HYDROLOGIC ASSESSMENT OF A SMALL WATERSHED TO COMBAT AGRICULTURAL DROUGHT

By

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(2015-18-015)

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DECLARATION

I, hereby declare that this thesis entitled “**HYDROLOGIC ASSESSMENT OF A SMALL WATERSHED TO COMBAT AGRICULTURAL DROUGHT**” is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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CERTIFICATE

Certified that this thesis entitled "**HYDROLOGIC ASSESSMENT OF A SMALL WATERSHED TO COMBAT AGRICULTURAL DROUGHT**" is a record of research work done independently by Ms. Vallu Tejaswini under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

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VALLU TEJASWINI

Dedicated To

Agricultural Engineers

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SYMBOLS AND ABBREVIATIONS

%	:	percentage
95PPU	:	95 Percentage Prediction Uncertainty
AET	:	Actual Evapotranspiration
ALPHA_BF	:	Base flow alpha factor
ALPHA_BNK	:	Base flow alpha factor for bank storage
AMC	:	Antecedent Moisture Condition
APEX	:	Agricultural Policy/ Environmental Extender
ASTER	:	Advanced Space Borne Thermal Emission and Reflection Radiometer
BMP's	:	Best Management Practices
CH_N2	:	Manning's "n" value for main channel
CH_K2	:	Effective hydraulic conductivity of main channel
CN2	:	Curve Number
CWC	:	Central Water Commission
DEM	:	Digital Elevation Model
DWSM	:	Decision Support System for Agro Technology Transfer
EPCO	:	Plant uptake compensation factor
ESCO	:	Soil evaporation compensation factor
ESRI	:	Environmental Systems Research Institute
ET	:	Evapotranspiration
et al.,	:	and others
Etc	:	et cetra
GAML	:	Green Ampt Mein Larson
GIS	:	Geographical Information System
GLUE	:	Generalized Likelihood Uncertainty Estimation

GW_DELAY : Ground water delay time

GW_REVAP : Ground water revap coefficient

GW_Q : Ground Water flow

GW_QMN : Threshold depth of water in the shallow aquifer

Ha : hectare

HRU’s : Hydrologic Response Units

HRU_SLOPE : Average slope steepness

HSPE : Hydrological Simulation- Program Fortran

i.e., : Which is to say, in other words

IMD : Indian Meteorological Department

IRS : Indian Remote Sensing Satellite

Km^3 : Cubic Kilometer

Km^2 : Square Kilometer

LAT_Q : Lateral flow

LISS : Linear Imaging And Self Scanning

MCMC : Markov Chain Monte Carlo

MIKE SHE : European Hydrological System Model

mm : millimeter

m^3/s : Cubic meter per second

MUSLE : Modified Universal Soil Loss Equation

NSE : Nash Sutcliffe Efficiency

OV_N : Manning’s “n” value for overland flow

ParaSol : Parameter Solution

PBIAS : Percent Bias

PET : Potential Evapotranspiration

PSO : Particle Swarm Optimization

R^2 : Coefficient of Determination

RCHRG_DP : Deep aquifer percolation fraction

REVAPMN : Threshold depth of water in the shallow aquifer for “revap” to occur

RMSE	:	Root Mean Square Error
RSR	:	RMSE-Observations Standard Deviation Ratio
SCS-CN	:	Soil Conservation Service – Curve Number
S.D	:	Standard Deviation
SHE	:	SystemeHydrologiqueEuropeen
SLSUBSN	:	Average slope length
SOL_AWC	:	Available water holding capacity of soil
SOL_BD	:	Soil bulk density
SOL_K	:	Soil hydraulic conductivity
SOL_Z	:	Depth from soil surface to bottom of layer
SRTM	:	Shuttle Radar Topography Mission
SUFI-2	:	Sequential Uncertainty Fitting
SUR_Q	:	Surface Runoff
SURLAG	:	Surface Lag Coefficient
SWAT	:	Soil and Water Assessment Tool
TOPO	:	Toposheet
UTM	:	Universal Transverse Mercator Co-ordinate System
viz.,	:	Namely
WBSCD	:	World Business Council for Sustainable Development
WEPP	:	Water Erosion Prediction Project
WWDR	:	World Water Development
WYLD	:	Water Yield

CHAPTER I

INTRODUCTION

Land and water are the two basic natural resources required to be conserved and judiciously used for sustainable agriculture and for all life forms. Unfortunately these resources are becoming scarce day by day. Among these water is the major cause of concern as it is subjected to very high spatial and temporal variation. Nearly 70% of the earth is covered by water in which about 97% is in the oceans leaving just 3% as fresh water. Of this small share of fresh water, nearly 2.5% is locked up in glaciers and ice and is not available for use. Human beings should rely on this 0.5% fresh water for their needs. Out of this 0.5%, 10^7Km^3 is stored in the underground water formations, 91,000 Km^3 in natural lakes, 5,000 Km^3 in manmade storage structures, 2,120 Km^3 in rivers and 1,19,000 Km^3 lost to atmosphere through evaporation (WBCSD, 2006). So, managing this small fraction of fresh water judiciously assumes outmost priority for the survival of life on this planet. Water conservation is the need of the hour and hence, effective and scientific interventions are required in this area to avoid and mitigate water scarcity issues.

Water scarcity is one of the major problems faced all over the world, irrespective of the geographic or continental locations. The demand for water for all needs including irrigation is growing continuously. Water scarcity is associated with many factors such as over exploitation, growing population, water pollution, excessive use of water resources, and more importantly lack of proper conservation measures. It is expected that in future, there will be gradual increase in water demand in all sectors of production. By 2050, global water demand is estimated to increase by 55%, mainly due to growing demands from different sectors such as agriculture, industries, domestic and other uses (WWDR, 2015). According to the United Nations, water usage has increased two times than the population growth. By 2025, it is estimated that approximately 1.8 billion people may live in areas plagued with water scarcity.

World population growth projected to reach over 8 billion in 2030 and to level off at 9 billion by 2050, which shows the signs of severe water scarcity in highly populated countries such as China and India in future (WBCSD, 2006). India is one of the 10 countries that posses 60% of the world's available fresh water supply. Though the country is blessed with moderate quantity of rainfall, many parts of it are facing severe water scarcity due to lack of awareness and also failure in executing water resource development projects. In India, it was estimated that there will be a gradual increase in total water demand from 22% by 2025 to 32% by 2050 (Amarasinghe *et al.*, 2007). Even the areas receiving high magnitude of annual rainfall are now facing water shortage due to lack of appropriate water management practices. Kerala state is a best example of this ironical situation which lies on the southern part of the country. Hence, sustainable water management is the only choice to fill the gap between demand and supply and to reduce the ill effect of water scarcity.

The science that deals with the occurrence, circulation and distribution of water in the earth is termed as "Hydrology". Hydrologic cycle deals with the circulation of water from the oceans and land surface in to the atmosphere, air to land and then back to oceans over the land surface or underground. Hence, basic knowledge about various hydrological phenomena is required for all aspects of soil and water conservation. Though water management plays a key role in tackling the various water resources development activities, it is a challengeable task for decision makers in private and public sectors. Water management in relation to conservation and utilization should be planned on a watershed basis as watershed is an independent hydrological unit. Conservation of water at watershed scale is a prerequisite since all the hydrologic process takes place within individual micro watersheds. Generally, a watershed is a topographically delineated area which collects and discharges stream flow in to a common outlet or mouth.The main principle of watershed management is to manage the available natural resources in a sustainable way.

For understanding the watershed systems, models play an important role which can also be very useful for extrapolating the current conditions to potential future conditions. A model represents the real world system in a simplified manner by predicting system behavior and helps in understanding various hydrological processes. Based on different factors, models are classified into many types but one of the most important classifications is empirical, conceptual and physically based models. Empirical models are also called as metric, observation oriented and black box models. These models are sometimes known as data driven models since they take information from the existing data and does not consider the features and processes of the hydrologic system. Empirical models involve mathematical equations just derived from concurrent input and output series but not from the physical process of watershed and hence these are applicable only within the boundaries of that particular watershed. Conceptual or parametric models involve semi empirical equations in which the model parameters are assessed not only from field data but also through calibration. Physical/mechanistic/white box models can be considered as idealized representation of real system since these models includes the principles of physical processes. Physical models represent the various hydrological process of water movement by finite difference equations and use the parameters having physical interpretation and can provide the large amount of information even outside the boundary. A physical model can be useful for a wide range of situations and it can also overcome the defects of other two types of models such as empirical and conceptual.

Watershed models are considered as an important management tool for water resources as they simulate the natural processes of flow of water, sediments, chemicals, nutrients and microbial organisms. Simulation of these natural processes plays a major role in exploring various watershed based problems. Hence now, watershed scale modeling has emerged as an important scientific research in addressing a wide spectrum of watershed problems such as water resources, environmental, social and economical problems and thus helps in dealing with watershed management issues.

Hydrological modeling is powerful in planning water resources; however, it is also a challenging task since it involves many complex interactions, highly non linear processes and spatial variability's at basin scale. Hydrological models use mathematical equations to represent the hydrologic processes and interactions between them. Hence there is a necessity of using physically based distributed watershed models for estimating hydrological processes within individual micro watersheds, since these models consider the hydrologic process taking place in a spatially distributed manner. Multiple forms of spatial data are needed to carry out various water resource management activities. Geographical information systems can provide a common frame work to work with different spatial data obtained from various sources. The ability of GIS to integrate, manage and analyze the large volume of data made it more advantageous than other technologies. Simulation models integrated with GIS will be more efficient and easy for identifying and evaluating the potential solutions to water resource problems of a large area.

Soil and water assessment tool is one of the widely used free domains, physically based distributed watershed model. It is a GIS based watershed model developed by Agriculture Research Service of United States Department of Agriculture. SWAT model is a continuous time, physically based distributed watershed or river basin model that can operate on different time steps. It is computationally very efficient and can be used for small as well as large watersheds. It was designed to predict the impact of land use and management on water, sediment and agricultural chemical yields in watersheds with varying soils. The model breaks the basin in to number of sub basins which are further divided into hydrological response units (HRU's). The spatial datasets required by the model are DEM, land use and soil maps. Daily rainfall, maximum and minimum air temperature, relative humidity, solar radiation and wind speed are the meteorological data used by this model. Since the model possesses excellent capabilities in simulating hydrological processes within micro watersheds, it was selected and used in this study.

Drought is considered as an extreme hydrological event occurring in an area which can affect the socio economic status of the people. Rainfall deficit occurring in a region for a period of time could lead to various degrees of drought conditions. The concept of drought may vary from place to place since the rainfall varies significantly among different regions. Kerala receives a normal annual average rainfall of about 300 cm, about two and half times higher than the national average. However, the state experiences different orders of drought during summer season. Effective and scientific water management is the only solution for the state to tide over this situation.

Keeping the above point in view, a small and independent watershed of Bharathapuzha river basin was selected which encompasses the Kuttippuram block panchayath. Domestic and agricultural water scarcity is very much prevalent in this watershed. Therefore, this study has been initiated with the given below specific objectives.

1. To calibrate and validate the watershed model, Soil & Water Assessment Tool (SWAT) for the selected watershed using observed daily river flow.
2. To predict watershed processes at micro watershed scale to quantify the spatial and temporal distribution of water availability within the sub basin.
3. To suggest remedial measures to combat water scarcity in the study area.

The scope of this study is limited to the calibration of the SWAT model for an unguaged watershed and to determine water balance components at micro watershed level using the calibrated physically based distributed model and to suggest interventions for solving water scarcity. Major limitation of the study was the short duration of time availability. Building a physically based distributed watershed model such as SWAT for an ungauged basin itself is a very difficult task. Unavailability of discharge at the basin outlet was another limitation in judging the accuracy of regionalization technique in the calibration process.

CHAPTER II

REVIEW OF LITERATURE

This chapter deals with the review of previous research work done on watershed modeling with special reference to physically based distributed watershed models, sensitivity analysis, calibration and validation. Reviews on hydrologic assessment of watershed using SWAT model has been elaborately presented.

2.1 WATERSHED HYDROLOGIC MODELING

The integration of hydrologic process such as precipitation, snow melt, interception, evapotranspiration, surface runoff, infiltration and sub surface runoff takes place within individual micro watersheds. Hydrological modeling which involves formulating the mathematical models to represent these watershed process and interaction between them can be a challenging task because there are many complex interactions, non linear processes and spatial variability within watershed scale.

2.1.1 History of hydrologic modeling

Todini (2007) reviewed the past, present and future issues in hydrological modeling. The history of hydrological modeling ranges from the rational method to the distributed hydrological models which are presently available. The evolution of hydrologic modeling is continuing from the mid nineteenth century with the development of understanding the physical process, data retrieving facilities and computational efforts (Islam, 2011). Over the years, many approaches to the study of watershed problems have been evolved as evidenced by the periodicals and proliferating books in this stream.

2.1.2 Classification and importance of watershed modeling

According to physical process involved in the modeling, hydrological models can be classified as conceptual and physically based models. According to spatial description of the watershed, they can be classified as lumped and distributed models. Usually, the conceptual models are lumped while the physically based models have to be distributed. Hydrological models can be classified into many types such as Lumped Vs Distributed, Stochastic Vs Deterministic; Event based Vs Continuous and Prediction Vs Water budget models (Warren and Garry, 2003).

Mirchi *et al.* (2009) studied about the importance of modeling for watershed planning, management and decision making. They presented the examples that illustrate some of the environmental and socio economic challenges that can arise from improper watershed planning and management practices. They also presented modeling approaches, scope and addressed many problems. They listed two types of modeling errors that can be expected by the future watershed process models such as developing an overlay complex model which cannot be properly calibrated and verified, developing a model that fails to make use of high quality and available data. The models ability to simulate hydrologic process with greater accuracy at finer spatial and temporal resolution will continue to improve with increased use of remotely sensed data, improvements in GIS and data management systems. They finally concluded that understanding the watershed systems is very important for sustainable watershed planning , management decisions and hence watershed modeling has become a powerful tool for water resources system design, planning and decision makings at affordable cost and reasonable time frame.

2.2 PHYSICALLY BASED DISTRIBUTED HYDROLOGICAL MODELS

Around the late 1960's, the development of physically based hydrologic modeling was started (Islam, 2011). According to Pechlivanidis *et al.* (2011), the use of distributed models have been increased in hydrological applications due to easy availability of spatial data sets at finer resolutions, information about physical catchment properties at relatively small catchment scales and increased availability of computer resources . But, most of the physically based distributed watershed models have some limitations such as inability to perform continuous-time simulations, inability to characterize the area in the needed spatial detail and failure of simulating at appropriate temporal and spatial scale.

2.2.1 Comparison of different physically based distributed watershed models

Some of the physically based models developed and presently in use are TOPMODEL (Beven and Kirkby, 1979), SHE, MIKE SHE, WEPP (Laflen *et al.*, 1991) and SWAT (Arnold *et al.,* 1998).

Based on the review of eleven models, Borah and Bera (2004) selected three models: SWAT, HSPF and DWSM and they compiled seventeen SWAT, twelve HSPF and eighteen DWSM applications. They found SWAT and HSPF are suitable for predicting yearly flow volumes, sediment and nutrient loads with similar accuracy. Saleh and Du (2004) compared the simulated values of SWAT and HSPF with the observed values of average daily flow, sediment loads and nutrient loads collected at five sites during both for calibration and validation period for the upper North Bosque River located in Texas. They found that the values simulated by the SWAT are closer to the observed values than HSPF.

Among the recently available models, SWAT is one of the latest models that is widely used and highly recommended by the researchers because of its various advantages and capabilities than the others models (Nietsch *et al.*, 2005).

Golmohammadi *et al.* (2014) evaluated the performance of three hydrologically distributed watershed models which are based on GIS i.e., SWAT, MIKE SHE and APEX. The three models were evaluated for their ability to simulate hydrological process of Canagagigue watershed located in Grand River Basin in Sothern Ontario. All the models were calibrated and validated for stream flow with independent data sets for a four year period. The simulated and observed values were compared on daily, monthly and annual basis. They concluded that all the three models are able to simulate the hydrology in an acceptable way. They found that MIKE SHE model was slightly better in predicting stream flow variation, followed by SWAT model. SWAT models performance was only differed from MIKE SHE in the validation period. They found that the performance of APEX was not as good as other two models.

From the above discussion, it can be inferred that SWAT is the most efficient physically based distributed hydrologic model that is being used by the many scientists to predict hydrology, sediment flow and water quality.

2.3 APPLICATION OF GIS IN WATERSHED MANAGEMENT

Wilson *et al.* (2000) examined how various combinations of simulation models and geographic information systems have been used to advance knowledge of water resource assessment and management. They identified four sets of innovations to develop careful, long term solutions to problems such as development of simulation models, development of GIS and decision support systems that are easy to use, identifying and adoption of inexpensive useful water resource indicators and to develop improved methods in order to quantify the risk and uncertainty incorporated in the decision making process. They also suggested some advancement needed in three broad areas such as development of new models and research, continuous work on representative issues and development, inclusion of new spatial analysis functions inside the GIS. They finally concluded that GIS technologies are playing a key role in the development of distributed watershed models which provides the chance for improving our understanding of spatial processes and patterns that effects the distribution and movement of water in landscapes or watersheds as well as impact of land use on water resources over the long term.

Ma (2004) studied about GIS applications in watershed management and stated that the capability of GIS to integrate and analyse spatial data made it more advantageous than other software’s such as multitude of graphics, computer aided design, drafting and mapping software systems. GIS can be used effectively for environmental applications such as best management practices, watershed management, storm management, forestry management, wetlands delineation, wildlife habitat management etc. He stated that GIS made us to understand the past and present state of watershed, landscapes which make it widely acceptable by the resource managers to deal with water management issues. Finally he concluded that GIS technology will greatly helps the managers to provide communities with the tools to inform their watershed situation and to realize the impacts of various situations.

Jadhao *et al.* (2009) suggested that the tediousness and time consuming nature of extraction of watershed parameters can be eliminated by means of remote sensing technology and GIS in addition to obtaining high accuracy. Input data for the model can be extracted with the use of GIS mainly from the map layers including land use/cover, DEM, soil, slope, drainage and watershed and sub-watershed boundaries. Many studies have applied SCS-CN model for estimating the surface runoff by deriving curve numbers using satellite data and GIS technique. Knowing the importance of empirical models, remote sensing data and GIS techniques the study was undertaken with the use of a widely used empirical model (SCS-CN) using these techniques. The watershed parameters such as area, channel length, drainage density, slope and area under different soil textures could be derived accurately using various maps viz. DEM, drainage map, watershed and sub watershed boundaries and soil texture map in GIS environment.

2.4 SOIL AND WATER ASSESSMENT TOOL AND COMPONENTS

The SWAT model is a physically based distributed watershed model developed by USDA Agriculture Research Service (Arnold *et al.*, 1998) and has undergone many capability expansions over the years. SWAT is one of the promising models for continuous simulations in predominantly agricultural watersheds (Bora and Bera, 2003). SWAT model was found to be computationally efficient in simulating the hydrology and water quality of the catchments in continuous time periods (Neitsch *et al.,* 2005). SWAT is a GIS interface model which divides the catchments into number of sub catchments. These sub catchments are further sub divided into hydrological response units which are the smallest computational units in SWAT. The concept behind the simulations of SWAT model is water balance (Nietsch *et al*., 2011). SWAT is an effective and useful tool in simulating the hydrologic process ranging from large river basins (Devkota and Gyawali, 2015) to small basins (Malunjkar *et al*., 2015).

2.4.1 Estimation of Surface runoff

The flow that occurs when the rainfall intensity or rate of water application to the ground surface exceeds the infiltration rate can be referred to as surface runoff. SWAT provides two methods for estimating surface runoff such as SCS curve number method and the Green & Ampt infiltration method. SCS Curve number method was designed for computing direct runoff whereas Green-Ampt is an infiltration equation. SWAT incorporates rational method for estimating peak discharge. SCS-CN method holds good for accounting seasonal variations than Green Ampt Mein Larson (King *et al.,* 1999).

Research conducted in the watersheds worldwide has proved that soil and water assessment tool provides a useful tool for runoff estimation which facilitates proper planning for land and water resources management.

Asres and Awulachew (2010) conducted a study on SWAT based runoff and sediment yield modeling for Gumera watershed in the Blue Nile basin in order to test the potential of water management measures and to reduce sediment loadings from hotspot areas. They also calibrated the model using five years of flow and sediment data and validated the model with next three years of independent data set. Sensitivity analysis was also carried out before calibration in order to find out the sensitive parameters of surface runoff, base flow and sediment yield. The calibration results of flow showed good agreement between observed and simulated values with R^2 (correlation coefficient) of 0.87 and NSE of 0.76. Similarly, NSE value of 0.68 and R^2 (correlation coefficient) of 0.83 during validation period indicates that there is a good match between observed and simulated values. Similar trend was also seen during the calibration and validation periods for sediment yield. They found that 72% of the watershed is erosion prone contributing high sediment loads and finally concluded that SWAT model can be used effectively as a planning tool for watershed management.

Jain *et al.* (2010) conducted a study on runoff and sediment yield for a Himalayan watershed using SWAT model. The model was calibrated for the daily and monthly surface runoff and sediment yield using the observed data of 1993 and 1994 and the validation period was carried out for a data set of three years of 1995 through 1997. They evaluated the model using some graphical, statistical methods and the results showed that model was satisfactory for estimating runoff and soil erosion from a remote watershed with scarce data.

Santra *et al.* (2013) simulated runoff water from a selected watershed of western catchment of Chilika lagoon through ArcSWAT in order to estimate future runoff potential from western catchment. They used the inputs such as SRTM DEM, soil map, land use map, weather data to run the model and observed monthly runoff values during the period of 2004-2006 for calibration and validation. They assessed the efficiency and performance of the model calibration with NSE and RMSE, both together measures the goodness of fit between predicted and observed values. Their modelling results revealed that about 60% of rainfall is runoff water which carries significant amount of sediment load to Chilika lake. They finally concluded that mean monthly runoff from the catchment was estimated reasonably. Hence the calibrated SWAT model can be useful for assessing the runoff potential in future and thus helps in implementing soil and water conservation measures to avoid water loss and to reduce sediment loads that enters through runoff water.

Shivhare *et al.* (2014) applied the SWAT model on monthly basis for simulating surface runoff from a Burhanpur watershed of Tapi river lying in the states of Madhya Pradesh, Maharastra and Gujarat states. The model using ArcGIS environment, calculated the surface runoff at various monitoring points in the catchment. The simulated flows at the basin outlet have been compared with the observed flows for four years of record (1992-93 to 1995-96) and the model performance was evaluated using statistical methods. The coefficient of determination (R^2) values for the years 1992-93 to 1995-96 were reported as 0.82, 0.68, 0.92 and 0.69 which indicated the good performance of the model.

Malunjkar *et al.* (2015) conducted a study on estimation of surface runoff using SWAT model for Maheshgad watershed with an area of 45.04 ha and average annual rainfall of 553 mm. After calibration and validation they also compared the observed, simulated values and found that few values are under predicted and over predicted but they concluded that there is a close agreement between observed and simulated values since the maximum points are on 1:1 line. The values of statistical evaluators such as NSE and coefficient of determination was 0.62 and 0.98 for calibration period, 0.74 and 0.95 for validation period which indicates the satisfactory performance of the model. Their results indicated that SWAT model is an effective tool for simulating surface runoff from small watersheds.

Priyanka and Patil (2016) conducted a study on runoff modeling for Malaprabha sub-basin using SWAT hydrological model. Selecting the sensitive parameters based on available literature, they carried out calibration and validation manually using observed runoff for the period 1982-1989. They found that observed values have shown good agreement with the simulated values and finally concluded that SWAT model performed well for the runoff simulation.

Swami and Kulkarni (2016) selected SWAT model having an interface with Arc-view GIS software to simulate runoff and sediment yield for Kaneri watershed. They also calibrated and validated the model and also evaluated the model's simulation performance with graphical and statistical methods. They got the satisfactory R^2 value for both calibration and validation and finally succeeded in developing a SWAT model for Kaneri watershed to simulate runoff and sediment yield for any time period.

2.4.2 Estimation of Evapotranspiration

Evapotranspiration is a collective term which includes evaporation from the soil, transpiration, evaporation from plant canopy and also sublimation. SWAT model provides three methods for estimating potential evapotranspiration namely combination based Penman-Monteith method (Monteith, 1965), radiation based Priestly-Taylor method (Priestly and Taylor, 1972) and temperature based Hargreaves method (Hargreaves *et al*., 1985).

Wang *et al.* (2006) conducted a study on influences of potential evapotranspiration estimation methods on SWAT's hydrologic simulation in a North Western Minnesota watershed. They compared the three simulated stream flows obtained from calibrated SWAT-Penman, SWAT-Priestly and SWAT-Hargreaves models at daily, monthly, seasonal and annual time steps through some statistics and their results indicated that all the three calibrated models shows a comparable performance in AET and discharge predictions with small differences. They found that the SWAT-Priestly model predicted more accurately the discharges with higher values whereas the SWAT-Hargreaves model predicted the discharges with lower values more accurately. But the SWAT-Penman model predicted the values which are greater than the predicted values obtained by SWAT-Hargreaves and lower the values obtained by SWAT-Priestly model. They concluded that Priestley-Taylor method is more appropriate for wet hydrologic conditions, Hargreaves method is appropriate for dry hydrologic conditions and for transitional conditions any of the three methods are suitable.

Alemayehu *et al.* (2013) investigated the possibility of estimating spatial variability of evapotranspiration in Mara river basin between Kenya and Tanzania using SWAT model as well remote sensing products and suggested that, in data scarce areas, the prediction abilities of hydrologic models can be improved by using ET estimates from remote sensing data during calibration and validation.

Izady *et al.* (2013) estimated evapotranspiration (ET) at a regional scale on annual basis using SWAT model in the Neishaboor watershed of North-east Iran. They found that during their ten year period of study from 2000-2010; the actual evapotranspiration to precipitation ratio at mountainous part of study watershed was 99%, 80% and 77% for 2001-2002 as a normal year and 2004-2005 as a wet year, respectively. Mean of ten years actual ET and precipitation was estimated as 230 and 270mm, respectively.

2.4.3 Estimation of base flow

The flow that originates from the ground water and enters in to the stream can be referred as base flow. Arnold *et al.* (2000) compared base flow estimation using SWAT model with digital recursive filter techniques and concluded that the base flow values obtained by the SWAT model are in good agreement with the values obtained by the filter technique. They also found that SWAT over estimates base flow in the areas with high runoff values and with deep soils. This over estimation may be due to difficulty of model in estimating aquifer storage and also that parameter was not calibrated. They calibrated the total stream flow without separating base flow from it and hence analyzing the regions where model underestimates the base flow found difficult for them. But over all comparison shows that both the methods followed the same regional trends.

2.5 HYDROLOGICAL MODELING USING SWAT

Simulating the hydrological components of watershed is a prerequisite to find the impact of proposed land management on various climatic cycles. To simulate these management scenarios realistically, the model should have sufficient capabilities to simulate the individual components of the hydrologic cycle realistically. Based on many scientific findings, SWAT was found to be one of the most capable hydrologic models that simulate the components of hydrologic cycle more realistically.

Arnold and Allen (1996) tested multi component watershed model known as SWAT model for three Illinois watersheds i.e., Panther creek, Hadley creek and Goose Creek using SWAT model. They found that the simulated results of the model compared well with the historical water budget calculations. The model also performed relatively well in predicting monthly trends in ground water levels which includes tracking the decline in levels in autumn and subsequent rise in the winter and spring. Underflow was not well simulated by the SWAT since they require information about transmissivity and water level fluctuations which are generally limited or not available for rural watersheds. They concluded that SWAT model is able to simulate all the water balance components within acceptable limits on both daily and monthly basis.

Spruill *et al.* (2001) evaluated SWAT by modelling daily stream flows in a small watershed over a two-year period. They used observed stream flow data of year 1996 for calibration and 1995 for evaluation. They found that some of the peak flows and recession rates during the last half of 1995 were poorly predicted but overall they got satisfactory results .Their results indicated that SWAT model is an effective tool for simulating monthly runoff from small watersheds. They finally gave a conclusion that SWAT model has got excellent capabilities in simulating surface runoff on monthly basis from small watersheds.

Abbaspour *et al.* (2007) used SWAT model to simulate the hydrological process affecting water quantity, sediment and nutrient loads in the catchment. They mainly evaluated the performance of SWAT model and also feasibility of using this model to simulate flow at watershed scale. They used SUFI-2 which was interfaced with SWAT for calibration and two measures such as d-factor, 95PPU in order to assess the goodness of calibration. They qualified the calibration and validation results of the watershed as excellent which was due to good quality input data as well as small conceptual model errors in the dominant process of watershed. They concluded that SWAT can be assessed to be a reasonable tool to use for water quantity and water quality but proper calibration and uncertainty analysis should be needed to get accurate results.

Fadil *et al.* (2011) applied SWAT model, an ArcGIS interface for hydrological modeling of Boregreg watershed in Morocco. They started the study with an aim to simulate the stream flow, to establish water balance and to estimate the inflow volume to the dam which is located at basin outlet on monthly basis. After finding the most sensitive parameters they calibrated the model using auto- calibration method from 1989 to 1997 and validated from 1998 to 2005. Based on statistical evaluators, they observed a good correlation between the monthly observed and simulated river discharge with satisfactory R^2, NSE, PBIAS, RSR values for both calibration and validation. They finally succeeded in developing a calibrated model in order to predict the inflow volume in to the dam and thus help in facilitating the storage and release water management. They concluded that SWAT model had efficient ability to simulate water quantity and also a well calibrated model can be used in future in order to deal with other watershed management issues.

Hosseini *et al.* (2011) selected SWAT, a semi-distributed watershed model for developing a data base system in order to investigate the changes in water balance components with different land uses within Talegan watershed of Tehran. Sequential Uncertainty Fitting (SUFI-2), a program that is linked with SWAT in Calibration Uncertainty Program known as SWAT CUP was used for calibration and validation analysis. By using two factors known as t-stat and P-value which are provided in SWAT CUP to evaluate the sensitivity of parameters, three parameters was considered to be most sensitive for the watershed such as ALPHA_BF, SFTMP and GW_DELAY. Higher t-stat value and p-value closer to zero indicates the parameter is more sensitive. Based on the sensitivity analysis, calibration was done for the most sensitive parameters and the statistical analysis indicates a fair model calibration and validation for discharge by SWAT and SUFI-2 interface in the basin. They finally succeeded in developing a customized SWAT model for future planning of land and water developments within Talegan watershed with favorable results.

Sathian (2012) used SWAT model for hydrologic assessment of Kunthipuzha tributary of Bharatapuzha river, Kerala in order to quantify the hydrologic elements of the watershed and to find out localized variations in water scarcity. He calibrated the model initially with annual basis and then extended to monthly and ten days basis. His results show that high sloping areas have low potential of ground water i.e, lateral flow is the major flow component and ET is also higher in sub-watersheds with high ground water recharge. In case of HRU water balance also, the similar trend as seen in water balance of sub watershed was observed.

Ghoraba (2015) applied the SWAT model for hydrological modeling of Simly dam watershed in Pakistan. The model was calibrated using the data from 1990 to 2001 and validated from 2002 to 2011. Manual calibration and validation was carried out initially annual basis and followed by monthly basis. The efficiency of model was tested by coefficient of determination, NSE, PBIAS and RMSE-observation standard deviation ratio. The coefficient of determination and NSE efficiency on monthly basis has been given by 95% and 84% respectively for calibration, and 84% and 80% respectively for validation period which indicates the high predictive ability of model. Finally it was concluded that a well calibrated model can be used to understand and determine the various hydrological components which helps in optimal utilization of dam water and also to analyze the impact of land and climatic changes on water resources as well as the water quality, agricultural chemical and sediment yields.

Leta *et al.* (2016) evaluated the applicability of SWAT model for a small watershed which suffers from data scarcity. Their findings suggests the suitability of SWAT model for hydrological modeling of a watershed under scarcity of climate data but they also suggested that better stream flow and climatic data will improves the model results in simulating some low and peak flows.

Patel and Kumar (2016) used SWAT model to estimate flooding potentiality of Anjana Khadi micro-watersheds which is a part of Tapi basin located in West India. They used input files such as DEM, drainage network map, soil map, land use map, weather input file to run the model and simulated the model for the monsoon period of year 2006. They estimated the daily, monthly and yearly runoff using SWAT model and obtained the peak discharge for different watersheds. They also calibrated and validated the model for the watershed with the observed data of nearby watersheds since there is no any established gauge station on the focused watershed. Finally they found runoff prone areas and also suggested to place those areas under land use regulation to limit the flood damage potential. They finally concluded that SWAT is an efficient tool for watershed modeling which helps water resource managers in decision making to carry out development activities at watershed scale.

2.6 COMPARISON OF DIFFERENT DIGITAL ELEVATION MODELS

Topography represented in the form of DEM has major applications in watershed modeling. Hence, choosing a correct DEM with reasonable accuracy for hydrological modeling is prerequisite.

Sharma *et al.* (2014) studied about a comparative appraisal of hydrological behaviour of SRTM DEM at catchment level. They studied the hydrological behaviours of SRTM DEM and TOPO DEM in terms of catchment response to runoff and sediment yields. They used the ArcSWAT model to simulate runoff and sediment yields and predictions were done at monthly time step for monsoon season during the years from 2002-2005. Initially they calibrated the model using TOPO DEM and the same calibrated model was run with same spatial data except SRTM DEM in place of TOPO DEM. Their final calibration statistics indicated that runoff was predicted more accurately than sediment yield by using both DEM's. They also found that runoff prediction was more accurate when using SRTM DEM, whereas in case of sediment yield prediction, reverse case was observed. The reason behind the greater runoff prediction accuracy by SRTM DEM was it facilitates delineation of drainage network, basin boundary and micro watershed more accurately when compared to TOPO DEM. But the variation in the prediction of runoff values using the two DEMs was only marginal. They finally concluded that SRTM DEM can be a valuable data for hydrological analysis/applications.

2.7 IMPROVING THE PREDICTION ACCURACY OF MODEL

2.7.1 Sensitivity analysis

Sensitivity analysis can be considered to be an important element of evidence building (Satelli *et al*., 2000). To identify the key parameters that affect the model performance, sensitivity analysis is needed. Sensitivity analysis plays an important role in model parameterization, optimization, calibration and uncertainty quantification.

Lenhart (2002) conducted a study on comparison of two different approaches of sensitivity analysis by using SWAT, a physically based continuous time hydrological model. In both the approaches, one parameter varied at a time while keeping the other parameters fixed, only the way defining the range of variation is different. He found that both the approaches attained similar results and suggested that parameter sensitivity may be determined without the results being influenced by the chosen method.

Generally there are two types of sensitivity analysis: local, by changing values one at a time and global, by allowing all parameters values to change. Both the analysis may yield different results and each one has their own disadvantages. The problem with one-at-a-time sensitivity analysis was: since the sensitivity of one parameter often depends on the value of other related parameters, the correct values of other parameters that are fixed are never known. The disadvantage of global sensitivity analysis was it requires more number of simulations (Arnold *et al.,* 2012).

Song *et al.* (2015) reported four different categories of sensitivity analysis such as Local and Global sensitivity analysis, Quantitative and Qualitative sensitivity analysis, Screening and Refined sensitivity analysis, Mathematical, Statistical and Graphical sensitivity analysis. Generally, global sensitivity analysis is recommended in hydrological modeling applications since they have certain advantages than local sensitivity methods. These advantages include their ability to incorporate influence of input parameters over the whole range of variation and be well suited for non linear and non-montonic models.

Pianosi *et al.* (2016) provided the purposes of sensitivity analysis as follows:

1. Ranking aims at generating the ranking of input factors according to their relative contribution to the output variability.
2. Screening aims at identifying the input factors that have negligible effect on the output variability.
3. Mapping aims at determining the region of the input variability space that produces significant, e.g., output values, extremes.

2.7.2 Calibration and validation

The effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty can be referred to as calibration. Model calibration is a process in which a generalized model is adjusted in order to represent the site specific process and conditions more realistically. Validation is the process of running a model with the parameters that were determined during calibration process with a data set which is not used for calibration. Validation should carry out in order to build confidence whether the model represents the real system accurately or not.

Calibration can be done either manually or by using auto calibration tools like SWAT-CUP for SWAT. Eckhardt and Arnold (2001) studied about automatic calibration of a distributed catchment model and explained that a manual calibration is more or less a trial and error process in which parameter values have to be changed and the model has to be run several times.User's experience in modelling, recognizing parameters are the two main significant skills to achieve success in manual calibration whereas automatic calibration requires only input files to be filled out once. These files contain the information that controls the program, the measured values with which the model output is to be compared and the declarations of parameter constraints and interdepencies. Their results showed that distributed watershed models as complex as Soil and Water Assessment Tool (SWAT) can successfully be automatically calibrated.

For proper calibration and validation, large amount of measured data are necessary (Abbaspour *et al.,* 2007).

Usually, a good calibration and validation should involve the following things

1. Observed data which includes wet, average and dry years
2. Multiple evaluation techniques
3. Calibrating all constituents to be evaluated; and
4. Verification that other important model outputs are reasonable.

Arnold *et al.* (2012) studied SWAT model use, calibration and validation. Many calibration techniques were developed for SWAT which includes manual calibration, automated procedures and other common methods. Recently, SWAT-CUP was developed which provides decision making framework incorporating a semi-automated approach such as SUFI-2 that uses both manual and automated calibration. SWAT-CUP also incorporates sensitivity and uncertainty analysis. Further, it has provision to adjust parameters and ranges through manual means between auto calibration runs. They also suggested there is a need to build confidence in model results and to improve conservation. Their suggestions for future developments were improving accountancy for hydrologic process in order to obtain model simulations accurately at all locations, improving spatial calibration and to improve run-time efficiency. They also recommended calibrating base flow and surface runoff separately to get accurate results by separating the base flow from the observed total daily stream flow using a base flow filter.

Lu *et al.* (2015) stated that multi variable and multi temporal calibration methods provide better simulated values. They compared the simulated values with the observed values for both calibrated and uncalibrated models. For the uncalibrated model, the simulated values are not well matched with the observed values, at the same time the PBIAS value was too large which indicated the under prediction of model. After calibrating the model, they got satisfactory PBIAS value with good match between simulated and observed values. They concluded that a calibrated model is essential for the realistic representation of the site conditions and also stated that understanding drainage characteristics is very helpful and crucial for model calibration.

2.7.3 Calibration and validation using SUFI-2

The calibration of large scale distributed watershed models has become difficult due to large model uncertainty, input uncertainty and parameter non-uniqueness. SWAT CUP is a generic interface and stand alone program developed for SWAT model calibration (Abbaspour *et al.,* 2007). SWAT CUP includes several techniques such as PSO, SUFI-2, GLUE, Parasol and MCMC. The SUFI-2 procedure was developed for inverse modelling that uses a sequence of steps in which the initial uncertainties in the model parameters are reduced until certain calibration requirement is reached. Sequential Uncertainty Fitting Algorithm (SUFI-2) is very advantageous since it combines optimization with uncertainty analysis and can handle large number of parameters.

Abbaspour *et al.* (2007) conducted a study on modelling hydrology and water quality in the Pre-alpine/Alpine Thur watershed using SWAT model. They performed calibration and uncertainty analysis with SUFI-2 and explained the conceptual basis of the SUFI-2 uncertainty analysis routine. They used two measures in order to assess the goodness of calibration such as percentage of data bracketed by the 95% prediction uncertainty and d-factor. Both the factors showed excellent results for discharge and nitrate and quite good results for sediment and total phosphorus.

Schuol *et al.* (2008) successfully applied well established semi distributed SWAT model in combination with ArcGIS and SUFI-2 calibration procedure to quantify the fresh water availability for the whole African continent at a detailed sub basin level and monthly basis with uncertainty analysis. They concluded that Sequential Uncertainty Fitting Algorithm (SUFI-2) is very efficient not only in terms of localizing an optimum parameter range but also in terms of number of simulations.

Yang *et al.* (2008) conducted a study on comparing uncertainty analysis techniques for a SWAT application to the Chaohe basin in China. They compared GLUE, ParaSol, SUFI-2, MCMC and Importance Sampling uncertainty analysis techniques with respect to posterior parameter distributions, performances of their best estimates, conceptual basis, prediction uncertainty, computational efficiency and difficulty of implementation. They found that there are big differences in concepts and performance of these techniques; on the other hand GLUE, SUFI-2 and MCMC led to similar prediction uncertainty bands. They also concluded that SUFI-2 is very convenient to use but the only drawback is, it is semi-automated and requires the interaction of the modeller to check a set of suggested posterior parameters which needs a good knowledge of the parameters and their effects on the output. This drawback may add additional error called “modeller’s uncertainty” to the list of other types of uncertainties. The basic rules which help in parameter regionalization can be obtained from Abbaspour *et al.* (2015).

2.8 HYDROLOGIC MODELING IN UNGAUGED BASINS

As watershed models are data driven models, calibration is possible for only gauged watersheds. There are many watersheds, where no monitoring data is available and it is always a challenging task for the water resource managers for managing water resources in ungauged basins where there is a high risk of natural hazards. Many hydrologists have attempted for developing strategies to estimate model parameters (e.g., James, 1972; Magatte *et al.,* 1976), but it remains as an unsolved problem. Now a days, the prediction in ungauged basin is attempted through “regionalization” which refers to transferring of parameters from the neighbouring gauged catchments into an ungauged catchment.

Gitau and Chaubey (2010) conducted a study to investigate the possibility of developing regionalized SWAT model parameter sets to use in ungauged watersheds. They evaluated two regionalization methods such as global averaging and regression based parameters, on the SWAT model using data from the selected gauged watersheds in Arkansas. Resulting parameters were tested and model performance was determined using performance analysis in three gauged watersheds. They found that model performance obtained using both the global averaged and regression-based parameters were comparable to that obtained through calibration. They concluded that regionalized parameter sets obtained from the SWAT model can be used for making satisfactory hydrologic response predictions in ungauged watersheds.

Emam *et al*. (2016) also used SWAT to model hydrologic process in an ungauged basin of Central Vietnam by applying regionalization approach and succeeded in implementing the BMP's for the agricultural lands located in the ungauged basin. From the above discussions, it can be inferred that regionalization is the best approach that provides facility for calibrating ungauged watersheds and thus helping in water resource management.

2.9 APPLICATION OF SWAT MODEL IN AGRICULTURAL WATER SCARCITY MANAGEMENT

SWAT model provides realistic estimates of various hydrologic components taking place in a watershed that helps in solving variety of problems related to agricultural water scarcity.

Richards (2010) used SWAT model for irrigation management in Rio Nuevo watershed. He selected a sub basin where agricultural activities take place and by using water balance components on monthly basis from SWAT results, determined whether stream flow was adequate for the dry months of the year. Based on the SWAT results, he suggested suitable planning measures that should take place in the future to avoid agricultural drought and finally concluded that SWAT is an efficient model in exploring a variety of problems related to agricultural drought and thus helps in reducing water scarcity in a particular area.

SWAT model also enables computation of drought indices by providing good simulation of the meteorological and hydrological variable (Zou *et al.,* 2017).

2.10 LIMITATIONS AND IMPROVEMENTS NEEDED

Though SWAT model is highly adopted by the several scientists to carry out hydrologic simulations, it has also got some limitations which indicate the necessity of some improvements in the model.

Qiu *et al.* (2012) evaluated and tested the feasibility of Soil and Water Assessment Tool (SWAT) model on runoff and sediment load simulation in the Zhifanggou watershed of china. They used daily flow and sediment data from 1998 to 2008; out of this, data from 1998 to 2003 was used for calibration and 2004 to 2008 for validation. During the evaluation of runoff simulation, the statistical results were found to be satisfactory for both calibration and validation periods. Even though the statistical analysis results showed reasonable agreement between the observed and simulated runoff, they found that SWAT underestimated the runoff during high flow periods. The reason for this underestimation, it is said, may be partly due to inability of curve number technique to generate accurate runoff prediction for a day that experiences several storms. They finally concluded that SWAT did a reasonably good job in estimating runoff from the watershed but the only weakness of the SWAT model is the underestimating of high flow events. This underestimation can be attributed to dependency of model on semi-empirical and empirical models such as MUSLE and SCS-CN number methods which causes the SWAT model to track the peak runoff and sediment loads less accurately. They finally suggested there is a need to modify the model for taking the rainfall intensity and its duration into account to enhance the model accuracy on peak flow and sediment load simulation when it is applied to flood prediction.

Pereira *et al.* (2016) stated that the SWAT model can provide good estimates of water balance components but model needs still improvements because they found that model faces some difficulties in simulating some stream flow peaks both in calibration and validation. They cited that “under simulation” of SWAT with peak flows may be due to continuous variation of rainfall both spatially and temporally.

CHAPTER III

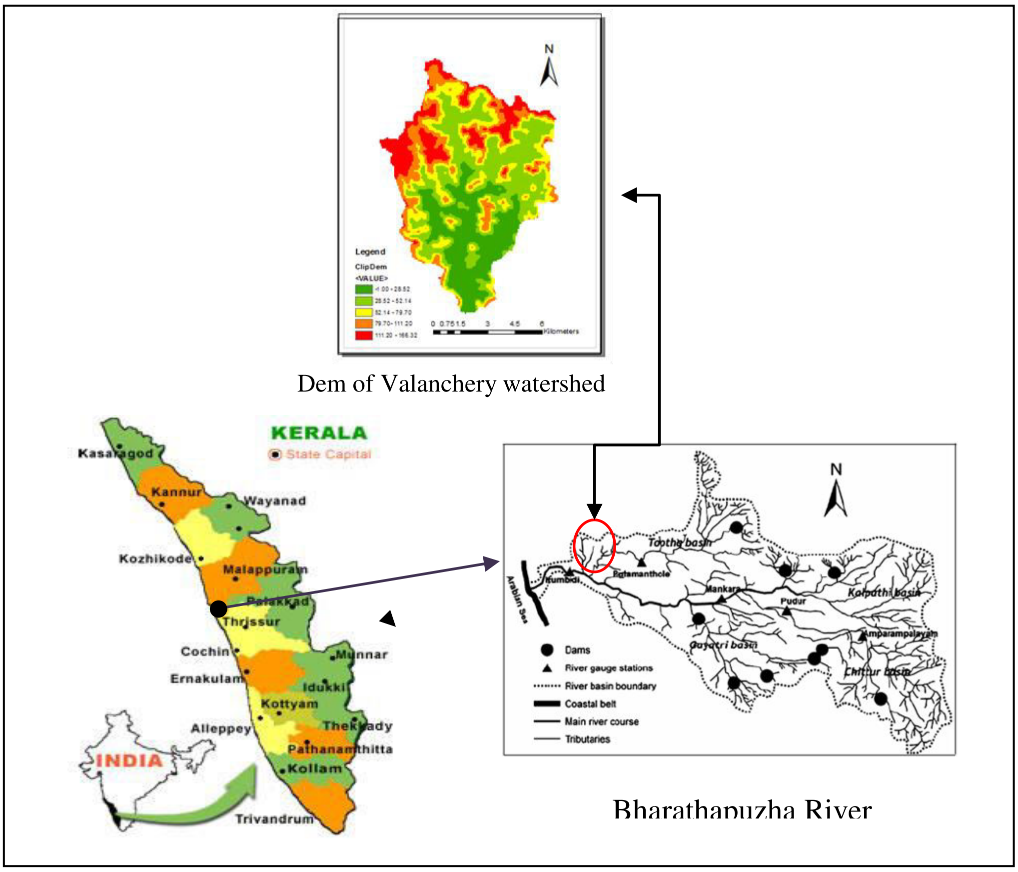
MATERIALS AND METHODS

This chapter describes the study area, watershed model and tools used for the study. The methodology adopted to set up and run the model and the procedures for sensitivity analysis, calibration and validation of the model are also detailed. Based on different reviews related to hydrological models, SWAT model was selected and used for the study. A computer program which was developed for calibrating SWAT models known as SWAT-CUP was used for sensitivity analysis, calibration and validation of the model.

3.1 DESCRIPTION OF STUDY AREA

A small sub catchment of Bharathapuzha river basin (longest river in Kerala) which joins laterally with the main stream of the river has been chosen for the study. The location map of the catchment is shown in Fig. 3.1. The watershed encompasses one of the important commercial town Valanchery and hence, it is named as Valanchery watershed. The area of the watershed was about 80 Km^2. The small stream from the study area flow towards South and joins about 3 km to the South of Valanchery town. The delineated watershed of the study area lies within the range of 10^o47’47.48’’N latitude to 10^o58’27.84’’N latitude and 75^o58’57.72’’E longitude to 76^o11’49.2’’E longitude. The hydrological analysis of the watershed has been done using the SWAT model. Calibration of the model for the study area was not possible as there is no discharge data for the stream originating from the study watershed. Therefore, the neighbouring Kunthipuzha sub basin of Bharathapuzha has been taken for the calibration and validation of the model.

Kunthipuzha river is an important tributary of Bharathapuzha river basin, the second largest river basin in Kerala. Total catchment area of the Bharatapuzha river is 6400 Km^2 and lies between 10˚25’N - 11˚25’N and 75˚50’-76˚55’ E. The river originates from the Western Ghats and 70% of its catchment is spread in Kerala and the remaining in Tamilnadu state. The four main tributaries of Bharathapuzha river are Gayathripuzha, Chitturpuzha, Kalpathipuzha and Kunthipuzha. Kunthipuzha, sub basin lies in the North East part of the Bharathapuzha river basin. The sub basin lies in the latitude longitude range of 100 53’N, 760 04’E to 110 14’N, 76041’E and has a total catchment of 940 Km^2 at the confluence point with the main river.



Dem of Valanchery watershed

Bharathapuzha River

Fig. 3.1 Location of the study area

Catchment area at Pulamanthole river gauging station (100 53’ 50’’ N, 760 11’50’’E) manned by Central Water Commission, India is 822 Km^2. Elevation of the catchment varies from 20 to 2300 m. Mean annual rainfall of the area is 2300 mm. About 80% of the total rainfall is received during June to September, 15% from October to November and about 5% during December to May. Mean temperature of the area is 27.3^{o}C. The average daily flow ranged from a minimum of 0.1 m^3/s to a maximum of 1020 m^3/s during the period of analysis.

3.2 SOFTWARES AND TOOLS USED

Different software’s and tools were used for this study and their brief description is given below.

3.2.1 ArcGIS 10.2.2

ArcGIS is a proprietary Geographic Information System used to display the geographic information on a map. ArcGIS provides a common frame to work with different spatial data obtained from various sources. The ability of GIS to work with spatial data in multiple formats made it more advantageous than other technologies. ArcGIS was developed by Environmental Systems Research Institute (ESRI) and was initially released at New York in 1999. ArcGIS for Desktop includes number of integrated applications such as ArcCatalog, ArcMap, ArcToolbox. ArcMap is used for primary display application i.e., to display, query, edit, create and analyze the geographically referenced data. Arc catalogue helps to browse, search, explore, view and also to manage the data. Arc tool box is a geoprocessing tool used to perform geoprocessing operations such as data conversion, buffering, overlay processing, proximity analysis, map transformations etc.

ArcGIS 10.2.2 which was released in 2014 was used in this study. ArcGIS 10.2.2 was used for changing the projection of SWAT inputs such as DEM, land use and soil maps. Georeferencing the toposheet of the study area, digitization and the preparation of digital elevation model was also done using this software.

3.2.2 Soil Plant Atmosphere Water (SPAW) Hydrologic Budget Model

SPAW model developed by Keith Saxton, United States Department of Agriculture (USDA)-Agricultural Research Service (ARS) is a daily hydrologic model used for calculating the characteristics of soil. Soil Water Characteristics is a program that estimates hydraulic conductivity, soil water tension and water holding capacity based on organic matter, soil texture, gravel content, salinity and compaction. The soil characteristics such as hydraulic conductivity, available water, electrical conductivity and bulk density were obtained using this model in order to prepare user soils database.

3.2.3 SWAT-CUP

The calibration/uncertainty or sensitivity program can easily be linked to SWAT through a generic interface called SWAT-CUP. SWAT CUP is an interface that provides sensitivity analysis, calibration and validation of SWAT models. Recent version SWAT CUP 2012 version 5.1.6 was used for the study to carry out calibration and uncertainty analysis. SWAT CUP which is a public domain program includes several methods such as SUFI2, PSO, GLUE, ParaSol and MCMC for the purpose of calibration and uncertainty analysis. In this study, SUFI 2 was employed to perform parameter sensitivity analysis, calibration and validation.

SUFI 2 determines uncertainty through the sequential fitting process and also in this method, parameter uncertainty accounts for all sources of uncertainties such as model input, model structure, parameters and measured data. Among all the methods, SUFI 2 is very easy to handle and can give comparably good results.

3.3 SWAT MODEL OVERVIEW

SWAT is a physically based distributed watershed model that can operates on different time steps. Initially it was developed for United States by United States Department of Agriculture but later it was adopted by the whole world for watershed modeling. Its excellent capabilities in simulating the water balance components made it widely acceptable. It is a comprehensive tool that enables the impacts of land management practices on water, sediment and agricultural chemical yields for the watersheds with varying soils, land use and management practices. SWAT can also simulate sediment yield, transport of nutrients and pesticides through catchments which made it also a non-point source pollution model. For the model to run, it requires input data such as DEM, land use, soil maps and hydrometereological data. SWAT divides the basin into sub basins using digital elevation model and then each sub basin is further discretized into hydrological response units based on soil and land use information. Simulation of soil water content, surface runoff, nutrient cycles, sediment yield, crop growth and management practices will carry for each HRU and then aggregates for the sub basin by a weighted average.

The two major components of watershed hydrology are land phase and routing phase. The land phase controls the quantity of water, sediments, nutrients and pesticide loadings to the main stream in each sub basin whereas the routing phase controls the movement of water, sediments etc through the channel network to the catchment outlet (Arnold *et al.,* 2012).

Simulating the individual components of water balance such as surface runoff, evapotranspiration, lateral flow etc., is essential for water management strategies.

SWAT model uses water balance equation for simulating hydrologic cycle which is shown below

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

Where,

SW_t = final soil water content (mm H_2O)

SW_o= initial soil water content on day i (mm H_2O)

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

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

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

w_{seep} = amount of water entering the vadose zone fromthe soil profile on day i (mm H_2O)

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

3.3.1 Surface runoff

The flow that occurs along the sloping surface can be referred as surface runoff or overland flow. SWAT simulates surface runoff volumes and peak runoff rates for each HRU's using daily or sub daily rainfall amounts. SWAT model provides two methods in order to estimate surface runoff namely SCS-CN method and Green-Ampt infiltration method. SCS-CN method is based on rainfall-runoff relationships and was designed for computing direct runoff whereas Green-Ampt is an infiltration equation. For analyzing the impacts of land use on runoff, Green-Ampt infiltration method is more suitable provided that if the rainfall data is available at a sub-hourly time step. And also if Green-Ampt method is selected to calculate surface runoff, the rainfall interception by canopy should be calculated separately. Green-Ampt method is more suitable for predicting runoff because the infiltration parameters in this method can be directly related to watershed characteristics but its requirement of precipitation data at a sub-hourly time step limits its use.

Due to the unavailability of precipitation data at sub hourly time steps, SCS-CN procedure was used for predicting runoff volume. SWAT model applies a modification of soil conservation service curve number (SCS-CN) method which is based on hydrologic group, land use and AMC for each HRU for determining surface runoff. The equation for SCS-CN method was

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

Where,

Q_{surf} = rainfall excess (mm)

R_{day} = daily rainfall (mm)

I_a = initial abstraction (mm)

S = retention parameter (mm)

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

Where,

CN = curve number for the day

Initial abstractions is commonly approximated as 0.2 S, then above equation becomes

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

SWAT also calculates the peak runoff rate using modified rational formula which is shown below

$$q_{peak} = \frac{(\alpha_{tc} * Q_{Sur} * Area)}{3.6 * t_{conc}}$$

where,

q_{peak} = peak runoff rate(m^3/s)

α_{tc} = fraction of daily rainfall that occurs during time of concentration

Q_{Sur} = surface runoff (mm)

t_{conc} = time of concentration for the sub basin (hr)

A = area of sub basin (Km^2)

3.3.2 Time of concentration

It is the amount of time from the beginning of a rainfall event until the entire sub basin is contributing to flow at the outlet. Time of concentration is calculated by adding the flow time of both overland and channel flows.

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

where,

t_c = time of concentration for the sub basin in hours

t_{ov}= time of concentration of overland flow in hours

t_{ch} = time of concentration of channel flow in hours

3.3.3 Evapotranspiration

Evapotranspiration is a collective term which includes evaporation from the soil, transpiration, evaporation from plant canopy and also sublimation. Evaporation of water in the soil and plant transpiration is estimated separately by the SWAT. Measuring AET is very difficult, also time consuming and costly process as it is related with number of parameters that can vary spatially and temporally. Generally it is common to compute AET based on PET which can be determined using appropriate methods. There exists several methods for computing PET but SWAT incorporates only three of them such as temperature based Hargreaves method (Hargreaves *et al.*, 1985), radiation based Priestly-Taylor method (Priestley and Taylor 1972), and combination based penman-monteith method (Monteith 1965). Hargreaves requires inputs such as extra terrestrial radiation, daily maximum and minimum temperature. Priestly-Taylor method requires inputs related to mean daily temperature and net radiation whereas Penman-Monteith method need more number of inputs such as net radiation, air temperature, relative humidity and wind speed. Generally, the AET variable in SWAT represents the water removed actually from the HRU through evaporation from soil and plant canopy, transpiration and sublimation if snow is present. First SWAT calculates the rainfall evaporates from plant canopy and next it calculates the maximum amount of transpiration and soil water evaporation. The evaporation of soil water is estimated as an exponential function of soil depth and water content based on PET and soil cover index whereas transpiration is simulated as a linear function of depth of root, leaf area index, soil water content and PET. The Penman-Monteith method was utilized in this study.

3.3.4 Lateral flow

The stream flow contribution which originates below the surface but above the zone where rocks are saturated with water can be referred as lateral sub surface flow or inter flow. Lateral subsurface flow in soil profile can be calculated simultaneously with percolation. For predicting lateral flow, SWAT incorporates kinematic storage model equation which uses kinematic approximation for its derivation which is shown below

$$q_{lateral} = 0.024\left(\frac{2S*K_{sat}*sin\alpha}{\theta_d*L}\right)$$

Where,

S = drainable volume of soil water per unit area of saturated thickness (mm/day)

K_{sat} = saturated hydraulic conductivity (mm/h)

θ_d = drainable porosity

L= flow length (m)

α = slope of the land

From the above equation it was clear that the model accounts for variation in slope, soil water content and conductivity.

3.3.5 Percolation

After the inputs such as precipitation or irrigation has ceased at the soil surface there will be a continuous movement of water through a soil profile. Percolation will occur based on the differences in water content in the profile. In SWAT model, percolation component uses a water storage technique for predicting flow through each soil layer in the root zone. The solution obtained from the equation of water storage technique provides the magnitude of percolation. Generally, downward flow occurs if field capacity of a soil layer exceeds and the layer below is not saturated. Percolation is also a function of soil temperature and hence daily soil temperature is simulated as a function of maximum and minimum air temperature. If 0^oC is noticed in any particular layer, no percolation is allowed from that layer

3.3.6 Base flow

Base flow can be referred as volume of stream flow originating from the ground water. SWAT simulates base flow by using the equation as shown below

$$Q_{gwj} = Q_{gwj-1} * e^{(-\alpha_{gw} .\Delta t)} + W_{rchrg} * (1 - e^{(-\alpha_{gw} .\Delta t)})$$

Where,

Q_{gwj} = ground water flow into the main channel on day j,

$^{-\alpha}{}_{gw}$ = base flow recession constant,

Δt = time step

3.3.7 Deep aquifer recharge

Also in each sub basin SWAT simulates two aquifers i.e. shallow aquifer and deep aquifer. The confined aquifer that contributes to flow in main channel is called shallow aquifer. Generally the water yielding potential of a deep aquifer will be low for a watershed because major portion of the water that enters into the aquifer will see outside the watershed.

3.4 INPUT DATASETS

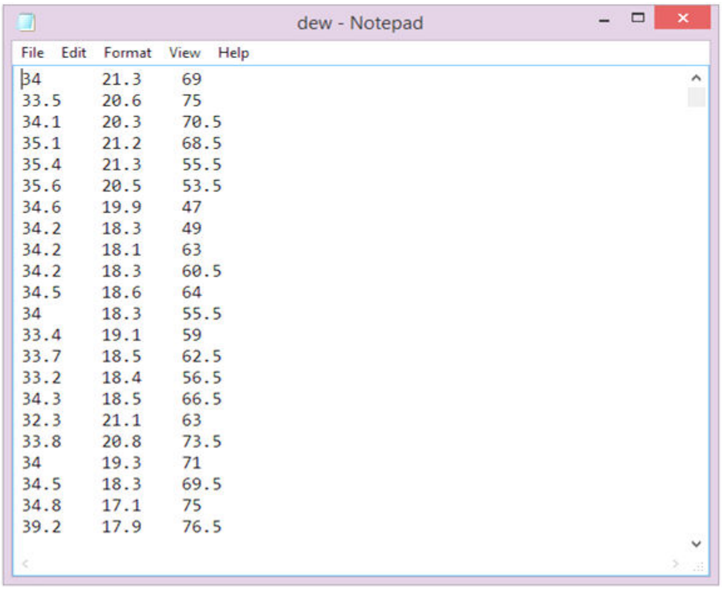
The input data required by the SWAT model are meteorological data, hydrological data and spatial datasets. Daily rainfall data from two rain gauge stations i.e., Pattambi and Mannarkkad were used for the model simulation. Meteorological data related to rainfall, temperature, relative humidity, wind speed and solar radiation data was obtained from Regional Agricultural Research Station, Pattambi, Kerala Agricultural University, IMD and Water Resources Department, Government of Kerala for the period of 1989 to 2013. Stream flow data for Pulamanthole gauging station was collected from CWC and Water Resources Department. SWAT model requires thematic maps such as digital elevation model, soil map, land use map and drainage network map. Digital elevation models can provide hydrologic relevant parameters and hence they are very important in hydrological modeling. DEM can be generated from contour interpolation and also often derived from satellite imagery such as stereoscopic SPOT images. For comparing different DEM accuracy in hydrological assessment, 4 DEM's are taken for the study. TOPO DEM, SRTM DEM, ASTER DEM and BHUVAN DEM were taken for comparison in terms of catchment delineation and hydrological modeling whereas TOPO DEM was used for the detailed hydrologic analysis. TOPO DEM was prepared from toposheet by digitizing the contour lines. Georeferencing the toposheet, changing and defining the coordinate systems and digitizing the contour lines were done in ArcGIS 10.2.2. Finally, using spatial analyst tools in ARCGIS, DEM was prepared by using contour shapefile. Shuttle Radar Topographic Mission (SRTM) DEM of 30m resolution was downloaded from earthexplorer.usgs.gov.in website. SRTM DEM was provided by the Consultative Group for International Agriculture Research Consortium for Spatial Information. SRTM 1 Arc-Second Global DEM offers worldwide coverage of void filled data at a 30m resolution. ASTER DEM was also downloaded from the earthexplorer.usgs.gov.in website whereas BHUVAN DEM was downloaded from the Bhuvan website. Drainage network map was prepared for the study area by digitizing the streams from the toposheet. Land use map derived from the LISS (III) imagery of IRS P6 satellite of 2008 was used for the study. The Soil map and the morphological characteristics of the soil collected from the Directorate of Soil Survey & Soil conservation of Kerala State were used for running the model. All the data sets were transformed into WGS_1984_UTM_ZONE_43N coordinate system in ARCGIS before feeding into the model. Both the land use map and soil map were rasterised in ARCGIS 10.2.2 before feeding into SWAT model.

3.4.1 Preparation of text files and tables

In order to specify the SWAT land cover code to be modeled for each category in the land use map grid, a land use look up table can be prepared manually and entered into the model. Similarly, soil look up table can also be prepared manually to specify the type of soil to be modeled for each category in the soil map grid. While choosing to give the manually prepared look up tables into the model, the data regarding soil characteristics of the study area should be entered in the user soil found in SWAT2012.mdb which will be read by the model.

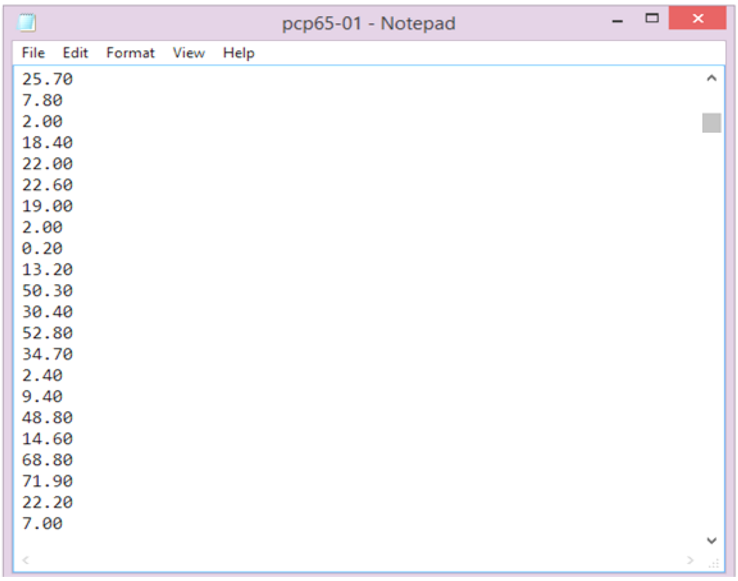
While preparing data for precipitation, two types of tables are required such as precipitation gauge location table and daily precipitation data table. The precipitation gauge location table is used to specify the location of rain gauges whereas daily precipitation data table is used to store the daily precipitation for an individual rain gauge. The precipitation gauge location table should possess ".txt" i.e., ".text" extension. Daily precipitation table should be formatted only as an ASCII text file, dbase tables which were taken by the previous versions of ArcSWAT are no longer supported by the current model version. The daily precipitation location files should be located in the same folder as the precipitation gauge location table. In case of temperature, daily maximum and minimum temperature data table must be formatted only as an ASCII text file. Like precipitation, temperature gauge location table should also have ".txt" extension. Other climatic parameters such as solar radiation, wind velocity and relative humidity should also be prepared in the same format.

The name begins with "WGEN_" in the SWAT 2012.mdb will be picked by the model. If "WGEN_user" was selected in the locations table, the user must define the data in "WGEN_user" found in SWAT2012.mdb. SWAT model needs weather data such as daily precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed. The weather generator data file involves some statistical data, needed to generate representative daily climate data for the sub basins. Statistical parameters used by the weather generator of the swat model was calculated using excel sheet, pcpSTAT.exe and dew02.exe. Using pcpSTAT.exe, statistical parameters of daily precipitation data were calculated. The average daily dew point temperature was calculated using dew02.exe and the remaining parameters were calculated using excel sheet. The input files must be in ASCII text format with single column for pcpSTAT.exe and three columns for dew02.exe as shown in Fig. 3.2 and Fig. 3.3. The single column in pcpSTAT.exe input file represents daily precipitation data whereas in dew02.exe input file: the first, second and third columns represents daily maximum temperature, daily minimum temperature and average daily humidity data respectively.



```
34      21.3    69
33.5    20.6    75
34.1    20.3    70.5
35.1    21.2    68.5
35.4    21.3    55.5
35.6    20.5    53.5
34.6    19.9    47
34.2    18.3    49
34.2    18.1    63
34.2    18.3    60.5
34.5    18.6    64
34      18.3    55.5
33.4    19.1    59
33.7    18.5    62.5
33.2    18.4    56.5
34.3    18.5    66.5
32.3    21.1    63
33.8    20.8    73.5
34      19.3    71
34.5    18.3    69.5
34.8    17.1    75
39.2    17.9    76.5
```

Fig. 3.2 Input file for dew02.exe



```
25.70
7.80
2.00
18.40
22.00
22.60
19.00
2.00
0.20
13.20
50.30
30.40
52.80
34.70
2.40
9.40
48.80
14.60
68.80
71.90
22.20
7.00
```

Fig. 3.3 Input file for pcpSTAT.exe

3.5 METHODOLOGY TO RUN SWAT MODEL

To run the SWAT model, the spatial data sets required by the SWAT are digital elevation model, land use and soil maps. DEM should be in ESRI GRID format whereas land use and soil maps should be in any one of the three formats such as ESRI GRID, shapefile or feature class. Along with spatial data, meteorological data such as precipitation, temperature, solar radiation, relative humidity and wind speed are also required by the SWAT in the required formats.

3.5.1 Create a new ArcSWAT project

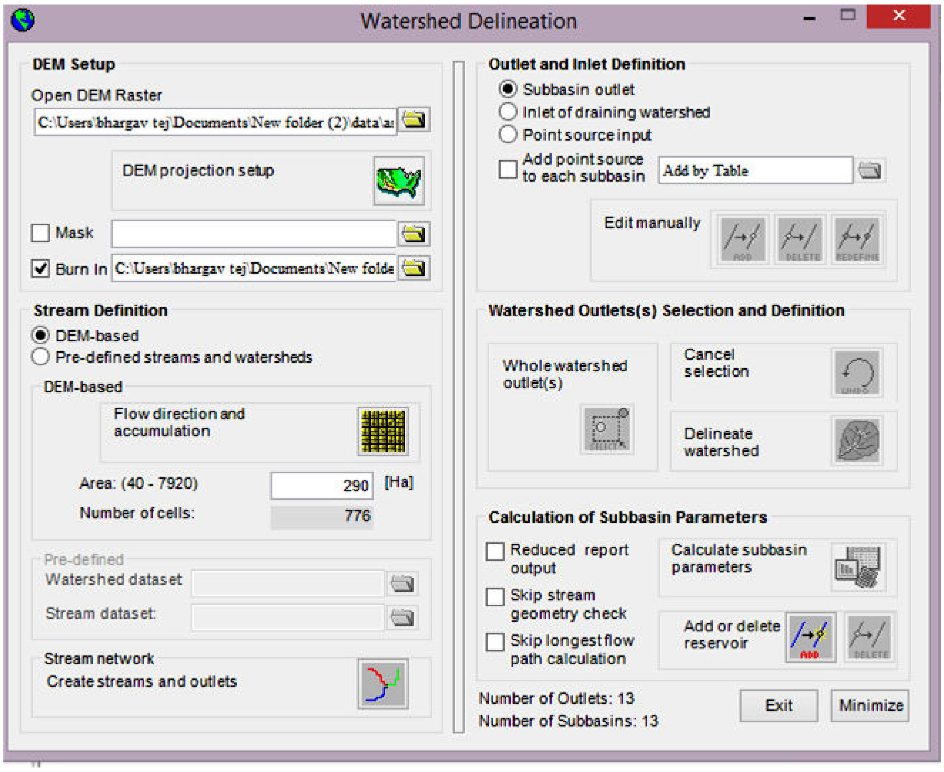
In the project set up dialogue box, set the project directory in which all the SWAT geodatabase will be stored and click ok which will finish project set up.

3.5.2 Watershed delineation

Watershed delineation in SWAT model includes five steps i.e., DEM set up, stream definition, inlet and outlet definition, watershed's outlet selection and definition and finally calculation of sub basin parameters. After, loading the DEM, there will be two options provided such as mask and burn-in. Mask option is used to reduce the processing time of GIS functions by allowing the interface to cover only the masked area. "Burn in" option allows superimposing the stream network onto the DEM and used to force the SWAT sub basin reaches to follow known stream location which improves hydrographic segmentation and watershed delineation. The stream network polyline shapefile was prepared from toposheet and was used to burn in onto the loaded DEM. After the completion of watershed delineation, the results can be viewed in watershed reports created by the interface.

3.5.3 HRU analysis

HRU's are the units or the areas with unique combination of slope, soil and land use. HRU analysis comprises of two steps such as land use, soil, slope definition and overlay and HRU definition. In SWAT model, reclassifying the land use and soil maps is prerequisite step in order to convert the user's land use, soils database into SWAT data base. After reclassifying the land use, soil and slope layer, they should be overlaid. A detailed report regarding land use, soil and slope distribution within each sub basin is added to the current project. HRU definition allows to specify criteria used in determination of HRU distribution and final HRU definition report will be created by the model. SWAT interface for watershed delineation and HRU analysis was shown in Fig. 3.4 and Fig. 3.5.



Watershed Delineation

DEM Setup

Open DEM Raster: C:\Users\bhargav tej\Documents\New folder (2)\data\a

☐ Mask

☑ Burn In C:\Users\bhargav tej\Documents\New folde

Stream Definition

● DEM-based

○ Pre-defined streams and watersheds

Area: (40 - 7920) 290 [Ha]

Number of cells: 776

Outlet and Inlet Definition

● Subbasin outlet

○ Inlet of draining watershed

○ Point source input

☐ Add point source to each subbasin

☐ Reduced report output

☐ Skip stream geometry check

☐ Skip longest flow path calculation

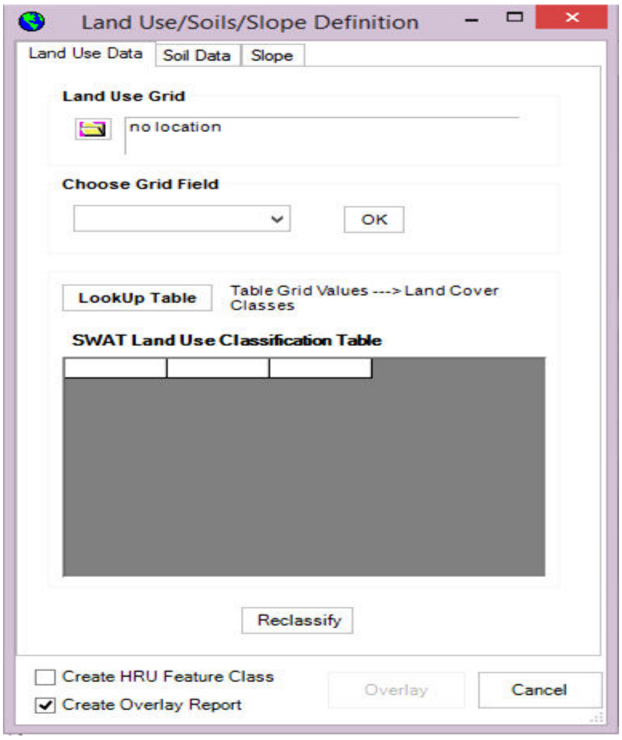
Number of Outlets: 13

Number of Subbasins: 13

Fig. 3.4 SWAT interface for watershed delineation

3.5.4 Write input tables

In this menu, the weather stations command is used to load the weather stations locations. "Weather Data Definition" dialogue box allows user to feed data regarding rainfall, temperature, relative humidity, solar radiation and wind speed. Before giving the other data, the user must set the weather generator data first otherwise the interface will not allow processing the other input data. The "write SWAT Input Tables" command act as interface to manage the creation of ArcSWAT geodatabase tables which stores values for SWAT input values. Initial SWAT ASCII inputs files are also generated.



Land Use Grid: no location

☐ Create HRU Feature Class
☑ Create Overlay Report

Fig. 3.5 SWAT interface for HRU analysis

3.5.5 Edit SWAT input

This menu allows the user to edit SWAT model databases and the watershed database files containing the current inputs for the SWAT model.

3.5.6 SWAT simulation

This menu allows the user to finalize the input set up for the model and to run the SWAT model. The period of simulation allows user to specify the starting and ending dates of the simulation. "Set up and run SWAT model" dialogue box contains several sections, after defining all the options by clicking the "Set up SWAT Run" button the final input files based on the settings defined will be generated. After set up SWAT Run, the user can run the model by clicking "Run SWAT" button. The flow chart for SWAT model set up was shown in Fig. 3.6.

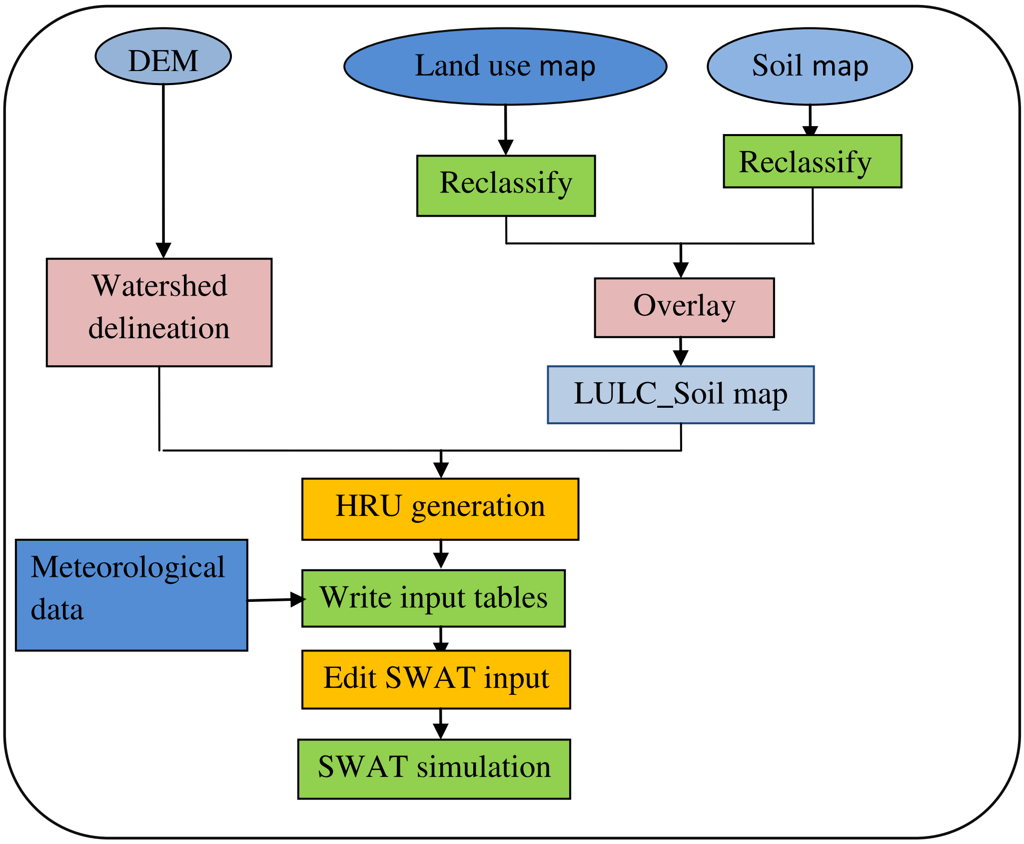


Fig. 3.6 Flow chart for SWAT model set up

3.6 SENSITIVITY AND UNCERTAINTY ANALYSIS

Sensitivity analysis is increasingly used in environmental modelling for a variety of purposes such as model calibration and diagnostic evolution, uncertainty assessment and robust decision making. Sensitivity analysis helps in understanding the behaviour of the system and also to evaluate the applicability of the model (Van Griensven *et al.,* 2016). The parameter selection for sensitivity analysis as shown in Table 3.1 was done based on characteristics of the study area as well as literature review (Sathian, 2010; Varughese, 2016).

Table 3.1 Initial chosen parameters for performing sensitivity analysis

S.No	Initial chosen parameters
1.	CN2
2.	ALPHA_BF
3.	GW_DELAY
4.	GW_QMN
5.	GW_REVAP
6.	ESCO
7.	CH_N2
8.	CH_K2
9.	ALPHA_BNK
10.	SOL_AWC
11.	SOL_K
12.	SOL_BD
13.	OV_N
14.	SURLAG
15.	EPCO
16.	REVAPMN
17.	RCHRG_DP
18.	SLOPE
19.	SLSUBSN
20.	SOL_Z

The SWAT-CUP package got provision for doing both type of sensitivity analysis such as one-at-a time and global sensitivity analysis. For applying parameter identifiers, the changes made to the parameters should have physical meanings and should reflect the physical factors such as land use, soil, elevation etc, hence the following scheme is suggested (Abbaspour, 2015).

x_<parname>.<ext>_<hydrogrp>_<soltext>_<landuse>_<subbasin>_<slope>

where,

x_ indicates the type of change to be applied to the parameter
v_ means the existing parameter value is to be replaced by the given value
a_ means the given value is added to the existing parameter value
r_ means the existing parameter value is multiplied by (1+ a given value)
<parname> = SWAT parameter name
<ext> = SWAT file extension code for the file containing the parameter
<hydrogrp> = (optional) soil hydrological group i.e., ‘A’, ‘B’, ‘C’, ‘D’
<soltext> = (optional) soil texture
<landuse> = (optional) name of the landuse category
<subbsn> = (optional) sub basin number(s)
<slope> = (optional) slope

Any combination of the above factors can be used to describe a parameter identifier which provides the opportunity for a detailed parameterization of the system. Omitting the optional identifiers such as <hydrogrp>, <soltext>, <landuse>, <subbsn> and <slope> allows global assignment of parameters.

Uncertainty analysis is needed to perform the best estimation and uncertainty identification of hydrologic models. The uncertainty test and analysis was done using SUFI-2 uncertainty analysis techniques. In SUFI-2, uncertainty is defined as difference between observed and simulated variables in SUFI-2, where it is counted by variation between them. In SUFI-2, uncertainty of input parameters is depicted as a uniform distribution, while model uncertainty is quantified at the 95 PPU. A conceptual illustration of uncertainty analysis of the SUFI-2 algorithm is depicted graphically in Fig. 3.7. The figure explains that a single parameter value leads to a single model response which is shown by point in “a”, where as the propagation of the uncertainty in a parameter which is shown by line in “b” leads to 95 PPU (shaded region in “b”). When the uncertainty in parameter increases, the uncertainty in output also increases as represented in “c”. The cumulative distribution of the output variable is obtained through Latin hypercube sampling. Initially, SUFI-2 starts by assuming a large parameter uncertainty within a physically meaningful range, so that the measured data fall within 95 percent prediction uncertainty (95 PPU) and then gradually narrows this uncertainty in steps while monitoring p_factor and r_factor. Parameters are updated in a manner such that the new ranges are always smaller than the previous ranges, and are centred around the best simulation (Abbaspour *et al.,* 2007). The p_factor is the fraction of measured data (plus its error) bracketed by the 95 PPU band and r_factor is the ratio of average thickness of 95 PPU band to the standard deviation of the corresponding measured variable. A p_factor of “1” and r_factor of “0” represents a perfect model simulation considering the uncertainty and exactly corresponds to the measured data.

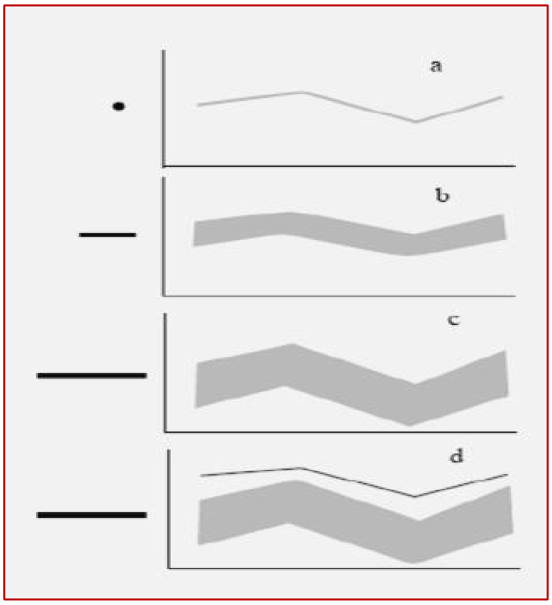


Fig. 3.7 Conceptualization of the relationship between parameter uncertainty and prediction uncertainty

SWAT-CUP provides two types of sensitivity analysis; one-at-a time sensitivity analysis and global sensitivity analysis. Both the analysis has their own advantages and disadvantages.

3.6.1 One-at-a-time sensitivity analysis

One-at-a-time sensitivity analysis should be carried out for only one parameter at a time. This method is very simple to implement and perform, computationally efficient and the sensitivity is clearly attributed to one parameter but the disadvantage of this method is, the sensitivity is only assessed locally. In order to perform one-at-a-time sensitivity analysis, the sensitivity of one parameter is checked at a time by keeping the values of other parameters to be constant with reasonable values.

3.6.2 Global sensitivity analysis

Global sensitivity analysis estimates the combined effect of all inputs on the variation of output based on many model runs. Global sensitivity analysis evaluates the effect in the entire ranges of uncertain parameters but the most challenging issues for global sensitivity analysis is the intensive computation needed.

3.7 CALIBRATION AND VALIDATION

Calibration and Validation are the two important process needed to be carried out for process based hydrological models in order to assess the hydrological behaviour of the watershed.

3.7.1 Calibration of the model

Since there is no gauging station available in the study watershed, calibration was done for the nearby Kunthipuzha basin which has similar characteristics with the study area. Using regionalization technique, the parameters of Kunthipuzha basin were transferred to the study watershed. The model was calibrated using observed daily flow records for a 7 year period from January 2000 to December 2006. The model parameters were adjusted manually by trial and error based on some statistical indicators and characteristics of the area. Nash-Sutcliffe efficiency and coefficient of determination are used to evaluate the hydrological goodness of fit. Calibration was carried out using the average observed daily flow values at Pulamanthole gauging station. Calibration was done for the monthly time series. The linkage between SWAT and SWAT-CUP was shown in Fig. 3.8. The following steps were involved

1. Initially, the calibration program writes model parameters in model in (IN file).
2. SWAT_Edit.exe edits the SWAT input files with new parameter values.
3. The SWAT simulator (swat.exe) is run and
4. Swat_extract.exe program extracts the desired variables from SWAT output files and writes them into model out (OUT file). The procedure continues as required by the calibration program.

The calibration was performed by changing the more sensitive parameters sequentially for obtaining the simulated values of river flow to exactly match with the observed river flow values. SUFI2 program which accounts for all uncertainties and utilizes a combined optimization-uncertainty analysis was used for calibration, validation and uncertainty analysis.

Methodology for calibration in SWAT-CUP using SUFI2 technique:

1. Create a new project and import a swat TxtInOut directory into the project.
2. Select the calibration method to be used for the project. After saving, the program creates a project directory and copies the TxtInOut files from the indicated location into SWAT-CUP directory.
3. Edit the files such as Par_inf.txt, SUFI2_swEdit.def, observation.Rch, extraction and objective function files under calibration inputs.

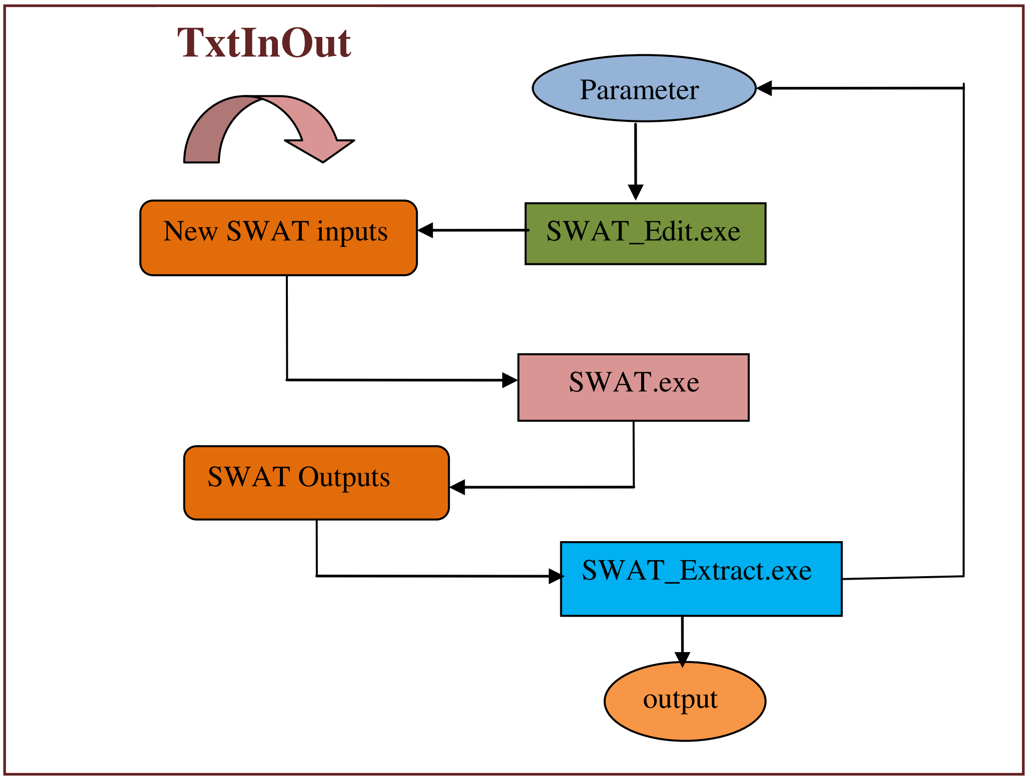


Fig. 3.8 Linkage between SWAT and SWAT-CUP

4. In Par_inf.txt, the number of parameters to be optimized and number of simulations to make in the current iteration should be specified. SUFI2 is iterative i.e., each iteration consists number of simulation, around 500 simulations in each iteration and 4 iterations are sufficient to reach an acceptable solution (Abbaspour, 2015).
5. In SWAT_swEdit.def file, the beginning and ending simulation numbers should be mentioned.
6. In observation.rch file, the observed data that will be used to compare with the output. rch file should be copied and pasted here. Edit the information under this section such as number of observed variables, name of the variable and sub basin number to be included in the objective function and number of observed data points.
7. Under Extraction two files need to be modify such as Var_file_rch.txt and SUFI2_extract_rch.def files. In Var_file_rch.txt, the file names of the observations defined in the “Observed_rch.txt” should be defined. In

SUFI_extract_rch.def, how the variables should be extracted from the output.rch file should be defined.

8. Under objective function, there are two files which are needed to define such as observed.txt and Var_file_name.txt. In observed.txt, the same information as in “Observation_rch.txt” and some additional information for calculating objective function should be defined. In Var_file_name.txt, all the variables that should be included in the objective function should be defined.
9. Once the above steps are completed, by selecting the “Execute all items” under calibrate wheel the simulation process starts and after the completion of process the iteration can be saved under which all the calibration outputs are saved. Iterations should be continued by adjusting the parameters until an acceptable solution is reached. Based on the new parameters obtained from the last iteration (New_par.txt) and by observing the 95 PPU plot, the parameters need to be adjusted can be known. Generally 4 iterations with 500 simulations each will be sufficient to reach acceptable solution. A schematic view of step by step creation of SWAT-SUFI2 input files was shown in Fig. 3.9.

3.7.2 Manual calibration

In SWAT simulation command, the “Manual calibration helper” dialogue box allows the user to adjust the parameters across a user defined group of HRU’S and sub basins during the manual calibration process. Manual calibration was done to obtain more accurate values of parameters and to get best match between simulated values and calibrated values with best NSE and R^2 values. The final parameters obtained from the automatic calibration are used for manual calibration and evaluated using NSE and R^2 factors.

3.7.3 Validation of the model

Validation is the comparison of model results with an independent observed data set which is not used for calibration in order to build the confidence of model accuracy without further changes in parameters. Validation of the model was performed using data for 3 year period from 2007-2009. In order to perform the validation in SUFI2, the files as observation.rch, extraction should be edited to reflect the validation period. Once all the changes are made, simply by using the calibrated parameters and making one iteration of 500 simulations will give validation results.

3.8 EVALUATION OF MODEL PERFORMANCE

The efficiency criteria used to evaluate the hydrologic model in this study are Nash-Sutcliffe efficiency and coefficient of determination.

3.8.1 Nash-Sutcliffe Efficiency (NSE)

It was proposed by Nash and Sutcliffe (1970) and was defined as one minus the sum of the absolute squared differences between the simulated and observed values normalized by the variance of the observed values during the period under investigation. The equation for NSE was as follows:

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(y_o - y_s)^2}{\sum_{i=1}^{n}(y_o - \overline{y}_o)^2}$$

Where,

y_o is the observed value,
y_s is the simulated value,
$\overline{y}_o$ is the mean of the observed values.

The range of NSE lies between 1 and -α where 1 indicates the perfect fitting.

3.8.2 Coefficient of determination

According to Bravais Pearson, it is defined as the squared value of the coefficient of correlation. Coefficient of determination used to analyze how differences in one variable can be explained by a difference in a second variable.

$$r^2 = \left\{\frac{\sum_{i=1}^{n}(y_o-\overline{y}_o)(y_s-\overline{y}_s)}{\sqrt{\sum_{i=1}^{n}(y_o-\overline{y}_o)^2}\sqrt{\sum_{i=1}^{n}(y_s-\overline{y}_s)^2}}\right\}$$

Where,

$\overline{y}_s$= mean of simulated values

The value of coefficient of determination ranges between 0 and 1, where 0 indicates no correlation and 1 indicates that the dispersion of the prediction is equal to that of observation.

The general performance ratings given by the Moraisi *et al.* (2007) for SWAT model was given in Table 3.2.

Table 3.2 Performance ratings for model evaluation statistics

Performance rating	**RSR**	**NSE**	**PBIAS (%)**	
			Streamflow	**Sediment**
Very good	0.00<RSR<0.50	0.75< NSE<1.0	PBIAS<±10	PBIAS<±15
Good	0.50<RSR<0.60	0.65<NSE<0.75	±10≤PBIAS<±15	±15<PBIAS<±30
Satisfactory	0.60<RSR<0.70	0.50<NSE<0.65	±15≤PBIAS<±25	±30<PBIAS<±55
Unsatisfactory	RSR>0.70	NSE<0.50	PBIAS≥±25	PBIAS>±55

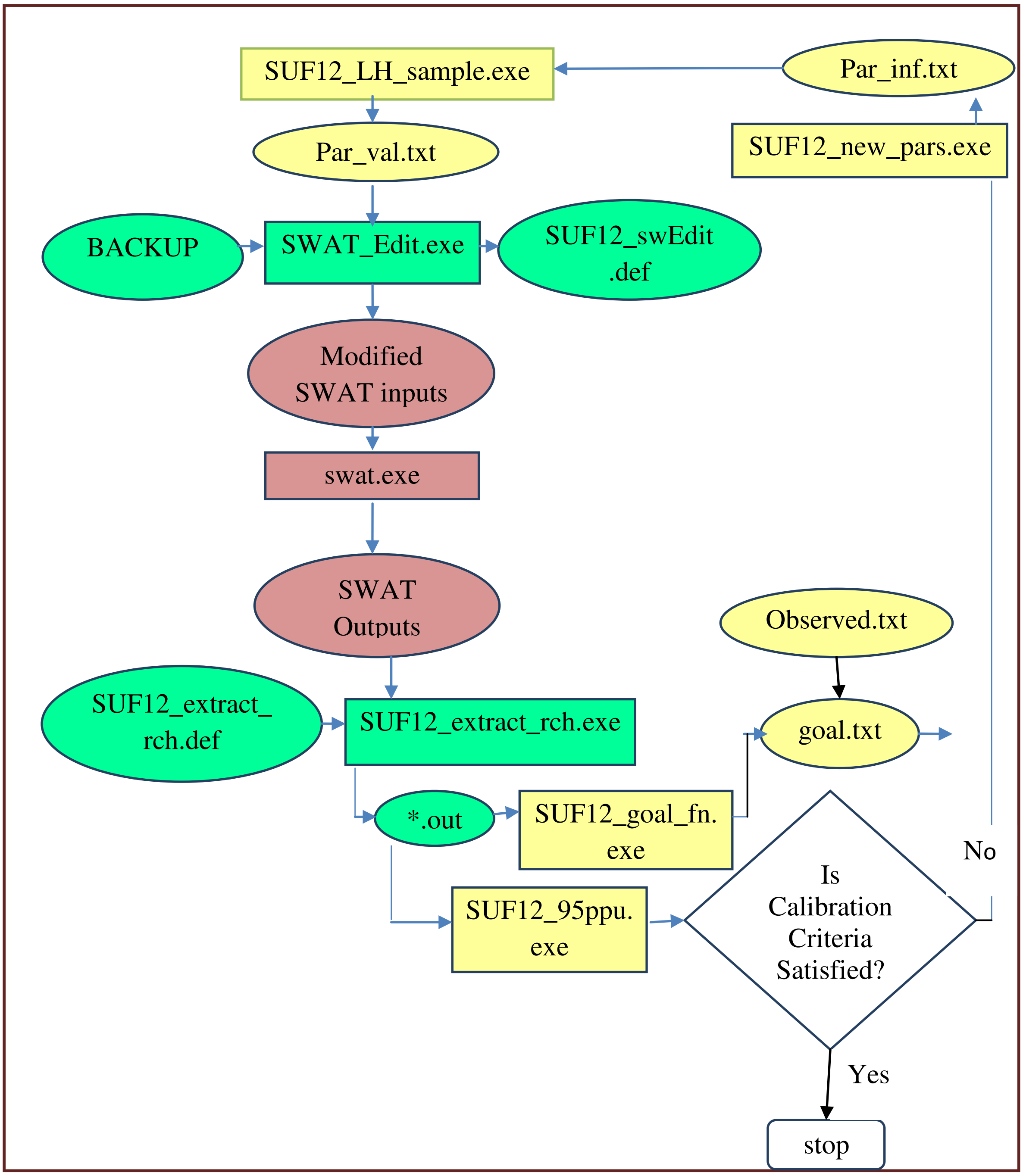


Fig. 3.9 Flow chart for step by step creation of SWAT-SUFI 2 input files

CHAPTER IV

RESULTS AND DISCUSSION

This study was aimed at assessing the hydrologic components of a small watershed using SWAT model to find feasible solution to agricultural drought in the area. SWAT model with regionalized parameters was employed to predict the hydrologic processes elements of the study watershed. The results of the study and their inferences are presented in this study.

4.1 SWAT MODEL SET UP FOR KUNTHIPUZHA BASIN

The spatial data set for running the SWAT model viz. DEM, land use and soil maps are presented in Fig. 4.1 to Fig. 4.3. The elevation of the watershed was varying from 0 to 2330 m. 18.95% of the area was within the elevation band of 0 to 50 m. Land use map shows that major land cover of the area was plaintains (31.53%) followed by rubber trees (19.98%) and forest evergreen (12.37%). Soil map indicates that major geographical representation was for Mannursree series (21.10%) followed by Karinganthodu (19.23%) and Mannamkulam (11.01%).

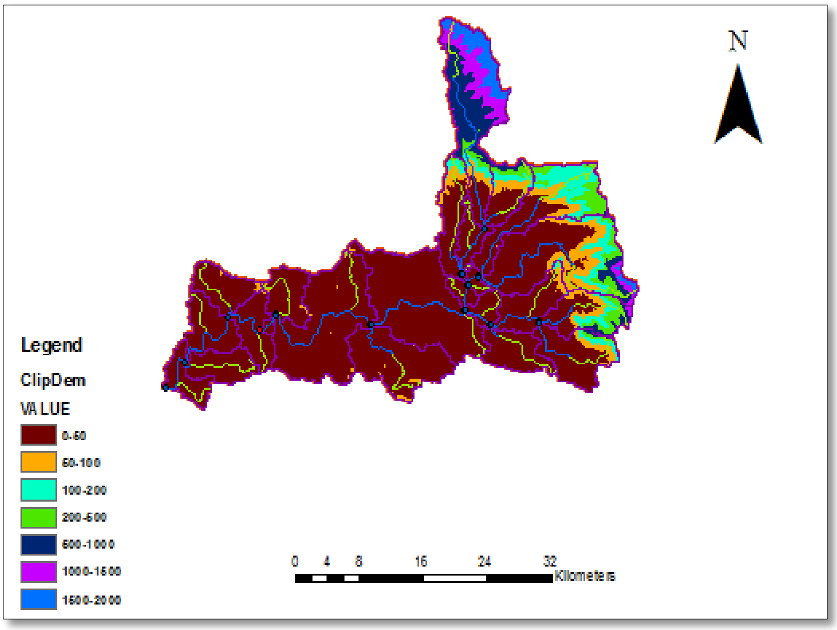


Fig. 4.1 Digital elevation model of Kunthipuzha basin

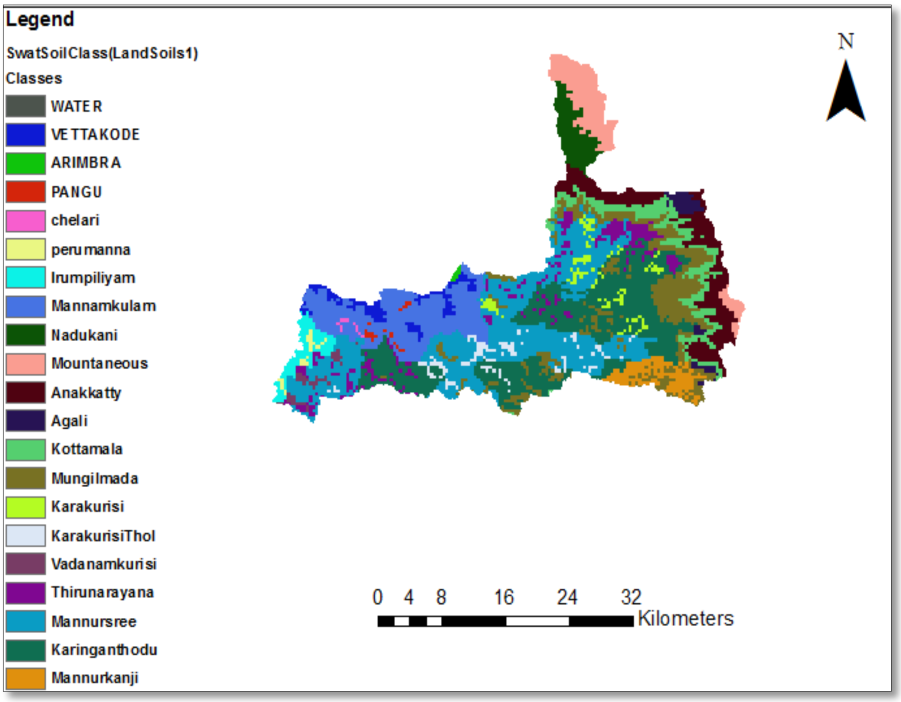


Fig. 4.2 SWAT soil classification for Kunthipuzha river basin

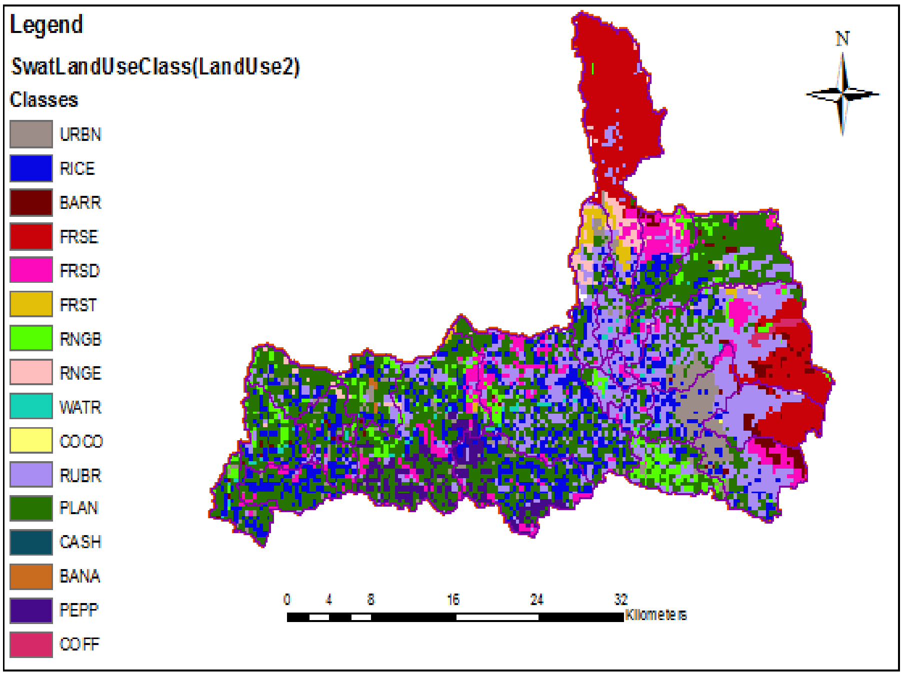


Fig. 4.3 SWAT land use classification for Kunthipuzha river basin

The model was run from 1st January 1997 to 31st December 2011 with a 3 year warm up period with default parameters. The result of the model simulation with the pre calibrated model is shown in Fig. 4.4 as a comparison with the observed annual river flow values. Marked deviation can be seen between the observed and simulated and this reveals the importance of model calibration in order to obtain satisfactory prediction accuracy. The NSE and R^2 values for the simulation were 0.75 and 0.76 respectively.

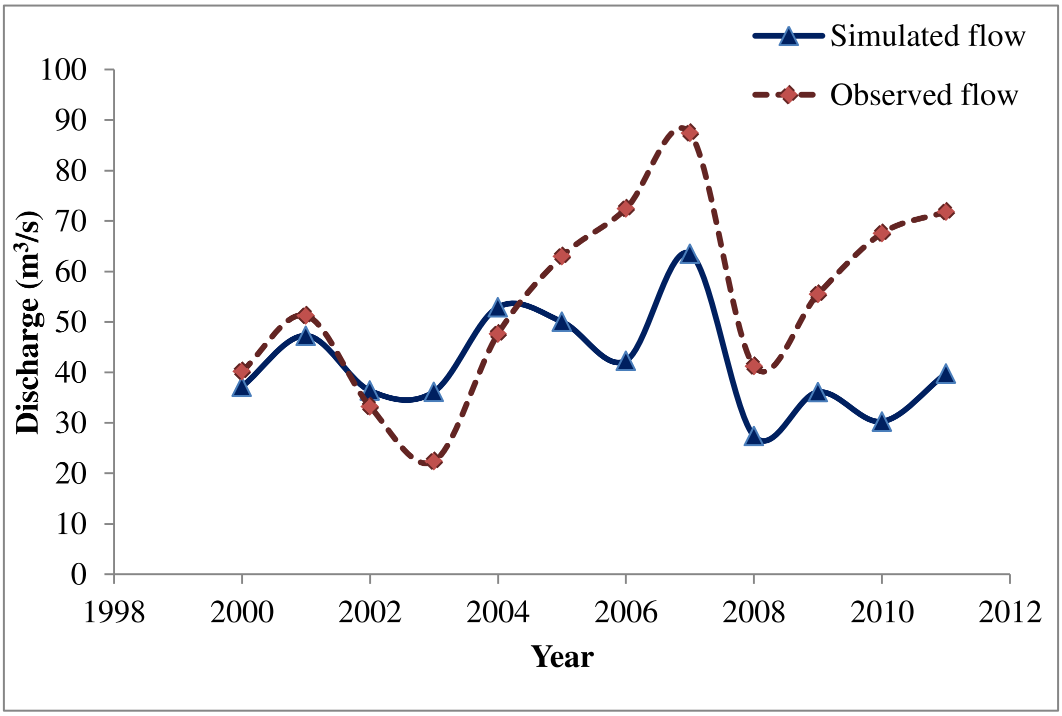


Fig. 4.4 Average annual observed and simulated flow of Kunthipuzha river basin using pre-calibrated model

4.2 SENSITIVITY ANALYSIS, CALIBRATION AND VALIDATION

The results obtained from the sensitivity analysis, calibration and validation using SUFI-2 algorithm in SWAT-CUP package was presented under this section.

4.2.1 Sensitivity analysis

Based on the one-at-a-time sensitivity analysis results and then performing global sensitivity analysis, the limited dominant parameters that affect the output of the model was ranked and used for calibration. The results of sensitivity analysis carried out on the 20 most sensitive parameters as presented in section 3.6 is presented in Table 4.1.

Table 4.1 Identifying sensitive parameters in different analysis

One-at-a-time sensitivity analysis	Global sensitive analysis
CN2	ALPHA_BF
ALPHA_BF	CH_K2
GW_DELAY	CN2
GW_QMN	SOL_Z
ESCO	SURLAG
RCHRG_DP	RCHRG_DP
SOL_Z	ESCO
SLOPE	
SURLAG	
CH_K2	
SOL_K	
SOL_AWC	
SOL_BD	

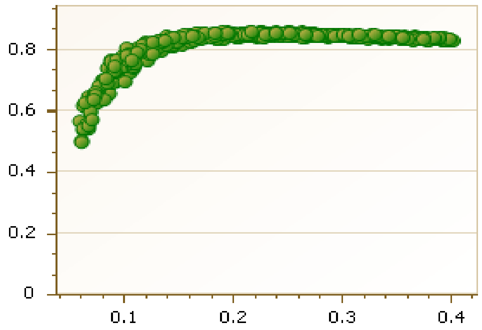
The most sensitive factor is ALPHA_BF followed by CH_K2, CN2, SOIL_Z and SURLAG. Many other studies (Sathian, 2010; Sathian, 2012; Sandra and Sathian, 2016; Varughese, 2016) for the region have also reported similar or comparable results. The most predominant factor of river flow for the Kunthipuzha sub basin is base flow and therefore the appearance of base flow alpha factor as the first ranking sensitive parameter is justifiable. Similarly, the most important surface runoff influencing factor CN2 has come as the third sensitive factor also goes with the logic. High channel hydraulic conductivity suggest that drainage channels can assist both ground water discharge and recharge depending upon the relative elevation between the water table and channel bottom. The most sensitive parameters used for calibration and their ranking for Kunthipuzha basin was shown in Table 4.2.

Table 4.2 Sensitive parameters and their ranking for Kunthipuzha basin

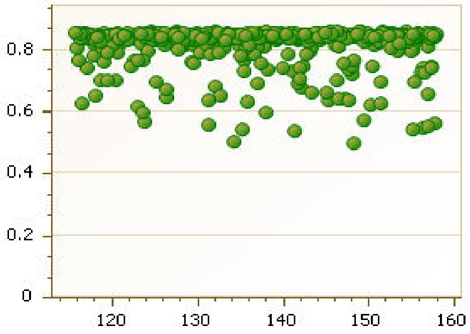
Sensitivity rank	Parameter	Description	t-value	p-value
1	ALPHA_BF.gw	Base flow alpha factor	16.64	0.00
2	CH_K2.rte	Effective hydraulic conductivity of main channel	-2.03	0.04
3	CN2.mgt	Curve number	1.94	0.05
4	SOL_Z.sol	Depth from soil surface to bottom of layer	1.70	0.08
5	SURLAG.bsn	Surface lag coefficient	-1.48	0.13
6	RCHRG_DP.gw	Deep aquifer percolation fraction	-1.01	0.31
7	ESCO.hru	Soil evaporation compensation factor	0.93	0.34

4.2.1.1 Dotted plots

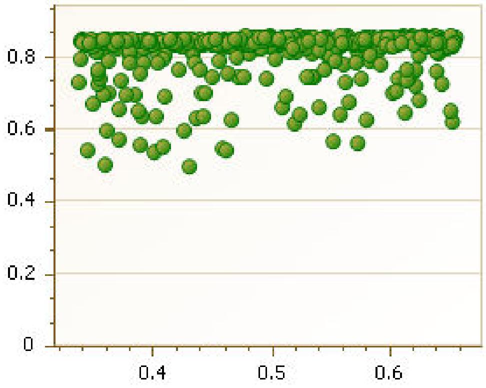
Dot plots are the plots of parameter values or relative changes versus objective function which shows the distribution of sampling points as well parameter sensitivity. Dot plots for the seven sensitive parameters are shown in Fig. 4.5. The dotted plots also indicate that the most sensitive parameter is ALPHA_BF.



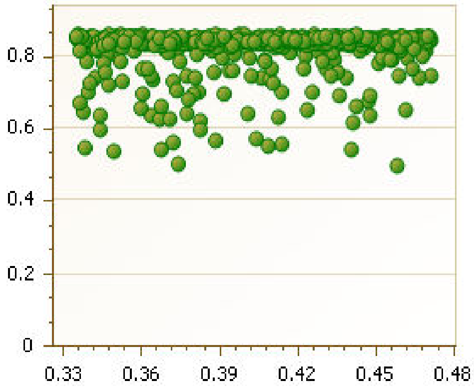
1: V_ALPHA_BF.gw



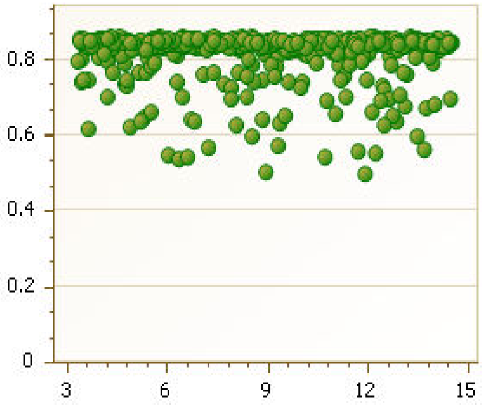
2: V_CH_K2.rte



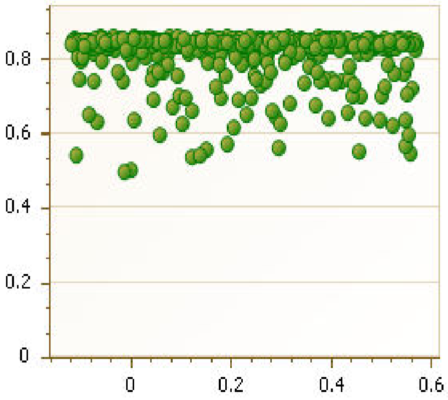
3: R_CN2.mgt



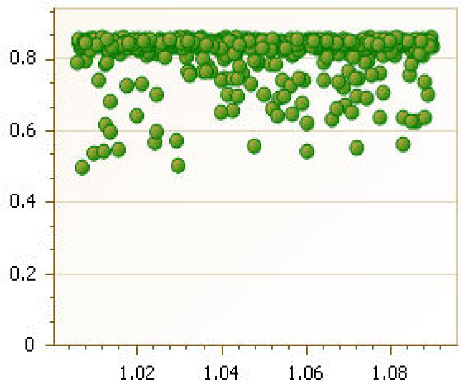
4: R_SOL_Z.sol



5: V_SURLAG.bsn



6: RCHRGE_DP.gw



7: V_ESCO.hru

Fig. 4.5 Dotted plots of sensitive parameters

4.2.2 Calibration of the model

Calibration is necessary for tuning the parameters of the model and for the successful use of any hydrologic simulation in future. Sequential Uncertainty Fitting program (SUFI-2) which is linked to SWAT model was used for the calibration and uncertainty analysis. Out of 15 years of data, keeping 3 years as warm up period, initial 7 years of data was used for calibration and the last 3 years for validation. Calibration was done from 1st January 2000 to 31st December 2006. Sensitive parameters with their default and fitted range of values after calibration were shown in Table 4.3. Initially, the SWAT model assigns "0" as default value for CH_K2 which means that there is no loss of water expected from the stream bed but in case of humid and semi-arid tropics there can be loss of water from the stream bed. Based on the sensitivity analysis, CH_K2 has emerged as the second most sensitive parameter and hence the value of this parameter was increased based on the suggested value ranges.

Table 4.3 Sensitive parameters with their default and fitted range of values

Sensitive parameter	Unit of parameter	Default parameter range	Parameter range after calibration
v_ALPHA_BF.gw	Fraction	0 to 1	0.04 to 0.38
v_CH_K2.rte	mm/h	5 to 130	25.11 to 76.59
r_CN2.mgt	%	-0.2 to 0.2	-0.18 to -0.01
r_Soil_Z.sol	%	-0.8 to 0.8	-0.35 to 0.73
v_SURLAG.bsn	Day	0.05 to 24	9.39 to 22.59
v_RCHRG_DP.gw	Fraction	0 to 1	0 to 0.07
v_ESCO.hru	Fraction	0 to 1	0.89 to1.0

4.2.3 Evaluation of model performance using statistical measures

In order to evaluate the model performance, comparison of observed and simulated flow using statistical criteria's such as NSE and Coefficient of determination are used.

Table 4.4 Performance indices during calibration and validation periods

Statistical criteria	After calibration	During validation
NSE	0.81	0.73
R^2	0.82	0.88
P-factor	0.69	0.57
R-factor	0.47	0.51

The model evaluation statistics for the calibration and validation period was shown in Table 4.4 and the results showed good performance of model prediction over the entire catchment. Before calibration, the values of NSE, R^2

were 0.75 and 0.76 which shows the moderate predictive ability of the model even without calibration.

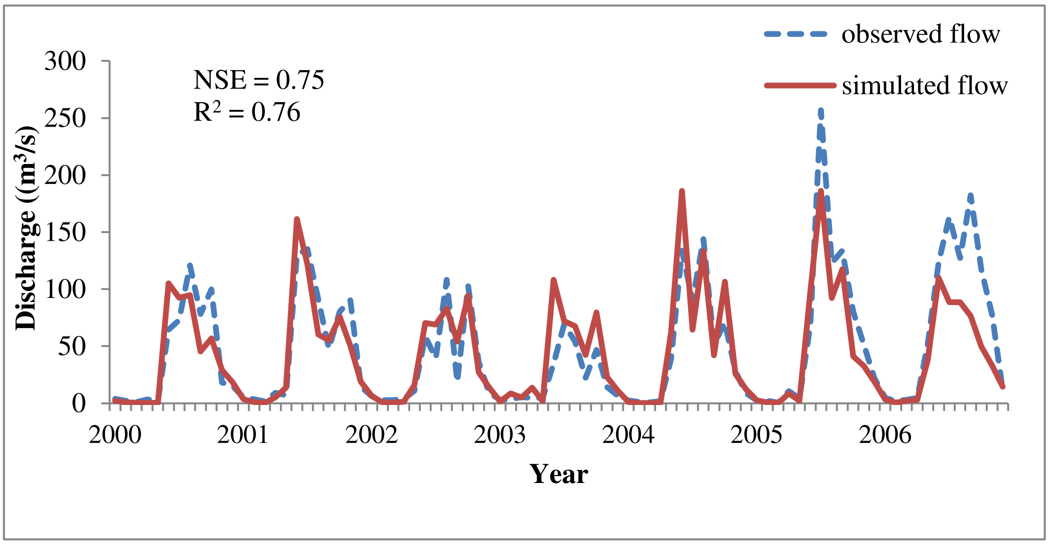


Fig. 4.6 Observed and simulated monthly stream flows at Pulamanthole before calibration

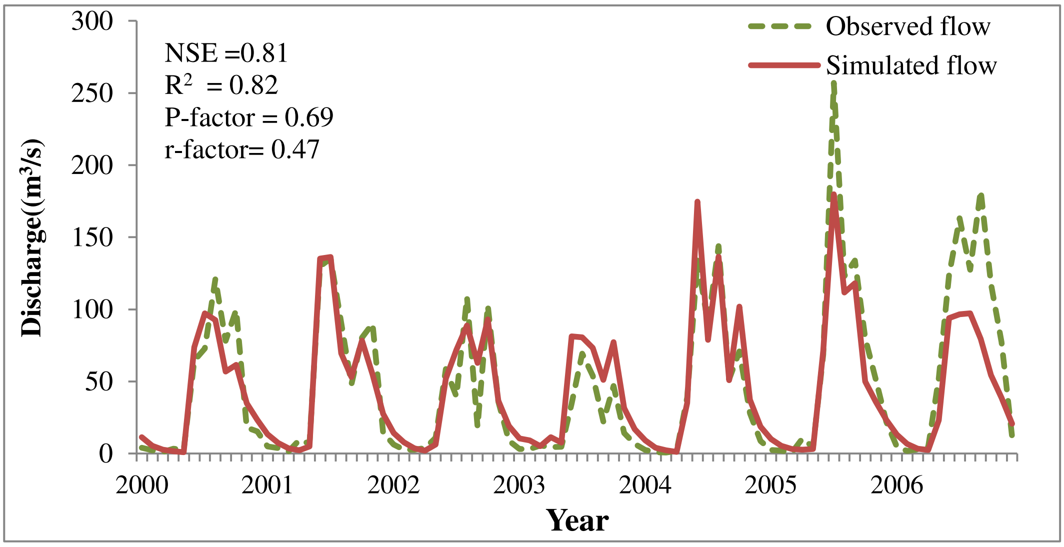


Fig. 4.7 Observed and simulated monthly stream flows at Pulamanthole after calibration

After the calibration, the values of NSE and R^2 were 0.80 and 0.81 which shows further improvement in the model prediction. From the Fig. 4.6 and Fig.4.7, it was clear that after calibration, the variation between simulated and observed peak reduced. However, even after calibration, some of the peak flows were under simulated by the SWAT. Varughese (2016) explained these discrepancies may be due to inaccurate meteorological data obtained, errors in input data sets such as land use and soil maps and also errors during data preparation and processing. These uncertainties in model can also be accounted for great variations in topography and rainfall both spatially and temporally. Qui *et al.* (2012) reported these discrepancies of SWAT model in estimating peak flows may be due to dependency model entirely on an empirical method known as SCS curve number method for calculating runoff which does not consider duration and intensity of precipitation. A similar pattern of under estimation of peak flows by the SWAT model was observed in the study conducted by Pereira *et al.* (2016).

4.2.4 Validation of the model

Model validation was performed with an independent data set starting from 1st January 2007 to 31st December 2009.

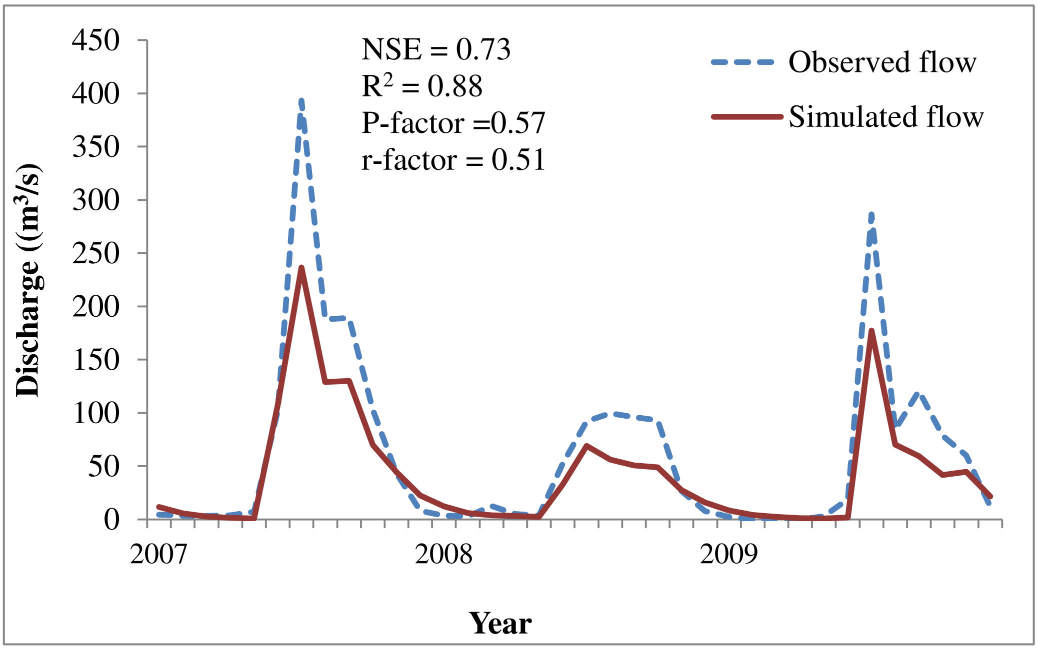
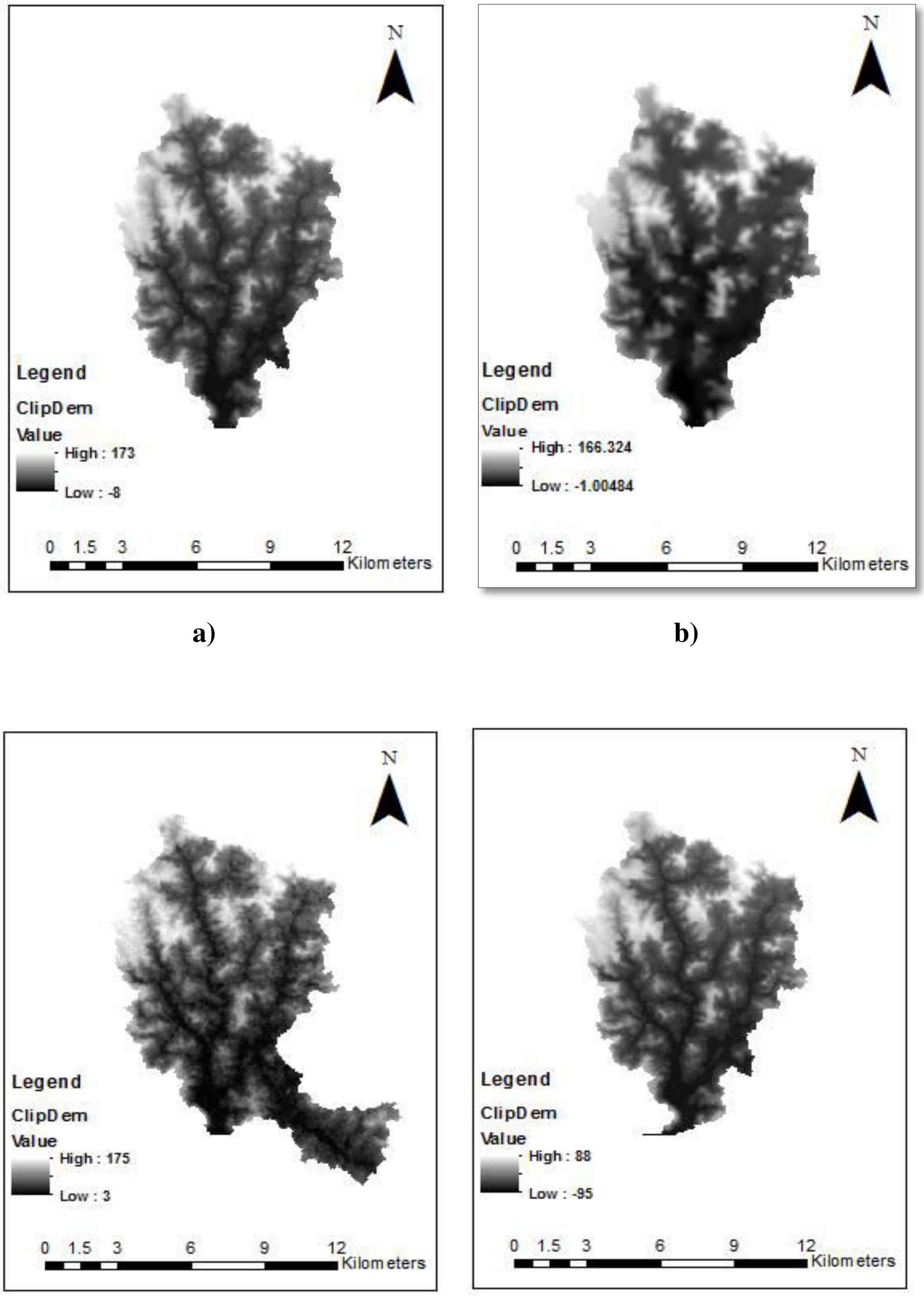


Fig. 4.8 Observed and simulated stream flows at Pulamanthole during validation period

The values of model evaluation statistics such as NSE and R^2 during validation period were 0.73 and 0.88 respectively and it indicates that the calibrated model is good for prediction during the period which is outside the purview of calibration. With these calibrated parameters, SWAT model was run for the study area and the results were shown in the following sections.

4.3 SELECTION OF DIGITAL ELEVATION MODEL FOR THE STUDY

An attempt has also been included in this study to identify the best source of DEM to be used in the SWAT model. For this, a DEM was prepared from the topographic data from the toposheet prepared by Survey of India. Three readily available DEMs viz. SRTM and ASTER of USGS and Bhuvan DEM of ISRO were taken for comparison. For each of the DEM, delineation was done with and without burning with stream network. Watersheds delineated by the SWAT corresponding to different DEM inputs by burning with the stream network are shown in the Fig. 4.9. Area of the watershed delineated by different DEMs under the two conditions of with and without burning with the streams is shown in Table 4.5. It is observed that there is no considerable difference in the delineation of the watershed with and without the burning of drainage lines. However, between the DEMs, ASTER showed different pattern of delineation, and all other DEMs behaved in similar lines. The percentage variation of area delineated by SRTM, Bhuvan, ASTER with respect to toposheet DEM was 1.50%, 1.86% and 20.09% respectively. The performance of the SRTM DEM was more close to that of toposheet DEM. Hence, it can be concluded that SRTM DEM is more reliable dataset for hydrological analysis. Contour interpolated toposheet based DEM was used for this study since it is prepared by direct ground survey and can have more accuracy when compared to others.



a) b)

c) d)

Fig. 4.9 a) SRTM DEM b) TOPO DEM c) ASTER DEM d) BHUVAN DEM

Table 4.5 Topographical details of watershed using different sources of DEM

DEM	Minimum elevation (m)	Maximum elevation (m)	Mean elevation (m)	S.D (m)	No. of sub basins	Area (Ha)
Aster with drainage map	3	175	54.21	34.80	17	9512.44
Aster without drainage map	3	171	53.75	34.29	15	9463.02
Bhuvan with drainage map	-95	88	-31.98	36.35	13	8068.18
Bhuvan without drainage map	-95	74	-33.01	35.31	9	7971.03
SRTM with drainage map	-8	173	56.97	36.72	13	8039.63
SRTM without drainage map	-8	164	55.82	35.57	11	7931.55
TOPO DEM with drainage map	-1	166	58.71	36.78	13	7920.40
TOPO DEM without drainage map	-1	166	58.19	36.34	9	7865.49

4.4 SWAT MODEL SET UP

SWAT model set up was done in mainly four steps such as watershed delineation, HRU analysis, writing SWAT input tables and editing SWAT inputs. The details of the outputs obtained in different steps were also shown.

4.4.1 Watershed delineation

A Contour interpolated DEM which was prepared in ArcGIS 10.2.2 and converted to WGS_1984 UTM_ZONE_43N was given to the model for watershed delineation. Using “burn in” option available in SWAT model, drainage network map was superimposed on to the DEM in order to obtain more accurate generation of stream network by the model and for proper sub watershed delineation. After assigning a threshold area of 290 ha and by selecting the watershed outlet as the stream section close to the main river Bharathapuzha, the entire basin was divided into 13 sub basins. The first part in the model set up was completed and shown in Fig. 4.11. The elevation of the whole watershed ranges from 1 m to 166 m with mean elevation of 58.7 m and standard deviation of 36.78 m.

Table 4.6 Topographical details of the sub watersheds generated by SWAT

Sub watershed No.	Minimum elevation (m)	Maximum elevation (m)	Mean elevation (m)	S.D of elevation (m)	Area (Ha)
1	34	150	84.87	30.04	561.44
2	34	158	78.78	32.86	569.30
3	14	166	93.86	39.44	314.90
4	16	164	93.96	33.71	531.56
5	11	149	63.73	35.18	1206.19
6	10	150	53.24	30.15	653.34
7	11	120	54.02	26.71	326.11
8	12	120	47.18	27.79	400.07
9	9	63	25.2	13.75	57.90
10	8	109	32.87	24.16	441.16
11	1	114	29.93	25.77	416.88
12	3	162	49.51	32.23	2203.20
13	2	106	30.64	28.32	238.32

Topographic details such as minimum elevation, maximum elevation, mean elevation, standard deviation and area of the 13 sub watersheds delineated within the basin was shown in Table 4.6. The mean elevation of the 13 sub watersheds ranges from 25.2 to 93.96 m. A hypsometric curve of the whole watershed is presented in Fig. 4.10.

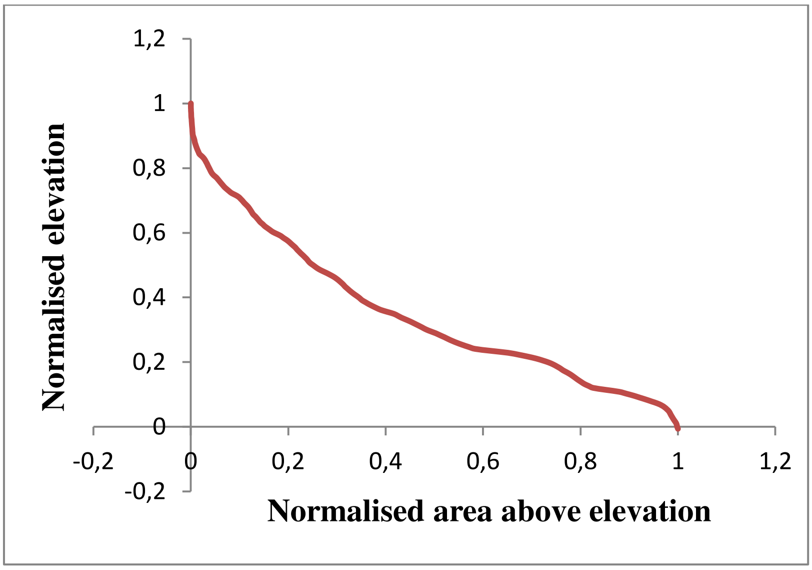


Fig. 4.10 Hypsometric curve for the watershed

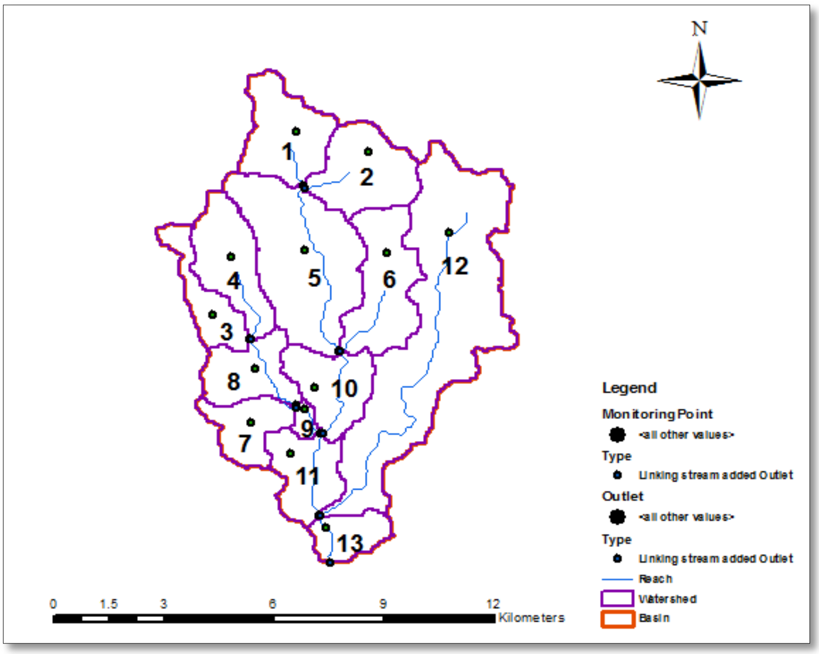


Fig. 4.11 Watershed delineation by the SWAT model

4.4.2 HRU analysis

4.4.2.1 Land/soils/slope definition

In this step, the land use, soil maps are loaded in to the model and reclassified with SWAT land cover classes and soil classes by using look up tables. Three slope classes were selected for slope definition. After all the layers are reclassified, they are overlaid. The swat land use and soil classification was shown in Fig. 4.12 and Fig. 4.13. Major land use types present in the watershed are rice, plantation crops, barren area, forest and urban settlement. The area coverage of different land use types and soil series were shown in Tables 4.7, 4.8 and 4.9.

Table 4.7 Land use of Valanchery watershed

Classes	Area (Ha)	Percentage of Watershed Area
Residential	221.89	2.80
Rice	2058.83	25.90
Forest-Evergreen	9.53	0.12
Range-Brush	682.46	8.62
Range-Grasses	398.80	5.04
Barren	33.55	0.42
Water	2.28	0.03
Rubber plantation	630.99	7.97
Plantains	3882.04	49.01

Table 4.8 Soil classification of Valanchery watershed

Series	Area (Ha)	Percentage of Watershed Area
Irumpiliyam	5555.03	70.14
Perumanna	1177.34	14.86
Vettakode	1183.44	14.94
Water	4.57	0.06

Table 4.9 Slope classification of Valanchery watershed

Slope class	Area (Ha)	Percentage of Watershed Area
0 -5	2956.71	37.33
5- 10	1648.20	20.81
> 10	3315.48	41.86

4.4.2.2 HRU definition

Classification of the basin into land use/soil/slope combinations known as HRU's were created in this step, which are very useful in quantifying the spatially varying ET and other hydrologic conditions for different land covers and soils. In this section, the multiple HRU option was selected and threshold values of 20%, 25% and 20% was given for the land use, soils and slope respectively. This eliminates the percentage of land use, soil and slope which are less than the threshold values and the area of the remaining land uses is reapportioned so that 100% of the land use, soil and slope in the sub basin is modeled. In this way, a total of 67 HRU's were defined within the basin.

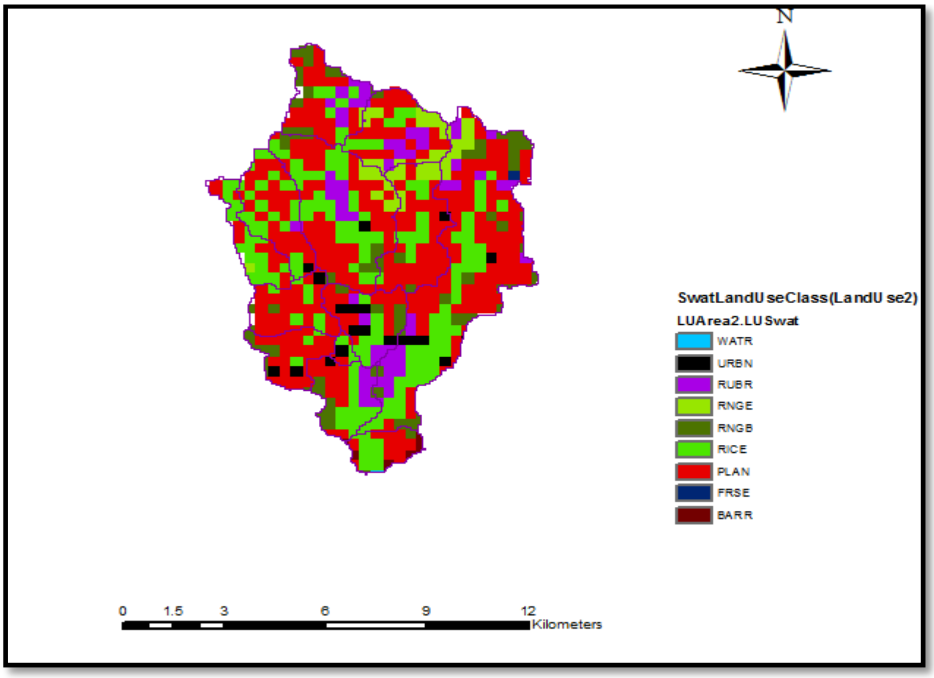


Fig. 4.12 SWAT Land use classification for Valanchery watershed

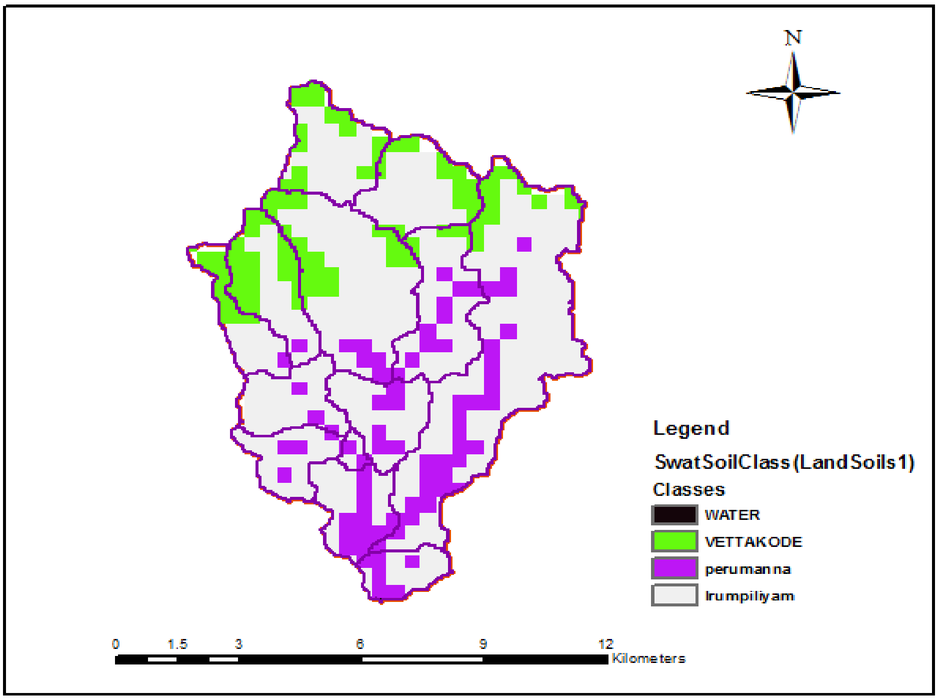


Fig. 4.13 SWAT Soil classification for Valanchery watershed

4.4.3 Writing input tables

In this section, all the weather data was imported in to the model using weather data definition option. After importing, the model sets the values automatically based on the watershed delineation and land use\soil\slope characterization or from defaults. At this point, the model becomes ready for simulation.

4.4.4 SWAT simulation

SWAT simulation was done from 1st January 1997 to 31st December 2011 with a warm up period of 3 years. The files that are needed to be imported to database was selected and imported and finally the simulation was saved.

4.5 ANALYSIS OF THE SWAT SIMULATION

The mean monthly discharge of the watershed as simulated by the SWAT model was shown in Fig. 4.14. Discharge maximum in July followed by August and September. Discharges during the six months from June to Nov are reasonably high, but during the summer months, it assumes very low values. Hence, storing the water during monsoon months by constructing water harvesting structures within the stream channel can make the stream more live during the summer months. It is also possible to mitigate the agricultural drought and drinking water scarcity and maintaining environmental flow in this watershed.

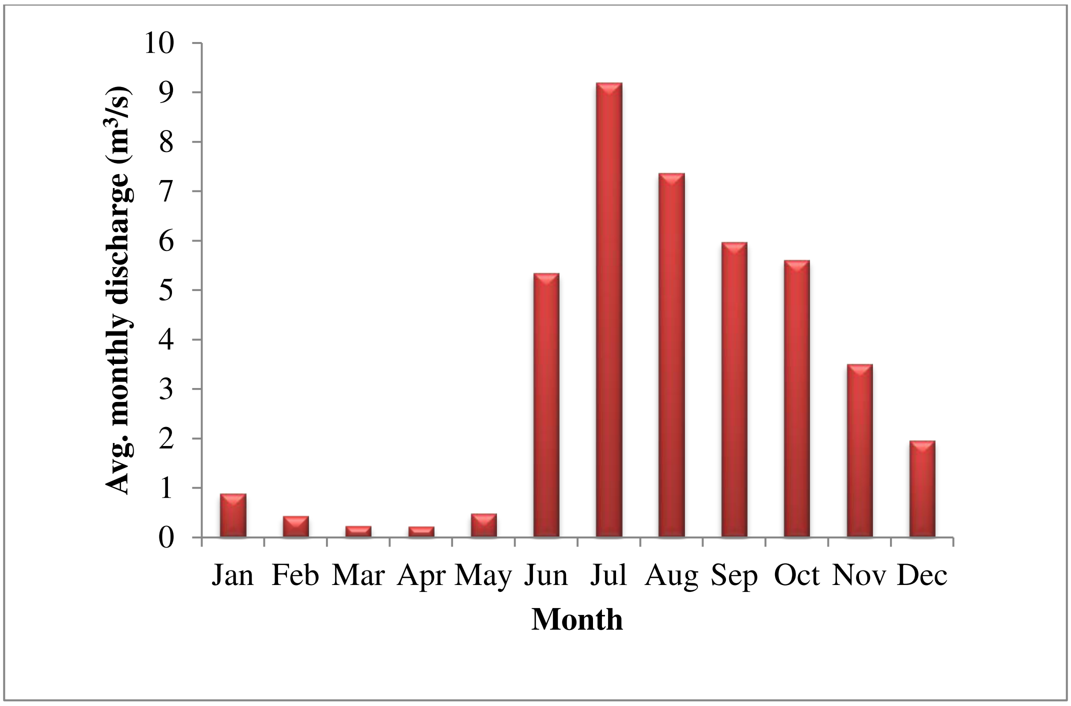


Fig. 4.14 Average monthly discharge at watershed outlet

The average monthly yield components of the whole watershed were presented in Fig. 4.15. Surface runoff is the major component of stream flow followed by ground water. In some of the sub watersheds, ground water is found to be the major component. More water harvesting measures have to be adopted in areas having high surface runoff generation. Low presence of lateral flow indicates that major portion of the infiltrated water results in deep percolation.

The average annual discharge at different reaches was presented in Fig. 4.16. Discharge at different reaches decreases proportionately as the watershed area corresponding to the reaches decreases. The annual discharge at reach 13 was maximum (3.5 m^3/s) followed by reach 11(2.5 m^3/s). The annual discharge at reach 1 is the lowest on account of its smallest catchment area. Check dams are possible for all the reaches except for reach number 1. Hence, the reaches 5,10,11 and 13 can have check dams with appropriate storage capacity so that the water can be stored in the periods of monsoon season and can facilitate water supply in the dry periods to solve domestic and agricultural water scarcity**.**

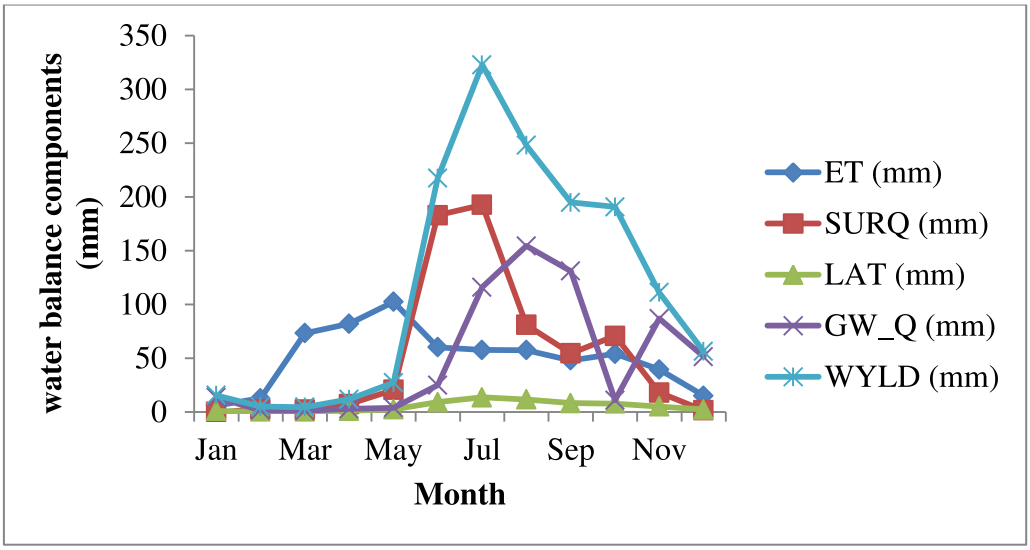


Fig. 4.15 Average monthly water balance components for the whole watershed

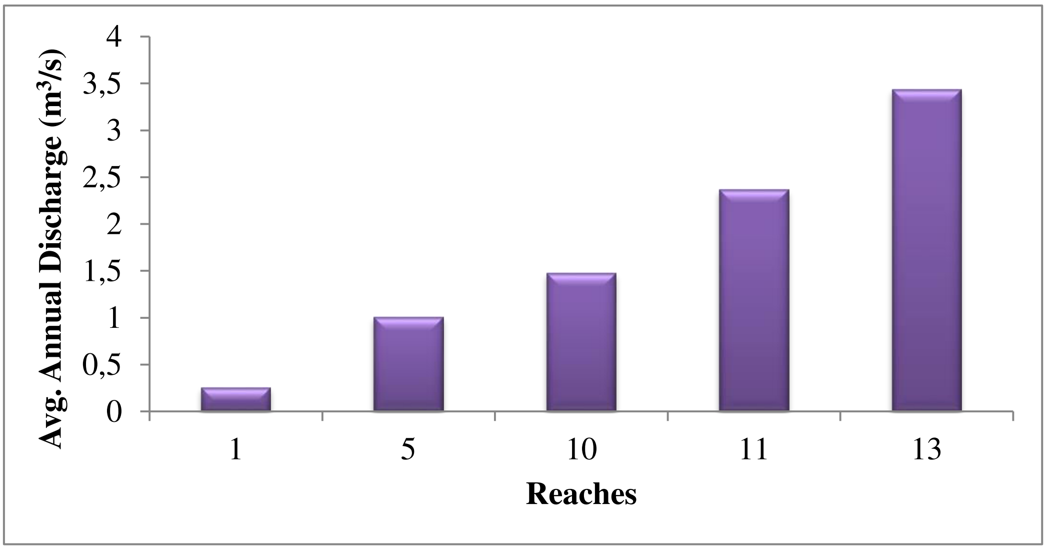


Fig. 4.16 Average annual discharge at different reaches in the main channel

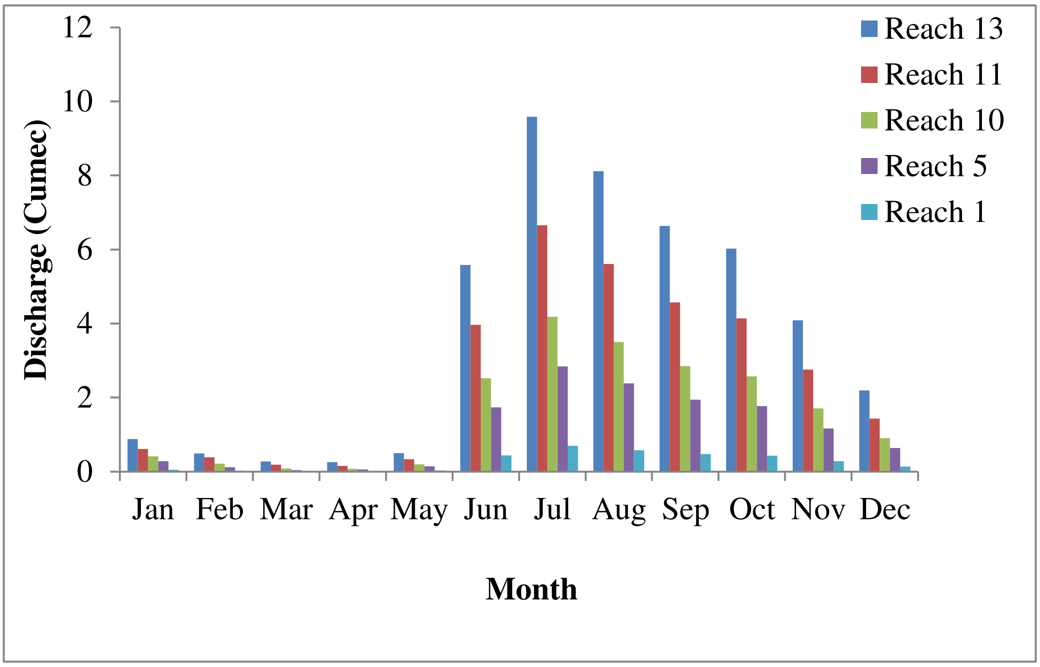


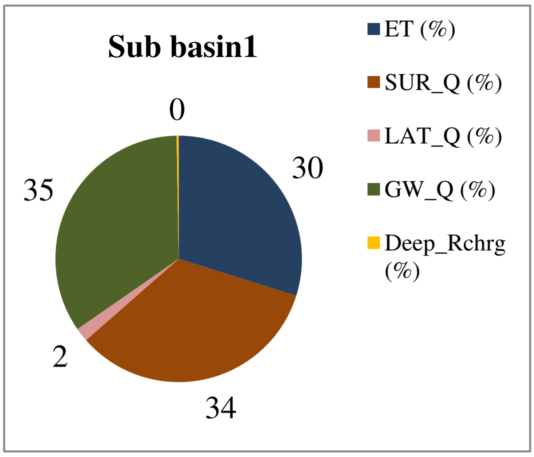
Fig. 4.17 Average monthly discharge at different reaches in the main channel

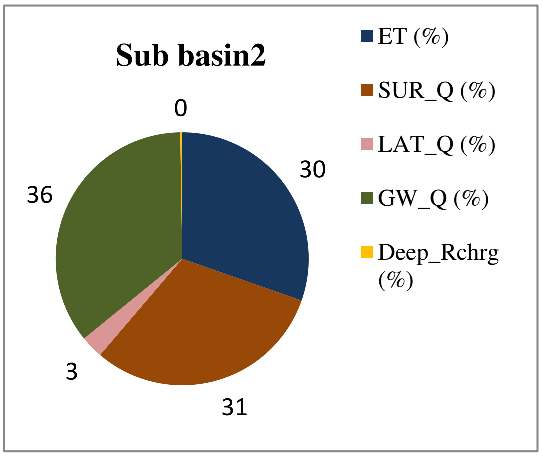
Monthly discharges of the five reaches considered on the main channel were analyzed and presented in Fig. 4.17. From the above graphs, it is clear that the maximum discharge was found in the months of July followed by August, September and October. The pattern of monthly discharges also points to the need of water conservation structures in the main channel during monsoon months.

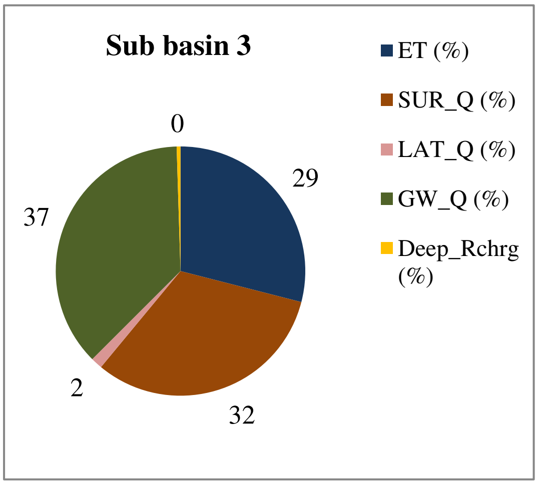
The water balance components of different sub basins are shown in Table 4.10. There are variations in the water balance components between sub basins. Most of the cases the variations lie within plus or minus 15%. Among the major three components of water yield, the lateral flow is very less. The water balance components as a percentage of annual rainfall are given in Fig. 4.18. In almost all cases, maximum water yield is from base flow followed by surface runoff. Lateral flow component is only about 2%. Deep aquifer recharge shows very less percentage ranges between 0-4%.

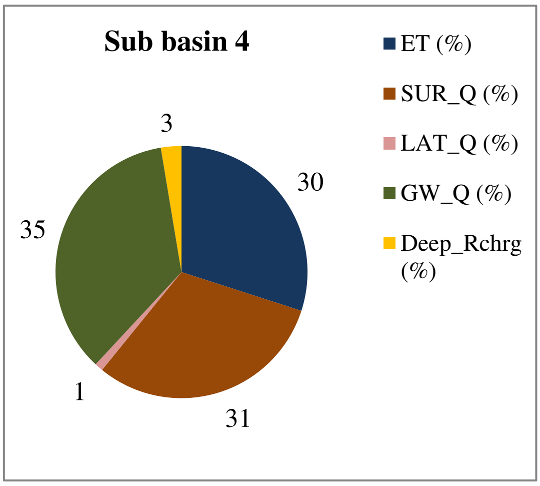
Table 4.10 Water balance components in different sub basins

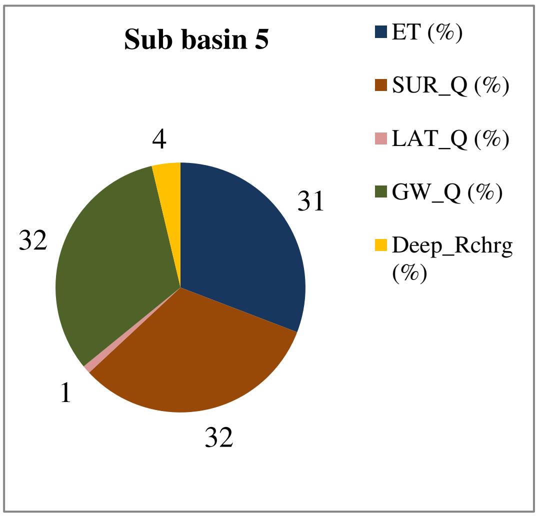
SUB BASIN	ET (mm)	SUR (Q) (mm)	LAT (mm)	GW_Q (mm)	WYLD (mm)
1	652	710	38	700	1480
2	651	663	62	764	1496
3	554	631	29	640	1390
4	613	632	22	725	1387
5	642	671	22	669	1370
6	662	692	32	620	1351
7	659	692	31	621	1351
8	633	695	22	627	1350
9	598	717	20	669	1413
10	637	669	30	669	1375
11	594	623	13	773	1418
12	620	663	17	695	1352
13	609	635	64	696	1403

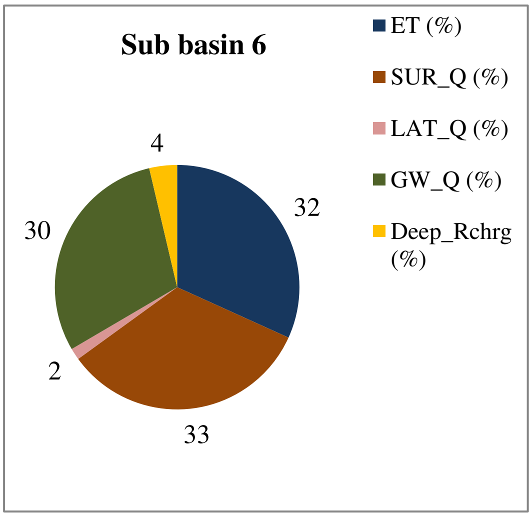

Sub basin1
0
30
35
2
34
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)

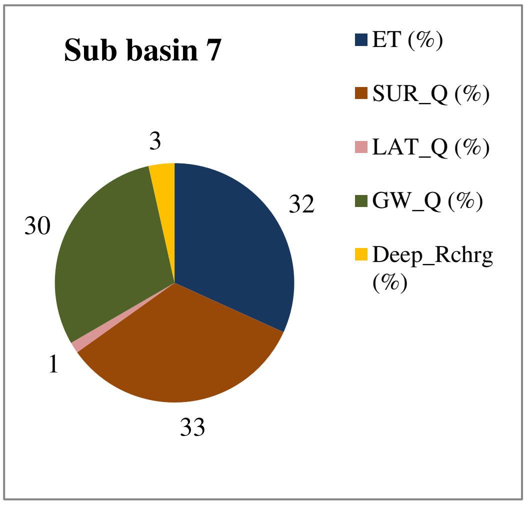

Sub basin2
0
30
36
3
31
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)

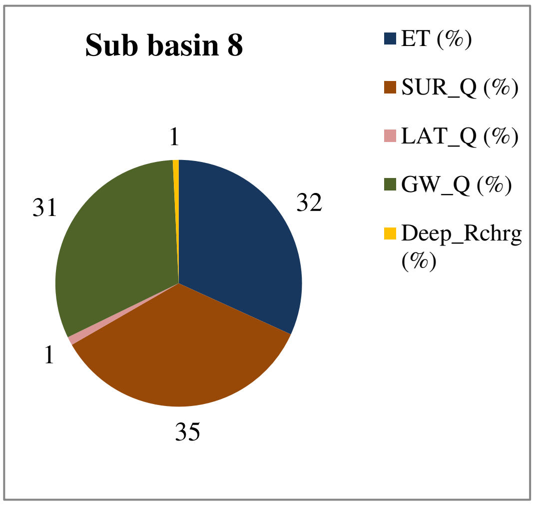

Sub basin 3
0
29
37
2
32
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)

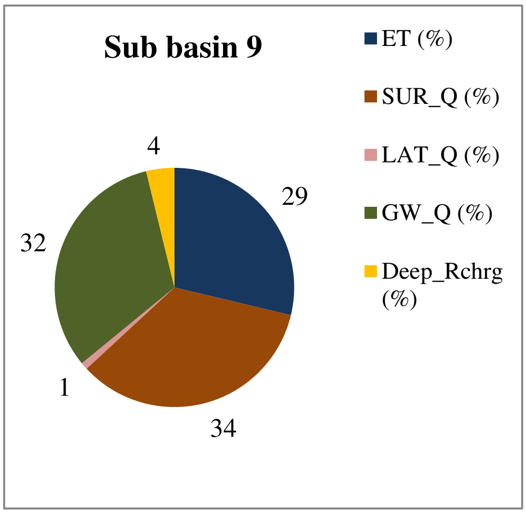

Sub basin 4
3
30
35
1
31
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)

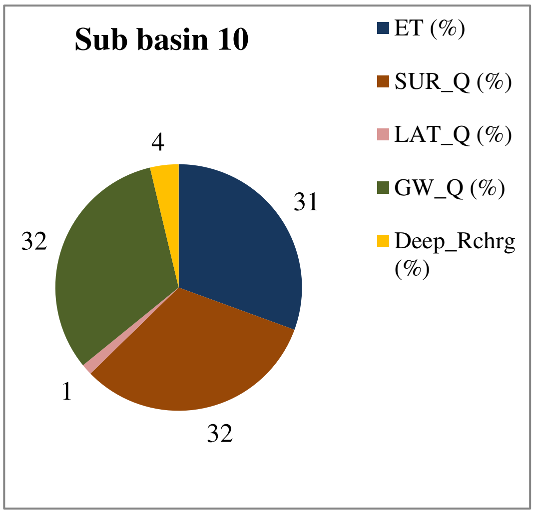

Sub basin 5
4
31
32
1
32
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)

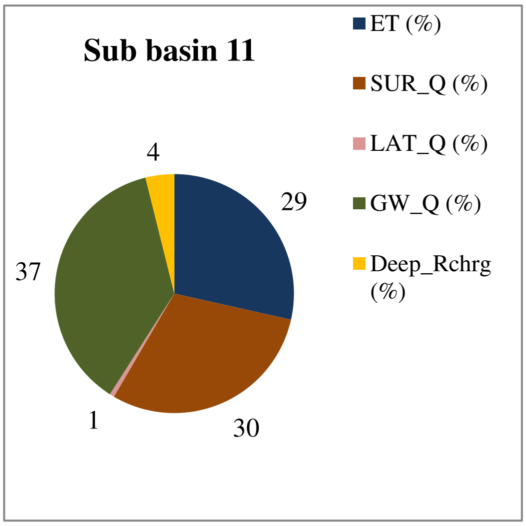

Sub basin 6
4
32
30
2
33
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)

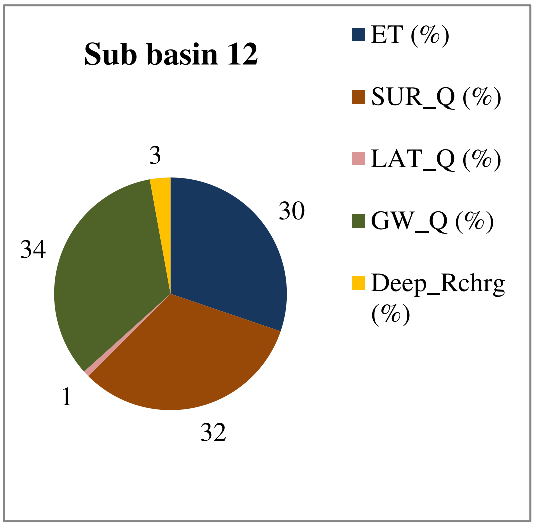

Sub basin 7
3
32
30
1
33
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)


Sub basin 8
1
31
32
1
35
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)


Sub basin 9
4
29
32
1
34
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)


Sub basin 10
4
31
32
1
32
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)


Sub basin 11
4
29
37
1
30
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)


Sub basin 12
3
30
34
1
32
■ ET (%)
■ SUR_Q (%)
■ LAT_Q (%)
■ GW_Q (%)
■ Deep_Rchrg (%)

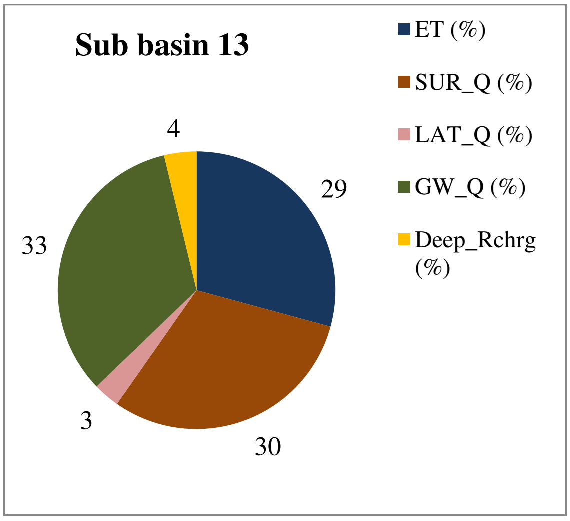


Fig. 4.18 Water balance components (%) at different sub basins

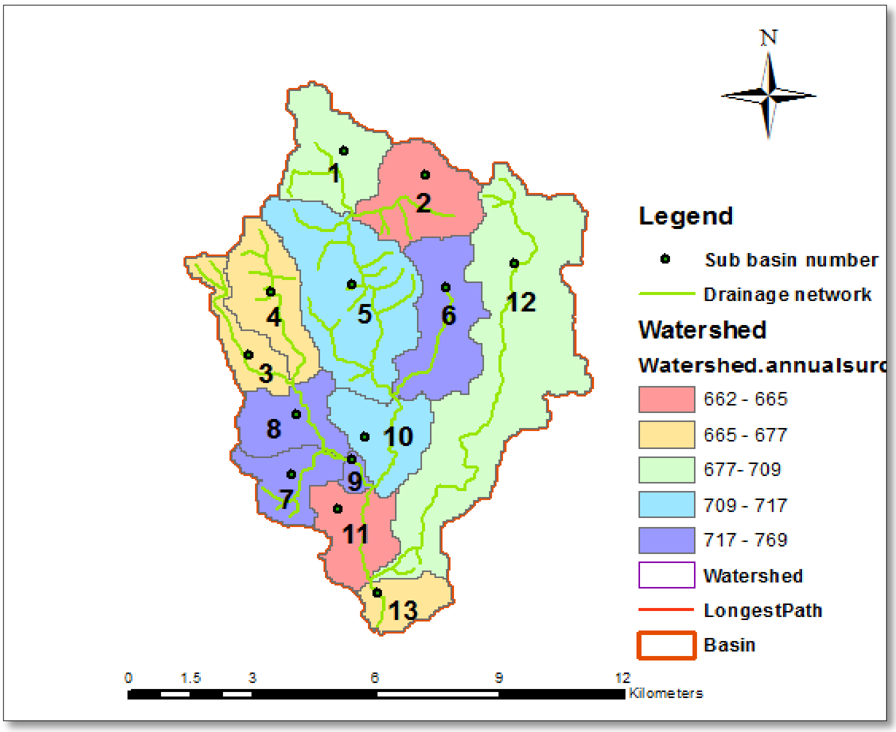


Fig.4.19 Average annual surface runoff (mm) in different sub basins

4.6 REMEDIAL MEASURES TO COMBAT AGRICULTURAL DROUGHT

Using the calibrated SWAT model, by the regionalization technique, water balance of the Valanchery watershed and its micro watersheds have been computed. Also, the discharge along the main channel and different spatial and temporal intervals has been computed. Using these results, various water harvesting, conservation and storage measures can be scientifically planned within the watershed as follows.

1. Out of the total rainfall received in the basin, only 30.5% goes out as ET and 69.5% is available as water yield on annual basis. On annual basis, the water yield is sufficient to meet all water requirements of irrigation and domestic requirements. However, due to the temporal variations in water yields, the estimated monthly yields during summer period are not sufficient to meet the agricultural water requirements. Therefore, water conservation measures need to be carried out both in the land areas and in the drainage channels.

2. In order to increase the water yield during summer, the base flow component has to be increased which in turn demands more deep percolation of rain water. This can be achieved, by taking percolation pits of 2 to 3 m deep near all residential and commercial buildings and other impervious catchments. This measure will bring the twin beneficial effect of enhancement of groundwater recharge and reduction of surface runoff and its ill effects of soil erosion.

3. In high altitude places (greater than 75 m), sub watershed numbers 1 to 8, where water table is deep during summer months, direct well recharge measures will be more effective in solving water scarcity.

4. All agricultural areas having slope groups greater than 5% may be treated with contour or graded bunds, contour trenches or terraces to increase the infiltration and thereby to reduce the surface runoff. Many areas of sub watersheds except 9, 11, and 12 may be given these measures.

5. Construction of check dams will be the best interventions to conserve water in the stream channels. The main drainage channels of the watershed are about 10 km long. In the first 2 km of the channel from the ridge of the watershed, gully plugging measures with loose boulder or gabion check dams to slow down the velocity of channel flow may be adopted. Between the reach lengths 2 to 6 km, impervious check dams of height 2 to 4 m height with overflow provision may be constructed at about 200 m intervals. Between reaches of 6 to 10 km, check dams of 3 to 5 m height at an interval of 300 m may be constructed.

6. Proper conveyance systems have to be planned to route the water to agricultural areas from the check dams so that efficient irrigation is possible using the water stored in these check dams.

CHAPTER V

SUMMARY AND CONCLUSION

Judicious conservation of land and water resources is the only practical solution to tide over all kinds of water crisis such as drought, flood or water quality. Quantifying different hydrologic processes at micro watershed level both on temporal and spatial scale is an important prerequisite for scientific and insitu water conservation. Use of physically based distributed watershed models is necessary for complete understanding of hydrologic processes. However, physically based watershed models require calibration using observed data for reliable results. This poses a major hindrance to the application of physically based model to ungauged basins. There are regionalization techniques by which calibrated parameters of a gauged basin can be transferred to an ungauged basin.

Hence, this study has been undertaken to analyze the hydrologic processes of a ungauged basin using the physically based SWAT model from the perspective of solving water scarcity with the given below objectives.

1. To calibrate and validate the watershed model, SWAT for the selected watershed using observed daily river flow.
2. To predict watershed processes at micro watershed scale to quantify the spatial and temporal distribution of water availability within the sub basin.
3. To suggest remedial measures to combat water scarcity in the study area.

Initially, the model has been set up and calibrated for Kunthipuzha, an important sub basin of Bharathapuzha river basin. This sub basin is nearby to the ungauged basin under study. The model was calibrated for a period of 7 years from 2000-2006 and validated for a period of 3 years from 2007-2009. Very good NSE and R^2 values were obtained during both calibration and validation. The most sensitive parameters used in the calibration were ALPHA_BF, CH_K2, CN2, SURLAG, SOL_Z, RCHRG_DP and ESCO. The calibrated values of these sensitive parameters were then transferred to the study watershed viz. Valanchery watershed which encompasses the Valanchery town and its main stream joins laterally with the Bharathapuzha main river.

Using the calibrated model, the hydrologic processes of Valanchery watershed were simulated for the entire watershed and also at micro watershed scale. The average annual discharge at the outlet was 3.44 m^3/s. Annual average discharges at four other outlets considered along the main channel reach were 2.37, 1.48, 1.01 and 0.26 m^3/s respectively. Annual water balance components for the whole watershed were SUR_Q = 706 mm, LAT_Q = 30 mm, ET = 674 mm, GW_Q = 756 mm and Water yield = 1493 mm. Water balance components were also estimated at micro watershed scale and it was found that surface runoff and ground water flow were the major water yield components and lateral flow fraction was very small amounting to just 2% of the annual rainfall. The study revealed that the analysis of the water balance and the river flow at different reaches was very effective in formulating interventions to solve water scarcity scenario with location specificity.

The specific conclusions drawn out of from this study are as follows:

1. The sensitivity and uncertainty analysis can considerably reduce the effort involved in calibration of the physically based SWAT model. Calibrated model showed very good predictive capability as indicated by NSE (0.81) and R^2 (0.82).
2. Most sensitive parameters of the SWAT model as revealed by this study were base flow alpha factor, channel hydraulic conductivity and curve number and this result tallies with previous studies from Kerala.
3. Calibrated model can be used effectively in predicting the hydrologic processes of a watershed and its micro watersheds.
4. The information of sub basin water balance components and discharges at different reaches of the drainage channels can be used very effectively in formulating interventions to mitigate the water scarcity issues at higher spatial resolution.

The following are the suggestions for future research work regarding watershed modeling using SWAT model for ungauged basins.

1. Other techniques may be applied and experiments may be conducted at micro watershed scale to quantify the hydrologic process elements so that reliability of the SWAT model prediction on these items can be assessed.

2. More techniques can be used for calibrating the ungauged basins and a protocol in this regard may be worked out.

3. Hydrologic processes at HRU level may be considered in planning and formulating interventions for water resources management.

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APPENDIX I

Variations in hydrological components using different sources of DEM

DEM	Surface runoff (mm)	Lateral soil Q (mm)	Ground water (mm)		Deep AQ recharge (mm)	Total AQ recharge (mm)	ET (mm)	Total water yield (mm)
			Shallow (aq)	Deep (aq)				
Aster with drainage	708.42	62.25	733.35	7.81	7.82	781.92	655.33	1511.83
Aster without drainage	705.93	63.66	739.15	7.87	7.88	787.78	1516.60	650.55
Bhuvan with draiange	709.11	47.85	727.69	7.75	7.76	776.23	1492.40	674.6
Bhuvan without drainage	709.87	47.11	726.32	7.73	7.75	774.84	1491.40	775.48
SRTM with drainage	705.18	42.23	739.58	7.87	7.88	788.24	1494.85	788.88
SRTM without drainage	704.38	42.91	740.15	7.87	7.89	788.82	1495.32	671.7
TOPO with draiange	706.37	29.27	749.09	7.97	7.98	797.87	1492.69	674.3
TOPO without draiange	713.54	28.15	752.53	8.00	8.01	801.32	1502.22	664.8

APPENDIX II

Average monthly discharge at different reaches in the main channel

Month	Reach 13	Reach11	Reach 10	Reach 5	Reach 1
Jan	0.88	0.61	0.41	0.28	0.05
Feb	0.49	0.39	0.22	0.11	0.02
Mar	0.27	0.19	0.08	0.04	0.01
Apr	0.25	0.16	0.08	0.05	0.01
May	0.50	0.34	0.20	0.14	0.03
Jun	5.58	3.96	2.52	1.73	0.44
Jul	9.59	6.65	4.18	2.84	0.69
Aug	8.12	5.61	3.50	2.39	0.57
Sep	6.64	4.57	2.85	1.95	0.47
Oct	6.02	4.14	2.57	1.77	0.43
Nov	4.09	2.76	1.71	1.17	0.28
Dec	2.19	1.43	0.91	0.64	0.14

APPENDIX III

Average monthly water balance components for the whole watershed

Month	ET (mm)	SURQ (mm)	LAT (mm)	GW_Q (mm)	WYLD (mm)
Jan	6.06	0.12	1.02	13.6	15.61
Feb	12.73	2.52	0.46	1.6	5.1
Mar	73.29	2.35	0.62	1.16	4.56
Apr	82.05	7.35	1.18	2.89	11.92
May	102.48	20.63	2.48	3.96	27.33
Jun	60.25	183.02	9.25	24.92	217.44
Jul	57.7	192.67	13.65	116.1	322.9
Aug	57.63	81.02	11.8	154.4	247.99
Sep	47.97	54.64	8.38	130.99	194.93
Oct	54.2	70.87	7.88	11.04	190.79
Nov	39.59	18.18	5.11	86.92	111.17
Dec	15.17	1.59	2.41	51.44	56.32

HYDROLOGIC ASSESSMENT OF A SMALL WATERSHED TO COMBAT AGRICULTURAL DROUGHT

By

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ABSTRACT OF THESIS

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ABSTRACT

Water is the most indispensable natural resources for the survival of all living beings. On the other hand, water availability is declining and the demand is increasing, making the gap between these two wider day by day.Scientific water management is a must to sustain the domestic and irrigation water needs. Quantifying the elements of hydrologic processes at micro watershed scale and at weekly or monthly temporal scale is the most important prerequisite for water resources development of a locality. For understanding the watershed characteristics and behavior, models play an important role which are also useful for extrapolating the current conditions to potential future conditions. Hydrological modeling is considered as a powerful technique in planning water resources. In this study, the hydrology of Valanchery watershed, a small sub watershed of Bharathapuzha, was modeled using SWAT, a physically based distributed watershed model. The study aims to calibrate the model, simulate the hydrologic elements and stream flow and to suggest remedies to combat the water scarcity in the study area.

Using ArcGIS 10.2.2, the datasets required for the ArcSWAT was prepared. As the watershed selected for the study was ungauged, the model was calibrated for Kunthipuzha basin which lies in the immediate neighbourhood and having similar characteristics with the study area. For this, the model was initially set up and ran for Kunthipuzha basin and using the daily observed stream flow at Pulamanthole gauging station, the model was calibrated and validated. The calibration and validation periods were respectively, 2000 to 2006 and 2007 to 2009. An NSE = 0.81 and R^2 = 0.82 was obtained for calibration, an NSE = 0.73 and R^2 = 0.88 was received for validation. With these calibrated parameters, the model was set up and ran for the Valanchery watershed using regionalization technique. The whole watershed characteristics and behavior and that of sub watersheds and of different reaches of the mainstream were determined and predicted. It was found that the characteristics and hydrologic process elements such as surface runoff, lateral flow, deep percolation, base flow and ET of the

various sub watersheds were varying considerably. Using these vital information, water resources conservation and utilization can be planned scientifically at micro spatial levels to mitigate the water scarcity scenario.