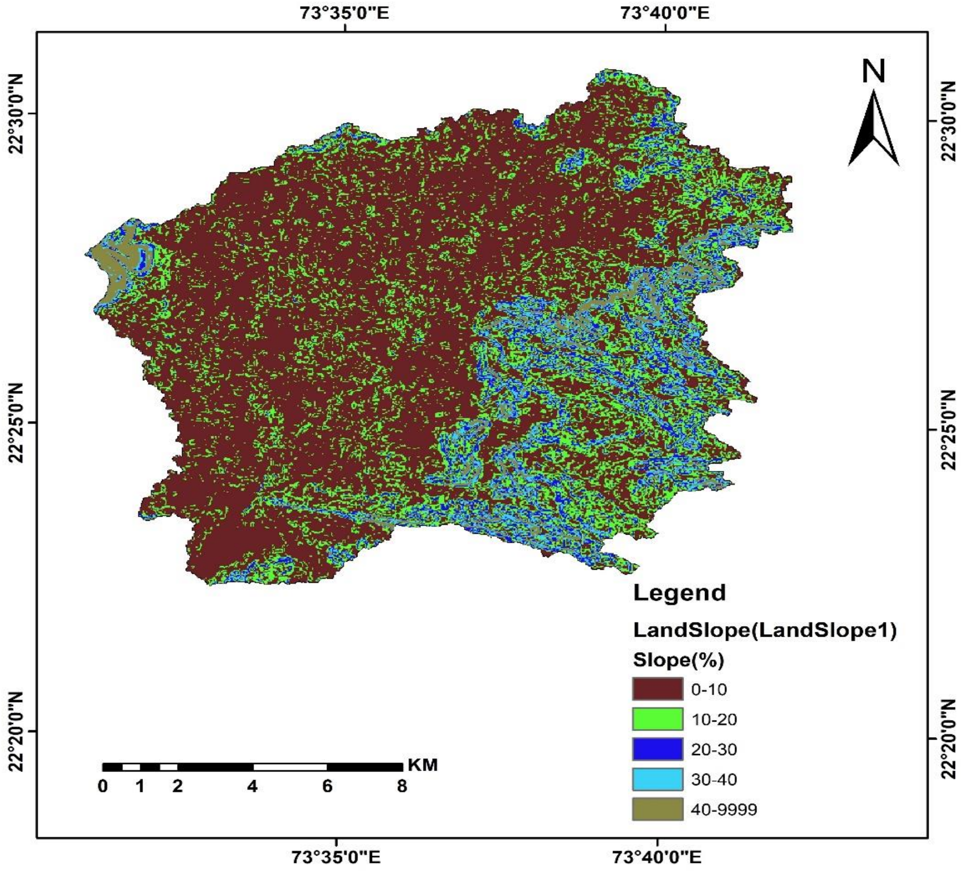


Figure 6.4 Slope Map

6.2.5 HRU Report of Sub-Basin Generated by SWAT

The soil and water assessment tool (SWAT) uses hydrologic response units (HRUs) as the basic unit of all model calculations. HRU is the unique combination of land use, soil and slope range.

Having thresholds 5%, 5% and 10% for Land use, Soil and Slope, 94 HRUs were generated. Hence, the characteristics of HRUs are the key factor for affecting Runoff. Table 6.5 shows the Full HRU Report of Deo River Sub-basin.

Table 6.5 HRU Report

HRU No.	Sub-Basin	Area(Ha)	Unique Combination	% Watershed area
1	1	79.85	1_FRSD_LOAM_10-20	0.41
2	1	34.67	1_FRSD_LOAM_20-30	0.18
3	1	118.06	1_FRSD_LOAM_0-10	0.61
4	1	170.40	1_FRSD_CLAY_0-10	0.88
5	1	61.16	1_FRSD_CLAY_10-20	0.31
6	1	355.83	1_RNGB_LOAM_10-20	1.83
7	1	385.29	1_RNGB_LOAM_0-10	1.98
8	1	207.60	1_RNGB_LOAM_20-30	1.07
9	1	126.78	1_RNGB_LOAM_30-40	0.65
10	1	146.08	1_RNGB_LOAM_40-9999	0.75
11	1	167.62	1_RNGB_CLAY_10-20	0.86
12	1	292.94	1_RNGB_CLAY_0-10	1.51
13	1	90.75	1_RNGB_CLAY_20-30	0.47
14	1	348.95	1_AGRL_LOAM_10-20	1.80
15	1	695.51	1_AGRL_LOAM_0-10	3.58
16	1	977.50	1_AGRL_CLAY_0-10	5.03
17	1	301.97	1_AGRL_CLAY_10-20	1.55
18	1	145.67	1_PAST_LOAM_10-20	0.75
19	1	313.25	1_PAST_LOAM_0-10	1.61
20	1	198.98	1_PAST_CLAY_10-20	1.02

21	1	553.41	1_PAST_CLAY_0-10	2.85
22	2	46.27	2_FRSD_CLAY_10-20	0.24
23	2	231.61	2_FRSD_CLAY_0-10	1.19
24	2	226.21	2_AGRL_CLAY_10-20	1.16
25	2	1495.12	2_AGRL_CLAY_0-10	7.69
26	2	67.96	2_BARR_CLAY_10-20	0.35
27	2	221.61	2_BARR_CLAY_0-10	1.14
28	2	141.45	2_PAST_CLAY_10-20	0.73
29	2	721.58	2_PAST_CLAY_0-10	3.71
30	3	15.70	3_FRSD_CLAY_0-10	0.08
31	3	6.62	3_FRSD_CLAY_10-20	0.03
32	3	2.54	3_RNGB_CLAY_0-10	0.01
33	3	1.79	3_RNGB_CLAY_10-20	0.01
34	3	12.04	3_AGRL_CLAY_0-10	0.06
35	3	4.04	3_AGRL_CLAY_10-20	0.02
36	3	1.36	3_BARR_CLAY_10-20	0.01
37	3	4.70	3_BARR_CLAY_0-10	0.02
38	3	1.35	3_PAST_CLAY_10-20	0.01
39	3	4.52	3_PAST_CLAY_0-10	0.02
40	4	67.78	4_FRSD_LOAM_0-10	0.35
41	4	20.86	4_FRSD_LOAM_20-30	0.11
42	4	63.47	4_FRSD_LOAM_10-20	0.33
43	4	43.18	4_FRSD_CLAY _20-30	0.22
44	4	130.15	4_FRSD_CLAY _0-10	0.67
45	4	97.46	4_FRSD_CLAY _10-20	0.50
46	4	106.47	4_RNGB_LOAM_20-30	0.55
47	4	157.72	4_RNGB_LOAM_0-10	0.81
48	4	226.49	4_RNGB_LOAM_10-20	1.17
49	4	78.97	4_RNGB_CLAY_0-10	0.41
50	4	75.87	4_RNGB_CLAY_20-30	0.39
51	4	42.03	4_RNGB_CLAY_30-40	0.22
52	4	114.91	4_RNGB_CLAY_10-20	0.59

53	4	148.40	4_AGRL_LOAM_10-20	0.76
54	4	192.85	4_AGRL_LOAM_0-10	0.99
55	4	42.03	4_AGRL_LOAM_20-30	0.22
56	4	136.49	4_AGRL_CLAY_10-20	0.70
57	4	417.83	4_AGRL_CLAY_0-10	2.15
58	4	83.61	4_PAST_LOAM_10-20	0.43
59	4	115.92	4_PAST_LOAM_0-10	0.60
60	4	23.31	4_PAST_LOAM_20-30	0.12
61	4	266.35	4_PAST_CLAY_0-10	1.37
62	4	115.81	4_PAST_CLAY_10-20	0.60
63	5	223.02	5_FRSD_CLAY_10-20	1.15
64	5	821.26	5_FRSD_CLAY_0-10	4.23
65	5	213.79	5_AGRL_CLAY_10-20	1.10
66	5	1519.32	5_AGRL_CLAY_0-10	7.82
67	5	753.66	5_PAST_CLAY_0-10	3.88
68	5	97.60	5_PAST_CLAY_10-20	0.50
69	6	157.51	6_FRSD_CLAY_10-20	0.81
70	6	296.84	6_FRSD_CLAY_0-10	1.53
71	6	21.73	6_RNGB_LOAM_10-20	0.11
72	6	15.06	6_RNGB_LOAM_0-10	0.08
73	6	11.83	6_RNGB_LOAM_20-30	0.06
74	6	191.17	6_RNGB_CLAY_10-20	0.98
75	6	133.53	6_RNGB_CLAY_20-30	0.69
76	6	83.75	6_RNGB_CLAY_30-40	0.43
77	6	209.83	6_RNGB_CLAY_0-10	1.08
78	6	544.04	6_AGRL_CLAY_0-10	2.80
79	6	121.88	6_AGRL_CLAY_10-20	0.63
80	6	136.41	6_BARR_CLAY_0-10	0.70
81	6	41.00	6_BARR_CLAY_10-20	0.21
82	6	69.31	6_PAST_CLAY_10-20	0.36
83	6	247.48	6_PAST_CLAY_0-10	1.27
84	7	358.55	7_WATR_CLAY_0-10	1.84

85	7	43.68	7_WATR_CLAY_10-20	0.22
86	7	177.02	7_FRSD_CLAY_0-10	0.91
87	7	41.47	7_FRSD_CLAY_20-30	0.21
88	7	94.76	7_FRSD_CLAY_10-20	0.49
89	7	571.03	7_AGRL_CLAY_0-10	2.94
90	7	84.88	7_AGRL_CLAY_10-20	0.44
91	7	71.61	7_BARR_CLAY_0-10	0.37
92	7	19.26	7_BARR_CLAY_10-20	0.10
93	7	254.96	7_PAST_CLAY_0-10	1.31
94	7	61.56	7_PAST_CLAY_10-20	0.32

6.3 PRECIPITATION ANALYSIS OF DEO RIVER BASIN

Annual precipitation varies from 470 mm to 1527.5 mm and average annual precipitation of 16 years (2002-2017) is found to be 929 mm. It is found that majority of rainfall occurs during July to September.

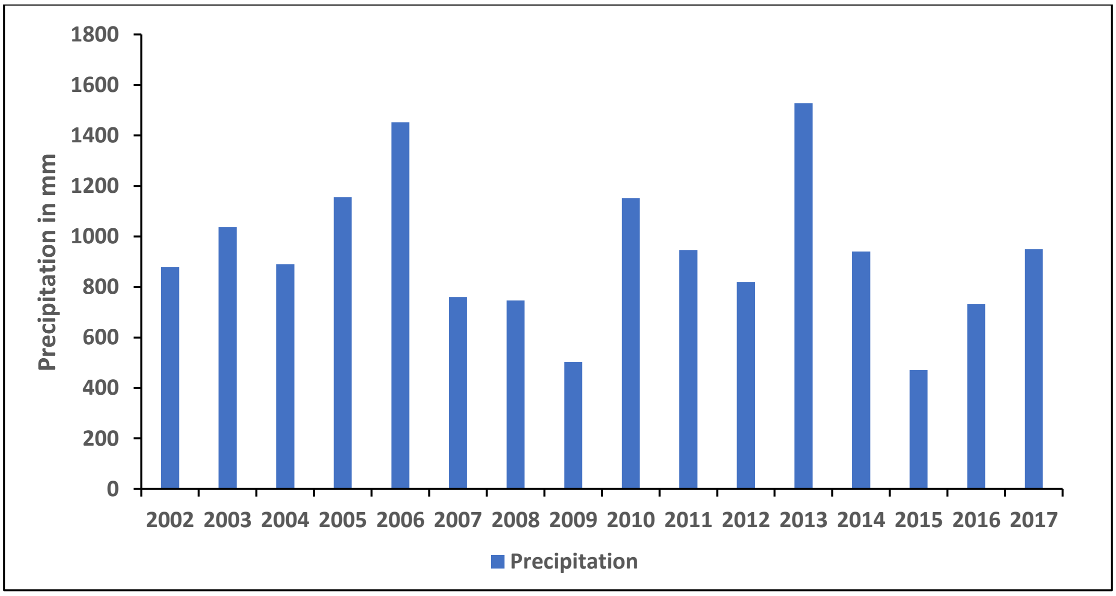


Figure 6.5 Annual Precipitation Variation in Deo River Sub-basin

6.4 WATER BALANCE OF DEO BASIN GENERATED BY SWAT

The average values of water balance components of deo river sub-basin during calibration period are shown in figure 6.7 and table 6.6.

Table 6.6 Hydrologic Component Values

Sr. No.	Hydrologic Component	Value in mm
1	Average annual Precipitation(mm)	943.2
2	Evaporation and Transpiration(mm)	343.8
3	Surface Runoff(mm)	469.99
4	Lateral Flow(mm)	10.57
5	Return Flow(mm)	85.27
6	Percolation to Shallow aquifer(mm)	130.74
7	Revap from Shallow aquifer(mm)	39.39
8	Recharge to Deep aquifer(mm)	6.54
9	Flow out of Watershed(mm)	0
10	Average Curve Number	84.91

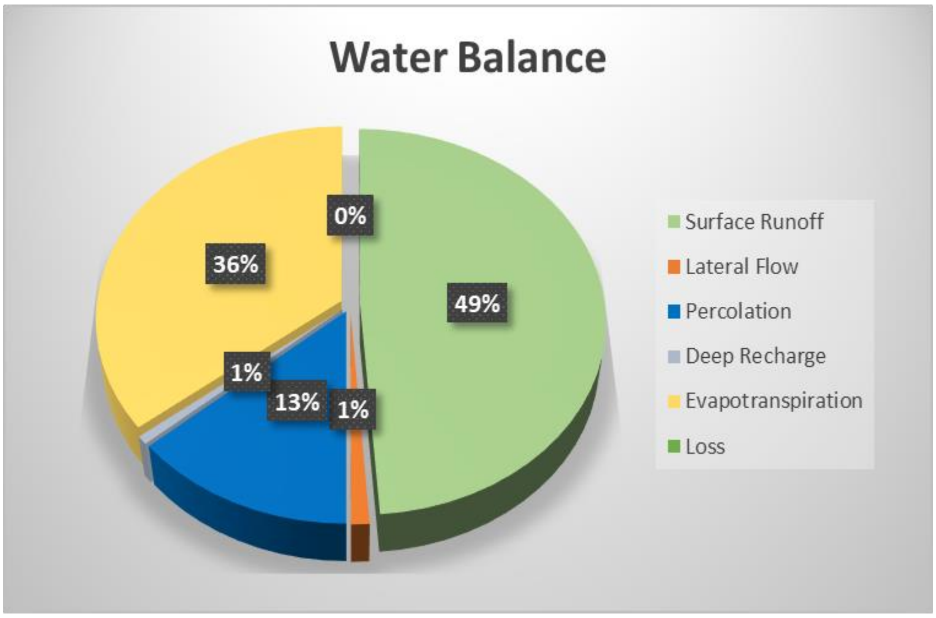


Figure 6.6 Percentage of Hydrologic Components Relative to Precipitation

From pie chart, we can say that from total precipitation 49% is obtained as surface runoff, 13% as percolation, 36% as evapotranspiration and 1% as deep recharge and lateral flow. So, 49% of precipitation flows as surface runoff. Curve number value 84.91 is near to 100 so it indicates that runoff will be more.

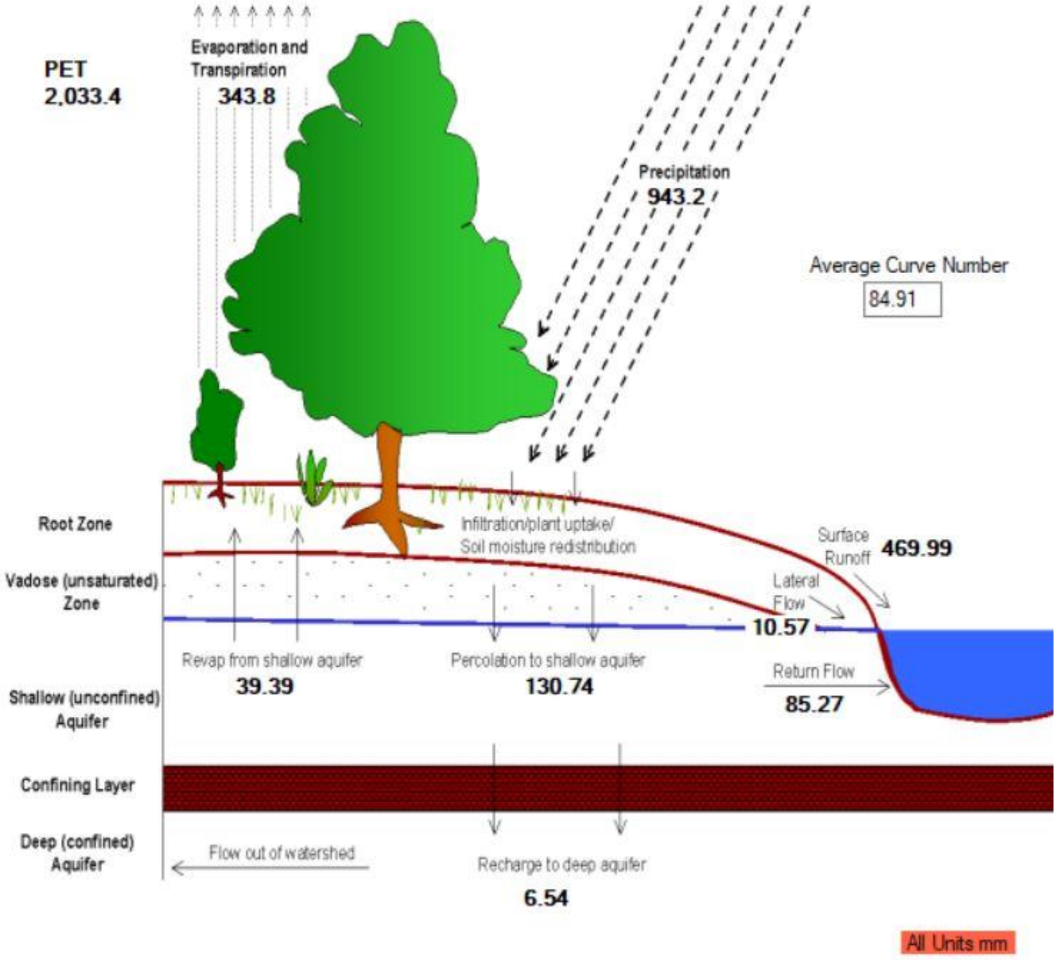


Figure 6.7 Water Balance Generated by SWAT Check

Average Monthly Basin Values of precipitation, runoff, lateral runoff, water yield and evapotranspiration as line graph are shown in figure 6.8.

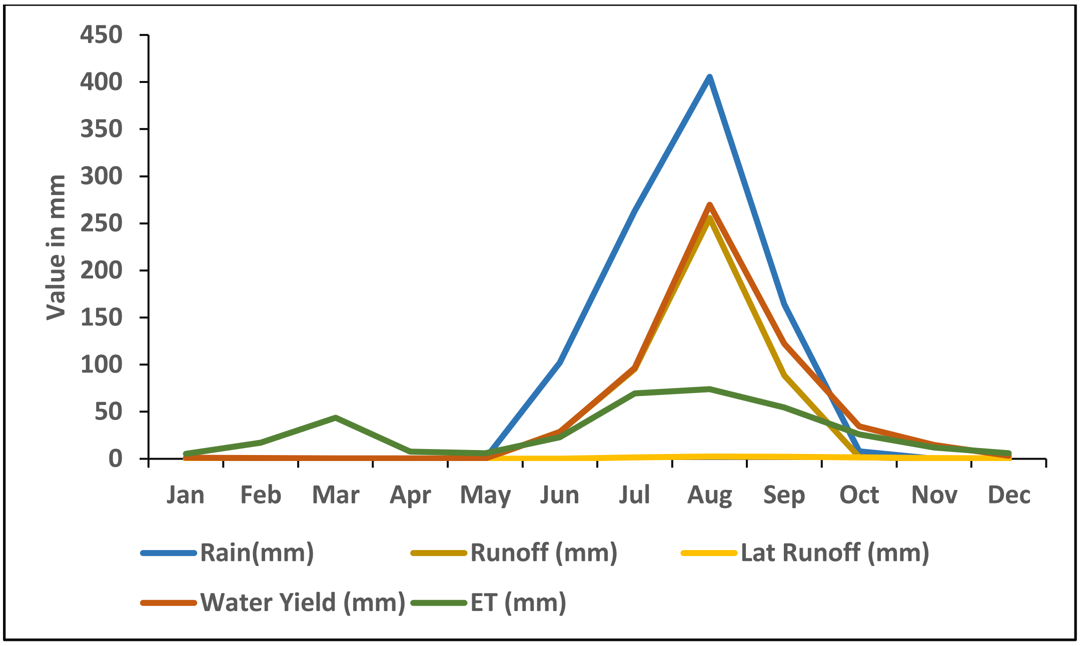


Fig 6.8 Average Monthly Basin Values of Hydrologic Components

6.4.1 Simulated Runoff by different Land use classes

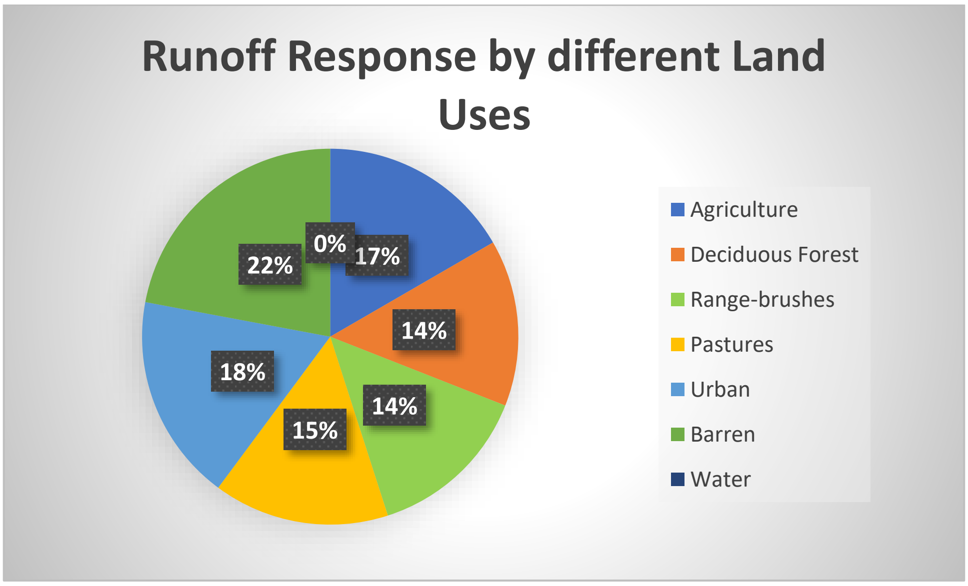


Figure 6.9 Percentage of Runoff from Different Land Use Classes

It can be observed from figure 6.9 that maximum runoff is contributed by barren land then followed by urban land cover. More runoff is observed from agricultural and pasture land than forests and brushes.

6.4.2 Average monthly Observed and Simulated Runoff

Average monthly observed and simulated runoff of Deo river basin are shown in figure 6.10. Bar chart shows that in the months of June, July and August simulated runoff is more than observed runoff while in the months of September and October observed runoff is more than simulated runoff

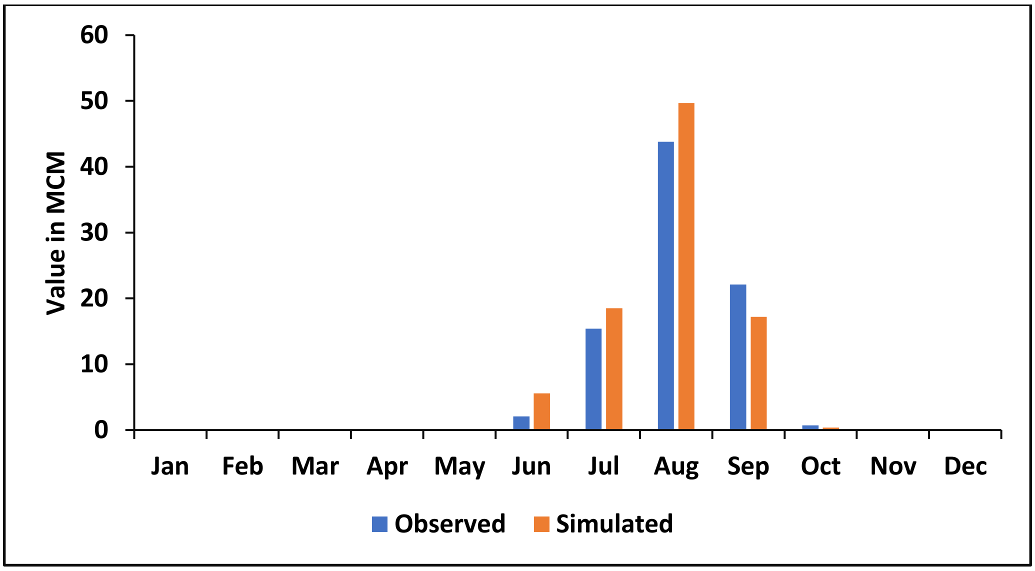


Figure 6.10 Comparison of Average Monthly Observed and Simulated Runoff of Calibration Period

6.5 CALIBRATION AND VALIDATION RESULTS

6.5.1 Calibration

For carrying out calibration, the observed data of outlet point (G&D which is Deo dam site, Halol, Panch Mahal in the Deo river basin was used. Observed data for the period 2000-2012 (13 years) was considered for the calibration process. The initial simulation showed a value of 0.89 and 0.86 for R^2 and NSE respectively at Deo dam site. With successive simulations, the final values of statistical parameters of calibration were improved.

The scatter plot between observed and simulated values of discharge during calibration period is shown in Figure 6.11. The model performance is satisfactory with a high Coefficient of Determination 0.89 for model calibration. Also the observed and computed discharge during calibration is plotted, which indicates a good correlation (Figure 6.14). The model performance statistics during calibration on the observed and estimated discharge has been given in Table 6.7. Overall, the model shows a good agreement between the observed and computed daily stream flow during calibration. Final simulated stream flow statistics for the Ong river basin is presented in Table 6.7.

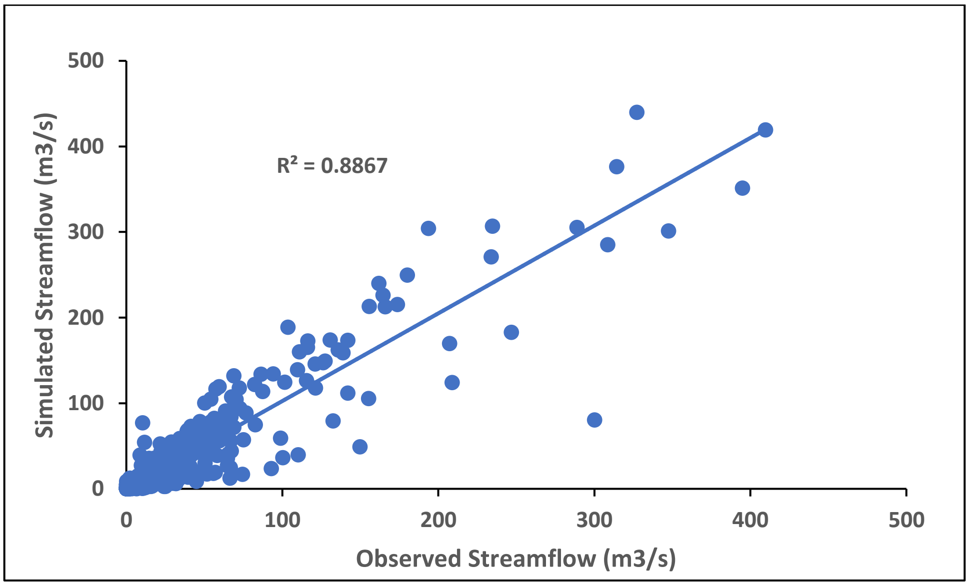


Figure 6.11 Scatter Plots of Daily Observed and Simulated Stream Flow During Calibration (2000-2012)

6.5.2 Validation

For validation purpose, the data of the same observation station were used. A period of five years was considered for validation purpose, from 2013 to 2017. By providing the proper input to SWAT-CUP, the following statistical outputs were observed and presented in the Table 6.7.

The scatter plot between observed and simulated values of discharge during validation period is shown in Figure 6.12. The model performance is satisfactory with a high Coefficient of Determination 0.88 for model validation. The model performance statistics during calibration on the observed and estimated discharge has been given in Table 4.4. Overall, the model shows a good agreement between the observed and computed daily stream flow during validation.

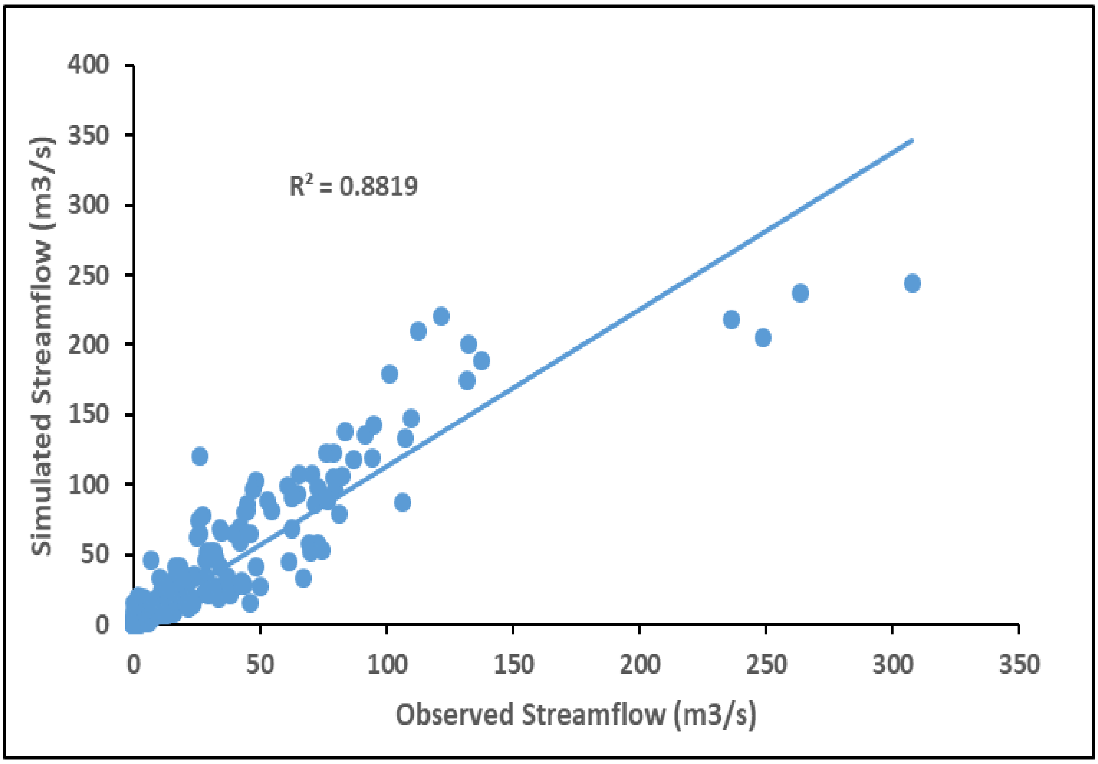


Figure 6.12 Scatter Plots of Daily Observed and Simulated Stream Flow During Validation (2013-2017)

Table 6.7 Calibration and Validation results of SWAT Model

	R^2	NSE	PBIAS	RSR
Calibration (2000-2012)	0.89	0.87	-3.8	0.37
Validation (2013-2017)	0.88	0.81	-30.6	0.43

Graphical representation of comparison between observed and simulated stream flow during calibration (2000-2012) and validation (2013-2017) were carried out. Figure 6.13 shows the graphical representation of calibration results and figure 6.15 shows graphical representation of validation results. By observing the figures it was revealed that the model was able to reproduce the historical data with good accuracy. For calibration R^2, NSE, PBIAS and PRSR are 0.89, 0.87, -3.8 and 0.37 respectively. Similarly, for validation R^2, NSE, PBIAS and PRSR are 0.88, 0.81, -30.6 and 0.43 respectively.

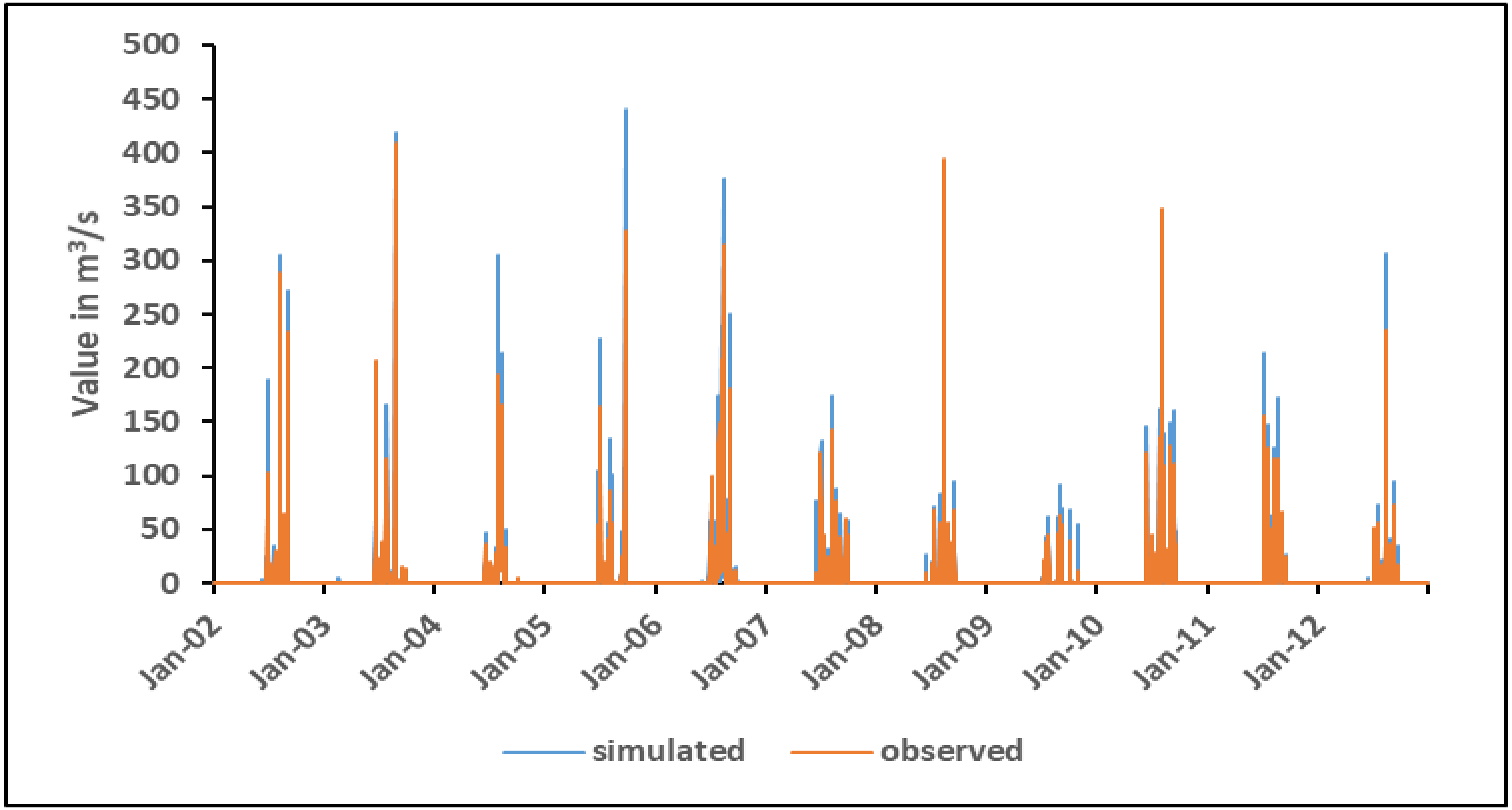


Figure 6.13 Comparison Between Observed and Simulated Streamflow during Calibration (2002-2012)

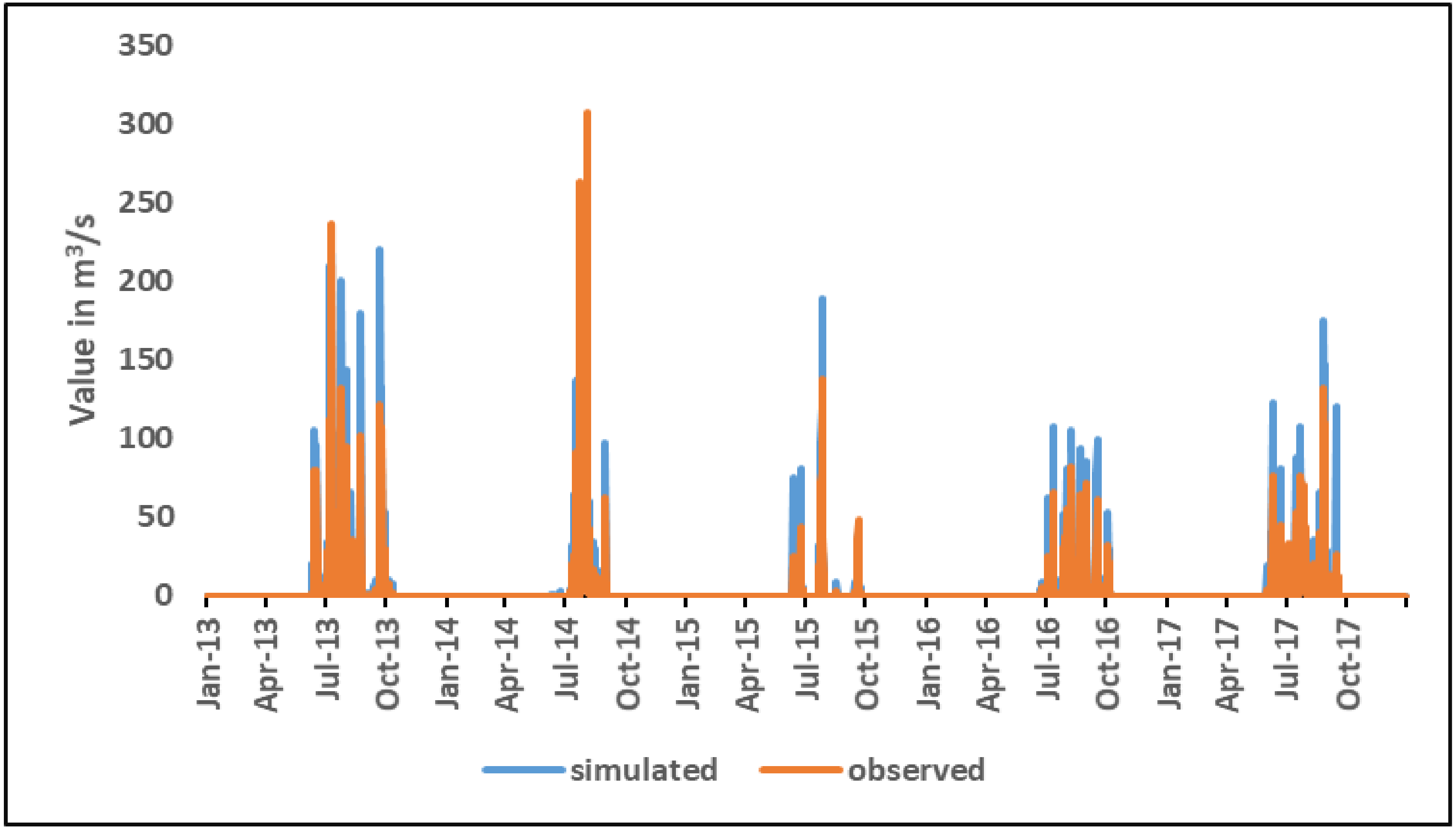


Fig 6.14 Comparison Between Observed and Simulated Streamflow during Validation (2013-2017)

As shown in Figure 6.13 and 6.14 the simulated stream flow is matching the observed stream flow with some exceptions. Throughout the analysis, model predicted the stream flow with very good accuracy. But later on, it was observed that during the months of July, August in the years of 2004, 2005, 2013 and 2017, the model overestimated the output as there is a sudden increase in the value of stream flow. This is due to the fact that a very high magnitude rainfall has occurred during those periods. Rest of the time the model estimated the observed stream flow in good accuracy. Variation of stream flow and the ability of the model to predict that flow shows similar trend both in calibration and validation period.

An effort has also been made to justify the physical meaning of the proposed parameter values before accepting the result of calibration. This was done by analysing the permissible range and the respective land use and soil characteristics of the study area. The calibration ranges and fitted values of calibrated parameters are listed in the Table 6.8.

Table 6.8 Calibration Range and Fitted Value of Different Parameters

Parameter Name	Lower Bound	Upper Bound	Fitting Value	Method
Initial SCS runoff curve number II (R_CN2.mgt)	-0.2	0.2	0.16	Relative
Base flow alpha factor (V_ALPHA_BF.gw)	0	1	0.97	Replace
Groundwater delay time (V_GW_DELAY.gw)	30	450	268	Replace
Threshold depth of water in the shallow aquifer required for return flow to occur (V_GWQMN.gw)	0	500	106	Replace
Groundwater "revap" coefficient (V_GW_REVAP.gw)	0	2	1.8	Replace
Soil evaporation compensation factor for basin (R_ESCO.hru)	0	1	0.433	Relative
Available water capacity factor (R_SOL_AWC.sol)	0	1	0.96	Relative
Saturated hydraulic conductivity (R_SOL_K().sol)	-0.8	0.8	-0.76	Relative
Threshold depth of water in the shallow aquifer for "revap" to occur (V_REVAPMN.gw)	0	500	150	Replace
Deep aquifer percolation fraction (V RCHRG_DP.gw)	0	1	0.56	Replace

6.5.3 Sensitivity Analysis

Sensitivity analysis was carried out for the period of calibration and warming up with the objective of number of parameter and their properties as the input for modelling. A total were 10 parameters were selected and vigorous iterations were performed to get better sensitive analysis. For this new project was set in SWAT-CUP with browsing TextInOut location of SWAT output and giving information of SWAT version and process architecture. SWAT parameters related to discharge were estimated using SUFI-2 algorithm. In calibration inputs like parameter information, number of simulation, file information, objective of the function were given properly. The Global sensitivity analysis was performed using LH-OAT technique highlighted the sensitive parameters for the runoff generation process inside Deo river basin as given in Table 6.9 though initially 10 parameters were considered for the calibration process.

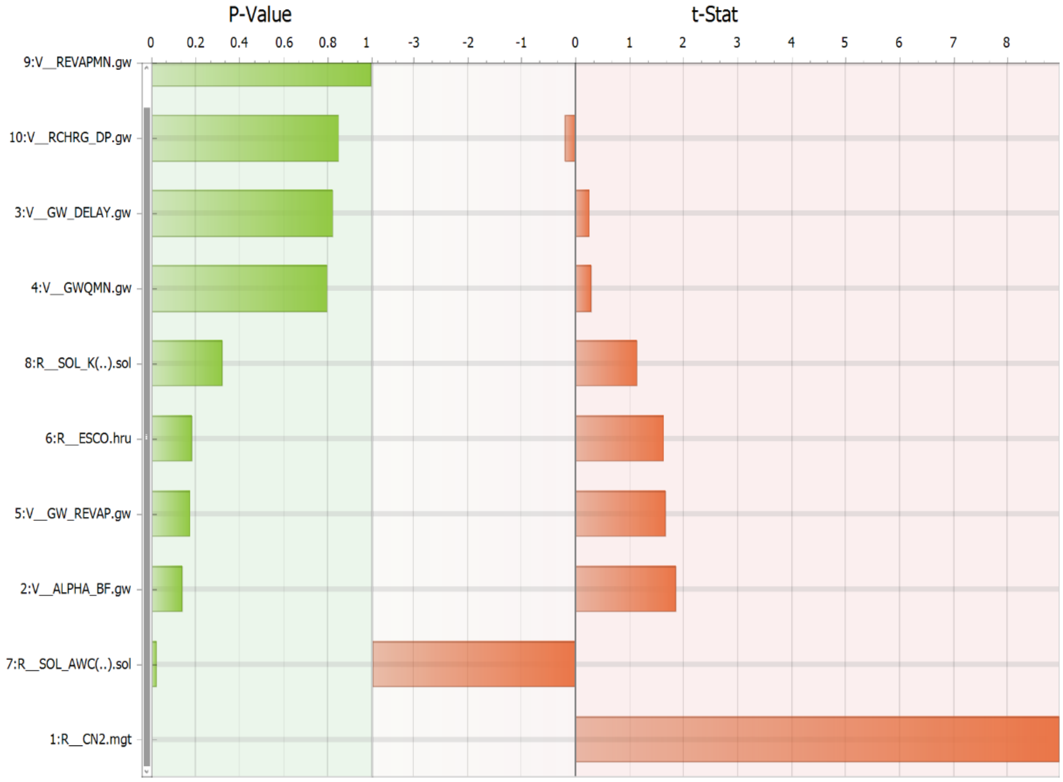


Figure 6.15 Sensitivity of Parameters Using Global Sensitivity Analysis

Table 6.9 Sensitivity Analysis Result of Calibrated Parameters

Parameter Name	Parameter name in SWAT-CUP	P-Value	Sensitivity Rank
Initial SCS runoff curve number II	R_CN2.mgt	0.00	1
Available water capacity factor	R_SOL_AWC(..).sol	0.02	2
Base flow alpha factor	V_ALPHA_BF.gw	0.14	3
Groundwater “revap” Coefficient	V_GW_REVAP.gw	0.17	4
Soil evaporation compensation factor for basin	V_ESCO.hru	0.18	5
Saturated hydraulic conductivity	R SOL_K(..).sol	0.32	6
Threshold depth of water in the shallow aquifer required for return flow to occur	V_GWQMN.gw	0.79	7
Groundwater delay time	V_GW_DELAY.gw	0.82	8
Deep aquifer percolation factor	V_RCHRG_DP.gw	0.84	9
Threshold depth of water in the shallow aquifer for "revap" to occur	V_REVAPMN.gw	0.99	10

These ranks were obtained according to the objective function: the P-Value of parameters for calibration between the observed and simulated values. Parameter having least p-value have the highest sensitivity. It is clearly observed that the stream flow is affected by management, soil, and groundwater parameters of the study area.

As a point to be noted, management characteristics of the basin always play a vital role in the estimation of runoff. Here also management characteristics like Initial SCS runoff curve number II (R CN2.mgt) has got the first, very high sensitivity value by showing that land use, planting, harvesting, irrigation applications, tillage operation, soil permeability and soil water condition of the basin that influences the runoff flow.

The parameter available water capacity of the soil layer (SOL_AWC) found to be the second sensitive parameter and it indicates that there might be a possibility of the runoff from this region which depends upon soil properties like soil texture and composition as it is important for vegetation growth, nutrient transport.

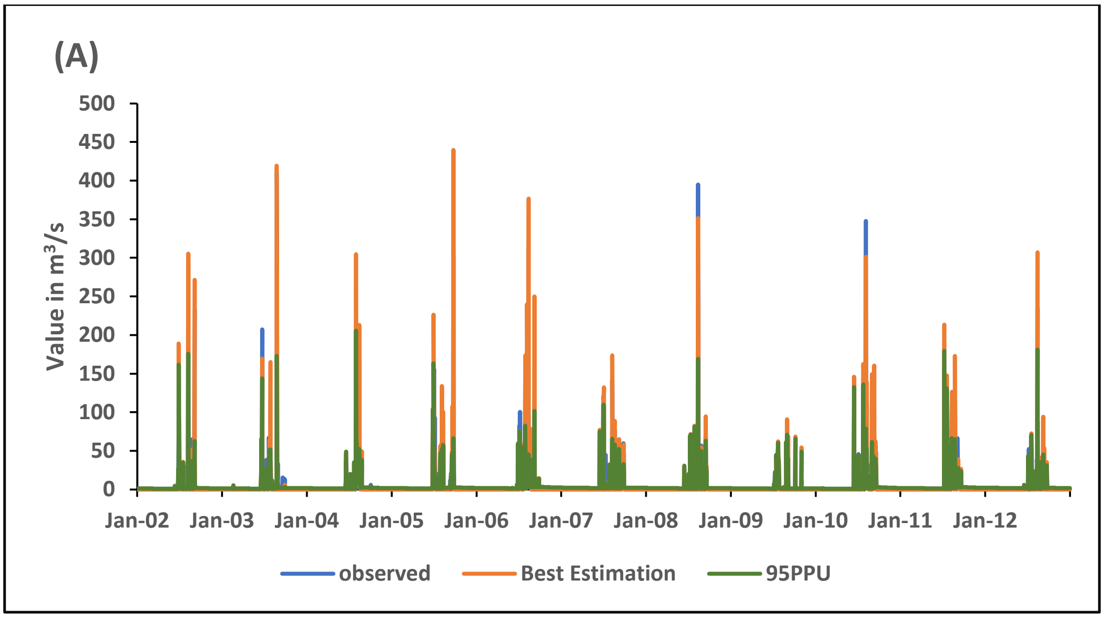
Base flow alpha factor (ALPHA_BF), parameter which describes groundwater flow response to changes in recharge of stream flow was found to be highly sensitive. This sensitivity analysis indicate that the stream flow of this area is also governed by ground water flow.

6.6 UNCERTAINTY ANALYSIS

The degree to which the uncertainties accounted in calibrated model are evaluated by P and R-factors. Theoretically, the value of the P-factor varies from 0 to 1 and the R-factor ranges from 0 to ∞. The P-factor of 1 and the R-factor of 0 indicates that simulation data closely corresponds to the measured data. The degree to which these variables deviate from these suggested figures can be used to assess the effectiveness of model calibration. Uncertainty is triggered by local rainfall variability, sudden climatic changes, dam construction, existence of reservoirs that influence the study area's watershed hydrology.

In this study, by altering the boundaries of parameters through trial and error method, the upper limit and lower limit of the parameters were set to minimize uncertainty. The calibration P-factor and R-factor were discovered to be 0.46

and 0.00 respectively. The validation P-factor and R-factor were discovered to be 0.43 and 0.00 respectively. Since the P-factor lies between 0-1 and the R-factor is 0, calibration and validation can be regarded satisfactory for this research. Full SWAT-CUP output showing Calibration (a) and Validation (b), the observed, the best simulated and the 95% prediction uncertainty (95PPU) are shown in Figure 6.16.



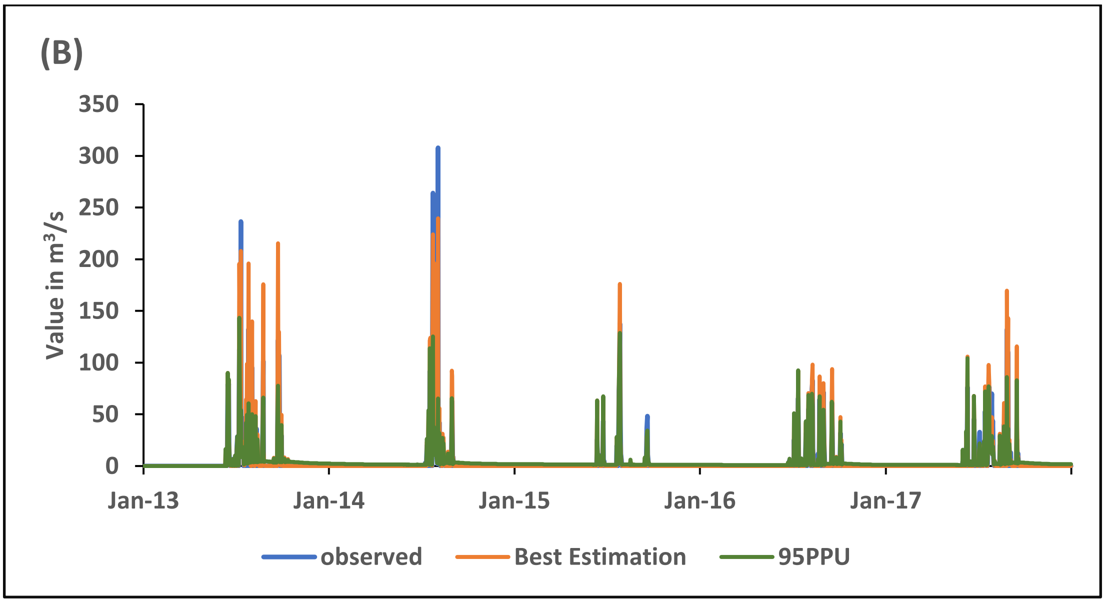


Figure 6.16 Illustration of Full SWAT-CUP Output Showing Calibration (A) and Validation (B), the Observed, the Best Simulated and the 95% Prediction Uncertainty (95PPU)

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 GENERAL

This chapter summarizes the present study based on the results obtained. Future scope of work is also discussed in this chapter.

7.2 NECESSITY OF ANALYSING HYDROLOGICAL PROCESSES

Increasing population, industrialization, and deforestation combined with ill-planned human-being activities results in fast changes in climate parameters and land use, resulting in long-term negative impacts in the hydrological processes and hydrological cycle. So land use/land cover, soil type and climate of a particular region plays a significant role in analysing a basin or watershed's stream flow patterns. In order to understand the different hydrological processes occurring in Deo river basin, which covers about 194.36 km^2 area with a very diverse hydrological variability, hydrological analysis of the basin has been carried out utilizing SWAT model.

7.3 WATERSHED CHARACTERISTICS

Deo river sub-basin characteristics are found by ArcSWAT. The minimum and maximum elevation in the Deo river basin is 66 m and 761 m respectively. SWAT generated 7 sub-basins having 94 number of HRUs.

Land cover plays an important role in runoff response for the watershed. Most of the land covers in Deo river sub-basin are agriculture and pasture land. Majority of crops grown in the basin are rice, maize, cotton and groundnut. It is observed that barren land (22%) gives highest runoff followed by urban area (18%). And vegetation cover gives less runoff than urban cover.

Characteristics of soil has the main function in runoff response. Deo basin contains mostly black cotton soil having clay and loam texture. Hydrologic group of soil in Deo river basin Is D which indicates very slow infiltration rate and high runoff potential with a high swelling potential.

Slope or topography of the watershed affects infiltration capacity and runoff values. Majority slope range of the basin is between 0-10 %, due to which soil erosion observed is less.

7.4 RAINFALL AND RUNOFF ANALYSIS

Average annual precipitation of 16 years (2002-2017) was found to be 929 mm. Average annual precipitation during calibration period was 943.2 mm out of which 470 mm (49%) was obtained as surface runoff, 130.74 (13%) as percolation, 343.8 (36%) as evapotranspiration and (6.54) 1% as deep recharge and lateral flow. Average Curve Number is found to be 84.91 which indicates a good amount of runoff can be obtained at outlet point. It is found that barren and urban land cover contributed more for runoff than vegetation land cover. Simulated daily streamflow using SWAT was obtained at Deo dam site of Deo river sub-basin and it was compared with observed streamflow. Simulated and observed streamflow values were found very close to each other indicating good performance of the model.

7.5 PERFORMANCE EVALUATION OF THE SWAT MODEL

The calibration process was carried out using SWAT-CUP tool with SUFI-2 algorithm. Observed stream flow data at Deo dam site, of the Deo basin for a period of 13 years (2000 to 2012) were given as input through auto calibration tool which gives Nash Sutcliff efficiency (NSE) of 0.87, R^2 value 0.89, PBIAS of -3.8%, RSR value of 0.37. The validation was also carried out by using the data of 5 years (2013 to 2017) which gives Nash Sutcliff efficiency (NSE) of 0.81, R^2 value 0.88, PBIAS of -30.6%, RSR value of 0.43 indicating a decent model performance.

Sensitivity analysis was also performed using LHS-OAT (Latin Hypercube Sampling and One-at-a-time) technique and out of 10 calibrated parameters 3 parameters viz. Initial SCS runoff curve number II, Available water capacity of the soil layer and Base flow alpha factor were found to be highly sensitive. A close observation to these sensitive parameters revealed that the flow characteristics of this area were affected by both surface water and groundwater flow properties.

The following specific conclusions were drawn from SWAT modelling experience during the study:

- The above study reveals that the use of the SWAT model in combination with remote sensing and GIS can be used to evaluate various hydrological parameters such as runoff from small to big reservoirs.
- SWAT model is useful in estimating with excellent precision various water balance components.
- This modelling method enables to identify hydrological sensitive parameters, analyse watershed hydrology, and can assign efficient management practices in the basin.
- As a semi-distributed catchment, time scale model, SWAT is capable of studying climatic, spatial and temporal variations happening inside the study area and can also co-relate it with the real world with a very good accuracy.

7.6 FUTURE SCOPE OF WORK

- SWAT model can also be used to estimate sediment yield, soil erosion prevention and control, non-point source pollution control and regional management in watersheds.
- SWAT model can also be used to predict the environmental impact of land use, land management practices and climate change.
- SWAT model can be easily applied on complex and large basins having many number of datas.
- SWAT model can be used for future flood forecasting during extreme rainfall events.
- Similar softwares can also be applied for Hydrological model like QSWAT, MWSWAT, AVSWAT, etc.

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