HYDROLOGICAL MODELLING OF WEST RAPTI RIVER BASIN OF NEPAL USING SWAT

A DISSERTATION

Submitted in partial fulfillment of the

requirements for the award of the degree

of

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in

IRRIGATION WATER MANAGEMENT (CIVIL)

By

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CANDIDATE'S DECLARATION

I hereby certify that the work presented in this dissertation entitled **"HYDROLOGICAL MODELLING OF WEST RAPTI RIVER BASIN OF NEPAL USING SWAT"** in partial fulfillment of the requirement for the award of the Degree of **Master of Technology In Irrigation Water Management** submitted in the Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee, is an authentic record of my own work carried out during the period from July 2017 to May 2018 under the supervision and guidance of Dr. Ashish Pandey, Associate Professor, Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee, India.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

Place: Roorkee
Date: May, 2018

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CERTIFICATE

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

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ABSTRACT

West Rapti River basin is a middle-class river basin (of Nepal) originating from northern mid hill of Western Nepal. It drains south to Karnali River (Ghaghara in India) which is the major left bank tributary of Ganges River. It is a transboundary river between Nepal and India and also a river of River linking project of Indian government. In this study, Hydrological modelling of the West Rapti river basin (Area 5281 km^2) using Semi distributed SWTA model for assessment of water availability and Sediment yield has been envisaged. The key objective of this study is to develop a suitable model to represent hydrology of West Rapti river basin for estimation of water balance components and sediment yield and to study the effect of different best management practices on sediment yield. SWAT model was simulation was carried out for discharge and sediment on monthly basis for 14 years (2000 to 2013). The SWAT model was calibrated and validated for the years 2003-2006 and 2007-2009 respectively, considering observed stream flow and rating curve generated sediment data using SWAT CUP model and sequential uncertainty fitting (SUFI2) technique. Calibration of the SWAT model was carried out using: (i) p-factor which is the percentage of data lying within the 95% prediction uncertainty, and (ii) r-factor, which is the ratio of the average thickness of the 95PPU band and the standard deviation of the observed value of discharge or sediment yield. Furthermore, Nash-Sutcliffe Efficiency (NSE), Coefficient of determination (R^2), Percentage bias (PBIAS), and ratio of root mean square error to the standard deviation of measured data (RSR) were also used to evaluate the performance of model. For monthly flow, the value of p-factor and the r-factor for calibration was found to be 0.83 and 0.40 and the value of p-factor and the r-factor for validation was found to be 0.67 and 0.42 respectively. Likewise, for monthly sediment yield, the value of p-factor and the r-factor during calibration was found to be 0.96 and 0.64 and the value of p-factor and the r-factor during validation was found to be 0.86 and 1.12 respectively. The results obtained from the model calibration and validation showed reliable estimate of monthly stream flow (R^2 = 0.96, NSE =0.95, PBIAS=4.7 and RSR=0.22) and sediment yield (R^2 = 0.71, NSE =0.68, PBIAS=15.10 and RSR=0.57) for calibration period. However, for the validation period, model performance was low as compared to the calibration period with parameter for flow (R^2 =0.78, NSE =0.78, PBIAS=5.3 and RSR=0.47) and sediment yield (R^2 = 0.69, NSE =0.69, PBIAS=-9.70, and RSR=0.56). Based on the statistical results obtained from the SWAT simulation, it is seen that the performance of the SWAT model in the West Rapti river basin is very good.

Furthermore, the water balance study of the basin showed that 48.60 % of the average annual rainfall of the basin contribute to evapotranspiration. The annual volume of water available at the basin outlet is 4.5 BCM. The average annual sediment yield of the basin is 16.67 t/ha/year and lies under high erosion class. Further, the calibrated SWAT model was used for assessment of Best Management Practices (BMPs) under different scenarios for reducing the sediment yield and recommendation of the most effective BMP for its implementation. This study would be useful for assessment of possibility of storage type project in the basin in terms of water availability and sediment yield. This study will also help in integrated water resources management and sustainable development of the West Rapti river basin, Nepal.

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LIST OF ABBREVIATIONS

ASML	Above Mean Sea Level
BMPs	Best Management Practices
CFSR	Climate Forecast System Reanalysis
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
DOI	Department of Irrigation
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization
GIS	Geographic Information System
GoN	Government of Nepal
GUI	Graphical User’s Interface
HEC DSS	Hydrologic Engineering Center Data Storage System
HEC HMS	Hydrologic Engineering Center Hydrologic Modelling System
HRU	Hydrological Response Units
HVB	Hydrologiska Byråns Vattenbalansavdelning
ICIMOD	International Centre for Integrated Mountain Development
ISRIC	International Soil Reference and Information Centre
LH-OAT	Latin Hypercube One-factor-at-a-Time
LU/LC	Land Use / Land Cover
MOI	Ministry of Irrigation
MUSLE	Modified Universal Soil Loss Wquation
NPS	Non-Point Source
NRSC	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Efficiency
NWP	National Water Plan
PBIAS	Percentage Bias
PET	Potential Evapotranspiration

SCS CN	Soil Conservation Service Curve Number
SOTER	Soil and Terrain
SRM	Snowmelt Runoff Model
SUFI	Sequential Uncertainty Fitting
SWAT	Soil and Water Assessment Tool
SWAT CUP	SWAT Calibration and Uncertainty Procedures
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
UTM	Universal Transverse Mercator
VIC	Variable Infiltration Capacity
WECS	Water and Energy Commission Secretariat
95PPU	95 Percent Prediction Uncertainty

CHAPTER 1
INTRODUCTION

1.1 Background

Reliable estimates of river flow generated from a catchment have always been information of interest for policy makers to make well informed reliable decision for planning and management. In any stream, there is wide spatial and temporal variations of flow characteristics including seasonal distribution of high and low flow and this always influence water resource system planning and modeling. One can make the best estimate of water quantity available in any stream based on the water level observed from gauging station of that stream. For this one has to convert observed water level to water estimate by using well defined and suitable rating curve developed. But the number of gauging stations may be limited or every river may not have gauging stations or data may not be available for much longer period or sometime to make comparison with measured flow, in such cases also we need to have estimation of stream flow. There are several methods available to make stream flow from catchment like making use of observed data or by empirical calculations and statistical technique or more commonly using rainfall runoff models. There are different approaches of rainfall runoff models and selection of suitable model depends upon the purpose of modeling, time constraints and budget available and tools and technical knowledge and skills available within the institutions (Vaze et al. 2012).

Water is crucial for life and environment. It is the essentials for inbuilt of habitat. It plays great role in economic development of the nation. Every human civilization had been originated nearby premises of the big rivers due to availability of the water and fertile land for daily life and agriculture. Water has played key role in development and organization of ancient societies like Nile river valley civilization in Egypt, Yellow river valley civilization in China, Indus River valley civilization in Indian sub-continent. Water resource is the prime input to the growth and prosperity of the nation. Based on these facts proper water balance study for any water basin is essential so that one can have the idea about total water availability and make plan for overall basin development plan for water use in integrated approach in sustainable manner and this study is a step for that. Accurate estimate of water availability and its planned use helps in prosperity of the locality and the whole nation.

Nepal is a mountainous country with 80 % of land lying in hilly and mountainous region and has more than 6000 rivers flowing from North to South draining to Ganges basin with total average yearly flow from all these Nepalese rivers is estimated about 225 billion cubic meters (BCM). In this context, West Rapti River basin, originating from Mahabharat range (Mid hills), so called medium class river is a perennial river with dominant monsoon flow and dry weather or low flow contributed by sustained groundwater and springs flow (WECS 2005). The planning and development of water resources of this basin in integrated approach could help in betterment of the locality and the whole Nepal and Hydrological modeling of the basin could be the first step for the development of water resource development plan of the basin.

Most of the developing countries have poor data recording system and its the case of Nepal also. So those data which are available will be taken/ bought from concerned offices and those which are not available are downloaded from open source website.

1.2 Objectives of the study

Looking to the aforementioned, the main objective of this study is to model the hydrological processes with in the watershed to estimate runoff and sediment yield from West Rapti river basin using SWAT model. The specific objectives of the study area as follows:

1. Calibration and validation of the SWAT model for simulation of discharge and sediment yield of the West Rapti Basin.
2. To study the different water balance components of the West Rapti Basin using SWAT model.
3. Identification of critical soil erosion prone areas and its spatial distribution in the West Rapti Basin.
4. Evaluation and recommendation of best management practices (BMPs) in the West Rapti Basin.

1.3 Organization of the dissertation

This dissertation report consists of four main chapter apart from Introduction with objectives, and summary and conclusion. Chapter one provides the brief introduction and objective of this study. Chapter two presents literature review on rainfall-runoff and sediment yield model, its type and review of some widely used computer based hydrological models. It also describes about hydrological modelling, sediment yield and assessment of BMPs using the SWAT model. Chapter three explains about the SWAT model and its theoretical consideration and integration with ArcGIS. Chapter four explains about study area, its location and adopted methodology i.e. data acquisition, processing, setting up of SWAT model, assessment of model performance and representation and evaluation methods of BMPs. Chapter five is about results and discussion of the works done and chapter six is all about summary and conclusion drawn from the study.

CHAPTER 2
LITERATURE REVIEW

2.1 General

For the study related to hydrological modeling, the modeler should have basic idea on selection of best suited model for the study of different hydrologic process, estimating the runoff generated from given rainfall data using suitable hydrological model and scope and application of developed rainfall runoff model in different field of water resource planning and management. Also, for Rainfall-Runoff modeling, a clear understanding of the hydrologic cycle at catchment scale is required. The catchment hydrologic cycle involves many processes which include precipitation, evaporation, snowmelt, infiltration, runoff and other processes in the hydrologic cycle. Depending on the details required in the analysis and the purpose of analysis each and every component of the hydrological cycle is grouped together into subsystem or broken down into new sub-processes. The processes have been summarized in a brief and illustrated in Figure 2.1.

Precipitation is considered as an essential process for the generation of runoff at a catchment scale. It can be in the form of snow, hail, dew, rain and fog. In this study precipitation is considered in the form of rain only. As rainfall on the Earth, it moves within a catchment in different directions. Some part of rainfall is intercepted by vegetation canopy, some is infiltrated down to the ground and remaining flows to the channel as surface flow. The rainfall on the vegetation moves down the vegetation as stem flow, drips off the leaves, or directly falls to the ground as through fall. Remaining rainfall remains at the land surface as depression storage and either evaporates, infiltrates or is discharged as overland flow.

The infiltrated rainwater moves initially in downward direction by unsaturated subsurface flow and recharges the saturated zone. This phenomenon is termed as percolation or natural recharge and fills the aquifers of groundwater system. In some cases, at the shallow subsurface layer where the lateral hydraulic conductivity is higher than the vertical one, the direct infiltration partly goes toward the channel through interflow or through flow.

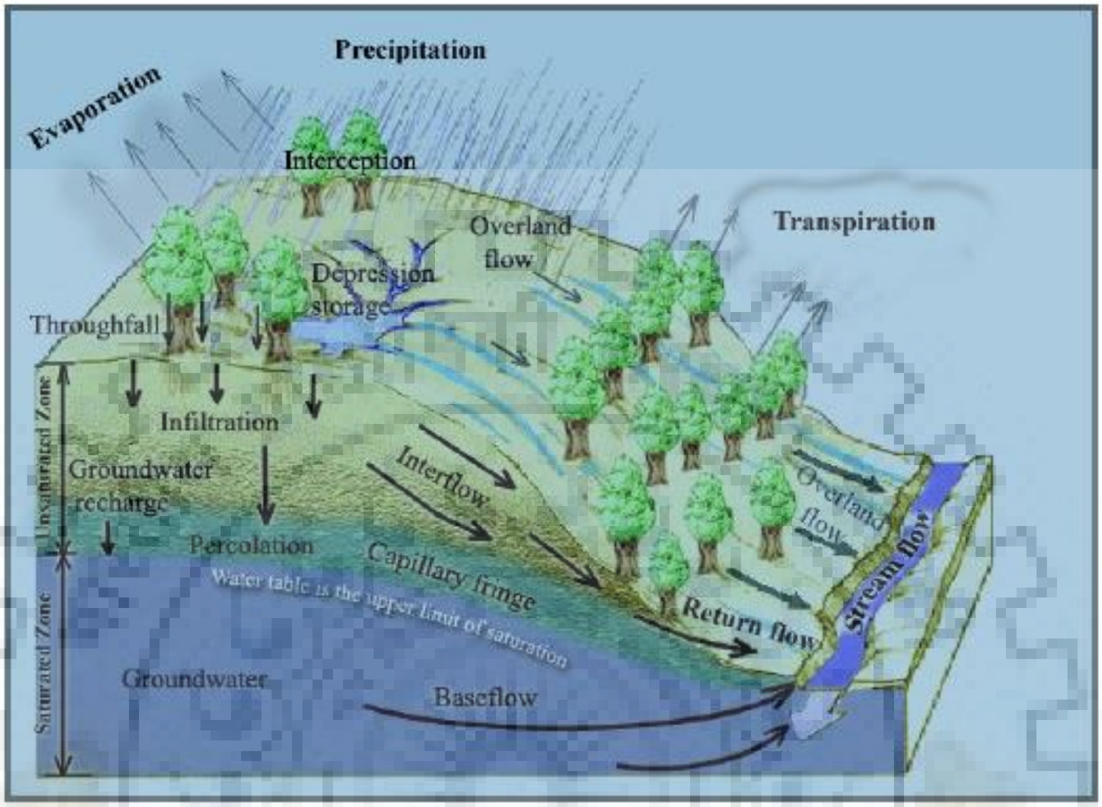


Figure 2.1: Physical process involved in runoff generation (Tarboton 2003)

The infiltrated groundwater is affected by the basin characteristics, especially the topographic conditions of the catchment, before it is discharged to the channel system. Aquifers of the groundwater system also discharge groundwater across the catchment boundary and finally contribute to stream flow.

There are a different number of ways that hydrological models can be used and most of these applications relate to providing information to support decision making for water related development and management policies. Some ways of the hydrological model application can be summarized as below.

- One can have the idea of yield and seasonal, annual and decadal variation of flow and sediment generation in time and space using rainfall runoff modelling.
- The relative flow contribution from sub basins to basins or larger scale can be estimated using hydrological models.

- Hydrological modelling is useful for studying the effect of different human activities like land use land cover change, agricultural practices on land and climate change on water availability, drought analysis, sediment yield or erosion in different time frame.
- When there is poorly observed data series in gauged stations, rainfall runoff model helps in compensating the gap arise due to poor or missing data sets.
- It also gives the idea about the amount of runoff contributed by the gauged watershed before the observation record and after the observation record or extrapolation.
- Using hydrological models, one can link the flow from an un gauged sub catchment to overall gauged catchment.
- Hydrological models in combination with hydraulic models can be used for flood forecasting and preparations of inundation map.

2.2 Rainfall runoff models

The starting point of rainfall runoff modelling can be taken as Rational Method by Irish engineer Thomas James Mulvaney who developed a single equation Q_p=CAR, relating Peak flow not the whole hydrograph, with catchment area (A), rainfall intensity (R) and the empirical constant (C) (Beven, 2012). After that in recent decades, many computer based mathematical models has been developed by different researchers and scientists (Xu, 2002).

Rainfall runoff models can be categorized in to different types based on different modes of classification. Hydrologic models are the very much essential tools for the study of hydrological processes and the effect of human caused factors on the hydrologic system. The comprehensive classification of hydrologic models is as shown in Figure 2.2.

Based on runoff process within watershed, hydrological models are classified as event based and continuous time. Event based model takes in to account of single rainfall event from hours to some days and continuous time scale accounts for certain period of years. Event based models are generally used for flood forecasting and inundation mapping whereas continuous models are used to keep a continuous account of the watershed surface and groundwater conditions (Devi et al., 2015).

Based on spatial or geographical variations incorporated in watershed, watershed models can be lumped or semi distributed or distributed. Lumped model ignores the spatial variations in parameters of the hydrological systems in their formulation i.e. it assumes homogenous or average conditions over all or portions of a watershed. Lumped model approach assumes watershed as a single unit for computations of parameters and parameter variables are averaged over this unit (Dwarakish and Ganasri 2015). Lumped model is also called as **Black Box** model. Example of lumped model are SCS-CN based models, IHACRES, WATBAL etc. **Distributed model** is one in which parameter characteristics and processes are allowed to vary spatially at resolution of user's choice. These models consider the locations of various watershed conditions such as land use/land covers, soil types, and topography to calculate total runoff. Spatial heterogeneity in distributed models are represented in the form of grids (Dwarakish and Ganasri, 2015).

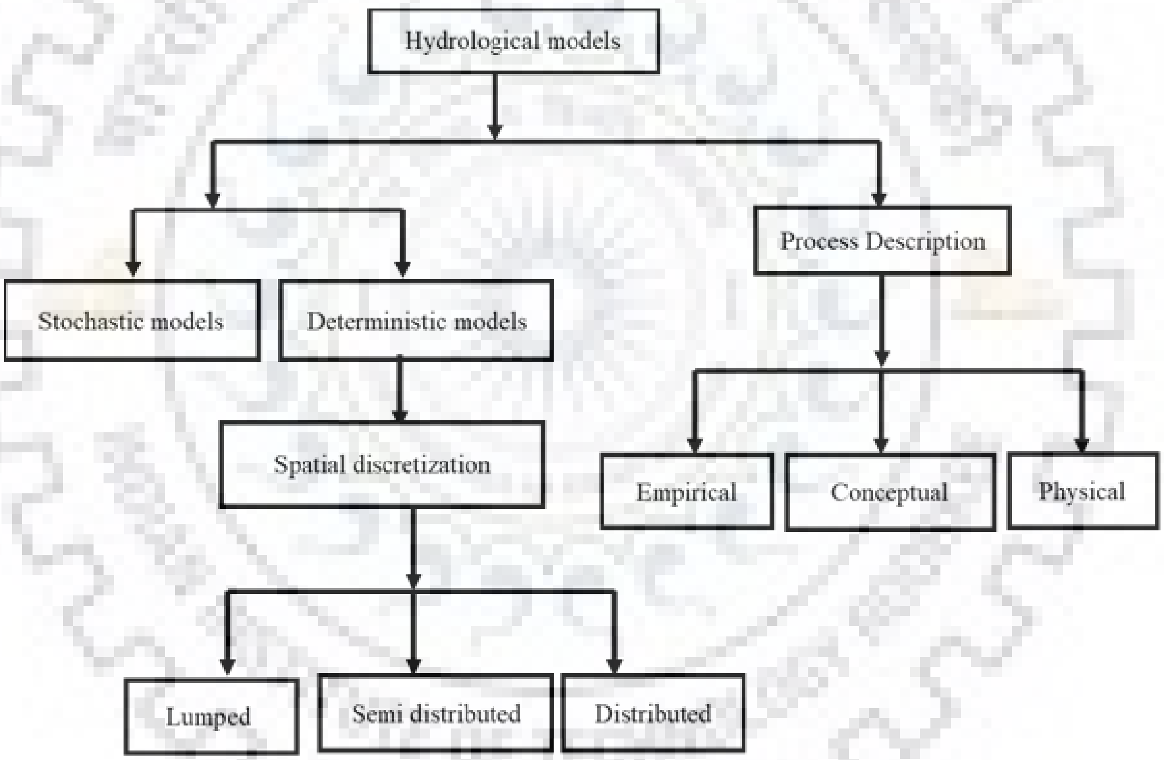


Figure 2.2: Classification of Hydrological models, (Dwarakish and Ganasri ,2015)

The models having the features of both the lumped and distributed model is termed as quasi- or semi-distributed models. In semi distributed hydrological models, the parameters are allowed to vary partially in spatial and temporal scale and thus dividing the basin in to smaller sub basins (Moradkhani and Sorooshian, 2008).

Hydrological models representing a watershed can be deterministic or stochastic based on certainty or uncertainty of data in watershed. In deterministic model, no variables are allowed to random variation and the model output is fully determined by the parameter values and initial condition. A mathematical model is said to be stochastic if one or more variables of the models are random and changes in the variables over time are unpredictable.

2.3 Rainfall runoff modelling approach

Rainfall runoff modelling is the process of representation relation of rainfall and runoff with catchment area, length and shape of the basin and the physical phenomenon of the watershed using simple to complex mathematical equations. Methodology for using hydrological models starts from definition of the problem before developing a model to the field application of developed models. In between these, there comes many steps such as fixing the objective and purpose of the modelling, collecting different required and available datasets and checking their consistencies, picking suitable class of hydrological model and best suited model type from selected class, developing model project and calibration and validating the developed model and application of calibrated and validated model to fulfill the intended purpose (Xu, 2002).

2.4 Available rainfall runoff modelling tools

There are a number of hydrologic tools or models that can be used for hydrological modelling. Many computer-based watershed models have been developed in the last three/four decades. Among them few commonly used mathematical models are described below.

2.4.1 HEC- HMS

The Hydrologic Modeling System (HEC-HMS), developed by US Army Corps of Engineers Hydrologic Engineering Center, is the model that can be used to simulate both continuous and event-based hydrological processes (Chu and Steinman, 2009). HEC-HMS is a computer-based model containing different methods to represent watershed characteristics, flow channel and water structure behavior to predict flow depth and timing (Arekhi, 2012). Various components of hydrologic cycle can be incorporated using HEC HMS model. Urban flooding analysis, flood frequency analysis, flood warning system planning, reservoir spillway capacity analysis and stream restoration analysis can be done using HEC HMS model (Halwatura and Najim, 2013). It was subsequently improvised to solve different possible range of problems including large river basin water supply, flood hydrographs, and small urban or natural watershed runoff though initially it was developed to model rainfall runoff of dendritic watershed systems. (Dhami and Pandey, 2013). HEC-HMS can be used in the case where limited data in a selected basin is available. For watershed modeling, the HEC-HMS model contains four components: (i) Basin model, (ii) Meteorological model, (iii) Control specification, and (iv) Input data. HEC HMS offers free movement in different components of software and contains HEC DSS (data storage system) for storage of simulation results. HEC-HMS can be used in connection with ArcGIS and ArcGIS companion product helping the creation of basin models for projects. The GIS companion product, Geospatial Hydrologic Modeling extension (HEC- Geo HMS) can be used to create basin and meteorological models for use with the program (Scharffenberg, 2016). Sherif et al., (2011) used HEC HMS for Rainfall-Runoff modeling of Three Wadis in the Northern Area of UAE and found that the amounts of water storage in dams are highly connected to the assigned curve number especially for the wadi Bih and wadi Tawiyean out of three wadis. Likewise De Silva et al., (2014) used HEC HMS for Modeling of Event and Continuous Flow Hydrographs in Kelani River basin of Sri Lanka.

2.4.2 Variable Infiltration Capacity Model (VIC)

VIC is a large-scale, grid based, distributed hydrological model using both energy and water balance equations. The performance of VIC model is found to be best in moist conditions and so it is used for managing water efficiently on agricultural field. To run VIC model in water balance mode, DEM, soil and vegetation parameters and daily meteorological parameters like maximum and minimum temperature and wind speed should be given as input in grid wise basis as VIC model works on grid wise (Narendra et al., 2017). VIC model works dividing soil into three layers. Quick soil evaporation is allowed by top layer, dynamic response of soil is represented by middle layer and soil moisture behavior is considered by bottom layer. VIC model in these days has widely been used for prediction of climate change and land use scenario change in number of riverr basins. The model is nowadays applied to a number of river basins and helps in predicting climate and land cover changes over the study area (Devi et al., 2015).There is world wide application of VIC model throughout the world. Liu et al., (2013) used VIC model to find the effects of Land Use/Land Cover and Climate Change on Hydrology of the Qingyi River Watershed of China. Likewise Zhang et al., (2014) did an analysis of Land Use Change Dynamics and Its Impacts on Hydrological Processes in the Jialing River Basin od china using VIC model. Similarly Narendra et al. (2017) did hydrological simulation of a large scaleTekra catchment, a part of Godavari riverbasin of india using Variable Infiltration Capacity (VIC) model.

2.4.3 MIKE SHE (Systeme Hydrologique European) model

MIKE SHE is an deterministic, physically based, distributed, integrated hydrological model developed by Abbott et al., (1986) in collaboration with the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH (France) and the financial support was provided by Commission of the European Communities. This model can represent hydrological processes such as surface and ground water movements and their interactions like evapotranspiration, overland flow, channel flow and unsaturated flow, sediemnt, nutrirent and pesticides movement in the watershed along with varoius water quality issues. MIKE SHE model uses two dimensional Saint Venant's equations to simulate overland flow, water depth, sink filling and one simensional Saint Venant's equations to calculate channel flow or river runoff. The applicability of this model has been tested worldwide. Sandu and Virsta, (2015) used MIKE SHE to model hydrology in Argesel River Catchment and checked for it applicability also. Likewise, Zhang et al., (2015) studied the impact of uncertainty description on assimilating hydraulic head in the MIKE SHE model taking a case study of Karup catchment in Western Denmark.

2.4.4 HBV (Hydrologiska Byrans Vattenbalansavdelning) model

HBV model is a semi distributed conceptual model including conceptual description of hydrological processes. This model can simulate stream flow along with water quality in terms of sediment yield and dissolved solids. It requires less number data inputs i.e. daily and rainfall and air temperature and estimates daily or monthly potential evaporation. It also calculates snow accumulation using air temperature. The basic water balance equation used in HBV model is given as

$$P - E - Q = \frac{d(SP + SM + VZ + LZ + Lakes)}{dt} \qquad \text{... 2.1}$$

Where, P stands for precipitation, E stands for evapotranspiration, Q is for runoff, SP is for snow pack, SM is soil moisture, UZ indicates upper groundwater zone, LZ represents lower groundwater zone, and lakes is lake volume. Different versions of HBV model have been used throughout the world in different countries with different climatic conditions such as Sweden, Zimbabwe, India and Colombia. HBV model divides catchment area in to different sub basins and further sub basins are further divided in to zones based on elevation, lake area and vegetation cover. HBV-light, the newer version of HBV model has provision of using warm up period such that state variables will get its suitable values as per climatological data and parameter values (Devi et al., 2015).

2.4.5 TOPMODEL

TOPMODEL (Beven and Kirkby, 1979) is a physically based-as parameter can be theoretically measured, semi distributed watershed model and can be used to simulate components of hydrological cycle like infiltration-excess overland flow, saturation overland flow, infiltration, exfiltration, subsurface flow, evapotranspiration, and channel routing through a watershed. With the help of fluctuations of the water table, TOPMODEL simulates interactions between surface and ground water interactions which determines where saturated land-surface areas develop and have the potential to produce saturation overland flow. In single or multiple sub catchment, TOPMODEL can be used with elevation data in gridded form for the helps to predict the hydrological behavior of the basin. TOPMODEL was initially designed to simulate the hydrological response of catchments in humid areas based on variable contributing area concept but later on several modifications has been done to broaden the application range. TOPMODEL has been used worldwide at different climatological conditions and terrains, for example, Ahmed Suliman et al. (2014) used TOPMODEL in Pinang Catchment of Malaysia, Bhaskar et al., (2005) used TOPMODEL in mountainous catchment of USA and Campling et al., (2002) used TOPMODEL in humid tropical catchment of south-eastern Nigeria.

2.5 Application of SWAT Model

The extensive use of hydrological and water quality simulation models has been increasing to address the series of water resource problems across the globe including the effect of alternative best management practices (BMPs) future possible impact of climate change on stream flow and water quality (Gassman et al., 2014). Many computer-based models like HEC, SWAT, Win SRM, Wet Spa, Crawford, Tank, Nam, Mike-SHE, have been developed during last three – four decades and have been extensively used. SWAT is a public domain, river basin scale, semi distributed, physical based model strongly supported by the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas and can be used to quantify the impact of land management practices in small to large and simple to complex watersheds. SWAT model is one of the widely used tool for assessment of water resource development and management and non-point source of pollution (Gassman et al., 2007). It is being used widely all over the world for water and environmental problems. In developed country like USA, SWAT model is mostly used in water quality assessment and in majority of countries outside USA, SWAT is used for hydrological flow simulation and its calibration and validation.

There is wide variation and diversification in field of SWAT application and its application has been expanding day by day. Some past and present field of application of SWAT model are hydrological simulation of gauged and un gauged catchments, sediment yield modelling, hydropower potential assessment, Land Use/ Land Cover changes and its impact on runoff generation and erosion or sediment yield, soil water recharge, tile flow and related studies, snowmelt related application, study of impact of climate change, drought analysis, pollutant loss studies, applications incorporating wetlands, reservoirs and other impoundment, land use impact on pollutant studies, sensitivity, calibration and uncertainty analysis, DEM resolution, soil and land use resolution effects and comparison of SWAT model with other models (Gassman et al., 2007).

Bieger et al., (2013) use SWAT model for study of runoff generation, sediment yield and water balance in Xiangxi Catchment due change in land use caused by construction of Three Gorges Dam. To construct Dam People are shifted including relocation of agricultural land from bottom of valley to top slope land and despite of decrease in agricultural area than the past sediment input to the river is high and it is mainly due to cultivated sloping land. Their study concluded strong adoption of sustainable development and management of land use practice in better way.

At present days, climate change is hot topic everywhere as it is most important global environmental challenges. It is affecting the whole world inducing negative impacts on water availability or balance and supply, food production, health hazard, global temperature rise , livelihood and energy sector (Uniyal et al., 2015). In this context Uniyal et al., (2015) used SWAT model to study the effect of climate change on water availability Upper Baitarani River basin of India. They studied the impacts of twelve independent and 28 combined climatic conditions on water balance component of watershed. In case of combined climatic scenario, for 2 °C rise in temperature there is 15% rise in rainfall with maximum increase in annual surface runoff, base flow and groundwater recharge from baseline condition. Similarly, for 5 °C rise in temperature there is only 2.5 % increase in rainfall with maximum reduction of average annual runoff, base flow and ground water recharge from baseline condition.

Himanshu et al., (2017) used remotely sensed, satellite-based data products like precipitation and temperature with in GIS framework for evaluation of hydrology, sediment yield and water balance of Ken Basin of Central India using SWAT model. Observed discharge and sediment data have been used for validation of model. From the study, it is found that 44.6% of total annual rainfall of the study area has contributed to evapotranspiration, 34.7% of rainfall has contribution to river flow and aquifer recharge is about 19.5% of rainfall. On the other hand, average annual yield of sediment is found to be 15.41 t/ha/year, keeping the study area under high erosion class. This study strongly helped to come to the conclusion that SWAT model is the best for simulation of hydrology and sediment yield hence the result obtained can be used for best management practice and formulation and implementation of agro environmental policies.

Water is key element to sustain the life, the population of the world is increasing day by day and hence the demand of water is also rising. Availability of water on any region is mainly dependent on amount of rainfall of that region and rainfall is affected by various other reasons (Kundu et al., 2017a). Water yield, surface runoff, evapotranspiration of any watershed are affected by climate change and present and future land use pattern (Kundu et al., 2017b). In this context, to know about future trend of water balance due to change in climate and land use, Kundu et al., (2017b) did study on the individual and combined effect of land use and climate change on Narmada River basin of Madhya Pradesh, India. By making prediction of future precipitation, maximum and minimum temperature, they came to a conclusion for the study area that climate change is affecting more on water yield from the basin and land use change is affecting more on evapotranspiration.

Water used for agriculture accounts for 70% of total water resources and it is very essential to control losses of irrigation water by optimization of irrigation scheduling so that water saving can be done and crop water productivity can be increased (Sun and Ren, 2014). In this sense Sun and Ren, (2014) did study on crop yield and crop water productivity assessment and optimization of irrigation scheduling for winter wheat and summer maize using SWAT model in Haihe plain under historic and sufficient irrigation condition with sufficient fertilizer input.

The process of freezing and melting of snow makes the snowmelt modelling approach complicated and very less studies have been done for snowmelt runoff simulation using single SWAT model. MENG et al., (2015) developed energy balance based distributed snowmelt runoff model and coupled it with SWAT model to simulate mountain snowmelt and runoff from Juntanghu watershed of china.

Pandey et al., (2014) used SWAT model along with spatial technologies to assess the water available from Mat River basin, India and combined the output from SWAT with satellite data to find out the hydropower potential of the basin using GIS technology. In the similar way Kusre et al., (2010) measured the hydropower potential of Kopili River basin, a hilly watershed in Assam India using a spatial tool - GIS and SWAT model. Data related to topography, soil, land use, weather and discharge have been used in both of the study. As hydropower potential has been correctly assessed from both studies, it can be concluded that SWAT model along with spatial technology can be best used for hydropower potential estimation.

SWAT model has been extensively used for assessment of water quality throughout the world. With the main objective of testing performance of SWAT model and its feasibility on using to simulate the flow and transport process at watershed scale, Abbaspour et al., (2007) used SWAT to model out the different phenomenon affecting the quality of water, loading of sediments and nutrients from the Pre-alpine/alpine Thur watershed of Switzerland and the results obtained were good. Use of chemicals in agricultural field is increasing in South East

Asia and to know about the response of different contaminants like herbicides, pesticides and insecticides with the environment and to make simulation of hydrology (Bannwarth et al., 2014) used SWAT model and they became success in simulation of pesticides fade in different ways using SWAT model coupled with a calibration approach - ANSELM .

Very few research has been conducted using SWAT model in Nepal. (Dahal et al., 2016) conducted a research on estimating the effect of climate change on available water from Bagmati River basin, Nepal. Similarly (Devkota and Gyawali, 2015) also conducted a research focused on impact of climate change on hydrological regime and water resource management of Koshi river basin. Palazzoli et al., (2015) conducted a research in Indrawati river basin of Nepal about how the climate change has been affecting the water resources availability and crop yield from the basin. So, most of the latest studies are focused on impact of climate change on different fields.

Though the very few researches have been conducted using SWAT in Nepal, the literature shows the applicability of SWAT model to simulate hydrological processes of West Rapti River basin with reasonable accuracy. As one can easily make use of different data sets that are available online and offline from different sources, the applicability of SWAT model has been increasing worldwide and has been accepted.

2.6 Best management Practices (BMPs)

Best Management Practices (BMPs) are the management practices with in watershed for the control of pollution sources in water bodies. These are the most effective and practicable means to control nonpoint source (NPS) pollution at desired levels (Xie et al., 2015). The pollution to water bodies may be in the form of sediment from erosion and nitrate or any other pesticides used in farming that moves to water bodies via water medium. Water-based soil erosion and sedimentation are two of the most serious environmental problems facing the world today and through this many landscapes across the globe have been adversely affected (Phomcha et al., 2011). Assessment of BMPs on sediment control and establishing a proper sediment control measures helps in erosion control so that threat to life of reservoirs due to silting caused by erosion from watershed could be minimized and huge amount of cost invested could be saved. Best way of sediment control is to beat the sediment where it originates. BMPs are of two types i.e. structural BMPs and Non-Structural BMPs. Non-Structural BMPs is the form of planning and design approaches in broader sense including principles and policies also and are less “structural” in their form but non-structural BMPs have very important physical consequences (Pennsylvania Stormwater Best Management Practices Manual, 2006). No tillage, conservation tillage, residue management, nutrient management plans, cover crops etc. are some examples of Non-structural BMPs. Structural BMPs includes implementation of more or less artificial structural change with in the watershed from where pollution is generating. Livestock fencing along streams, grassed waterways, filter strips, strip cropping, riparian buffers, diversion dikes, porous gully plug and artificial forestation are some the example of structural BMPs (Srinivasan, 2008).

The basic concept of the BMPs is the application of an economically possible practice or combination of practices for a specific water quality problem (Jiang et al., 2014). Dechmi and Skhiri, (2013) did a study on evaluation of BMPs under intensive irrigation using SWAT model. Twenty BMPs scenarios like conservation and no tillage, optimum irrigation and fertilizer application were tested for irrigation return flow (IRF), total suspended solid (TSS), soluble phosphorus and total phosphorus (TP) and economic impacts of the BMPs on crop gross margin were also evaluated. The results indicated that the BMP adjusted irrigation water use was best with reduction in IRF by 31.4%, TSS loads by 33.5% and TP loads by 12.8% and the load reductions were even increased when individual BMPs were combined.

Parajuli et al., (2008) studied the effect of BMP vegetative filter strip (VFS) of different length on control of fecal bacteria and sediment yield in a 950 km^2 upper Wakarusa watershed of northeast Kansas of USA. 0, 10, 15 and 20m length of VFS were tested and VFS 15m was found to be most effective on reducing fecal bacteria.

Sommerlot et al., (2013) used RUSLE-2, SEDMOD and SWAT model for evaluation of impact of field scale BMPs on water quality improvement and the cost associated with it. Based on these research works it is clear that best management practices can widely be used for runoff control and water quality control in terms of sediment, nitrogen and phosphorus.

Some more application of SWAT model in different field of study including BMPs are presented Table 2.1 below.

Table 2.1: Application of SWAT Model.

Researchers and year	Regions, Area (SqKm)	Results/Remarks/Conclusion
Garg et al., (2012)	Upper Bhima River basin, 46066 Sq km	Spatial mapping of agricultural productivity of water was assessed and found that agricultural water productivity for sugarcane, sorghum and millet were found to be significantly lower than the potential of the basin. Also it is suggested that the maximization of the area by provision of supplemental irrigation to rainfed areas as well as good farm water management schemes can help to improve water productivity.
Worku et al., (2017)	Beressa Watershed, Ethiopia, 213.2 Sq km	Land use/land cover changes and its response to runoff and sediment yield was modelled using SWAT. Study revealed the significant increase of runoff and sediemnt yield and it was due to LU/LC change.
Memarian et al., (2014)	Hulu Langat Basin, Malaysia, 390.26 Sq km	The study was focused on the effect of LU/LC change on stream flow and sediemnt generation. The results from SWAT simulation using the past and conservative scenarios revealed heavy decrease in monthly direct runoff and sediment load, and simulation based on the future scenario showed large increase in monthly runoff, sediment load and groundwater recharge in comparision to datum conditions.
Betrie et al., (2011)	Upper Blue Nile River basin, 184560 Sq km	SWAT model was used for sediment management modelling using BMPs. The BMPs like applying filter strips, stone bunds and reforestation scenarios decreased thecurrent sediment production from the sub- basins and the basin outlets.
Bracmort et al., (2006)	Black Creek watershed, Indiana, USA, 50 Sq km	Long term (20 years) water quality impact of BMPs was studied using SWAT model. Field evaluation results were used to represent the current field conditions of previously developed structuural BMPs. Sthe study revealed that the BMPs in good condition decreased average average annual sediment yield by 16% to 32% and the average annual phosphorus yield by 10% to 24%. And BMPs in current condition decreased sediment yield by only 7% to 10% and phosphorus yield by 7% to 17%.
Dhami et al., (2018)	Karnali River Basin, Nepal, 45,954 Sq km	SWAT model along with SRM model was used to study the water balance of snow fed mountainous river basin and the result showed that SWAT can be used in mountainous river basin along with SRM to model out the hydrology and water balance study.

CHAPTER 3
THEORITICAL CONSIDERATIONS

Theoretical background behind any hydrologic model is necessary to understand the model and to know how the model represents or simulates various physical processes in the watershed. This chapters describes about some theoretical aspects of hydrological processes that are being used with in SWAT model. Also, it describes in brief about ArcGIS mapping software. Details of theory that governs SWAT model can be studied on Neitsch et al., (2011).

3.1 SWAT Model

SWAT – Soil and Water Assessment Tool developed by USDA Agriculture Research Service is a physical based continuous or long term yielding model and used to study the effect of various land management practices on water, sediment and chemical yield from agriculture in large complex watershed having numerous soil type or texture, land use scenario and watershed or field management practice over a length of time (Neitsch et al., 2011). It is a widely accepted complete interdisciplinary watershed modelling tool. In SWAT model, any study area watershed is divided in to sub watershed and sub watershed divided further in to hydrological response units (HRUs). These HRUs are the areas of same type of land use, land slope and soil properties and it is the percentage of watershed area which is not spatially identified at the time of swat simulation (Gassman et al., 2007). Similarly sub watershed is characterized by dominant land use, soil type and management practices (Kalcic et al., 2015). Whatever may be the study using SWAT model, Water balance is the key force behind every process in a watershed. Whatever be the area of study, water balance is the key to every process occurring within watershed. To exactly simulate the different ongoing phenomena with in a watershed, watershed hydrological cycle can be divided in to two phases viz land phase and routing phase as below.

3.1.1 Land Phase of hydrological cycle.

The general sequence of processes used by SWAT to model the land phase of the hydrologic cycle is shown in Figure 3.1. The different inputs and processes involved in this phase of the hydrologic cycle are summarized in the following sections.

3.1.1.1 Weather

The climatological information of a watershed is utilized to get the moisture and energy inputs which control the water balance and help to decide the relative significance of various features of hydrology. The climate parameters that are utilized by SWAT for hydrological simulation are daily maximum and minimum temperature, daily precipitation or rainfall, solar radiation, relative humidity and wind speed. The model has capability of reading these inputs directly from the input file or it will take average monthly data of number of years, do analysis and generate the daily values of weather parameter. SWAT uses WXGEN weather generator model to generate climate data or to fill gaps in the measured records if any (Worku et al., 2017).

3.1.1.2 Hydrology

SWAT model simulates hydrological process based on following water balance equation.

$$SW_t = SW_0 + \sum_{i=1}^{1}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \quad \text{... 3.1}$$

Where, SW_t = final soil water content (mm H_2O),

SW_o = initial soil water content (mm H_2O),

t = time in days,

R_{day} = amount of precipitation on day i (mm H_2O),

Q_{surf} = amount of surface runoff on day i (mm H_2O),

E_a = amount of evapotranspiration on day i (mm H_2O),

W_{seep} = amount of percolation and bypass exiting the soil profile bottom on day i (mm H_2O),

Q_{gw} = amount of return flow on day I (mm H_2O).

The pathways of water movement simulated by SWAT in the HRUs are shown in Figure 3.2 and some keys are explained below.

3.1.1.2.1 Canopy Storage

Water captured by vegetative layers, where it falls and evaporates is called canopy storage. When we use SCS CN method for runoff calculation canopy storage is taken in to account, but if Green and Ampt method is used for infiltration and runoff calculation canopy storage should be modeled separately. We can give the value of maximum canopy storage and Leaf area index for land cover as input in SWAT model and based on these we can compute maximum storage and hence evaporation. When computing evaporation water is first removed from canopy storage.

3.1.1.2.2 Infiltration and runoff

Infiltration is the process of downward movement of water in to the soil profile. As infiltration time goes on increasing, soil becomes wet and infiltration rate decreases and attains a constant or steady value. It means as infiltration goes on decreasing, surface runoff goes on increasing. There are two options available in SWAT model for calculation of runoff. One is Modified SCS curve number method and another is Green & Ampt Infiltration equation. The curve number method requires daily rainfall data and is unable to model infiltration directly. The quantity of water that entering to the soil layers is obtained from the difference between rainfall and surface runoff. On the other hand, the Green & Ampt method uses rainfall data of smaller interval than daily and computes infiltration as a function of wetting front matric potential and effective hydraulic conductivity.

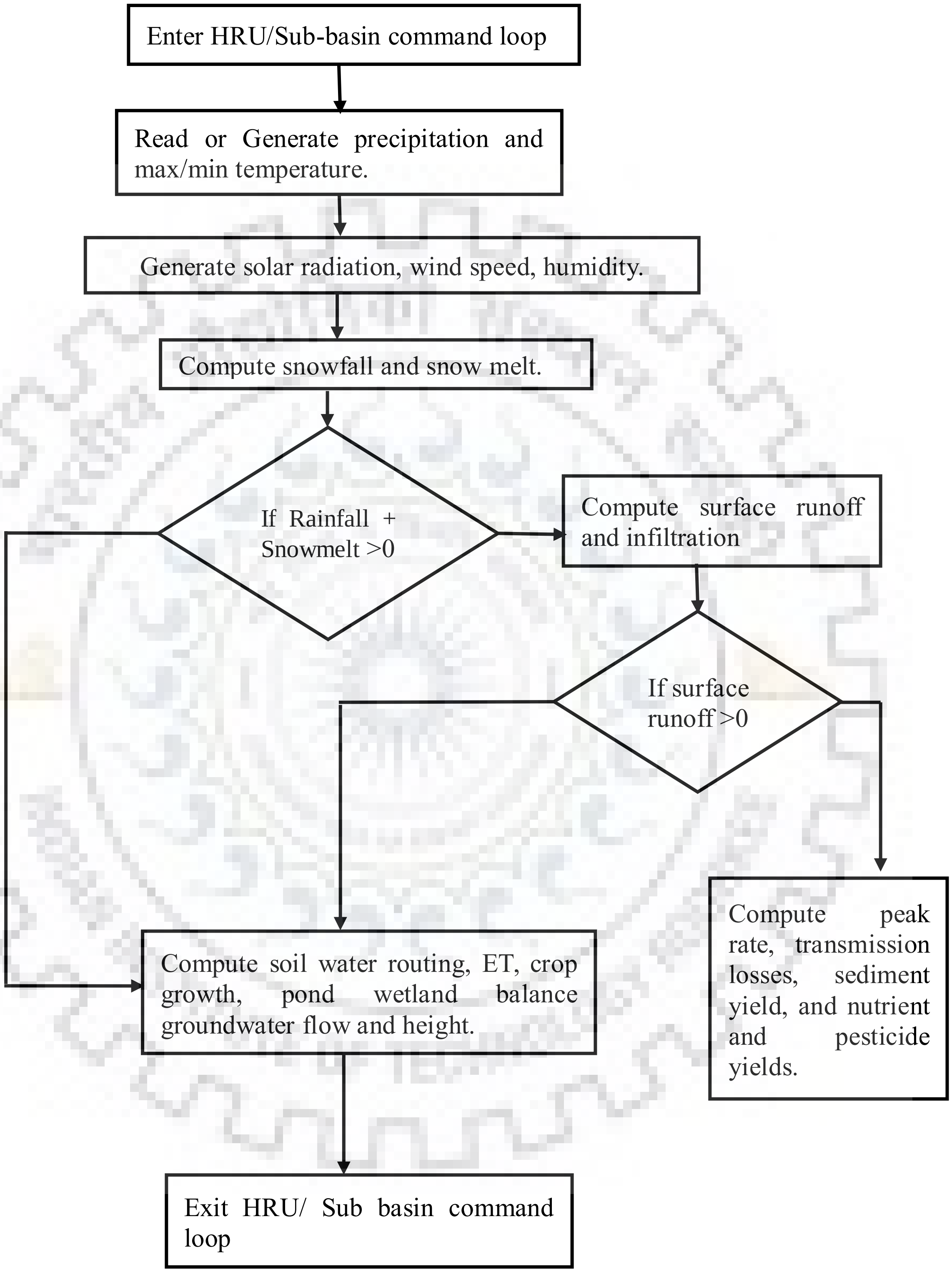


Figure 3.1:General sequence of processes used by the SWAT model (Neitsch et al., 2011)

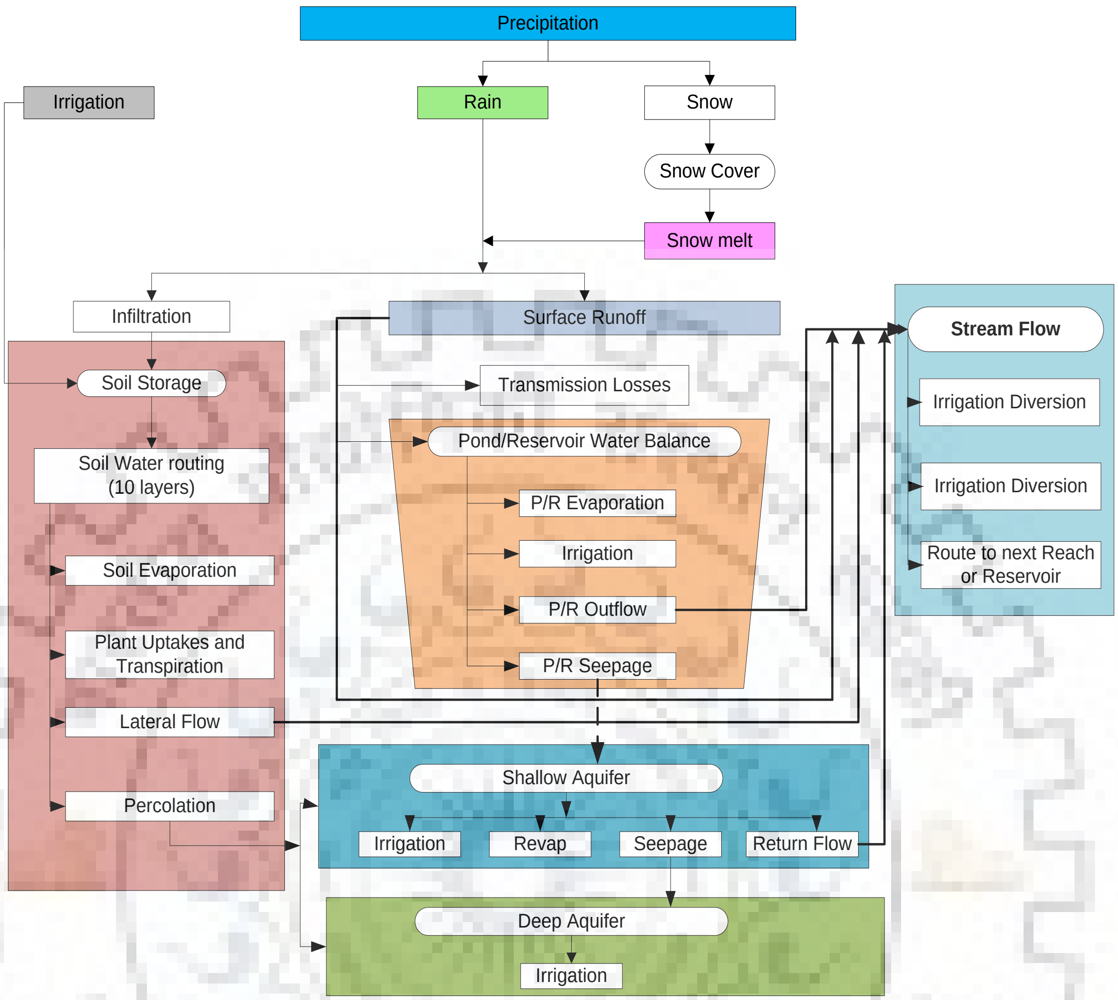


Figure 3.2: Pathways for water movement in SWAT (Neitsch et al. 2011)

The SCS Curve number equation used by SWAT is given below.

$$Q = \frac{(P - Ia)^2}{(P - Ia) + S} \qquad \ldots 3.2$$

Where Q = runoff depth in (mm), P = effective depth of precipitation in (mm), I_a = initial abstraction of water in (mm), S = maximum potential retention. The initial abstraction of water (Ia) is the function of maximum potential retention S and can be expressed as I=λS, where λ = a constant value usually taken as 0.2 or 20%. Therefore, I_a=0.2S. Hence by combining above equations we have,

$$Q = \frac{(P - 0.2S)^2}{(P - 0.2S) + S} \qquad \ldots 3.3$$

The runoff process starts when P = 0.2 S. Depending on soil types, topography and slope of the catchment, and land use practices, maximum potential retention varies and the maximum potential retention ‘S’ has been correlated with dimensionless parameter curve number expressed in the following equation.

$$S = \left(\frac{25400}{CN}\right) - 254 \qquad \text{... 3.4}$$

where, maximum potential retention is in mm. The curve number decreases as the soil attains the wilting point and increases to near 100 as the soil reaches to saturation.

Modified rational method is used for calculation of peak runoff rate. Rational method assumes that that if a rainfall of intensity i falls continuously for time period more than the time of concentration t_c, runoff will increase until t_c when maximum runoff occurs and all of the area of sub-basin contributes to flow at the outlet. In the modified rational formula, the peak runoff rate is given by:

$$q_{peak} = (\alpha_{tc}\, Q_{Sur}\, Area)/3.6\, t_c \qquad \text{...3.5}$$

Where, q_{peak} is the peak runoff rate (m^3s-1); α_{tc} is the part of daily rainfall occurring during the time of concentration; Area is the sub-basin area (km^2); and t_c is the concentration time for a sub-basin (hr.).

The concentration time for sub basin is obtained by adding time for overland flow and time for channel flow.

$$t_c = t_{ov} + t_{ch} \qquad \text{... 3.6}$$

Where, t_c is the time of concentration for a sub-basin (hr.), tov and tch are the time of concentration for overland flow and channel flow (in hour) respectively.

The overland flow time of concentration, t_{ov}, is computed using the equation.

$$\boldsymbol{t_{ov} = \frac{{l_{slp}}^{0.6} n^{0.6}}{slp}} \qquad \text{...3 .7}$$

Where, L_{slp} is the sub-basin slope length (m), n is the Manning's roughness coefficient and slp is the average slope in the sub-basin (m m^{-1}).

The channel flow time of concentration, tch is computed using the equation.

$$t_{ch} = \frac{0.62Ln^{0.6}}{Area^{0.125} {Slp_{ch}}^{0.375}} \qquad ... 3.8$$

Where, t_{ch} is the time of concentration for channel flow (hr.), L is the channel length from the most distant point to the sub-basin outlet (km), n is the Manning's roughness coefficient for the channel, Area is the sub-basin area (km^2) and Slp_{ch} is the channel slope (mm^{-1}).

3.1.1.2.3 Evaporation

Evaporation is the process by which water in solid or liquid gets converted to vapors. Evaporation occurs from rivers, lakes, snow areas, vegetative surfsces and within plants. Potential soil water evaporation is estimated as function of potential evapotranspiration (PET) and leaf area index. PET is the rate at which evapotranspiration will occur when unlimited amount of water is supplied to the large area covered uniformly with growing vegetation. In SWAT model three options are available for estimation of PET viz Priestley-Taylor (Priestley and Taylor, 1972), Hargreaves (Hargreaves et al., 1985), and Penman-Monteith (Monteith, 1965).

3.1.1.2.4 Percolation

Percolation is calculated for each soil layer in the profile. Water can percolate if water content exceeds the field capacity for that layer. The flow rate is governed by the saturated conductivity of the soil layer.

3.1.1.2.5 Lateral sub surface flow

Lateral subsurface flow is the contribution of stream flow originating below the surface and above the zone where rocks are saturated with water. SWAT model uses a kinematic storage model to estimate the lateral flow in each soil layer and kinematic storage model takes in to account of variation in soil conductivity, slope and soil water content.

3.1.1.2.6 Ground water flow

SWAT divides the groundwater in to two aquifer systems. One is Shallow, unconfined aquifer which contributes return flow to streams with in watershed and another is a deep, confined aquifer system which contributes return flow to stream outside the watershed. Water balance for each aquifer are calculated separately.

3.1.1.2.7 Transmission loss

Transmission losses occurs by leakage from the bed of flow channels when ground water table is below the bed of channels. Transmission losses decrease surface runoff and SWAT makes use of Lane's method described in USDA SCS Hydrology Handbook, (1983) to find the losses during transmission.

3.1.1.3 Erosion

Erosion is the main cause of sediment production with in watershed. It is an important economic and environmental concern across the world. Sediment produced due to erosion pollutes water and degrades quality (Sporton 2009). SWAT uses Modified universal soil loss equation – MUSLE (Williams 1975) is used in SWAT to estimation of sediment generated from the watershed. MUSLE uses the amount of runoff to simulate erosion and sediment yield (Neitsch et al. 2011). MUSLE equation is given as

$$A = 11.80\,(V_Q Q_P)^{0.56} KLSCP \qquad \text{... 3.9}$$

Where A is sediment yield t acre^{-1} year^{-1}, $(V_Q\ Q_p)^{0.56}$ is the runoff factor, V_Q is volume of runoff (m^3), Q_p is peak flow rate (m^3/s), K is the soil erodibility factor, which is the erosion rate per unit of erosion index for specified soil, LS is the slope length and gradient factor, C is the cropping management factor, and P is the erosion control practices factor, which is the ratio of soil loss with contouring, strip cropping or terracing to that with straight row farming, up and down slope.

3.1.2 Routing phase of hydrological cycle.

Once the amount of water, sediment, nutrients and pesticides to the main channel are determined using SWAT model, these are routed through the stream network with in the watershed. Routing process takes place in main channel and reservoir. Routing for water, sediment, nutrients and pesticides are required either it is main channel or in reservoir. As our study is concerned with sediment and flow routing, flood routing and sediment routing will be discussed here.

3.1.2.1 Flood routing

SWAT model uses variable coefficient method developed by Williams (1969) or Muskingum routing method to route the flow through main channel. It is necessary to define the depth and width of the flow channel along with the length, slope and Manning's 'n' value of the channel by the user itself. Manning's equation for uniform flow in a channel is used to calculate the rate and velocity of flow in a reach segment for a given time step.

3.1.2.2 Sediment routing

Deposition and degradation are the main phenomena for sediment routing through channel or reach. Peak channel velocity is the main factor in sediment routing through channel that influences the maximum amount of sediment that can be transported from a reach segment. Stream power causes loosening and removal of bed material and excess stream power further degrades bed of channel (Neitsch et al. 2011).

3.2 ArcGIS

ArcGIS is a software developed by Environmental Systems Research Institute (ESRI), is the mapping and analytics platform for viewing and analyzing geospatial information. It provides contextual tool for mapping and spatial reasoning so that one can locate data and location-based insights. It helps to create deeper understanding, allowing to see quickly how things are happening and information are being connected to them.

ArcGIS helps in location-based analysis using contextual tools to analyze and visualize data. Some of the capabilities of GIS are spatial analytics, mapping and visualization, real time GIS, imagery and remote sensing, data collection and management and 3D GIS. Spatial analytics is the heart and soul of GIS and it is helpful to find best location or locating place of concern. Mapping and visualization helps in spotting spatial patterns of study data so that better decision and suitable action can be taken.

Arc GIS is the common tool that brings Geographical Information Systems (GIS) desktop. It is well equipped with graphical user's interface (GUI) which enables visualization, exploring and analysis of spatial data. It is capable of displaying, viewing, editing of vector dataset called shape files. And processing modelling, visualization and interpretation of grid-based raster data set can be performed using spatial analyst extension.

Several extensions can be incorporated in Arc GIS to perform task and the SWAT model chosen in this study is also added to ArcGIS as an extension as ArcSWAT. We use ArcGIS for study area map preparation and its location, soil data analysis, land use / land cover map preparation and analysis and creation of watershed boundary and river system using Digital Elevation Model and showing spatial distribution of hydrological and meteorological station and information related to these stations. Here ArcGIS 10.2 version was used for study and its details can be read from http://resources.arcgis.com/en/help/.

CHAPTER 4
MATERIALS AND METHODS

Chapter four is about the description of study area and its location, accessibility, general climatic conditions, stream network in the study area and the rationale behind selecting West Rapti basin for study. Further this chapter discuss about different data sets required for the study, their source, acquisition and processing. It also discusses about SWAT model setup, sensitivity analysis and calibration and validation using SWAT CUP, statistics about model performance evaluation criteria, representation of BMPs and evaluation method of BMPs performance.

4.1 Study Area

4.1.1 Introduction

The study area, West Rapti River basin lies in the mid-western region of Nepal and it extends from 27^0 56' 50" to 28^0 02'30" North latitudes and from 81^0 45'00" to 81^0 40' 00" East longitudes (Figure 4.1). The entire districts of Rolpa, Pyuthan and a few parts of Arghakhanchi, Banke and Dang districts are occupied by the West Rapti basin up to the southern boundary of India. The northern boundary is formed by Mahabharat range and the southern part by flat Terai plains. The catchment area of the study basin is 5281 km^2 and the length of main stream channel is 257 km to Kusum outlet. The river originates from the middle mountains of Nepal, then enters to the flat area and finally drains to India to join the Ganges River. The runoff generation in West Rapti river is due mainly due to monsoon rainfall and groundwater and the average slope of the basin is 16.8% (Talchabhadel and Sharma, 2014).

4.1.2 Accessibility

In lower region of watershed, the study area of the river stretch is parallel to the east-west highway from Khaskushma to Samshergunj where right bank is accessible to motorable roads. But the downstream area of Samshergunj is not easily accessible and fair-weather roads lead to the flood affected villages and river banks could be reached by foot. In the upper region of watershed most of the station are accessible via district roads and most of the station lies in the district headquarters. The nearest airport is in Nepalgunj, which has daily flights from Kathmandu and Vice Versa. From Nepalgunj the study area is accessible by East West highway and District Roads.

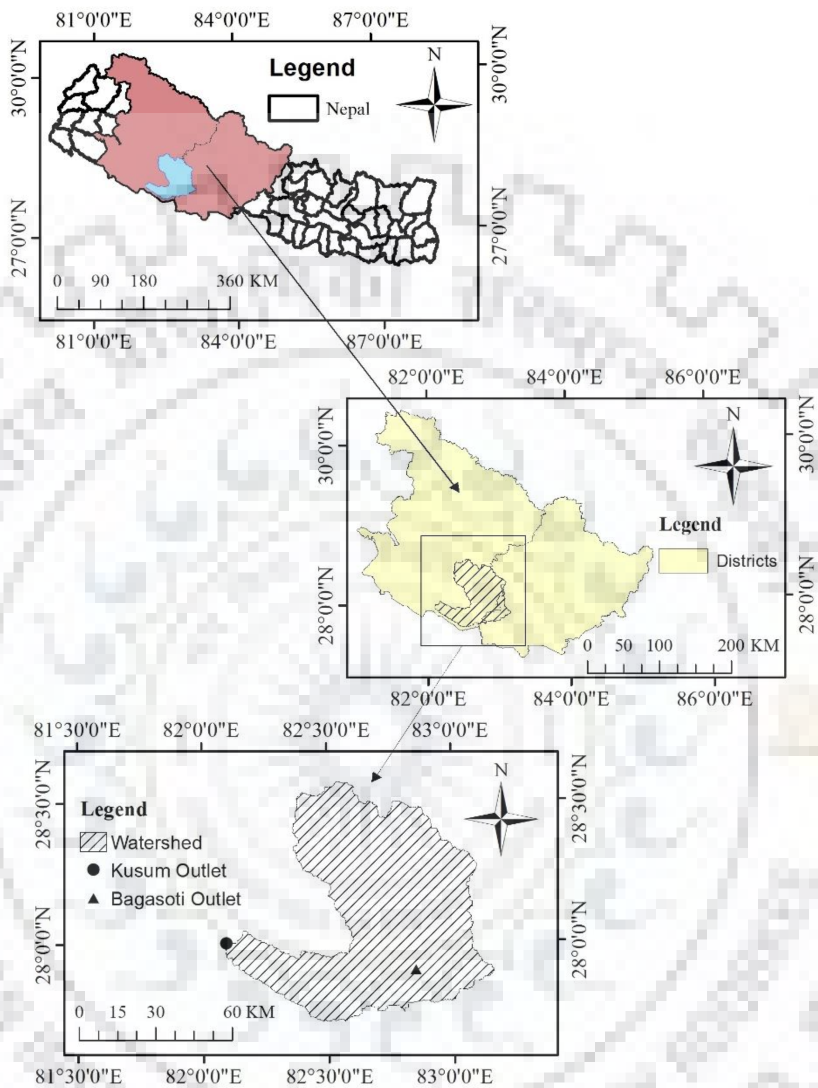


Figure 4.1: Location map of the study area

4.1.3 General climate

Upper part of the study area has deciduous climate and that of lower part varies from tropical to sub-tropical. It is very hot and dry from March to June, hot and humid from July to August, pleasant from September to October and cool and dry from November to February.

Temperature in lower part of study area goes up to 46 ℃ in summer and falls below 2 ℃ in upper part in winter (Talchabhadel and Sharma, 2014). Coldest month is January and hottest month lies between May to August.

The average annual rainfall of the study area is about 1600 mm with around 80% of rainfall occurring during the four months of monsoon. The southeast monsoon contributes rainfall from June to September.

The relative humidity (RH) of the study area goes down up to 60% in May and above 90% in January (Talchabhadel et al., 2015).

4.1.4 River and basin conditions

The West Rapti River has several tributaries. The Network of tributaries of West Rapti River are shown in Figure 4.2. Lungri Khola, Mari Khola, Jhimruk Khola and Arung Khola are major tributaries of West Rapti River.

Jhimruk khola has catchment area of 643 km^2 at Charneta and it starts from an altitude of 3000 m and joins Mari river at Airawati village. Mari river originating from an altitude of 2880 m joins Jhimruk river and these two rivers together flow downwards as West Rapti river. The catchment area of Mari river at Nayagaun station is around 1951 km^2. Dunduwa khola is also a major tributary of West rapti river but lies below the last outlet (Kusum Outlet) of our study basin. West Rapti River joins Ghagra (or Karnali) River in India.

The drainage network of the river basin is shown Figure 4.3. The catchment area of the basin at Nayagaon, Bagasoti, Jalkundi and Kusum discharge gauging stations is 1951 km^2, 3580 km^2, 5132 km^2 and 5281 km^2 respectively.

4.1.5 Why West Rapti Watershed?

Based on the origination from Himalayas, river system of Nepal can be divided in to three: Gandaki, Sapta Koshi and Karnali. The river of our concern West Rapti is the major tributary of Karnali and it meets Karnali River (Ghaghara River in India) in Indian Territory (Hannah et al., 2005). West Rapti River is a medium sized perennial river with ground water and springs for maintaining the river flow during dry period. It originates from Mahabharat range (WECS, 2005).

As one of the main tributary of Karnali (Ghaghara) River, this river is also a river of concern for river linking project of India (Misra et al., 2007). Till date no study has been carried out for the river basins of Nepal for its hydrological modelling and water balance. Talchabhadel et al., (2015) did rainfall runoff modelling on West Rapti watershed taking event based hourly rainfall data. The outcome of the study was used for its flood forecasting. Other studies conducted in West Rapti river basin are community based flood damage assessment approach under impact of climate change (Perera et al., 2015), real time data analysis of West Rapti River Basin of Nepal (Talchabhadel and Sharma, 2014) and vulnerability of freshwater resources in large and medium Nepalese basin to environmental change (Pandey et al., 2010).

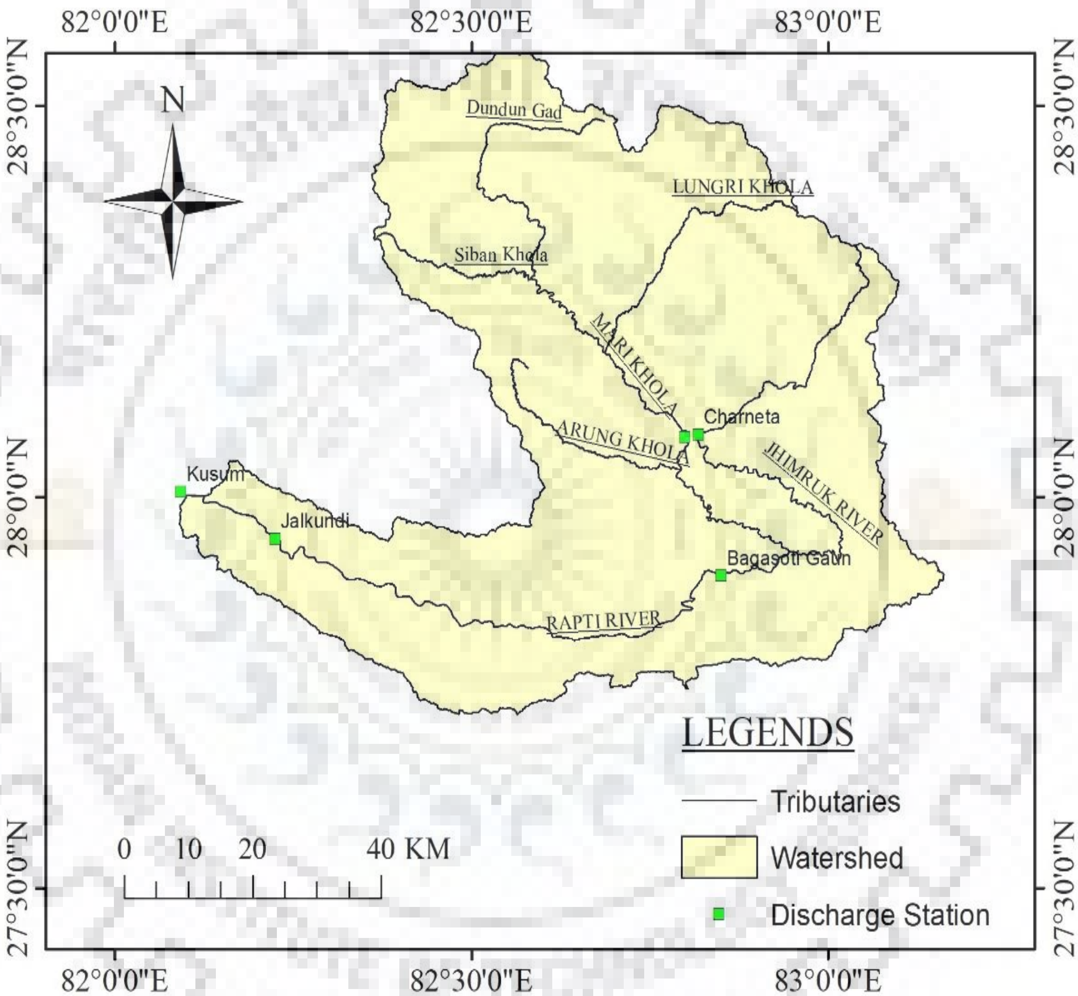


Figure 4.2: Tributaries of West Rapti River

One major project has already been started to construct in the basin, but no any hydrological and water balance study has been carried out. Looking to the aforementioned, the present study has been carried out to study the overall water balance of the West Rapti River Basin.

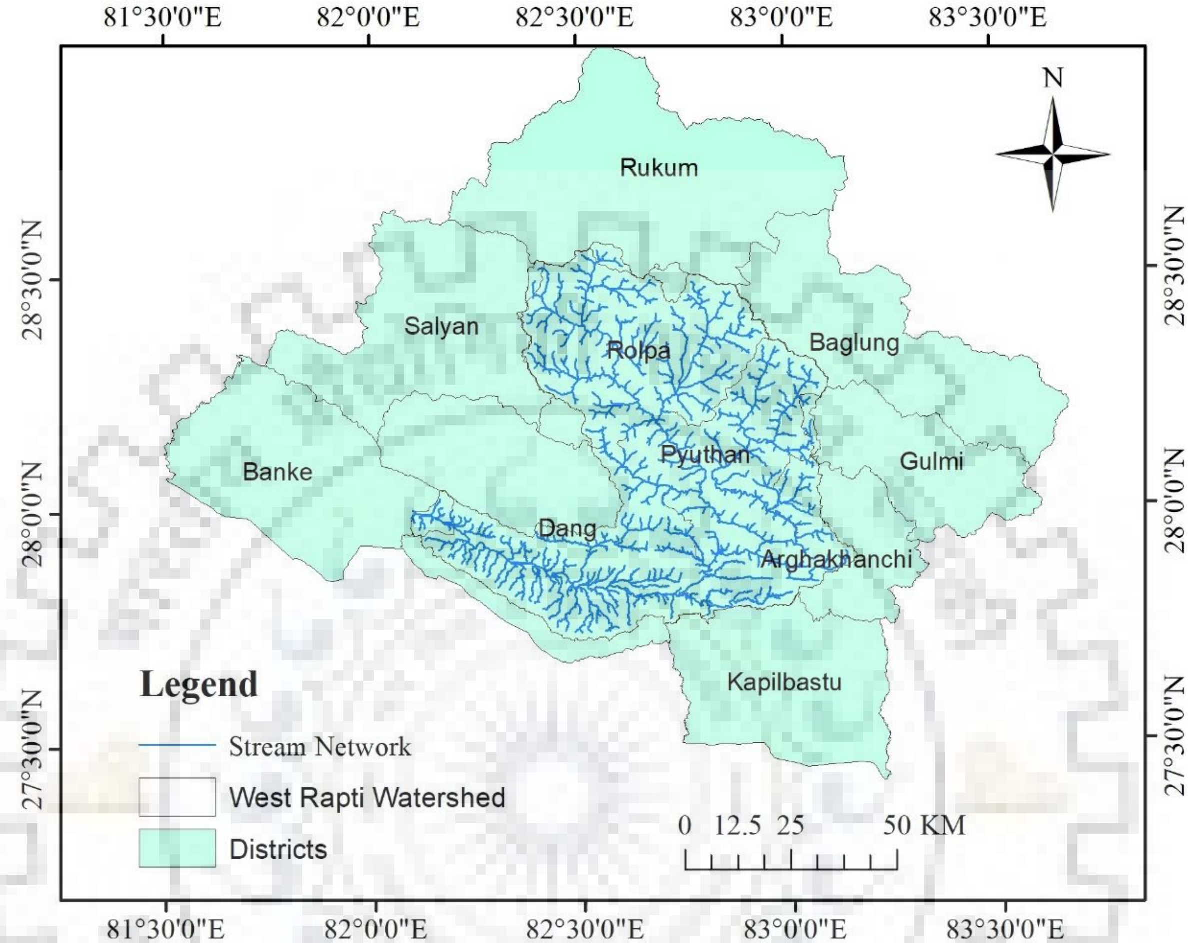


Figure 4.3: Basin Map of West Rapti Basin

4.2 Data acquisition and Processing

4.2.1 Topographic Data

The Topographic data, DEM of the study area was downloaded from website of National Remote Sensing Centre (NRSC) and Indian Space Research Organization (ISRO) open data and product archive portal. DEM presents the spot height of any point of the area at a specified spatial resolution. DEM is used for delineation of watershed characteristics like boundary of watershed, drainage patterns and network and slope and length of channel. The DEM used was of 30 m resolution i.e. 30 m x 30 m grid size. This DEM was generated from the information gathered by Cartosat-1 satellite launched by India and are freely available. The filled DEM generated by processing under ArcGIS10.2 platform is shown in Figure 4.4.

4.2.2 Land Use

LU/LC cover of any watershed affects the runoff generation by affecting soil erosion and evapotranspiration of the area. So, it is of great importance for planning and management activities of natural resources and essential for hydrological modelling using SWAT. The LU map of study area was taken from ICIMOD, Nepal (Uddin et al., 2015) and extracted using topo map obtained from DOS, Nepal. The developed land use map is shown in Figure 4.5. The different land use area in km^2 with percentage distribution is shown is shown in Table 4.1.

4.2.3 Soil Data

SWAT model requires different soil properties such as soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type. The soil map of study area was prepared by analyzing and merging the soil and

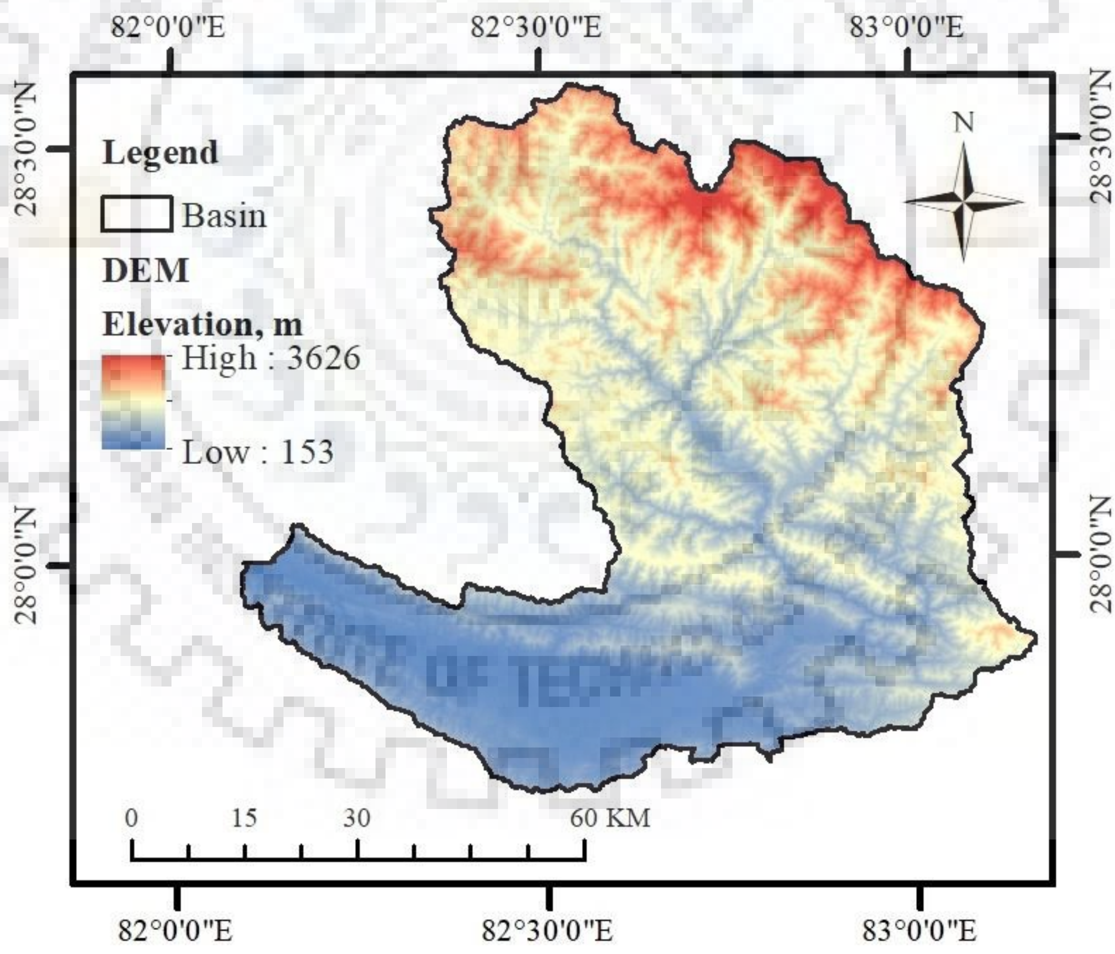


Figure 4.4:Filled DEM of West Rapti Watershed

Table 4.1: Distribution of land Use type

SN	Land Use	Land Use Code	Area, Km^2	Percentage	Remarks
1	Forest	FRST	3117.11	59.03	
2	Shrub Land	RNGB	115.50	2.19	
3	Grass Land	RNGE	109.95	2.08	
4	Agriculture area	AGRL	1857.80	35.18	
5	Barren area	BARR	58.94	1.12	
6	Water body	WATR	19.75	0.37	
7	Built up area	URLD	1.90	0.04	
Total			5281	100	

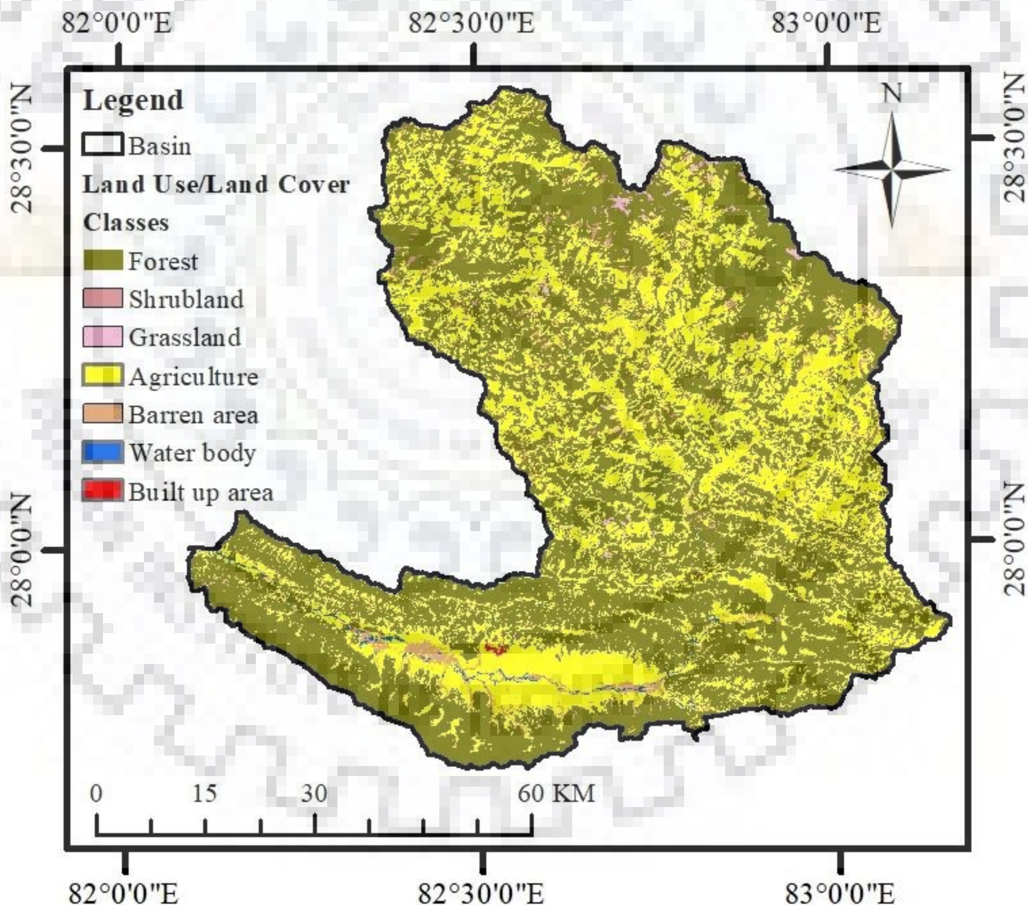


Figure 4.5: Land Use map of study area

terrain (SOTER) database compiled by Food and Agriculture Organization (FAO) and Nepal's survey Department that is freely available from the website of International Soil

Reference and Information Centre (ISRIC) – World Soil Information http://www.isric.org/ or can be obtained from survey department of Nepal.

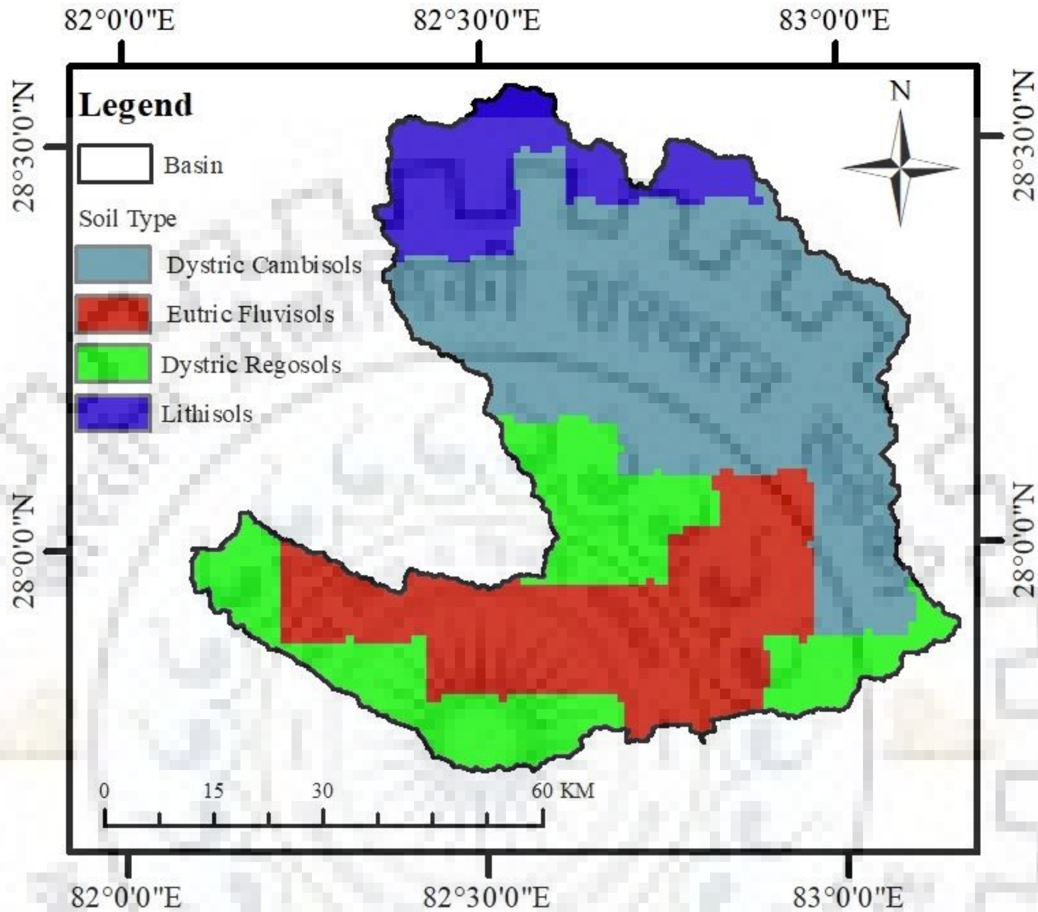


Figure 4.6: Soil map of the basin

Table 4.2: Soil area distribution with texture and group

SN	Soil	Soil Mapping Code	Area, km²	Percentage	Texture	HYSG	Remarks
1	Dystric Cambisols	Bd34-2bc-3663	2275.32	43.09	Loam	C	
2	Eutric Fluvisols	I-Bh-U-c-3717	563.80	10.68	Loam	C	
3	Dystric Regosols	Je75-2a-3759	1297.81	24.58	Clay Loam	C	
4	Lithosols	Rd30-2b-3851	1144.08	21.66	Clay Loam	D	
Total			5281	100			

The soil distribution of study area is shown in Figure 4.6. Major four types of soil are found to be existing in the area viz Dystric Cambisols, Eutric Fluviosols, Dystric Regosols and Lithisols. The percentage distribution of the area and texture of the soil with mapping code in SWAT is presented in Table 4.2.

4.2.4 Land Slope

Slope plays key role in the hydrological simulation process. SWAT model has simply two options of choosing slope classes viz single slope class or multiple slope classes and ArcSWAT uses slope class or classes in combination with different land use and soils to divide the sub watersheds in to different numbers of HRUs.

Figure 4.7 shows the slope map of study area classified in to five different classes as shown in Table 4.3 and it has been prepared using DEM of study area. Our study area varies from elevation 153 amsl to 3626 amsl. Most of the area lies within the slope range 25 to 50 % i.e. 32.80 % area. 26.64 % area lies in percentage slope range 50 to 75 %. Similarly, 3.89 % of area has percentage slope even greater than 100 and 25.04 % area lies in between percentage slope ranging from 0 to 25%.

Table 4.3: Classification of Land Slope in West Rapti River basin

SN	% Land Slope	Area, Km^2	Percentage	Remarks
1	0-25	1322.32	25.04	
2	25-50	1732.03	32.80	
3	50-75	1406.66	26.64	
4	75-100	614.61	11.64	
5	>100	205.46	3.89	
Total		5281	100	

4.2.5 Weather data

SWAT requires daily climate data that either can be obtained from measurement done at meteorological station or can be produced by weather generator model included within ArcSWAT. Weather data required for hydrological balance study in ArcSWAT daily precipitation (Rainfall), maximum and minimum air temperature, relative humidity, wind speed and solar radiation. In this study, daily rainfall data of study area from 2000 to 2013 were taken from Department of Hydrology and Meteorology (DHM), Nepal. All other remaining weather datasets were downloaded freely from SWAT global weather database-[(https://globalweather.tamu.edu/)](https://globalweather.tamu.edu/). Average annual rainfall distribution of West Rapti watershed is presented in Figure 4.8.

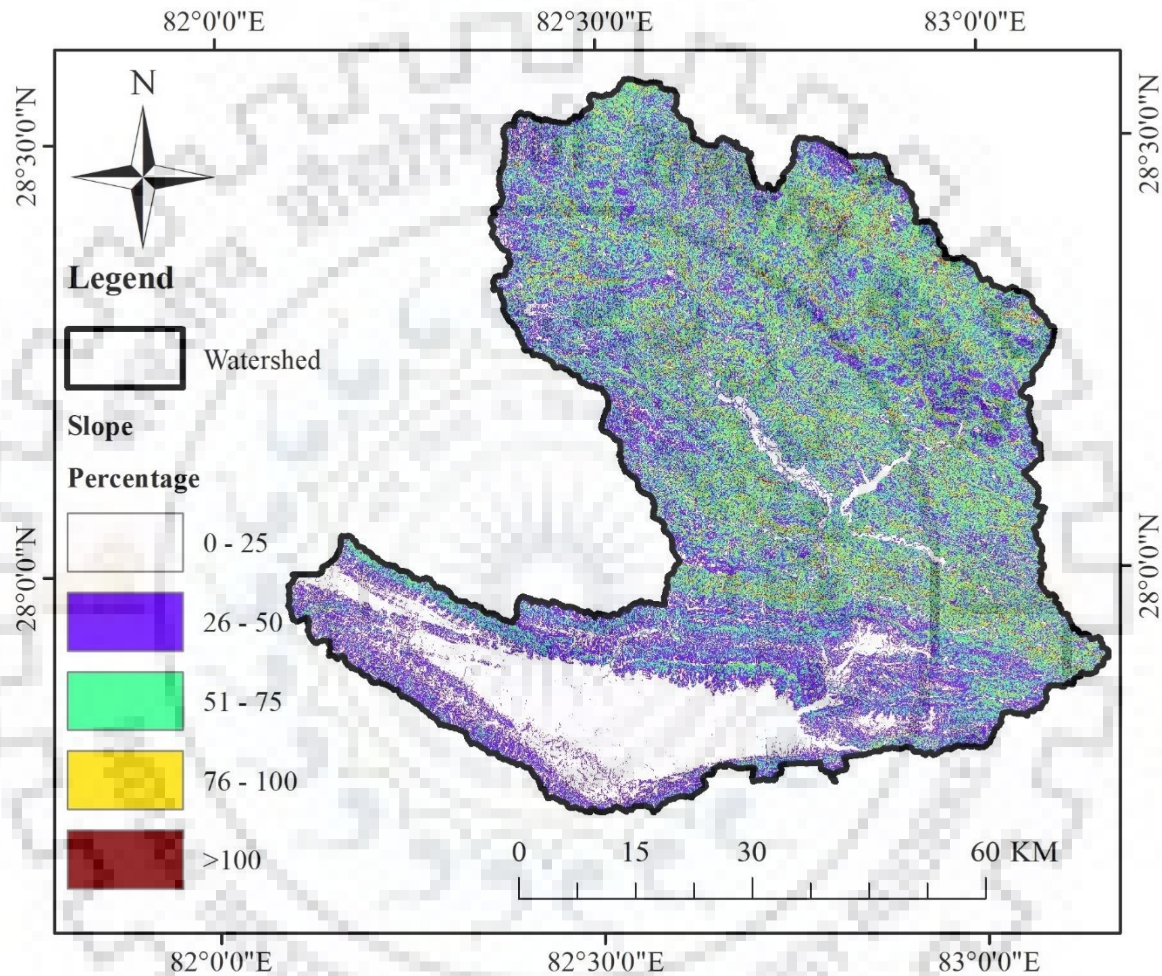


Figure 4.7 : Land Slope map of West Rapti River Watershed

4.2.6 Stream discharge and sediment data

For hydrological simulation using SWAT model daily river discharge data is required and the river discharge data for the study area was obtained from the Department of Hydrology and Meteorology (DHM), Nepal. A list of hydrological stations in the study area is shown in Table 4.4. Spatial distribution of hydrological and meteorological stations of the study area is shown in map in Figure 4.9.

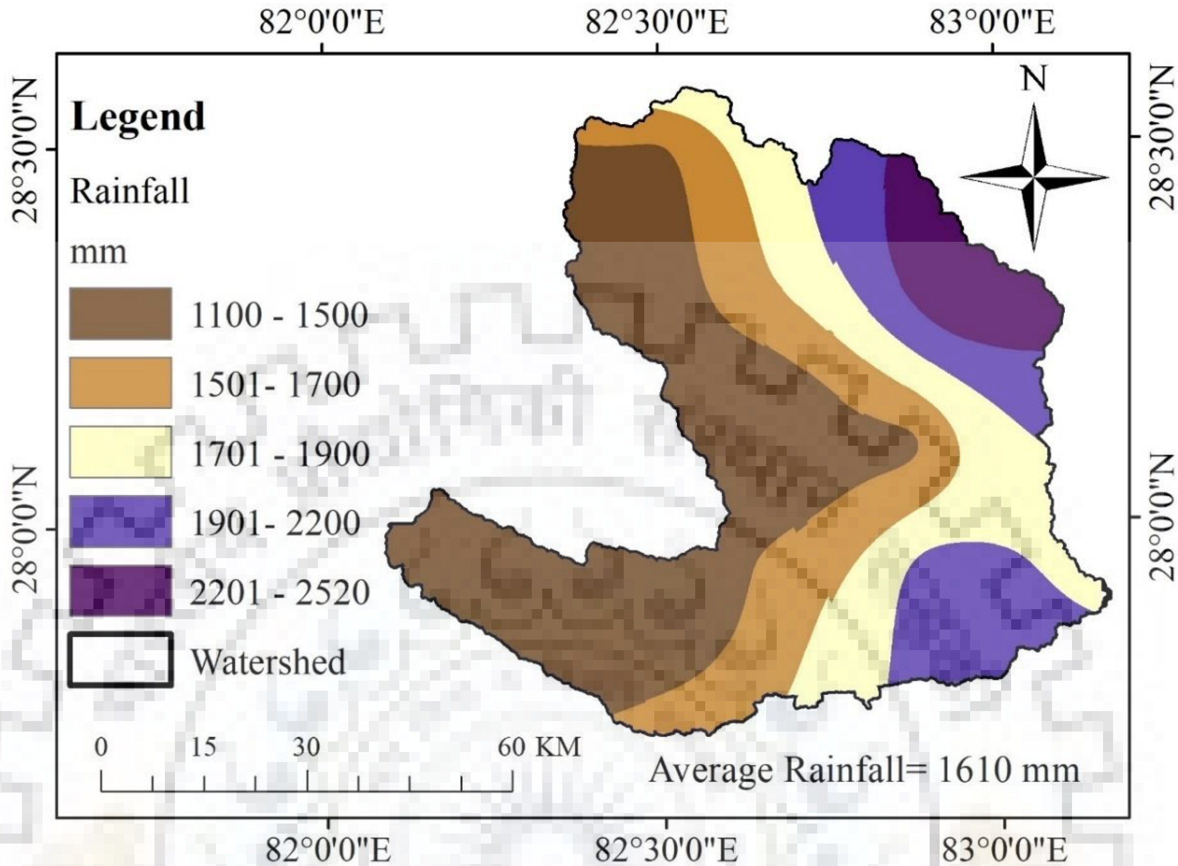


Figure 4.8 : Rainfall map of West Rapti watershed

Table 4.4: Available river discharge stations within study area.

S.N.	Station No.	Site Name	River	Longitude	Latitude	Remarks
1	330	Nayagaon	Mari Khola	82.798889	28.076667	
2	350	Bagasoti Gaun	Rapti River	82.850000	27.900000	
3	360	Jalkundi	Rapti River	82.225000	27.947222	
4	375	Kusum	Rapti River	82.093056	28.007500	

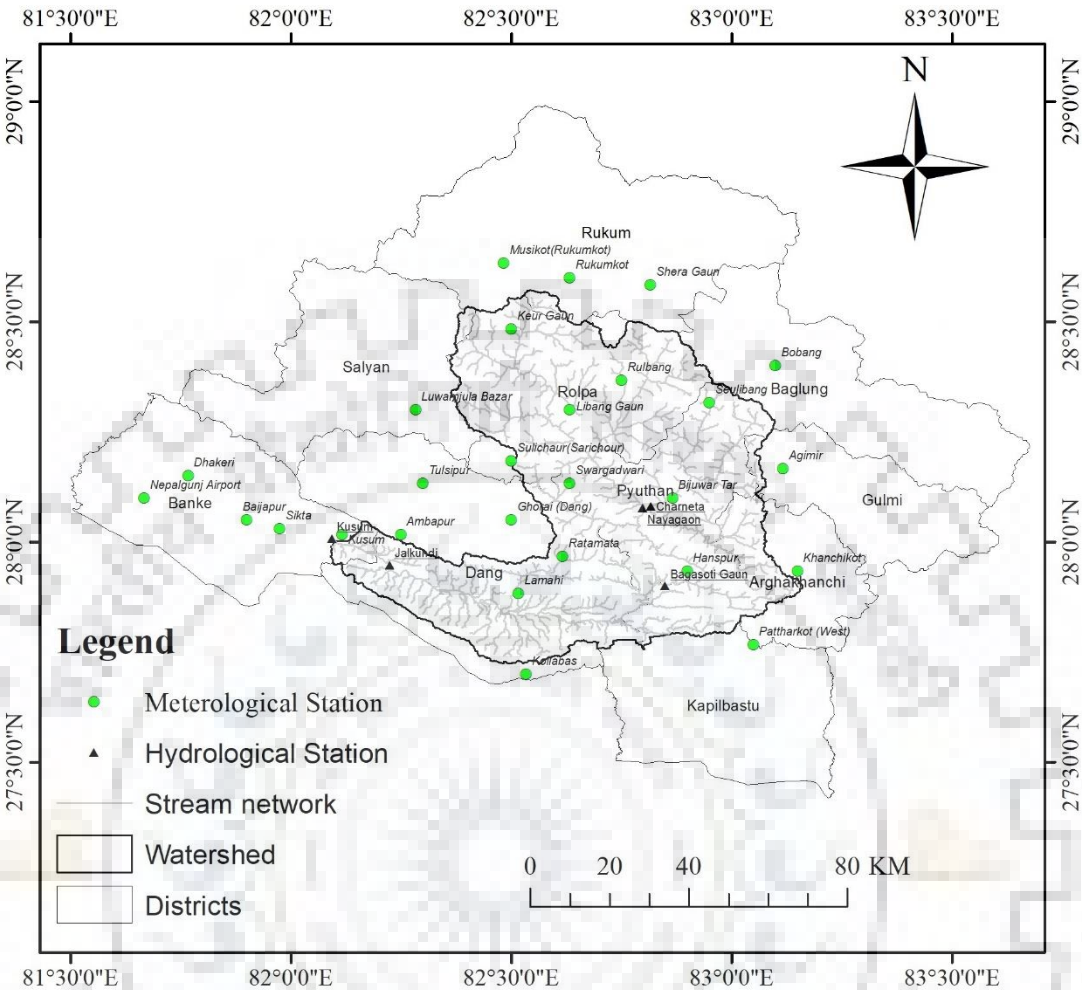


Figure 4.9 : Spatial distribution of Hydrological and Meteorological stations

Daily discharge data in m^3/s, measured at Kusum and Bagasoti Gaun stations for the year 2003 to 2013 and the suspended sediment data in PPM measured at the Bagasoti Gaun station for the year 1978 and 1985-1988 were taken from DHM, Nepal. The sediment load in ton/day was calculated and sediment rating curve was developed using available sediment load and discharge data of Bagasoti Gaun station. The rating curve (power equation) developed was, $\boldsymbol{S\left(\frac{ton}{day}\right) = 0.59\, Q^{1.97}}$ with co-relation coefficient, $R^2 = 0.75$ where, S is sediment load and Q is the daily discharge in m^3/s. The co- relation coefficient developed was weak because of scattered sediment data for same discharge. So, to develop a suitable rating curve, the daily stream discharge values were sorted in to descending order and regrouped in to classes. For lower discharge narrower class interval was adopted and for higher discharge wider class interval was adopted as suggested by Khanchoul et al., (2007). The mean of stream flow and sediment load were calculated, converted to log values and was plotted to obtain the rating equation. The rating equation obtained was, $\boldsymbol{S}\left(\frac{\boldsymbol{ton}}{\boldsymbol{day}}\right) = \mathbf{1.64}\ \boldsymbol{Q}^{\mathbf{1.98}}$ with $R^2 = 0.97$. Using this developed rating curve, Sediment load was calculated and percentage error on sediment load estimation was calculated using relation, $\boldsymbol{Error}\ \% = \left(\frac{\boldsymbol{rating\ curve\ estimate}}{\boldsymbol{load\ from\ measurement}} - \mathbf{1}\right) * \mathbf{100}$ and the percentage error was found to be -19 % which is assumed satisfactory and the negative value indicated underestimation of sediment. Based on developed final sediment discharge rating equation, sediment load ton/day data was calculated and from the developed daily data series monthly sediment data was developed which was used for calibration and validation of the model. The discharge sediment rating curve developed using all point data and the mean values of the class interval are presented in Figure 4.10 and Figure 4.11.

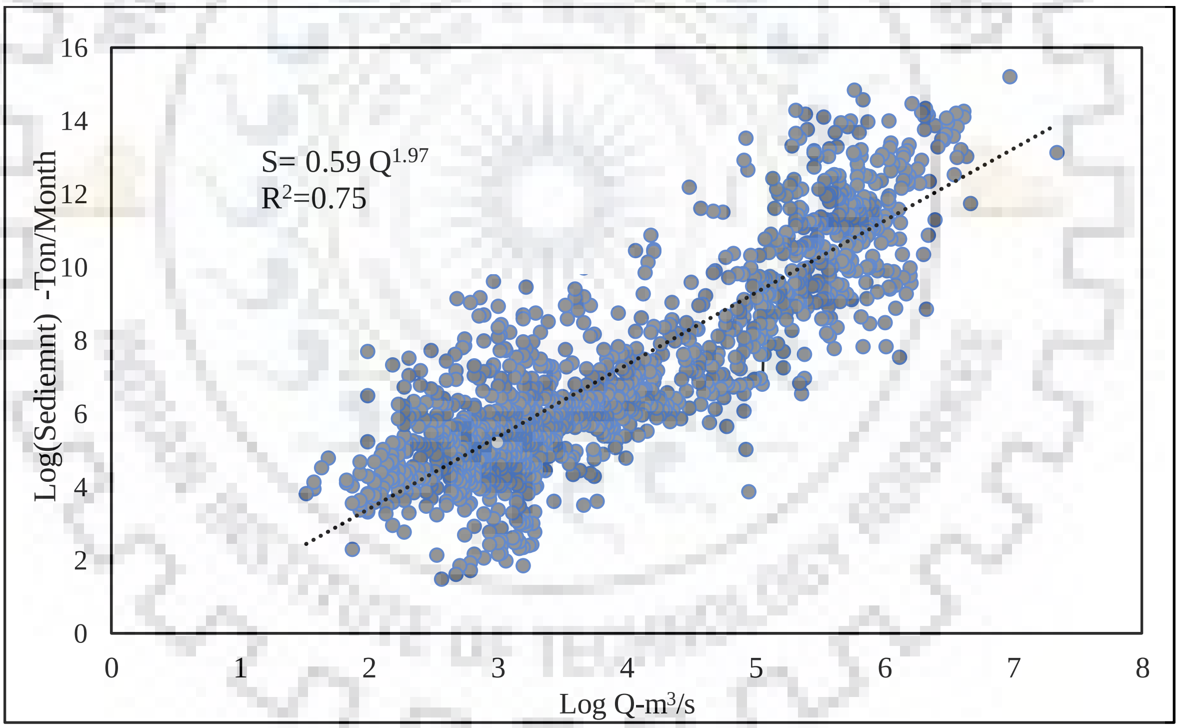


Figure 4.10: Rating curve developed taking all measured suspended sediment concentrations and discharges. The dots are for all measured concentrations and discharges.

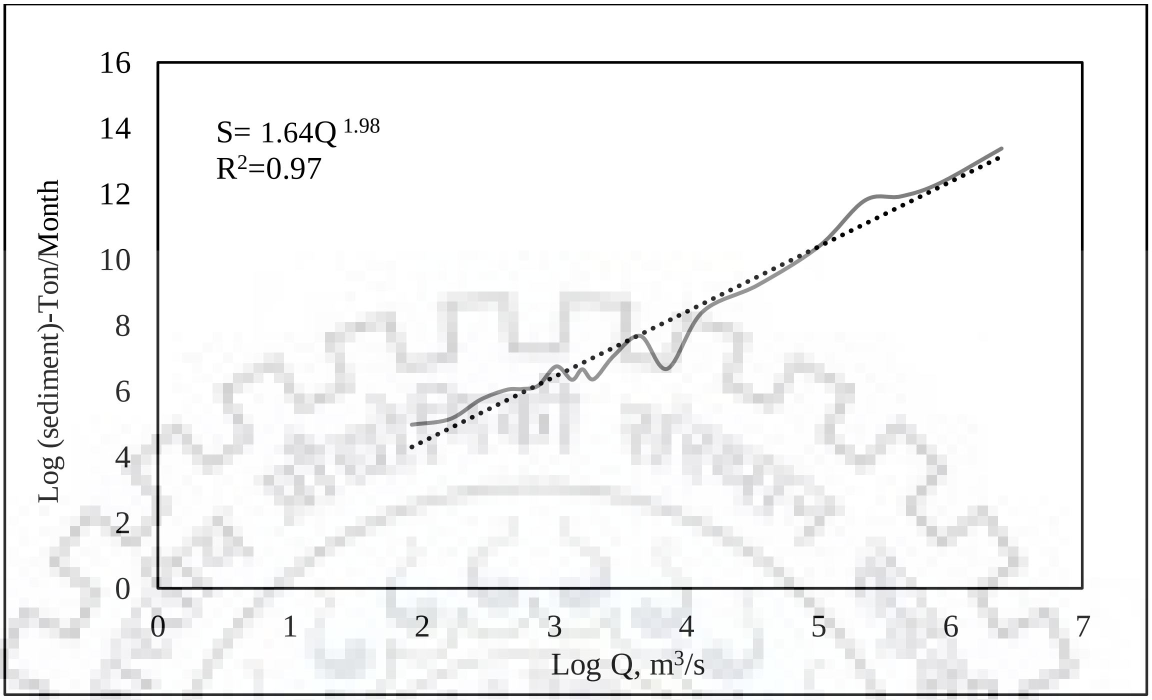


Figure 4.11 : Sediment rating curves developed on mean water discharges and mean suspended sediment concentrations of all data

4.3 SWAT Model Setup

SWAT model setup works in five steps. They are a. data preparation, b. watershed discretization, c. HRU definition, d. sensitivity analysis and e. calibration and uncertainly analysis. Details of the working methodology has been presented in Figure 4.12.

4.3.1 Data Preparation

The Required DEM, land use / landcover and soil map dataset were prepared in Arc GIS 10.2 and projected in UTM 44N zone. The land use / land cover is to be reclassified in to SWAT land cover, plant and urbanization type and proper codes are assigned for different a user lookup table is to be prepared in .txt format. The study area soil database that were not present in US based SWAT database were prepared and assigned in the soil data base of the SWAT model. For soil data also, a user lookup table was prepared in .txt format.

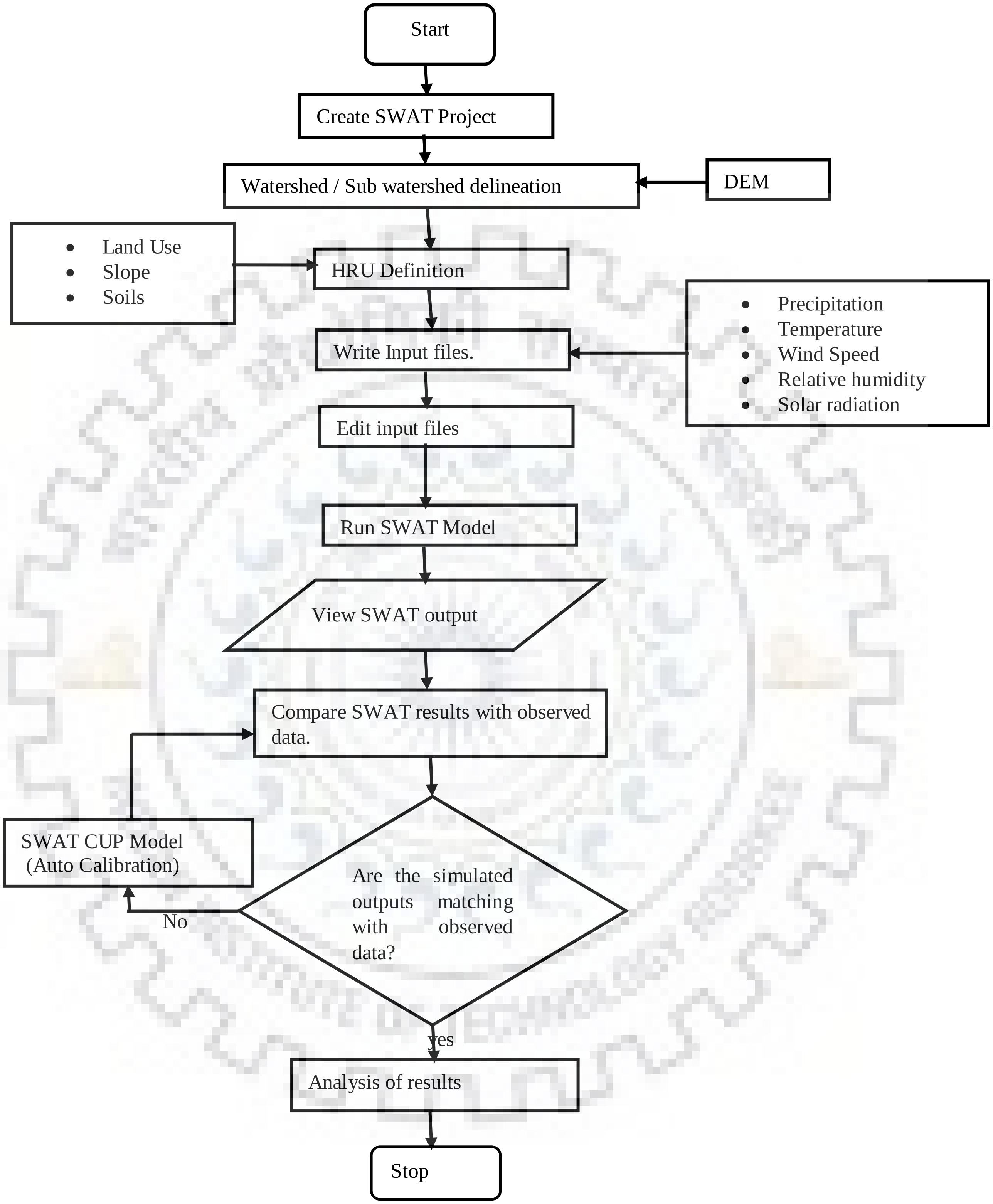


Figure 4.12 : Conceptual framework of SWAT model and its setup

4.3.2 HRU Definition

Hydrological response unit (HRUs) are the smallest spatial unit of the model consisting similar land use, soil and slope with in the sub basin (Kalcic et al., 2015). In the HRU definition process, sub-basins are further divided into numerous similar hydrologic response units of same land use, soil type and slope. HRU definition may be single or multiple. The division of sub-basins into smaller units like HRUs, help to study the variations in evapotranspiration and other hydrological components for different LU/LC, soil type and land slopes. ArcSWAT user's manual suggest 20% land use, a 10 % soil and 20 % slope threshold values to be sufficient for definition of multiple HRUs and same was done in this study also but the users may change this value based on their field conditions. The land use, soil and slope datasets were imported, overlaid and linked with the SWAT2012 databases.

4.3.3 Sensitivity analysis

Selection of sensitive parameters based on sensitivity analysis makes calibration and validation process easier and saves time. SWAT CUP has two options for sensitivity analysis and they are global and one at a time (OAT) sensitivity analysis. OAT sensitivity analysis is performed taking one parameter at a time keeping other parameter's value constant to identify the parameters sensitive to the model and global sensitivity analysis is performed after an iteration to get the rank of sensitivity of all the selected sensitive parameters from OAT sensitivity analysis. Global sensitivity analysis is determined on the basis of t-stat and p- value. Higher the absolute t-stat value and smaller p-value, the parameters are assumed to be more sensitive (Abbaspour, 2015).

4.3.4 Calibration and uncertainty analysis

Calibration trains the model with respect to selected hydrological conditions which are those resembled by the observed data. Calibration can be done in different ways. One is calibration through optimization of model performances. This is a trial and error method for which initial guess of model parameter is done, the model is run and comparison of simulated values with observed values is made. If the values are different then simulation is assumed to be not satisfactory and the parameter values are again changed and model is run again. The simulation is repeated until a satisfactory value is obtained.

Another method of calibration is calibration through expert knowledge. Based on expertise or knowledge, parameter values are guessed and calibration is done and it avoids the need of observed data and this way is followed in case of ungauged catchment with no observed data. Also, for the calibration of model in ungauged catchment, one can transfer parameter values from nearest catchment of similar nature or showing similar response to flow and sediment yield. Another method of calibration is use of auto calibration software like SWATCUP.

After calibration of any model it is recommended that the developed model, before using it in practice, is to be check for its performances in the real field application and the test process is called validation. Very simple way of validation is to divide observed data in two groups and use one group for calibration and the other group for validation.

In this study, for uncertainty analysis using SWAT CUP, based on available literature, some of the model sensitive parameters were initially selected and Latin hypercube once at a time sensitive analysis was carried out. Sensitive parameters were identified, and calibration and validation were carried out. The SUFI-2 accounts for all the sources of uncertainties and quantifies them in terms of p- factor and r- factor. The p- factor is the percentage of observed data captured within 95% prediction uncertainty (95PPU) and r- factor indicates the average thickness of the 95 PPU band divided by the standard deviation of the observed data.

The theoretical value of p- factor ranges from 0 to 100%, that of r-factor ranges from 0 to ∞. The p factor of 1 and r factor of zero is the ideal condition of simulation i.e. exact matching of simulated data with observed ones. While calibration and validation of model our concern is always getting reasonable values of these two factors. We try to capture most of the observations in 95 PPU band (p factor near to 1) and at the same time we want smaller envelope (smaller r factor). So, a balance between p factor and r factor is required to judge the strength of calibration (Abbaspour, 2015), (Worku et al., 2017). For discharge, p factor > 0.7 is recommended to be enough and r factor around 1 depending up on situation would be desirable as per Abbaspour et al., (2015). For sediment, slight deviations (smaller p-factor and larger r- factor) on above values for discharge are acceptable as accurate estimation of sediment is quite tough job.

4.4 Model performance evaluation

Evaluation of model performance or the measure of degree of fit was done taking four objective function in SWAT CUP. The objective functions were Nash-Sutcliffe efficiency (1970) (NSE), Coefficient of Determination (R^2), ratio of root mean square error to the standard deviation of measured data (RSR) and the percentage bias (PBIAS). The coefficient of determination (R^2) is given by the relation,

$$R^2 = \frac{\left[\sum_i (Q_{m,i} - \bar{Q}_m)(Q_{s,i} - \bar{Q}_s)\right]^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2 \sum_i (Q_{s,i} - \bar{Q}_s)^2} \quad \ldots 4.1$$

Nash-Sutcliffe efficiency (1970) (NSE) is given by the relation

$$NS = 1 - \frac{\sum_i (Q_m - Q_s)^2{}_i}{\sum_i (Q_{m,i} - \bar{Q}_m)^2} \quad \ldots 4.2$$

Percentage bias (PBIAS) and the ratio of root mean square error to the standard deviation of measured data (RSR) are given by following relations.

$$PBIAS = 100 * \frac{\sum_{i=1}^{n} (Q_m - Q_s)_i}{\sum_{i=1}^{n} Q_{m,i}} \quad \ldots 4.3$$

$$RSR = \frac{RMSE}{StdDev_{obs}} = \frac{\sqrt{\sum_{i=1}^{n} (Q_m - Q_s)^2{}_i}}{\sqrt{\sum_{i=1}^{n} (Q_{m,i} - \bar{Q}_m)^2}} \quad \ldots 4.4$$

Where Q is the variable and 'm' stand for measured and 'S' stands for simulated values, bar stands for average and i is the i^{th} measured or simulated variable. R^2 value ranges from 0 to 1, value near to 1 indicating strong linear relation between measured and simulated values. NSE value varies from $-\infty$ to 1 showing how strongly the simulated results and measured data fit the 1:1 line. The NSE value less than or near to zero indicates poor model performance and near to 1 indicates best results from the model. The PBIAS value shows the deviation (in percentage) of simulated values from observed values (Van Liew et al., 2007). PBIAS is the measure of average tendency of the simulated values to be larger or smaller than their observed values. PBIAS with optimal value zero is assumed to be best and deviation towards negative or positive from zero indicates model simulation is biased. The negative value of PBIAS is the condition of underestimation and positive value is the condition of over estimation (Gupta et al., 1999). The ideal value for RSR is 0 and increases towards positive value. Zero value of RSR means zero Root Mean Square Error (RMSE) or residual variation indicating perfect simulation of model. So, Lower the RSR, lower the RMSE and better the model simulation performance (Moriasi et al., 2007).

4.5 BMPs representation

In this study the calibrated and validated SWAT model was used for BMPs study. BMPs assessed in this study were grassed water way, parallel terrace or stone bunds, vegetative filter strips or field border, parallel terrace or stone bunds, grade stabilization structures, forestation on agricultural lands and recharge structures are explained as below.

4.5.1 Grassed waterways (SC1-GWW)

Grassed water way in the field can be achieved by increasing channel cover, reducing channel erodibility and increasing channel roughness and these conditions in SWAT model were achieved by adjusting parameters CH_COV2.rte, CH_ERODMO.rte and CH_N2.rte respectively. In this study, the calibrated value of values of CH_COV2.rte, CH_ERODMO.rte and CH_N2.rte were 0.58, 0.46 and 0.10 respectively and for BMPs, the values of CH_COV2.rte, CH_ERODMO.rte were changed to zero and values of CH_N2.rte equal to 0.24 was assigned as suggested by Chow, (1959) for dense grass and also used by Bracmort et al. (2006).

4.5.2 Parallel terrace or stone bunds(SC2-PT/SB)

Stone bunds are the embankments of stones constructed along the contour and across the slope of land so that velocity of overland flow and consequently the soil erosion can be reduced (Gebremichael et al. 2005). As application of the stone bunds or parallel terrace reduces the overland flow, sheet erosion and slope length and these are achieved by adjusting the parameters CN2.mgt, USLE_P.mgt and SLSUBBSN.hru respectively in SWAT model (Bracmort et al. 2006). In this study value CN2.mgt for BMP condition was decreased by 5 from final calibrated value and value of USLE_P.mgt equal to 0.10 was adopted as suggested by Srinivasan, (2008). The value of SLSUBBSN kept default to that obtained from calibration.

4.5.3 Vegetative filters or field border(SC3-VFS-5m,10m)

Filter strips are a length of herbaceous vegetation between cropland, grazing land, or any disturbed land and environmentally sensitive area (Tuppad et al., 2010). Filter strips or field border are to be installed in agricultural areas within the watershed (Betrie et al., 2011). Filter strips, the vegetative strips, filters the runoff and traps the sediment in the watershed (Bracmort et al., 2006). SWAT parameter that is to be changed in SWAT model for filter strips or field border is FILTERW.hru which is the breadth of filter strip. The value of FILTERW.mgt equal to 5 m and 10 m was adopted in this study.

4.5.4 Grade stabilization structures(SC4-GSS)

Another BMP used for study was installation of grade stabilization structures in the field and this reduces gully erosion and slope steepness of main channel. These were obtained by adjusting parameters CH_ERODMO.rte and CH_S2.rte respectively. The value of CH_ERODMO.rte was adopted as explained earlier and CH_S2 was kept default as obtained from calibration.

4.5.5 Forestation (partly) on agricultural lands (SC5-PF)

Adoption of forestation to some percentage of agricultural area of the watershed can be taken as BMP. Reforestation has tendency to decrease overland flow and rainfall erosivity (Betrie et al., 2011). In this study the effect of forestation was simulated not by changing any parameter but by changing land use scenario and 25% of agricultural land was changed to forest area to study the effect of forestation on sediment yield.

4.5.6 Recharge structures (SC6-RS)

Recharge structures, small dam like structures constructed across the flow channel let the water infiltrate and percolate to reach shallow ground water tables (Tuppad and Srinivasan, 2008). Also recharge structures kills the energy of the streams and decrease the sediment carrying capacity. Recharge structures works effectively in case of highly permeable soils. The condition of recharge structures can be created in SWAT model by replacing effective hydraulic conductivity of soil in tributary channels, CH_K1.sub by 25 mm/hr. (Tuppad et al., 2010). In this study, this value of CH_K1.sub value was applied in all sub basins regardless of soil permeability. The summary of the BMPs and the parameter changed in ArcSWAT are presented in Table 4.5.

Table 4.5: Representation of BMPs in SWAT

BMPs	Function	Representative SWAT Parameters		
		Input variable	Value with no BMP	Value with BMP
1.Grassed waterway	Channel cover increase	CH_COV2.rte	0.58	0
	Decrease channel erodibility	CH_ERODMO.rte	0.46	0
	Channel roughness increase	CH_N2.rte	0.10	0.24
2.Parallel terrace/Stone bunds	Reduce overland flow	CN2.mgt	Assigned By SWAT	Reduced by 5
	Decrease sheet erosion	USLE_P.mgt	0.21	0.10
	Reduce slope length-removed	SLSUBBSN.hru	Assign by SWAT	No change
3.Field border or vegetative filter strips	Increase sediment trapping	FILTERW.hru	0.0	5m, 10m
4.Grade stabilization structure	Reduce gully erosion	CH_ERODMO.rte	0.46	0.0
	Reduce slope steepness	CH_S2.rte	Assign by SWAT	No change
5.Recharge structures	Create infiltration or percolation scenario	CH_K1.sub	0.0	25 mm/hr.
	Reduce peak runoff and energy of stream	CH_N1.sub	0.92	0.08
6.Forestation	Reduces runoff and erosion.	Assigned by land use change		

4.6 BMPs Evaluation

The effect of BMPs implementation was evaluated in terms of percentage reduction in sediment yield at the outlet (in Ton/ha/yr.) from base line. Average annual sediment yield under each scenario of BMPs was noted and the percentage reduction in sediment yield was calculated as using the formula $\% \boldsymbol{reduction} = \mathbf{100} * \frac{(\boldsymbol{Baseline - BMP})}{\boldsymbol{Baseline}}$. Simulations by developed model with calibrated parameter was used as baseline for estimation of percentage reduction in sediment yield. Rank of BMPs based on percentage reduction sediment yield in comparison to baseline condition was prepared and theoretically most effective BMP was suggested for field application.

CHAPTER 5
RESULTS AND DISCUSSION

This chapter encompasses analysis and discussion of the results obtained from the present study including sensitivity analysis of the SWAT model parameters and its calibration and validation. Graphical representation of discharge and sediment yield, spatial distribution of water balance component and sediment yield, effectiveness of BMPs on sediment reduction and runoff generation are also included in this chapter.

5.1 Sensitivity analysis

Based on SWAT, SWAT CUP user manual and as suggested by Abbaspour et al. (2007), a list of parameters sensitive to discharge/flow and sediment were prepared. One at a time sensitivity analysis were performed in SWAT CUP and 22 parameters sensitive to flow and sediment were selected for calibration and validation. Further, for model calibration and validation in the beginning, as flow is the main controlling variable, parameters sensitive to flow only were selected (Abbaspour et al., 2007) and the calibration was done. After calibrating for flow, keeping flow parameter ranges as obtained from flow calibration, parameters sensitive to sediment were added again as suggested by Abbaspour et al. (2007). After that, global sensitivity analysis was carried out (Abbaspour, 2015). List of parameters sensitive to flow and sediment with SWAT CUP fitted values and rank from global sensitivity analysis are presented in Table 5.1.

OAT sensitivity analysis is done for the identification of parameters that are sensitive to the model developed for the study area and the global sensitivity analysis evaluates the effects of relative changes on a number of distributed parameters (selected from OAT sensitivity analysis) on the model output and ranks the parameters based on their final effects. global sensitivity analysis gives t stat and p value. Higher the absolute t-stat value and smaller p-value, the parameters are assumed to be more sensitive. Rank 1 is for the maximum effect and lowest rank equal to the number of parameters chosen is for smallest effect.

The results of sensitivity analysis presented in Table 5.1 shows that USLE support practice factor (USLE_P) is the most sensitive parameter followed by aquifer percolation coefficient and (RCHRG_DP) and so on. Other parameters like average channel slope along channel length (CH_S1), ground water delays (GW_DELAY), manning's n value for main channel (CH_N2), SCS runoff curve number (CN2), Peak rate adjustment factor for sediment routing in the main channel (PRF_BSN), average slope of main channel (CH_S2), average slope steepness (HRU_SLP), soil erodibility factor (USLE_K) are also ranked to top sensitive parameters and average slope length (SLSUBBSN), soil bulk density (SOL_BD), effective hydraulic conductivity in tributary channel alluvium (CH_K1), soil hydraulic conductivity (SOL_K1) and channel cover factor (CH_COV2) are ranked as least sensitive parameters and lie in the bottom part of the sensitivity table.

5.2 Calibration and validation

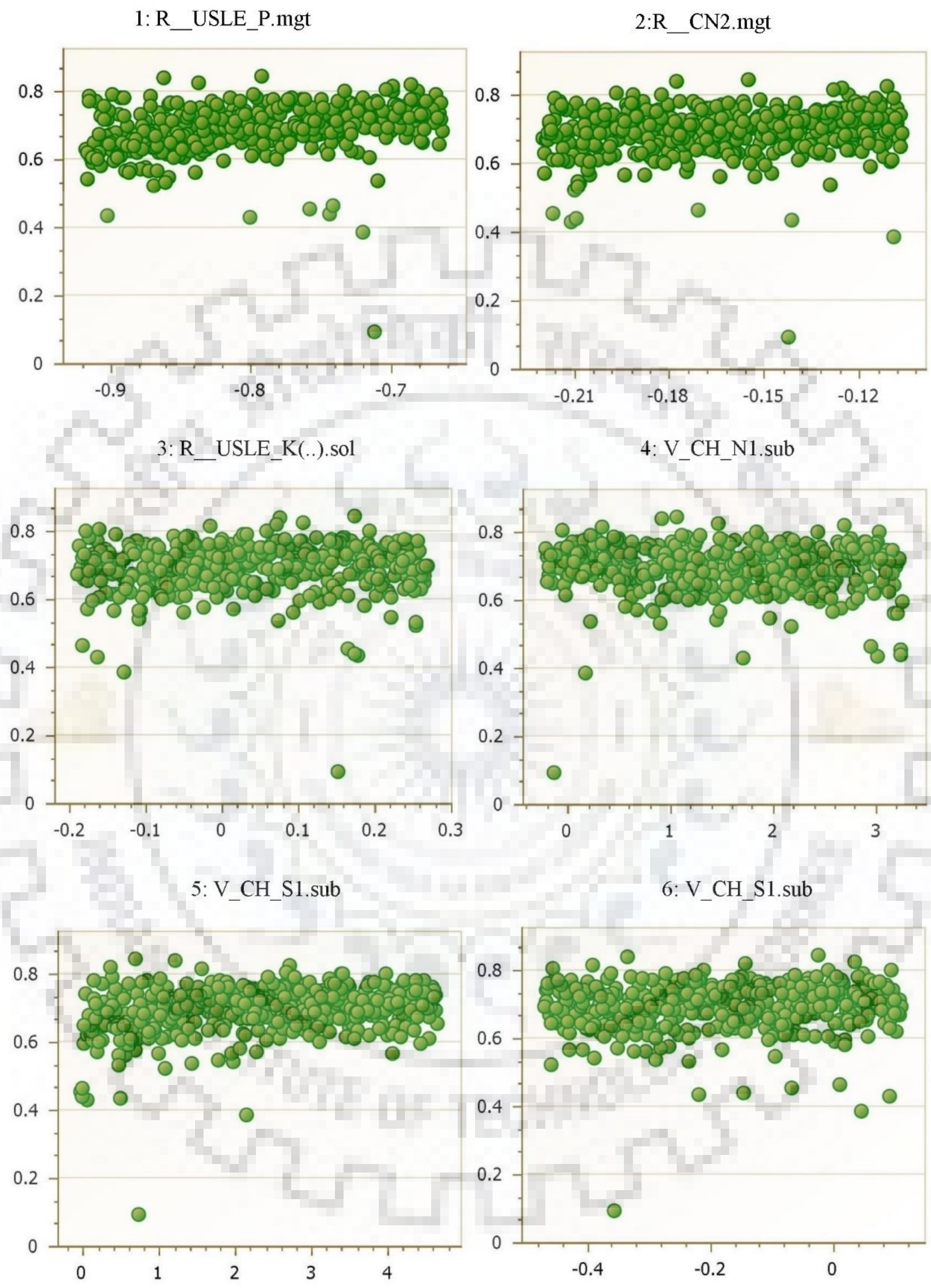
In this study, SWAT model was run for the period 2000 to 2013, taking three years as warm up period. Before calibration, inconsistency in the hydrological data of the years 2003- 2013 was checked by mass curve method and it was found that the data of the years 2010 to 2013 were inconsistent. The inconsistency in data set may be mainly due to error in rating curve. Thus, model was calibrated and validated using shorter data sets and in this context, Cui et al., (2015) studied the effect of duration of the observed dataset available to calibrate the distributed hydrological model SWAT in the Heihe Basin of China. They made comparison of results from calibration of single year and three years datasets of discharge and the result obtained were same for the both cases of datasets i.e. one year and three-year data sets. And it indicates that one can use discharge data of limited durations to calibrate the SWAT model effectively in poorly gauged basins or in case of basin with data availability for shorter period due to erroneous data recording. Thus, SWAT model was calibrated and validated using monthly data sets of shorter duration i.e. from 2003 to 2006 (four years - calibration) and from 2007 to 2009 (three years - validation).

Table 5.1: Final calibrated parameter with their global sensitivity rank and calibrated parameter with range.

Rank	Parameter	Physical description	Range of Calibrated parameter			t-stat	P value	Sensitive to
			Min	Max	Fitted			
1	R_USLE_P.mgt	USLE support Practice factor	-0.92	-0.66	-0.79	6.83	0.00	Sediment
2	V_RCHRG_DP.gw	Aquifer Percolation coefficient	0.25	0.90	0.39	-6.78	0.00	Flow
3	V_CH_S1.sub	Average channel slope along channel length, mm/meter	-0.03	4.66	0.68	5.79	0.00	Sediment
4	V_GW_DELAY.gw	Ground water delays, Days	32.70	110.93	32.99	-5.61	0.00	Flow
5	V_CH_N2.rte	manning's n value for the main channel	0.01	0.30	0.10	-3.79	0.00	Sediment
6	R_CN2.mgt	SCS Runoff curve number for moisture condition II	-0.22	-0.11	-0.16	3.64	0.00	Flow, Sediment
7	V_PRF_BSN.bsn	Peak rate adjustment factor for sediment routing in the main channel.	0.20	1.50	1.39	2.74	0.01	Sediment
8	V_CH_S2.rte	Average slope of main channel m/m	0.24	0.68	0.57	1.67	0.10	Sediment
9	R_HRU_SLP.hru	Average slope steepness, m/m	-0.15	0.02	-0.14	1.44	0.15	Flow, Sediment
10	R_USLE_K(..).sol	Soil erodibility factor	-0.19	0.27	0.17	1.43	0.15	Flow, Sediment
11	R_SOL_Z(..).sol	Depth from soil surface to bottom of layer, mm.	-0.03	0.42	0.23	-1.40	0.16	Flow, Sediment
12	V_ADJ_PKR.bsn	Peak rate adjustment factor for sediment routing in the sub basin (tributary channels)	0.50	2.00	1.59	1.35	0.18	Sediment
13	V_CH_ERODMO(..).rte	Monthly channel erodibility factor	0.40	0.60	0.46	-1.30	0.19	Sediment
14	V_CH_N1.sub	manning's n value for tributary channel.	-0.21	3.26	1.06	-1.17	0.24	Sediment
15	V_OV_N.hru	manning's n value for overland flow	0.01	5.00	1.81	1.09	0.28	Sediment
16	V_ESCO.hru	soil evaporation compensation factor	0.09	0.90	0.71	0.98	0.33	Flow
17	V_CANMX.hru	maximum canopy storage	43.24	89.76	43.41	0.76	0.45	Flow
18	R_SLSUBBSN.hru	average slope length	-0.35	0.05	-0.18	0.75	0.45	Sediment
19	R_SOL_BD(..).sol	Soil bulk density	-0.47	0.11	-0.02	0.73	0.46	Flow, Sediment
20	V_CH_K1.sub	Effective hydraulic conductivity in tributary channel alluvium.	0.00	10.00	1.84	-0.41	0.68	Sediment
21	R_SOL_K(..).sol	Soil hydraulic conductivity	-0.94	0.22	-0.72	0.17	0.87	Flow, Sediment
22	V_CH_COV2.rte	Channel cover factor.	0.36	1.00	0.58	0.07	0.94	Sediment
Note: v_ means parameter value is to be replaced by given value within the range and r_ means the parameter value is multiplied by (1+ the give value)								

Generally, calibration is started taking default range of parameter and calibration process is stopped after getting the performance evaluation statistics within acceptable range. Dotty plots guide us to select parameter value or it relative change within a range (minimum and maximum value or relative change) for next iteration so that best calibration values of parameters and performance statistics will be obtained.

In this study, the relative value of USLE_P is giving good results between the range of -0.92 to -0.66 (relative change) of default value and most of the distribution points are scattered above the threshold value of objective function (0.5). In similar way, we can see the distribution of values within a given range with respect to objective function for other parameters also.


1: R__USLE_P.mgt
0
0.2
0.4
0.6
0.8
-0.9
-0.8
-0.7
2:R__CN2.mgt
0
0.2
0.4
0.6
0.8
-0.21
-0.18
-0.15
-0.12
3: R__USLE_K(..).sol
0
0.2
0.4
0.6
0.8
-0.2
-0.1
0
0.1
0.2
0.3
4: V_CH_N1.sub
0
0.2
0.4
0.6
0.8
0
1
2
3
5: V_CH_S1.sub
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0.2
0.4
0.6
0.8
0
1
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6: V_CH_S1.sub
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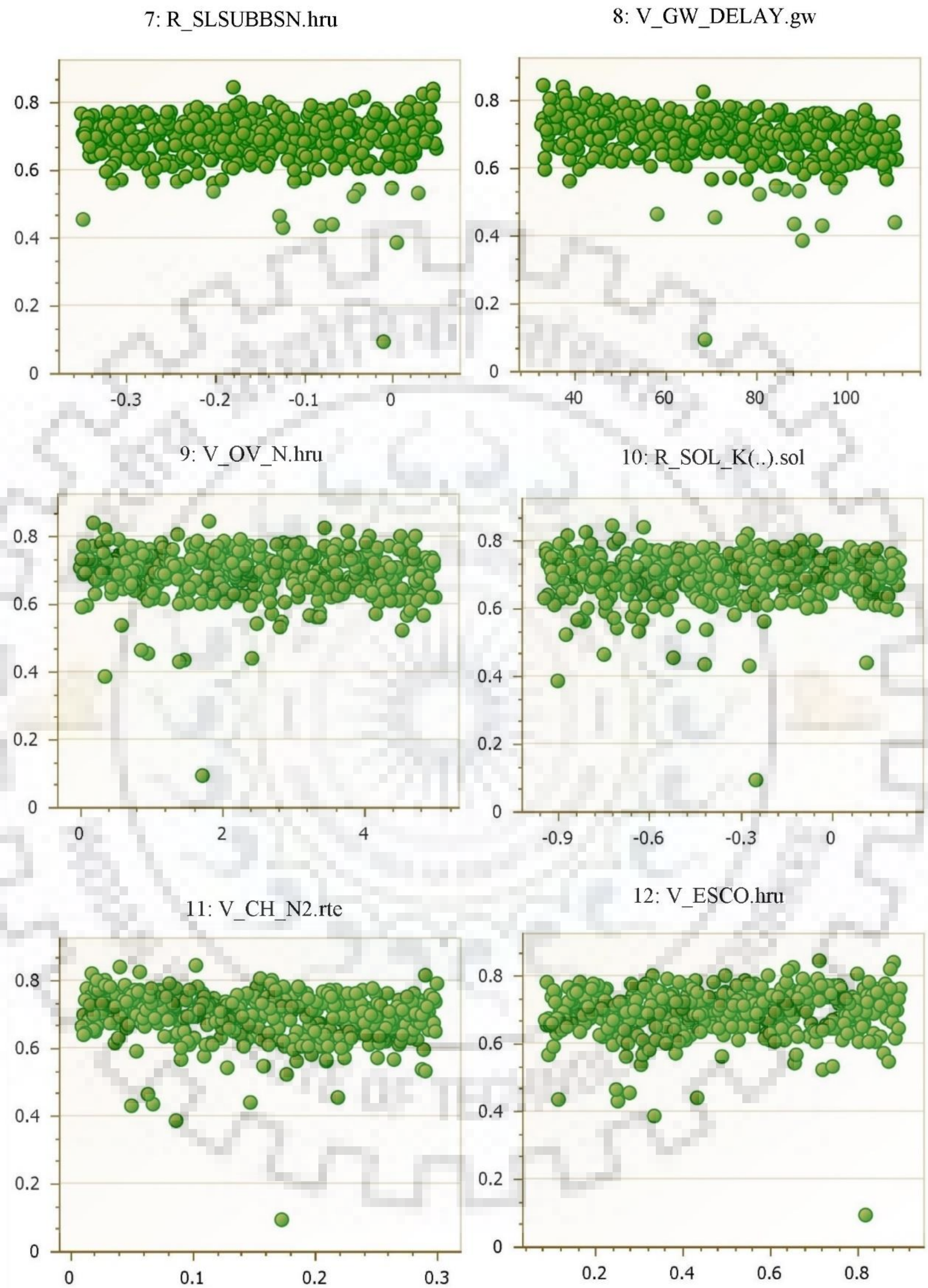
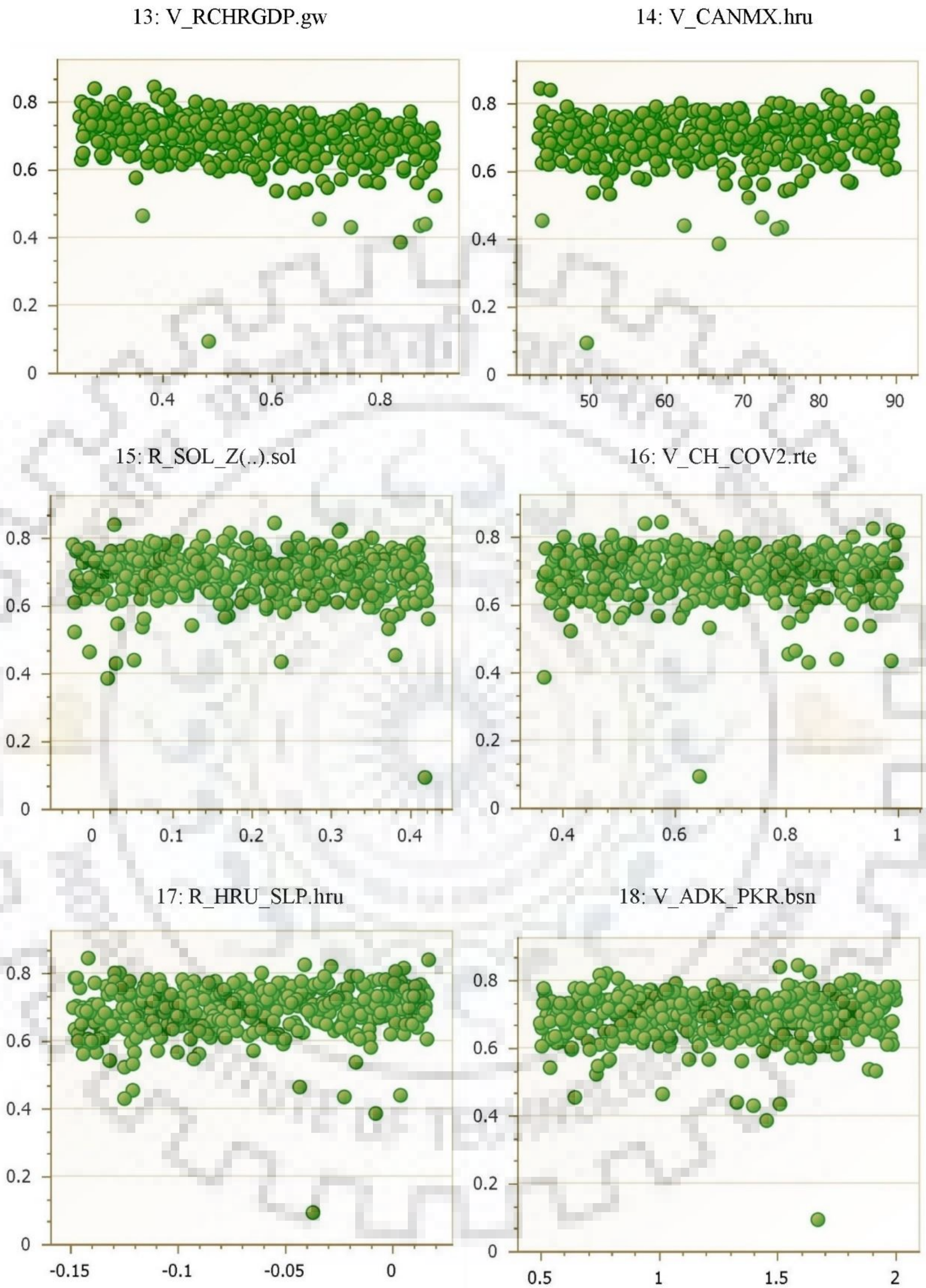
-0.2
0


7: R_SLSUBBSN.hru
8: V_GW_DELAY.gw
9: V_OV_N.hru
10: R_SOL_K(..).sol
11: V_CH_N2.rte
12: V_ESCO.hru
0.8
0.6
0.4
0.2
0
-0.3 -0.2 -0.1 0
40 60 80 100
0 2 4
-0.9 -0.6 -0.3 0
0 0.1 0.2 0.3
0.2 0.4 0.6 0.8


13: V_RCHRGDP.gw
14: V_CANMX.hru
15: R_SOL_Z(..).sol
16: V_CH_COV2.rte
17: R_HRU_SLP.hru
18: V_ADK_PKR.bsn
0
0.2
0.4
0.6
0.8
0.4 0.6 0.8
50 60 70 80 90
0 0.1 0.2 0.3 0.4
0.4 0.6 0.8 1
-0.15 -0.1 -0.05 0
0.5 1 1.5 2

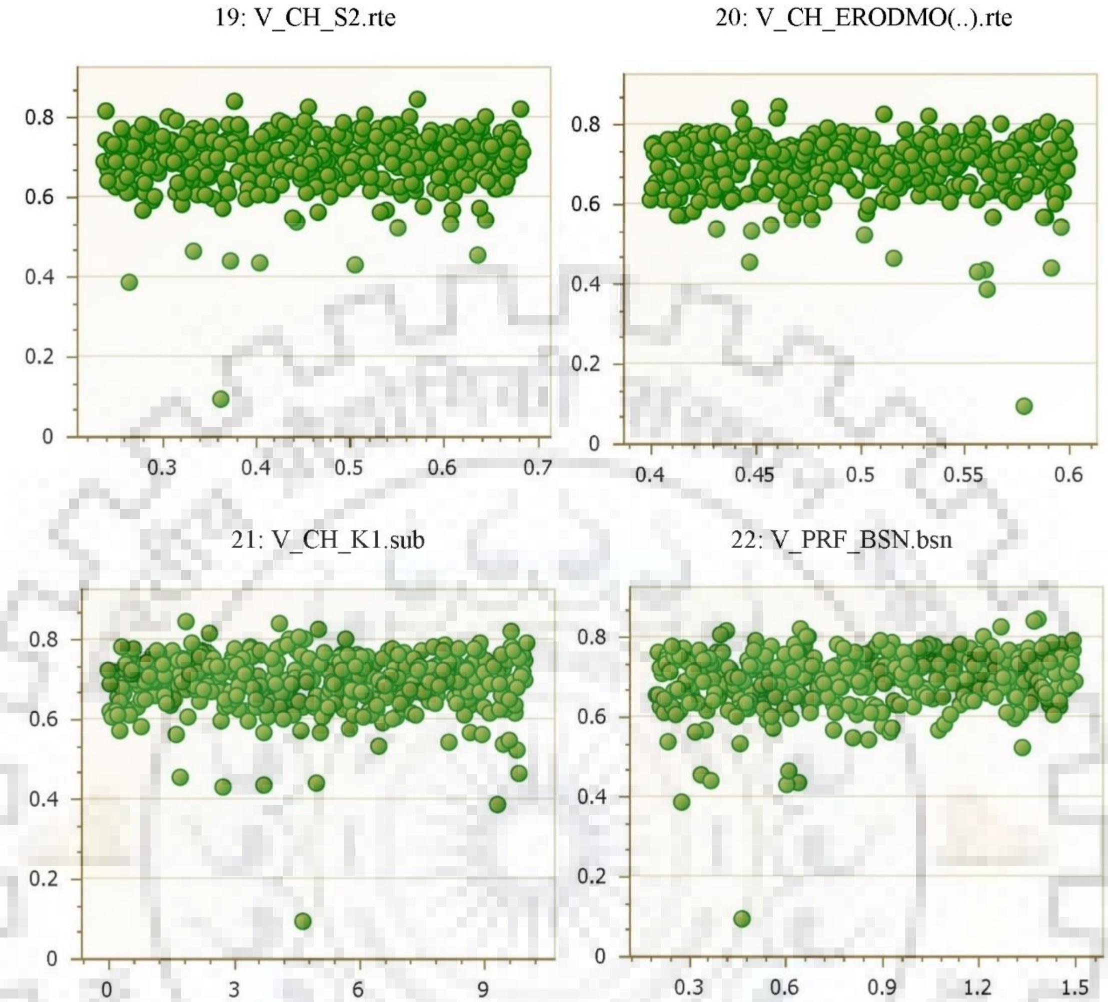


Figure 5.1: Dotty plots of parameter values vs objective function

Moriasi et al., (2007) recommended a statistics for SWAT model performance ratings as presented in Table 5.2 based on Saleh et al., (2000) and Van Liew et al., (2007). The results of calibration and validation obtained and the performance rating based on the SWAT model performance rating criteria is provided in Table 5.2 and Figure 5.3.

Table 5.2 Monthly time step statistics for general performance evaluation of SWAT

Rating	NSE	PBIAS		RSR	R^2
		Stream flow	Sediment		
Very good	0.75<NSE ≤1.0	< ±10	< ±15	0 < RSR < 0.5	>0.5
Good	0.65<NSE≤0.75	±10 < PBIAS< ±15	±15 < PBIAS< ±30	0.5 < RSR < 0.6	
satisfactory	0.5<NSE≤0.65	±15 < PBIAS< ±25	±30 < PBIAS< ±55	0.6 < RSR < 0.7	
unsatisfactory	NSE ≤ 0.50	PBIAS < ±25	PBIAS < ±55	RSR > 0.70	<0.5

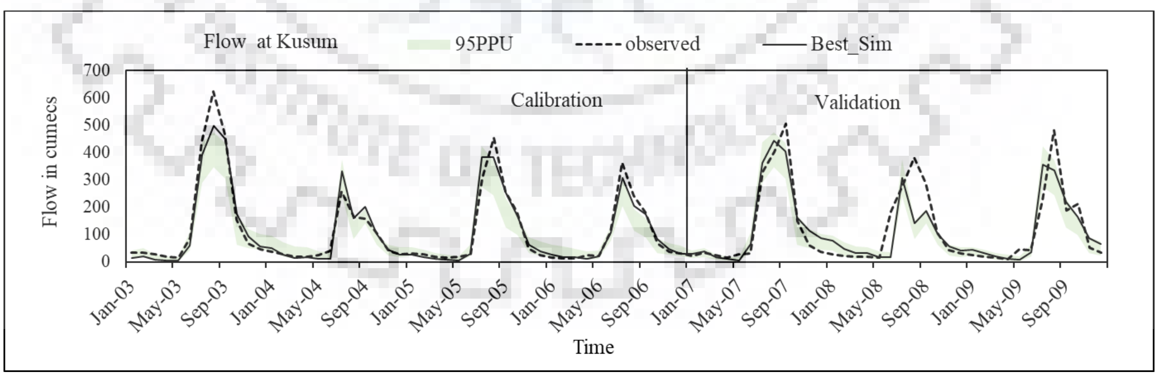
Table 5.3: Results of Calibration (2003-06) and Validation (2007-09)

Parameters	Kusum (Flow)		Bagasoti (Flow)		Bagasoti (sediment yield)	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
p- factor	0.83	0.67	0.73	0.67	0.96	0.86
r- factor	0.40	0.42	0.41	0.46	0.64	1.12
R^2	0.96, Very Good	0.78, Very Good	0.90, Very Good	0.74, Very Good	0.71, Very Good	0.69, Very Good
NSE	0.95, Very Good	0.78, Very Good	0.90, Very Good	0.73, Good	0.68, Good	0.69, Good
PBIAS	4.70, Very good	5.3, Very Good	4.70, Very good	0.90, Very Good	15.10, Good	-9.70, Very Good
RSR	0.22, Very good	0.47, Very good	0.32, Very good	0.52, good	0.57, Good	0.56, Good

Based on the values of R2, NSE, PBIAS and RSR and performance ratings provided in Table 5.3, it is confirmed that model performance was good for calibration and validation.

5.3 Graphical representation of discharge and sediment yield

The SWAT model performance can be visualized by graphical way in the form of 95 PPU. The 95 PPU for sediment and discharge obtained from SWAT CUP (calibration and validation) for different stations are shown in Figure 5.2.



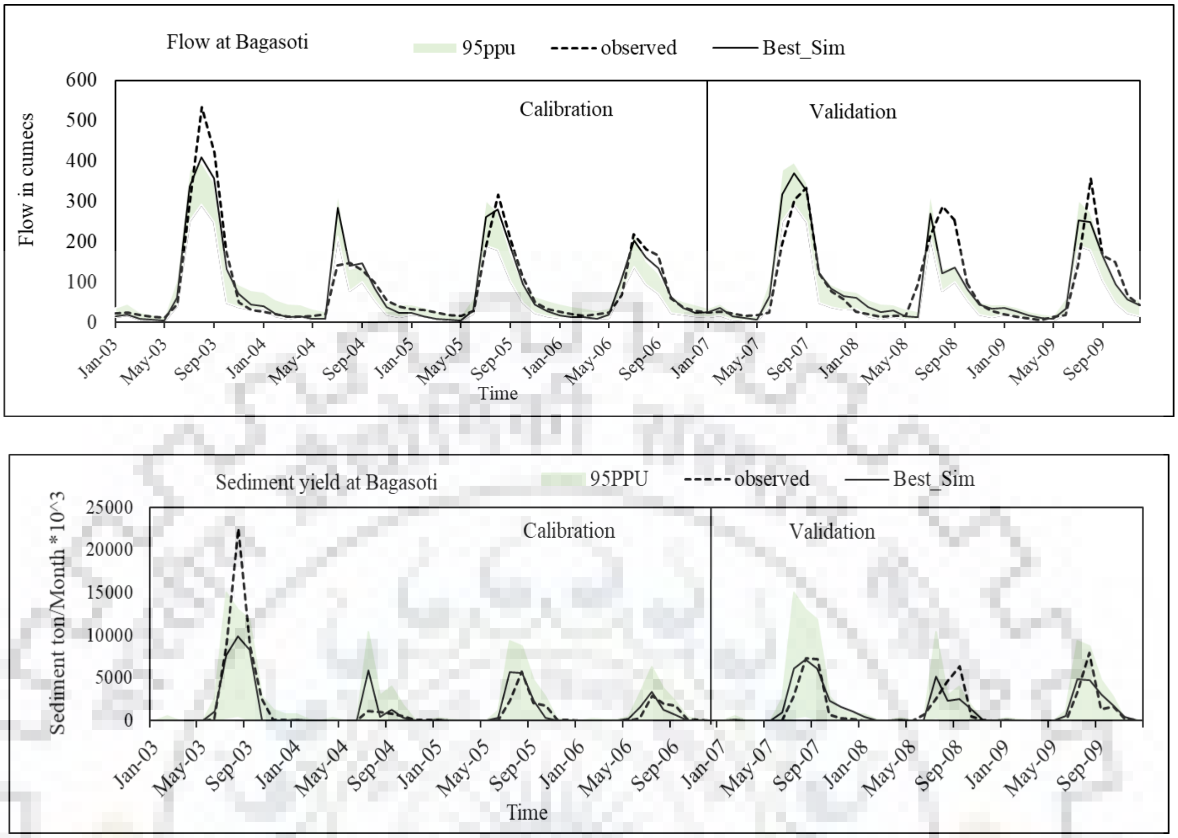


Figure 5.2: 95 PPU plots for stream flow and sediment yield

The observed and the simulated average annual value of flow and sediment yield of different outlets for calibration and validation period are presented in Table 5.4 and Table 5.5. From the observed and simulated average annual discharge presented in Table 5.4, it is seen that the discharge is underestimated with negative values of percentage deviation. And, average annual sediment yield (in ton) at Bagasoti outlet and deviation of simulated sediment yield from observed values are presented in Table 5.5 the percentage deviations are within acceptable range for both calibration and validation.

Statistical as well as geographical evaluation showed that the simulation of stream flow and sediment yield during calibration is good and validation is satisfactory but the 95 PPU plots shows that SWAT underestimated runoff most of the time during high flow (peak) period. This may be because of adoption of SCS Curve Number (CN) method for calculation of runoff. SCS CN method determines CN values considering moisture content of the soil of previous day and without considering the change in moisture content due to same day rain fall. Another reason for under estimation of peak runoff may be due to taking sum of all the rainfall occurring in single day and assuming it as single rainfall event in SCS CN method. (Kim and Lee 2008), (Gull et al. 2017).

Table 5.4 : Annual average simulated and observed discharge

Station	Calibration/Validation	AOF, m^3/s	ASF, m^3/s	% deviation	Remarks
Kusum	Calibration	114.27	108.86	-4.7	
	Validation	122.96	116.50	-5.3	
Bagasoti Gaun	Calibration	89.34	85.17	-4.7	
	Validation	93.05	92.23	-0.9	
AOF= Average Observed flow, ASF= Average simulated flow.					

Table 5.5: Annual average simulated and observed sediment yield

Station	Calibration/Validation	AOSY, Ton/year	ASF, Ton/year	% deviation	Remarks
Bagasoti Gaun	Calibration	16780978	14252771	-15.1	
	Validation	16169655	17734885	9.7	
AOF= Average Observed sediment yield, ASF= Average simulated sediment yield					

Most of the sediment transport occurs during high flow period so it is difficult but necessary to capture these high flow events during model calibration and validation. Therefore, r-factor for sediment which indicates the thickness of 95PPU envelope obtained were 0.64 (for calibration) and 1.12 (for validation) were quite higher than that of flow but can be accepted. The p-factor, the percentage of observed data enveloped by modelling results obtained, for sediment was 0.96 for calibration and 0.86 for validation which is also acceptable.

5.4 Water Balance and Sediment Yield

Water balance is the key concern and driving force irrespective of the problems that are studied in SWAT (Neitsch et al. 2011). In this study, once the model was calibrated and validated successfully, model was re-run for the period 2000-2013 taking the parameters values of best simulation during calibration and SWAT outputs were analyzed to carry out the water balance study. The hydrological cycle of the watershed obtained from SWAT model is shown in Figure 5.3. The monthly breakup of annual water balance component and sediment yield are shown in Table 5.6 and the components with balance closure is shown in Figure 5.4. From the water balance study, it is seen that average annual precipitation of the basin is 1677 mm and 48.60 % (815 mm out off 1677mm) of rainfall goes as annual evapotranspiration from the basin and this evapotranspiration value is quite high. The surface runoff from the basin is 273.00 mm, lateral sub surface flow or interflow accounts 155.00 mm and base flow or return flow is 269.00 and the total annual water yield is 854 mm. The total water volume available from the basin is 4.50 billion cubic meters. The amount of water that enters to deep aquifer is 169.00 mm and this amount of water also contributes to streamflow somewhere out of the watershed.

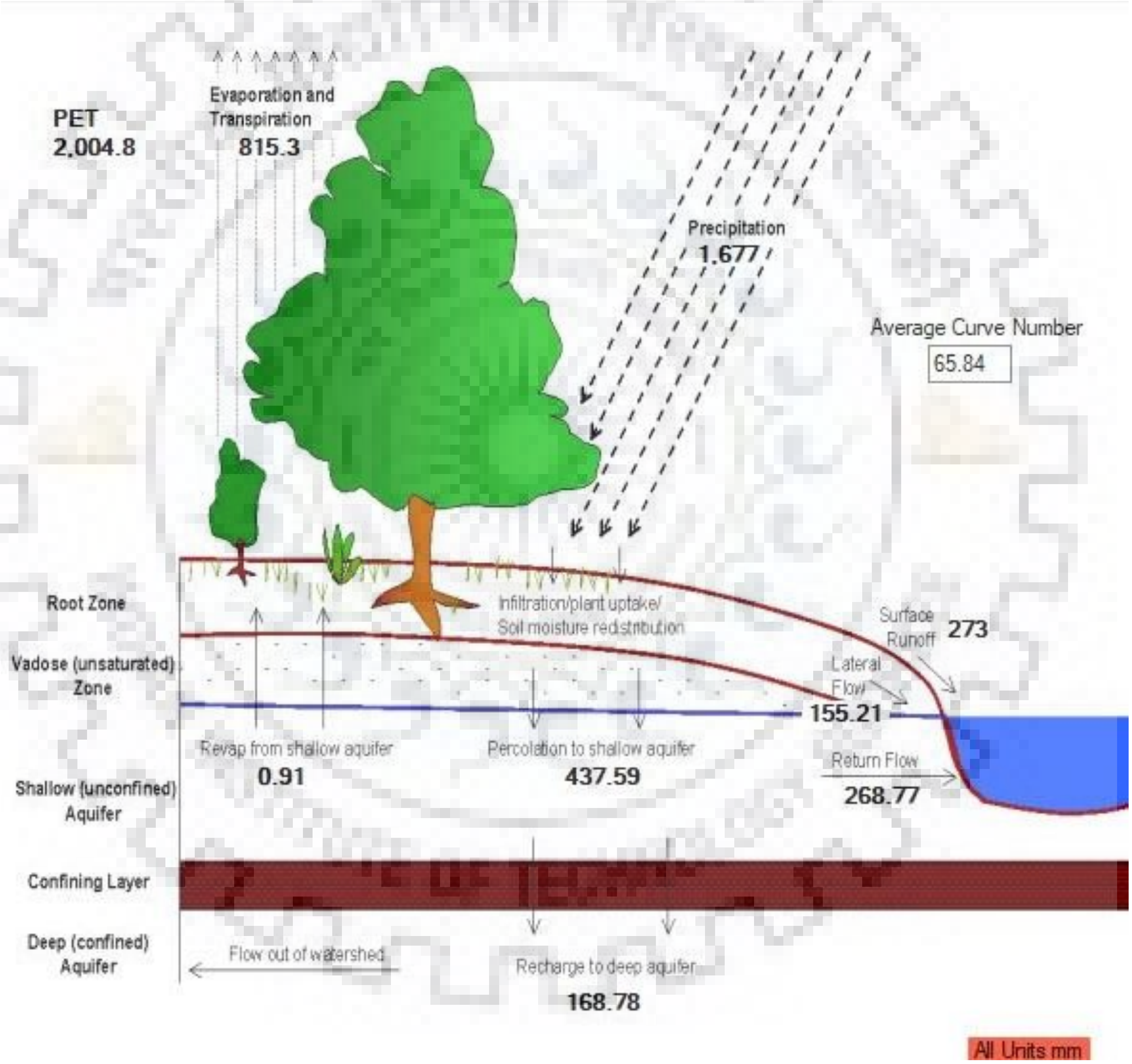


Figure 5.3: Hydrological cycle obtained from SWAT

Table 5.6: Monthly distribution of yearly water balance components

Month	Rainfall, mm	SURQ, mm	GWQ, mm	LATQ, mm	ET, mm	Water Yield, mm	Sediment, Ton/Ha
Jan	22	0.6	3.1	1.1	18.0	19.0	0.09
Feb	39	3	1.4	2	31	16	0.31
Mar	22	0	1.1	1	40	11	0.06
Apr	44	0	0.5	1	58	8	0.05
May	120	2	0.3	2	105	9	0.19
Jun	259	28	4.1	14	119	47	1.82
Jul	483	104	36.7	49	119	194	6.04
Aug	361	76	70.0	43	110	204	4.73
Sep	250	47	73.8	33	97	177	3.45
Oct	64	11	50.0	7	71	94	0.91
Nov	5	1	20.9	0	29	46	0.01
Dec	6	0	8.6	0	18	29	0.01
Annual	**1677**	**273**	**271**	**155**	**815**	**854**	**17.67**

Also, from the monthly distribution of rainfall and water yield, it is seen that 80 % of rainfall, 90 % of runoff and 73% of water yield occurs during four months of monsoon i.e. from June to September. The Evapotranspiration was also found to be high during monsoon season with highest value 119 mm in the month July and August. Sediment yield shows the proportional pattern with surface runoff. Surface runoff in July and August is 104 mm and 76 mm, accounting higher sediment yield of 6.04 and 4.73 Ton/Ha. The annual sediment yield of the study area is 17.67 Ton/ha/year and according to classification criteria mentioned by Himanshu et al. (2017) as presented in Table 5.7, the study area falls under high erosion class and needs attention on implementation of BMPs for erosion control. The average monthly sediment yield was obtained as shown in Figure 5.5. This shows that the average sediment yield is high during monsoon season i.e. from June to September when stream flow and rainfall are also high. The maximum sediment yield was obtained in July which is 6.04 Ton/Ha and minimum at November and December with 0.01 Ton/Ha.

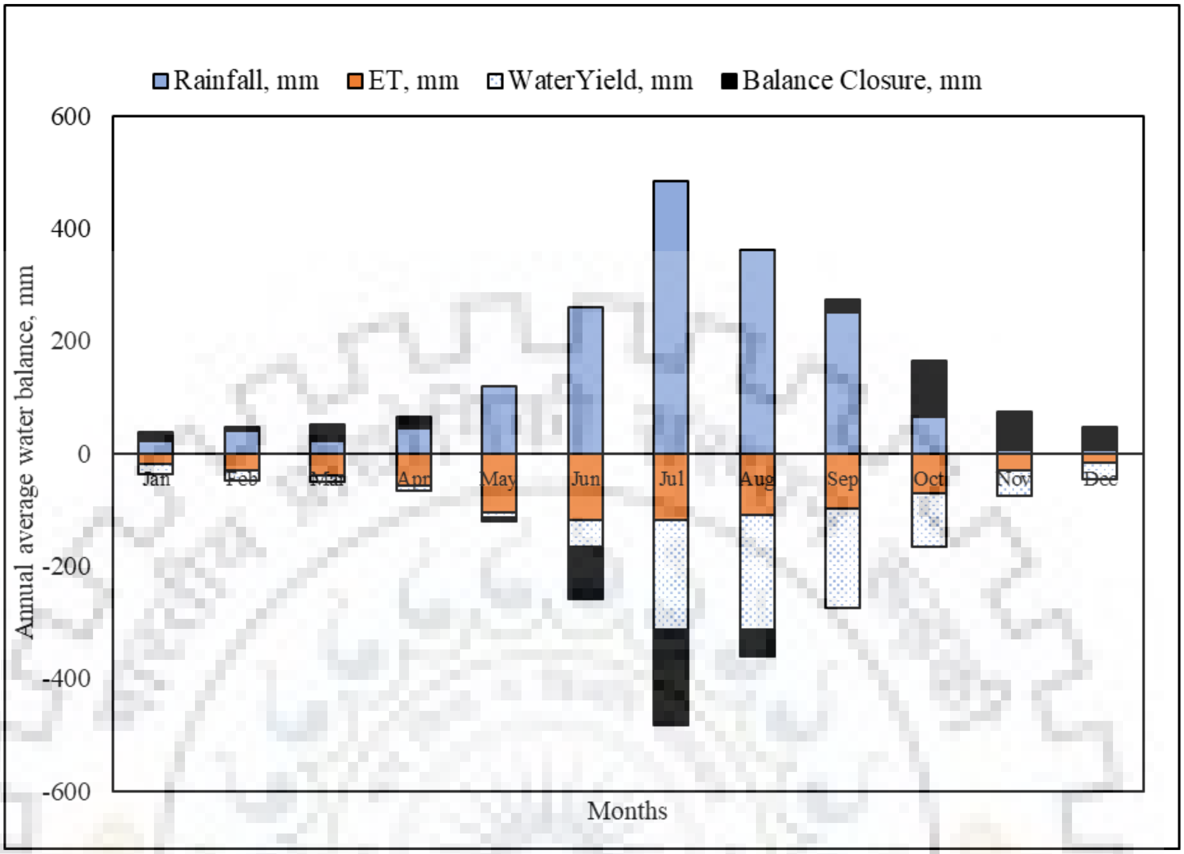


Figure 5.4: Monthly average values of water balance component

Table 5.7: Area under different classes of soil erosion

SN	Sediment yield (Ton/Ha/year)	Area, Km^2	% area	Erosion class	Remarks
1	0-5	984	19	Slight	
2	5-10	588	11	Moderate	
3	10-20	1987	38	High	
4	20-40	1082	20	Very High	
5	40-80	641	12	Severe	
6	>80	5282	100	Very Severe	

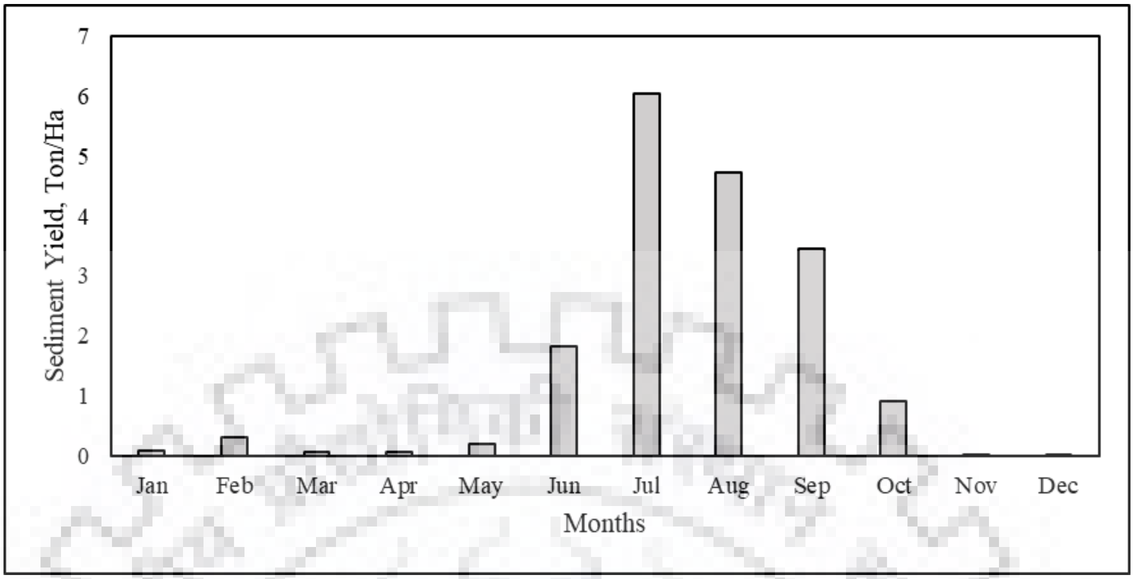


Figure 5.5: Average monthly Sediment yield

5.5 Spatial Distribution of Water Balance Component and Sediment Yield

SWAT is a powerful spatial analysis tool that helps in visualization of water balance component and average sediment yield distribution in sub basin or even in HRU level giving the idea of high rainfall, evapotranspiration, water yield and erosion prone areas. This helps in planning of some management option to control erosion from specific erosion prone areas. The spatial visualization of sub basin wise water balance components is shown in Figure 5.6 to 5.8 and that of sediment yield in tons/ha is shown in Figure 5.10. Similarly sub basin wise water balance components are shown in Table 5.8 and that with balance closure is shown in Figure 5.9.

Table 5.8: water balance components and sediment generated from sub basins

Sub basin	Area, Km^2	Rainfall, mm	SURQ, mm	GWQ, mm	LATQ, mm	ET, mm	Water Yield, mm	Sediment, Ton/Ha
1	290.81	1302.02	108.65	221.55	150.26	682.97	619.37	11.64
2	198.64	1302.02	114.82	237.34	132.37	668.96	633.37	9.24
3	257.29	1423.66	136.74	189.03	169.90	806.69	611.55	22.32
4	206.74	1260.49	111.05	172.10	126.26	739.85	506.94	7.49
5	193.05	1088.51	126.19	103.68	95.57	694.43	385.24	10.14
6	640.99	2513.25	432.15	513.33	386.78	854.12	1646.74	51.08
7	221.02	2513.25	421.08	516.97	381.84	863.78	1636.55	28.19
8	296.22	2513.25	454.58	533.11	366.98	819.24	1681.31	28.48
9	258.89	1088.51	152.38	76.06	44.24	763.60	316.12	17.70
10	188.39	1088.51	146.48	118.66	77.49	667.00	411.32	13.69
11	130.96	2251.65	404.70	365.64	212.28	1037.49	1202.89	30.79
12	530.69	1289.29	155.62	143.06	108.64	788.55	493.24	13.52
13	176.27	2251.65	465.21	382.60	142.52	1018.92	1220.50	25.29
14	260.79	1535.38	244.93	191.54	66.31	909.70	619.30	16.82
15	754.57	1221.96	229.17	135.69	17.86	755.21	464.68	2.82
16	228.93	1221.96	263.47	126.69	16.10	737.21	482.71	3.06
17	264.36	2251.65	406.41	414.38	125.61	1042.90	1196.15	16.20
18	182.47	2251.65	423.51	428.56	88.16	1040.19	1198.69	9.65

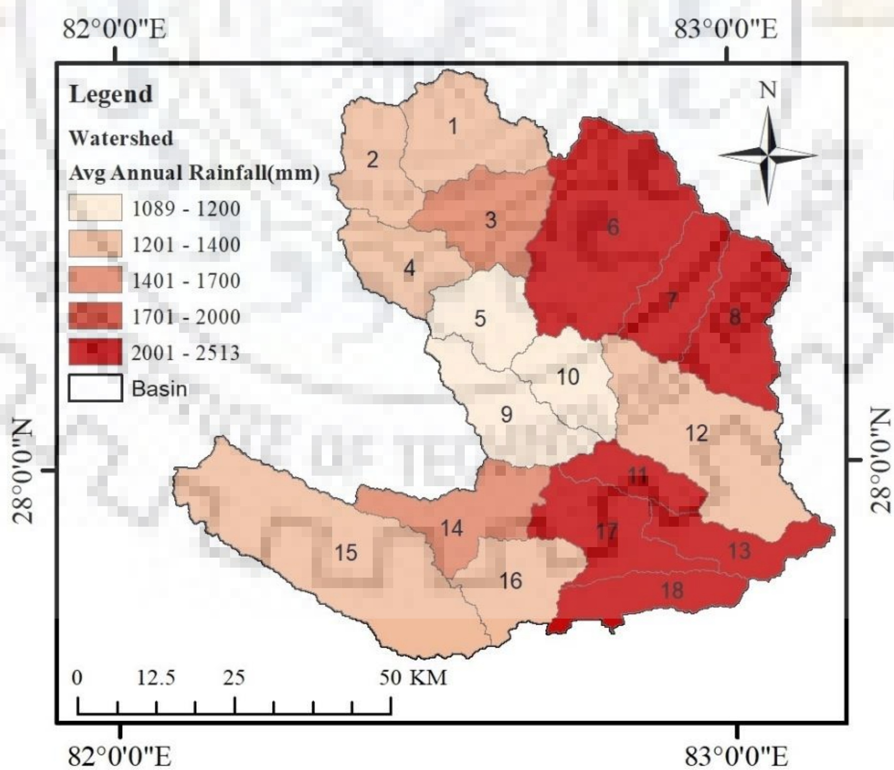


Figure 5.6: Average annual rainfall distribution within the watershed

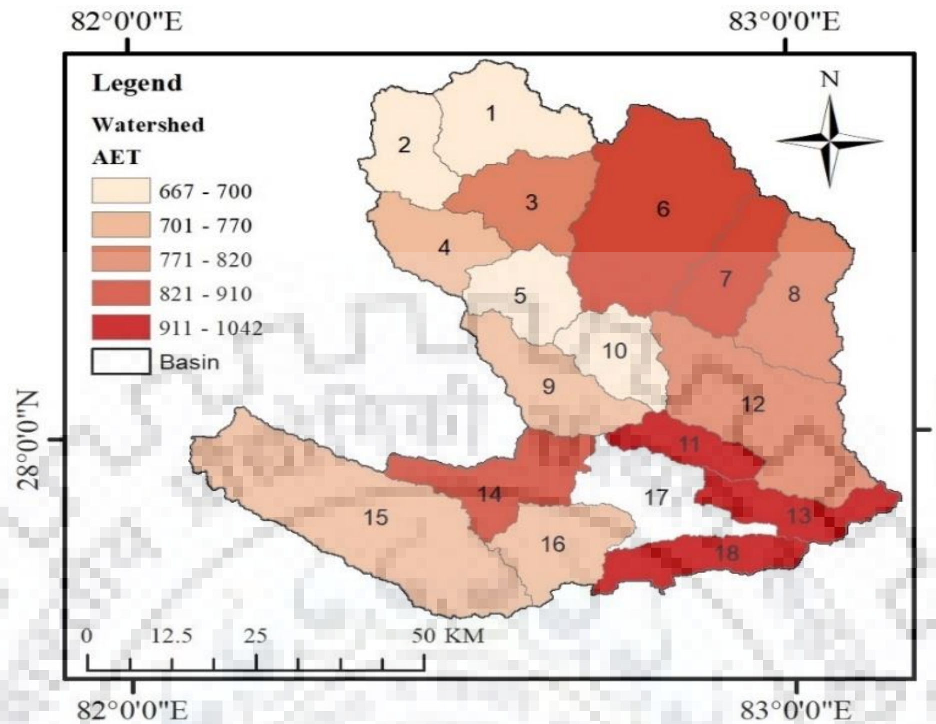


Figure 5.7: Average annual AET within the watershed

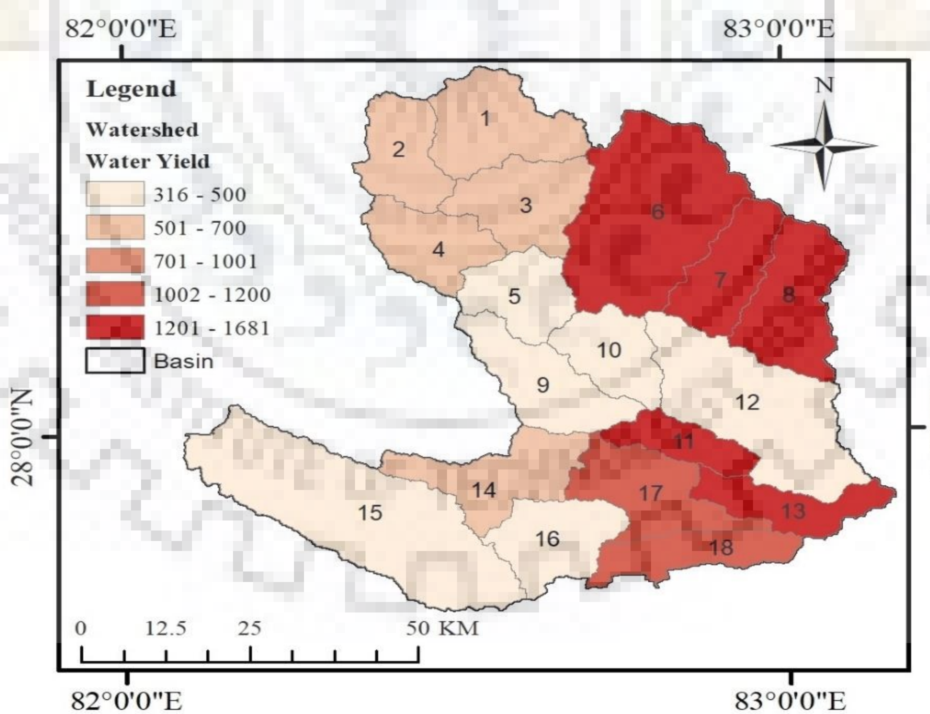


Figure 5.8: Annual average annual water yield within the watershed

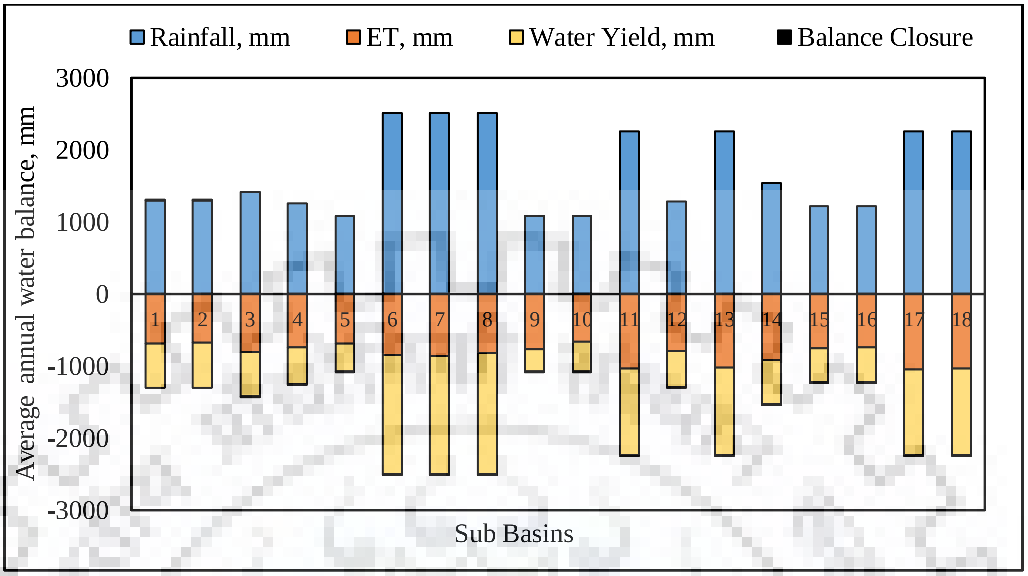


Figure 5.9: Average annual water balance in the sub-basins

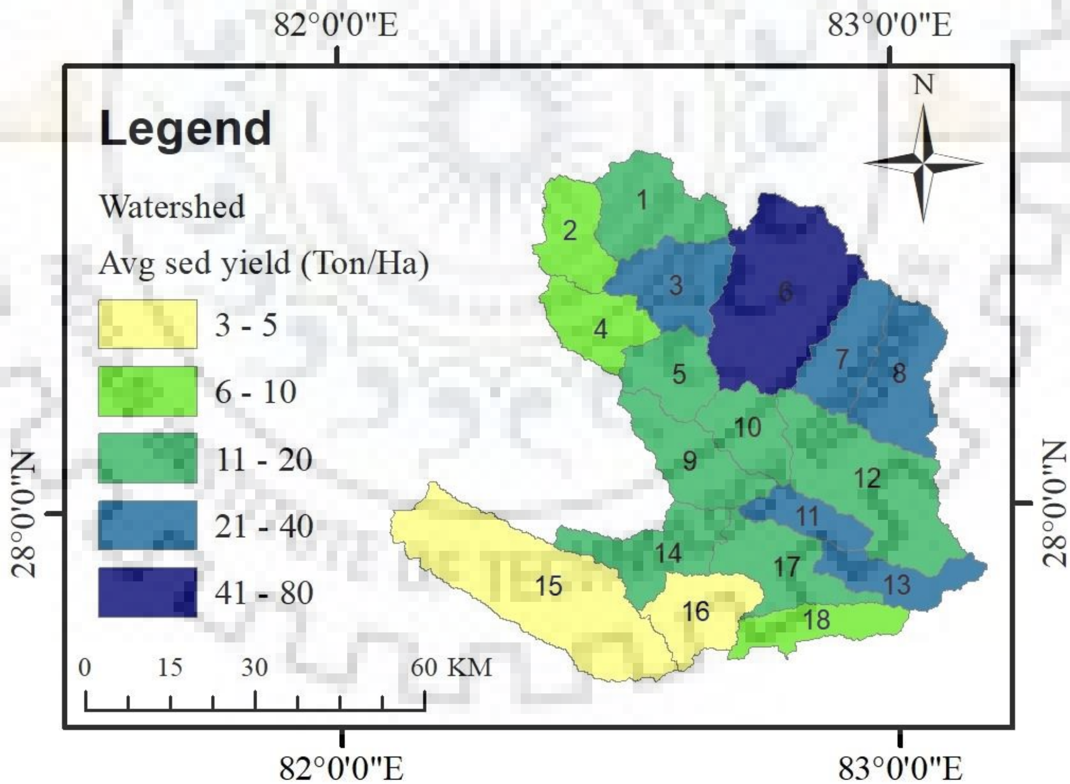


Figure 5.10: Sub basin wise spatial visualization of average annual sediment yield

The Bagasoti sub watershed (sub basin 13 in map) produces more sediment yield per hectare in comparison to Kusum sub watershed (sub basin 15 in map). Sub basin 6 produces high sediment (51 Ton/ha/yr.) compared to other sub basins and need special attention for erosion control. The average annual sediment yield (2003 to 2013) for all 18 sub basins in bar chart is also shown in Figure 5.11.

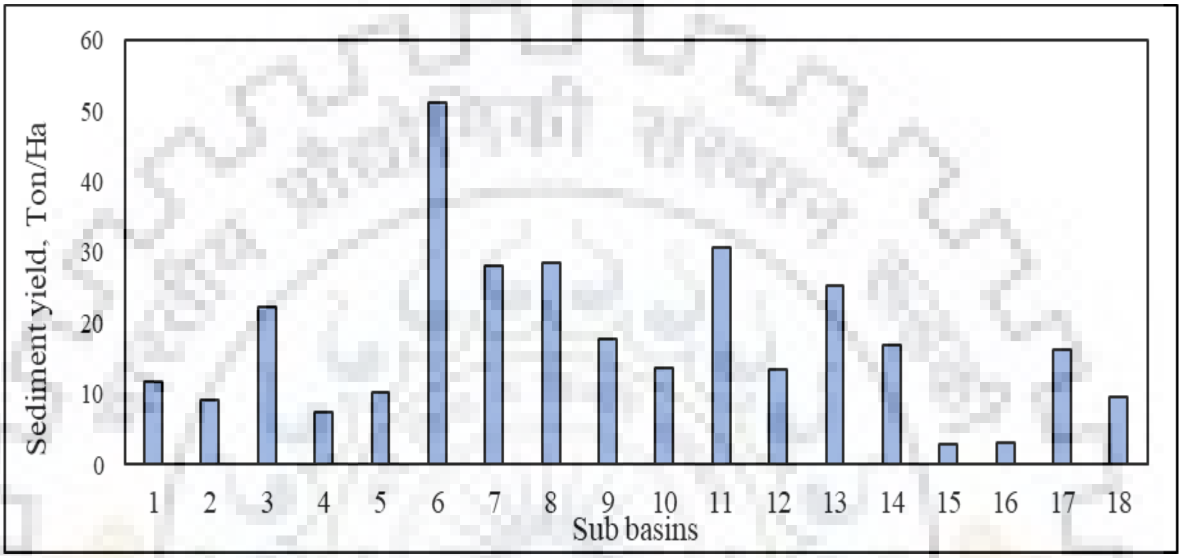


Figure 5.11: Sub basin wise Average annual sediment yield

5.6 Effectiveness of BMPs on reduction of sediment

The effect of BMPs in sediment yield reduction was studied for Bagasoti outlet as it is station used for sediment calibration and validation. The total sediment output at any outlet is obtained from. rch files in SWAT and .rch sediment output is the routed output in the river, which includes not only the output from that sub basin but also all the sub basins above that sub basin, giving total sediment. The monthly average and annual average sediment yield in ton/ha at Bagasoti outlet under different BMPs scenario are shown in tabular form in Table 5.9 and pictorial form in Figure 5.12. And the percentage reduction in average annual sediment yield in Ton/Ha/year due to different BMPs implementation in SWAT model are shown in Figure 5.13.

Table 5.9: Monthly average and Annual average sediment yield at Bagasoti outlet (Ton/Ha) due to different BMPs

Months	Base line	SC1-GWW	SC2-PT/SB	SC3-FS-5m	SC3-FS-10m	SC4-GSS	SC5-PF	SC6-RS
Jan	0.368	0.07	0.37	0.35	0.35	0.25	0.36	0.39
Feb	0.417	0.18	0.33	0.35	0.34	0.35	0.39	0.39
Mar	0.154	0.05	0.14	0.13	0.13	0.12	0.14	0.16
Apr	0.104	0.04	0.09	0.09	0.09	0.08	0.09	0.10
May	0.283	0.15	0.20	0.23	0.21	0.26	0.25	0.25
Jun	3.614	2.31	2.63	2.92	2.77	3.20	3.24	3.23
Jul	13.913	8.40	11.07	11.73	11.23	11.48	12.78	12.85
Aug	13.448	6.46	11.65	11.85	11.49	10.24	12.62	12.84
Sep	11.645	4.87	10.40	10.42	10.15	8.63	10.98	11.36
Oct	4.228	1.02	4.27	3.98	3.92	2.80	4.10	4.49
Nov	1.208	0.08	1.36	1.20	1.20	0.68	1.21	1.38
Dec	0.596	0.04	0.67	0.59	0.59	0.34	0.60	0.68
Annual	49.977	23.68	43.18	43.86	42.46	38.43	46.76	48.10
% Reduction in annual yield		52.62	13.60	12.24	15.04	23.11	6.44	3.75

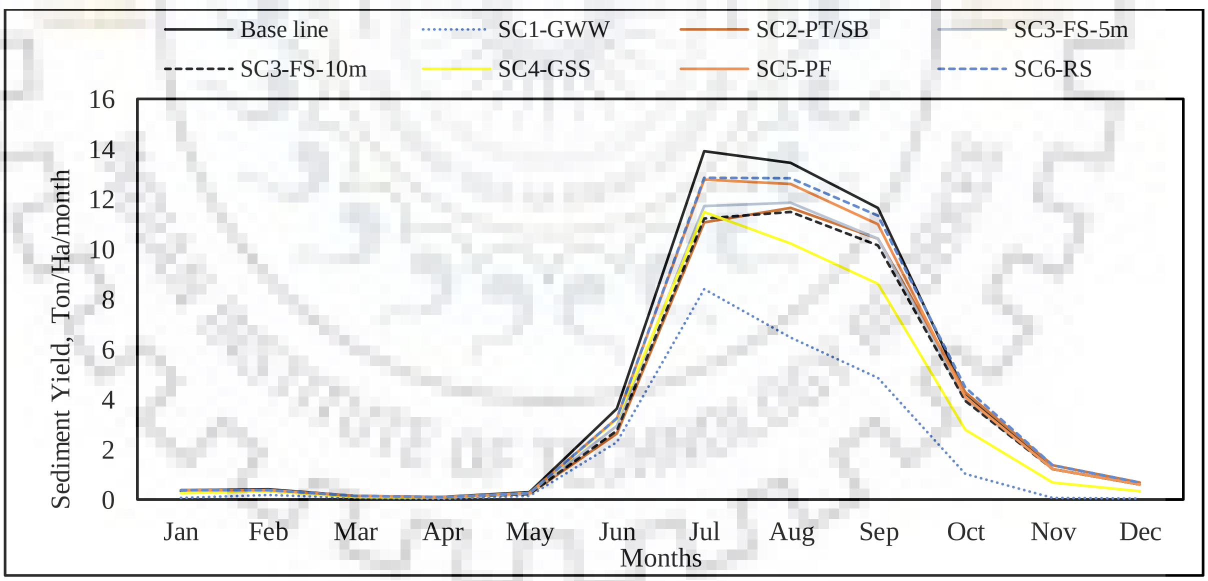


Figure 5.12: Monthly average sediment yield in Ton/Ha at Bagasoti outlet under different BMPs scenario.

Based on percentage reduction in sediment yield, it was found that the grassed water way is most effective with 53% reduction in sediment yield followed by grade stabilization structure with 23 % reduction. The least effective scenario is recharge structures with only 4 % reduction in sediment yield.

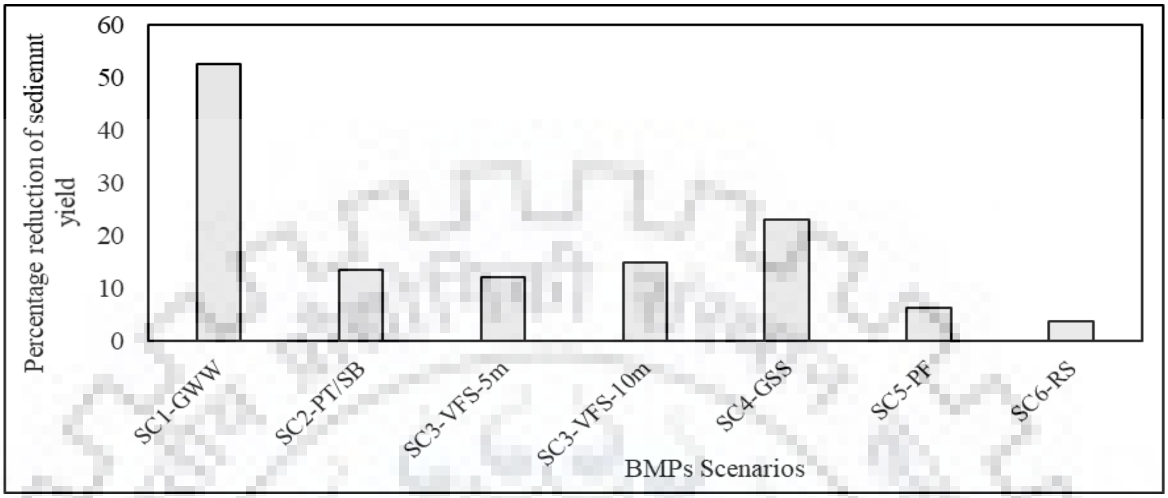


Figure 5.13: Reduction in average annual sediment yield under different BMPs

5.7 Effects of BMPs on Runoff generation

The water balance component for different BMPs has been shown in Table 5.10. From the analysis of results, the BMP Scenario, SC2- PT/SB showed more decrease in surface runoff and (from 273 to 215.5 mm) and increase in return flow (from 268 to 295 mm) followed by SC5-PF (partly forestation) with decrease in surface runoff (From 273 to 259 mm) and increase in return flow (from 268 to 271mm) and other BMPs did not affect that much in delayed runoff. The hydrological cycle from ArcSWAT for BMPs SC2- PT/SB and SC5-PF with water balance components are shown in Figure 5.13 and Figure 5.14 respectively.

Table 5.10: Effect of BMPs on water balance component- Runoff

BMPs	Surface runoff	Lateral flow	Return Flow	Percolation to shallow aquifer	Recharge to deep aquifer	ET	PPT	PET	Remarks
Baseline	273	155.21	268.77	437.59	168.78	815.3	1677	2004.8	
SC1 GWW	273	155.21	264.86	437.59	168.78	815.3	1677	2004.8	
SC2 PT/SB	215.70	167.05	295.17	480.58	185.36	817.2	1677	2004.8	
SC3-FS-5m	273	155.21	268.77	437.59	168.78	815.3	1677	2004.8	
SC3-FS-10m	273	155.21	268.77	437.59	168.78	815.3	1677	2004.8	
SC4-GSS	273	155.21	268.77	431.23	166.33	815.3	1677	2004.8	
SC5-PF	259	156.12	271.49	442.01	170.48	823.8	1677	2004.8	
SC6-RS	273	155.21	297.15	483.79	186.6	815.3	1677	2004.8	

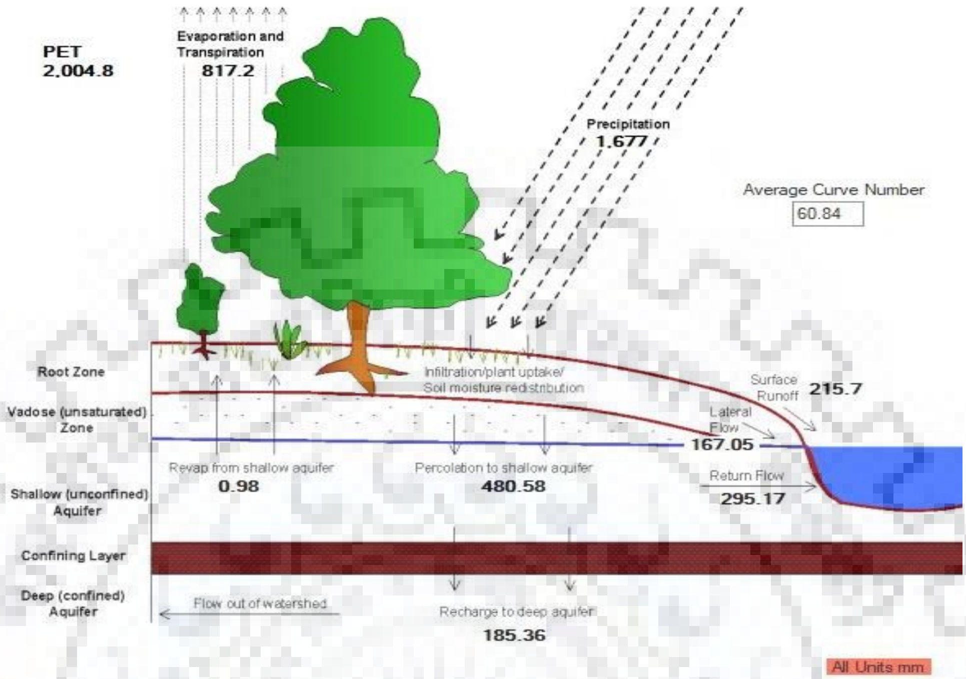


Figure 5.14: Water balance Component for BMPs SC2- PT/SB

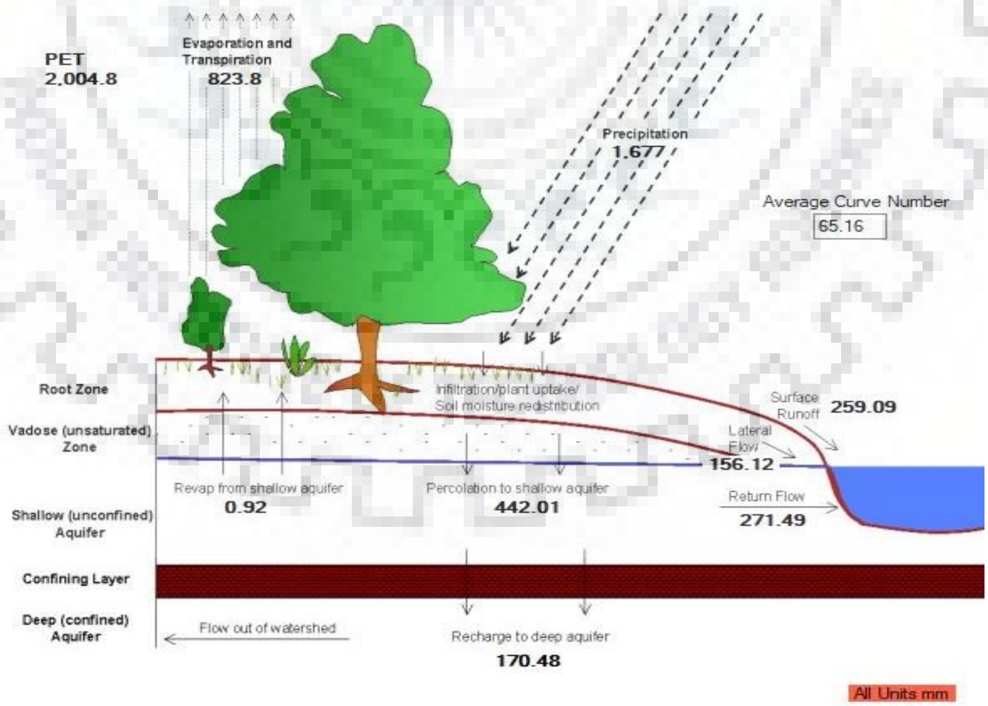


Figure 5.15:Water balance Component for BMPs SC5-PF

CHAPTER 6
SUMMARY AND CONCLUSION

This chapter covers the summary of the works along with conclusions drawn from this study.

6.1 Summary

This dissertation work includes hydrological modelling of middle class West Rapti River Basin of Western Nepal with catchment area of 5281 km^2. The main objective this study was to check the applicability of SWAT in the Nepalese river basin for modeling of hydrology and sediment yield, water balance and assessment of best management practices in the basin.

SWAT model was employed in integration with ArcGIS software as ArcSWAT. Various spatial and temporal data sets required for this study were taken from different sources and processed to give as input in ArcSWAT. Rainfall, discharge for the years 2003 to 2013 and sediment data of the years 1978 and 1985-1988 were taken from DHM, Nepal, 30 m resolution Land Cover of Nepal 2010 developed by ICIMOD, soil data jointly developed by DOS, Nepal and FAO was used and Digital Elevation Model (DEM) jointly generated by NRSC and ISRO India was processed and used in this study. Rating curve was developed and sediment data for the model calibration and validation period was generated. The model was run for the years 2000 to 2013. Calibration was done for the years 2003 to 2007 and validation for the year's 2007 to 2009 using SWAT CUP SUFI-2 technique.

For uncertainty analysis, based on available literature, some of the model sensitive parameters were initially selected and Latin hypercube once at a time sensitive analysis was carried out. Sensitive parameters were identified, and calibration and validation were carried out. The SUFI-2 accounts for all the sources of uncertainties and quantifies them in terms of p- factor and r- factor. The p- factor is the percentage of observed data captured within 95PPU and r- factor indicated the average thickness of the 95 PPU band. In addition, SWAT model performance was evaluated based on the different objective function values- R^2, NSE, PBIAS and RSR. The model performance has been found to be good both graphically as well as statistically.

After getting acceptable values of evaluation parameters for calibration and validation, final fitted values of sensitive parameters were written back in to ArcSWAT to get different component of water balance. For Assessment of best management practices and to represent the field conditions, values of different parameter were changed in ArcSWAT and developed SWAT model was re-run to get the values of sediment yield. The performance of BMPs were assessed based on percentage reduction in sediment yield taking initial calibrated model output as baseline and the best BMPs was recommended for future implications in the river basin.

6.2 Conclusion

Followings conclusions are drawn from this study.

- It was found that the basin gets average annual rainfall of 1677mm and 16.3 % (273 mm) contributes to surface runoff, about 9.2 % (155 mm) accounts as lateral flow, and about 48.6 % (853mm) accounts for Evapotranspiration from the basin.
- 4.50 BCM volume of water is available annually at the basin outlet (Kusum outlet). The average annual discharge available at Kusum 110 m^3/s.
- From monthly distribution of rainfall and water yield, 80 % of rainfall, 90 % of runoff and 73% of water yield occurs during four months of monsoon i.e. from June to September. The evapotranspiration was also found to be high during monsoon season with highest value of 119 mm in the month of July and August.
- 17.67 Ton/ha/year sediment is produced annually from the basin and the study area lies under high erosion class.
- Based on percentage reduction in sediment yield, it was found that grassed water way is the most effective with 53% reduction in sediment yield followed by grade stabilization structure with 23 % reduction. The least effective scenario is recharge structures with only 4 % reduction in sediment yield.
- With limited data availability or data scarce region like Nepal, for scientific planning, development and management of water resources, SWAT model along with SWAT CUP can be used effectively.

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