HYDROLOGICAL MODELLING OVER GANGA RIVER BASIN USING VIC MODEL

A DISSERTATION

Submitted in the partial fulfilment of the requirements for the award of the degree
Of

MASTER OF TECHNOLOGY

In

IRRIGATION WATER MANAGEMENT

By

YOGESHA.M
Enrolment No. 16547008

DEPARTMENT OF WATER RESOURCES DEVELOPMENT AND MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247667, UTTARAKHAND (INDIA)

MAY, 2018

CANDIDATE 'S DECLARATION

I hereby certify that the work presented in this dissertation entitled, "**Hydrological Modelling Over Ganga River Basin using VIC Model**" in partial fulfilment of the requirement for the award of degree of **Master of Technology in Irrigation Water Management** submitted in the Department of Water Resources Development and Management, Indian Institute of Technology July 2017 to May 2018 under the supervision of **Dr. Ashish Pandey**, Associate Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, and **Dr. Praveen Gupta**, Scientist-SF, Space Applications Centre, ISRO, Ahmadabad, India.

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

Place: **ROORKEE**

Dated: 11th May, 2018 **(YOGESHA.M)**

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

(**Dr. Praveen Gupta**)
Scientist - SF
Space Applications Centre
ISRO, Ahmadabad (INDIA)

(**Dr. Ashish Pandey**)
Associate Professor
Department of Water Resources
Development and Management
Indian Institute of Technology Roorkee

ACKNOWLEDGEMENT

I wish to express my deep sense of gratitude and sincere thanks to my guides **Dr. Ashish Pandey, Associate Professor** of Water Resources Development and Management department, IIT Roorkee **and Dr. Praveen Gupta,** Scientist, Environment and Hydrology Division, EPSA/SAC/ISRO, Ahmedabad-15, for being helpful and a great source of inspiration. I would like to thank them for providing me with an opportunity to work on this excellent and innovative field of research. Their keen interest and constant encouragement gave me the confidence to complete my work. I wish to thank them for their constant guidance and suggestions without which I could not have successfully completed my thesis evaluation report.

I would also like to thank **Dr. S. K. Mishra**, HOD WRDM, IIT Roorkee for his constant support during my study. Also, I would like to thank all the teaching and non-teaching staff members of the department who have contributed directly or indirectly in successful completion of my thesis evaluation report.

I am very much thankful to Secretary, Water Resources Department, Government of Karnataka for deputing me to this esteemed Institute for Master degree program.

My special and sincere thanks go to Sri. Deen Dayal, Research Scholar, Department of WRD&M, IIT Roorkee for his immense help, timely assistance and invaluable suggestions during the course of study. I would like extend my appreciations to my friends, colleagues and loved one, who always keep me motivated and fortify my determination.

Date: 11th May, 2018

Place: **Roorkee** **(Yogesha.M)**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Effective watershed management is crucial for growth, sustainable development, protection of the environment, and prosperity of nation. Due to lack of watershed-wide hydrological data from in situ platforms, whether they are real time or historical, water management has been quite challenging. Under such circumstances, hydrologic models forced with widely available satellite-based datasets can be useful. Keeping this in mind, and availability of hydro-meteorological dataset, the present study was carried out to evaluate applicability of physically based VIC hydrologic model over Upper Ganga Basin up to Garhmukteshwar. Calibration, uncertainty analysis and validation of the VIC model on daily basis, was carried out for the years 2009 to 2010. A good agreement between the simulated and observed hydrographs for discharge indicates very good performance of the VIC model. After successful validation of the model output maps of runoff, ET and soil moisture were developed. Furthermore, Soil Water Index (SWI) was estimated using Scatterometer data and VIC derived soil moisture has been utilized for the development of an equation for soil moisture estimation using SWI. The correlation coefficient between VIC derived soil moisture and SWI was found to be good which indicated the potential of estimation of soil moisture using remote sensing datasets.

CHAPTER 1

INTRODUCTION

1.1 General:

Water resources assessment plays vital role concern to whole living things on earth to all extent. Water availability and distributions are a major key role in water assessment. As per the definition of the UNESCO/WMO, (1992) in the International Glossary of Hydrology water resources assessment is the "Determination of the sources, extent, dependability and quality of water resources for their utilization and control". Water resources of the basin are reckoned by the natural flow in a river basin. "Water resources assessment aims to measure quantity and quality of the water in a system, including data collection, data validation, and water accounting techniques, using both ground and remote sensing".

The quantitative assessment of discharge in catchments will provide information of changes in the river basin. This can be obtained by Land Use/Land Cover (LULC) changes over catchment area in long term. Which intern is related to quantitatively estimate of the Hydrological variables like, surface run-off, Evapotranspiration etc.

Since Water resources assessment manages estimating, gathering and dissecting parameters on the quantity and nature of water assets for advancement and a superior administration of water assets, the required information accumulation for the examination unit turns into a testing errand.

For any study the main challenging task is to collection of the data for assessment of the quality and quantity of the water resources. To assess and analyse the water parameters, in the perspective use of resources development and management issues reliable precise measurements methods useful.

In terms of climate scenarios, numerous studies of hydrological responses have been divided into two types, hypothetical scenarios and projections from general circulation models (GCMs) (Yu et al., 1999; Jones et al., 2006). Bao et al. (2012) investigated the hydrological responses (streamflow, soil moisture, and actual evaporation) to climate change for the Haihe River Basin of China and found that streamflow is much more sensitive than evapotranspiration and soil moisture to climate change. Fu et al. (2007) indicated that increase in precipitation could result in the increase in streamflow for a watershed in the Pacific Northwest, the United States; conversely, a decrease in precipitation could lead to the reduction in streamflow.

In the past, various hydrological models have been used across the world for the determination of hydrological variables i.e surface run-off, Evapotranspiration, infiltration, discharge measurement. Each model is having unique characteristics and their results are comparable to other. Some models require simple format data of inputs and also has limitations. All the hydrological models require basic data of rainfall, temperature (Maximum and Minimum), Wind velocity, LULC, Soil classification, LAI and other parameters.

The VIC model is a physically-based hydrological model, which was developed by Liang et al. (1994) and later improved by Lohmann et al. (1998). The model considers two types of runoff yield mechanisms, infiltration excess and saturation excess. The total runoff estimates of the VIC model consist of surface flow and base flow (Habets et al., 1999). The VIC model has been widely applied to a wide variety of sub-basins (Liang and Xie, 2001; Bao et al., 2012; Wang et al., 2012). In comparison with other hydrological models, the VIC model has advantages of physically-based interpretation, wide suitability for different climatic zones, and good performance for discharge simulation (Zhang and Wang, 2014).

1.2 Necessity of hydrological models

The Objective of any modelling depends on the scope and requirement of the study. There are two main core objectives for hydrological modelling. Firstly, to understand the variations in hydrological variables and effects from these variations in the river basin. Secondly, to synthesise the hydrological data for better prediction and forecasting. From these models impact over catchment by natural or human interventions may be studied by land use or climatic parameters easily. In hydrological modelling, conceptual methods are commonly used to represent important components to correlate input to output data.

1.3 Role of Remote Sensing and GIS in Hydrological Modelling

Adaptation of better data in a hydrological model will produce valid outputs. Climatic parameters play a major role in the hydrological study. Variations in the spatial and temporal change in these parameters are measured easily by remote sensing data. Hence with the help of physical based hydrological model output parameters like precipitation, ET, soil moisture, etc. after integration with remote sensing data will simplify in the field of water resources and management.

1.4 Variable Infiltration Capacity (VIC) Model

Variable Infiltration Capacity Model has both a hydrologic model and land surface scheme. Model balances both water and surface energy budgets within a grid cell, by semi-distributed macroscale level. Changes in the sub-grid are statistically captured by the VIC model. Variable Infiltration Capacity model gives a more realistic hydrology. Post-processing of the VIC outputs in order to simulation process works with linear based transfer function independent routing model (Lohmann, et al., 1996; 1998a; b).

1.5 Research Gap/Rationale

In India like country, hydrology has been hampered by lack of data, but there has been some change recently. Data about human interventions on the other river basins are not widely available, and so many studies have ignored them in their models. There is not enough monitoring of water flows through rivers in the country, and often data about river flows are not released Collection of data is not always monitored and controlled for quality. Even when data are available, state agencies have been reluctant to share them because of inter-state disputes and political sensitivities.

1.6 Objectives

Major objectives of the study are as follows:

1. Calibration and validation of the VIC model for simulation of discharge.
2. Application of VIC model for estimation of soil moisture and evapotranspiration.
3. Estimation of soil moisture using Scatterometer data.

CHAPTER 2

REVIEW OF LITERATURE AND OVERVIEW OF VIC MODEL

This chapter encompasses review of past research studies related to VIC model, overview of VIC hydrological model, working principle of hydrological parameter determination in VIC Model and methods of Routing of VIC model.

2.1 Background

A literature review is conducted to understand the latest advancement in the related field. Research papers published by authors are reviewed to understand the concept and to conduct the present study.

Liang et al. (1996) initial studies were carried over Kings Creek area, Kansas and given an impression like, model performed quite well, giving encouragement that the variable infiltration capacity (VIC) approach to parameterizing the spatial variability in the land surface properties, coupled with a simplified vegetation model, may be sufficient to represent the land surface fluxes at the Global Circulation Model (GCM) scale over long-term hydrologic and climatological data for Kings Creek. From this study reveal variable infiltration capacity model was formulated by the authors. The model formulated for both water and energy balance mode. In this study model was run by 2-Layer soil descriptions. The first layer characterized by soil moisture capability and second layer descripted by Arno model of conceptualization.

Abdulla et al. (1996) studied over Arkansas-Red river basin using VIC-2L model of approach for generalization of hydrological outputs. Author mentioned once again that model was developed for application for large area. Here study area divided into grid wise of 1° resolutions and the whole area concise to 61 grids. Input variables for model provided as per the grid data. Results from the specific study provides key information on simulated hydrograph generated from the model and Evaporation predicted by VIC-2L model over a large scaled area in southwestern part of Arkansas-Red river basin is quite well compared with derived values from atmospheric moisture budget of the same area. Author also suggested the model performance needs improvement and encouraged to ascertain for testing of global hydrological data.

Nijssen et al. (1997) used VIC hydrological model on a grid-based approach so that output of the result can be overlapped by predicted hydrographs for the study area on continental basins. Result reveals that annual runoff volumes, as well as hydrograph shapes, were simulated with an acceptable degree of accuracy. From the results, authors suggested the feasibility of method to simulate hydraulic fluxes for large scale catchments. They also found that soil parameters variations are the main causes for their differences.

Lohmann et al. (1998) explained routing method of VIC model and elaborated its functions over 2-layer soil models. It is coupled to a straight directing plan which is streamlined with simulated precipitation and streamflow information and is gotten autonomously from the VIC-2L Model. In linear routing method, it is clearly mentioned that stream runoff is independent of the travel time and errors are second order, which does not have much importance for validation. In terms of VIC model result, clarified as it captures fairly acceptable output over well-distributed soil depth and considering unconfined soil stratum type of aquifer.

Based on the observations from the VIC hydrological model, the patterns developed for soil moisture of large range will be sophisticated than other models (Nijssen et al., 2001). They mentioned that the collaboration between the recommended, shallow soil layer depth (1m) with more profound soil layers isn't cleared in the VIC model. A system for upward dispersion of soil dampness and maybe possible coupling with a local groundwater show are proposed as arrangements. In the study area of Illinois and central Eurasia, it is concluded that the annual cycle and spatial patterns in soil moisture matched well with observed values but soil moisture level of simulated data shows lower than the observed data over the study area. Nijssen et al., (2001) also explained that the outputs of snow cover extent, runoff component of water budget component related to global continental range shows somewhat lower than the observed values over north America.

VanShaar et al. (2002) studied forested catchments of Columbia River and come across the outcome that leaf area plays a major role in streamflow generation. Author experienced the difference with the other hydrological model like DHSVM and VIC in the study area. In the comparison, output of simulated runoff from DHSVM model had sensitive role in land cover changes than the VIC Model. They explained the parameterization of input variables like soil database and ET calculation in DHSVM model. Considering uniform vegetation cover over the catchments and using hydrological model, they studied the sensitivity of the cover area. Comparing the output with DHSVM and VIC model in the catchments of Columbia River, stream flow and evapotranspiration trends shows similar results on both the models. Also mentioned a clue that, pertaining to DHSVM model groundwater recharge contributes the soil moisture level in the roots other than snowmelt and precipitation which option lacks in VIC Model.

Christensen et al. (2004) studied climatic impacts on hydrology over Colorado basin using Variable Infiltration Capacity (VIC) Model for the data derived from statically downscaled GCM scenarios. From futuristic climate data of Colorado basin, annual temperature increase in 0.5°C warmer climate projects precipitation of 3 to 6% less compared to real values. And there by VIC Model produces 10% difference of simulated runoff compared to observed flow. From the research authors concludes that, under both activities like industrialization and settlements over the catchment area of Colorado basin, annual runoff values decrease from 14 to 17%.

Yuan et al. (2004) described the hydrological simulation work in Hanjiang River basin using VIC-3L model. Study reveals that VIC-3L model supports to assess the water resources based on the available climatic parameters. The study carried out at a scale of 25 Km × 25 km resolution and mentioned that VIC model predicts flood hazards, water resources management, and land and atmospheric interaction mechanism in the basin. Authors mentioned that, based on the future climatic data, VIC 3-L model forecast the water resources condition over the river basin and also informed that in water balance model, soil heterogeneity and vegetation parameter are the main dependent parameter for surface runoff generation. However, through the study on Hanjiang River using VIC-3L model, simulated and observed daily and monthly streamflow at six discharge stations shows very goodNash-Sutcliffe efficiency.

Study of Jha et al. (2005) reveals that SWAT model predicted 14% of the precipitation measured on the catchment comes as snow, while the GCM put this rate at 13– 22%. Runoff ranges vary from - 49% to +115% over the measured and simulated climate variables from SWAT Model. SWAT esteems for yearly streamflow were serially uncorrelated at all slacks and SWAT multi-model troupe results may give a substantial way to deal with surveying yearly streamflow in the study area of UMRB.

Hu et al. (2007) studied over Weihe River basin, using both hydrological models like VIC-3L and SWAT models and it was found that model underestimated the simulated runoff than observed stream flow on spring and winter seasons. Also mentioned SWAT model produces a higher value than VIC model in simulated runoff at summer season and lower values in winter. A critical distinction between demonstrate comes about is the capacity to the reaction of runoff to LUCC. In this study SWAT based hydrological model become more sensitive with respect to the Land Use changes than VIC 3-L model. From the facts and Figure authors mentioned changing the land use pattern reduces the runoff generation over the study basin. Study clarifies that, SWAT model proves the feasible method for watershed model for runoff simulation under LUCC.

Meng & Quiring (2008) found that VIC model produces comparatively better outputs, soil moisture sensitivity analysis results in the undistinguished error due to model parameters. VIC model parameters Ds, Dsmax, Ws, d1, and d2 are the more predominant in the model performance. From these studies, it mentions that model output accuracy does not depends on the complexity of the data provided. Soil moisture data output obtained from the model depends on both location and time of consideration. Finally, from the observation, concluded that simulation of model needed significantly for change in time gap. This study shows that DSSAT is more sensitive than VIC Model and climatic parameter affectability is more emphatically controlled than by changes in soil properties.

Warrach et al. (2008) studied the role of soil parameters for streamflow generation in the catchment and parameters of soil moisture and Evapotranspiration are accountable to this list. The study mentioned that VIC model computes the hydrological parameters over an extent of the large area. The recreation of the streamflow insufficiencies in the hydraulic conductivity parameterization and the connected soil database. Changing the parameterization of the hydraulic conductivity and diffusivity and a higher determination soil surface classification prompted the huge change in the streamflow recreation.

Linde et al. (2008) compared hydrological models over Rhine basin. In this study, authors performed land surface models of HBV and VIC concepts to the study area. Author suggested that meteorological constraining information has an impressive influence on model execution, independently to the sort of model structure and the requirement for ground-based meteorological estimations. As per the comparison of both hydrological model studies, HBV model predicts better outputs than VIC model. Also here researchers suggested that HBV (a semi distributed model) is robust and quick for long periodic data of simulation. Overall study of the rhine basin preferred HBV model for all climatic conditions.

Zhao et al. (2012) studied VIC-3L model performance with different rainfall seasons and it was found that results are dominant to the summer oriented catchment zones. Based on the observations, VIC-3L model can be well calibrated against the water balance criteria and also capable of reproducing observed daily streamflow. In this study authors determined ungauged streamflow at 191 catchments over southeast part of Australia. From research over the basin, calibration parameters like, b and soil layer depth d_2 has wide ranges with varying rainfall zones considering all other parameters static. Thickness of soil reduces the peak flow generation and reduces the evapotranspiration rate and increases the soil moisture level. For the calibration of the model authors selected steepest gradient method of calibration. Outcome of these parameter ensured that efficiency has incredibly raised over the study area.

Ford& Quiring (2013) studied water balance using VIC model over Oklahoma sites. Study reveals that soil moisture accountability is not influenced by LAI parameter. Research conducted at the Oklahoma site and obtained outputs are considerably matched with the observed in situ values for the initial period. The same procedure conducted to obtain soil moisture over Oklahoma area for a drought period in which precipitation is below the normal. Outputs shows that, LAI sensitivity directly plays role in soil moisture values obtained. From the conclusion of the research, the zonal areas cover under drought severity to monitor the drought management, the sensitivity of LAI parameterization plays a vital role in proper functioning in the VIC model. Therefore, authors suggested that, for better sensitivity of intensity and drought condition monitoring purpose, LAI parameter consideration become most essential under Model simulation.

Livneh et al. (2016) carried out hydrological study over multiple watersheds of the Java Island and described the performance of the model. As per the output, the model produced very satisfactorily to very good results with Nash Sutcliffe Efficiency (NSE) ranging from 0.31 to 0.89. The infiltration parameters, Base Flow Index (BFI) and 1/b, which are related to infiltration equation of the model are highly correlated. They mentioned that, soil surface pattern plays role in direct surface runoff and base flow. In this model performance carried out under Java Island, authors came out with better results of NSE. NSE values proves comparatively good to the observed values and witnessed that model performance variation depends upon the peak flow and soil characteristics. Runoff and baseflow become more sensitive with variations in climate change. Particularly wet season, heavy rainfall occurrence leads to increase in soil moisture content and there by generation of surface flow.

Wang et al. (2017) studied climate change scenarios over Xiangjiang River Basin based on the output of 14 GCM model outputs using VIC Model and described that VIC model performs well with better execution for hydrometric stations on the river stream of the Xiangjiang River than for tributary catchments. To perform the VIC Model simulation, study area divided into 0.50°×0.50° resolution. The re-enacted yearly releases are essentially connected to the recorded yearly releases for all the eight other target stations over the Xiangjiang River basin. From the study author mentioned that, Xiangjiang River Basin may encounter water deficiencies actuated by environmental change. Output of Model shows the better simulation values over all stations coming under the Xiangjiang River Basin. In this study futuristic data are adopted to VIC Model to predict the variations in water resources over the river basin for better management practices.

Narendra et al. (2017) mentioned characteristic feature of VIC Model. From the study, authors described as gird wise soil moisture content, unequivocal portrayal of vegetation classification and nonlinear baseflow parameter strengths to simulate the hydrological variable. Author selected VIC 2-L model for the study of large catchment area for the period of June to Sep or monsoon period of 2009. Outcome from the model with respect to NSE and RMSE ranging 0.66 and 30.03% for daily simulated data and also mentioned that from the uncertain input data, output variables simulated from model predicts over and underestimation values. Finally, from the results of Tekra study area, researcher concludes that, VIC Model works good over large catchment areas.

2.2 Overview of VIC Model

2.2.1 General

VIC model is physically based hydrological model in which water budget components are derived. Input variable derived from the satellite remote sensing technique and integration with the model, output of water budget parameters has been derived. Parameter like minimum and maximum temperature, rainfall, wind speed, soil, and vegetation plays major role in this model.

Some advantages of the VIC model are as follows:

1. It runs both the modes i.e., Water Balance and Energy Balance
2. Captures variations statistically at sub-grid level.

3. Three layers of soil profile consideration.
4. Sub-daily level water budget calculation.
5. Variable infiltration accountability.
6. Non-linear base flow.

VIC is a large scale, semi-distributed macroscale hydrologic model developed by **Liang** (1996) at the University of Washington. VIC balances both the water and surface energy budgets within the grid cell, and its sub-grid variations are captured statistically. In this model, evapotranspiration is calculated according to the Penman-Monteith equation. VIC model includes distinguishing characteristics like, sub grid variability in land surface vegetation classes, soil moisture storage capacity, drainage from the lower soil moisture zone (base flow) as a nonlinear recession, the inclusion of topography that allows for orographic precipitation and temperature lapse rates resulting in more realistic hydrology. It has been extensively used in studies on topics related to land use/land cover variations, streamflow observations and effects of climate change in the watershed (Hu et al., 2007, Yuan et al., 2004, Zhao et al.,2012). From this model reflection from radiations over the surface captures the surface temperature, which replace the consideration of air temperature instead of the actual soil temperature.

The evapotranspiration is a function of net radiation and vapour pressure deficit. Actual evapotranspiration is the aggregate of canopy evaporation and transpiration from every vegetation tile and bare soil evaporation from the bare soil tile, weighted by coverage fraction for each surface cover class. Related with each land cover type are a solitary canopy layer and multiple soil layers. The canopy layer intercepts rainfall according to a Biosphere-atmosphere transfer scheme (BATS) parameterization (Dickinson et al., 1986) as a function of LAI. Related with each land cover class, soil layer 1 (upper zone) and soil layer 2 (lower zone) the upper layer (soil layer 1) is intended to dynamic conduct that reacts to precipitation occasions, and the lower layer (soil layer 2) receives moisture from the middle layer through gravity drainage, which is regulated by a Brooks-Corey relationship (Brooks and Corey, 1988) for the unsaturated hydraulic conductivity. The bottom soil layer characterizes seasonal soil moisture behavior and it only responses to short-term rainfall when the top soil layers are saturated. The runoff from the bottom soil layer is according to the drainage described by the Arno model (Franchini and Pacciani, 1991). The Conceptual framework of VIC model is presented in Figure **2.2**.

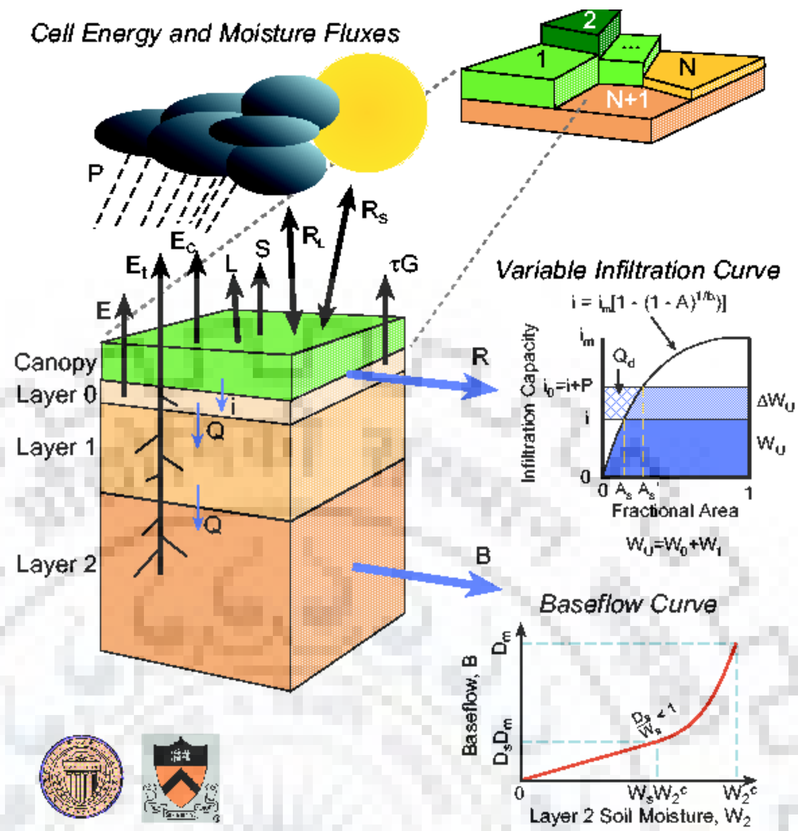


Figure 2.1: Conceptual framework of VIC model.

For the routing purpose, VIC model processes the outputs with unique independent routing model developed by Lohmann, et al., (1996; 1998a,b).

The VIC model runs on both water balance mode or water-and-energy balance mode. The water balance mode does not explain the surface variation adjustment. In water balance mode it expects that the surface temperature is equivalent to the air temperature for the present time step. By taking out the ground heat flux solution arrangement and the iterative procedures required to close the surface energy balance, the water balance mode requires altogether less computational time than other model modes.

2.3 Working principles of VIC Model

2.3.1 Water balance:

Water balance in the follows continuity equation in each time-step:

$$\frac{d\Delta S}{dt} = P_i - E_t - R \qquad \text{...(2.1)}$$

where, $\frac{d\Delta S}{dt}$ = the change of water storage,

P_i = Precipitation, mm

E_t= evapotranspiration, mm

R =runoff, mm.

For canopy layer interception equation (1) expressed as:

$$\frac{dIw}{dt} = P - Ec - Pt \qquad \text{…(2.2)}$$

where, I_w = canopy intercepted water (mm),

E_c = evaporation (canopy layer) (mm),

P_t = througfall (mm).

2.3.2 Evapotranspiration(E_t)

Estimation of Evapotranspiration in VIC model is as follows:

a) Canopy layer evaporation (E_c),

b) Transpiration (E_t),

c) Bare soil Evaporation (E_b).

Evapotranspiration can be expressed as:

$$E_t = \sum_{n-1}^{N} Cn * (Ec + Et) + C_{n+1} * E_b \qquad \text{…(2.3)}$$

where, E_c = Canopy layer Evaporation,

E_t = transpiration of each vegetation class,

E_b = bare soil evaporation,

C_n = n^{th} vegetation fractional tile,

$C_{N+1=}$ bare soil fraction, and

$\sum_{n-1}^{N} C_n = 1$

a) Canopy evaporation (E_c):

When precipitation occurs over the canopy, it evaporates maximum intercepted value into evaporation (E_c, mm) through VIC model under each type of vegetation tile. This canopy evaporation may be calculated using the formulation as below:

$$E_c = (\frac{W_i}{W_{im}})^{2/3} * E_p * \frac{r_w}{r_w + r_0} \qquad \text{…(2.4)}$$

where, W_{im} = Max water that Canopy intercept (mm),

r_0 = Architectural resistance between the canopy and overlying air (s/m)

r_w = Aerodynamic resistance (s/m) = $\frac{1}{C_w U_Z}$

U_z = wind speed (m/s),

C_w = Water transfer coefficient,

E_{pet} = Potential evapotranspiration(mm)

$$\lambda_v E_p = \frac{\Delta(R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma} \qquad \text{…(2.5)}$$

Where, λ_v = Latent heat of evaporation (J kg),

R_n = Net radiation (W/m^2),

G = soil heat flux density (W/m^2),

(e_s - e_a) = saturation vapour pressure deficit (Pa)

ρ_a = Density of air pressure (kg/m^3),

C_p = Specific heat of air (J/(kg K)),

Δ = slope vapor pressure (Pa/K),

γ = Psychrometric constant (KPa).

Canopy evaporation may vary, in case intercepted water cannot meet the atmospheric demand due to lower rate of continues rainfall than canopy evaporation within time period. The equation for such condition may be written as,

$$E_c = f * E_c \qquad \text{…(2.6)}$$

Where, f = Fraction of intercepted water,

$$f = \min(1, \frac{w_i + P * \Delta t}{E_c * \Delta t})$$

b) Transpiration (E_t):

Transpiration of vegetation estimated using the formulae:

$$E_t = \left(1 - \left(\frac{W_i}{W_{im}}\right)^{\frac{2}{3}}\right) * E_p * \frac{r_w}{r_w + r_0 + r_c} \qquad \text{…(2.7)}$$

r_c = Canopy resistance (s/m)

$$r_c = \frac{r_{0c} * G_t * G_{vd} * G_{PAR} * G_S}{LAI}$$

Where, r_{0c} = Min canopy resistance (s/m),

G_t = Factor for temperature,

G_{vd} = Factor for vapour pressure deficit,

G_{PAR} = Factor for photosynthesis active radiation flux,

G_s = Factor for soil moisture,

Transpiration through vegetation may occurs two different conditions. First criteria for single step of time log evaporation through canopy layer and secondly through transpiration but not canopy evaporation. equation for such conditions as mentioned below.

$$E_t = (1-f) * E_p * \frac{r_w}{r_w+r_0+r_c} + f * \left(1-\left(\frac{W_i}{W_{im}}\right)^{\frac{2}{3}}\right) * E_p * \frac{r_w}{r_w+r_0+r_c} \quad \ldots(2.8)$$

Where, f is the fraction of time

Here, first term mentions canopy evaporation for time step and second term part of both canopy evaporation and transpiration at a time step.

c) Bare soil Evaporation (E_b):

Actual process of bare soil mode of evaporation occurs on top thin layer of soil. When soil is not fully saturated then such type of condition model performs the function on the principle of Arno formulation to determine the evaporation rate of the soil.

2.3.3 Runoff:

For runoff generation VIC model adopts variable infiltration curve to admit the spatial heterogeneity of the zone (Zhao et al., 1980). In this model runoff of the area generates from the upper layers of soil when soil moisture attains field capacity. Over which occurrence of precipitation leads contribution to runoff with the lag time. And for the base flow VIC model considers Arno concept of algorithm (Franchini and Pacciani, 1991; Todini, 1996). Liang et .al (1996) explained initially in the study, the working procedure of genetic algorithm of VIC-3L for determination of soil moisture and runoff parameters.

Total runoff Q is expressed as:

$$Q = \sum_{n-1}^{N+1} C_n * (Q_d + Q_b) \quad \ldots(2.9)$$

Where Q_d (mm) = the direct surface runoff and

Q_b (mm) = and base flow for n^{th} land cover tile.

Direct surface runoff, Q_d : The thin layer of upper soil surface has very small level of water holding capacity. To calculate the direct surface runoff each time lag for upper layers of D1 and D2, it is given by:

$$Q_d = \begin{cases} P - Z_2 * (\theta_s - \theta_2) + Z_2 * \theta_s * \left(1 - \frac{i_0 + P}{i_m}\right)^{1+b}, P + i_0 \le i_m \\ P - Z_2 * (\theta_s - \theta_2), \qquad P + i_0 \ge i_m \end{cases} \qquad \ldots(2.10)$$

Where, i_o, i_m and b are infiltration capacity factors.

Sub surface runoff (base flow) Q_b :

For formulation of base flow VIC model applies Arno model conceptualisation, which is expressed as below:

$$Q_b = \begin{cases} \frac{D_s D_m}{W_s \theta_s} \theta_3, \qquad 0 \le \theta_3 \le W_s \theta_s \\ \frac{D_s D_m}{W_s \theta_s} \theta_3 + \left(D_m - \frac{D_s D_m}{W_s}\right) * \left(\frac{\theta_3 - W_s \theta_s}{\theta_s - W_s \theta_s}\right)^2, \theta_3 \ge W_s \theta_s \end{cases} \qquad \ldots(2.11)$$

Where, D_m = Max subsurface flow (mm/day),

D_s = Fraction of max subsurface flow (D_m),

Ws = Fraction of soil moisture,

G_{PAR} = Factor for photosynthesis active radiation flux,

G_s = Factor for soil moisture,

2.3.4 Soil moisture:

As per assumptions of VIC model there is no lateral flow from the top two soil layers. Therefore, soil moisture movement in the top two layers are described by one dimensional equation explained as shown below:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D(\theta)\frac{\partial \theta}{\partial z} + \frac{\partial K(\theta)}{\partial z}\right) \qquad \ldots(2.12)$$

Where, θ = vol soil moisture content,

∂θ = soil water diffusivity (mm^2/day),

Kθ = hydraulic conductivity (mm/day),

And Z = depth of soil (m).

Integrated with the atmospheric forcing, soil moisture for the layers may be elaborated as:

$$\frac{\partial \theta}{\partial t} * Z_i = I - E - K(\theta)\big|_{-Z1} + D(\theta)\frac{\partial \theta}{\partial z}\big|_{-Z1} \; (i = 1,2) \qquad \ldots(2.13)$$

Where, I= Infiltration rate (mm/day),

Z_i = Z_1 and Z_2 depth of soil layers,

For baseflow, that is the lower soil layer sub surface drainage are lumped and formulation derived based on large scale hydrology.

$$\frac{\partial \theta_3}{\partial t} * (Z_3 - Z_2) = K(\theta)\big|_{-Z2} + D(\theta)\frac{\partial \theta}{\partial z}\big|_{-Z2} - E - Q_b(i = 1,2) \qquad ...(2.14)$$

In this equation, term evapotranspiration (E) comes to active if vegetation roots go through lower soil layer then evapotranspiration. Otherwise E will be zero (0) for bare soil layer of evaporation.

2.4 Routing of VIC model

From the simulated fluxes, using separate routing model developed by Lohmann, et al. (1996, 1998) for routing the stream flow as described through Figure 2.2 below. In the simulation part, model run on water balance mode only. The simulation results are obtained in the form of daily fluxes for individual latitude and long gird cell. The output contains runoff, baseflow and other default outputs which are in model criteria at single instance.

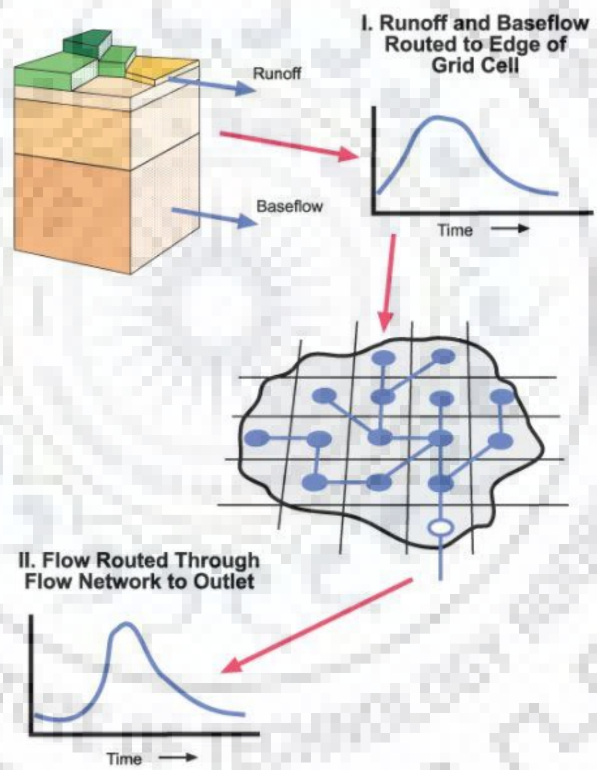


Figure 2.2: Schematic map of VIC routing model.

Total runoff and baseflow of each individual grid cell concentrated to a single point representing through unit hydrograph from its origin to channel network. In the model each grid cell represents the node in channel network. Using the saint venant's two-dimensional equation for routing each grid cells to the streamflow of the river.

3.1 General

This chapter documents, description about study area briefly stated. As well as collection process of data which are required to setup and run the VIC hydrological model. Output from the hydrological model depends on the input data quality which are provided for analysing in the model. Highlighting to the importance of data quality, spending time to collecting and processing feasible data to run the model over the study area of Upper Ganga basin.

3.1.1 Study area map

The Ganga river is one of the prime rivers of India and it flows east through the Gangetic plains of Northern India.

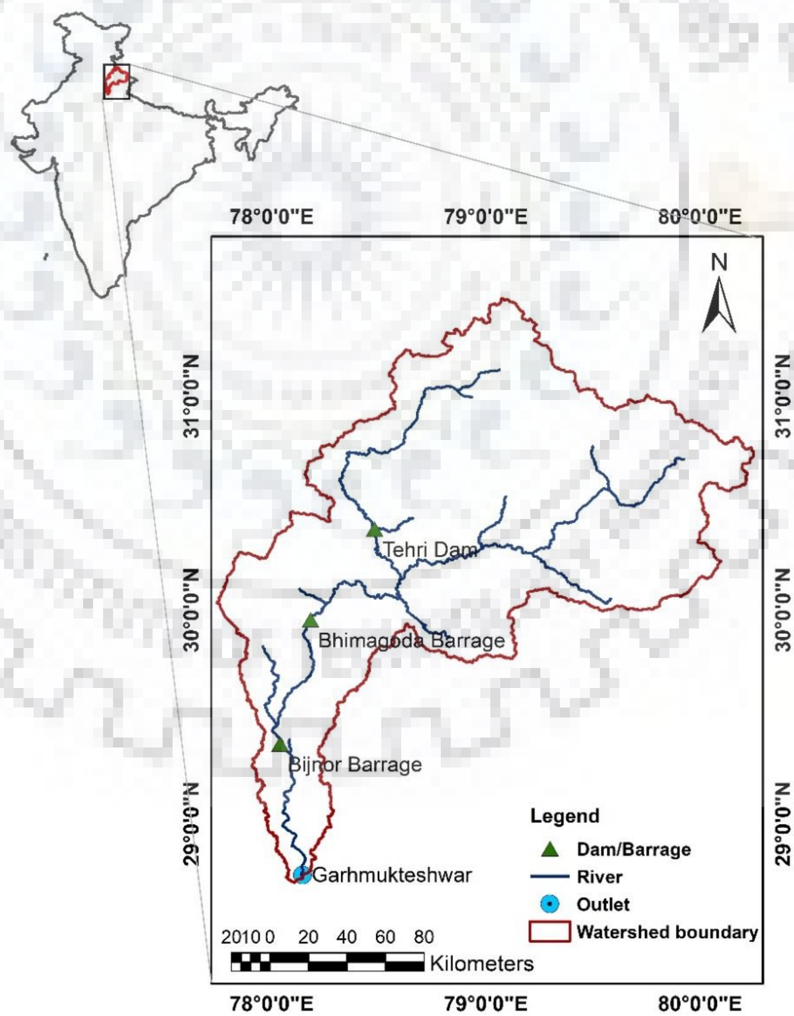


Figure 3.1: Location map of the study area

The Ganga River has many tributaries, both in the Himalayan region before it enters to the plains at Haridwar and further downstream before its confluence with the Bay of Bengal. In this study, Ganga sub-basin is selected up to Garhmukteshwar CWC G& D site, which comes under Upper and Middle Ganga basin area and lies between 77.59°E to 80.58°E longitude and 28.51°E to 31.46°E latitude (Fig.). Total area of the basin is about 29,899 km^2 and total length of the river from its origin to its outlet is about 290km. (*Source: http://india-wris.nrsc.gov.in)*

3.1.2 Topography

Topography of Ganga basin widely divided into three groups the Himalayan Fold Mountains, the Gangetic plain, and the central Indian highlands. The study area for the research falls under the Gangetic plains, in which the main stem of Ganga lies and constitute the most of the sub-basin situated between the Himalayan plateau and the Deccan plateau. Therefore, it is a valley of alluvial formation due to vast flat deposition of sediments transported from higher peak rising from an elevation above 7000 m to below elevation of 300m. Thus, the zone ideally suits for the intensive cultivation.

3.1.3 Climate and Rainfall:

The hydrologic cycle in the Ganga basin is governed by the southwest monsoon. About 84 percent of the total rainfall occurs in the monsoon from June to September. The mean maximum daily temperature even in the coldest month (January) does not fall below 21°C (except in the higher hills). Whereas the air temperature starts rapidly rising all over Ganga basin from March onwards, beginning a hot season that prevails from April to June. The annual rainfall ranges from 400 - 2000 mm (Average) (India-WRIS) in which 80% percent of the rainfall occurs during the monsoon months i.e. between June and October. (*Source: http://india-wris.nrsc.gov.in*)

3.1.4 Geology:

The Indo-Gangetic fields in which the investigation zone lies, are expansive, tedious, level fields developed of quaternary alluvium was brought around the waterways depleting the Himalayas and which frames the significant unit in, the topography of the Indian subcontinent. It incorporates the colossal alluvial tract of the Ganges. Geologists trust that underneath the alluvial covering, there is a calculable assorted variety in the constituents of a stone arrangement. The gauge of the thickness of the Ganga alluvium has been gone from around 15 km to 4.5 km.

3.2 INPUT DATA

3.2.1 DEM

For the study of this basin, Shuttle Radar Topographic Mission (SRTM) 90 m digital elevation model (DEM) (Fig. 3.2) was acquired from www.cgiar-csi.org. Elevation ranges from the lowest value of 197 m downside of the map near Garhmukteshwar, CWC G&D site to highest value of 7512 m in peak area of mountain range.

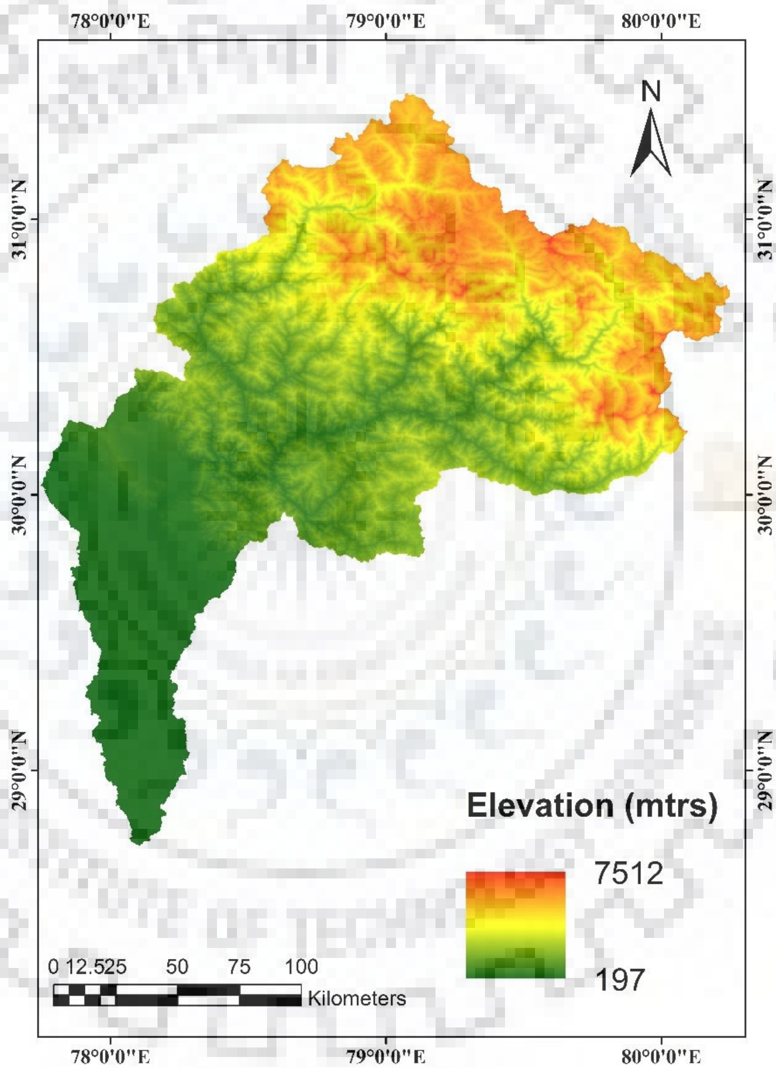


Figure 3.2: Digital elevation model of the study area.

3.2.2 Soil

Soil texture file acquired from NBSSLUP (1:250000 scale) for the study area. Table 3.1 showing below explains classified soil texture and area of soil type in the basin. Total study area of 28,922 Sq.km bifurcated into 6 types of soil class, loamy soil which contributes the highest value of

54.67% to the lowest range of Clayey soil 2.65%. Figure 3.3 shown below mentions the spatial coverage of each soil class in the study area.

Table 3.1: Soil texture information of the study area basin map.

S. No.	Soil class	Area (sqkm)	Area in %
1	Sandy soil	3311.48	11.44
2	Loamy Soil	14976.54	54.67
3	Clayey	75.54	2.65
4	Loamy-skeletal	4702.17	16.25
5	Rock outcrops	3358.69	11.61
6	Glaciers and rock outcrops	1660.46	5.74
	Total	**28,922.00**	**100.00**

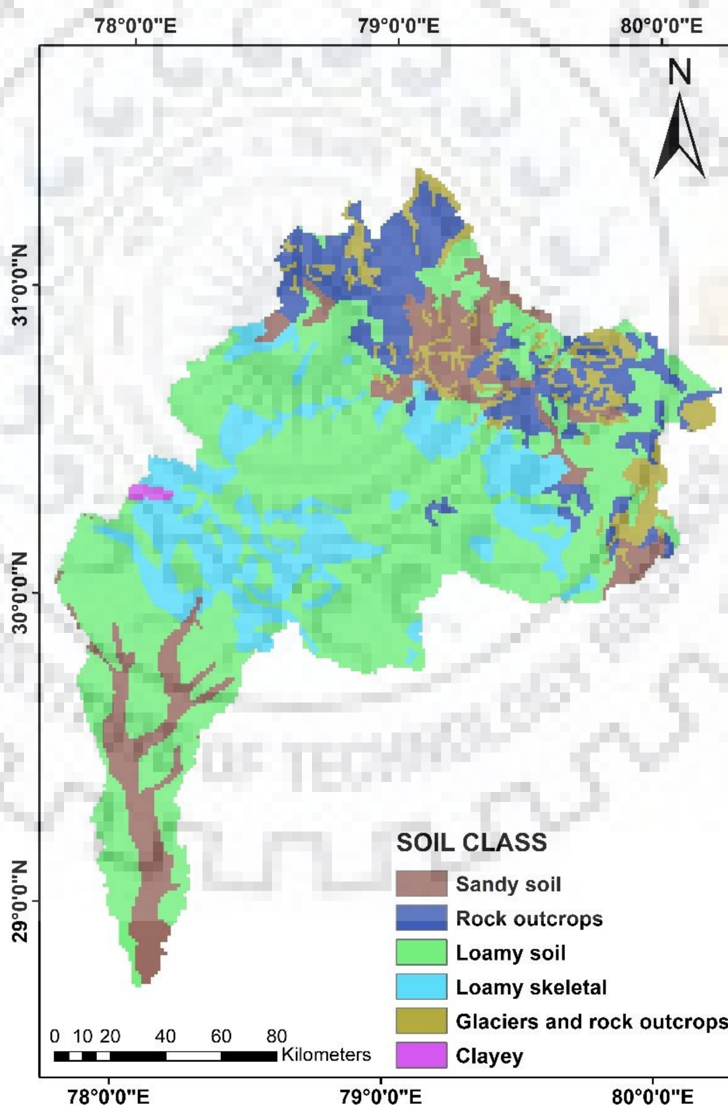


Figure 3.3: Soil texture map of the study area.

3.2.3 Satellite Images

Satellite images of Landsat-8 (OLI) (30m resolution) have been downloaded from USGS webpage (http://earthexplorer.usgs.gov) for preparation of LULC map. Details of Satellite images for the study area are enlisted in table 3.2.

Table 3.2: Satellite image downloaded path

S.No	Satellite (Sensor)	Path-Row	Date of pass	Spatial Resolution
1	Landsat-8 (OLI)	144-41	19-Sep-2016	30m
2	Landsat-8 (OLI)	145-38, 145-39, 145-40, 145-41	19-Sep-2016	
3	Landsat-8 (OLI)	146-38, 146-39, 146-40, 146-41	19-Sep-2016	

3.2.4 Climatic parameters.

VIC is physical based model, in this study model was run on water balance mode. Meteorological parameter file is one of the main variable required to run the model. To prepare the meteorological file the below mentioned data are essential:

a) Temperature

Daily basis maximum and minimum air temperature data for the 25 years period of 1990 to 2014 acquired from India Meteorological Department (IMD), Pune at a grid size of 1° × 1° spatial resolution for basin area.

b) Rainfall

Similarly, Rainfall data of the study area for the period of 1990 to 2014 acquired from Indian Meteorological Department's (IMD) at a grid size of 0.25° × 0.25° resolution for basin area.

c) Wind Speed

Along with Temperature and Rainfall, Wind Speed data are essential. wind speed data plays vital role for determination of evapotranspiration (ET). Station wise wind data are available in NCDC-GSOD (ftp://ftp.ncdc.noaa.gov/pub/data/gsod/GSOD_DESC.txt) database. For this study, nearby station data are gathered for preparation of meteorological forcing file.

METHODOLOGY

4.1 General

In this chapter, processing of input data to required format for compile VIC model. As model output depends on the quality of input provided to the model. Indian meteorological data, Global weather data and satellite images are processed limiting to study area underlying importance of time. The process of input data which are used are described as below.

4.2 Overview of Methodology:

The accompanying stream diagrams portrays the overall approach to run the VIC model on study area:

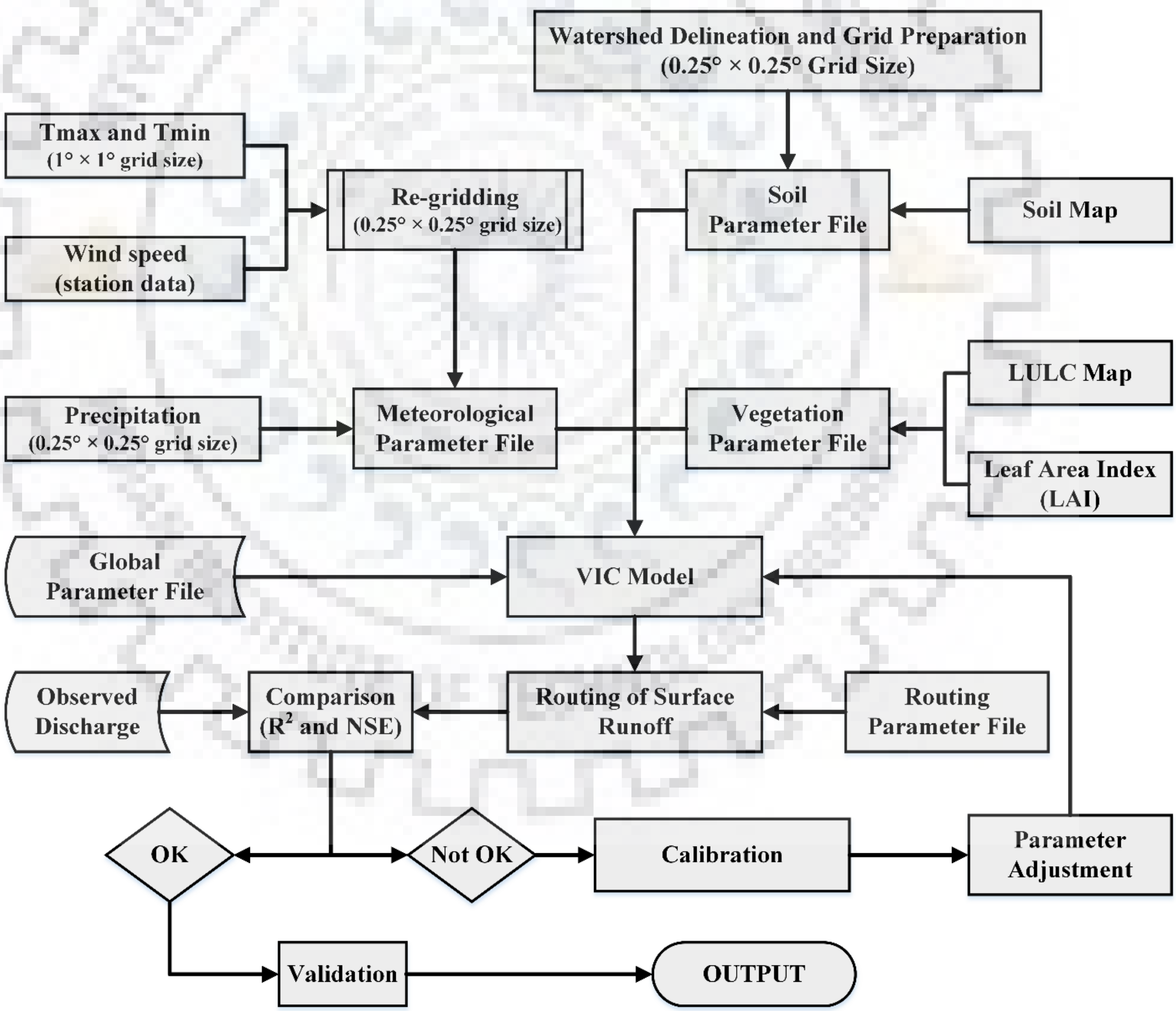


Figure 4.1: Flow chart explaining approach of work.

4.3 Watershed delineation and Grid Preparation

From the downloaded SRTM DEM of 90 m resolution, catchment of the study area is delineated (Fig. 4.2) using ArcGIS 10.4 application through various tools such as Fill, Flow direction, and Flow Accumulation basin.

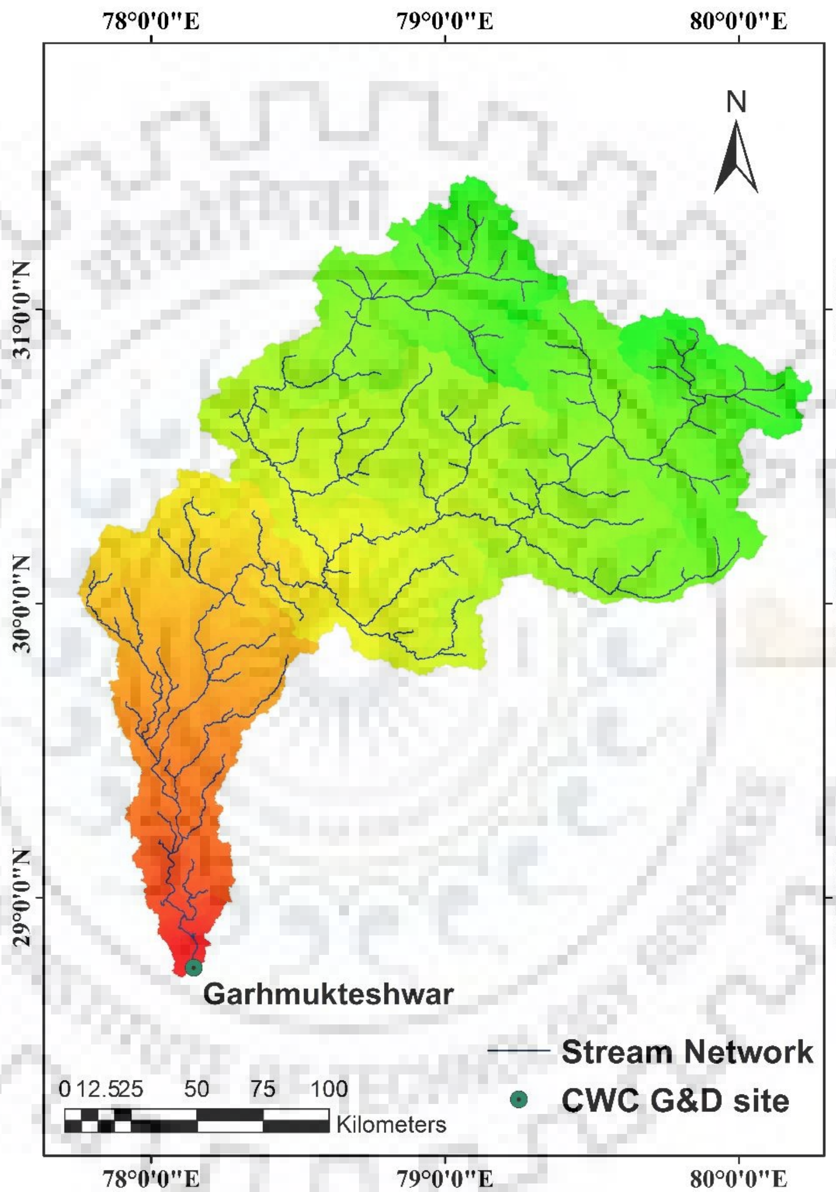


Figure 4.2: Watershed map of the study area.

Basin map of the study area lying between 77.59°E to 80.58°E longitude and 28.51°E to 31.46°E latitude. Using ArcGIS software, grid map (0.25°×0.25° grid size) of the study area have been prepared (Fig. 4.3). Grid prepared contains 13 rows and 12 columns, starting from the upper left corner and going the right-downward direction and numbering for each grid cell was accordingly.

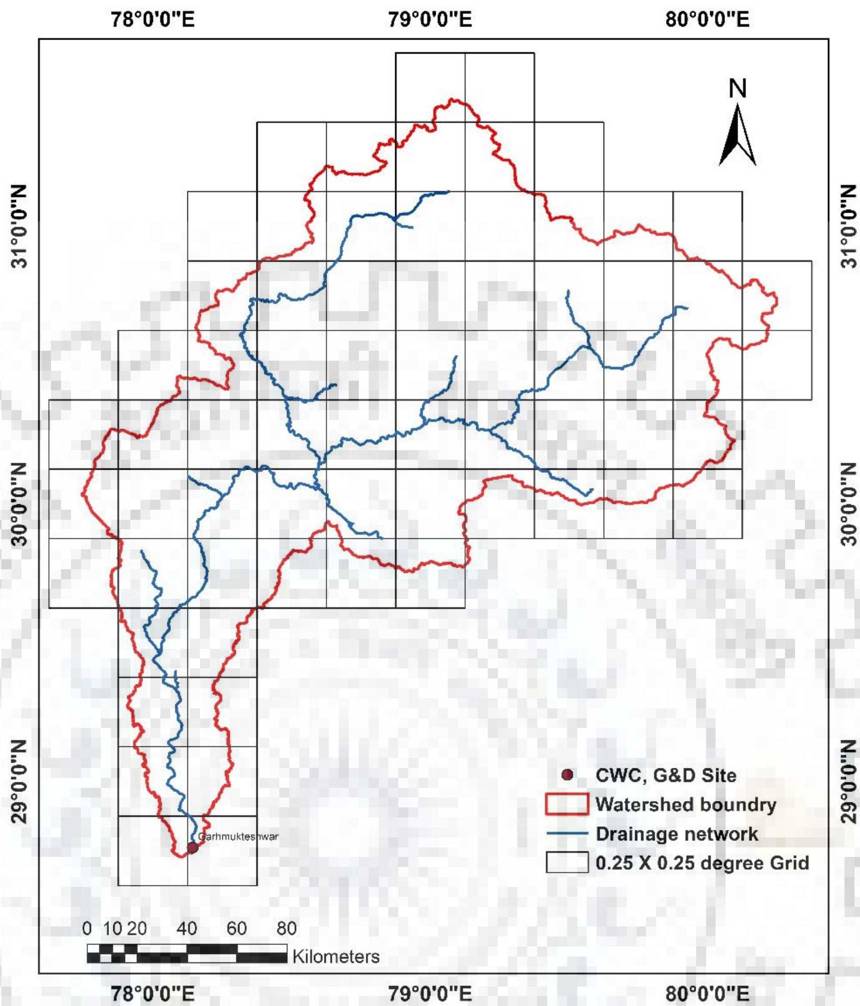


Figure 4.3: Grid map of the study area.

4.4 Meteorological Data preparation

Temperature (Max, Min), data acquired from the India Meteorological Department (IMD), Pune are at 1° × 1° grid size. To run the model, we need the dataset at 0.25° × 0.25° resolution. To make the dataset at same spatial resolution we need to do the interpolation. The methodology adopted for preparation of temperature and wind data is as follows:

1. Gridded data are sorted and added to ArcGIS 10.4
2. Using ArcGIS tool, shapefile created with Latitude and Longitude.

FID	long	lat	Day1	Day2	Day3	Day4	Day5	Day6	Day7	Day8	Day9	Day10	Day11	Day12	Day13
0	77.5	26.5	9.8	7.4	6.34	9.69	9.89	9.28	6.38	4.94	9.04	6.38	7.44	5.31	6.74
1	78.5	26.5	10.16	7.81	5.47	8.45	8.8	9.55	6.06	4.2	7.6	5.72	8.23	6.23	6.96
2	79.5	26.5	11.68	8.43	5.34	7.81	9.33	10.43	6.73	4.28	7.7	6.27	9.58	7.78	7.51
3	80.5	26.5	12.44	9.89	6.83	8.55	10.49	11.36	7.45	4.82	8.69	7.48	10.79	8.52	8.23
4	77.5	27.5	7.89	4.68	3.84	8.51	7.74	6.86	5.35	4.33	7.8	5.03	6.47	5.26	7.18
5	78.5	27.5	9.06	6.33	4.74	7.78	8.13	8.56	5.61	4.51	7.52	5.5	7.42	6.24	7.2
6	79.5	27.5	10.64	7.47	5.39	7.99	8.58	9.22	6.43	4.9	7.6	6.13	8.31	7.27	7.64
7	80.5	27.5	11.65	8.74	6.51	8.08	9.38	10.04	6.84	4.82	8.11	6.79	9.46	8.15	8.1
8	77.5	28.5	7.28	4.75	3.53	7.19	6.66	5.62	5.32	4.76	7.39	5.08	6.34	5.47	7.65
9	78.5	28.5	8.33	5.76	4.55	7.42	7.34	6.45	5.6	5	7.49	5.24	6.67	5.98	8.05
10	79.5	28.5	9.01	5.94	4.2	6.57	7.29	7.6	4.97	3.95	6.37	4.57	6.82	6.4	6.94
11	80.5	28.5	9.39	6.68	4.87	6.72	7.54	7.89	5.56	4.48	6.98	5.15	7.58	6.63	6.98
12	77.5	29.5	6.52	4.85	4.55	6.59	5.88	4.85	4.27	4.56	6.1	4.22	5.22	4.93	7.41
13	78.5	29.5	6.94	4.77	3.88	5.75	5.48	4.1	4.05	4.24	5.72	3.93	4.95	4.2	6.42

3. Interpolation of data using Inverse Distance Weighted (IDW) method in ArcGIS software.
4. Converting raster file to ASCII using conversion tool in ArcGIS.
5. Similarly, wind speed data are formatted to VIC model requirement.
6. Figure below shows the Format of a meteorological forcing file of a particular grid (Lat 28°30’ and long 78°45’)

data_28.50_78.75 | data_28.50_79.00 | data_

1	0.00	13.52	5.17	2.59
2	0.00	14.81	5.08	1.49
3	0.00	16.36	3.45	1.63
4	0.00	15.93	3.92	2.53
5	0.00	17.41	4.76	3.82
6	0.00	19.50	5.43	3.47
7	0.00	21.53	6.09	3.23
8	0.00	19.82	7.13	4.80
9	0.00	17.65	6.65	5.17
10	0.00	20.01	6.08	5.07
11	0.00	22.22	7.60	5.55
12	0.00	23.33	6.98	4.23
13	0.00	24.13	7.68	3.20
14	0.00	25.46	8.02	3.19
15	0.00	23.87	7.27	4.19
16	0.00	23.25	6.62	3.87
17	0.00	24.71	8.19	4.91
18	0.00	26.34	10.49	5.79
19	0.00	27.04	11.15	6.95
20	0.00	25.31	11.58	6.54
21	0.00	25.88	11.21	3.51
22	0.00	26.71	10.75	4.07
23	0.00	26.50	10.48	4.68
24	0.00	24.76	10.24	4.28

Figure 4.4: Sample meteorological forcing file of single grid.

4.5 Vegetation Parameter and vegetation library

For preparation of vegetation files first we need to prepare LULC map. For this, we used Landsat-8 imagery. Satellite images were pre-processed (Stacking, Mosaicing etc) and K-means method under unsupervised classification was used to do the classification in ERDAS software. Image was clustered into 200 groups and each group was identified with the help of high resolution images of Google Earth and field data. After the classification, data are imported to ArcGIS 10.4software and reclassified into 7 categories to obtain LU/LC map of the basin as shown below in Fig: 4.6.

Flowchart for LULC map generation may be shortened as (Fig. 4.5):

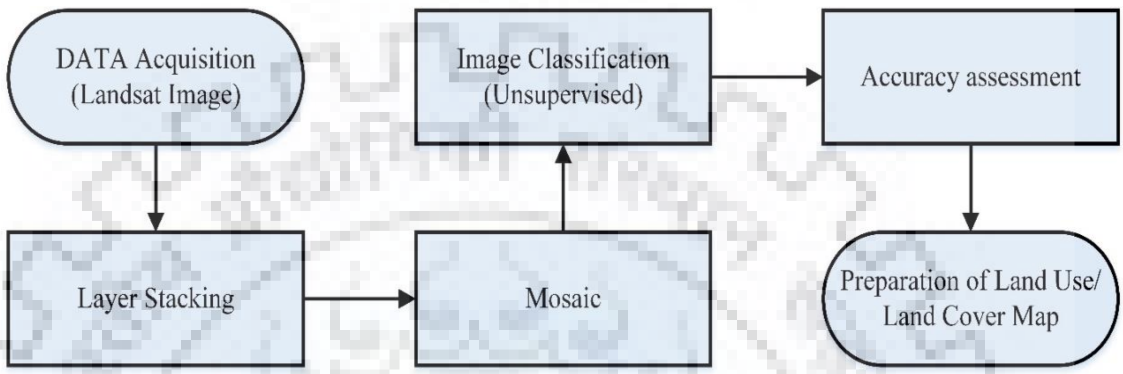


Figure 4.5: Flowchart of LU/LC map preparation method.

Table showing below showing classification of land use/ land cover of the study area. In which basin map is classified into 7 categories to easily understand variations in the study area. Which are covering like the Agricultural land of 22.20%, Forest of 51.11%, Shrubs and bushes of 14.98%, Barren land of 1.65%, Snow and ice of 9.03%, Water bodies of 0.565%, and urban areas of 0.455%. Details are enlisted in Table.3 below:

Table 4.1: showing LULC classification of the study area basin map.

S.no	Class	Area in Sq.km	Area in %
1	Agricultural land	6,419.88	22.20
2	Forest	14,781.03	51.11
3	Shrubs and bushes	4,334.40	14.98
4	Barren land	1,578.23	1.65
5	Snow and ice	2,613.46	9.03
6	Water bodies	163.40	0.565
7	Urban areas	131.51	0.455
		28,922.00	100.00

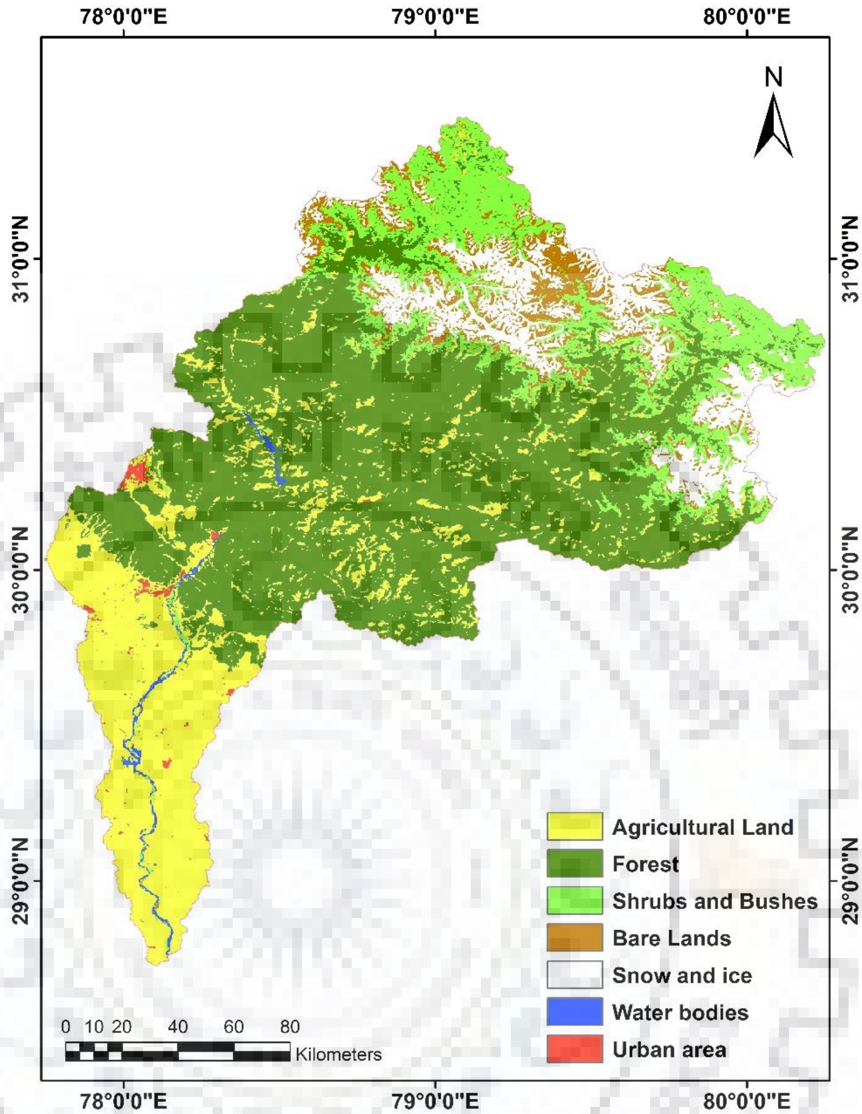
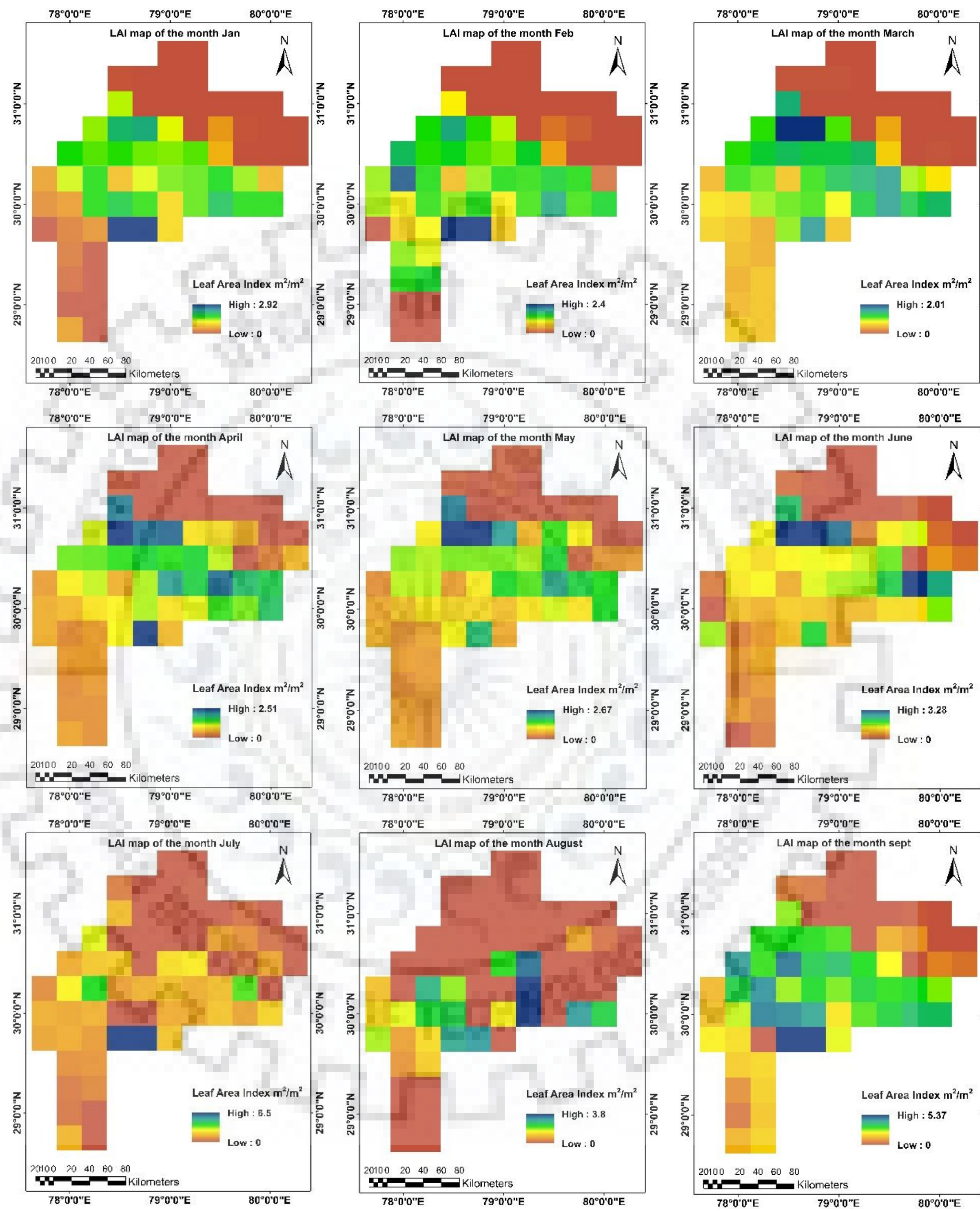


Figure 4.6: Land Use/ Land Cover map of the study area.

Vegetation information in VIC is isolated into two documents. One of them is vegetation library and other is vegetation parameter file.

a. Vegetation parameter:

Vegetation parameter file contains the matrix cell ID number, number of sorts of vegetation classes at every grid cell, vegetation class ID (Defined in vegetation library), portion of each vegetation class in a grid cell, root profundity at various layer, portion of root at various root profundity layer, LAI at various months. Monthly TERRA-MODIS LAI data downloaded from http://neo.sci.gsfc.nasa.gov/Search.html. Using ArcGIS spatial analysis tool, LAI information was extracted for each grid cell.


LAI map of the month Jan
Leaf Area Index m²/m²
High : 2.92
Low : 0
LAI map of the month Feb
Leaf Area Index m²/m²
High : 2.4
Low : 0
LAI map of the month March
Leaf Area Index m²/m²
High : 2.01
Low : 0
LAI map of the month April
Leaf Area Index m²/m²
High : 2.51
Low : 0
LAI map of the month May
Leaf Area Index m²/m²
High : 2.67
Low : 0
LAI map of the month June
Leaf Area Index m²/m²
High : 3.28
Low : 0
LAI map of the month July
Leaf Area Index m²/m²
High : 6.5
Low : 0
LAI map of the month August
Leaf Area Index m²/m²
High : 3.8
Low : 0
LAI map of the month sept
Leaf Area Index m²/m²
High : 5.37
Low : 0
78°0'0"E
79°0'0"E
80°0'0"E
31°0'0"N
30°0'0"N
29°0'0"N
N
20100 20 40 60 80
Kilometers

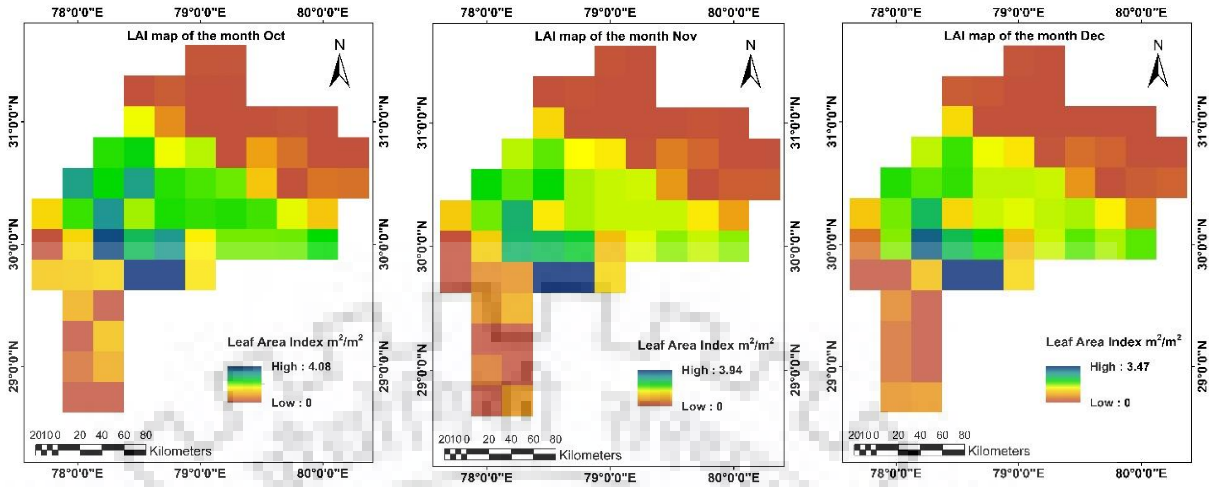


Figure 4.7: LAI map of the study area.

Using the land use and land cover data which are prepared in the above section covered vegetation parameter file was prepared to run the model. perspective of designed vegetation parameter document is appeared in Figure showing underneath:

```
1 5
   7 0.203941 0.10 0.10 1.00 0.65 1.00 0.25
     0.437 0.525 0.300 0.150 0.162 0.188 0.363 0.825 1.112 0.837 0.438 0.363
   8 0.002187 0.10 0.10 1.00 0.65 0.50 0.25
     0.225 0.300 0.463 0.538 0.325 0.913 2.538 1.925 0.500 0.200 0.200 0.213
   9 0.378018 0.10 0.10 1.00 0.65 0.50 0.25
     0.350 0.237 0.312 0.550 0.337 0.337 0.800 0.712 0.250 0.175 0.538 0.538
  10 0.061900 0.10 0.10 1.00 0.70 0.50 0.20
     0.200 0.138 0.138 0.138 0.175 0.438 1.062 1.250 0.900 0.338 0.163 0.138
  11 0.353954 0.10 0.10 0.75 0.60 0.50 0.30
     0.534 0.942 0.618 0.132 0.100 0.115 0.157 0.501 0.706 0.415 0.148 0.200
2 5
   7 0.114900 0.10 0.10 1.00 0.65 1.00 0.25
     0.400 0.450 0.250 0.125 0.138 0.162 0.350 0.800 1.050 0.837 0.463 0.363
   8 0.274877 0.10 0.10 1.00 0.65 0.50 0.25
     0.225 0.300 0.463 0.538 0.325 0.913 2.538 1.925 0.500 0.200 0.200 0.213
   9 0.063649 0.10 0.10 1.00 0.65 0.50 0.25
     0.400 0.262 0.312 0.550 0.337 0.337 0.663 0.587 0.287 0.225 0.587 0.587
  10 0.138897 0.10 0.10 1.00 0.70 0.50 0.20
     0.200 0.138 0.138 0.138 0.175 0.438 1.062 1.250 0.900 0.338 0.163 0.138
  11 0.298881 0.10 0.10 0.75 0.60 0.50 0.30
     0.488 0.850 0.600 0.150 0.100 0.125 0.175 0.575 0.863 0.525 0.175 0.200
3 3
```

Figure 4.8: Sample vegetation file of the study area

b) Vegetation Library:

Physical condition of the land is depicted by land cover through the land use practices of the area. Fluxes creating by the precipitation wholly dependent on the land cover classification and its density. Prioritising to the extent of the land cover classification LAI plays key role in fluxes generation. Generally, vegetation library file for the model captured from the GLDAS site. In this VIC model considers Inter-yearly varieties associated with vegetation highlights and LAI esteems are steady for year to year for a particular class compose. Also, model accounts the vegetation roughness, wind height, architectural resistance, minimum stomatal resistance, displacement height of vegetation.

4.6 Soil parameter file

Soil parameter file comprises data of every lattice cells soil attributes. Soil parameter file alluded to be a standout amongst the most critical record relating to VIC model. Every matrix cells having exceptional data about soil properties according to the model prerequisite. It concludes the soil surface, soil water holding capacity, soil transmission characteristics to reaching precipitation into ground surface. For preparation of soil database, study of variability in average temperature and mean annual precipitation over the study area required. Figure below shows the glimpse of the above mentioned patterns over the basin.

Average temperature of July month of the study area is required for the preparation of soil parameter file. Temperature data for period 1990 to 2014 have been averaged to individual grid points. The map below shows the spatial distribution of average July temperature over the study area.

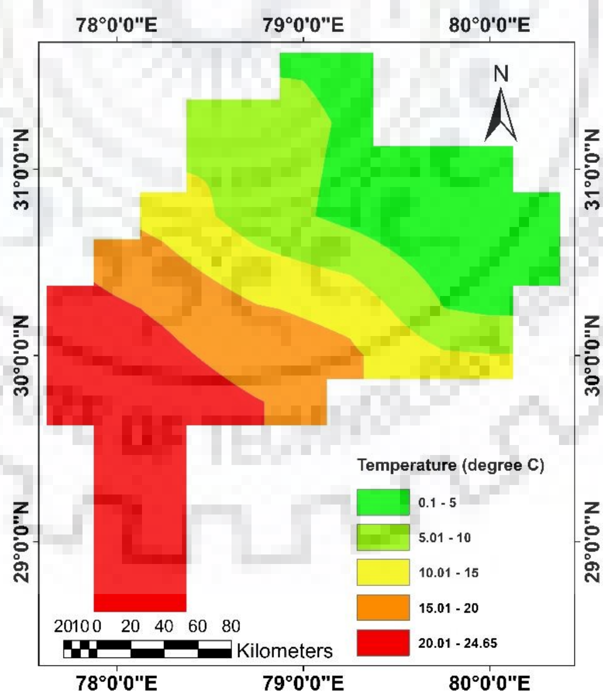


Figure 4.9: Map of Average July temperature of the study area.

Similarly, mean annual precipitation from period of 1990 to 2014 was prepared as per soil database requirement to run the model. Variations of annual precipitation over the basin as picturised below:

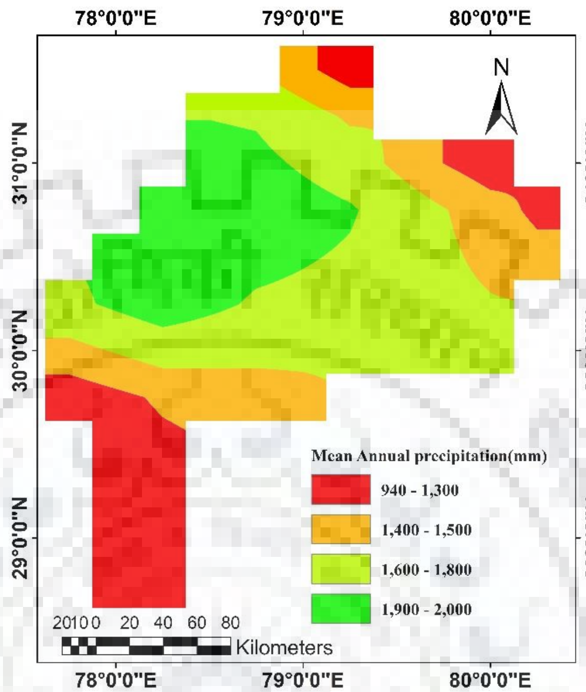


Figure 4.10: Map of Mean Annual precipitation of the study area.

From the prepared soil map explained in section 3.2.2 (soil), the classes of soil types are obtained. Soil properties of each grid cell produced by soil classes obtained by soil map, Average temperature and average annual precipitation produced from IMD data for the study area and accordingly soil parameter file was prepared.

The parameters included in Soil parameter file are as follows (Table 4.2):

Table 4.2: Soil parameter file information.

Column 1	active grid indicator
Column 2	Grid cell number
Column 3	Latitude of grid cell
Column 4	Longitude of grid cell
Column 5	Variable infiltration curve parameter
Column 6	Fraction of D_{smax} where non-linear baseflow begins
Column 7	Maximum velocity of baseflow
Column 8	Fraction of maximum soil moisture where non-linear baseflow

Column 9	Exponent used in baseflow curve (normally set to 2)
Column 10-12	Exponent n in Campbell's equation for hydraulic conductivity
Column 13-15	Saturated hydrologic conductivity
Column 16-18	Soil moisture diffusion parameter
Column 19-21	Initial layer moisture content
Column 22	Average elevation of grid cell
Column 23-25	Thickness of each soil moisture layer
Column 26	Average soil temperature
Column 27	Soil thermal damping depth
Column 28-30	Bubbling pressure of soil
Column 31-33	Quartz content of soil
Column 34-36	Bulk density of soil layer
Column 37-39	Soil particle density
Column 40	Time zone offset from GMT
Column 41-43	Fractional soil moisture content at the critical point
Column 44-46	Fractional soil moisture content at the wilting point
Column 47	Surface roughness of bare soil
Column 48	Surface roughness of snowpack (0.005m~0.2m)
Column 49	Average annual precipitation
Column 50-52	Soil moisture layer residual moisture
Column 53	frozen soil algorithm (if set to 1 then it is activated)

Sample of soil parameter file is presented in the Figure 4.11:

#Run	GRID	LAT	LONG	b_inf	Ds	Dsmax	Ws	C	EXP_C1	EXP_C2	EXP_C3	K_sat1	K_sat2	K_sat3	phi_s	phi_s
1	1	28.7500	78.0000	0.4000	0.0010	0.1000	0.9000	2.0000	9.4750	10.1800	10.1800	435.0300	248.1750	248.1750	-9999.0000	-9999.0
1	2	28.7500	78.2500	0.4000	0.0010	0.1000	0.9000	2.0000	9.3800	9.8400	9.8400	454.7100	343.1900	343.1900	-9999.0000	-9999.0
1	3	29.0000	78.0000	0.4000	0.0010	0.1000	0.9000	2.0000	9.4550	10.0875	10.0875	426.4850	267.9500	267.9500	-9999.0000	-9999.0
1	4	29.0000	78.2500	0.4000	0.0010	0.1000	0.9000	2.0000	9.3500	9.6850	9.6850	435.1800	374.2350	374.2350	-9999.0000	-9999.0
1	5	29.2500	78.0000	0.4000	0.0010	0.1000	0.9000	2.0000	9.4350	9.9950	9.9950	417.9400	287.7250	287.7250	-9999.0000	-9999.0
1	6	29.2500	78.2500	0.4000	0.0010	0.1000	0.9000	2.0000	9.3200	9.5300	9.5300	415.6500	405.2800	405.2800	-9999.0000	-9999.0
1	7	29.5000	78.0000	0.4000	0.0010	0.1000	0.9000	2.0000	9.4175	9.8650	9.8650	459.9600	358.9525	358.9525	-9999.0000	-9999.0
1	8	29.5000	78.2500	0.4000	0.0010	0.1000	0.9000	2.0000	9.3750	9.5850	9.5850	472.8450	454.2000	454.2000	-9999.0000	-9999.0
1	9	29.7500	77.7500	0.4000	0.0010	0.1000	0.9000	2.0000	9.3700	9.8300	9.8300	473.9200	357.2400	357.2400	-9999.0000	-9999.0
1	10	29.7500	78.0000	0.4000	0.0010	0.1000	0.9000	2.0000	9.4000	9.7350	9.7350	501.9800	430.1800	430.1800	-9999.0000	-9999.0
1	11	29.7500	78.2500	0.4000	0.0010	0.1000	0.9000	2.0000	9.4300	9.6400	9.6400	530.0400	503.1200	503.1200	-9999.0000	-9999.0
1	12	29.7500	78.5000	0.4000	0.0010	0.1000	0.9000	2.0000	9.4400	9.7850	9.7850	985.9450	937.7100	937.7100	-9999.0000	-9999.0
1	13	29.7500	78.7500	0.4000	0.0010	0.1000	0.9000	2.0000	9.4500	9.9300	9.9300	1441.8500	1372.3000	1372.3000	-9999.0000	-9999.0
1	14	29.7500	79.0000	0.4000	0.0010	0.1000	0.9000	2.0000	9.7650	10.2300	10.2300	1216.2650	1146.3550	1146.3550	-9999.0000	-9999.0
1	15	29.7500	79.2500	0.4000	0.0010	0.1000	0.9000	2.0000	10.0800	10.5300	10.5300	990.6800	920.4100	920.4100	-9999.0000	-9999.0
1	16	30.0000	77.7500	0.4000	0.0010	0.1000	0.9000	2.0000	9.2650	9.5000	9.5000	508.0800	476.2950	476.2950	-9999.0000	-9999.0
1	17	30.0000	78.0000	0.4000	0.0010	0.1000	0.9000	2.0000	9.2600	9.4650	9.4650	681.5675	664.6150	664.6150	-9999.0000	-9999.0
1	18	30.0000	78.2500	0.4000	0.0010	0.1000	0.9000	2.0000	9.2550	9.4300	9.4300	855.0550	852.9350	852.9350	-9999.0000	-9999.0

Figure 4.11: Sample Soil database file for the study area.

4.7 Routing file preparation

After preparation of input parameters files, Linux Operating System has been used to compile the VIC source code and to run the model for simulation. After running the model fluxes (such as runoff, base flow, soil moisture etc.) have been generated and to compare these fluxes with the observed flow, runoff and base flow should be routed to an outlet. Routing of these fluxes can be performed in a separate routing model. For routing, flow direction fraction and station location files to be created according to the model requirement. Routing model also requires typical Unit hydrograph of the basin. The procedure for preparation of required files for routing has been discussed in the following sections:

4.7.1 Flow direction file:

Working principle of VIC routing model with respect to flow direction is different from the ArcGIS:

1. Flow direction is derived from SRTM DEM by using hydrology tool of ArcGIS through generating the Fill and Flow Accumulation grid.
2. Modification of stream line network is required in developed flow accumulation. Flow direction in the grid cells not directed to right course or outside direction grids to be converted.
3. Flow direction file created by ArcGIS counts from east and continuous to clockwise direction but in VIC model it starts from north direction as shown in Figure 4.12.

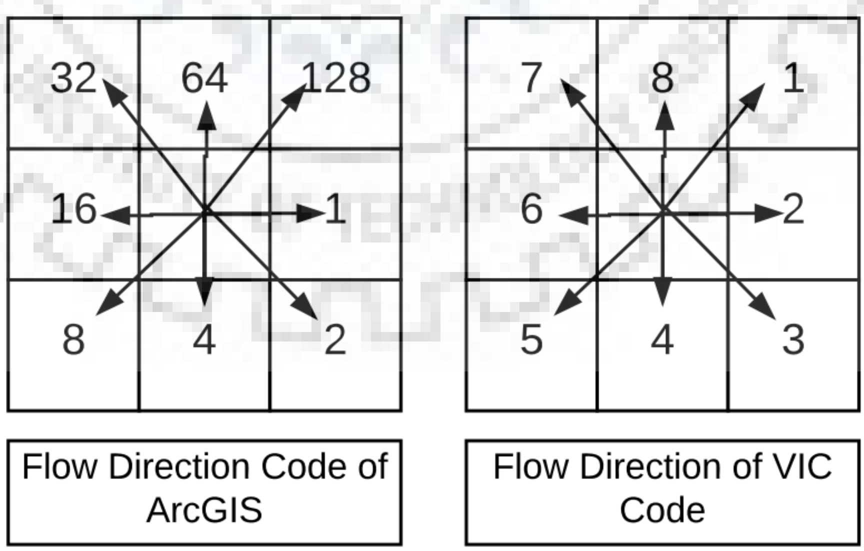


Figure 4.12: Flow direction code for VIC Model.

4. Using raster calculator toolbox in ArcGIS, direction of flow to be modified as shown in Figure 4.12. A sample of flow direction file have been presented in Figure 4.13.

```
ncols         13
nrows         12
xllcorner     77.375
yllcorner     28.625
cellsize      0.25
NODATA_value  -9999
-9999 -9999 -9999 -9999 -9999 -9999 1 3 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 6 5 1 2 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 5 6 6 4 5 6 1 -9999 -9999
-9999 -9999 -9999 6 5 5 5 5 5 6 6 1 -9999
-9999 -9999 7 6 5 5 5 5 6 7 7 6 -9999
-9999 5 5 5 6 7 7 7 7 5 5 -9999 -9999
-9999 4 5 6 7 5 6 5 6 5 5 -9999 -9999
-9999 3 5 7 5 5 5 6 -9999 -9999 -9999 -9999 -9999
-9999 -9999 4 7 5 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 5 5 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 4 5 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 3 5 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
```

Figure 4.13: Flow direction file of the study area.

4.7.2 Fraction file:

Fraction file for VIC routing model has been prepared using ArcGIS. Procedure for preparation of fraction file is as follows:

1. Shape file of the study area has been projected into UTM to evaluate the area of each grid cell contributing in the flow.
2. Basin to be intersected to grid cell size of 0.25°× 0.25°.
3. Dividing the area of the square grid (0.25°×0.25°) to obtain the fraction of flow corresponds to each grid.

a sample of fraction file is presented in Figure 4.14 below.

```
ncols         13
nrows         12
xllcorner     77.375
yllcorner     28.625
cellsize      0.25
NODATA_value  -9999
-9999 -9999 -9999 -9999 -9999 -9999 0.09763402 0.02880174 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 0.04597265 0.3232931 0.7770813 0.4739747 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 0.2672768 1 1 1 0.4779749 0.3478207 0.03651366 -9999 -9999
-9999 -9999 -9999 0.4119846 1 1 1 1 1 1 0.7675027 0.2181857 -9999
-9999 -9999 0.04349886 0.5786934 1 1 1 1 1 1 0.5563224 0.06159518 -9999
-9999 0.1183282 0.6366283 1 1 1 1 1 1 1 0.5684205 -9999 -9999
-9999 0.3003529 1 1 1 1 1 0.2040811 0.3549677 0.3602894 0.06066415 -9999 -9999
-9999 0.03177914 1 1 0.3337218 0.1892228 0.3425713 0.01247124 -9999 -9999 -9999 -9999 -9999
-9999 -9999 0.6856722 0.6011103 6.881394e-005 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 0.6615149 0.4044109 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 0.4793692 0.4495956 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 0.1219285 0.09762422 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
```

Figure 4.14: Sample fraction file of the study area.

4.7.3 Station location file

In this study station point selected at Garhmuktheshwar, CWC, G&D site for streamflow output. Station location file for the study area prepared in the required text format as mentioned below:

```
1       Garh    4       1       -9999
NONE
```

Figure 4.15: Sample Station location file of the study area.

1. “1” means route model will be simulated at that location.
2. Garh: Name of the CWC, G&D site.
3. 4, and 1: Column, and Row number of Gauging station location in the fraction file.
4. -9999: Default.
5. NONE: Default.

RESULT AND DISCUSSION

This chapter includes output of initial simulation from VIC model, sensitivity analysis of upper layer parameters, calibration and validation of output data obtained by VIC model with observed data, estimation of runoff, soil moisture and evapotranspiration and Soil Moisture Estimation using Scatterometer Data.

5.1 VIC Model Setup:

In the VIC model, whole basin is discretized into number of grids based on the user defined threshold and the required spatial and weather datasets as specified in previous chapter were prepared using ArcGIS software. The grid size of 0.25°×0.25° has been used in this study because precipitation data is available at the same grid size. The Ganga sub-basin was divided into 68 grids.

The Hydrological analysis in the VIC model was carried out at grid level, in daily time steps using water balance mode. Runoff, base flow, soil moisture and several other parameters were simulated for the period of 25 years (1990 to 2014) and subsequently discharge and base flow have been routed to the outlet using Lohman's routing model. In the present study, only one outlet was selected because observed flow was available for only one station. Further, simulated discharge was compared with the observed flow for the year 2009 (based on the availability of observed flow) (Figure 5.1) to check the performance of uncalibrated VIC model.

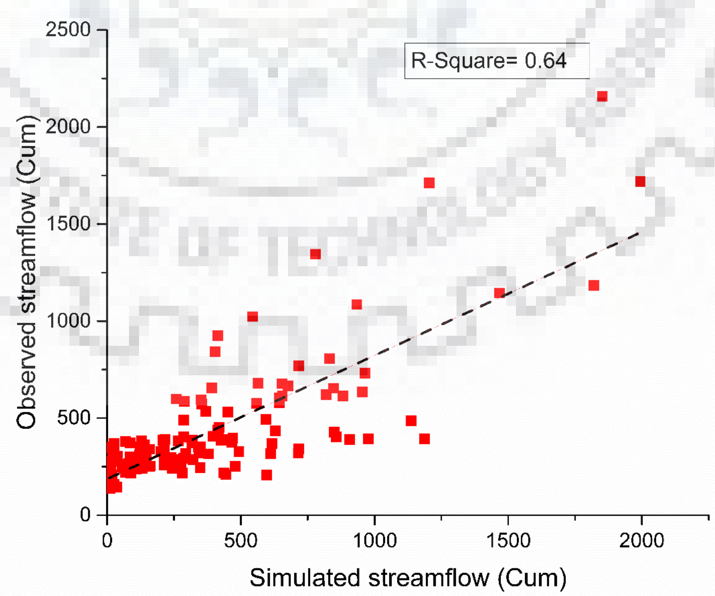


Figure 5.1: Comparison between the pre-calibrated observed and simulated daily discharge at Garhmuktheshwar for the period June-2009 to Oct-2009.

Because of highly regulated flow in the study area during non-monsoon season, the comparison between observed and simulated flow was done only for the monsoon season. It can be observed that simulated flow followed the trend of observed flow Figure 5.2 with coefficient of determination (R^2) =0.64. However, a Nash Sutcliffe efficiency of 0.38 shows that the results are not satisfactory and model calibration is required.

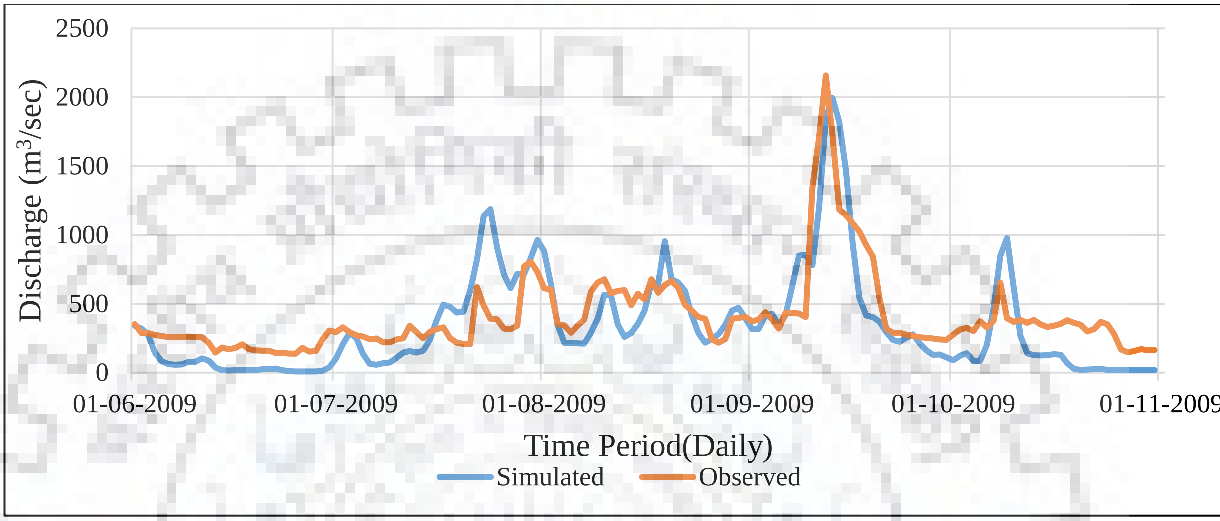


Figure 5.2: Pre-calibrated simulated discharge and observed flow on daily basis

5.2 Sensitivity Analysis

Over-parameterization is a well-known and often described problem with hydrological models. When the number of parameters in a model are much, it is difficult to select which parameters should be calibrated so that the model response mimics the actual field. In such cases, sensitivity analysis is helpful to identify parameters that have a significant influence on model simulations of real world observations for specific catchment.

sensitivity analysis was performed to recognize the parameters which are sensitive in for the study area. These parameters were changed in accordance with play out a further alignment with reference to the literature review of past studies, different adjustment parameters have been considered. The depiction, the scopes of parameters and their most proper esteems utilized for the study area are listed in Table 5.1:

Table 5.1: Sensitive parameters and respective ranges.

S.No	Parameters	Description	Lower boundary	Upper boundary	default
1	Ds	Fraction of Ds_{max} where non- linear baseflow begins.	0	1	0.001
2	Ds_{max}	Max baseflow that can occur from the lowest soil layer(mm/day).	0	~30 mm/day	0.9
3	Ws	Fraction of maximum soil moisture where non-linear baseflow occurs. This is analogues to Ds.	0	1	0.001
4	b_{inf}	The amount of available infiltration capacity as a function of relative saturated grid cell area.	0	~0.40	0.25-0.35
5	Soil Depth (d2 and d3)	In general, for runoff considerations, thicker soil depths slow down seasonal peak flows and increase the loss due to evapotranspiration.	0.1 to 1.5m (of each layer)		d2 - 1.5 & d3-0.22

In spite of the fact that the VIC model contains numerous parameters, it is more appropriate to modify some of these parameters amid adjustment than others. Frequently, the refinement is based on how much the parameter esteems can really be observed or measured. Main parameters which contributes surface flow are upper layer parameters, which are soil depth (d2 and d3) and infiltration curve (b_i) and remaining are lower layer parameter. In this study, basically model was calibrated to first on upper layer parameters and from the resultant parameter standards, lower layer parameters are assigned.

5.2.1 Sensitivity of depth of soil layers:

After simulations for various combinations of different soil layer depths (d2 & d3), obtained results were compared with observed values using coefficient of determination (R^2). As results shown in Figure 5.3, best cases are selected. It is observed that, best results are obtained when soil layers are D2=1.50m & D3=0.60 m. When D3 soil layer is fully saturated, it increases the baseflow.

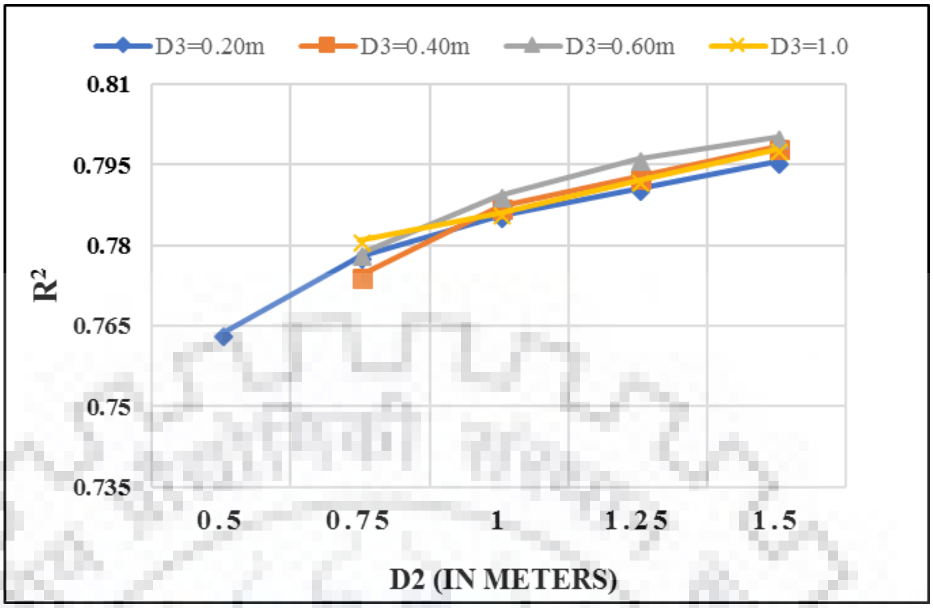


Figure 5.3: R^2 for different d2-d3 (soil depths) combinations.

5.2.2 Sensitivity of infiltration parameter (b_i)

Infiltration (b_i) is the parameter that characterizes the state of variable infiltration capacity curve. It depicts the measure of accessible invasion limit as a component of relative saturated grid cell zone. Higher estimates bring down invasion and yield higher surface runoff. Theoretically, infiltration parameter (b_i) can take the value between 0 to 0.4. Figure 5.4 indicates the sensitivity of b_i at different depths of D2. As the depth of second layer of soil increases, coefficient of determination (R^2) increases with increases in infiltration parameter. Therefore, the infiltration parameter is the most sensitive parameter in the present study.

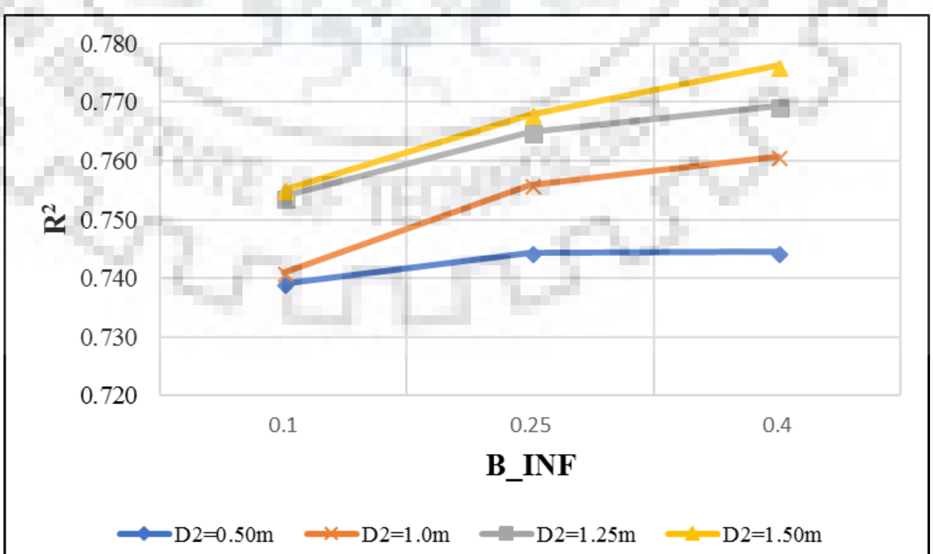


Figure 5.4: Sensitivity of infiltration parameter (bi) for the study area.

5.3 Calibration of the VIC Model

While a significant number of the parameters for the VIC model depends on satellite perceptions or topographical studies, some of them are either heterogeneous in space. For calibration parameters, either should make suspicions about their esteems or adjust them (find ideal esteems for them) that limit the contrasts between simulated yield and Observed gauge.

A parameter estimation conspires for the land surface model (VIC-3L) is examined. VIC-3L parameters are decided for adjustment by an orderly manual alignment approach in the storm records of June to October for the catchment to predict the streamflow.

Comparisons of the simulated results, after calibration demonstrate that the adjusted parameters can diminish bias and increment the Nash Sutcliffe efficiency and coefficient of determination (R^2). An affectability examination on adjusted parameters will indicate which parameters are more sensible. In this manner, appropriate adjustment for the parameters (particularly for the variable infiltration curve parameter and the profundity of the second soil layer d2) is critical for re-enacting in a particular locale.

The typical approach includes adjustment of six parameters:

a) **The infiltration parameter (bi),** which controls the partitioning of rainfall (or snowmelt) into infiltration and direct runoff.

b) **d2 and d3**, which are the second and third soil layer thicknesses (d1, the top soil layer depth)

c) **Dsmax, Ds, and Ws,** which are baseflow parameters and furthermore are evaluated through adjustment. Dsmax is the most extreme baseflow, Ds is the part of baseflow, and Ws is the portion of greatest soil dampness substance of the third soil layer at which non-straight baseflow happens. These three baseflow parameters decide how rapidly the water put away in the third soil layer is cleared as baseflow. The three baseflow parameters and the third soil layer (d3) are utilized with just minor modification amid the alignment, while the infiltration parameter (bi) and the second soil layer (d2) are focused for concentrated adjustment.

The adjustment of these parameters is led through an experimental technique that prompts an adequate match of model simulated with observed streamflow. Other than visual examination of hydrographs, two target capacities are frequently utilized:

- Coefficient of determination (R^2): which describes linearity between the modelled streamflow as compared to the observed streamflow value.

$$R^2 = \left[\frac{\sum_{i=1}^{N}(\mathrm{Qobs,i} - \mathrm{Qav\ obs,i})(\mathrm{Qsim,i} - \mathrm{Qav\ sim,i})}{\sum_{i=1}^{N}(\mathrm{Qobs,i} - \mathrm{Qav\ obs,i})^2 \sum_{i=1}^{N}(\mathrm{Qsim,i} - \mathrm{Qav\ sim,i})^2}\right]^2$$

- Nash-Sutcliffe efficiency (NSE): which describes the prediction skill of the modelled streamflow as compared to the observed streamflow value.

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{N}(\mathrm{Qsim,i} - \mathrm{Qobs,i})^2}{\sum_{i=1}^{N}(\mathrm{Qobs,i} - \overline{\mathrm{Q}}_{\mathrm{obs}},\mathrm{i})^2}$$

- The Error (Er): between simulated and observed mean streamflow are calculated as:

$$Error = \overline{\mathrm{Q}}_{\mathrm{sim}} - \frac{\overline{\mathrm{Q}}_{\mathrm{obs}}}{\overline{\mathrm{Q}}_{\mathrm{obs}}}$$

Calibration of model was carried out on daily base time scale in which observed flow data was obtained from concerned authorities. In this study, data from the month of June, 2009 to October, 2009 are considered due to availability of observed flow at the outlet for the purpose of calibration. The results are provided in Table 5.2.

Table 5.2: Statistical analysis of observed and simulated daily discharge at Garhmuktheshwar: model Calibration.

S. No	Statistical Indices	Streamflow (m^3/sec) during June, 2009 to Oct, 2009		
		Observed	Pre-calibrated	Calibrated
1	Mean	405.29	343.88	381.89
2	Standard Deviation	-	43.42	16.55
3	Count	153	153	153
4	R^2	-	0.64	0.76
5	NSE	-	0.38	0.65
6	Error	-	0.15	0.06

After calibration, the values of R^2 and NSE obtained for the period of June, 2009 to October, 2009 are 0.76 and 0.65 respectively and percentage error is 6% (Table 5.2) which indicates that the model performance has been improved.

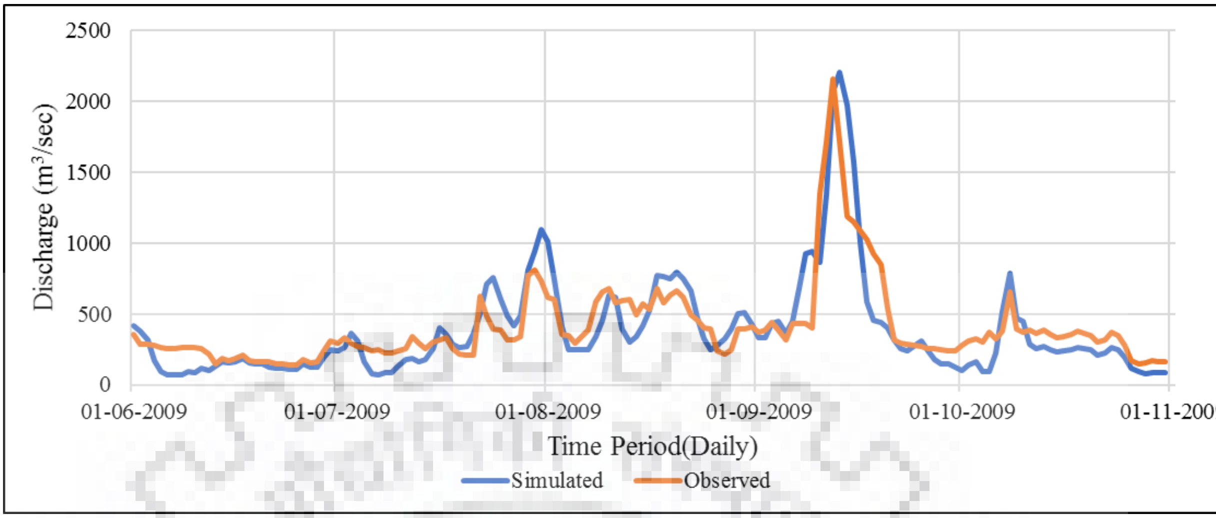


Figure 5.5: Calibrated model results showing with daily simulated hydrograph.

However, Figure 5.5 presents a comparison between observed and simulated flow. From the Figure, it is evident that the simulated flow matched very well with the observed flow. However, the peak flow is overestimated in some cases.

5.4 Validation of VIC Model

Validation of the VIC model was carried out by running the model without changing any parameters after calibration and with a different set of input data. For this, total available observed data series were divided into two parts i.e. 2009 for calibration and 2010 for validation. Validation was carried out on the basis of comparison of estimated and observed streamflow during the validation period (June 2010 to October 2010) using statistical indices, viz., coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) (Table 5.3).

Table 5.3: Statistical analysis of observed and simulated daily discharge at Garhmuktheshwar: model validation.

S. No.	Statistical Indices	Streamflow (m^3/sec) during June, 2010 to Oct, 2010	
		Observed	Simulated
1	Mean	1758.11	1428.31
2	Count	153	153
3	R^2	-	0.78
4	NSE	-	0.73
5	Error	-	0.18

Average streamflow during the validation period was quite high. R2 and NSE values are found to be 0.78 and 0.73 respectively which indicates that the model performed well during the validation period.

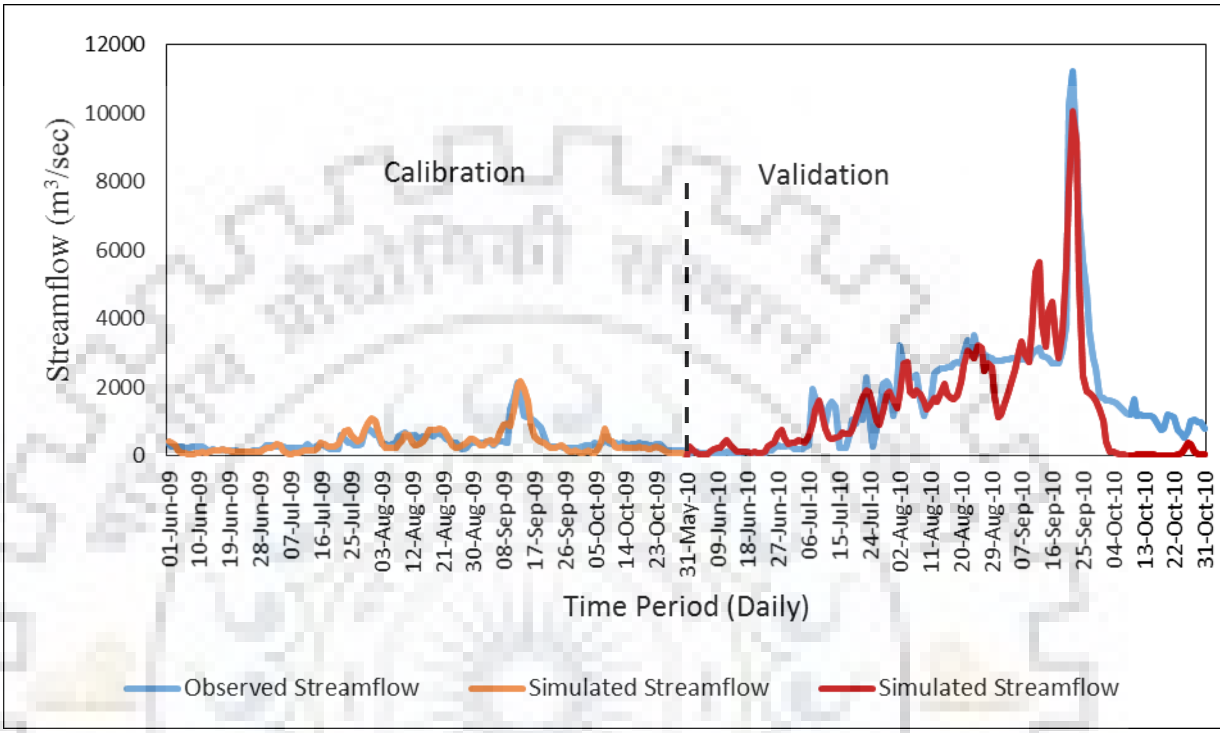


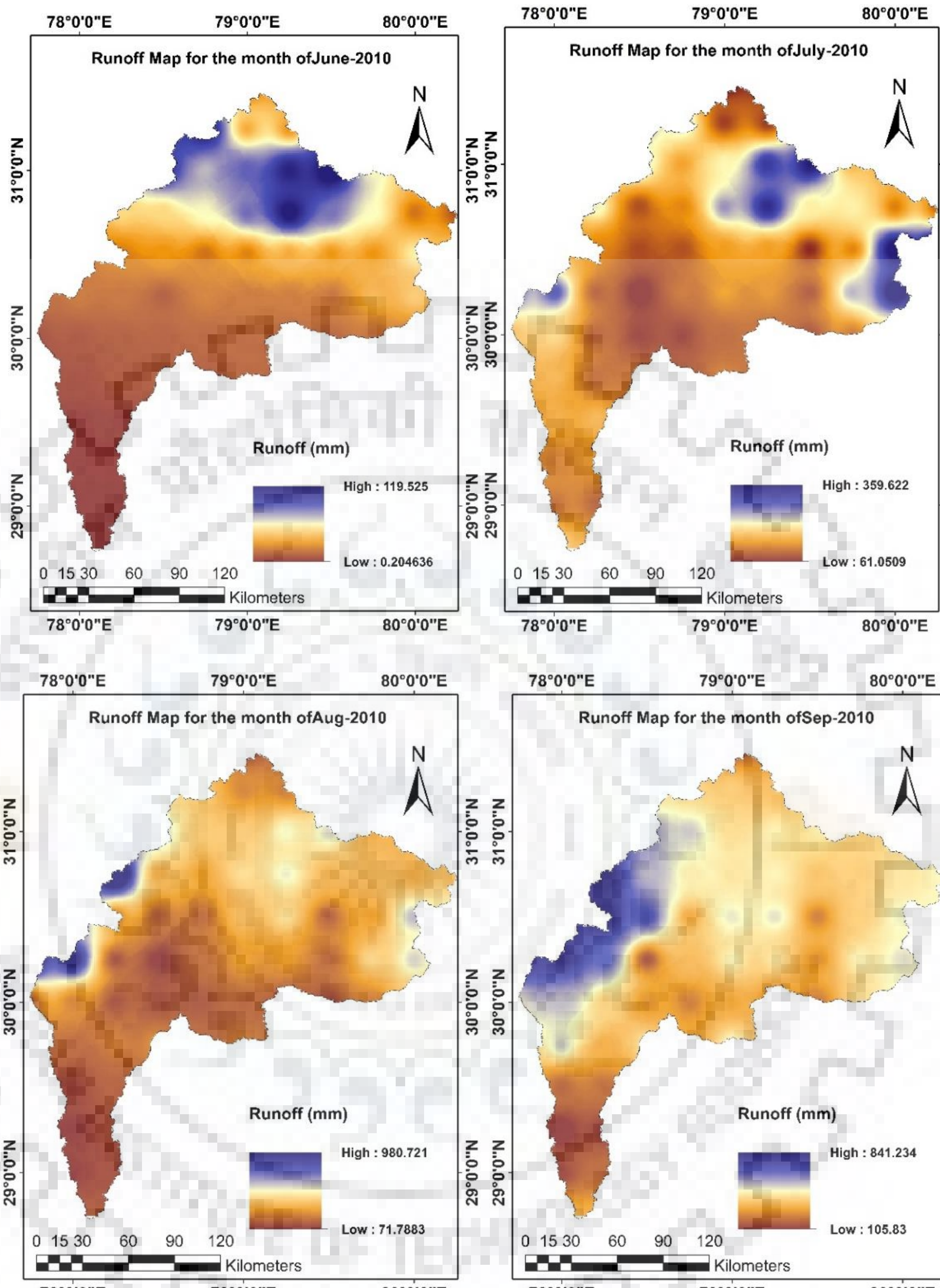
Figure 5.6: Calibration and Validation of VIC model

Figure 5.6 shows the plot of simulated and observed streamflow for calibration and validation period over the study area. From Figure, it can be noticed that, during the validation period, the peak of simulated streamflow matched well with observed streamflow. The overall pattern of the simulated streamflow during calibration possessed a good agreement with the observed streamflow.

Calibrated and validated model was used for determination of surface runoff, Evapotranspiration (E_t) and soil moisture over the study area. And the results obtained are described as below:

5.5 Surface Runoff assessment of the study area

Surface runoff was generated as output by VIC model. Spatial distribution of the surface runoff is presented in Figure 5.7. Highest surface runoff (980 mm) was observed in the month of August while that of lowest (0.01 mm) was observed in the month of October.


Runoff Map for the month ofJune-2010
Runoff (mm)
High : 119.525
Low : 0.204636
Runoff Map for the month ofJuly-2010
Runoff (mm)
High : 359.622
Low : 61.0509
Runoff Map for the month ofAug-2010
Runoff (mm)
High : 980.721
Low : 71.7883
Runoff Map for the month ofSep-2010
Runoff (mm)
High : 841.234
Low : 105.83
N
0 15 30 60 90 120
Kilometers
78°0'0"E
79°0'0"E
80°0'0"E
31°0'0"N
30°0'0"N
29°0'0"N

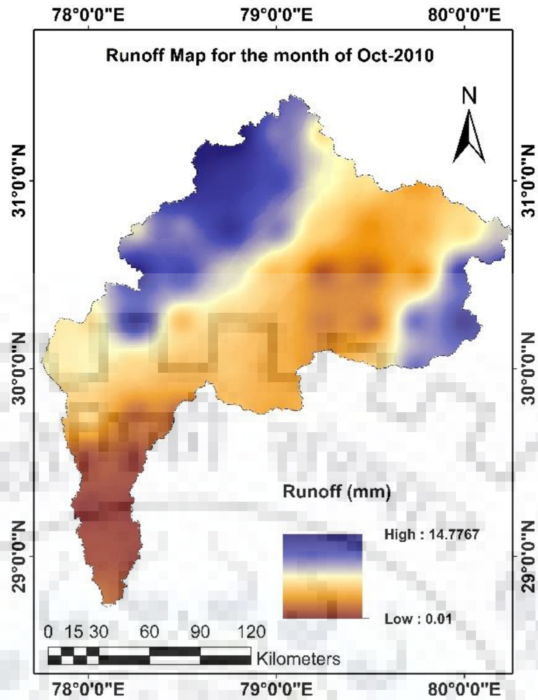
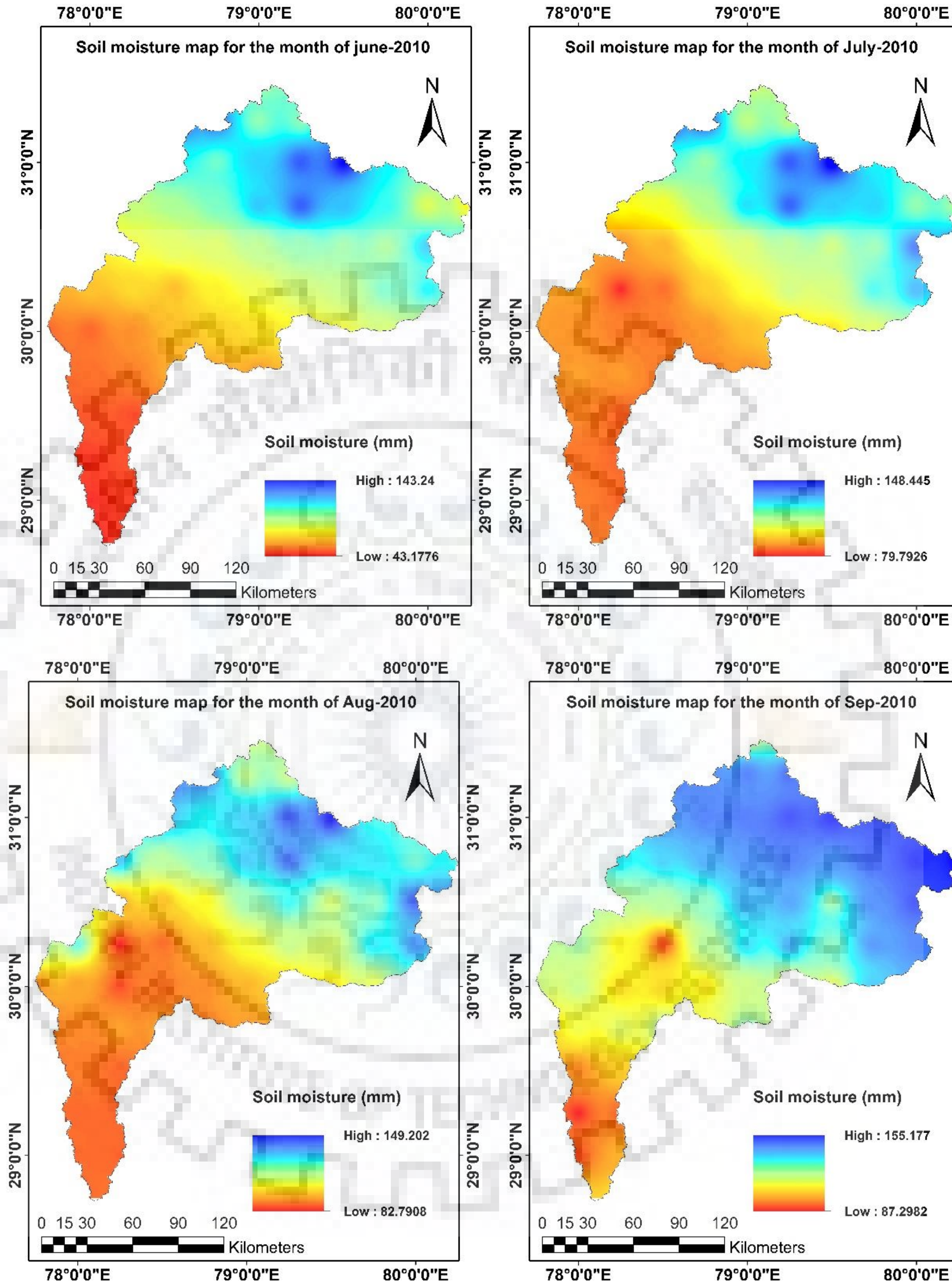


Figure 5.7: Surface Runoff Maps of the study area.

From the above Figure, it can be observed that surface runoff is higher in the hilly regions whereas the same is lower in the flat regions of the catchment. This can be attributed to the higher slope and consequential lower infiltration rate in the hilly regions and vice versa. The higher slope leads to reduction in the opportunity time to infiltrate and hence produces higher runoff.

5.6 Estimation of soil moisture using VIC model:

Soil moisture for the study area was also generated from the simulation of VIC model. The cumulative monthly soil moisture ranges from 43mm to 155mm. spatial distribution of moisture level for the period of June to October of 2010 is presented in Figure 5.8.


Soil moisture map for the month of june-2010
Soil moisture (mm)
High : 143.24
Low : 43.1776
Soil moisture map for the month of July-2010
Soil moisture (mm)
High : 148.445
Low : 79.7926
Soil moisture map for the month of Aug-2010
Soil moisture (mm)
High : 149.202
Low : 82.7908
Soil moisture map for the month of Sep-2010
Soil moisture (mm)
High : 155.177
Low : 87.2982
N
0 15 30 60 90 120
Kilometers
78°0'0"E
79°0'0"E
80°0'0"E
29°0'0"N
30°0'0"N
31°0'0"N

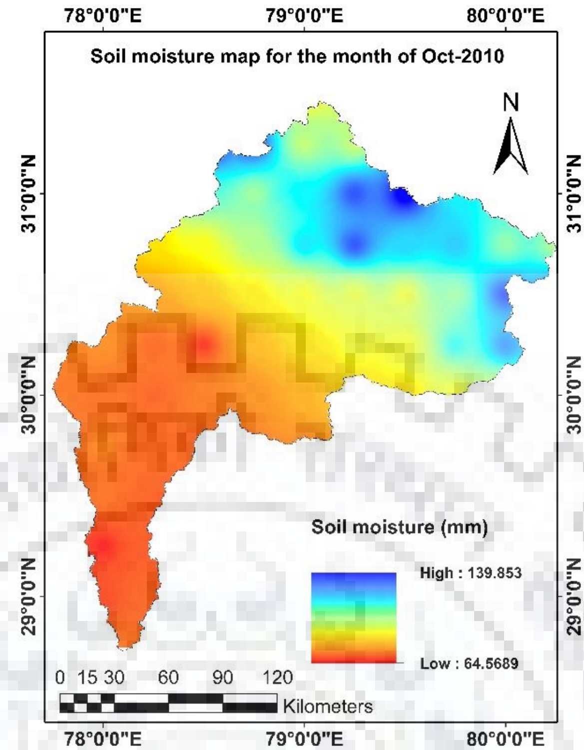
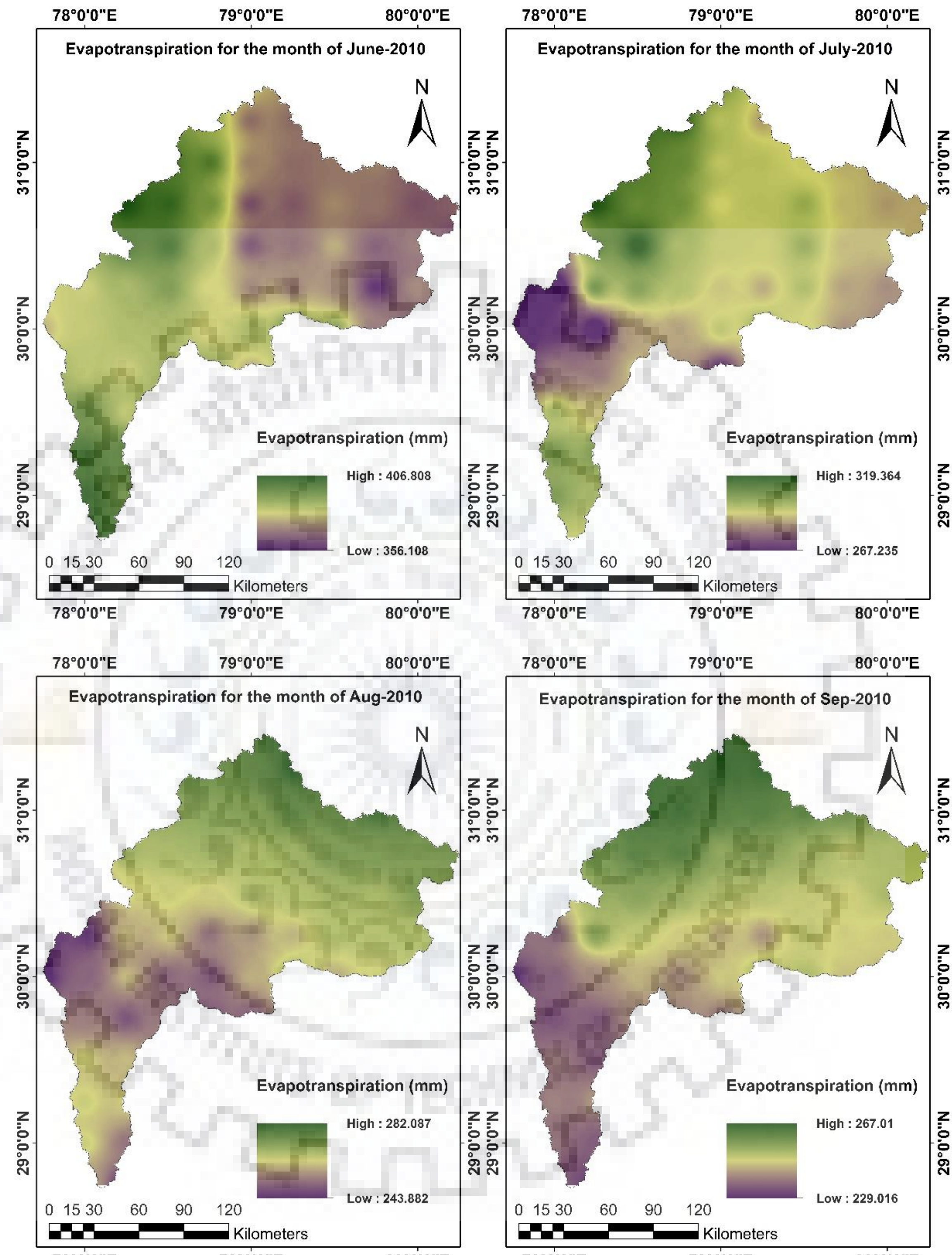


Figure 5.8: Soil Moisture Maps of the study area.

From the maps, highest and lowest soil moisture values were observed in September and October months respectively. Maps are indicating that soil moisture values are highest in the upper region of the study area. These results are very useful for irrigation scheduling and drought related studies in the basin. Further, these results have been used as benchmark for the estimation of soil moisture using the Scatterometer data.

5.7 Estimation of Evapotranspiration:

Evapotranspiration was generated by VIC model. The spatial distribution of ET over the study area is presented in Figure 5.9. ET values range between 229 mm to 406 mm across regions within the catchment.



Evapotranspiration for the month of June-2010
Evapotranspiration (mm)
High : 406.808
Low : 356.108
Evapotranspiration for the month of July-2010
Evapotranspiration (mm)
High : 319.364
Low : 267.235
Evapotranspiration for the month of Aug-2010
Evapotranspiration (mm)
High : 282.087
Low : 243.882
Evapotranspiration for the month of Sep-2010
Evapotranspiration (mm)
High : 267.01
Low : 229.016
0 15 30 60 90 120
Kilometers
N
78°0'0"E
79°0'0"E
80°0'0"E
29°0'0"N
30°0'0"N
31°0'0"N

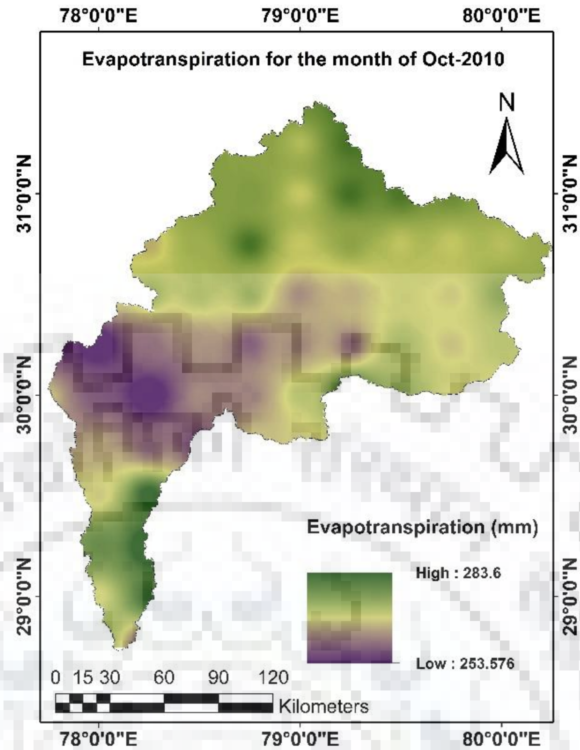


Figure 5.9: Evapotranspiration Maps for the study area.

ET depends on the vegetation transpiration, canopy evaporation and bare soil evaporation. From Figure 5.9, it can be observed that forest and croplands indicating high ET values in the month of June. However, the mountainous region yields high ET values in subsequent months.

5.8 Soil Moisture Estimation using Scatterometer Data

Backscattered signal measured in the microwave region of the electromagnetic spectrum at low frequencies contains substantial information about soil moisture (Ulaby et al., 1982). Several authors have proposed methods for retrieving soil moisture from Scatterometer data (Woodhouse and Hoekman, 2000; Zine et al., 2005). In the past studies, it was found that the variation in the backscatter coefficient is mainly due to variation in the soil moisture content. Owing to the absence of observed soil moisture data for the period under investigation and an excellent reconciliation of VIC streamflow with that of observed data, the soil moisture generated by VIC is set as a reference for evaluation of Scatterometer derived product i.e. Soil Water Index (SWI)

In the present study, methodology adopted for the estimation of soil moisture using Advance Scatterometer (ASCAT) data is as follows:

1. ASCAT 2-daily backscatter coefficient data at VV polarization for the study area was downloaded for the year 2010.
2. Raw data was pre-processed (Stacking and Georefencing) with the help of MATLAB and ENVI softwares.
3. Long term maximum and minimum values of backscatter coefficient for each pixel was calculated.
4. Applied the change detection approach proposed by Wagner et al. (1999) for computation of relative soil moisture or soil moisture index (SWI).

$$SM_t = \frac{\sigma^o(t,\ \theta_{ref}) - \sigma^o_{dry}(t,\ \theta_{ref})}{\sigma^o_{wet}(t,\ \theta_{ref}) - \sigma^o_{dry}(t,\ \theta_{ref})} \quad \ldots(5.1)$$

where, $\sigma^o(t, \theta_{ref})$ is the backscatter coefficient measured on day t with reference angle θ_{ref}; $\sigma^o_{dry}(t, \theta_{ref})$ and $\sigma^o_{wet}(t, \theta_{ref})$ are the historically lowest (representing driest conditions) and highest (representing wettest conditions) values of backscatter coefficients respectively.

5. SWI was resampled to deal with the mismatch between VIC grid resolution and ASCAT derived SWI.
6. A relationship between SWI and top layer soil moisture from VIC model was developed.

The above mentioned procedure was followed for a grid location of 28° N; 79° E and a relationship was developed between the values of SWI derived from Scatterometer data and soil moisture derived from the simulation of VIC model. From the graph shown in Figure 5.10 below, it is seen that there is a very good correlation between SWI from Scatterometer data and simulated soil moisture from VIC model. The value of coefficient of determination (R2) was found to be 0.71 and seems reasonable. The following relationship was developed between soil moisture (SM) and SWI:

$$SM = 20.75 \times (SWI) + 10.64$$

However, this equation is valid for a particular grid only and calibration is necessary for the calculation of soil moisture at other grids. These results can be further improved by eliminating the effect of irrigation which could not be captured in the VIC model.

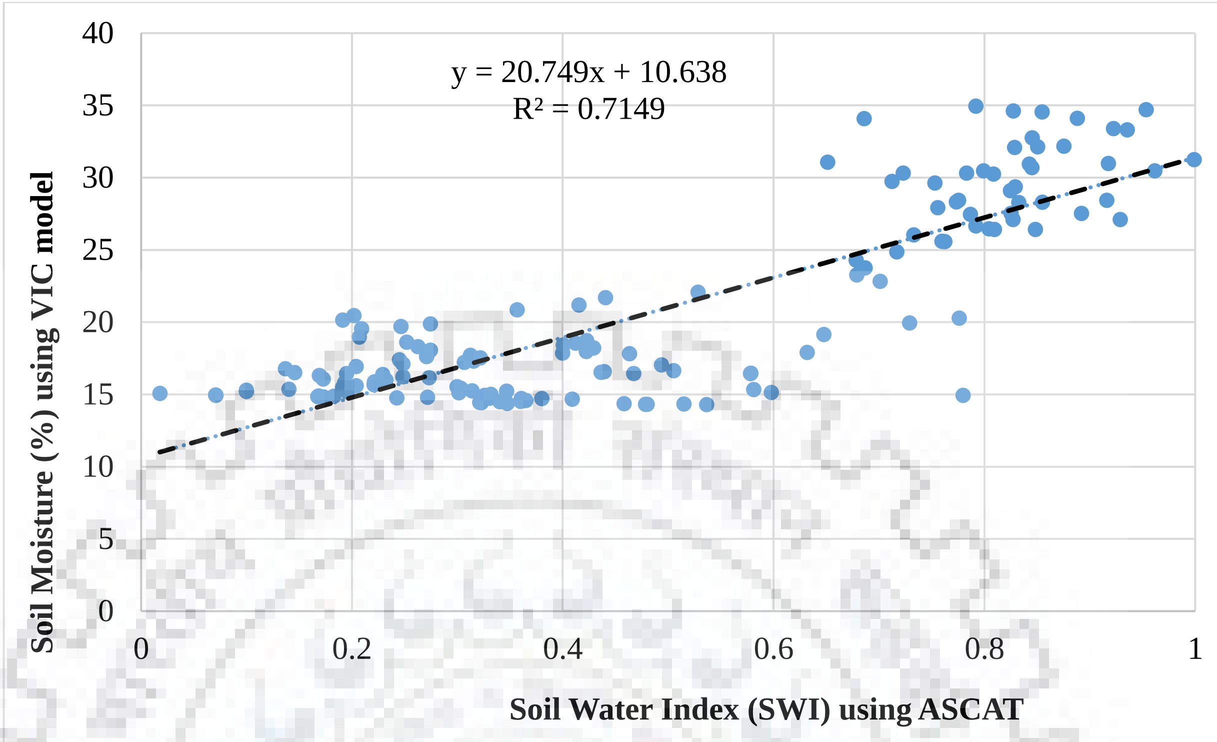


Figure 5.10: Relationship between soil moisture and ASCAT derived SWI.

CHAPTER 6

SUMMARY AND CONCLUSION

In the present study, VIC model has been used to simulate hydrologic processes over Upper Ganga river basin. For the simulation, ancillary data (soil type), meteorological data (rainfall, temperature and wind speed) and various satellite derived products (LULC, LAI) have been utilized. Sensitivity analysis has been performed and sensitive soil parameters were calibrated for the basin. The optimal parameters were selected based on NSE and R^2 values during the calibration period with the help of observed discharge. Remaining observed discharge have been utilized for the validation of the results. Other than runoff, VIC model provides some useful output such as ET, Soil moisture at each layer which plays very important role in the planning of irrigation project. The soil moisture results from VIC showed very good agreement with Scatterometer derived Soil Water Index. Thus, there is a potential to estimate the soil moisture only from satellite data and VIC model can play a very important role in the validation of satellite derived soil moisture product.

Following conclusions are drawn from the present study:

1. Statistical analysis of pre-calibrated simulated discharge and observed flow on daily basis shows descent agreement in terms R^2 of 0.64 and NSE 0.38.
2. From the sensitivity analysis, infiltration parameter (b_i) and soil layer depth (D2 and D3) are found to be the most sensitive parameter for flow simulation.
3. The result shows coefficient of determination (R^2) for calibration and validation is 0.76 and 0.78 respectively.
4. A good agreement between the VIC simulated and observed daily streamflow (NSE = 0.65, and 0.73 for calibration and validation respectively) indicates very good performance of the model with various satellite inputs.
5. Evapotranspiration range between 229 mm to 406 mm across regions within the catchment. the mountainous region yields high ET values in the monsoon months.
6. Highest surface runoff (980 mm) was observed in the month of August while that of lowest (0.01 mm) was observed in the month of October.
7. The cumulative monthly soil moisture ranges from 43mm to 155mm. highest and lowest soil moisture values were observed in September and October months respectively.

8. VIC derived soil moisture product showed very good agreement with ASCAT derived Soil Water Index.
9. VIC hydrologic model has potential for hydrologic simulation for discharge and soil moisture and it can be used for the validation of satellite derived moisture products.

Abdulla, F. A., Lettenmaier, D. P., Wood, E. F., & Smith, J. A. (1996). Application of a macroscale hydrologic model to estimate the water balance of the Arkansas-Red River Basin. *Journal of Geophysical Research: Atmospheres*, *101*(D3), 7449-7459.

Bao, Z., Zhang, J., Liu, J., Wang, G., Yan, X., Wang, X., & Zhang, L. (2012). Sensitivity of hydrological variables to climate change in the Haihe River basin, China. Hydrological Processes, 26(15), 2294-2306.

Christensen, N. S., Wood, A. W., Voisin, N., Lettenmaier, D. P., & Palmer, R. N. (2004). The effects of climate change on the hydrology and water resources of the Colorado River basin. *Climatic change*, *62*(1), 337-363.

Dickinson, R. E. (1986). Biosphere-Atmosphere Transfer Schemes (BATS) for the NCAR Community Climate Model. *Tech. Note NCAR/TN-275+ STR*, *69*.

Ford, T. W., & Quiring, S. M. (2013). Influence of MODIS-derived dynamic vegetation on VIC-simulated soil moisture in Oklahoma. Journal of Hydrometeorology, 14(6), 1910-1921.

Franchini, M., & Pacciani, M. (1991). Comparative analysis of several conceptual rainfall-runoff models. *Journal of Hydrology*, *122*(1-4), 161-219.

Fu, G., Barber, M. E., & Chen, S. (2007). Impacts of climate change on regional hydrological regimes in the Spokane River Watershed. Journal of Hydrologic Engineering, 12(5), 452-461.

Gao, H., Tang, Q., Shi, X., Zhu, C., Bohn, T. J., Su, F., & Wood, E. F. (2010). Water budget record from Variable Infiltration Capacity (VIC) model. Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records.

Hu, H., Wanga, G., Bic, X., Yanga, F., & Ea, C. (2007, June). Application of two hydrological models to Weihe River basin: a comparison of VIC-3L and SWAT. In *Proc. of SPIE Vol* (Vol. 6754, pp. 67541T-1).

Liang, X., & Xie, Z. (2001). A new surface runoff parameterization with subgrid-scale soil heterogeneity for land surface models. *Advances in Water Resources*, 24(9), 1173-1193.

Liang, X., Wood, E. F., & Lettenmaier, D. P. (1996). Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. *Global and Planetary Change*, *13*(1-4), 195-206.

Livneh, B., Rajagopalan, B., & Kasprzyk, J. (2017). Hydrological model application under data scarcity for multiple watersheds, Java Island, Indonesia. *Journal of Hydrology: Regional Studies*, *9*, 127-139.

Lohmann, D. A. G., NOLTE-HOLUBE, R. A. L. P. H., & Raschke, E. (1996). A large-scale horizontal routing model to be coupled to land surface parametrization schemes. *Tellus A*, *48*(5), 708-721.

Lohmann, D., Mitchell, K. E., Houser, P. R., Wood, E. F., Schaake, J. C., Robock, A., ... & Higgins, R. W. (2004). Streamflow and water balance intercomparisons of four land surface models in the North American Land Data Assimilation System project. *Journal of Geophysical Research: Atmospheres*, *109*(D7).

Lohmann, D., Raschke, E., Nijssen, B., & Lettenmaier, D. P. (1998a). Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model. *Hydrological Sciences Journal*, *43*(1), 131-141.

Lohmann, D., Raschke, E., Nijssen, B., & Lettenmaier, D. P. (1998b). Regional scale hydrology: II. Application of the VIC-2L model to the Weser River, Germany. *Hydrological Sciences Journal*, *43*(1), 143-158.

Meng, L., & Quiring, S. M. (2008). A comparison of soil moisture models using Soil Climate Analysis Network observations. *Journal of Hydrometeorology*, 9(4), 641-659.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885-900.

Narendra, H., Eldho, T. I., & Subimal, G. (2017). Hydrological Simulation of a Large Catchment Using the Variable Infiltration Capacity Model. In *Development of Water Resources in India* (pp. 19-30). Springer, Cham.

Nijssen, B., Lettenmaier, D. P., Liang, X., Wetzel, S. W., & Wood, E. F. (1997). Streamflow simulation for continental-scale river basins. *Water Resources Research*, *33*(4), 711-724.

Nijssen, B., Schnur, R., & Lettenmaier, D. P. (2001). Global retrospective estimation of soil moisture using the variable infiltration capacity land surface model, 1980–93. *Journal of Climate*, *14*(8), 1790-1808.

Praskievicz, S., & Chang, H. (2009). A review of hydrological modelling of basin-scale climate change and urban development impacts. *Progress in Physical Geography*, *33*(5), 650-671.

Refsgaard, J. C. (1997). Parameterisation, calibration and validation of distributed hydrological models. *Journal of hydrology*, *198*(1-4), 69-97.

Sivapalan, M., & Woods, R. A. (1995). Evaluation of the effects of general circulation models' subgrid variability and patchiness of rainfall and soil moisture on land surface water balance fluxes. *Hydrological processes*, *9*(5-6), 697-717.

Sood, A., & Smakhtin, V. (2015). Global hydrological models: a review. *Hydrological sciences journal*, *60*(4), 549-565.

Takle, E. S., Jha, M., & Anderson, C. J. (2005). Hydrological cycle in the upper Mississippi River basin: 20th century simulations by multiple GCMs. *Geophysical research letters*, *32*(18).

Te Linde, A. H., Aerts, J. C. J. H., Hurkmans, R. T. W. L., & Eberle, M. (2008). Comparing model performance of two rainfall-runoff models in the Rhine basin using different atmospheric forcing data sets.

Ulaby, F. T., Moore, R. K., & Fung, A. K. (1982). Microwave remote sensing: Active and passive. Volume 2-Radar remote sensing and surface scattering and emission theory.

UNESCO/WMO (1992) International Glossary of Hydrology. (Second edition)

VanShaar, J. R., Haddeland, I., & Lettenmaier, D. P. (2002). Effects of land-cover changes on the hydrological response of interior Columbia River basin forested catchments. Hydrological Processes, 16(13), 2499-2520.

Wagner, W., Lemoine, G., & Rott, H. (1999). A method for estimating soil moisture from ERS scatterometer and soil data. Remote sensing of environment, 70(2), 191-207.

Wang, G. Q., Zhang, J. Y., Xu, Y. P., Bao, Z. X., & Yang, X. Y. (2017). Estimation of future water resources of Xiangjiang River Basin with VIC model under multiple climate scenarios. *Water Science and Engineering*, *10*(2), 87-96.

Warrach-Sagi, K., Wulfmeyer, V., Grasselt, R., Ament, F., & Simmer, C. (2008). Streamflow simulations reveal the impact of the soil parameterization. Meteorologische Zeitschrift, 17(6), 751-762.

Woodhouse, I. H., & Hoekman, D. H. (2000). A model-based determination of soil moisture trends in Spain with the ERS-scatterometer. IEEE transactions on geoscience and remote sensing, 38(4), 1783-1793.

Yu, Z., Lakhtakia, M. N., Yarnal, B., White, R. A., Miller, D. A., Frakes, B., & Schwartz, F. W. (1999). Simulating the river-basin response to atmospheric forcing by linking a mesoscale meteorological model and hydrologic model system. Journal of Hydrology, 218(1), 72-91.

Yuan, F., Xie, Z., Liu, Q., Yang, H., Su, F., Liang, X., & Ren, L. (2004). An application of the VIC-3L land surface model and remote sensing data in simulating streamflow for the Hanjiang River basin. Canadian Journal of Remote Sensing, 30(5), 680-690.

Zhang, J. Y., & Wang, G. Q. (2014). Variation of stream flow and quantitative identification for attribution.

Zhao, F., Chiew, F. H., Zhang, L., Vaze, J., Perraud, J. M., & Li, M. (2012). Application of a macroscale hydrologic model to estimate streamflow across southeast Australia. Journal of Hydrometeorology, 13(4), 1233-1250.

Zine, S., Jarlan, L., Frison, P. L., Mougin, E., Hiernaux, P., & Rudant, J. P. (2005). Land surface parameter monitoring with ERS scatterometer data over the Sahel: A comparison between agro-pastoral and pastoral areas. Remote Sensing of Environment, 96(3-4), 438-452.