Impact of Temporal Changes of Land use on Surface Run-off

A Case Study on Musi Basin Using Soil and Water Assessment Tool (SWAT)

Report Submitted to
Jawaharlal Nehru Technological University, Hyderabad

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DECLARATION

I, **Vangala Savinai** hereby declare that the dissertation entitled upon "**Impact of Temporal Changes of Land use on Surface Runoff: A case study on musi basin using Soil and Water Assessment Tool (SWAT)"** is an authenticated work carried out by me at ICRISAT under the guidance of **Dr. Murali Krishna Gumma, Head- RS/GIS unit, Senior Scientist- GIS/Geospatial Science (RS and GIS Unit), at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India,** during the period of my study as a part of curriculum of Master of Technology in Water and Environmental Technology

Date:

Place: HYDERABAD

Vangala Savinai

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Abstract

Land and water are the two most vital natural resources of the world. Proper planning and management of these two most vital natural resources is, therefore, of utmost necessity. For proper planning and efficient utilization of the land and water resources it is necessary to understand the hydrological cycle and estimate the hydrological parameters. In the present study SWAT2012 (Soil and Water Assessment Tool, ArcSWAT10.2.2), a physical based semi distributed hydrologic model having an interface with ArcGIS 10.2.2, GIS software was applied for Musi Basin, a sub-basin of river Krishna, covering an area of 11268.54 sq.km in order to model the various hydrological components and to assess the impact of land use/land cover on the surface flow.

In order to study the impact of land use/land cover on surface runoff, simulations were carried out for the crop periods of kharif 2005-06 and kharif 2010-11 using the same precipitation file. Results indicated that with an increase in irrigated land and increase in urban land, during the period from 2005 to 2010 surface runoff has increased by 8.47mm (18.6% to 19.6% of precipitation) showing that the land use/land cover has an impact on the hydrological regime. Then the simulations were carried out for the land use of 2005-06 kharif with and without irrigation operation for a time period of 35 years (1979-2013) and the simulations showed that the surface runoff was more for the model under irrigation by 7.6%. Runoff had increased from 24.8% to 32.4 % of precipitation. These results clearly show how land use changes and agricultural management practices impact hydrological parameters like runoff.

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Abbreviations

Abbreviation	Full Form
AGNPS	Agricultural Non-Point Source Pollution
AMC	Antecedent Moisture Condition
AVSWAT	Arc View SWAT
AWC	Available Water Capacity
CFSR	Climate Forecast Reanalysis System
CN	Curve Number
CREAMS	Chemicals, Runoff, Erosion from Agricultural Management Systems
DEM	Digital Elevation Model
EPIC	Erosion-Productivity Impact Calculator
ERDAS	Earth Resources Data Analysis Systems
ESCO	Soil Evaporation Compensation Factor
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
FAO	Food and Agricultural Organization
GIS	Geographical Information System
GLEAMS	Groundwater Loading Effects of Agricultural Management System
HEC-HMS	Hydrologic Engineering Center- Hydrologic Modeling System
HRU	Hydrological Response Unit
HSPF	Hydrological Simulation Program- FORTRAN
HYMO	Hydrological Model
ISODATA	Iterative Self-Organizing Data Analysis Technique
LULC	Land use/Land cover
MFDC	Mega File Data Cube
MIKE-SHE	MIKE-Système Hydrologique Européen
MODIS	Moderate Resolution Imaging Spectroradiometer
MUSLE	Modified Universal Soil Loss Equation
MVC	Maximum Value Composite
NDVI	Normalized Difference Vegetation Index
PET	Potential Evapotranspiration
ROTO	Routing Outputs to Outlet
SAC-SMA	Sacramento Soil Moisture Accounting
SCS	Soil Conservation Service
SMT	Spectral Matching Technique
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
SWAT-G	SWAT Giessen

SWRRB	Simulator for Water Resources in Rural Basins
USDA	United States Department of Agriculture
USDA-ARS	United States Department of Agriculture- Agricultural Research Service
UTM	Universal Transverse Mercator

1. Introduction

Land and water are the two most vital natural resources of the world and these resources must be conserved and maintained carefully for environmental protection and ecological balance. Prime soil resources of the world are finite, non-renewable over the human time frame, and prone to degradation through misuse and mismanagement. In India, out of a total geographical area of 328 M ha, an estimated 175 M ha of land, constituting an area of 53% suffers from deleterious effect of soil erosion and other forms of land degradation and with the increasing population pressure, exploitation of natural resources, faulty land and water management practices, the problem of land degradation will further aggravate. Land use change within a region has not only an impact on various hydrologic landscape functions but also affects the habitat quality and thus the biodiversity of a landscape.

Water resources degradation is an issue of significant societal and environmental concern. Water pollution originates either from point or non-point source or from both. Non-point source pollution has been identified as a major reason for water quality problems. Also point source pollutions such as effluent from industries, feedlots and erosion from gully are also getting mixed with stream water causing pollution of water resources.

Proper planning and management of these two most vital natural resources is, therefore, of utmost necessity. Watershed is considered to be the ideal unit for management of these natural resources. Proper watershed management, which is a comprehensive term meaning the rational utilization of land and water resources for optimal production and minimum hazard to natural resources could be the solutions to all these problems. Watershed analysis provides a framework for ecosystem management, which is currently the best option for conservation and management of natural resources.

The basic issue underlying the water resources problems are: flood, drainage congestion, soil erosion, human influence on environment and so on and calls for its integrated use for drinking, irrigation generation of hydropower, navigation, pisciculture, recreation etc. For proper planning and efficient utilization of the land and water resources in a region it is necessary to understand the hydrological cycle and estimate the hydrological parameters.

The reliable prediction of the various hydrological parameters including runoff and sediment yield for remote and inaccessible areas are tedious and time consuming by conventional methods. So it is desirable that for hydrologic evaluation of watersheds, some suitable methods and techniques are to be used/ evolved for quantifying the hydrological parameters from all parts of the watersheds. Use of mathematical models for hydrologic evaluation of watersheds is the current trend and extraction of watershed parameters using remote sensing and geographical information system (GIS) in high speed computers are the aiding tools and techniques for it.

Hydrological modeling is a powerful technique of hydrologic system investigation involved in the planning and development of integrated approach management of natural resources. Models are important tools because they can be used to understand hydrologic processes, develop management practices, and evaluate the risks and benefits of land use over various periods of time(Spruill, 2000). The fundamental objective of hydrological modelling is to gain an understanding of the hydrological system in order to provide reliable information for managing water resources in a sustained manner to increase human welfare and protect the environment. A model aids in making decisions, particularly where data or information are scarce or there are numbers of options to choose from. It is not a replacement for field observations. Its value lies in its ability, when correctly chosen and adjusted, to extract the maximum amount of information from the available data, so as to aid in decision making process.

A number of simulation models have been developed to simulate the impact of land management on water, sediment, nutrient loss etc. at both field and watershed scale. Widely used field scale models include CREAMS (Chemicals, Runoff, Erosion from Agricultural Management Systems), EPIC (Erosion-Productivity Impact Calculator), and GLEAMS (Groundwater Loading Effects of Agricultural Management System).Watershed scale models include storm event based AGNPS (Agricultural Non-Point Source Pollution) and continuous daily time step model SWRRB (Simulator for Water Resources in Rural Basins). These models were developed for their specific reasons with some limitations for modeling watersheds.

The SWAT (Soil and Water Assessment Tool) is one of the most recent models developed jointly by the United States Department of Agriculture (USDA), Agricultural Service and Agricultural Experiment Station in Temple, Texas. It is a physically based, continuous time, long-term simulation, lumped parameter, deterministic, and originated from agricultural models. The computational components of SWAT can be placed into eight major divisions: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. The application of ArcSWAT (integrated with ArcGIS) in the present study provides the capabilities to stream line GIS processes tailored towards hydrologic modeling and to automate data entry communication and editing environment between GIS and the hydrologic model. Thus, ArcSWAT represents a preprocessor and as well as a user interface to SWAT model.

1.1 Role of Remote Sensing in Hydrological Modelling

A major problem in the hydrology is the inadequate field measured data to describe the hydrologic process. Remote Sensing has been identified as a tool to produce information in spatial and temporal domain, instead of point measurement, in digital form, with high resolution. The remotely sensed data acquired from space borne platforms, owing to its wide synoptivity and multi spectral acquisition provides spatial information about the various processes of the land phase of the hydrological cycle. This spatial information can be used as input data for hydrological models and are extremely relevant as a means of estimating a number of key variables specifically in situation where distributed hydrological models are used. Remote Sensing techniques can produce high spatial coverage of important terms in water balance for large areas, but at the cost of a rather sparse temporal resolution. Hydrological model can produce all the terms of water balance at a high temporal, but low spatial resolution. The use of remote sensing data, in combination with distributed hydrological model, provides new possibilities for deriving spatially distributed time series of input variables, as well as new means for calibration and validation of the hydrological model.

Some of the main hydrological application fields of remote sensing are:

- Spatial rainfall patterns
- Evaporation and soil moisture
- Groundwater
- Topography
- Water Bodies
- Vegetation

In the present study remote sensing data has been used to generate input data of thematic maps such as land use/land cover for a physically based distributed hydrological model.

1.2 Role of GIS in Hydrological Modelling

The use of remote sensing technology involves large amount of spatial data management and requires an efficient system to handle such data. Hence Geographic Information System makes it possible to store, analyze and retrieve data for large and complex problems.

Geographical Information System (GIS) is a computer based system designed tool applied to geographical data for integration, collection, storing, retrieving, transforming and displaying spatial data for solving complex planning and management problems. This tool focuses on proper integration of user and machine for providing spatial information to support operations, management, analysis and decision making. Since, GIS does not directly land itself to time varying studies, its features are utilized in hydrological studies by coupling it with hydrological models. Two types of approaches are possible for this purpose. In the model driven approach, a model or set of models is defined and thus the required spatial (GIS) input for the preparation of the input data and output maps. The other approach is the data driven approach. It limits the input spatial data to parameters which can be obtained from generally available maps, such as topographic maps, soil maps etc. The possibility of rapidly combining data of different types in a GIS has led to significant increase in its use in hydrological applications. It also provides the opportunities to combine a data from different sources and different types. One of the typical applications is use of a digital elevation model (DEM) for extraction of hydrologic catchment properties such as elevation matrix, flow direction matrix, ranked elevation matrix, and flow accumulation matrix. It also provides the ability to analyze spatial and non-spatial data simultaneously.

1.3 Rationale of the Study

The Musi basin has the climate of semi-arid type. Climate change, faulty cultivation practices and urbanization within the basin result in huge loss of productive soil and water as surface runoff. There is an urgent need for developing integrated watershed management based on hydrological simulation studies using suitable modeling approach. A research work was formulated to study the changes in the land use within the catchment using remote sensing data and to understand the effect of land use changes on the flow behavior and other hydrological parameters.

Considering hydrological behavior of the study area and applicability of the existing models for the solutions of aforesaid problems, the current study was undertaken with the application of SWAT2012 in integration with Remote Sensing and GIS to estimate the surface runoff and other hydrological parameters of the Musi basin located in Telangana State of India. The specific objectives of the present study include:

1. Extraction of watershed characteristics, and land use/ land cover information of the study area using Remote Sensing and GIS

2. Physical based semi distributed hydrological modelling for Musi river basin.

3. To analyze the impact of land use/land cover on the surface runoff.

2. Literature Review

2.1 Application of Remote Sensing and GIS in Hydrological Modelling

The scope of hydrological applications has broadened dramatically with the advent of remote sensing and GIS. The remotely sensed data acquired from space borne platforms, owing to its wide synoptivity and multi-spectral acquisition offers unique opportunities for study of soils, land use/ land cover and other parameters required for hydrologic modeling of large areas(Schultz, 1998). Remote Sensing and GIS are being widely used for solving environmental problems like degradation of land by water logging, soil erosion, contamination of surface and groundwater resources, deforestation, changes in ecological parameters and many more(Jasrotia, 2002).

Tripathi, M.P. et. al. (2002) used remote sensing and GIS techniques for generation of land use, soil and contour map which were used for runoff modeling for a small watershed in Bihar(Tripathi, 2002).

Jasrotia, A.S. et. al. (2002) determined the rainfall-runoff relationship for the Tons watershed using SCS curve number technique by deriving the curve numbers through Remote Sensing and GIS techniques(Jasrotia, 2002).

Several other studies have been conducted in different parts of the world (Gupta, 2001; Sharma, 2001; Legesse, 2003)for modeling hydrological components integrated with Remote Sensing and GIS. Kaur and Dutta (2002) highlighted the advantages of GIS based digital delineation of watersheds over conventional methods which is a pre-requisite for proper planning and development of watershed.

2.2 Impact of Land use/ Land cover changes on hydrological response

In order to assess the impact of land use changes on hydrological response a case study was carried out by Sharma. et. al. (2001) for an area of 89.16 km^2 in Jasdan taluka (district) of Rajkot in Gujarat, India(Sharma, 2001). The Curve number (CN) model was used for estimating runoff from the watershed. Satellite and other collateral data were used to derive information on land use, hydro geomorphology, soils and slope which were integrated to identify the problems and potential in the watershed and recommend measures for soil and water conservation. The impact of these conservation measures were assessed by computing runoff under alternative land use and management practices and it was observed that the runoff yield decreased by 42.88% of the pre-conservation value of the watershed.

Noorazuan (2003) evaluated the impact of urban land use- land cover change on hydrological regime for the period 1983 -1994 in Langat river basin, Malaysia, covering an area of 2271km^2.The study revealed that the landscape diversity of Langat significantly changed after 1980’s and as a result, the changes also altered the Langat’s streamflow response. Surface runoff increased from

20.35% in 1983-1988 to about 31.4% of the 1988-1994 events. Evidence from the research suggests that urbanization and changes in urban related land use-land cover could affect the stream flow behavior(Noorazuan, 2003).

A study conducted by Ranjit Premlal De Silva et.al.(2000) to evaluate the impact land use/ land cover on hydrological regime revealed no obvious impacts of the changes of tree cover or any other land use changes on the river flow during rainy season. However obvious deviations were observed in the dry weather flow for both the sub catchments. The increase of the dry weather flow could be related to the increase of the tree cover and the reduction in canopy cover could be attributed to the decrease in dry weather flow at Kotmale. The study provided conclusive evidence that the increase in tree cover would positively contribute to the water yield in the catchments in addition to its protective role of the environment(Ranjit Premalal De Silva, 2000).

2.3 Soil and Water Assessment Tool (SWAT)

Soil and Water Assessment Tool (SWAT) is a physically based distributed parameter model which have been developed to predict runoff, erosion, sediment and nutrient transport from agricultural watersheds under different management practices(Arnold, 1998). SWAT is freely available which is linked to a GIS system (ArcGIS) through an interface that makes data processing and visualization easy. The model can simulate long periods, up to several years, operating with a daily time step. SWAT requires soils data, land use/management information and elevation data to drive flows and direct sub-basin routing. SWAT lumps the parameters into Hydrological Response Units (HRU) and storm runoff for each HRU is predicted with the CN equation.

SWAT is most versatile model. SWAT has been widely used in various regions and climatic conditions on daily, monthly and annual basis (Arnold, 1998) and for the watershed of various sizes and scales(Kannan, 2007, 2008). SWAT has been successfully used for simulating runoff, sediment yield and water quality of small watersheds for Indian conditions (Tripathi, 1999, 2003; Pandey, 2005, 2008)

2.4 Application of SWAT in Hydrological Modelling

The development of SWAT model, its various components, operation, limitations has been described by Arnold. et. al. (1998) in his paper on “Large Area Hydrologic Modelling and Assessment Part-1: Model Development”. In his paper an overview has been made on SWAT model development which was developed mainly to assist water resource managers in assessing water supplies and non-point source pollution on watersheds and large river basins. The paper highlights the various components of the SWAT, methodology involved in simulating the various hydrological components, data requirement etc. The paper also gives an overview of the model limitations in simulating the various components of the hydrological cycle.

Singh et. al. made a comparative study for the Iroquois river watershed covering an area of 2137 sq. miles with the objectives to assess the suitability of two watershed scale hydrologic and water quality simulation model namely HSPF and AVSWAT2000. Based on the completeness of meteorological data, calibration and validation of the hydrological components were carried out for both the models. Time series plots as well as statistical measures such as Nash- Sutcliffe efficiency, coefficient of correlation and percent volume errors between observed and simulated streamflow values on both monthly and annual basis were used to verify the simulation abilities of the models. Calibration and validation results concluded that both the models could predict stream flow accurately(Singh, 2004-08). Spruill et. al. (2000) evaluated the SWAT model and parameter sensitivities were determined while modeling daily streamflow in a small central Kentucky watershed comprising an area of 5.5 km^2 over a two year period. Streamflow data from 1996 were used to calibrate the model and streamflow data from 1995 were used for evaluation. The model accurately predicted the trends in daily streamflow during this period. The Nash-Sutcliffe R^2 for monthly total flow was 0.58 for 1995 and 0.89 for 1996 whereas for daily flows it was observed to be 0.04 and 0.19. The monthly total tends to smooth the data which in turn increases the R^2 value. Overall the results indicated that SWAT model can be an effective tool for describing monthly runoff from small watersheds.(Spruill, 2000)

Fohrer et. al.(2002) applied three GIS based models from the field of agricultural economy (ProLand), ecology (YELL) and hydrology (SWAT-G) in a mountainous mesoscale watershed of Aar, Germany covering an area of 59.8 km2 with the objective of developing a multidisciplinary approach for integrated river basin management. For the SWAT –G model daily stream flow were predicted. The model was calibrated and validated followed by model efficiency using Nash and Sutcliffe test. In general the predicted streamflow showed a satisfying correlation for the actual land use with the observed data(Fohrer, 2002).

Francos et. al. (2001) applied the SWAT model to the Kerava watershed (South of Finland), covering an area of 400 km^2.Various spatial data was used for the study. The temporal series comprised temperature and precipitation records for a number of meteorological stations, water flows and nitrogen and phosphorus loads at the river outlets. The model was adapted to the specific conditions of the catchment by adding a weather generator and a snowmelt sub model calibrated for Finland. Calibration was made against water flows, nitrate and total phosphorus concentrations at the basin outlet. Simulations were carried out and simulated results were compared with daily measured series and monthly averages. In order to measure the accuracy obtained, Nash and Suttcliffe efficiency coefficient was employed which indicated a good agreement between measured and predicted values(Francos, 2001).

Eckhartd and Arnold (2001) outlined the strategy of imposing the constraints on the parameters to limit the number of interdependently calibrated values of SWAT. Subsequently an automatic calibration of the version SWAT-G of the SWAT model with a stochastic global optimization algorithm and Shuffled Complex Evolution algorithm is presented for a mesoscale catchment(Eckhartd, 2001).

Tripathi et. al.(2003) applied the SWAT model for Nagwan watershed (92.46km^2) with the objective of identifying and prioritizing of critical sub-watersheds to develop an effective management plan. Daily rainfall, runoff and sediment yield data of 7 years (1992-1998) were used for the study. Apart from hydro-meteorological data, topographical map, soil map, land resources and satellite imageries for the study area were also used. The model was verified for the monsoon season on daily basis for the year 1997 and monthly basis for the years 1992-1998 for both surface runoff and sediment yield. Critical sub-watersheds were identified on the basis of average annual sediment yield and nutrient losses during the period of 3 years (1996-1998) and priorities were fixed on the basis of ranks assigned to each critical sub-watershed according to ranges of standard soil erosion classes. The study confirmed that the model could accurately simulate runoff, sediment yield and nutrient losses from small agricultural watersheds and can be successfully used for identifying and prioritizing critical sub-watersheds for management purpose.(Tripathi, 2003)

The review indicated that SWAT is capable of simulating hydrological processes with reasonable accuracy and can be applied to large ungauged basin. Therefore to assess the impact of temporal changes of land use/land cover on runoff, ArcSWAT2012 with ArcGIS interface was selected for the present study.

3. Study Area

3.**1 Location of the Watershed**

Major portions of the study area, Musi basin (watershed), fall in the districts of Rangareddy (includes Hyderabad) and Nalgonda of Telangana State, India. Minor portions of the study area fall in the districts of Warangal, Mahaboobnagar and Medak of Telangana State, India. The extent of the watershed stretches from 16.7302^0 to 17.8901^0 N and 77.8459^0 to 79.73207^0 E and covers an area of 11268.6 km^2. The Musi River is a major left bank tributary of Krishna, having its origin in the hills of Anathagiri near Vikarabad, Rangareddy District, Telangana. It flows through Hyderabad city and runs mostly west to east until the Aleru river joins it. Flowing southwards, it meets the river Krishna near Wadapally at an elevation of about 61 m. When it confluences with Krishna river, Musi river has already flown for 267 km. Figure 1 depicts the location of the study area. The river has a rocky and very steep fall. It brings very heavy and sudden floods during the monsoon. During the year 1908, Musi swelled up in high floods and submerged a major portion of Hyderabad city and many villages on its banks, and caused severe damages to the property and life.

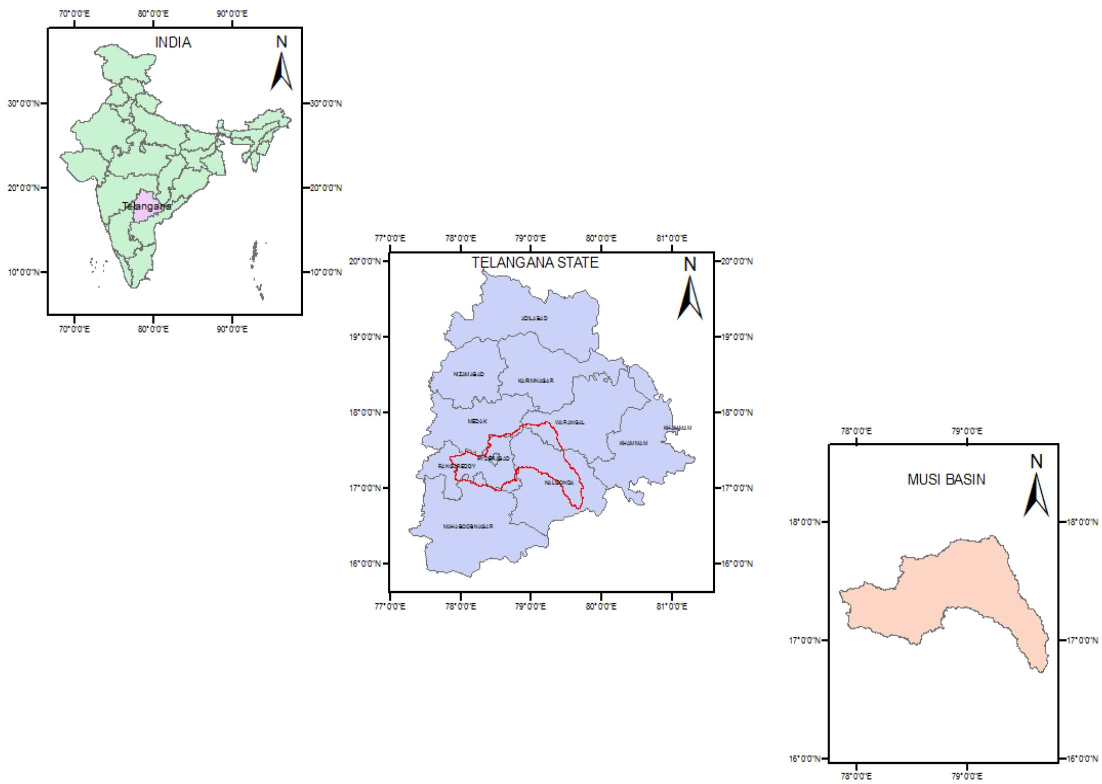


Figure 1: Location of Study Area

3.2 Land use/Land cover

The major land units in the Musi watershed can be catergorized into Agriculture, Settlement, Shrubland and Water body. Agriculture constitutes the major area of the watershed with major crops being rice and cotton. Apart from these major crops vegetables, maize, sugarcane, sorghum are grown.

The natural vegetation consists of forest trees, shrubs and grasses. There are numerous small villages in the watershed.

3.3 Drainage

The study area has a southeast slope. Main river in the study area is Musi, which is a tributary of river Krishna. The stream of Musi passes through the districts of Rangareddy, Hyderabad and Nalgonda.

3.4 Soils

The soil types in the area fall in the order of Alfisols, Inceptisols, Entisols and Vertisols. The soils in general in the area are clay loam to clay in texture, moderately well drained and the soil depth varies from very shallow to very deep. The productivity of the soils ranges from low to medium.

3.5 Climate

The climate is characterized by having hot summers and temperate winters. The climate is influenced by the elevation differences and seasonal variations and on the whole, the climate of study area is semi-arid type. The mean temperature ranges from 12.9 ^{0}C to 37.6 ^{0}C and the annual average rainfall from 1979-2013 is 1042 mm.

Table 1: Climatic variables for the past 35 years (1979-2013)

Month	Average Precipitation (mm)	Maximum Temperature ^{0}C	Minimum Temperature ^{0}C	Wind Speed (m/s)	Relative humidity	Solar Radiation MJ/m^2
January	8.7	26.7	13.6	2.5	0.5	16.4
February	5.1	29.7	15.3	2.6	0.4	18.4
March	11.6	33.5	18.4	2.5	0.3	20.1
April	8.5	36.4	22.4	2.5	0.3	19.6
May	25.2	37.6	25.3	2.8	0.3	19.1
June	152.2	32.3	23.6	3.6	0.5	14.9
July	193.9	28.6	21.6	3.7	0.6	14.9
August	228.0	27.0	20.6	3.5	0.7	14.9
September	221.2	28.0	20.2	2.5	0.7	16.8
October	137.0	27.5	18.2	2.1	0.6	16.7
November	42.3	26.5	15.2	2.2	0.6	16.0
December	9.2	25.9	12.9	2.3	0.5	15.7

3.5.1 Precipitation

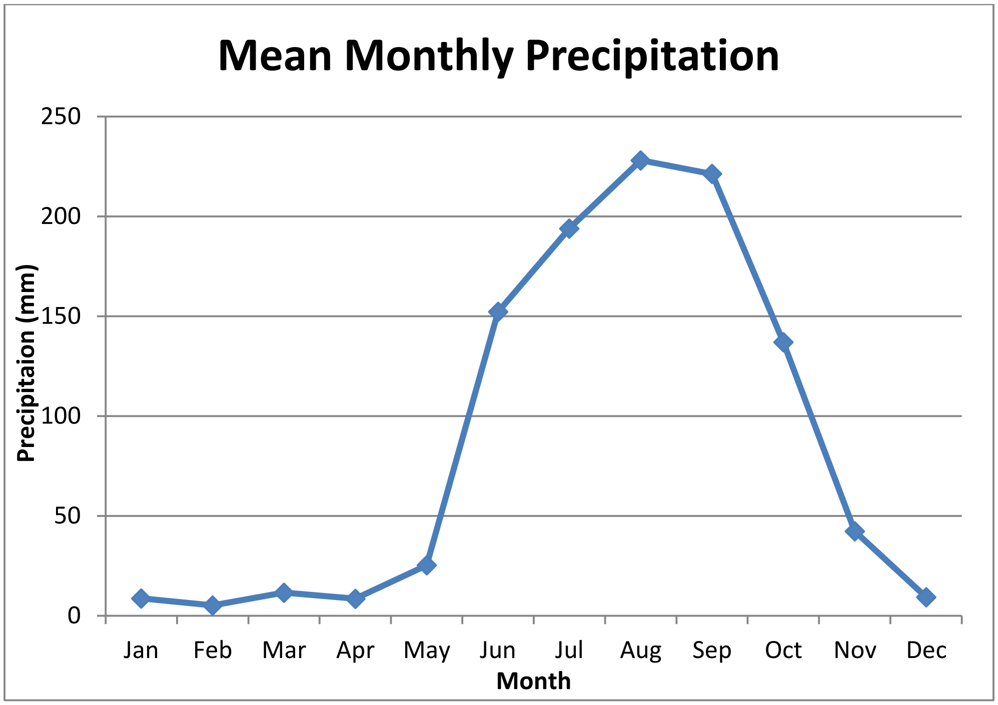


Figure 2: Variation of mean monthly precipitation from 1979 to 2013

3.5.2 Temperature

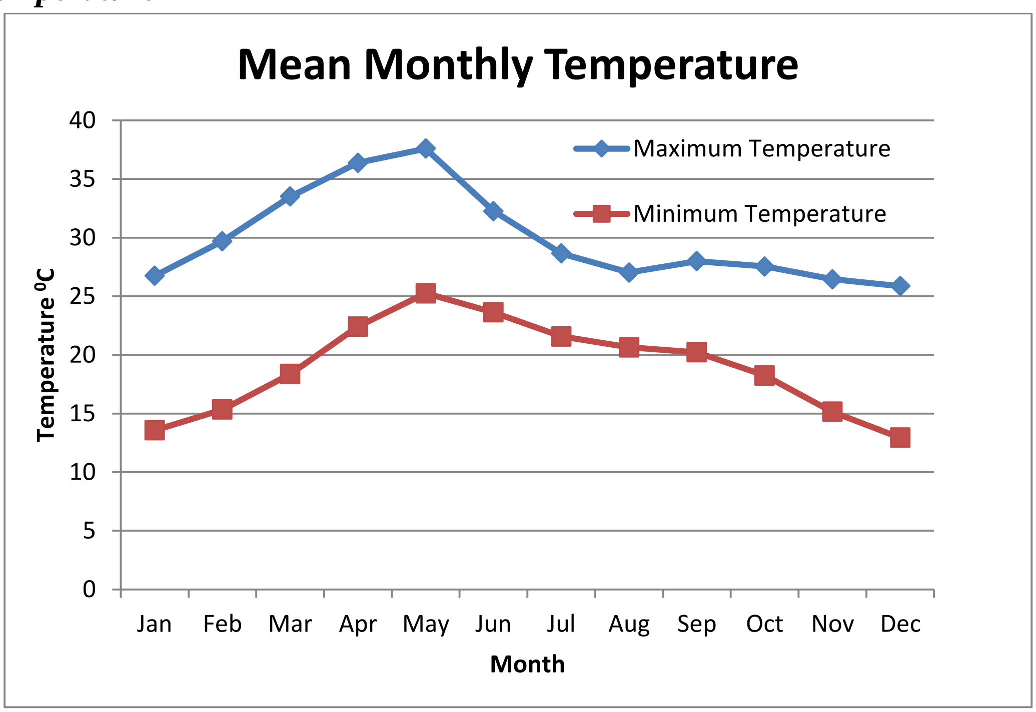


Figure 3: Variation of mean monthly maximum and minimum temperature (1979-2013)

3.5.3 Wind Speed

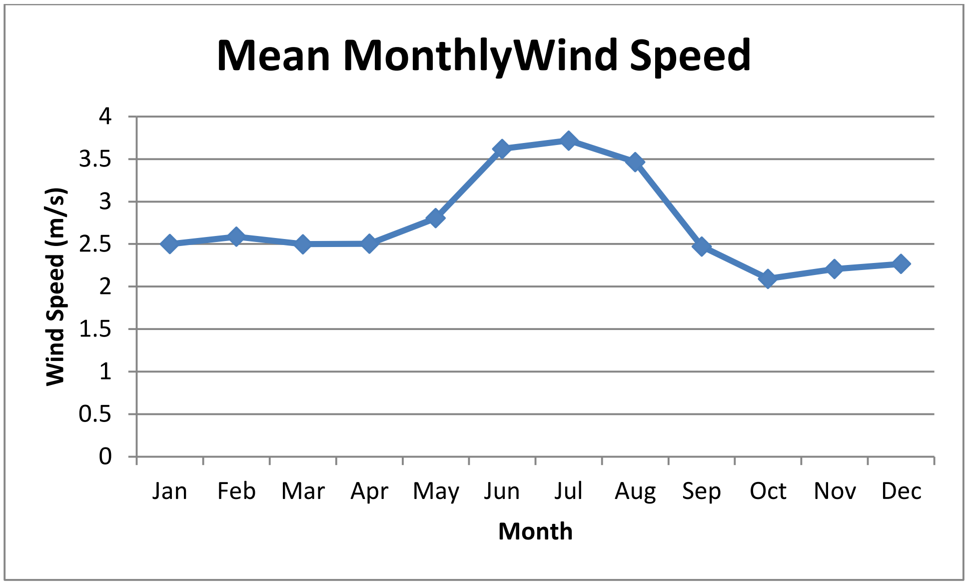


Figure 4: Variation of mean monthly wind speed (1979-2013)

3.5.4 Humidity

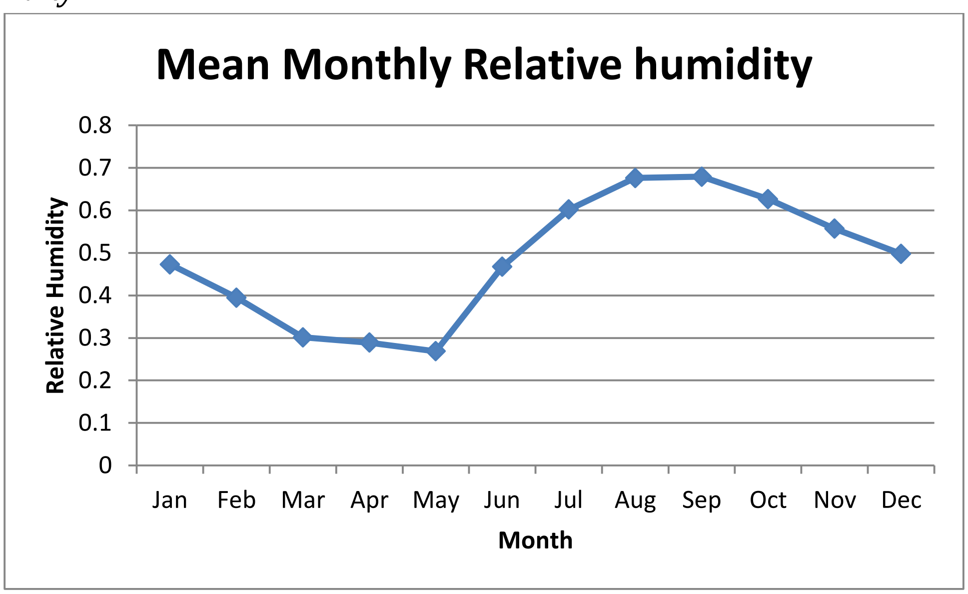


Figure 5: Variation of mean monthly relative humidity (1979-2013)

3.5.5 Solar Radiation

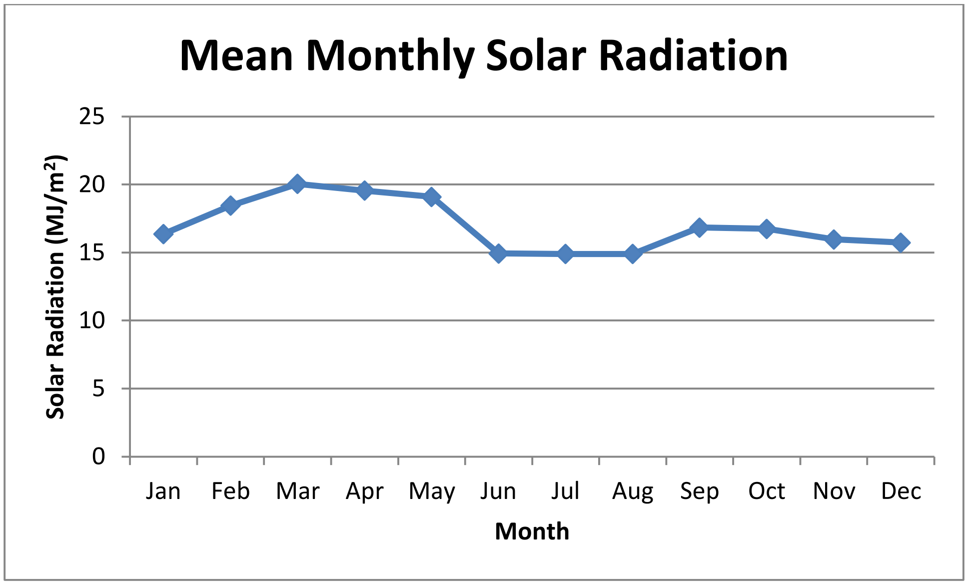


Figure 6: Variation of mean monthly solar radiation (1979-2013)

4. Model Description

This chapter deals with the theoretical consideration related to the SWAT2012 model. A brief description of various components and the mathematical relationships used to simulate the different processes and their interactions in the model as described by Neitsch et al. (2002) are considered.(Neitsch, 2002)

4.1 Overview of SWAT

SWAT is a spatially distributed, continuous time scale watershed scale model developed by Dr. Jeff Arnold for the USDA-ARS. It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. Weather, soil properties, topography, vegetation and land management practices are the most important inputs for SWAT to model hydrologic and water quality in a watershed (Neitsch, 2002)

SWAT allows a basin to be subdivided into sub-basins to evaluate hydrology, weather, sediment yield, nutrients and pesticides, soil temperature, crop growth, tillage and agricultural management practices.

The major components of the model are grouped under sub-basin and routing and are briefly discussed below

4.2 Sub-basin components

4.2.1 Hydrology

The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{n} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where, SW_t is the final soil water content (mmH_2O), SW_o is the initial soil water content (mmH_2O), t is time in days, R_{day} is amount of precipitation on day i(mmH_2O),Q_{surf} is the amount of surface runoff on day i(mmH_2O),E_a is the amount of evapotranspiration on day i(mmH_2O),w_{seep} is the amount of percolation and bypass exiting the soil profile bottom on day i (mmH_2O),Q_{gw} is the amount of return flow on day i (mmH_2O).

Since the model maintains a continuous water balance, the subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Thus runoff is predicted separately for each sub area and routed to obtain the total runoff for the basin. This increases the accuracy and gives a much better physical description of the water balance.

4.2.1.1Surface Runoff

Surface runoff component simulates the surface runoff volume and the peak runoff rates provided daily rainfall data are fed.

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

Surface runoff volume predicted in SWAT using SCS curve number method is given below

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)}, \qquad R > 0.2S$$

where, Q_{surf} is the accumulated runoff or rainfall excess (mm),R_{day} is the rainfall depth for the day (mm),and S is retention parameter (mm).

Runoff will occur when $R_{day} > 0.2S$.The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as

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

where CN is the curve number for the day

4.2.1.2 Peak Runoff Rate

The model calculates the peak runoff rate with a modified rational method. The rational method is based on the assumption that if a rainfall of intensity *i* begins at time $t = 0$ and continues indefinitely, the rate of runoff will increase until the time of concentration, $t = t_{conc}$, when the entire sub-basin area is contributing to flow at the outlet. The rational formula is:

$$q_{peak} = \frac{C \cdot i \cdot Area}{3.6}$$

where, q_{peak} is the peak runoff rate (m^3s^{-1}), C is the runoff coefficient, i is the rainfall intensity (mm/hr), *Area* is the sub-basin area (km^2) and 3.6 is a unit conversion factor.

4.2.1.2.1Time of Concentration

The time of concentration is the amount of time from the beginning of a rainfall event until the entire sub-basin area is contributing to flow at the outlet. The time of concentration is calculated by summing the overland flow time and the channel flow time:

$$t_{conc} = t_{ov} + t_{ch}$$

where,, t_{conc} is the time of concentration for a sub-basin (hr), t_{ov} is the time of concentration for overland flow (hr), and t_{ch} is the time of concentration for channel flow (hr).

4.2.1.2.2 Overland flow time of concentration

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

$$t_{ov} = \frac{L_{slp}^{\,0.6} . n^{0.6}}{18 . slp^{\,0.3}}$$

where, L_{slp} is the sub-basin slope length (m), n is the Mannings's roughness coefficient and slp is the average slope in the subbasin (mm^{-1})

4.2.1.2.3 Channel flow time of concentration

The channel flow time of concentration, t_{ch} is computed using the equation

$$t_{ch} = \frac{0.62 . L . n^{0.75}}{Area^{\,0.125} . slp_{ch}^{\,0.375}}$$

where, t_{ch} is the time of concentration for channel flow (hr), L is the channel length from the most distant point to the subbasin outlet (km), *n* is the Manning's roughness coefficient for the channel, *Area* is the subbasin area (km^2) and slp_{ch} is the channel slope ($m\ m^{-1}$)

4.2.1.2.4 Runoff Coefficient

The runoff coefficient is the ratio of the inflow rate, i.*Area*, to the peak discharge rate, q_{peak}. The coefficient will vary from storm to storm and is calculated with the equation:

$$C = \frac{Q_{surf}}{R_{day}}$$

where Q_{surf} is the surface runoff (mm H_2O) and R_{day} is the rainfall for the day (mm H_2O).

4.2.1.2.5Rainfall Intensity

The rainfall intensity is the average rainfall rate during the time of concentration. Based on this definition, it is calculated with the equation:

$$i = \frac{R_{tc}}{t_{conc}}$$

where i is the rainfall intensity (mm/hr), R_{tc} is the amount of rain falling during the time of concentration (mm H2O), and t_{conc} is the time of concentration for the sub basin (hr).

4.2.1.2.6Modified Rational Formula

The modified rational formula used to estimate peak flow rate is presented as follows

$$q_{peak} = \frac{\alpha_{tc} \cdot Q_{surf} \cdot Area}{3.6 \cdot t_{conc}}$$

where, q_{peak} is the peak runoff rate (m^3s^{-1}) and α_{tc} is the fraction of daily rainfall that occurs during the time of concentration.

4.2.1.3 Percolation

Percolation is calculated for each soil layer in the profile. Water is allowed to percolate if the water content exceeds the field capacity for that layer. The volume of water available for percolation in the soil layer is calculated as:

$$SW_{ly,excess} = SW_{ly} - FC_{ly} \quad \text{if } SW_{ly} > FC_{ly}$$

$$SW_{ly,excess} = 0 \quad \text{if } SW_{ly} \leq FC_{ly}$$

where, $SW_{l,excess}$ and SW_{ly} are the drainable volume of water and water content in the soil layer, respectively on a given day (mm) and FC_{ly} is the water content of the soil layer at field capacity (mm).

The amount of water that moves from one layer to the underlying layer is calculated using storage routing methodology. The equation used to calculate the amount of water that percolates to the next layer is

$$w_{perc,ly} = SW_{ly,excess} \cdot \left(1 - \exp\left[\frac{-\Delta t}{TT_{perc}}\right]\right)$$

where, $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm), Δt is the length of the time step (hrs), and TT_{perc} is the travel time for percolation (hrs).

The travel time for percolation (TT_{perc}) is unique for each layer. It is calculated as:

$$TT_{perc} = \frac{SAT_{ly} - FC_{ly}}{K_{sat}}$$

where TT_{perc} is the travel time for percolation (hrs), SAT_{ly} is the amount of water in the soil layer when completely saturated (mm H_2O), FC_{ly} is the water content of the soil layer at field capacity (mm H_2O), and K_{sat} is the saturated hydraulic conductivity

4.2.1.4 Lateral Subsurface Flow

Lateral subsurface flow, or interflow in the soil profile is calculated using a kinematic storage model developed by Sloan and Moore (1984). The kinematic wave approximation of saturated subsurface or lateral flow assumes that the lines of flow in the saturated zone are parallel to the impermeable boundary and the hydraulic gradient equals the slope of the bed. The drainable volume of water stored in the saturated zone of the hill slope segment per unit area, $SW_{ly,excess}$, is

$$SW_{ly,excess} = (1000.H_o.\varphi_d\ .Lhill) / 2$$

where, $SW_{ly,excess}$ is the drainable volume of water stored in the saturated zone of the hill slope per unit area (mm), H_o is the saturated thickness normal to the hill slope at the outlet expressed as a fraction of the total thickness (mm/mm), φ_d is the drainable porosity of the soil (mm/mm), L_{hill} is the hill slope length (m), and 1000 is a factor needed to convert meters to millimeters.

4.2.1.5 Ground water flow

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

The water balance for the shallow acquifer is

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg} - Q_{gw} - w_{revap} - w_{deep} - w_{pump,sh}$$

where, $aq_{sh,i}$ is the amount of water stored in the shallow aquifer on day i (mm), $aq_{sh,i-1}$ is the amount of water stored in the shallow aquifer on day i-1 (mm), w_{rchrg} is the amount of recharge entering the aquifer (mm), Q_{gw} is the groundwater flow, or base flow, into the main channel (mm), w_{revap} is the amount of water moving into the soil zone in response to water deficiencies (mm), w_{deep} is the amount of water percolating from the shallow aquifer into the deep aquifer (mm), and $w_{pump,sh}$ is the amount of water removed from the shallow aquifer by pumping (mm).

The water balance for the deep acquifer is

$$aq_{dpi} = aq_{dp,i-1} + w_{deep} - w_{pump,sh}$$

where, $aq_{dp,i}$ is the amount of water stored in the deep aquifer on day *i* (mm), $aq_{dp,i-1}$ is the amount of water stored in the deep aquifer on day i-1 (mm), and $w_{pump,dp}$ is the amount of water removed from the deep aquifer by pumping on day *i* (mm).

4.2.1.6 Evapotranspiration

Evapotranspiration is a collective term that includes all processes by which water at the earth's surface is converted to water vapor. It includes evaporation from the plant canopy, transpiration, sublimation and evaporation from the soil. Evapotranspiration is the primary mechanism by which water is removed from a watershed.

Numerous methods have been developed to estimate ET. Three of these methods have been incorporated into SWAT2012: the Penman-Monteith method (Monteith, 1965; Allen, 1986; Allen et al., 1989), the Priestley-Taylor method (Priestley and Taylor, 1972) and the Hargreaves method (Hargreaves et al., 1985).

The Penman-Monteith equation combines components that account for energy needed to sustain evaporation, the strength of the mechanism required to remove the water vapor and aerodynamic and surface resistance terms. The Penman-Monteith equation is

$$\lambda E = \frac{\Delta.(H_{net} - G) + \rho_{air}.c_p.[e_z^{\,o} - e_z]/r_a}{\Delta + \gamma.(1 + r_c / r_a)}$$

where, λE is the latent heat flux density ($MJm\text{-}^{2}d^{-1}$), E is the depth rate evaporation (mmd^{-1}), D is the slope of the saturation vapor pressure-temperature curve, *de/dT* ($kPa^{o}C^{-1}$), H_{net} is the net radiation ($MJm^{-2}\ d^{-1}$), G is the heat flux density to the ground ($MJ\ m^{-2}d^{-1}$), ρ_{air} is the air density (kgm^{-3}), c_p is the specific heat at constant pressure (MJ kg-1^{o}C $^{-1}$), e_z^{o} *is* the saturation vapor pressure of air at height z (kPa), e_z is the water vapor pressure of air at height z (kPa), γ is the psychrometric constant ($kPa^{o}C^{-1}$), r_c is the plant canopy resistance (sm^{-1}), and r_a is the diffusion resistance of the air layer (aerodynamic resistance) (sm^{-1}).

Priestley and Taylor (1972) developed a simplified version of the combination equation for use when surface areas are wet. The aerodynamic component was removed and the energy component was multiplied by a coefficient, α_{pet} = 1.28, when the general surroundings are wet or under humid conditions:

$$\lambda E_o = \alpha_{pet} \cdot \frac{\Delta}{\Delta + \gamma} \cdot (H_{net} - G)$$

where, λ is the latent heat of vaporization (MJ kg^{-1}), *Eo* is the potential evapotranspiration (mm d^{-1}),α_{pet} is a coefficient, D is the slope of the saturation vapor pressure-temperature curve, *de/dT* (kPa^{o}C^{-1}), γ is the psychometric constant (kPa^{o}C^{-1}),

H_{net} is the net radiation (MJ m^{-2} d^{-1}), and *G* is the heat flux density to the ground (MJ m^{-2} d^{-1}).

The Priestley-Taylor equation provides potential evapotranspiration estimates for low advective conditions. In semiarid or arid areas where the advection component of the energy balance is significant, the Priestley-Taylor equation will underestimate potential evapotranspiration.

The Hargreaves method estimates potential evapotranspiration as a function of extraterrestrial radiation and air temperature. The modified equation used in theSWAT2012 is:

$$\lambda E_o = 0.0023 . H_o . (T_{mx} - T_{mn}) 0.5 . (T_{av} + 17.8)$$

where, λ is the latent heat of vaporization (MJ kg^{-1}), E_o is the potential evapotranspiration (mm d^{-1}), H_0 is the extraterrestrial radiation (MJ $m^{-2}d^{-1}$), T_{mx} is the maximum air temperature for a given day (^{o}C), T_{mn} is the minimum air temperature for a given day (^{o}C), and T_{av} is the mean air temperature for a given day (^{o}C).

4.2.1.7 Transmission loss

Transmission losses are losses of surface flow via leaching through the stream bed. This type of loss occurs in ephemeral or intermittent streams where groundwater contribution occurs only at certain times of the year, or not at all. The abstractions, or transmission losses, reduces runoff volume as the flood waves travel downstream. Lane's method described in USDA SCS Hydrology Handbook (1983) is used to estimate transmission losses. Water losses from the channel are a function of channel width and length and flow duration. Both runoff volume and peak rate are adjusted when transmission losses occur in tributary channels.

4.2.2 Weather

SWAT uses precipitation, air temperature, solar radiation, relative humidity and wind speed in driving hydrological balance. The model can read these inputs directly from the file or generate the values using monthly average data analyzed for a number of years. It includes the WXGEN weather generator model (Sharpley, 1990) to generate climate data or to fill in gaps in measured records. The weather generator first independently generates precipitation for the day, followed by generation of maximum and minimum temperature, solar radiation and relative humidity based on the presence or absence of rain for the day. Finally, wind speed is generated independently.

4.2.2.1 Precipitation

The precipitation generator is a Markov chain-skewed or Markov chain exponential model (Williams, 1995). A first-order Markov chain is used to define the day as wet or dry. When a wet day is generated, a skewed distribution or exponential distribution is used to generate the precipitation amount.

4.2.2.1.1Occurence of Wet or Dry Day

With the first-order Markov-chain model, the probability of rain on a given day is conditioned on the wet or dry status of the previous day. It is required to input the probability of a wet day on day *i* given a wet day on day *i* –1, $P_i(W/W)$, and the probability of a wet day on day *i* given a dry day on day *i*–1, $P_i(W/D)$, for each month of the year. From these inputs the remaining transition probabilities can be derived:

$$P_i(D/W) = 1 - P_i(W/W)$$

$$P_i(D/D) = 1 - P_i(W/D)$$

where, $P_i(D/W)$ is the probability of a dry day on day *i* given a wet day on day *i*–1 and $P_i(D/D)$ is the probability of a dry day on day *i* given a dry day on day *i*–1.

To define a day as wet or dry, model generates a random number between 0 and 1. This random number is compared to the appropriate wet-dry probability, $P_i(W/W)$ or $P_i(W/D)$. If the random number is equal to or less than the wet-dry probability, the day is defined as wet. If the random number is greater than the wet-dry probability, the day is defined as dry.

4.2.2.1.2 Amount of Precipitation

The model provides two options to describe the distribution of rainfall amounts: a skewed distribution and an exponential distribution. The equation used to calculate the amount of precipitation on a wet day is:

$$R_{day} = \mu_{mon} + 2.\sigma_{mon}.\left(\frac{\left[\left(SND_{day} - \frac{g_{mon}}{6}\right).\left(\frac{g_{mon}}{6}\right) + 1\right]^3 - 1}{g_{mon}}\right)$$

where, R_{day} is the amount of rainfall on a given day(mmH_2O), μ_{mon} and σ_{mon} are the mean and standard deviation of daily rainfall (mm), respectively for the month. SND_{day} is the standard normal deviate calculated for the day, and g_{mon} is the skew coefficient for daily precipitation in the month.

4.2.2.2 Solar Radiation and temperature

The procedure used to generate daily values for the maximum/minimum temperature and solar radiation is based on the weekly stationary generating process (Richardson and Wright, 1984). The temperature model requires monthly means of maximum and minimum temperatures and their standard deviations as inputs.

The solar radiation model uses the extreme approach extensively. Thus, only monthly means of daily solar radiation are required as inputs. The continuity equation relates average daily solar radiation adjusted for wet or dry conditions to the average daily solar radiation for the month.

$$\mu rad_{mon}.days = \mu Wrad_{mon}.days_{wet} + \mu Drad_{mon}.days_{dry}$$

where, μrad_{mon} is the average daily solar radiation for the month (MJm^{-2}), $days_{tot}$ are the total number of days in the month, $\mu Wrad_{mon}$ is the average daily solar radiation of the month on wet days (MJm^{-2}),$days_{wet}$ are the number of wet days in the month, $\mu Drad_{mon}$ is the average daily solar radiation of the month on dry days (MJm^{-2}), $days_{dry}$ arethe number of dry days in the month.

4.2.2.3 Relative Humidity

Daily average relative humidity values are calculated from a triangular distribution using average monthly relative humidity. The triangular distribution used to generate daily relative humidity values requires four inputs: mean monthly relative humidity, maximum relative humidity value allowed in month, minimum relative humidity value allowed in month, and a random number between 0.0 and 1.

4.2.2.4 Wind Speed

Wind Speed is required by SWAT when the Penman-Monteith equation is used to calculate potential evapotranspiration. Mean daily wind speed is generated in SWAT using a modified exponential equation :

$$\mu_{10m} = \mu wnd_{mon}.(-\ln(rnd_1))^{0.3}$$

where, μ_{10m} is the mean wind speed for the day ($m\ s^{-1}$), μwnd_{mon} is the average wind speed for the month ($m\ s^{-1}$), and rnd_1 is a random number between 0 and 1.

4.2.3 Erosion and Sediment Yield

The sediment yield for each sub-basin, in the SWAT model is computed by using the Modified Universal Soil Loss Equation (MUSLE) (Williams,1975)

$$sed = 11.8.(Q_{surf}.q_{peak}.area_{hru})^{0.56}.K_{USLE}.C_{USLE}.P_{USLE}.LS_{USLE}.CFRG$$

where, *sed* is the sediment yield on a given day (metric tons), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor, C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and *CFRG* is the coarse fragment factor.

K_{USLE} is calculated using the following equation (Williams, 1995)

$$K_{USLE} = f_{csand} \cdot f_{cl-si} \cdot f_{orgc} \cdot f_{hisand}$$

where f_{csand} is a factor that gives low soil erodibility factors for soils with high coarse-sand contents and high values for soils with little sand, f_{cl-si} is a factor that gives low soil erodibility factors for soils with high clay to silt ratios, f_{orgc} is a factor that reduces soil erodibility for soils with high organic carbon content, and f_{hisand} is a factor that reduces soil erodibility for soils with extremely high sand contents. The factors are calculated:

$$f_{csand} = \left(0.2 + 0.3.\exp\left[-0.256.m_s.\left(1 - \frac{m_{silt}}{100}\right)\right]\right)$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3}$$

$$f_{orgc} = \left(1 - \frac{0.25.orgC}{orgC + \exp[3.72 - 2.95.orgC]}\right)$$

$$f_{hisand} = \left(1 - \frac{0.7\left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left[-5.51 + 22.9\left(1 - \frac{m_s}{100}\right)\right]}\right)$$

where m_s is the percent sand content (0.05-2.00 mm diameter particles), m_{silt} is the percent silt content (0.002-0.05mm diameter particles), m_c is the percent clay content (<0.002 mm diameter particles), and orgC is the percent organic carbon content of the layer

C_{USLE} factor is estimated using the following equation:

$$C_{USLE} = \{\exp(\ln(0.8) - \ln(C_{USLE})).\exp(-0.00115.rsd_{surf}) + \ln(C_{USLE,mn})\}$$

where, $C_{USLE,mn}$ is the minimum value of the crop cover management factor for the land cover and rsd_{surf} is the amount of residue on the soil surface (kg/ha).

LS_{USLE} factor is estimated using the following equation:

$$LS_{USLE} = \left(\frac{L_{hill}}{22.1}\right)^{m}.(65.41.\sin^2(\alpha_{hill}) + 4.56.\sin\alpha_{hill} + 0.065)$$

where, L_{hill} is the slope length (m), m is the exponential term, and α_{hill} is the angle of the slope. The exponential m is calculated:

$$m = 0.6.(1 - \exp[-35.835.slp])$$

where slp is the slope of the HRU expressed as rise over run(m/m). The relationship between αhill and slp is:

$$slp = \tan\alpha_{hill}$$

The coarse fragment factor is calculated:

$$CFRG = \exp(-0.053.rock)$$

4.2.4 Nutrients and Pesticides

The SWAT models the complete nutrient cycle for nitrogen and phosphorus. Three forms of nitrogen in mineral soils are organic nitrogen associated with humus, mineral forms of nitrogen held by soil colloids, and mineral forms of nitrogen in solution. Nitrogen may be added to the soil by fertilizer, manure, fixation by symbiotic or non-symbiotic bacteria, and rain. Nitrogen is removed from the soil by plant uptake, leaching, volatilization, denitrification and erosion. SWAT monitors the five different pools of nitrogen in the soil.

Unlike nitrogen which is highly mobile, phosphorus solubility is limited in most environments. Phosphorus combines with other ions to form a number of insoluble compounds that precipitate out of solution. These characteristics contribute to a build-up of phosphorus near the soil surface that is readily available for transport in surface runoff. SWAT monitors six different pools of phosphorus in the soil. Three pools are inorganic forms of phosphorus while the other three pools are organic forms of phosphorus.

SWAT simulates pesticide movement into the stream network via surface runoff, and into the soil profile and aquifer by percolation. The equations used to model the movement of pesticide in the land phase of the hydrologic cycle were adopted from GLEAMS(Leonard, 1987).

4.2.5 Soil Temperature

Daily average soil temperature is simulated at the center of each soil layer using daily maximum and minimum air temperature. Soil temperature for each layer is simulated using a function of damping depth, surface temperature and mean annual air temperature. Damping depth is dependent upon bulk density and soil water content.

4.2.6 Crop Growth

The plant growth component of SWAT is a simplified version of the EPIC plant growth model. As in EPIC, phenological plant development is based on daily accumulated heat units, potential biomass is based on a method developed by Monteith, a harvest index is used to calculate yield, and plant growth can be inhibited by temperature, water, nitrogen or phosphorus stress.

4.2.7 Agricultural Management

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

In addition to these basic management practices, operations such as grazing, automated fertilizer and water applications, and incorporation of every conceivable management option for water use are available. The latest improvement to land management is the incorporation of routines to calculate sediment and nutrient loadings from urban areas.

4.3 Components of channel routing

4.3.1 Channel Flood Routing

Routing in the main channel can be divided into four components: water, sediment, nutrients and organic chemicals. As water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another potential loss is removal of water from the channel for agricultural or human use. Flow may be supplemented by the fall of rain directly on the channel and/or addition of water from point source discharges. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the

Muskingum routing method. Users are required to define the width and depth of the channel when filled to the top of the bank as well as the channel length, slope along the channel length and Manning's 'n' value. Manning's equation for uniform flow in a channel is used to calculate the rate and velocity of flow in a reach segment for a given time step.

The variable storage routing method was developed by Williams (1969) and used in the HYMO (Williams and Hann, 1973) and ROTO (Arnold, 1995) models. For a given reach segment, storage routing is based on the continuity equation:

$$V_{in} - V_{out} = \Delta V_{stored}$$

where V_{in} is the volume of inflow during the time step (m^3 H_2O), V_{out} is the volume of outflow during the time step (m^3 H_2O), and V_{stored} is the change in volume of storage during the time step (m^3 H_2O). This equation can be presented as :

$$\Delta t.\left(\frac{q_{in,1} + qi_{n,2}}{2}\right) - \Delta t.\left(\frac{q_{out,1} + q_{out,2}}{2}\right) = V_{stored,2} - V_{stored,1}$$

where, Δt is the length of the time step (s) and $q_{\text{in},1}$ and $q_{in,2}$ are the inflow rate at the beginning and end of the time step (m^3 /s), respectively. $q_{out,1}$ and $q_{out,2}$ are the outflow rate at the beginning and end of the time step (m^3/s). $V_{stored,1}$ and $V_{stored,2}$ are the storage volume at the beginning and end of the time step (m^3).

Travel time is computed by dividing the volume of water in the channel by the flow rate.

$$TT = \frac{V_{stored}}{q_{out}} = \frac{V_{stored,1}}{q_{out,1}} = \frac{V_{stored,2}}{q_{out,2}}$$

where, TT is the travel time (s), V_{stored} is the storage volume (m^3), and q_{out} is the discharge rate (m^3/s).

The relationship between travel time and storage coefficient is represented as:

$$q_{out,2} = \left(\frac{2.\Delta t}{2.TT + t}\right).qi_{n,av} + \left(1 - \frac{2.\Delta t}{2.TT + \Delta t}\right).q_{out,1}$$

The storage coefficient is calculated as:

$$SC = \frac{2.\Delta t}{2.TT + \Delta t}$$

Finally the volume of outflow is calculated as

$$V_{out,2} = SC.(V_{in} + V_{stored,1})$$

4.3.2 Transmission Loss

The transmission losses reduce runoff volumes and peak rates from the watersheds as flood waved travels down streams. Transmission losses are estimated with the equation:

$$tloss = K_{ch}.TT.P_{ch}.L_{ch}$$

where, *tloss* are the channel transmission losses (m^3), K_{ch} is the effective hydraulic conductivity of the channel alluvium (mm/hr), P_{ch} is the wetted perimeter (m), and L_{ch} is the channel length (km).

Transmission losses from the main channel are assumed to enter bank storage or the deep aquifer.

4.3.3 Evaporation Loss

Evaporation losses from the reach are calculated as:

$$E_{ch} = coef_{ev}.E_o.L_{ch}.W.fr_{\Delta t}$$

where, E_{ch} is the evaporation from the reach for the day (m3), $coef_{ev}$ is an evaporation coefficient, E_o is potential evaporation (mm), *W* is the channel width at water level (m), and *fr* is the fraction of the time step in which water is flowing in the channel (travel time/length of the time step).

4.3.4 Bank Storage

The amount of water entering bank storage on a given day is calculated:

$$bnk_{in} = tloss.(1 - fr_{trns})$$

where, bnk_{in} is the amount of water entering bank storage (m^3) and fr_{trns} is the fraction of transmission losses partitioned to the deep aquifer.

4.3.5 Channel Water Balance

Water storage in the reach at the end of the time step is calculated:

$$V_{stored,2} = V_{stored,1} + V_m - V_{out} - tloss - E_{ch} + div + V_{bnk}$$

where, *div* is the volume of water added or removed from the reach for the day through diversions (m^3), and V_{bnk} is the volume of water added to the reach via return flow from bank storage (m^3).

4.4 Channel Sediment Routing

Sediment transport in the channel network is a function of two processes, deposition and degradation, operating simultaneously in the reach. SWAT computes these two processes using the same channel dimensions for the entire simulation. The model simulates down cutting and widening of the stream channel and update channel dimensions throughout the simulation. In SWAT2012, the equations are simplified and the maximum amount of sediment that can be transported from a reach segment is a function of the peak channel velocity. The peak channel velocity, $v_{ch,pk}$ is calculated

$$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}}$$

where, $q_{ch,pk}$ is the peak flow rate (m^3/s) and A_{ch} is the cross-sectional area of flow in the channel (m^2).

The peak flow rate is defined as:

$$q_{ch,pk} = prf \cdot q_{ch}$$

where, *prf* is the peak rate adjustment factor and q_{ch} is the average rate of flow (m^3/s). The maximum amount of sediment that can be transported from a reach segment is calculated as:

$$conc_{sed,ch,mx} = c_{sp} \cdot v_{ch,pk}^{\,spexp}$$

where, $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (ton/m^3), c_{sp} is a coefficient defined by the user, $v_{ch,pk}$ is the peak channel velocity (m/s), and *spexp* is an exponent defined by the user. The exponent, *spex*p, normally varies between 1 and 2.

The net amount of sediment deposited is calculated:

$$sed_{dep} = (conc_{sed,ch,i} - conc_{sed,ch,mx}) \cdot V_{ch}$$

where, sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), and V_{ch} is the volume of water in the reach segment (m^3).

If $conc_{sed,ch,i} < conc_{sed,ch,mx}$, degradation is the dominant process in the reach segment and the net amount of sediment reentrained is calculated as:

$$sed_{\deg} = (conc_{sed,ch,mx} - conc_{sed,ch,i}).V_{ch}.K_{CH}.C_{CH}$$

where sed_{deg} is the amount of sediment reentrained in the reach segment (metric tons), $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (kg/L or ton/m^3), $conc_{sed,ch,i}$ is the initial sediment concentration in the reach (kg/L or ton/m^3), V_{ch} is the volume of water in the reach segment (m^3 H_2O), K_{CH} is the channel erodibility factor (cm/hr/Pa), and C_{CH} is the channel cover factor.

Once the amount of deposition and degradation has been calculated, the final amount of sediment in the reach is determined:

$$sed_{ch} = sed_{ch,i} - sed_{dep} + sed_{\deg}$$

where sed_{ch} is the amount of suspended sediment in the reach (metric tons), $sed_{ch,i}$ is the amount of suspended sediment in the reach at the beginning of the time period (metric tons).

The amount of sediment transported out of the reach is calculated as:

$$sed_{out} = sed_{ch}.\frac{V_{out}}{V_{ch}}$$

where, sed_{out} is the amount of sediment transported out of the reach (metric tons), sed_{ch} is the amount of suspended sediment in the reach (metric tons),V_{out} is the volume of outflow during the time step (m^3H_2O), and V_{ch} is the volume of water in the reach segment (m^3H_2O)

4.4.1 Channel downcutting and widening

While sediment transport calculations have traditionally been made with the same channel dimensions throughout a simulation, SWAT will model channel downcutting and widening. When channel downcutting and widening is simulated, channel dimensions are allowed to change during the simulation period.

Three channel dimensions are allowed to vary in channel downcutting and widening simulations: bankfull depth, $depth_{bnkfull}$, channel width, $W_{bnkfull}$, and channel slope, slp_{ch}. Channel dimensions are updated using the following equations when the volume of water in the reach exceeds $1.4x10^6$ m^3.

The amount of downcutting is calculated (Allen et al., 1999):

$$depth_{dcut} = 358.depth.slp_{ch}.K_{CH}$$

where $depth_{dcut}$ is the amount of downcutting (m), *depth* is the depth of water in channel (m), slp_{ch} is the channel slope (m/m), and K_{CH} is the channel erodibility coefficient (cm/h/Pa).

The new bankfull depth is calculated as:

$$depth_{bnkfull} = depth_{bnkfull,i} + depth_{dcut}$$

where $depth_{bnkfull}$ is the new bankfull depth (m), $depth_{bnkfull,i}$ is the previous bankfull depth, and $depth_{dcut}$ is the amount of downcutting (m).

The new bank width is calculated as:

$$W_{bnkfull} = ratio_{WD} . depth_{bnkfull}$$

where $W_{bnkfull}$ is the new width of the channel at the top of the bank (m), $ratio_{WD}$ is the channel width to depth ratio, and $dept_{hbnkfull}$ is the new bankfull depth (m).

The new channel slope is calculated as:

$$slp_{ch} = slp_{ch,i} - \frac{depth_{dcut}}{1000 . L_{ch}}$$

where slp_{ch} is the new channel slope (m/m), $slp_{ch,i}$ is the previous channel slope (m/m), $depth_{bnkfull}$ is the new bankfull depth (m), and L_{ch} is the channel length (km).

5. Materials and Methods

5.1 Materials used

5.1.1 Remote sensing and other data used

1. SRTM DEM (90 meter resolution)
2. MODIS (250 m resolution) time series NDVI multi-spectral data (2005-06 and 2010-11)
3. FAO soil layer
4. Weather (SWAT Global Weather Data-CFSR(Daniel R. Fuka, 2013))

5.1.2 Software used

Software used for the research:

I. Land use/Land cover Mapping
   - ERDAS Imagine 10.4
   - Google Earth Pro

II. Geospatial Analysis
   - ArcGIS 10.2.2

III. Runoff Model Implementation
   - SWAT 2012 (ArcSWAT 10.2.2)

IV. Analysis and Report writing
   - Microsoft Excel and Word

5.2 Research Methodology

For runoff estimation, SWAT model is used. SWAT is a physically based model. It is a comprehensive model which requires detailed information about weather, soil properties, topography, vegetation and land management practices in the watershed. Regardless of what is studied with SWAT, hydrology remains the driving force behind all the physical processes. SWAT divides the simulation of hydrology into two parts. The first division is the land phase of the hydrologic cycle which controls the amount of water, sediment, nutrient and pesticide loadings to the main channel. The second division is the routing phase of the hydrologic cycle which defines the movement of water, sediments and nutrients through the drainage network of the watershed to the outlet.

In SWAT model, a river basin is divided into a number of sub-basins. Each sub-basin contains at least one Hydrologic Response Unit (HRU), a tributary channel and a main channel or reach. Sub-basin possess a geographical position and is spatially interconnected, flow from one sub-basin enters another. These sub basins are further partitioned into HRUs, which are lumped land areas that are comprised of unique land cover and soil combinations. The partition of sub-basin into HRUs, increases accuracy and gives a much better physical description of the water balance.

Contrary to flow among sub-basin, there is no interaction between the HRUs. Runoff and sediment yield are predicted separately for each HRU and summed up to obtain the total loading from the sub-basin.

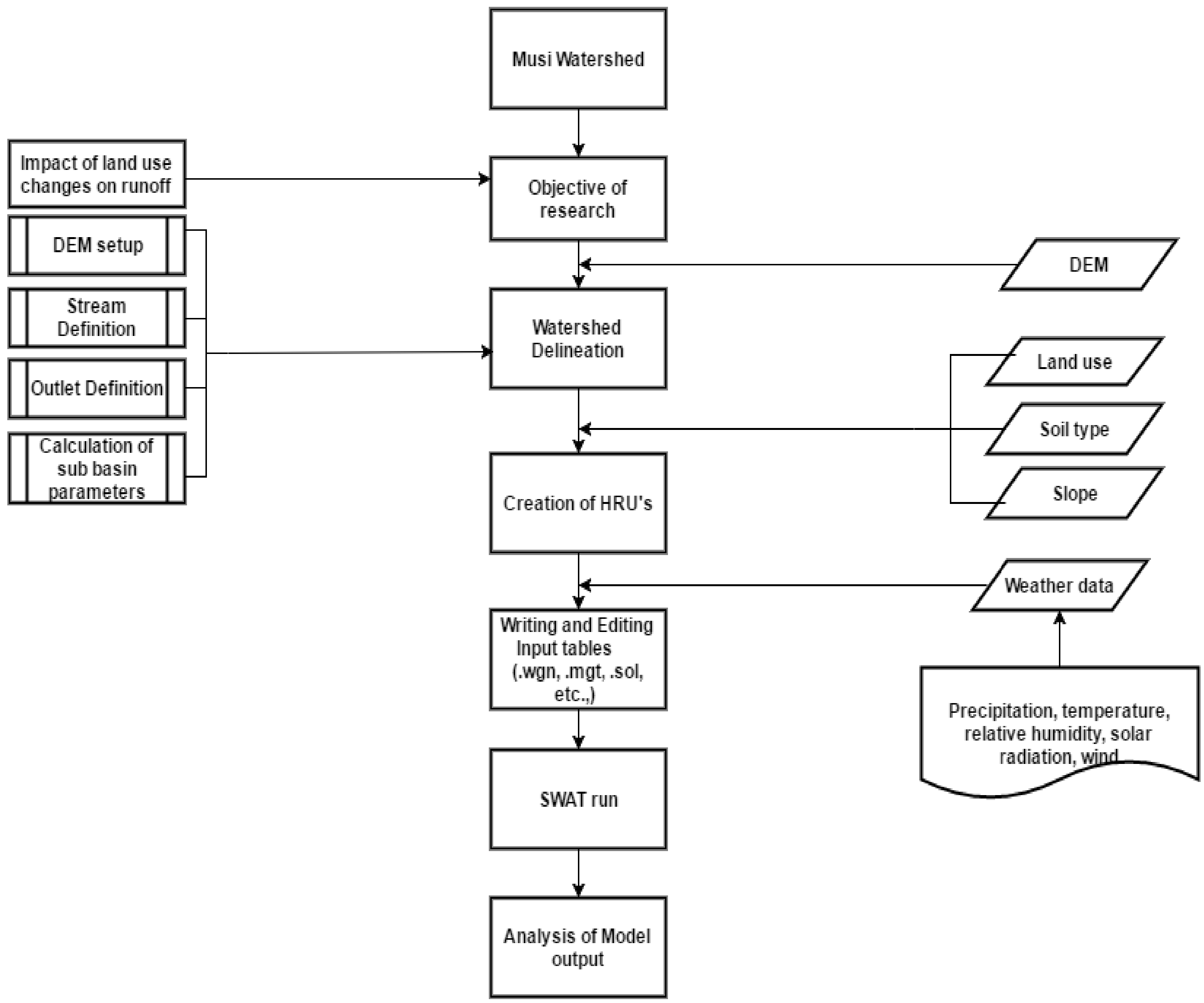


Figure 7: Methodology flow chart of SWAT model

5.2.1 Modelling runoff with SWAT

SWAT simulates surface runoff volumes for each HRU using either of the two methods: the SCS Curve Number (CN) procedure and the Green & Ampt infiltration method. Later requires sub daily precipitation data thus restricting its use.

The SCS runoff equation is an empirical model which originated after 20 years of studies involving rainfall-runoff relationships from small rural watershed across the U.S., the model predicts amount of runoff under varying land-use and soil types.

The SCS curve number equation is:

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

Where Q_{surf} is the accumulated runoff (mm H_2O), R_{day} is the rainfall depth of the day (mm H_2O), I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O), and S is the retention parameter (mm H_2O). The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as:

$$S=25.4\{(1000/CN)-10\}$$

Where, CN is the curve number for the day. The initial abstraction I_a is estimated as $0.2S$ and thus the equation becomes:

$$Q_{surf} = (R_{day} - 0.2S)^2/(R_{day} + 0.8S)$$

Runoff will occur when $R_{day} > I_a$.

I_a for Indian conditions is estimated to be 0.3S. Its values are taken as 0.15S and 0.3S for red soil (alfisol) and black soil (vertisol) respectively (Indian Agricultural Statistics Research Institute).

The curve number is a function of the soil's permeability, land use and antecedent soil water conditions. Soil properties that influence runoff are related with saturated hydraulic conductivity, depth to seasonally high water table and depth to a very slowly permeable layer. Soil may be placed in one of the four groups according to its runoff potential. These are A, B, C, D, with increasing order from A to D, the runoff potential of soils keep increasing, 'A' having lowest runoff potential and 'D' having highest.

Table 2: Runoff curve numbers for hydrologic soil cover complexes for the Indian conditions (AMC II)

Sl. No.	Land use	Treatment/ Practices	Hydrologic Condition	Hydrologic Soil Group			
				A	B	C	D
1	Cultivated	Straight row	………..	76	86	90	93
		Contoured	Poor	70	79	84	88
			Good	65	75	82	86
		Contoured & terraced	Poor	66	74	80	82
			Good	62	71	77	81
		Bunded	Poor	67	75	81	83
			Good	59	69	76	79
		Paddy (rice)	…………	95	95	95	95
2	Orchards	With under stony cover	…………	39	53	67	71
		Without under stony cover	…………	41	55	69	73

3	Forest	Dense	………..	26	40	58	61
		Open	………..	28	44	60	64
		Degraded forest/shrubs	………..	33	47	64	67
4	Pasture		Poor	68	79	86	89
			Fair	49	69	79	84
			Good	39	61	74	80
5	Wasteland		………..	71	80	85	88
6	Hard Surface		………..	77	86	91	93

(*Source: Handbook of Hydrology, Ministry of Agri. and Cooperation, Govt. of India (1972)*)

Other than soil properties and land use, antecedent soil moisture conditions also affect the curve number, SCS defines three antecedent moisture conditions: 1 – dry (wilting point), II – average moisture and III – wet (field capacity). In SWAT, Curve Number for moisture condition II is provided to the model; subsequently it adjusts the CN according to the antecedent moisture condition calculated from daily rainfall data.

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

$$CN_3 = CN_2 \cdot \exp[0.00673 \cdot (100 - CN_2)]$$

The retention parameter is allowed to vary with the soil profile water content.

5.3 Data collection and processing

SWAT model is data driven, which requires several data ranging from topography, land use, soil, climate, etc. Data was collected from various sources, following section describes about the data collection and processing.

5.3.1 Digital Elevation Model (DEM)

SRTM 90 meter DEM of Andhra Pradesh (ESRI grid format) is taken from IIRS online database and clipped for the elevation data of the study area. Figure 8 shows the DEM of Musi Basin clipped from DEM of Andhra Pradesh

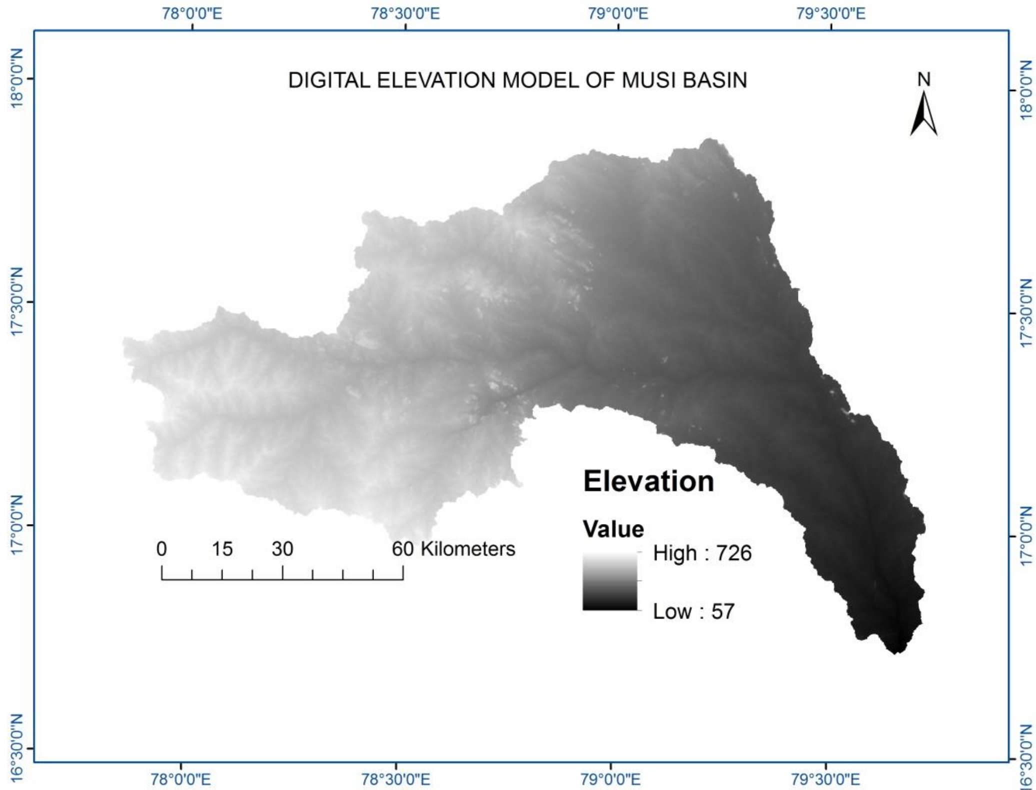


Figure 8: Digital Elevation Model of Musi Basin

5.3.2 Land use database

Land use for the crop years 2005-06 and 2010-11 are prepared using MODIS Time-Series Mega files of Normalized Difference Vegetation Index (NDVI) downloaded from the USGS website.

The **Normalized Difference Vegetation Index** (**NDVI**) is a simple graphical indicator that can be used to analyze remote sensing measurements, typically but not necessarily from a space platform, and assess whether the target being observed contains live green vegetation or not. NDVI is calculated from the visible and near-infrared light reflected by vegetation. Healthy vegetation absorbs most of the visible light that hits it, and reflects a large portion of the near-infrared light. Unhealthy or sparse vegetation reflects more visible light and less near-infrared light. **NDVI = (NIR — VIS)/(NIR + VIS)** where NIR is 'Near infrared' and VIS is 'Visible'. Calculations of NDVI for a given pixel always result in a number that ranges from minus one (-1) to plus one (+1); however, no green leaves gives a value close to zero. A zero means no vegetation and close to +1 (0.8 - 0.9) indicates the highest possible density of green leaves.

A mega file is a composite of time-series MODIS data involving Normalized Difference Vegetation Index (NDVI), and the NDVI Maximum Value Composites (MVC). MVC gives the highest NDVI/spectral value in a particular time span. 16 day MODIS NDVI spectral images are composited to get monthly maximum value composites using MODIS Re-projection Tool (MRTool). 12 NDVI MVCs (one for each month) of the study area are layer stacked into a single file and this single file is called mega file data cube.

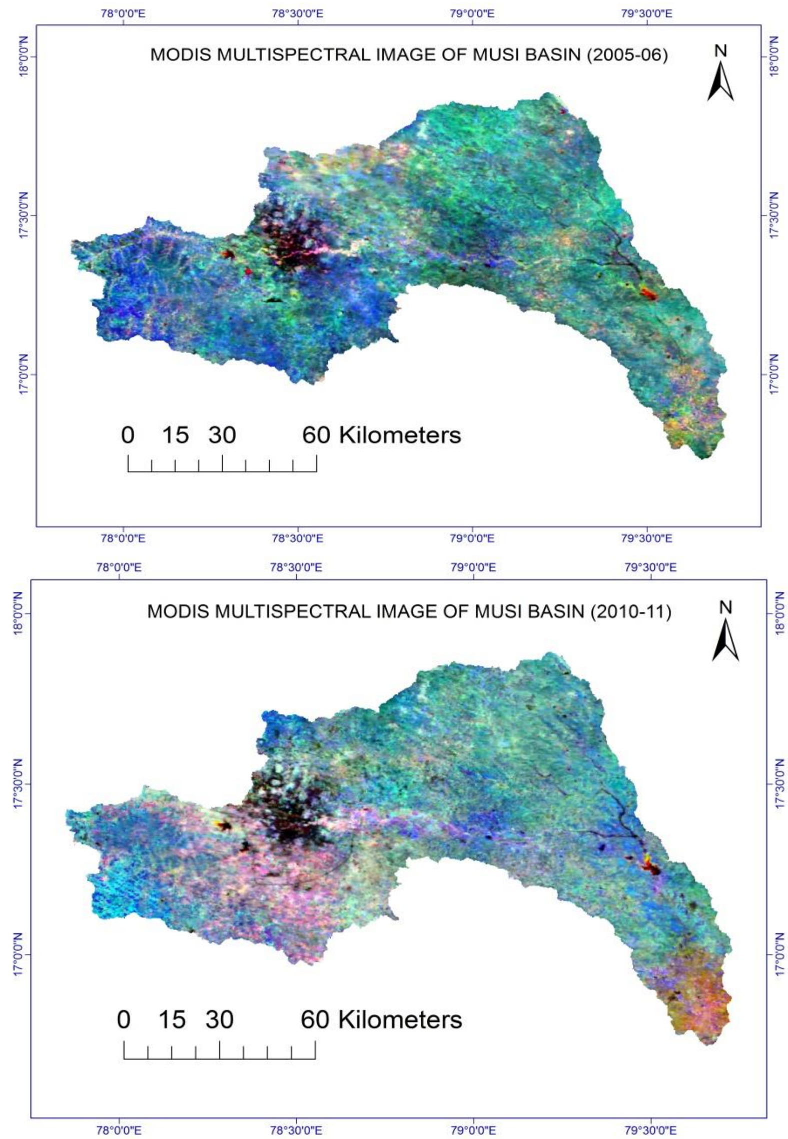


Figure 9: MODIS multispectral images of musi basin for the crop years 2005-06 and 2010-11

5.3.2.1 Mapping Land use/Land cover

After the generation of mega files, land use/ land cover for the years of study are mapped using ERDAS Imagine 2014 and google earth. Land use classification is done with the help of ‘unsupervised classification’ tool in ERDAS. Using this tool, 50 classes were divided and average

NDVI values are calculated for the mega files. Based on the average NDVI curves and ideal curves, the land use is classified into rice, cotton, water, built-up, maize, etc., and the similar classes are merged.

LU mapping involves various protocols such as unsupervised classification (Kreuter; Levien, 1999) and spectral matching techniques. In unsupervised classification, image processing software classifies an image based on natural groupings of the spectral properties of the pixels, without the user specifying how to classify any portion of the image. Conceptually, unsupervised classification is similar to cluster analysis where observations (in this case, pixels) are assigned to the same class because they have similar values. The user must specify basic information such as which spectral bands to use and how many categories to use in the classification or the software may generate any number of classes based solely on natural groupings. Common clustering algorithms include K-means clustering and ISODATA clustering.

Unsupervised classification yields an output image in which a number of classes are identified and each pixel is assigned to a class. These classes may or may not correspond well to land cover types of interest, and the user will need to assign meaningful labels to each class. Unsupervised classification often results in too many land cover classes, particularly for heterogeneous land cover types, and classes often need to be combined to create a meaningful map.

Unsupervised classification using ISOCLASS cluster algorithm (ISODATA in Imagine 2010™) followed by progressive generalization, was used on 12-band NDVI MFDC constituted for the crop years 2005-06 and 2010-11.The classification was set at a maximum of 100 iterations and convergence threshold of 0.99. In all 50 classes were generated for each segment. Use of unsupervised techniques is recommended for large areas that cover a wide and unknown range of vegetation types. The 50 classes obtained on time series composite from the unsupervised classification were merged using rigorous class identification and labeling using protocols.

Crop type mapping of data is performed using **spectral matching techniques(Thenkabail, 2007)**. SMTs are innovative methods of identifying and labeling classes. For each derived class, this method identifies its characteristics over time using MODIS time-series data. NDVI time-series (Thenkabail, 2005; Biggs, 2006; Gumma, 2008; V. Dheeravath, 2009; Gumma *et al.*, 2014a; Gumma *et al.*, 2017) are analogous to spectra, where time is substituted for wavelength. The principle in SMT is to match the shape, or the magnitude or both to an ideal or target spectrum (pure class or “end member”). The spectra at each pixel to be classified is compared to the end-member spectra and fit is quantified using the following SMTs(Thenkabail, 2007; Gumma *et al.*, 2011a; Gumma, 2015; Gumma *et al.*, 2016a); (1) spectral correlation similarity – a shape measure; (2) spectral similarity value (SSV)- a shape and magnitude measure; (3) Eucledian distance similarity (EDS)- a distance measure; and (4) modified spectral angle similarity (MSAS)- a hyperangle measure. The first two SMTs are used very often(Thenkabail, 2007).

Spectral matching techniques (SMTs) match the class spectra derived from classification with an ideal spectra-derived from MODIS MFDC (Mega file data cube) based on precise knowledge of land use from specific locations. In SMTs, **t**he class temporal profiles (NDVI curves) are matched with ideal temporal profile (quantitatively based on temporal profile similarity values) in order to group and identify classes.

The following are the ideal NDVI curves for different classes of land use:

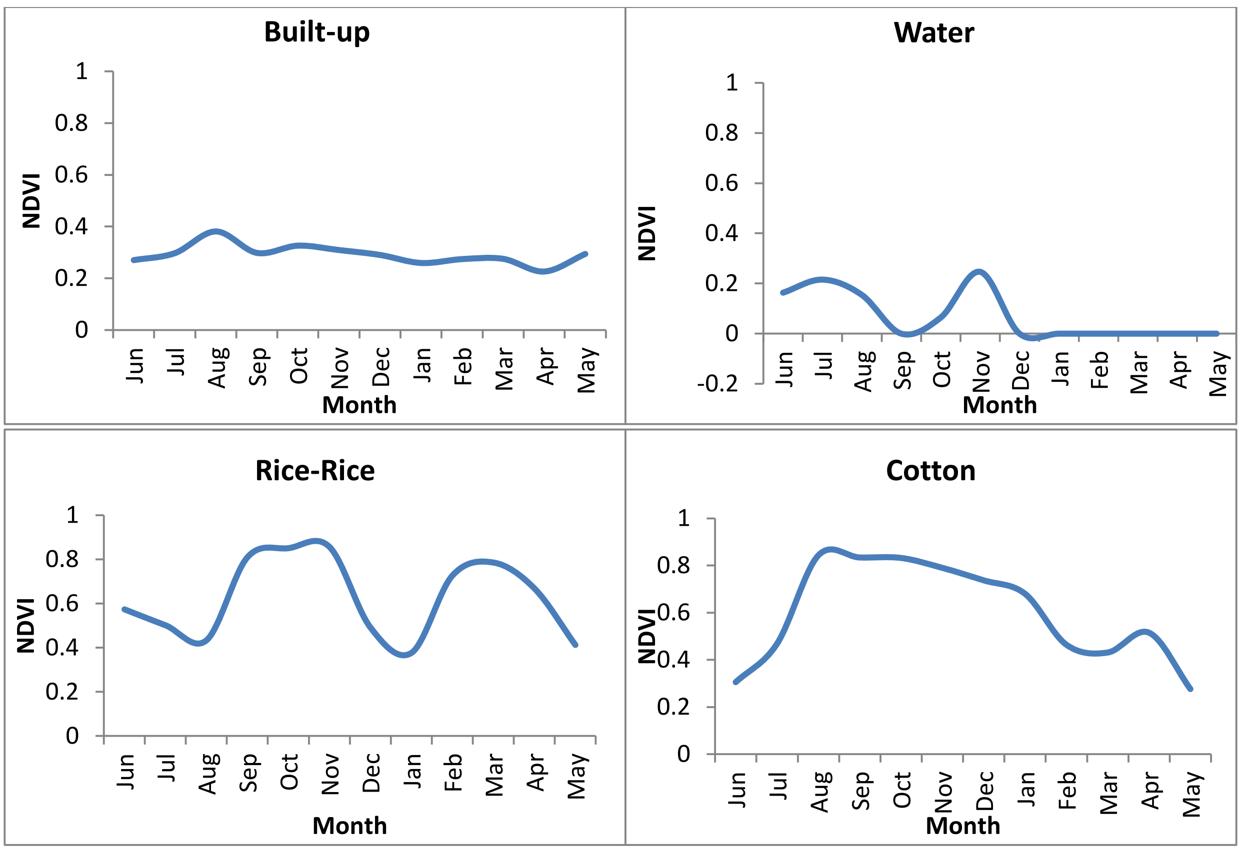


Figure 10: Ideal NDVI curves for some land use classes

<u>Class Identification and Labeling:</u>

The class identification and labeling process involves the use of Spectral Matching Techniques, location wise spectral signatures, ground survey data (Gumma *et al.*, 2011b; Gumma *et al.*, 2014b; Gumma *et al.*, 2015; Gumma *et al.*, 2016b) and Google Earth images. After grouping classes based on SMT, class names were assigned for each class.

Google Earth verification is used for class identification and labeling, since Google Earth provides very high-resolution images from 30 m to sub-meter resolution for free and is accessible through the web. This data set was also used for class identification and verification, especially in areas that are difficult to access during field visits(Gumma, 2014). Though Google Earth does not guarantee pinpoint accuracy, the zoom-in views of high-resolution imagery were used to identify the presence of any agriculture bunds, vegetation conditions, and irrigation structures (e.g., canals, irrigation channels, open wells). It was observed from the digital globe option on Google Earth that most of the high-resolution images were acquired after 2000.

Finally the 50 classes were reclassified based on similarity into 13 classes for 2005-06 and 14 classes for 2010-11and LULC maps are separated into Kharif and Rabi maps.

5.3.3 Soils

World soil layer prepared by Food and Agricultural Organization is taken for the soil data. The resolution of this layer is 1:5000000. Overlapping this soil layer with Musi watershed gives four types of soils which are in general clay-loam and clay in texture.

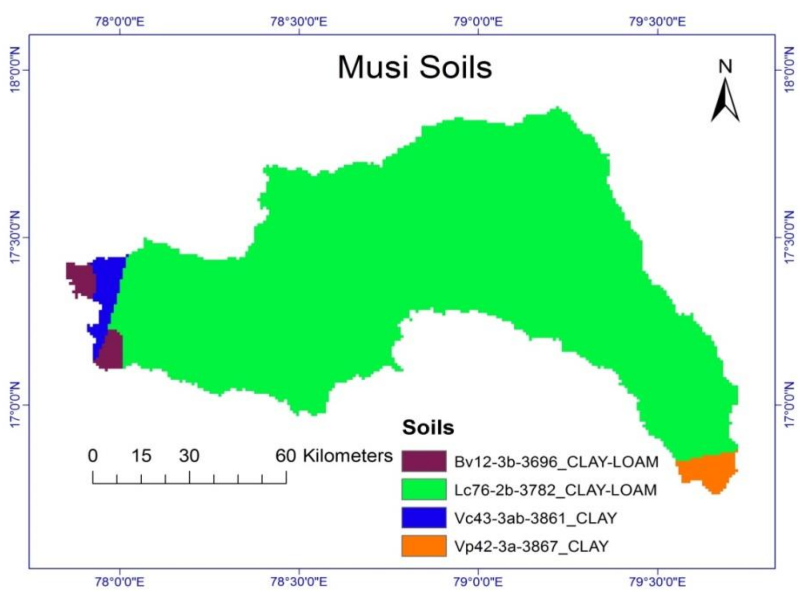


Figure 11: Soil data in raster format (ESRI Grid) for musi basin

The below tables show the soil profiles of the study area which includes the values of different soil parameters.

Table 3: Soil profiles of musi basin

SNAM	**Bv12-3b-3696**	**Lc76-2b-3782**	**Vc43-3ab-3861**	**Vp42-3a-3867**
NLAYERS	2	2	2	2
HYDGRP	D	C	D	C
SOL_ZMX	910	910	910	1000
ANION_EXCL	0.5	0.5	0.5	0.5
SOL_CRK	0.5	0.5	0.5	0.5
TEXTURE	CLAY-LOAM	CLAY-LOAM	CLAY	CLAY
SOL_Z1	300	300	300	300
SOL_BD1	1.5	1.2	1.6	1.1
SOL_AWC1	0.155	0.16	0.13	0.125
SOL_K1	2.65	13.76	1.72	21.88
SOL_CBN1	1.2	1	0.8	0.9
CLAY1	37	32	51	50
SILT1	28	25	30	27
SAND1	34	43	19	23
ROCK1	0	0	0	0
SOL_ALB1	0.0484	0.0712	0.1047	0.0863
USLE_K1	0.2274	0.2528	0.2067	0.2123
SOL_EC1	0	0	0	0
SOL_Z2	1000	1000	1000	1000
SOL_BD2	1.6	1.3	1.7	1.2
SOL_AWC2	0.155	0.16	0.13	0.125
SOL_K2	1.65	8.39	1.13	12.76
SOL_CBN2	0.5	0.6	0.4	0.5
CLAY2	42	39	56	53
SILT2	29	26	28	24
SAND2	28	35	15	23
ROCK2	0	0	0	0
SOL_ALB2	0.1867	0.154	0.2265	0.1867
USLE_K2	0.2274	0.2528	0.2067	0.2123
SOL_EC2	0	0	0	0

(Source: World soils, FAO)

Table 4: Description of soil parameters

Parameter	Units	Description
SNAM	na	Soil name
NLAYERS	na	Number of layers in the soil.
HYDGRP	na	Soil Hydrologic Group
SOL_ZMX	[mm]	Maximum rooting depth of soil profile.
ANION_EXCL	[fraction]	Fraction of porosity (void space) from which anions are excluded.
SOL_CRK	[fraction]	Crack volume potential of soil.
TEXTURE	na	Texture of soil layer.
SOL_Z	[mm]	Depth from soil surface to bottom of layer.
SOL_BD	[g/cm3]	Moist bulk density.
SOL_AWC	[mm/mm]	Available water capacity of the soil layer.
SOL_K	[mm/hr]	Saturated hydraulic conductivity.
SOL_CBN	[%]	Organic carbon content .
CLAY	[%]	Clay content.
SILT	[%]	Silt content.
SAND	[%]	Sand content.
ROCK	[%]	Rock fragment content.
SOL_ALB	na	Moist soil albedo.
USLE_K	na	USLE equation soil erodibility (K) factor.
SOL_EC	[dS/m]	[Not currently active] Electrical conductivity.

5.3.4 Weather Data

Rainfall is the most important parameter for runoff estimation. Weather data for the relevant years of study, consisting of precipitation (rainfall), temperature, relative humidity, solar radiation and wind speed is downloaded from the Global Weather Database of SWAT (Daniel R. Fuka, 2013) in the required formats, i.e., in the form of .txt and .csv files.

The data downloaded has the weather data from 18 points located in the spatial extent of the study area.

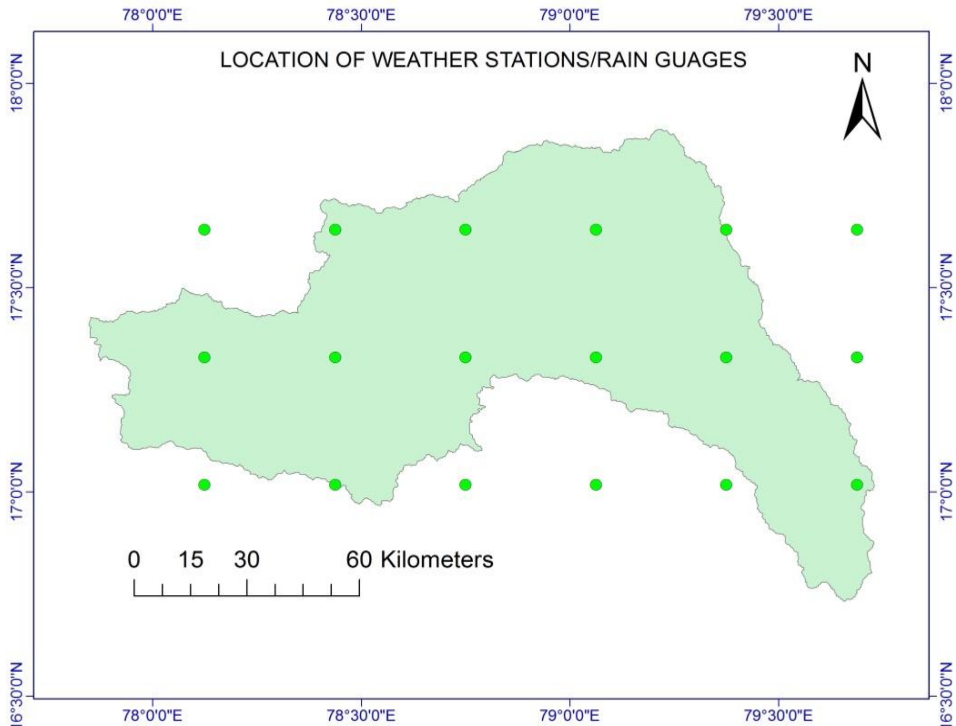


Figure 12: Location of weather points/rainguages in musi basin

5.4 SWAT Model Implementation

5.4.1 DEM set up

First step in modelling was defining the DEM data to the model. Base DEM for the model chosen is SRTM 90 meter resolution. Horizontal and vertical units of the DEM were defined in meters and it was projected to the Universal Transverse Mercator (UTM) under north zone 44th. (DEM data was a projected data, but the user has to redefine it in the ArcSWAT interface). Mask containing the spatial extent of the study area was provided for reducing the time of processing.

5.4.2 Automatic delineation of the watershed

SWAT model extracts the watershed area on the basis of flow accumulation algorithm considering drainage map. Flow accumulation algorithm route flow of cell to 8 different directions depending upon the cell value. For extraction of Musi watershed, outlet point is defined as the base point for delineation. Higher the resolution of DEM, better the extraction of the watershed. Figure 13 shows the interface for automatic delineation of watershed.

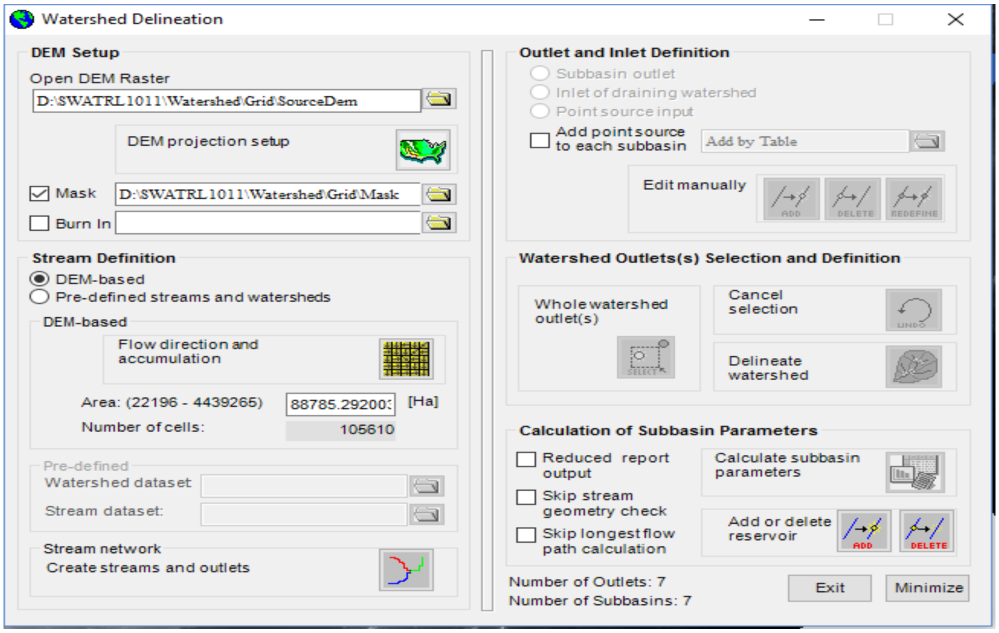


Figure 13: User interface for automatic watershed delineation in ArcSWAT

The appropriate inputs required for the study like stream definition (threshold area for flow direction and accumulation), stream network creation, outlet selection and definition are to be given in the above interface. Figure 14 shows the delineated watershed.

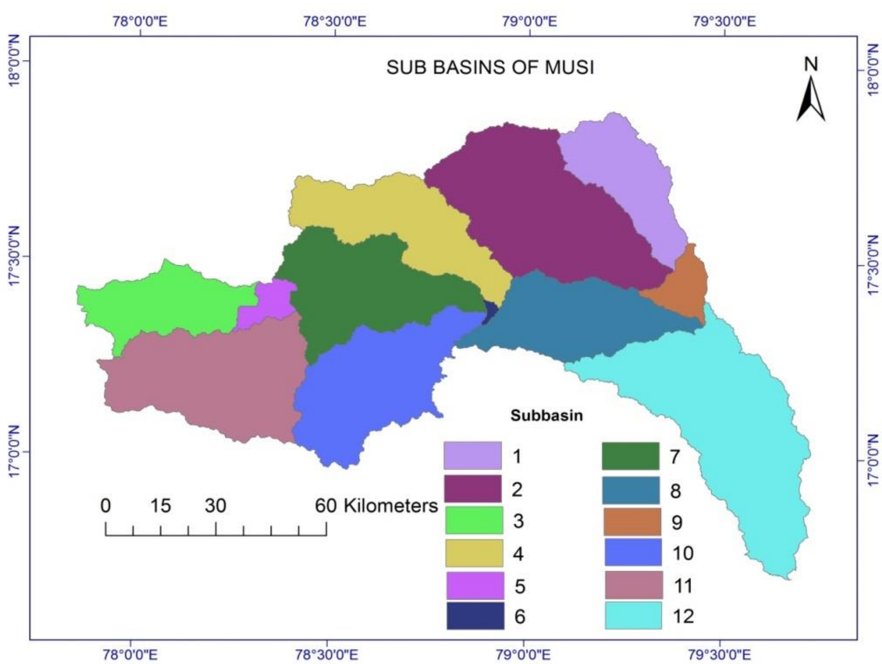


Figure 14: Delineated musi basin with 12 sub-basins

5.4.3 Defining land use/soil data

Land use

For each of the delineated sub-basin, land use and soil data were defined for modelling of various hydrological and other physical processes. The prepared composite land-use from visual and digital maps was given as input to the model. The look up table containing various SWAT land cover/use class codes was used for linking the SWAT's land-use database to the land-use layer. It was linked through the look up table option and based on the table values the land-use map was reclassified.

MUSI LU	**SWAT LU**
RICE	RICE
VEGETABLES	AGRC (Agricultural land close grown)
MIXEDCROPS	
COTTON	COTP (Cotton)
JOWAR	AGRR (Agricultural land row crops)
MAIZE	
CASTORSEED	
PULSES	
SHRUBLAND_CROP_MIX	RNGB (Range Brush)
SHRUBLAND_PLANTATION	
SHRUBLAND	
WATER	WATR (Water)
BUILT_UP	URMD (Urban Residential Medium Density)

LULC_Lookup - Notepad

File Edit Format View Help

```
"VALUE","NAME"
0,AGRL
1,RICE
2,AGRC
3,AGRC
4,COTP
5,AGRR
6,AGRR
7,AGRR
8,AGRR
9,RNGB
10,RNGB
11,RNGB
12,WATR
13,URMD
```

Figure 15: Linkage of land-use layer with the land-use database through look up table.

Soil

Soil physical attributes were initially stored to the SWAT's soil database through an interface, relevant information required for hydrological modeling and soil erosion modeling was provided to the model, description of the soil data is given in the previous section (5.3.3). The database was linked to soil map through the look up table which was again linked to the soil map, which was given as input to the SWAT model (Figure 16).

soil lookup - Notepad

File Edit Format View Help

```
"VALUE","NAME"
1,Bv12-3b-3696
2,Lc76-2b-3782
3,Vc43-3ab-3861
4,Vp42-3a-3867
```

Figure 16: Soil lookup table for linking soil data to ArcSWAT database

Subsequently, land use and soil map were overlaid for each sub-basin which forms the basis for the formation of Hydrological Response Units (HRUs).

5.4.4 HRU Distribution

After the overlay of the land-use and soil maps was completed the distributions of the Hydrological Response Units (HRUs) were determined. Subdividing the watershed into areas having unique land use and soil combinations enables the model to reflect differences in evapotranspiration and other hydrologic conditions for different land covers/crops and soils. There are two methods for creation of HRU, one was dominant land use and soil, in which the dominant land use type and soil type is used to define one HRU for each sub-basin. The second method considers multiple HRUs for each sub-basin; number of HRUs can vary according to the requirement of user. The second method was chosen, purpose was to analysis the effect of different land use and soil type combinations to runoff and sediment yield, further using small and relatively uniform HRUs reduces the error due to lumping (Geza, 2008)

Detailed report regarding the land use, soil types and description of HRUs for each sub-basin was generated.

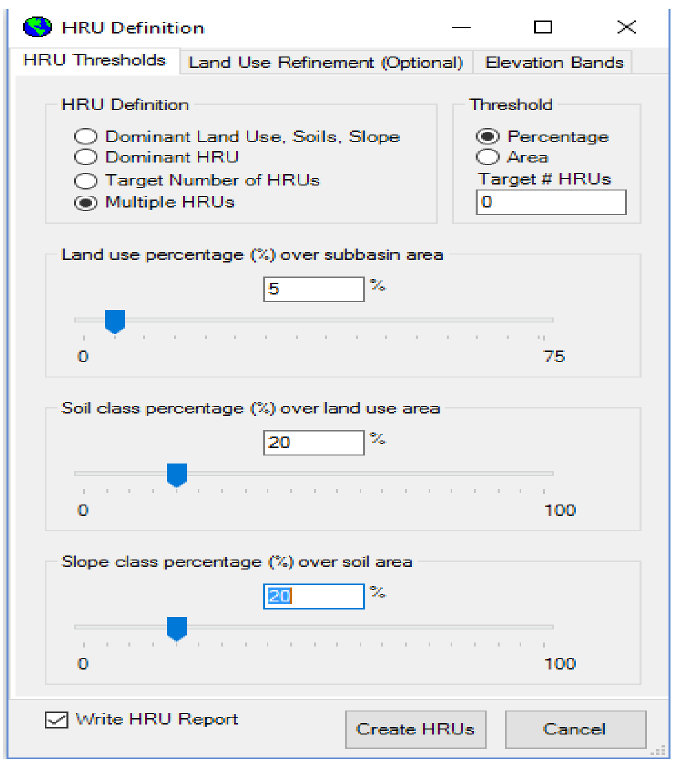


Figure 17: Interface of HRU definition in ArcSWAT

5.4.5 Defining weather database

SWAT requires daily values for precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed for modelling of various physical processes; daily rainfall being most important.

Weather data (precipitation, temperature, solar radiation, relative humidity and wind speed) from 18 weather stations is provided to the model in the required formats which contained the daily values for rainfall and other weather parameters.

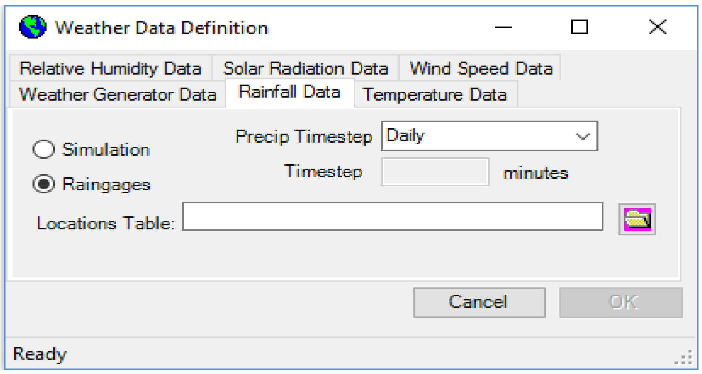


Figure 18: Weather generator interface in ArcSWAT

After giving weather data definition input tables are written using 'Write SWAT input tables' option under Write input tables menu.

5.4.6 Defining management options

Important step in the modelling was to define information relating to management for the various land cover/use. For the main crops such as rice and cotton, plant growing season, tillage practices, irrigation and harvesting periods were defined. Figure 19 shows the interface for defining the management data.

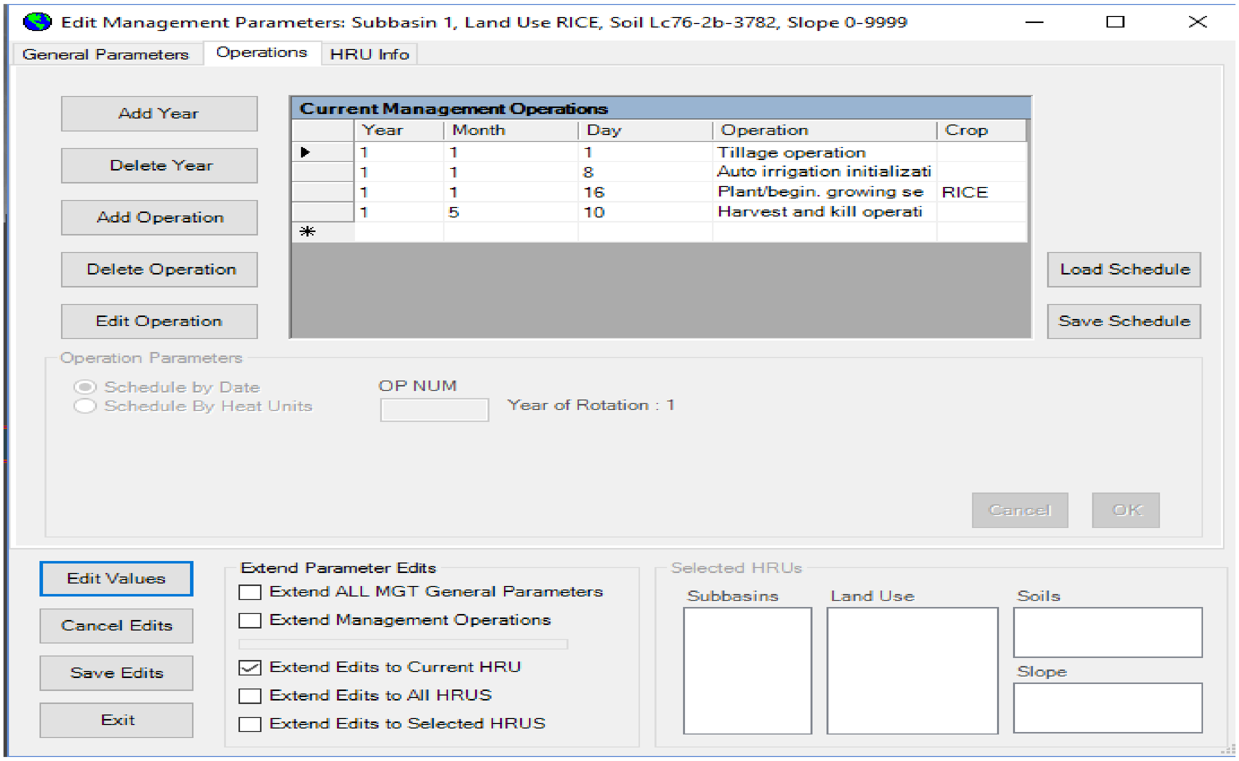


Figure 19: Interface for editing management operations in ArcSWAT

After editing management data of sub basins using 'Edit SWAT input' , input tables are rewritten using 'Rewrite input tables' option under Edit SWAT Input menu.

5.4.7 Setting up the model for simulation

Evapotranspiration is the primary mechanism by which water is removed from watershed. It includes evaporation from plant canopy, transpiration, sublimation and evaporation from the soil. SWAT uses three methods for estimating Potential evapo-transpiration (PET). Out of these, Penman-Monteith method (Monteith, 1965) was chosen. Daily rain/CN/Daily which refers to daily rainfall/curve number runoff/daily routing, method was used for determining precipitation time step, runoff calculation method and routing time step.

Skewed Normal Distribution method (Nicks, 1974) was used to determine rainfall amount (rainfall map) for the area based on the daily rainfall data for the given locations. The other method of Mixed Exponential was ignored, which is used when the daily rainfall data is lacking. Model was run on the daily, monthly and annual basis.

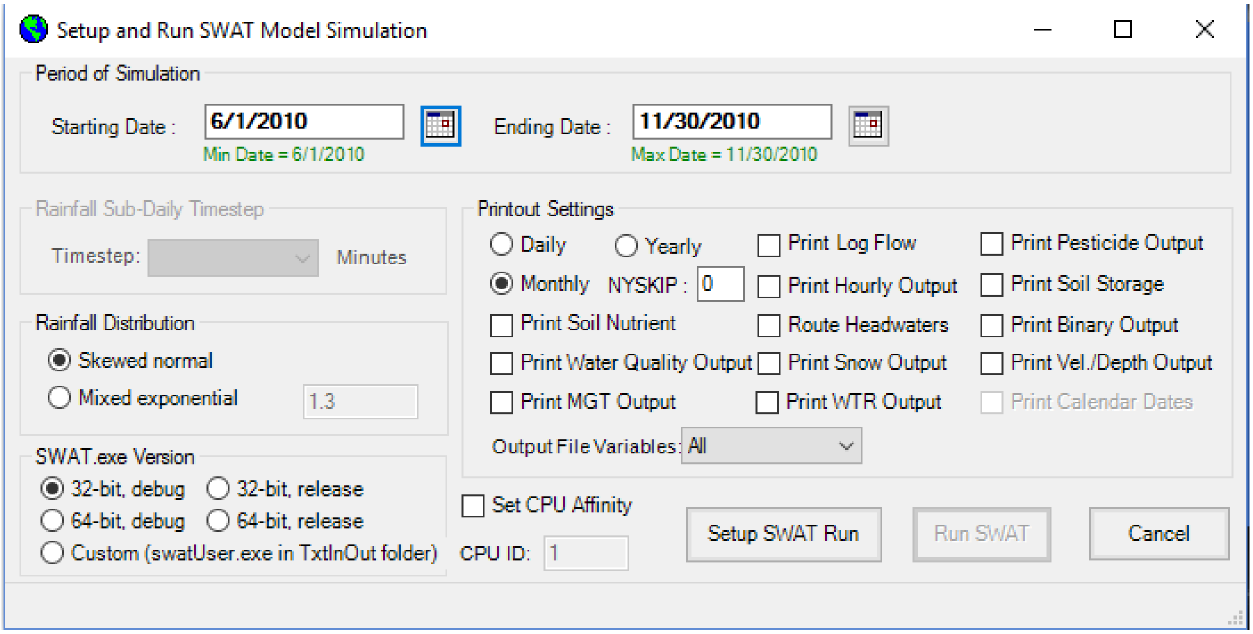


Figure 20: Interface for setting up SWAT model in ArcSWAT

6. Results and Discussion

In this chapter, the findings of land use/land cover changes and different scenarios developed using SWAT are presented and discussed to show the impact of land use/land cover changes on the hydrological parameters like runoff. Simulated runoff values are compared with the observed values to evaluate the performance of the model and results are discussed.

6.1 Land use/Land cover

Land-use/land-cover types in the basin are classified as rice, cotton, pulses, maize, jowar, castor seed, vegetables, mixed crops, crop fallows, shrub land, water and built-up.

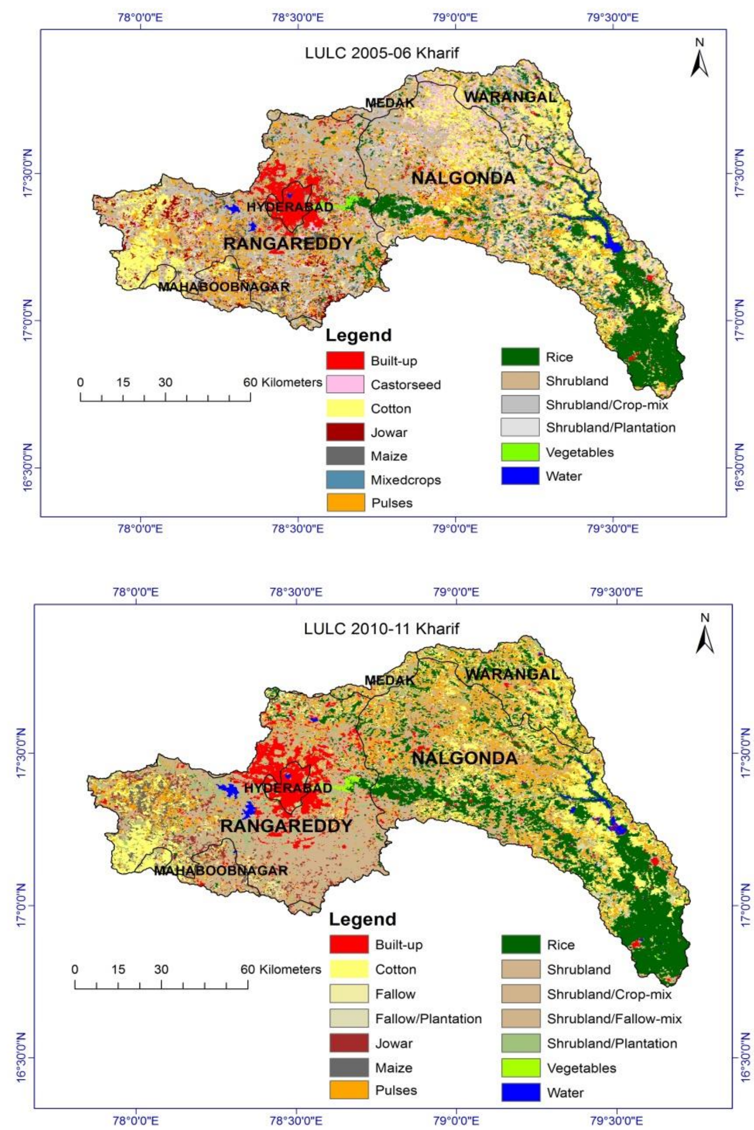


Figure 21: Final LULC maps of 2005-06 and 2010-11 kharif season

These classes are distributed in the districts of Nalgonda, Rangareddy, Hyderabad, Warangal, Mahaboobnagar and Medak. Major crops of the basin are rice (irrigated) and cotton (rainfed), followed by pulses and castor seed. Jowar and Maize are considered as minor crops of the basin, each crop constituting less than 3% of the study area. Both rice and cotton each occupy more than 10% area of the basin. Most of the irrigated area (rice) is distributed along the stream of river musi in Nalgonda district, with areas of upper musi and lower musi having the higher concentration of irrigated area. More than 80% of the rice crop is in Nalgonda district. Cotton is distributed in Nalgonda, Rangareddy and Warangal districts with major portion (~60%) in Nalgonda district. There is high concentration of castor seed crop in Nalgonda district (2005 Kharif) with minor distribution in Rangareddy. Pulses are distributed well in all the districts compared to other crops. Major portion of Built-up in the basin is observed in the districts of Hyderabad and Rangareddy having more than 80% of the built up of the total basin. The following tables (**Table 5** and **Table 6**) show how land-use/land-cover is distributed in the basin:

Table 5: % LULC distribution in Musi basin (2005-06 Kharif)

Crop/District	WARANGAL	MEDAK	NALGONDA	RANGAREDDY	HYDERABAD	MAHABOOBNAGAR
RICE	0.92	0.09	10.30	1.21	0.02	0.04
VEGETABLES	0.00	0.00	0.03	0.23	0.01	0.00
MIXEDCROPS	0.61	0.00	2.50	0.05	0.00	0.00
COTTON	2.83	0.11	10.67	3.57	0.00	0.53
JOWAR	0.01	0.00	0.26	1.86	0.00	0.19
MAIZE	0.06	0.02	0.35	2.67	0.07	0.17
CASTORSEED	1.79	0.13	6.64	1.16	0.01	0.06
PULSES	1.25	0.28	7.33	7.05	0.04	1.03
SHRUBLAND	1.38	1.05	7.63	17.10	0.14	1.42
WATER	0.01	0.00	0.39	0.14	0.02	0.00
BUILT_UP	0.15	0.02	0.70	2.45	1.21	0.03

Table 6: % LULC distribution in Musi basin (2010-11 Kharif)

Crop/District	WARANGAL	MEDAK	NALGONDA	RANGAREDDY	HYDERABAD	MAHABOOBNAGAR
RICE	1.76	0.17	15.65	1.18	0.01	0.05
VEGETABLES	0.00	0.00	0.16	0.28	0.02	0.00
COTTON	2.36	0.29	7.96	2.84	0.00	0.45
JOWAR	0.02	0.01	0.21	1.59	0.00	0.28
MAIZE	0.04	0.07	0.47	1.60	0.00	0.18
PULSES	2.39	0.30	8.85	3.70	0.03	0.28
SHRUBLAND	2.27	0.79	12.35	22.11	0.25	2.12
WATER	0.02	0.00	0.39	0.35	0.02	0.01
BUILT_UP	0.11	0.02	0.84	3.90	1.21	0.08

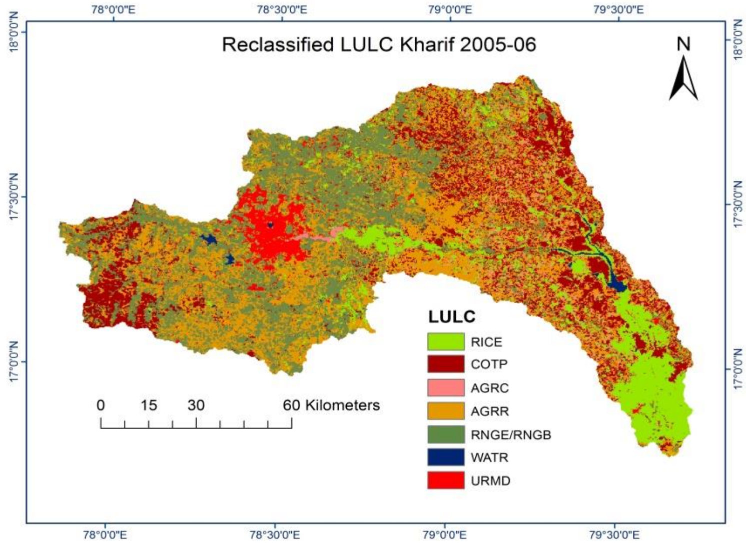
6.1.1 Temporal Changes of LULC:

The trend in change in land use category for both the years of study was analyzed. From the analysis it has been observed that there has been a significant change in the land use/land cover pattern within a span of 5 years (2005-2010). LULC maps (Figure 21) and tables (**Table 5** and **Table 6**) in the previous section clearly show the temporal changes of land-use/land-cover. Rice crop has increased significantly in the districts of Nalgonda and Warangal. This may be due to the crop rotation (rice replacing pulses or other crops), due to increase in rainfall or due to rise in demand. Cotton crop has decreased significantly with some area of cotton becoming fallow in Rangareddy, some area being replaced by other crops of crop rotation. There is no castor seed crop in 2010-11 Kharif as it is replaced by crops like rice, pulses or cotton which are the popular crop rotations for castor seed in Telangana region. According to a study conducted by R.P Singh and N.S Jodha (Economics group of ICRISAT) on crop rotation in traditional farming systems, major rotations in this area indicated cereals/oilseeds. Pulses have reduced significantly in Rangareddy district with most of the area converted to non-cropland or shrub land due to urbanization. There is no much change in minor crops like maize and jowar. Even though there have been a lot of crop rotations, on the whole the cropland has decreased in the basin, followed by increase in shrub land and built-up.

6.1.2 Reclassification of LULC for SWAT

2005-06	
MUSI LU	**SWAT LU_Code**
RICE	RICE
VEGETABLES	AGRC (Agricultural land close grown)
MIXEDCROPS	
COTTON	COTP (Cotton)
JOWAR	AGRR (Agricultural land row crops)
MAIZE	
CASTORSEED	
PULSES	
SHRUBLAND_CROP_Mix	RNGB (Range brush)
SHRUBLAND_PLANTATION _Mix	
SHRUBLAND	
WATER	WATR (Water)
BUILT_UP	URMD (Urban Residential Medium Density)

2010-11	
MUSI LU	**SWAT LU_Code**
RICE	RICE
VEGETABLES	AGRC (Agricultural land close grown)
COTTON	COTP (Cotton)
PULSES	AGRR (Agricultural land row crops)
JOWAR	
MAIZE	
SHRUBLAND_PLANTA	RNGB (Range brush)
SHRUBLAND_FALLOW	
SHRUBLAND_CROP_Mix	
FALLOW_PLANTATION_ Mix	
FALLOW	
SHRUBLAND	
WATER	WATR (Water)
BUILT_UP	URMD (Urban Residential Medium Density)



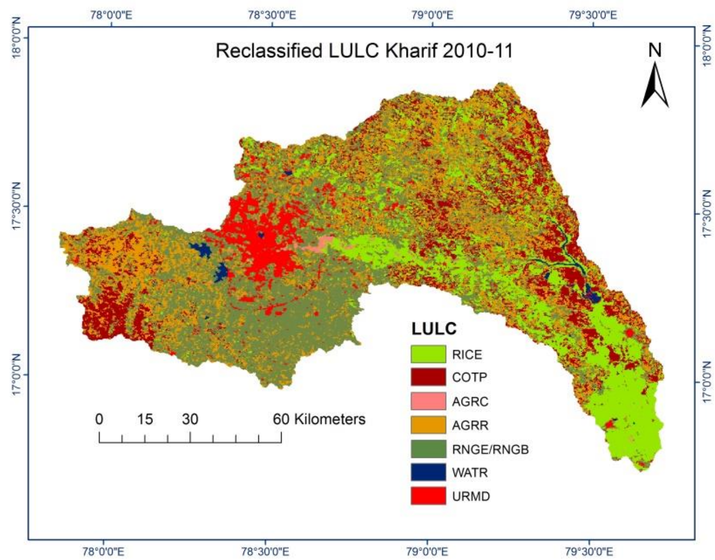


Figure 22: Reclassified LULC maps of Kharif 2005-06 and 2010-11

6.1.3 Area Statistics of LULC

Table 7: District wise areas of reclassified LULC in sq.km (2005-06 Kharif)

DISTRICT	RICE	COTP	AGRC	AGRR	RNGB	WATR	URMD
WARANGAL	103.78	316.66	69.16	346.82	153.73	1.09	16.53
MEDAK	9.69	11.48	0.48	46.41	115.57	0.00	2.60
NALGONDA	1162.13	1202.06	285.78	1638.04	860.92	45.13	79.43
RANGAREDDY	136.86	400.99	31.32	1432.75	1930.93	15.98	277.13
HYDERABAD	2.66	0.15	1.22	13.24	16.46	2.03	137.56
MAHABOOBNAGAR	5.02	59.08	0.18	161.84	157.99	0.49	2.86

Table 8: District wise areas of reclassified LULC in sq.km (2010-11 Kharif)							
DISTRICT	**RICE**	**COTP**	**AGRC**	**AGRR**	**RNGB**	**WATR**	**URMD**
WARANGAL	198.60	264.57	0.00	298.12	229.11	1.81	12.80
MEDAK	18.70	32.85	0.00	52.12	77.57	0.00	2.00
NALGONDA	1759.41	896.04	17.65	1163.65	1291.30	43.20	94.35
RANGAREDDY	132.01	319.86	31.64	1028.93	2228.71	39.58	438.29
HYDERABAD	0.89	0.28	2.65	4.93	25.74	2.39	136.44
MAHABOOBNAGAR	5.11	50.26	0.00	103.09	217.97	0.87	8.80

Table 9: District wise change in areas of LULC in musi basin for the years of study (% of basin area)							
DISTRICT	**RICE**	**COTP**	**AGRC**	**AGRR**	**RNGB**	**WATR**	**URMD**
WARANGAL	0.85	-0.46	-0.61	-0.43	0.67	0.01	-0.03
MEDAK	0.08	0.19	0.00	0.05	-0.34	0.00	-0.01
NALGONDA	5.34	-2.70	-2.38	-4.20	3.85	-0.02	0.13
RANGAREDDY	-0.04	-0.72	0.00	-3.57	2.68	0.21	1.44
HYDERABAD	-0.02	0.00	0.01	-0.07	0.08	0.00	-0.01
MAHABOOBNAGAR	0.00	-0.08	0.00	-0.52	0.54	0.00	0.05

Above tables (**Table 8**,**Table 9** & **Table 10**) clearly indicate that there is significant decrease in cropland in Nalgonda and Rangareddy districts; and significant increase in urban area in Rangareddy district. Though total crop land has decreased in Nalgonda, area of rice crop has a significant increase.

Table 10: Changes in areas of LULC for the periods of study in total musi basin

LULC_Kharif	**2005-06**		**2010-11**	
	Area (sq.km)	**% Area**	**Area (sq.km)**	**% Area**
RICE	1421.76	12.63	2117.31	18.84
AGRC (Agricultural land close grown)	388.75	3.45	51.99	0.46
COTP (Cotton)	1992.09	17.70	1561.04	13.89
AGRR (Agricultural land row crops)	3640.58	32.34	2654.86	23.62
RNGB (Range Brush/Shrubland)	3232.69	28.72	4072.34	36.24
WATR (Water)	64.08	0.57	88.09	0.78
URMD (Urban Residential Medium Density)	515.89	4.58	692.13	6.16

Area under rice crop has increased from 1421.76 sq.km in 2005-06 (12.63 percent of total area of watershed) to 2117.31 sq.km in 2010-11 (18.81 percent of total area of watershed). This increase could be due to rise in demand for rice or due to more rainfall in 2011 ie., 909 mm compared to that of 855 mm in 2005. Area under cotton crop has decreased from 1992.09 sq.km in 2005-06 (17.7% of the total area of watershed) to 1561.01 sq.km in 2010-11 (13.89 % of the total area of watershed). Urban area has increased from 515.89 sq.km in 2005-06 (4.58% of total area of watershed) to 692.13 sq.km (6.16% of the total area of watershed). Area under agricultural land closed grown category which includes vegetables and other mixed crops has decreased from 3.45% of total watershed area to 0.46% of total watershed area. Area under agricultural land row crops category which includes pulses, jowar and other minor crops has reduced from 32.34 % to 23.62% of the total watershed area. Area under Range Brush category which includes shrub land, wasteland, agricultural fallows etc., has increased from 28.72 % to 36.24 % of the total watershed area.

6.2 Outputs of SWAT Model

Different simulations were carried out using SWAT (Soil and Water Assessment Tool) and the results obtained were analyzed.

The model was run on daily basis for the year 2005 from June to December (Kharif season) and the simulated values obtained were plotted for rice (irrigated) and cotton (rain fed) crops which shows how the model works in relation to theory.

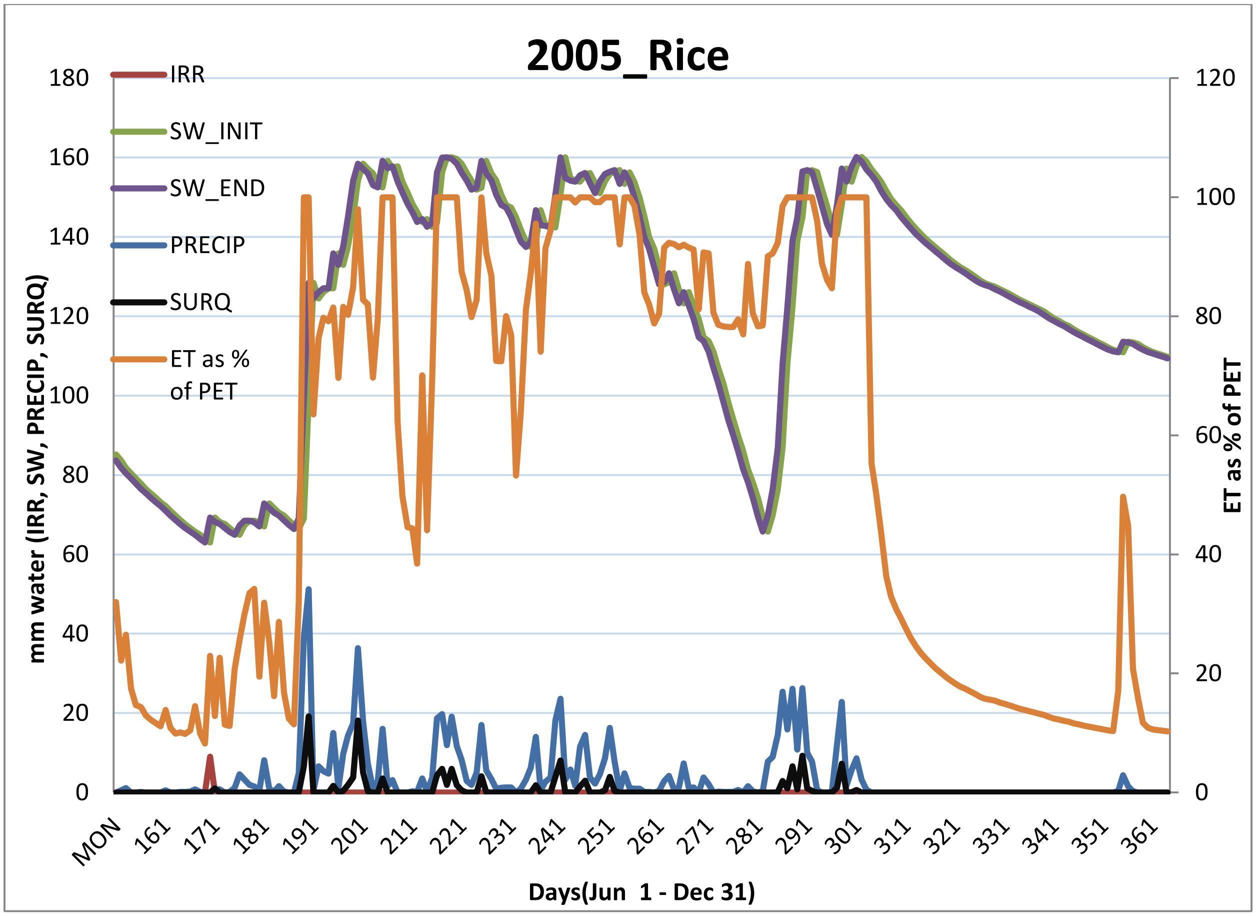


Figure 23: Trend of hydrological parameters for rice (irrigated) crop (IRR-irrigated water, SW-soil water initial and end, PRECIP-precipitation, SURQ-surface runoff, ET-Evapotranspiration, PET-Potential Evapotranspiration)

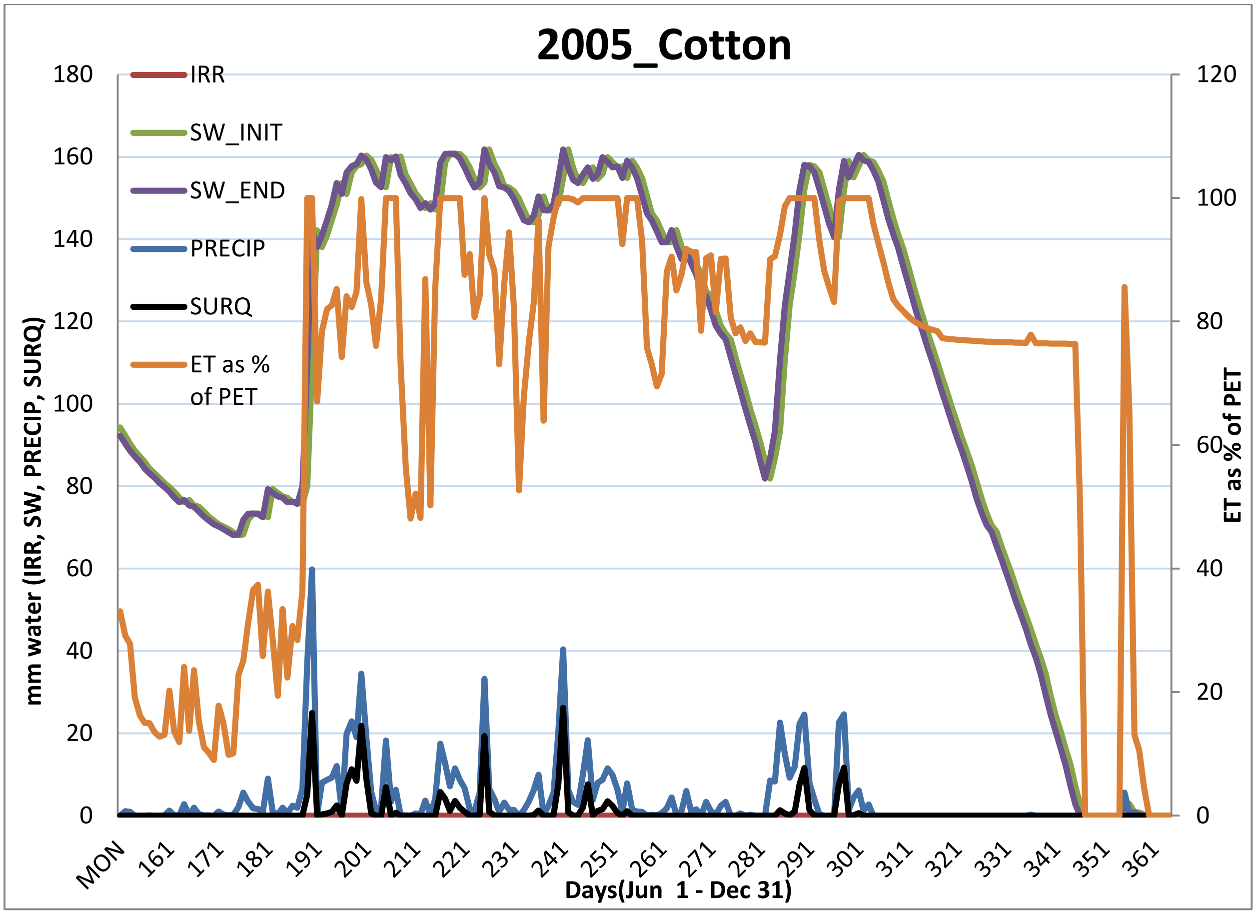


Figure 24: Trend of hydrological parameters for cotton crop (IRR-irrigated water, SW-soil water initial and end, PRECIP-precipitation, SURQ-surface runoff, ET-Evapotranspiration, PET-Potential Evapotranspiration)

From the above two plots (Figure 23 and Figure 24), it can be observed that irrigation of rice crop (a red peak in the rice plot) has been done when the soil water has reached to a threshold value (63.85 mm), surface runoff has been generated when the soil water reaches near to maximum with precipitation more than the difference of AWC (Available Water Capacity – 160 mm) and soil water, ET has reached its potential (100 % of PET) where soil water has reached maximum. Same kind of results can be observed for the cotton crop but as cotton is rain-fed irrigation peak (red peak) cannot be seen in the plot of cotton crop.

6.2.1 Impact of land use/land cover on surface runoff

The model was run on monthly basis for the land use/land cover of the 2005-06 Kharif and 2010-11 Kharif using the s ame precipitation file (2005-06) and the surface runoff estimated by the model was plotted. There was an increase in runoff from 160 mm to 168.47 mm.

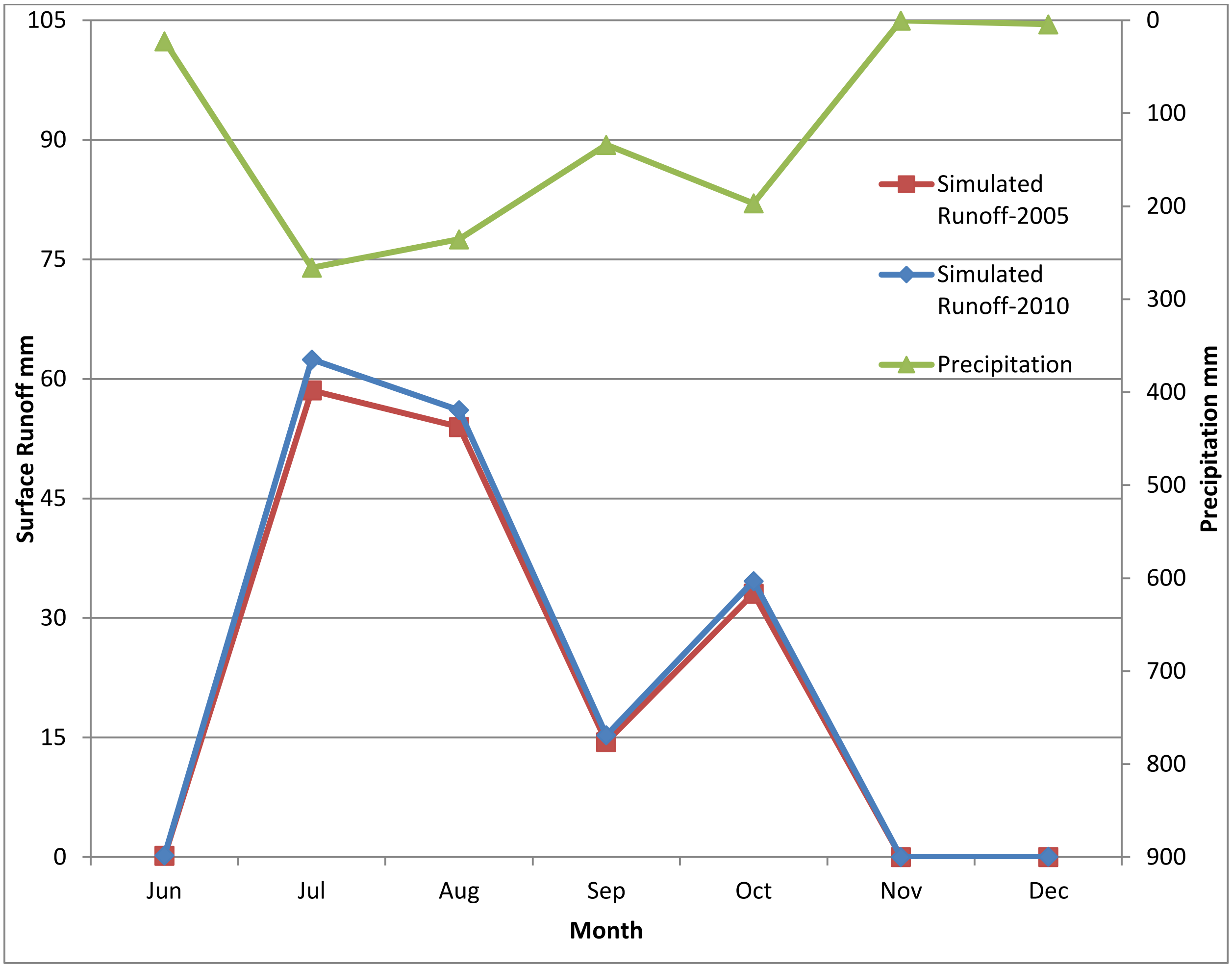


Figure 25: Variation of runoff in 2005 and 2010 Kharif seasons showing the impact of land use on runoff

From the above plot (Figure 25), it can be observed that runoff generated is slightly high in case of 2010-11 Kharif compared to that of 2005-06 Kharif. This is because the area under irrigated crop (rice) has increased from 2005-06 to 2010-11 as discussed in section 6.1 of this chapter. Irrigation results in the saturation of the soil which in turn results in generation of surface runoff when precipitation occurs. In addition to irrigated area, urban area has also increased from 2005 to 2010 which makes the land impermeable and increases runoff. On the whole, runoff has increased from 160mm to 168.37 mm. The above results show how the temporal changes of land use/land cover has an impact on runoff.

6.2.2 Scenarios:

To support the above results, two scenarios were developed by running SWAT model on yearly basis from 1982 to 2013 on both Kharif and Rabi seasons of the year 2005-06 with and without management practices (tillage, irrigation, etc.,) and the results were analyzed with respect to variation of surface runoff.

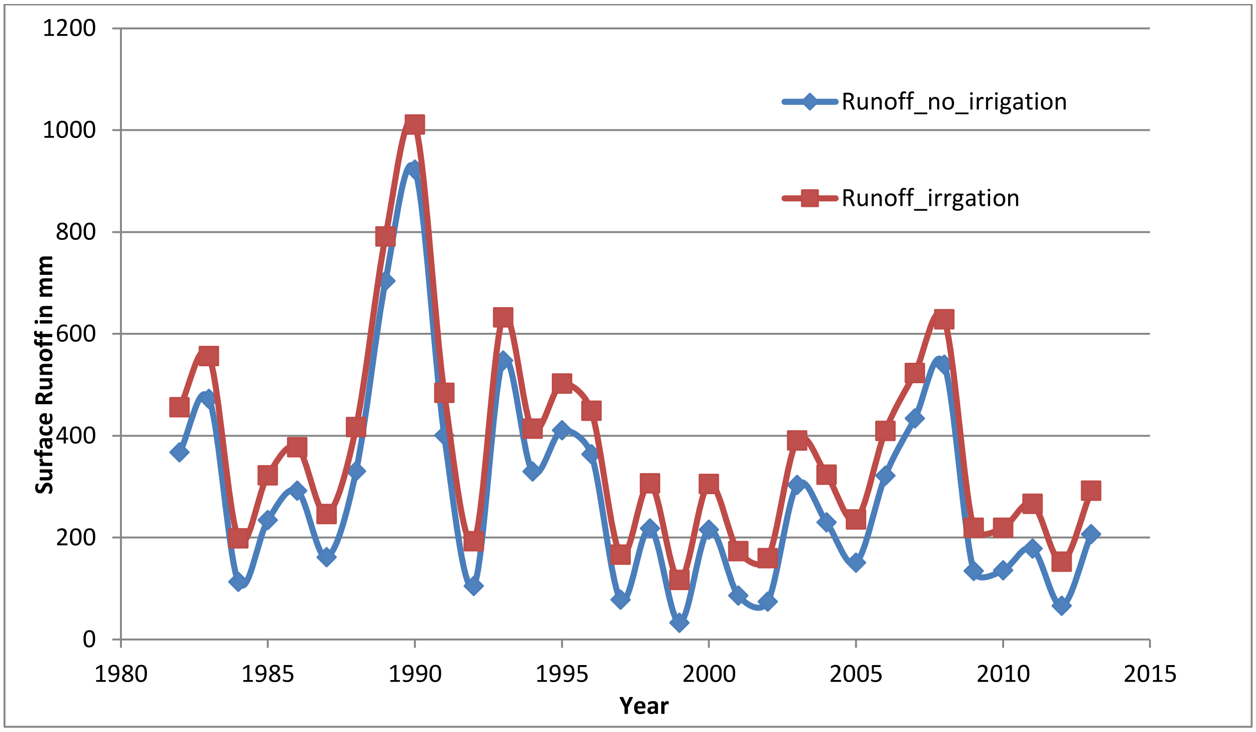


Figure 26: Simulated runoff using kharif land use of 2005-06 with and without irrigation operation

From the above plot (Figure 26), it can be observed that runoff simulated with irrigation operation is more than that of without irrigation operation. A significant increase can be observed since kharif season has an adequate amount of rainfall which results in runoff generation from the saturated land. As the land is irrigated, the soil of the land use comes to saturated state sooner than the land that is not under irrigation. This saturation will not allow the infiltration of rain water resulting in surface runoff.

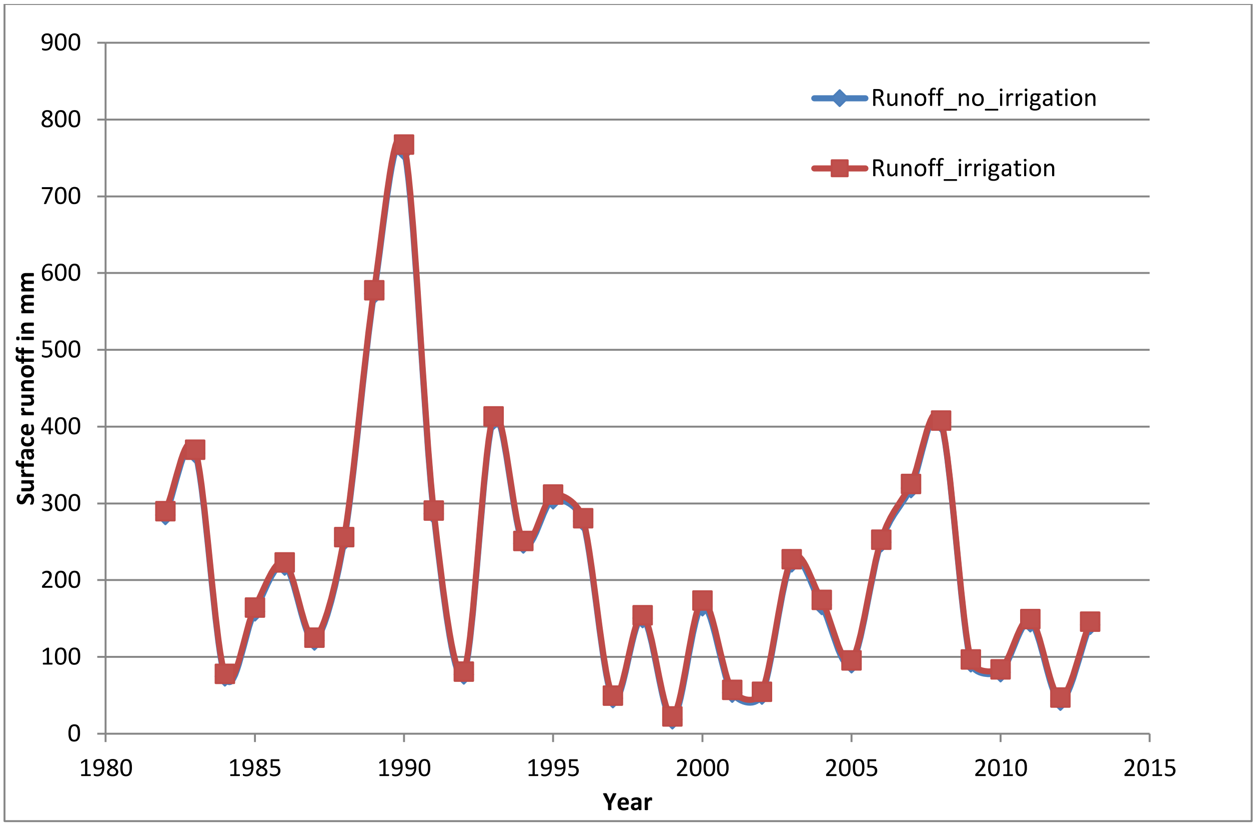


Figure 27: Simulated runoff using rabi land use of 2005-06 with and without irrigation operation

From the above plot (Figure 27), it can be observed that there is no significant change in runoff of rabi land use in both the cases of irrigation and without irrigation. This is because the rainfall during rabi season is significantly less compared to that of Kharif season and also the crop land is less. Therefore, even though irrigation operation is applied, the precipitation that occurs during this season is not enough to generate runoff as most of the water is evaporated, infiltrated and utilized by crops.

6.2.3 Comparison with observed values

The model was run on yearly basis from 1982 to 2013 for the LULC of 2005-06 Kharif season and the simulated inflow was compared to observed inflow at Osman Sagar reservoir by taking the observed values from 1982 to 2001(Kaushal K Garg, 2012). The correlation coefficient of the plot was 0.32 which is a positive but poor correlation.

The probable reasons for the poor correlation could be:

1. Uncertainty in input data or observed data.
2. Coarse resolution of input data (LULC and soil) and the non-dynamic nature of Land use.

3. Only two major crops of the study area being considered in the model leaving behind the other crops (other crops are taken as general agricultural land)

4. Soil depth being considered as a constant throughout the basin but which in reality varies from place to place.

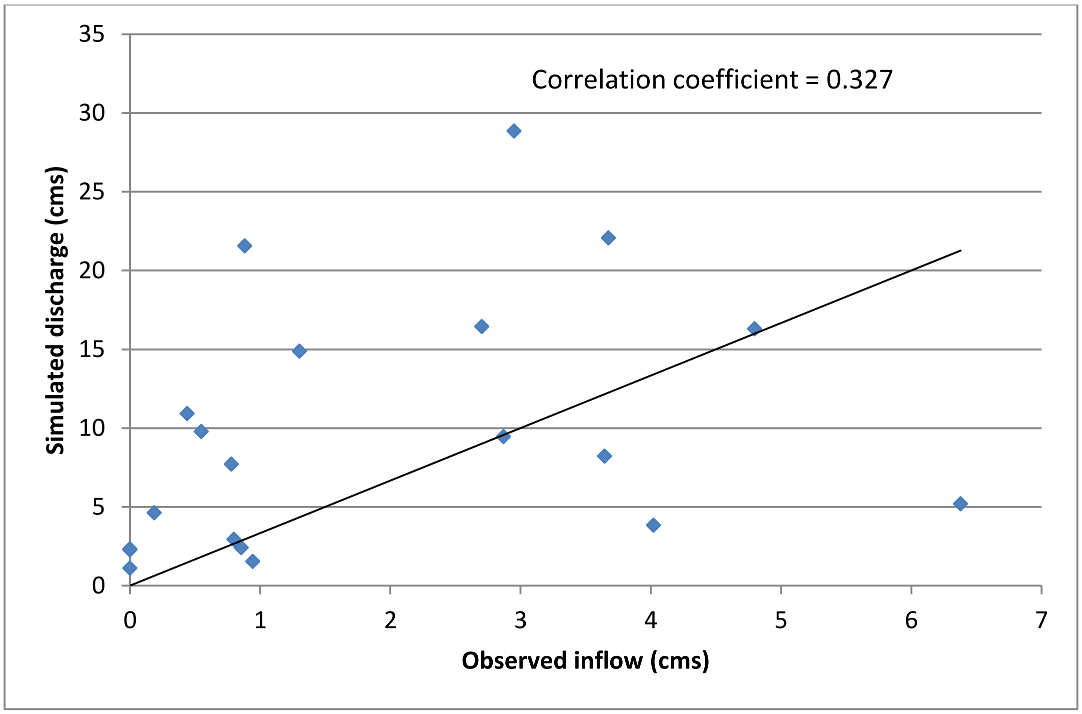


Figure 28: Correlation Analysis of simulated and observed inflow at Osman Sagar Reservoir

7. Conclusions and Recommendations

This chapter describes the conclusions that can be drawn from the results obtained and the future work or recommendations that can be suggested.

7.1 Conclusions

In the present study Soil and Water Assessment Tool (SWAT2012), a physical based semi distributed hydrological model having an interface with ArcGIS software was applied to Musi river basin for modeling the various hydrological components. The major objectives of the present study were

- Extraction of watershed characteristics, a nd land use/ land cover information of the study area using Remote Sensing and GIS
- Physical Based Semi Distributed Hydrological Modelling for Musi River Basin.
- To analyze the impact of land use/land cover on the surface runoff.

The above objectives were achieved and the following conclusions were drawn from the results obtained.

- It can be concluded that the change in land use will have a significant impact on hydrological parameters like surface runoff.
- As the comparison of simulated and observed inflow at Osman Sagar reservoir resulted in a poor correlation but yet positive correlation, it can be concluded that there are some uncertainties and limitations for the SWAT model.
- The uncertainties can be in input data (rainfall in this case) or observed data.

7.2 Recommendations

In order to deeply study the impact of land use/ land cover on hydrological parameters like surface flow and sediment yield simulation studies can be carried out for 20 to 30 years using high resolution data with significant changes in land use/land cover.

To handle uncertainties of the model, it should be calibrated by considering the sensitive parameters with their ranges approximately equal to the field values. To explain in detail, every model parameter has to be adjusted to a value by trial and error method till a good correlation is obtained between observed and simulated values. Parameterization (calibration) of the model is a big challenge as most of the parameters might not be much sensitive to the model output. In this study, the parameters like AWC, ESCO were altered but it is found that there is no significant change in the model output which suggests that more detailed ground data (high resolution data) or parameters has to be collected and incorporated into the model.

In addition to above recommendation of handling uncertainty by calibration, it is even more good if a way can be found out to avoid uncertainty in the first place. In order to avoid uncertainty, different hydrological models like SWAT, SACRAMENTO, MIKE-SHE, HEC-HMS, etc., should be studied and an ensemble of models should be compared by statistical analysis so that a best ensemble of less uncertainty can be obtained.

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