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MODELLING NON-POINT SOURCE POLLUTION: RAINFALL-RUNOFF MODELLING OF DIKRONG BASIN USING AVSWAT

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PREFACE

Non-point source (NPS) pollution is an important environmental and water quality management problem. The excessive use of mineral fertilizers for raising crop yields and meeting the demands of growing population growth in India has resulted in increased nutrient additions in river systems and caused the eutrophication of many freshwater ecosystems. A watershed protection approach is an important strategy to effectively protect a watershed and thereby restore aquatic ecosystems and protect human health. Recent studies on the control of agricultural NPS pollution mainly focus on the simulation models, such as AGNPS (Agricultural Non-point Source Pollution Model), ANSWERS (Areal Non-point Source Watershed Environment Response Simulation), SWAT (Soil and Water Assessment Tool) and BASINS (Better Assessment Science Integrating Point and Non-point Sources), etc.

Watershed modeling can be a valuable tool for studying the relationships between watershed conditions and the quality of water in a watershed. The Soil and Water Assessment Tool (SWAT) has been used in the present study. The SWAT model has proven to be an effective tool for assessing water resource and nonpoint-source pollution problems for a wide range of scales and environmental conditions across the globe. The SWAT model is a continuation of more than 30 years of modeling efforts conducted by the USDA Agricultural Research Service (ARS). SWAT has gained international acceptance as a robust interdisciplinary watershed modeling tool as evidenced by international SWAT conferences, hundreds of SWAT-related papers presented at numerous other scientific meetings, and various articles published in peer-reviewed journals. The model has also been adopted as part of the U.S. Environmental Protection Agency (USEPA) Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) software package and is being used by many U.S. federal and state agencies, including the USDA within the Conservation Effects Assessment Project (CEAP). However, little attempt has been made in this direction in India.

In context of the above scenario, the study on modeling non-point source pollution was taken up for Dikrong River Basin in North East India with the objective to simulate nutrient and sediment transport using watershed model - SWAT (Soil and Water Assessment Tool), so that positive actions for management of watershed quality and quantity can be planned and modeled. In the present report, various model components related to hydrological processes, flow routines, erosion processes, sediment and NPS pollutants yields involved in the SWAT model are discussed with their mathematical relationships used to simulate the processes and their interactions. An attempt has also been made to apply the distributed hydrologic model along with GIS and remote sensing techniques for estimating surface runoff from Dikrong River Basin in Arunachal Pradesh.

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ABSTRACT

Rainfall-runoff relationship is an extremely complex and difficult problem involving many variables, which are interconnected in a very complicated way. Most of the models work best when data on the physical characteristics of the watershed are available at the model grid scale. This kind of data is rarely available, even in heavily instrumented research watersheds. However, Remote Sensing (RS) and Geographic Information System (GIS) has made it easier to extract land surface properties at spatial and temporal scales. One of the most widely used techniques for estimating direct runoff depths from storm rainfall is the United States Department of Agriculture (USDA) Soil Conservation Service's (SCS) curve number (CN) method. Its use, however, requires a detailed knowledge of several important properties of the watershed which may not be readily available. Many researchers used information derived from satellite data and integrated them with GIS to estimate SCS CNs and runoff. Routing of runoff in river network may be undertaken using a variety of modelling procedures. In this study, variable storage method has been used.

In the present report, various model components related to hydrological processes, flow routines, erosion processes, sediment and NPS pollutants yields involved in the SWAT model are discussed with their mathematical relationships used to simulate the processes and their interactions. An attempt has also been made to apply the distributed hydrologic model along with GIS and remote sensing techniques for estimating surface runoff from Dikrong River Basin in Arunachal Pradesh. For the digitization of contours, formation of DEM, and other GIS related tasks, GIS software ArcGIS Desktop 9.3 (ArcInfo License) was used and the modelling part was carried out in distributed parameter model AvSWATX 2005 (Arc View Soil and Water Assessment Tool), which provides a user-friendly graphical user interface over GIS platform ArcView 3.1 for input and output to SWAT2005 model and runs SWAT executables in the backend.

The model was calibrated and validated for periods June 2005 to July 2007 and September 2007 to September 2008, respectively. Model was calibrated using the Manning's n parameter for overland and channel flows. Calibration and validation results revealed that model was predicting daily surface runoff in terms of inflow to proposed Pare reservoir of PHEP (Pare Hydro-Electric Project) at Hoz satisfactorily.

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1.0 INTRODUCTION

1.1 General

Sustainable development of agriculture essentially depends on the conservation and management of land and water resources. This is especially true for the humid and sub-humid regions of India where intensive runoff and concomitant losses of sediments and agro-chemicals are fast degrading the land resources and polluting the water resources. In these regions, the monsoon rains are concentrated in 18-38 events of high magnitude (RF>10 mm) which are effective in generating runoff during the four months monsoon period (Thapliyal, 1997). These high intensity monsoon rains are responsible to cause flood and severe erosion of the top soil which eventually lead to soil degradation and pollution of water bodies. The wide spread and diffused nature of the losses of sediment and agro-chemicals, commonly known as non-point source (NPS) pollutants, is strongly influenced by the hydrologic behaviour of the watershed. The rate of pollutant runoff from the watershed changes in response to several factors related to watershed characteristics and the time series of rainfall. Hence, knowledge of the mechanism of pollutant runoff from non point sources is very useful to understand the nature and extent of pollution and develop environmental management of the watershed, especially under rainy conditions. The deterioration of land and water resources can be contained effectively by designing engineering management on watershed basis. Since, the hydrologic responses of the watersheds vary spatially and temporally, an intensive study of the individual watershed is necessary for developing the management scenario and also for transforming the results from one watershed to another having similar characteristics.

The fast growing population in India and the use of mineral and organic fertilizers and pesticides to increase crop yield and the conversion of upland grazing, scrub and forest to terraced agricultural land in hilly regions are causes of major concern from the point of view of environmental degradation. Growing awareness of this situation calls for sustainable development of natural resources so that ecosystem stability is maintained. Further, for any proper river basin planning, whether long range or short term, before going into alternative plans for development, it is very essential to combine it with water quality problems and hydrological analysis. Such water quality analysis involves collection/monitoring of water quality data and use/development of mathematical models for managing/forecasting water quality.

During recent years, non-point sources of water pollution have been recognized as often being of greater importance than point sources particularly in rural catchments (NOOA, 1991; Duda, 1993; Jain and Ali, 2000). This is due in part to the continuing efforts to reduce pollution from point sources over the past few decades, as well as recognition that non-point sources, such as storm water, may contain harmful contaminants (Bay et al., 1996). In most cases, the sources and concentrations of non-point source pollutants are the result of land use interactions with the transport system. In rural areas, nutrients and pesticides are released in surface and ground water and may degrade the quality of drinking water and cause various health problems to humans (Walcott et al., 1990). Nutrients and pesticides, particularly, are of major concern because of eutrophication and high toxicity problems (Moore et al., 1988; Sharma, 1996). Nitrogen and phosphorous are transported from cropland either by being adsorbed onto eroded soil particles or dissolved in runoff water. This has resulted in a slow and steady degradation of our water resources and has emphasized the need to identify and quantify major sources of nutrients and pesticides deposited within the river system. The assessment of nutrients and sediment is a perfect example of a spatially and temporally complex, multidisciplinary environmental problem that exists over multiple scales (Corwin et al., 1998). Therefore, a proper watershed management approach needs to be adopted to tackle the problem of non-point source pollution, so that positive actions for management of watershed quality and quantity can be planned and modelled.

Information on the hydrology and associated water quality is very important for evaluating management strategies at a watershed level. Unfortunately, there are no such data available for Indian conditions. In context of the above scenario, it is essential to monitor and model non-point source pollution at watershed level.

The major factors influencing non-point source pollution include soil erosion and sedimentation and erosion of stream banks, washing out nutrients and organic material from livestock wastes and agricultural land, storm runoff from urban areas and atmospheric deposition. Adsorption to the surface of sediment particles provides a mechanism for transport of many contaminants derived from agricultural fertilizers, pesticides and industrial wastes. Deposition of sediments carrying such loads in the channel or on the flood plain can have detrimental consequences for ecology and agricultural activities. The sediment released into the river system can promote channel instability and cause bed degradation (Jain and Ali, 2000).

In most cases the sources and concentrations of non-point source pollutants are the result of land use interactions with the transport system (DeCoursey, 1985). It is a source transport problem in which the hydrologic cycle provides the transport processes to move pollutants from the source to ground water, a stream, or a reservoir (Donigian, 1982). Non-point sources can be urban, industrial, or agricultural pollutants that are distributed over the surface.

Estimation of pollutant loadings from non-point sources is usually accomplished either empirically through unit area loadings or deterministically through loading models. Unit area loadings are based on intensive sampling of a small area and then extrapolation of the resulting loading on a per unit area basis to the entire watershed. On the other hand loading model uses such factors as rainfall, soil type, land use, etc. to calculate the contribution available from a particular watershed and then estimate the fraction delivered to a water body.

In agricultural watersheds, the NPS pollution is largely contributed by the agricultural activities. The United States Environmental Protection Agency (USEPA) reported that the routine agricultural activities are responsible for more than 60 per cent of the surface water contamination (USEPA, 1993). In India also high consumption of nitrogenous fertilizers and the resulting 30-50% losses of nitrogen (Mondal and Kar, 1991) are reported to contaminate the surface and ground water bodies (Kar et al., 2000). Most of the watersheds being mixed type, all the area of a given watershed do not contribute equally to NPS pollution. Numerous studies have indicated that for many watersheds a few critical areas are responsible for a disproportionate amount of pollutant yield from the watershed (Mass et al., 1985; Dillaha, 1990). In order to design conservation structure for offsetting the ill effects of sedimentation in such mixed type watersheds, it becomes necessary to estimate runoff, sediment yield and NPS pollutants losses from different areas of the watershed.

The wide spread nature of NPS pollution poses a complex problem for its assessment and management. Areal extent of its contamination increases the complexity and due to this large volume of data is required for its assessment as compared to that for the typical point source pollution. Because of such high complexity, NPS pollution is assessed through modelling approach which combines hydrologic models with Remote Sensing (RS) and Geographic Information System (GIS) techniques. RS provides information on land use, land cover, topography etc. and the techniques of GIS help manipulate, retrieve and display large volume of spatial data along with efficient compilation and evaluation of the already existing data.

Watershed models can be used to estimate the impact of non-point source pollution on water resources and assist in various decision processes, e.g., identification of critical zones within a watershed, selection of agricultural practices to be tested on the watershed and assessment of attainable surface water quality. Several hydrological models can be used to simulate nutrient and sediment transport in agricultural watersheds.

Among the hydrologic models, the physically process based distributed parameter models are definitely superior over the empirical and conceptual models. A distributed parameter model has several advantages over the lumped parameter models in the estimation of NPS pollution. Their principal advantages include accurate representation of spatial variability of the watershed features and estimation of NPS pollutants losses at different locations within the watershed. The distributed parameter continuous time scale models coupled with RS and GIS techniques can assist management agencies in both identifying the most critical erosion prone areas and selecting appropriate management practices. Using these models, management scenarios can also be developed to minimize runoff, sediment yield and NPS pollutants losses from the critical erosion prone areas of the watershed.

Only a few physically based, distributed parameter continuous time scale watershed models are available for hydrologic and NPS water quality modelling such as Storm Water Management Model (SWMM), Simulator for Water Resources in Rural Basins - Water Quality (SWRRB-WQ), Hydrologic Simulation Program - Fortran (HSPF), MIKE SHE (System Hydrologique European) and Soil and Water Assessment Tool (SWAT). Among these, SWAT and HSPF are more promising and widely used models, which have been developed to simulate runoff, sediment yield and NPS pollutants losses from agricultural watersheds. Previous applications of SWAT in various parts of the United States for water flow and pollutant loading have shown favourable comparisons with the measured counterparts (Rosenthal et al., 1995; Arnold and Allen, 1996; Srinivasan et al., 1998; Arnold et al., 1999; Saleh et al., 2000; Santhi et al., 2001). Similarly the HSPF model has been successfully applied by a number of researchers in handling the hydrologic and water quality problems of the watersheds (Chew et al., 1991; Duru et al., 1999; Engelmann et al., 1999). These two models have been used worldwide mostly to simulate hydrological processes either for very large area or field size watersheds with unique land use and land cover. However, limited information is available on their suitability for small, multi-vegetated, mixed type watersheds of humid and sub-humid regions where NPS pollution of the water resources has increased to an alarming proportion. Hence, there is a necessity to adequately test these models and select the best suitable model based on their relative performance, for predicting hydrologic processes and NPS pollution in small mixed type watershed under sub-humid sub-tropical region.

In context of the above scenario, the study on modeling non-point source pollution was taken up for Dikrong River Basin in North East India. It was planned to consider nutrient and sediment load in its larger context to evaluate the current state of pollution through real time measurements at the down stream site of the Dikrong River Basin with the objective to simulate nutrient and sediment transport using watershed model - SWAT (Soil and Water Assessment Tool), so that positive actions for management of watershed quality and quantity can be planned and modeled. This will provide necessary information to guide current and future decision making at watershed scale. The study was planned with the following objectives:

i) Monitoring of non-point source pollution (nutrients and sediment load) at watershed level including storm events, and

ii) Development of strategy for analysis and modeling of watershed hydrology and non-point source pollution.

1.2 Scope of the Present Study

Among the major resources available in the country, the most important is land comprising soil, water, and associated plant and animals involving the total eco-system. The community's demand for food, energy and many other needs has to depend on the preservation and improvement of the productivity of these natural resources. The development and management of water resources require thorough understanding of basic hydrologic processes and simulation capabilities at the watershed scale. Watershed, a geographically dynamic unit area that contributes runoff to a common point, has been accepted as basic unit for planning and implementation of the protective, curative, and ameliorative programmes. An accurate understanding of the hydrological behaviour of a watershed is important for effective management. The characteristics of watershed are dynamic which vary both spatially and temporally. Intensive study of individual watersheds is, therefore, necessary for developing management plan and also for transforming the results of one watershed to another with similar characteristics. The impacts of changing scenarios, such as changes in land use, land management, and climate variability on water resources and water quality has led to the development of a number of hydrologic simulation models. Watershed modelling is the basic of integrated water resources management. State-of-the-art of watershed modelling is reasonably advanced. However, these models are yet to become common planning and decision making tools (Singh, 1995). A majority of watershed models simulate watershed response without or with inadequate consideration of water quality. Several empirical to physically based distributed hydrological models have been developed to predict runoff, erosion, sediment, and nutrient transport from agricultural watersheds under various management scenarios. Estimation of runoff and sediment yield is also necessary for design of soil conservation structures and watershed prioritization works.

Degradation of water and land resources is an issue of significant societal and environmental concern. The increasing pressure on land due to increased population has resulted in natural imbalance between soil forming and soil erosion processes leading to serious problem of erosion and land degradation. India receives an annual precipitation of 398 million hectare metre (Mha-m) of which 150 Mha-m infiltrates into the soil and 160 Mha-m is lost to the sea. Only 20 Mha-m is stored in surface reservoirs, whereas large part of the country suffers from drought. The need for accurate information on watershed runoff and sediment yield has grown rapidly during the past two decades along with the acceleration of the watershed management programmes for conservation, development, and beneficial use of natural soil and water resources available in the basin. Prediction of runoff and sediment yield is a necessity if adequate provision is to be made in the design of conservation structures to offset the ill-effects of sediment erosion. This information is required in prioritizing watersheds for implementing watershed management programmes, with the limited available funds and also for assessment of their impacts.

Remote sensing has emerged as a powerful tool for cost effective data acquisition in a short time at periodic intervals (temporal), at different wave length bands (spectral) and covering large area (spatial). The availability of GIS (Geographic Information System) tools and more powerful computing facilities makes it possible to overcome many difficulties and limitations and to develop distributed continuous time models, based on available regional information. Recent development of deterministic models provides some spatially distributed tools, such as AGNPS (Young et al., 1989), ANSWERS (Beasley et al., 1980), SWRRB (Arnold et al., 1990) and SWAT (Arnold et al., 1993). SWAT uses a modified formulation of the Soil Conservation Service (SCS) curve number (CN) technique (USDA-SCS, 1972) to calculate surface runoff. The CN technique relates runoff to soil type, land use and management practices and is computationally efficient (Arnold et al., 1995). The computational components of SWAT can be placed into eight major divisions: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management. AvSWAT represents both preprocessor and user interface to SWAT model.

Effective control of soil erosion requires proper implementation of best management practices in critical erosion prone areas. Different management scenarios can be developed to reduce surface runoff and sediment yield for the critical erosion prone areas of the watershed. The time series data on rainfall and runoff available through the gauging stations in the study watershed made it possible to analyze the cause-effect relationship between the various factors that affect the hydrologic response of the watershed. Therefore, in the present study an attempt has been made to apply a distributed hydrologic model along with GIS and remote sensing techniques for estimating surface runoff from Dikrong Basin in Arunachal Pradesh. The specific objectives of this part of the study are:

i) To describe the model components involved in the SWAT model. The various components related to hydrological processes, flow routines, erosion processes, sediment and NPS pollutants yields involved in the models are discussed with their mathematical relationships used to simulate the processes and their interactions.

ii) To calibrate the AvSWATX (rainfall-runoff) model for Dikrong Basin, and

iii) To validate the calibrated AvSWATX (rainfall-runoff) model for Dikrong basin.

2.0 REVIEW OF LITERATURE

This chapter deals with review of significant contributions made by various researchers in the field of soil and water management and planning using SWAT (Soil and Water Assessment Tool). A brief review of studies dealing with the application of SWAT in hydrological modelling of watersheds is presented here.

2.1 SWAT

Arnold et al. (1995, 1998) and Neitsch et al. (2001) developed Soil and Water Assessment Tool (SWAT) model, which is basically river basin, or watershed scale continuous model. SWAT is developed to predict the impact of land management practices on water, sediment yield, and agricultural chemical yields in a large complex watershed with varying soils, land use, and management conditions over a long period of time. The physical processes associated with water movement, sediment movement, crop growth and nutrient cycling are directly modelled by SWAT using required input data. SWAT was developed by merging SWRRB and ROTO models.

Srinivasan et al. (1993) applied SWAT model to the Seguin (24,469 km^2) and Naches (25,161 km^2) river basins in Texas and achieved good agreement between simulated and observed monthly flows for both basins. Srinivasan and Arnold (1994) used SWAT to model the Seco Creek watershed (114 km^2) in Texas, where 98% of the watershed was being used as rangeland. They reported that average monthly-predicted flows were 12% lower than measured flow.

Bingner (1996) applied SWAT in Goodwin Creek Watershed (21.31 km^2), divided into 14 sub-basins. The Sub-basins were described using the GRASS GIS, integrated with SWAT, to determine input parameters. SWAT simulated the relative trends of runoff produced from a variety of sub-basins, over a long term basis. However, the simulations of individual storm were less accurate and a small completely wooded sub-basin was the most difficult area to simulate. His study has shown that SWAT has the capability of adequately simulating the effects of temporal and spatial variability of watershed characteristics on runoff.

Arnold et al. (1998) used SWAT model to simulate the hydrology, soil erosion and sediment transportation in the Richland-Chambers watershed of the Trinity River basin in Texas. The GIS interface was used to accumulate the necessary input data for the model. The study demonstrated that GIS can be used to efficiently collect and manage data for SWAT model. SWAT predicted monthly stream flows, soil erosion, and sediment transportation satisfactorily.

Manguerra and Engel (1998) used SWAT model in Animal Science (3.28 km^2), Greenhill (113.8 km^2), and Camp Shelby watersheds. This study has shown that the adoption of the concept of hydrologic response units (HRUs) is sufficient to capture the spatial variability in the watershed. Watershed can be subdivided only in presence of site specific water impoundments and when significant channel abstractions are expected. This study has also shown that improved runoff predictions can be obtained through relatively easy and automated adjustments of return flow contribution to stream flow and curve numbers with time and space.

King et al. (1999) applied SWAT for evaluating SCS daily curve number method and Green-Ampt Mein-Larson methods of simulating excess rainfall on a large basin with multiple rain gauges. SWAT was modified to accept breakpoint rainfall data and route stream flow on sub daily time step for Green Ampt method. This study reported that no significant advantage can be gained by using breakpoint rainfall and sub-daily time steps when simulating the large basin.

Fohrer et al. (1999) calibrated and validated the SWAT for the gauged 'Aar' watershed with a land use map derived from satellite images. Fohrer et al. (2001) and Santhi et al. (2001) validated the SWAT modelling concept for watersheds with widely differing land use. An artificial watershed has been successfully employed to analyze the model sensitivity to crop parameters and land use changes. The model results showed the same tendencies as observed when applying the model to the complex Dietzholze catchment. In general, the effect of land use changes on the annual water balances was moderate. Surface runoff is the most susceptible to land use changes for both the artificial and the natural catchments.

Spruil et al. (2000) simulated daily and monthly stream discharge from small watersheds in Central Kentucky that had developed on karst hydrology. This study suggested that most sensitive parameters for the SWAT are saturated hydraulic conductivity, drainage area, channel length, and channel width. This study revealed that SWAT model can be effectively used for watersheds formed on karst geology.

Fontaine et al. (2001) calibrated SWAT for Black Hills of South Dakota having single precipitation gauge located at the centre of the drainage basin and reported that calibration of the model did not appeared to be hindered by the lack of additional rain gauges.

Lenhart et al. (2002) compared two different approaches for sensitivity analysis for SWAT. In the first approach variation in X is 10% of the initial value X_0 of the respective parameter X regardless of the potential range of this parameter. For the second approach the different relative width of the ranges is taken into account by varying X by 25% of the entire range, with X chosen as the mean. Results of this study have shown that both the approaches for sensitivity analysis show nearly similar results hence can be considered as equivalent.

Bosch et al. (2004) tested SWAT for a 22 km^2 sub-watershed of the Little river in Georgia. Results of this study indicated that SWAT can be used to simulate stream flow within Coastal Plain watersheds and can be expected to yield reasonable estimates of monthly and annual stream flow.

Tripathi et al. (2004) tested SWAT model for runoff and sediment yield of a small agricultural watershed in eastern India using generated rainfall. The capability of the model for generating rainfall was evaluated for a period of 18 years (1981-1998). Model simulated monthly rainfall for the period of 18 years was compared with observations. Simulated monthly rainfall, runoff and sediment yield values for the monsoon season of 8 years (1991-1998) were also compared with their observed values. In general monthly average rainfall predicted by the model was in close agreement with the observed monthly average values. Also, simulated monthly average values of surface runoff and sediment yield using generated rainfall compared well with observed values during the monsoon season of the years 1991-1998. Results of this study revealed that the SWAT model can generate monthly average rainfall satisfactorily and thereby can produce monthly average values of surface runoff and sediment yield close to the observed values. They concluded that SWAT model could be used for developing a multiple year management plan for the critical erosion prone areas of a small watershed

Jha et al. (2004) used SWAT for four Iowa watersheds (ranging from 2000 to 18000 km^2) to determine the appropriate level of sub-watershed division for simulating flow, sediment, and nutrient yield. The results indicated that variation in the total number of sub-watersheds has very little effect on stream flow. However the opposite result was found for sediment yield and nutrient loss. This study also suggested that the threshold drainage area of the sub-watersheds should range between 2 and 6% of the total drainage area, with median at 3%.

Chaplot (2005) used SWAT in Lower Walnut Creek watershed of central Iowa to determine the impact of the mesh size of the digital elevation model, DEM (from 20 to 500 m) and the soil map scale (1/25,000, 1/250,000 and 1/500,000 scale) to simulate runoff, sediment, and NO_3-N loads. Result of this study has shown that an upper limit to DEM mesh size of 50 m is required to simulate watershed loads. Decreasing the mesh size beyond this threshold does not substantially affect the computed runoff but generates prediction errors for nitrogen and sediment yields. Detailed soil map should be considered to accurately estimate the loads. Runoff, nitrogen, and sediment load estimates were more accurate when using the 1/25,000 instead of the 1/250,000 or 1/500,000 scale soil maps.

Tripathi et al. (2006) studied the effect of watershed subdivision on simulation of water balance components using SWAT for the Nagwan watershed in eastern India. The watershed and sub-watershed boundaries, slope, and soil texture maps were generated using a geographical information system. In order to study the effect of watershed subdivision, the watershed was spatially defined into three decomposition schemes, namely, single, 12, and 22 sub-watershed(s). Results of the study showed a perfect water balance for the Nagwan watershed under all of the decomposition schemes. Results also revealed that the number and size of sub-watersheds do not appreciably affect surface runoff. Except for runoff, there was a marked variation in the individual components of the water balance under the three decomposition schemes. Though the runoff component of the water balance showed negligible variation among the three cases, variations were noticed in the other components: evapotranspiration (5 to 48%), percolation (2 to 26%), and soil water content (0.30 to 22%). They concluded that watershed subdivision has a significant effect on the water balance components.

Schuol and Abbaspour (2007) used monthly weather statistics to generate daily data in a SWAT model application to West Africa. Daily precipitation and maximum–minimum temperatures were generated with a simple algorithm using the monthly statistics available from the Climatic Research Unit. The generated daily weather data were tested by using an application of the SWAT model to simulate monthly and annual river discharges in a large West-African watershed. This study has shown that the discharge simulations using generated data are superior to the simulations using available measured data from local climate stations. This generated data can benefit a SWAT application in two ways: (1) to generate more accurate daily data at the existing weather stations, which contain large amounts of missing data, and (2) by creation of new pseudo stations. This data can be used for data scarce regions or for regions with weather stations containing inaccurate or missing data.

2.2 Application of AvSWAT

AvSWAT (ArcView SWAT) is a complete preprocessor, interface, and post processor of the hydrological model SWAT. Without leaving the user friendly ArcView GIS environment the user is provided with a complete set of tools for the watershed delineation, definition, and editing of the hydrological and agricultural management inputs, running, and calibration of the model. The extension and the model constitute a comprehensive and user friendly tool for the watershed scale assessment and control of the agricultural and urban sources of water pollution.

Pandey et al. (2002) tested AvSWAT for identification of critical sub-watersheds and development of management scenarios for prioritized sub-watersheds. Model accurately simulated runoff, sediment yield, and nutrient losses on daily, monthly, and seasonal basis. They reported that conservation tillage could be used in place of existing conventional tillage, as it reduced the average sediment yield by 5%.

Schuol et al. (2003) performed a study to test the applicability of AvSWAT in large-scale (millions of sq. km) watersheds. This study was aimed to quantify the amount of the global country-based available freshwater starting with a (sub-) continental appraisal with special emphasis given to the quantification of the spatial and temporal distribution of the total available water as well as the soil water considering its importance for rainfed agriculture. It was reported that there were initial shortcomings but once these were overcome, first simulations gave promising results in respect of the freshwater quantification goal, even though detailed and quite challenging calibration efforts were still necessary.

Muthuwatta (2004) applied AvSWAT to the Naivasha basin in Kenya, to study the estimates of the lake water level fluctuations by estimating the lake water level based on the lake volumes. The results indicated that the model performed with an acceptable accuracy. The modelled lake levels, based on AvSWAT simulated stream flow, produced better results.

Vazquez-Amabile and Engel (2005) used AvSWAT to compute groundwater depth and stream flow in three watersheds of the Muscatatuck river basin in southeast Indiana. Their study has shown that AvSWAT simulates monthly stream flow well but poorly simulates daily stream flow. They also suggested the procedure to compute the water table depth of an aquifer using soil input data and the AvSWAT output "daily soil water content by layer" based on the DRAINMOD theory. The results of his study showed that the performance of the model in predicting the groundwater depth is not as good as stream flow but the model is able to predict the seasonal variations of the groundwater table.

Ilisu Environment Group (2005) applied AvSWAT to the Tigris catchment area at Ilisu. The main emphasis of this study was to compare the nutrients loss and sediment yield at present and at year 2020 assuming best waste water treatments for the later case. They showed that, the present quantity of Nitrogen (4,800 t/year) and Phosphorus input (1,300 t/year) will not be increased in near future due to water treatments. The model indicated that the magnitude of the annual sediment flowing into the Ilisu reservoir would reduce from 2,540,000 tons in 2005 to 1,608,000 tons in 2020.

Ndomba and Lillingtveit (2005) used AvSWAT model for Simiyu catchment, Tanzania. They concluded that AvSWAT model is also suitable for ungauged catchments. Study has also shown that peaks of hydrograph can be simulated better by using the soil map of better resolution.

Johney (2006) tested AvSWAT on daily and monthly basis for Barakar catchment of upper Damodar Valley. The calibrated and validated model was further used for identification of critical sub-watersheds, development of management scenarios, and calculating sedimentation and anticipated life of reservoir. Results of this study have shown that AvSWAT can be used successfully for calculating the reservoir sedimentation and anticipated life of reservoir.

Kannan et al. (2007 a, b) applied AvSWAT model to Colworth catchment (142 ha) in Bedfordshire, England. This study has shown that proper modelling of water balance components such as crop growth and evapotranspiration is crucial for correct representation of flow. The AvSWAT model with some modifications can be reliably used to model stream flow. They concluded that calibrating AvSWAT model for wet period produces better result as compared to dry period, temperature based Hargreaves method appears to be at least as good as more Complex energy based Penman-Montieth method in predicting daily evapotranspiration and curve number method performs better than Green Ampt Method in modelling runoff.

Tolson and Shoemaker (2007) described the successful development of an AvSWAT model of the Cannonsville watershed, New York for prediction of flow, sediment, and phosphorus transport into Cannonsville reservoir. Extensive datasets were derived for phosphorus inputs that varied spatially and temporally. When compared with a number of previous phosphorus modelling studies, this study reported better temporal and spatial model performance statistics in calibration and validation. The good spatial and temporal validation results indicated the potential value of the model as an NPS management tool. The manure mass balance approach and definition of corn-hay crop rotations with a constant area over time were important steps in the AvSWAT model application to the Cannonsville watershed.

3.0 MODEL DESCRIPTION: SWAT

The purpose of this chapter is to describe the model components involved in the SWAT model. The various components related to hydrological processes, flow routines, erosion processes, sediment and NPS pollutants yields involved in the models are discussed with their mathematical relationships used to simulate the processes and their interactions.

SWAT is a spatially distributed, continuous time step, watershed scale model developed by adding a new routing structure to the Simulator for Water Resources in Rural Basins - Water Quality (SWRRBWQ) model. The new routing structure adds flows down through basin reaches and reservoirs. The watershed can be divided into sub-basins or cells, typically delineated by soil type or land use. The major sub-basin components include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, ground water and lateral flow and agricultural management. It simulates hydrological processes, sedimentation, nutrient and pesticide transport in a watershed. It also provides the option to model the watershed for long term (100 years or more).

The model provides output on hydrology with estimates of surface runoff, subsurface runoff, total water yield, lateral water percolation and sediment yield. Besides these, the model estimates the pollutants such as nitrogen (N) and phosphorus contained with runoff and sediment. The nutrients N and P are essential plant nutrients and major contributors to surface as well as ground water pollution. All watershed characteristics and inputs are expressed at the sub-watershed level. Runoff is computed using the SCSCN method whereas the erosion is computed using the MUSLE equation.

The major components of the models are grouped under sub-basin and routing and are discussed as below.

3.1 Sub-basin Components

The major sub-basin components which have been studied under the present investigation are hydrology, weather, sedimentation, nutrients and agricultural management and are presented in the SWAT model as below.

3.1.1 Hydrology

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

$$SW_t = SW + \sum_{t=1}^{t} (R_t - Q_t - ET_t - P_t - QR_t) \qquad \ldots 1$$

where, SW_t is the final soil water content (mm), SW is the soil water content available for plant uptake, defined as the initial soil water content minus the permanent wilting point water content (mm), t is the time (days), R_t is the amount of precipitation (mm), Q_t is the amount of surface runoff (mm), ET_t is the amount of evapotranspiration (mm), P_t is the amount of percolation (mm) and QR_t is the amount of return flow (mm).

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

Surface runoff: The surface runoff model simulates surface runoff volume and peak runoff rates, provided daily rainfall data are fed.

a. The surface runoff volume: Surface runoff volume is computed using a modification of the SCS curve number method (USDA Soil Conservation Service, 1972). The curve number varies non-linearly with the moisture content of the soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation.

Surface runoff volume is predicted for daily rainfall by using the SCS curve number technique (USDA-SCS, 1972) as below:

$$Q = \frac{(R-0.2s)^2}{(R+0.8s)}, \qquad R > 0.2\ s \qquad \ldots 2$$

$$Q = 0.0, \qquad R \leq 0.2\ s \qquad \ldots 3$$

where, Q is the daily surface runoff (mm), R is the daily rainfall (mm) and s is a retention parameter, which depends on soil type, land use, management, slope and initial soil water content. s is related to Curve Number (CN) given by the USDA-SCS (1972) equation:

$$s = 254\left(\frac{100}{CN} - 1\right) \qquad \text{s in mm.} \qquad \ldots 4$$

The constant, 254, gives s in mm. CN is the curve number for antecedent moisture condition (AMC) II.

b. Peak runoff rate: The peak runoff rate is the maximum runoff flow rate that occurs with a given rainfall event. The peak runoff rate is an indicator of the erosive power of a storm and is used to predict sediment loss. SWAT calculates the peak runoff rate with a modified rational method.

The rational method is based on the assumption that if a rainfall of intensity i begins at time t = 0 and continues indefinitely, the rate of runoff will increase until the time of concentration, t = tconc, when the entire sub-basin area is contributing to flow at the outlet. The modified rational formula includes a stochastic element to allow realistic simulation of peak runoff rate, given only daily rainfall data. The rational formula is:

$$q_{peak} = \frac{C.i.A}{360} \quad \ldots 5$$

where q_{peak} is the peak runoff rate ($m^3\ S^{-1}$), C is the runoff coefficient expressing the watershed infiltration characteristics, i is the rainfall intensity (mm/hr) for the watershed's time of concentration, A is the sub-basin area (ha) and 360 is a unit conversion factor. The runoff coefficient can be calculated for each storm if the amount of rainfall and runoff are known,

$$C = \frac{Q}{R} \quad \ldots 6$$

Since, R is the basic model input and Q is computed from equation (2), C can be calculated directly.

Percolation: The percolation component is based on a storage routing technique combined with a crack-flow model to predict flow through each soil layer. The percolated water below the root zone is lost from the watershed and becomes the part of ground water or appears as return flow in downstream basins. The storage routing technique is based on the following equation,

$$SW_t = SW_{ot}.\exp\left(\frac{-\Delta t}{TT_t}\right) \quad \ldots 7$$

where, SW_o and SW are the soil water content at the beginning and end of the day in i^{th} layer in mm, Δt is the time interval (24 hours) and TT is the travel time through layer i in hours. Thus the percolation can be computed by subtracting SW from SW_o,

$$O_t = SW_{ot}\left[1 - \exp\left(\frac{-\Delta t}{TT_t}\right)\right] \quad \ldots 8$$

Where, O is the percolation rate in mm/d.

The travel time (TT_t) is computet for each soil layer by linear storage equation,

$$TT_t = \frac{(SW_t - FC_t)}{H_t} \quad \ldots 9$$

where, H is the hydraulic conductivity in mm/h and FC is the difference between field capacity and wilting point water content for layer i in mm. The hydraulic conductivity is varied from the saturated hydraulic conductivity value at saturation to near zero at field capacity,

$$H_t = SC_t \left(\frac{SW_t}{UL_t} \right)^{\beta_t} \qquad \ldots 10$$

where, SC_t is the saturated hydraulic conductivity for layer i in mm/h, UL_t is soil water content at saturation in mm/mm. β_t is a parameter that causes H_t to approach zero as SW_t approaches FC_t. β_t is estimated as below:

$$\beta_t = \frac{-\ 2.655}{\log_{10}(FC_t / UL_t)} \qquad \ldots 11$$

The constant (-2.655) was set to assure $H_t = O.002SC_t$ at field capacity. Upward flow may occur when a lower layer exceeds field capacity. The soil water to field capacity ratios of the two layers regulates the water movement from a lower layer to an adjoining upper layer. Percolation is also affected by soil temperature. If the temperature in a particular layer is 0°C or below, no percolation is allowed from that layer.

Lateral sub-surface flow: Lateral subsurface flow of water in the soil profile is calculated with the help of a kinematic storage model (Sloan et al., 1984) simultaneously with percolation as below:

$$q_{lat} = 0.024 \frac{(2SK_s \sin(a))}{\Theta_d L} \qquad \ldots 12$$

Where q_{lat} is the lateral flow of water (mm/d), S is the drainable volume of soil water (mh^{-1}), K_s is the saturated hydraulic conductivity, α is the slope (mm^{-1}), Θ_d is drainable porosity (mm^{-1}), and L is flow length (m).

If the saturated zone arises above the soil layer, water is assumed to flow to the layer above (back to the surface for upper soil layer). In case of multiple soil layers, the model is applied to each soil layer independently, starting from the upper soil layer.

Evapotranspiration: SWAT model offers three options for estimating potential evaporation, the Penman-Monteith (Monteith, 1965), the Priestley-Taylor (Priestley and Taylor, 1972) and the Hargreaves method (Hargreaves et al., 1985). The Penman-Montheith method has been found to be most suitable for the study area and it has been adopted in the present modelling study. The Penman-Monteith method requires solar radiation, air temperature, relative humidity and wind speed.

The Penman-Monteith equation is expressed as,

$$E_o = \frac{\dfrac{\partial(h_o - H) - 86.7AD(e_a - e_d)}{AR}}{HV\left(\partial + \gamma\left(1 + \dfrac{CR}{AR}\right)\right)} \qquad \ldots 13$$

where, E_o is the evaporation (g/m^2 -s), h_o is the net radiation (MJ/m^2), ∂ is the slope of the saturation vapour pressure curve ($kPa/^oC$), G is the soil heat flux (MJ/m^2), e_a is the saturated vapour pressure at mean air temperature (kPa), e_d is the vapour pressure at mean air temperature (kPa), HV is the latent heat of vaporization and γ is the psychrometer constant ($kPa/^oC$), AD is the air density (g/m^3), AR is the aerodynamic resistance for heat and vapour transfer (s/m) and CR is the canopy resistance for vapour transfer (s/m).

The model computes evaporation from soil and plants separately, as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential ET and leaf area index (LAI). Actual soil water evaporation is estimated by using exponential function of soil depth and water content. Plant water evaporation is simulated as a linear function of potential evaporation and leaf area index.

Transmission losses: Many semiarid and arid watersheds have alluvial channels that abstract large quantities of stream flow (Lane, 1982). The abstractions, or transmission losses, reduce runoff volume as the flood wave travels downstream. Lane's method, described in USDA (1983), is used to estimate transmission losses. Channel losses are the function of channel length, width and flow duration. Both runoff and peak rate are adjusted when transmission losses occurs.

Ponding of water: SWAT models four types of water ponding bodies: ponds, wetlands, depressions/potholes and reservoirs. Ponds, wetlands and depressions/potholes are located within a sub-basin off the main channel. Water flowing into these water bodies is originating from the sub-basin in which the water body is located. Reservoirs are located on the main channel network. They receive water from all sub-basins upstream of the water body.

3.1.2 Weather

SWAT uses precipitation, air temperature, solar radiation, wind speed and relative humidity in driving hydrological balance. Daily precipitation and maximum and minimum temperature data on daily basis can be directly given to the model as input. In case, unavailability of daily measure value SWAT uses WXGEN Weather Generator model (Sharpley and Williams, 1990) to generate climatic data or to fill in gaps in measured records. Solar radiation, wind speed and relative humidity are always generated by the weather generator based on mean monthly values and used by the model. One set of weather variables may be simulated for entire basin or different set of weather variables may be simulated for each sub-basin. Weather generator is very much useful when measure data is not available or climatic changes has to be studied and management scenario are being compared.

3.1.3 Erosion and sediment yield

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

$$Y = 11.8(V.q_p)^{0.56}.K.C.PE.LS \qquad \dots 14$$

where, Y is the sediment yield from the sub-basin in time t, V is the surface runoff volume for sub-basin in m^3, q_p is the peak flow rate for sub-basin in m^3/s, K is the soil erodibility factor, C is the crop management factor, PE is the erosion control practice factor, and LS is the slope length and steepness factor.

The LS factor is computed by the equation (Wischmeier and Smith, 1978):

$$LS = \left(\frac{\lambda}{22.1}\right)^{\xi}\left(65.41S^2 + 4.565S + 0.065\right) \qquad \ldots 15$$

The exponent ζ varies with slope and is computed by the equation:

$$\xi = 0.6\left[1 - \exp^{(-35.835s)}\right] \qquad \ldots 16$$

The crop management factor, C, is evaluated for all days when runoff occurs, by using the equation:

$$C = \exp[(-0.2231-CVM)\exp(-0.00115\ CV) + CVM] \qquad \ldots 17$$

where, CV is the soil cover above ground biomass + residue in kg/ha and CVM is the minimum value of C.

The value of CVM is estimated from the average annual C factor using the equation:

$$CVM = 1.463\ \ln(CVA) + 0.1034 \qquad \ldots 18$$

The value of CVA for each crop is determined from the values reported by Wischmeier and Smith (1978). Values for K can be estimated for each sub-basin using standard procedure. PE factor can be estimated for each sub-basin using information contained by Wischmeier and Smith (1978).

3.1.4 Nutrients

EPIC model (Williams et al., 1984) has been taken and modified to compute nutrient yield and cycling from the sub-basin in the SWAT model (Arnold et al., 1996). The model allows the simultaneous computations on each sub-basin and routes the water, sediment and nutrient from the sub-basin outlet to the basin outlet.

a. Nitrate: The amount of $N0_3$-N in runoff is estimated for each sub-basin by considering the top 10 mm soil layer only. The total amount of water leaving the layer is the sum of the runoff, lateral subsurface flow and percolation.

$$QT = Q + O_l + QR_l \qquad \ldots 19$$

where, QT is the total water lost from the first layer in mm, Q is the runoff volume in mm, O_l is the percolation from the first layer in mm, and QR_l is the lateral flow from the first layer in mm. The amount of the NO_3-N lost with QT is:

$$VNO_3 = (QT)\,(C_{NO3}) \qquad \ldots 20$$

where, VNO3 is the amount NO_3-N lost from the first layer and C_{NO3} is the concentration of NO_3-N in the first layer.

At the end of the day, the amount of NO_3-N left in the layer is:

$$WNO3 = WNO3_o - (QT)\,(C_{NO3}) \qquad \ldots 21$$

where, WNO3 and $WNO3_o$ are the weights of NO_3-N concentration in the layer at the beginning and end of the day.

The NO_3-N concentration can be estimated by dividing the weight of NO_3-N by the water storage volume:

$$C_{NO3} = C_{NO3} - C_{NO3}\left(\frac{-QT}{PO_1 - WP_1}\right) \qquad \ldots 22$$

where, C_{NO3} is the concentration of NO_3-N at the end of the day, PO is the soil porosity and WP is the wilting point water content for soil layer in mm.

Finite difference approximation of this equation yields:

$$C_{NO3} = C_{NO3} - \exp\left(\frac{-QT}{PO_1 - WP_1}\right) \qquad \ldots 23$$

Thus, VNO3 can be computed for any value of QT by integrating the above equation,

$$VNO3 = WNO3\left[1 - \exp\left(\frac{-QT}{PO_1 - WP_1}\right)\right] \qquad \ldots 24$$

The average concentration of QT for the day is given by,

$$C_{NO3} = \frac{VNO3}{QT} \qquad \ldots 25$$

The amount of the NO_3-N contained in the runoff, lateral flow and percolation loss are estimated as the product of the volume of water and the concentration from the above equation.

Leaching and lateral subsurface flows in lower layers are estimated with the same approach used in the upper layer except surface runoff is not considered.

Organic nitrogen loss along with the sediment transported is estimated by a loading function developed by McElroy et al. (1976) and modified by the Williams and Hann (1978) applicable to individual runoff events. Loading function estimates the daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield and enrichment ratio. It is given as below:

$$YNO = 0.001(Y)(CON)(ER) \qquad \ldots 26$$

where, YON is the organic N runoff loss at the outlet (kg/ha), CON is the concentration of organic N in the top soil layer (g/t), Y is the sediment yield (t/ha) and ER is the enrichment ratio.

The value of CON is the initial input to the model and is constant throughout the simulation. Enrichment ratio is logarithmically related to sediment concentration as described by Menzel (1980) and given as,

$$ER = X_1 C_a^{X_2} \qquad \ldots 27$$

where, C_a is the sediment concentration (g/m^3), X_1 and X_2 are parameters set by the upper and lower limits. The enrichment ration approaches to 1.0, the sediment concentration would be extremely high and vice versa.

SWAT uses a modified PAPRAN mineralization model (Seligman and Keulen, 1981) for N mineralization. The daily amount of immobilization is computed by subtracting the amount of N contained in the crop residue from the amount assimilated by the microorganisms. Immobilization may be limited by N availability. If the available N amount is less than the amount of immobilization predicted the decay rate constant is adjusted. To estimate the N contribution from rainfall, SWAT uses an average rainfall N concentration of 8 ppm for all the storms and whole watershed. The amount of N in rainfall is estimated as the product of rainfall amount and concentration. This concentration corresponds to 61b/acre (kg/ha) for 30 inches of rainfall.

Crop use of N is estimated by using a supply and demand approach. The daily crop N demand is computed by the following equation,

$$UND_i = (CN)_i B_i - (C_{NB})_{i-1} B_{i-1} \qquad \ldots 28$$

where, UND_i is the N demand of the crop (kg/ha) in ith day, C_{NB} is the potential N concentration of the crop and B is the accumulated N (kg/ha).

The crop is allowed to take the N from any soil layer which has roots. Uptake starts at the upper layer and proceeds downward until the daily demand is met or until the entire N has been depleted. If the soil can not supply the daily N demand for legumes, the deficit is attributed to N fixation.

b. Phosphorous: The SWAT uses the partitioning pesticides in to solution and sediment phase approach (Knisel, 1980). Since P is mostly associated with the sediment, the soluble P runoff is expressed as below:

$$YSP = \frac{0.01(C_{LPP})(Q)}{k_d} \qquad \text{... 29}$$

where, YSP is the soluble P (kg/ha) lost in runoff volume Q (mm), C_{LPP} is the concentration of soluble P in soil layer (g/t) and k_d is the P concentration in the sediment divided by that of the water (m^3/t). C_{LPP} is constant for the whole simulation and initially inputted to the model. The value for k_d used in SWAT is 175.

Sediment associated P is simulated with a loading function and given as below:

$$YP = 0.01(Y)(C_p)(ER) \qquad \text{... 30}$$

where, YP is the sediment associated P loss in runoff (kg/ha), C_p is the concentration of P in the topsoil layer (g/t) and ER is the enrichment ratio.

SWAT uses P mineralization and P immobilization models developed by Jones et al. (1984) and are similar to the same for N. The daily amount of immobilization is computed by subtracting the amount of P contained in the crop residue from the amount assimilated by the microorganisms.

3.2 Routing Components

Once SWAT determines the loadings of water, sediment, nutrients and pesticides from the sub-watersheds/sub-basins, the loadings are routed through the stream network of the watershed using a command structure similar to that of HYMO (Williams and Hann, 1972). In addition to keeping track of mass flow in the channel, SWAT models the transformation of chemicals in the stream and streambed.

3.2.1 Channel flood routing

Channel reach routing operates on daily basis without any iteration. This makes the model efficient for long term simulation on large basins. It does not need any detail channel cross section data. Channel input includes the reach length, channel slope, channel depth, channel top width, channel side slope, channel "n" and flood plain "n". Flow rate and average velocity in channels are calculated using Manning's equation. Travel time is computed by dividing channel length by velocity. These calculations are made for full channel depth and a depth of 0.1 times the full depth. Travel time is then related to flow using the non-linear relationship as below:

$$TT = x_1 qr^{x_2} \qquad \text{... 31}$$

where, TT is the travel time (h), qr is the flow rate (m^3/h), and x_1 and x_2 are parameters determined for each channel reach when flow is with in channel.

The procedure is repeated for a depth 1.5 times the full depth. When the flow rate exceeds full channel depth during routing, the relationship becomes,

$$TT = x_3 qr^{x_4} \qquad \text{... 32}$$

where, x_3 and x_4 are parameters determined for each reach when flow exceeds full channel flow.

The storage coefficient (SC) is estimated by using Williams and Hann (1973) equation,

$$SC = \frac{48}{2TT + 24} \qquad \text{... 33}$$

Outflow from the channel reach is determined by the following equation,

$$O_i = SC(I_i + S_{i-1}) \qquad \text{... 34}$$

where, O is outflow (m^3), I is inflow (m^3) and S_{i-1} is storage in the channel reach from the previous day (m^3). Outflow is then adjusted for transmission losses, evaporation, and return flow.

Storage in the channel reach is calculated from the balance equation,

$$S_i = S_{i-1} - I_i - O_i - TL - EV + dv + rt \qquad \text{... 35}$$

where, TL is channel transmission losses (m^3), EV is evaporation (m^3), dv is diversion (m^3) and rt is return flow (m^3).

Transmission losses: Many semiarid watersheds have alluvial channels which abstract large quantities of stream flow (Lane, 1982). The abstractions or transmission losses reduces runoff volume and peak rate of downward travelling flood wave. Transmission losses are estimated by the following equation,

$$tl = (k)(DUR)(wp)(CHL) \qquad \text{... 36}$$

where, tl is channel transmission losses (m^3), k is the effective hydraulic conductivity of the channel alluvium (m/h), DUR is the flow duration (h), wp is the wetted perimeter (m) and CHL is the channel length (m). Values of k for various alluvium materials are provided in standard literatures (SCS Handbook of Hydrology, USDA 1972, Chapter 19).

A shortcut method was also developed to determine wp for a given flow rate to eliminate the need for iteration and this uses a non linear relation as given below:

$$wp = 1.02qr^{0.565} \qquad \ldots 37$$

The constant parametric values (1.02 and 0.565) were determined by running several hypothetical channels for various flow depths.

Evaporation losses: The volume of water lost to evaporation from channel reach is,

$$ev = \eta\,(ev_p)(sa_{rch})(DUR) \qquad \ldots 38$$

when, η is an evaporation coefficient, ev_p is potential evapotranspiration (m/h), sa_{rch} is the surface area of reach (m_2) and DUR is the flow duration (h). The surface area is simplified as below:

$$sa_{rch} = (CHL)(w) \qquad \ldots 39$$

where, CHL is the channel length and w is the channel width at flow depth.

3.2.2 Impoundment routing

Watersheds have usually two types of water impounding bodies, off-stream and on-stream. The first one is more common and referred to the ponds, which are fed by storm water only without any significant base-flow and designed for extended detention times. On-stream water bodies are located in an opportunistic manner along the main stream of the watershed and receive a continuous base-flow. The SWAT model provides three kinds of reservoir study options. First modelling of the small but controlled reservoirs which has measure outflow, second option designed for small, uncontrolled reservoirs, requires only a water release rate. When the reservoir volume exceeds the principle storage, the extra water is released at the specified release rate where as the volume exceeding the emergency spillway is released within one day. The third option, designed for larger, managed reservoirs which has the specified monthly target release volumes.

Impoundment routing component of SWAT was designed to account the effects of reservoirs, farm ponds and wetlands on water yield. The relationships used to estimate evaporation and seepage are identical for all the impoundment types. The water balance is given by,

$$V = V_{vstored} - V_{flowin} - V_{flowout} - V_{pcp} - V_{evap} - V_{seep} \qquad \ldots 40$$

where, V is the volume of water in the impoundment at the end of the day (m^3), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3), V_{flowin} is the volume of water entering the water body during the day (m^3), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3), V_{pcp} is the volume of precipitation falling on the water body during the day (m^3), V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3) and V_{seep} is the volume of water lost from the water body by seepage (m^3).

The evaporation volume is computed with the equation,

$$V_{evap} = 10(\eta)(E_o)(SA) \qquad \ldots 41$$

where, V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3), η is an evaporation coefficient (0.6), E_o is the potential evapotranspiration for a given day (mm) and SA is the surface area of the water body (ha).

The volume of water lost by seepage through the bottom of the water body on a given day is calculated:

$$V_{seep} = 240.K_{sat}.SA \qquad \ldots 42$$

where, V_{seep} is the volume of water lost from the water body by seepage (m^3), K_{sat} is the effective saturated hydraulic conductivity of (mm/h) and SA is the surface area of the water body (ha).

Surface area of the impoundment is calculated with the following relationship,

$$SA = \omega_1 (V_{stored})^{\omega_2} \qquad \ldots 43$$

where, (ω_1) is a parameter (1.3×10^{-4}) and (ω_2) is a fairly constant parameter (0.9). The SWAT model assumes $\omega_2 = 0.9$ and determines ω_1 for each sub-basin using SA_{mx} and maximum V_{stored}.

Based on the water body types, the outflow criteria vary. For farm ponds, outflow occurs when the volume exceeds the permanent pool storage capacity and is described as below:

$$\begin{array}{ll} V_{flowrate} = V - V_{mx} & V > V_{mx} \\ V_{flowout} = 0 & V \leq V_{mx} \end{array} \qquad \ldots 44$$

When, V_{mx} is the maximum permanent pool storage of all ponds in the sub-basin (m^3).

Small and large reservoirs outflow is simulated by a different approach. The reservoir water balance component is similar to the pond component except it allows flow from principal and emergency spillways and expressed as below:

$$\begin{aligned} QOR &= VR - VR_F && VR > VR_F \\ QOR &= (RR)(\Delta t) && VRs < VR \leq VR_F \\ QOR &= 0 && VR < VRs \end{aligned} \quad \ldots 45$$

where, QOR is the daily outflow (m_3), VR is the volume of water in reservoir (m^3), VR_F is the reservoir capacity at the emergency spillway crest (m^3), RR is the principal spillway release rate (m^3/s) and VRs is the reservoir capacity at the principal spillway crest (m^3).

For large, regulated flood control reservoirs, a simplistic approach is used to simulate outflow (Arnold et al., 1996), which tries to mimic general release rules that may be used by reservoirs operators. Although the model cannot account for all decision criteria, it can realistically simulate major outflows and low flow periods.

Additional operation rules can also be added to model specific reservoirs or reservoir system. For this situation, the principal or normal spillway volume corresponds to maximum flood control reservation, while the emergency spillway volume corresponds to no flood control reservation. The model requires the beginning and ending months of the flood season. It also uses a target storage approach based on flood season and the hydrologic condition of the watershed.

$$\begin{aligned} QO &= \left(\frac{VR - VR_T}{ND_T} \right) + QR_{mo} && \\ QO &= QR_{mo} && VR < VR_T \end{aligned} \quad \ldots 46$$

Where, VR_T is the target storage (m^3), ND_T are the number of days to return to target storage and QR is the daily minimum reservoir release for month (m^3).

In non-flood season, no flood control is required and the target storage is set at the emergency spillway volume. During the flood season, the flood control reservation (target storage) is the function of soil water content in the watershed. The flood control reservation for wet ground conditions (field capacity) is set at the maximum and for dry ground condition (wilting point) the flood control reservation is set at one-half the maximum.

$$VR_T = VR_s - 0.5(1 - SWF)VR_S - VR_F \quad \ldots 47$$

where, SWF is the soil water factor and is defined by the following equation,

$$SWF = \frac{SW_w}{fcw} \quad \ldots 48$$

where, SW_w is the soil water content (mm) and fcw is the field capacity of the watershed drainage area (mm).

3.2.3 Channel sediment routing

Channel sediment routing comprises two operations simultaneously; deposition and degradation. Deposition in the stream channel is based on the Stokes' Law fall velocity with an assumption of 22°C temperature and sediment density 1.2t/m^3 and equation becomes,

$$V_f = 411(d^2) \qquad \text{... 49}$$

where, V_f is the fall velocity (m/h) and d is the sediment particle diameter. The fall depth (y_f) for the sediment particle size d during time TT is,

$$y_f = (V_f)(TT) \qquad \text{... 50}$$

The sediment delivery ratio (DR) through the reach is estimated with the equation,

$$DR = \frac{1 - 0.5 y_t}{d_q} \qquad y_f \leq d_q \qquad \text{... 51}$$

$$DR = \frac{0.5(d_q)}{t_t} \qquad y_f > d_q \qquad \text{... 52}$$

where, d_f is the depth of flow.

Finally deposition is calculated with the equation,

$$DEP = SED_{IN} (1-DR) \ (53) \qquad \text{... 53}$$

Steam power function is used to predict degradation in routing reaches. Williams (1980) used Bagnold's (1977) definition of stream power to develop a method for determining degradation in channels. Bagnold defined stream power, SP, by the following equation,

$$SP = \gamma q \, S_W \qquad \text{... 54}$$

where, y is the density of water, q is the flow rate and S_W is the water surface slope. By using the stream power to bed load predictions Bagnold (1977) and estimating model parameters (Williams, 1980), the equation for sediment resuspension or degradation, DEG_R, is

$$DEG_R = \alpha_{sp} \gamma^{1.5} (dur)(w)(d_q S_w V_c)^{1.5} \qquad \text{... 55}$$

where, α_{sp} is a parameter dependent on maximum stream power for the reach and V_c is the velocity in channel.

The parameter α_{sp} is estimated with the equation,

$$\alpha_{sp} = (\gamma_w q S_c)_{mx}^{-0.5} \qquad \dots 56$$

where, S_c is the slope of channel and the subscript mx refer to the maximum flow expected in the reach for extreme events. The value of q is assumed to equal some maximum rainfall intensity (250 mm/h) and α_{sp} becomes

$$\alpha_{sp} = (69.44\gamma DAS_c)^{-0.5} \qquad \dots 57$$

where, DA is the area drained to the reach (km^2).

All the stream power is used for re-entrainment of loose and deposited material until all of the material has been removed. When this occurs, degradation of the bed material, DEG_B, begins

$$DEG_B = K\ C\ DEG_R \qquad \dots 58$$

where, K and are MUSLE (William and Berndt, 1977) factors for the stream channel. Total degradation, DEG, is the sum of re-entrainment and bed degradation components. This amount is also allowed to be deposited before reaching the basin outlet.

$$DEG = (DEG_R + DEG_B)\ (1\text{-}DR)$$

Finally, the amount of sediment reaching to the basin outlet, SED_{out}, is

$$SED_{out} = SED_{in} - DEP + DEG \qquad \dots 59$$

where, SED_{in} is the sediment entering to the reach.

3.2.4 Impoundment sediment routing

The route sediment through the channel goes to the reservoirs. The reservoir sediment Balance is,

$$SR_i = SR_{i-1} + SR_{in} - SR_{out} - SR_{dep} \qquad \dots 60$$

where, SR_i is the total sediment in reservoir, SR_{i-1} is the total sediment in the reservoir on the previous day, SR_{in} is the incoming sediment, SR_{out} is the sediment transported in the sediment outflow and SR_{dep} is the amount of sediment deposited in the reservoir.

Sediment outflow from the reservoir is calculated with the following equation,

$$SR_{out} = C_o q_o \qquad q_o > 0 \qquad \dots 61$$
$$SR_{out} = 0 \qquad q_o = 0$$

where, C_o is the outflow sediment concentration. The outflow concentration is a function of the reservoir concentration at the beginning and end of the day,

$$C_o = \frac{CS_1 + CS_2}{2} \qquad \dots 62$$

where, CS_1 and CS_2 are the reservoir sediment concentration at the beginning and the end of the day.

The initial reservoir concentration is the input to the model. The inflow concentration Can be calculated since q_i and SR_{in} are simulated, but the linal reservoir concentration is unknown. It can be computed using the continuity equation:

$$V_2 CS_2 = V_1 CS_1 - q_i C_i - q_o C_o \qquad \dots 63$$

where, V_1 and V_2 are the storage volumes at the beginning and the end of the day. C_i is the inflow sediment concentration.

From the equation (62) and (63) the final sediment concentration,

$$CS_2 = \frac{V_1 CS_1 + q_1 C_1 - \left(\frac{q_o}{2}\right) CS_1}{V_2 + \left(\frac{q_o}{2}\right)} \qquad \dots 64$$

Between storms, the final reservoir concentration decreases to an equilibrium concentration according to the equation:

$$C_s = (CS_2 - CS_o)\exp(-k_s.t.d_{50}) - CS_o \qquad \dots 65$$

where, CS is the reservoir concentration t days after the value of CS_2 is obtained, k_s is the decay constant, d_{50} is the median particle size of the inflow sediment and CS_e is the equilibrium sediment concentration (input to the model). Value of k_s is evaluated by assuming that 99% of the 1 μm particles are settled within 25 days (k_s =0.184).

3.2.5 Nutrient routing

Nitrate routing: Once NO_3-N enters to the stream from the land area, it is considered as a conservative material for the duration of an individual runoff event (Williams, 1980). Thus, NO_3-N routing is simply adding the yields from all the sub-watersheds to determine the watershed or basin yield.

Organic N routing: Sediment associated organic N from sub-basin outlet to the basin outlet is routed by loading function approach.

$$YON_{Bj} = 0.01(Y_B)_j(CONSB)_j(ER_R)_j \qquad \ldots 66$$

where, YON_{Bj} is the organic N runoff loss at the basin outlet (kg/ha), Y_B is the sediment yield reaching to the basin outlet from sub-basin j (t/ha), CONB is the concentration of organic N in the sediment reaching to the sub-basin j outlet (g/t) and ER_R is the enrichment ratio for the channel routing from sub-basin j to the channel outlet.

The delivery ratio for the channel routing is given by,

$$DR = \frac{(Y_{SB})}{Y_B} \qquad \ldots 67$$

where, Y_{SB} is the sediment yield at the sub-basin outlet (t/ha) and Y_B is the sediment yield from sub-basin j after it has been routed to the sub-basin outlet (t/ha).

Soluble P routing: As with NO_3-N routing, once the soluble P enters to the stream, it is considered as a conservative material and routed by adding the yields from all the sub-basins to determine the basin yield.

Sedimentary P routing: The sediment associated P is routed based on loading function approach from the sub-basin outlets to the basin outlet and given as below.

$$YP_{Bj} = 0.01(Y_B)_j(C_{PSB})_j(ER_R)_j \qquad \ldots 68$$

where, YP_{Bj} is the P yield at the basin outlet (kg/ha) and C_{PSB} is the P concentration in the sediment reaching to the sub-basin j outlet (g/t).

3.3 Model Input/Output Files

The model files are divided in to basin, sub-basin and data type files. This facilitates more sub-basins and simplified GIS linkages. The main input output files are as below.

3.3.1 Main/basin input files

file.cio	This is Control Input Output file and contains all the input and output files used by the model.
crop.dat	This is the crop database input file which contains crop specific parameters used by the model. It contains the biomass conversion factor, harvest index, optimum and base temperatures, maximum leaf area, maximum root depth and several other specified crop data specified to be planted in the management (.mgt) file.
till.dat	This is tillage database input file and contains mixing efficiencies for a number of tillage operations can be selected in the management (.mgt) file.
cod	This is input control code file. It contains the number of years of simulation, beginning year, print codes, weather generation control codes and several others. All the inputs are common to the entire basin and not sub-basin dependent.
bsn	This is general basin input file. It contains input that are relevant to the entire basin that include drainage area, base-flow factors and initial soil water content.
pcp	This is measured precipitation (rainfall) input file. Daily rainfall values in mm are stored in this file.
tmp	This is measured temperature input file. Daily maximum and minimum temperature values in Celsius are stored in this file.
res	It is reservoir input file which contains reservoir data like surface area, storage for emergency and principal spillway, release rate, normal sediment concentration, beginning and ending months of flood, month and year of becoming operational etc.

3.3.2 Sub-basin input files

sub	This is general sub-basin input file which contains general inputs like curve number, land and channel slope and depths, USLE factor and initial residue cover.
rte	This is sub-basin routing file and contains information on channel dimensions for the main channel through sub-basin.
pnd	This is ponding input file and contains information about surface area, storage, normal sediment concentration and conductivity of the pond bottom.
sol	This is soil input file and contains soil data including bulk density, available water capacity, saturated conductivity, particle size distribution, organic carbon and maximum rooting depth. Each soil can have maximum 10 soil layers.
mgt	This is management input file. This contains input data for management operations for planting, harvest, irrigation, nutrient, pesticide and tillage operations.
gw	This is groundwater input file. It contains aquifer data including a recession parameter, specific yield, a revap coefficient and a deep aquifer percolation coefficient.

3.3.3 Output files

std	This is standard output file and contains all the model input informations and annual summery for the basin.
sbs	This is sub-basin output file. It reports output for each sub-basin by day, month and year related to water, sediment, nutrient and crops.
rch	This is channel reach output file. It reports output for each stream channel routing reach by day, month and year. Output variables include water, sediment and pollutants entering and leaving the reach.
rsv	This is reservoir output file. It reports output for each reservoir by day, month and year for water and sediment entering, leaving and deposited in the reservoirs.

4.0 THE DIKRONG RIVER BASIN

The state of Arunachal Pradesh lies between 28° N latitude and 95° E longitude with wet tropical climate having high humidity. Arunachal Pradesh falls under upper Brahmaputra River system constituted by 10 major river basins, viz., Tawang, Kameng, Dikrong, Subansiri, Siang, Sesseri, Dibang-Tellu and Tirap-Tiso. In Arunachal Pradesh, the River Dikrong is named after joining two main rivers – Pachin and Pare.

The Dikrong River Basin is one of the ten major river basins of Arunachal Pradesh. The Dikrong River Basin is situated in the western part of the Arunachal Pradesh between 27°00' to 27°25' N latitude and 93°00' to 94°15'E longitude (Fig. 4.1). The total area of the catchment is 1556 km^2, out of which 1278 km^2 falls in Arunachal Pradesh and rest in Assam. The total length of the Dikrong River is 145 km, out of which 113 km length is within Arunachal Pradesh and 32 km in Assam. Main Boundary thrust is dividing the basin into Lesser Himalaya and Outer Himalaya (Siwalik) in the north and south respectively. The southern (Lower) portion is made of Quaternary period and reported tectonically very unstable. Altitude ranges from 92 to 2,846 m above mean sea level. The Lower Dikrong river basin is under very humid environment. The annual average rainfall during monsoon season varies between 1519.4 and 4169.4 mm. The temperature of the study area varies widely between 10°C and 32°C.

The watershed of Dikrong River mainly consists of light textured unstable soils with prevalent practice of shifting cultivation which makes the whole watershed prone to soil erosion. The wet tropical and sub-tropical climate accompanied with humid condition favour the disintegration of the top layers of soil through the influence of several hydrologic factors, soil conditions, topographic conditions, which prevails in most part of the Arunachal Pradesh. In every monsoon the River Dikrong carries tremendous amount of silt, gravel, small boulder and causes flood in some parts of the catchment susceptible to erosion. This indicates serious threat to soil resources and there is a need for assessment of soil erosion and its control in the Dikrong river basin. The soil loss rate through Dikrong River is 100.98 t/ha/year (Singh, 1999).

With prevalent jhum cultivation practices, river basin is very much prone to soil erosion and other soil degradation activities which call for sustainable management practices. There is a need to develop appropriate management plans for soil conservation and water resources development to increase the productivity in sustainable manner. Moreover, Dikrong river basin is mostly un-gauged and there is no instrument installed to estimate sedimentation rate. Therefore, there is need for prioritization of the sub-watersheds. Pandey et al. (2007) has developed a DSS for prioritization and development of integrated watershed management plan for the Dikrong Basin in Arunachal Pradesh using morphological parameters. The developed DSS can help the end users for watershed prioritization and to suggest various watershed management practices.

The present study is limited to the part of the catchment which falls within Arunachal Pradesh only and was further shortened by DEM analysis to take up the modelling of daily surface runoff in terms of inflow to proposed Pare reservoir of PHEP (Pare Hydro-Electric Project) at Hoz, where observed daily discharges were available. This site is situated on Pare River upstream of the confluence of Pachin and Pare. The basin lacks hydro meteorological data which is a basic input for any rainfall-runoff modelling study. Only six rain gauge stations exit in the basin for which the data availability is scanty and not concurrent.

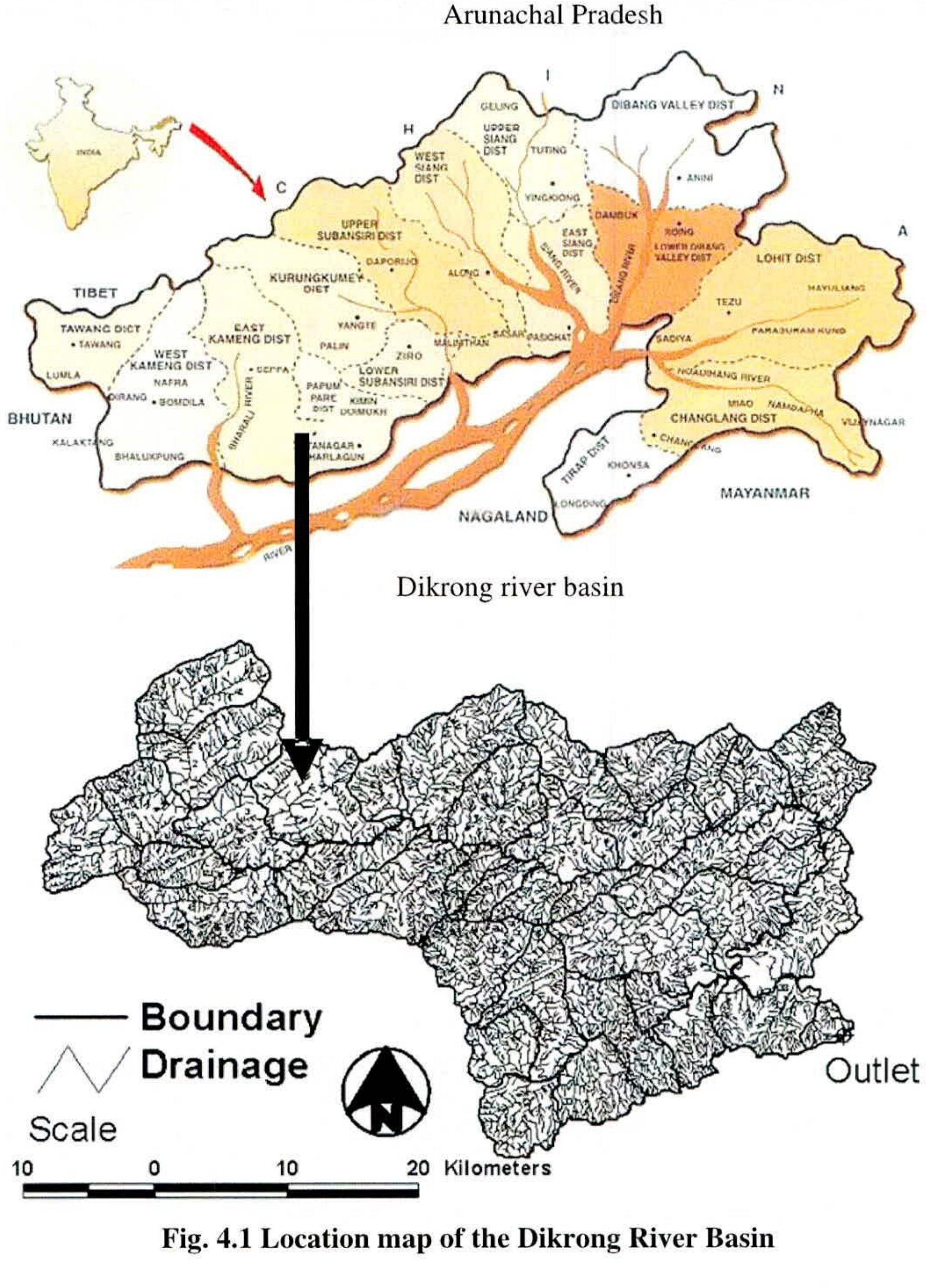


Fig. 4.1 Location map of the Dikrong River Basin

5.0 METHODOLOGY

5.1 Data Acquisition and Preprocessing

5.1.1 Hydrological data

Daily rainfall data at the six raingauge stations within the catchment, namely, Leporiang, Sagalee, Loptop, Ompuli, Hoz, and Jampa, and daily discharge data at Hoz, the proposed Pare reservoir site of PHEP (Pare Hydro-Electric Project) were collected from NEEPCO PHEP authorities through Chief Engineer, Water Resources Department, Govt. of Arunachal Pradesh. However, it was observed that the data were not concurrent and hence not suitable for modelling. After preliminary analysis two periods (June 2005 to July 2007 and September 2007 to September 2008) were identified for which concurrent rainfall data for four raingauge stations (Leporiang, Sagalee, Ompuli, and Hoz) and discharge data at Hoz were available. Hence the first set of data (June 2005 to July 2007) was used for calibration and the second set of data (September 2007 to September 2008) for validation of the model.

5.1.2 Topographic data

Scanned Survey of India toposheets of the watershed area (83 E/3, 83 E/4, 83 E/7, 83 E/8, 83 E/11, 83 E/12, 83 E/15, and 83 E/16) in the scale of 1:50,000 were collected from the office of the Chief Engineer, Water Resources Department, Govt. of Arunachal Pradesh. These toposheets were then georectified (into geographic coordinate system), mosaiced, and projected (into polyconic projection system) to have a single projected raster for the entire study area. The elevation contour lines were digitized from this raster into an Arc Coverage (Fig. 5.1), which was later used to form the DEM required by AvSWAT. Softwares used in this process are ERDAS Imagine 9.1 Professional and ArcGIS Desktop 9.3 (ArcInfo License).

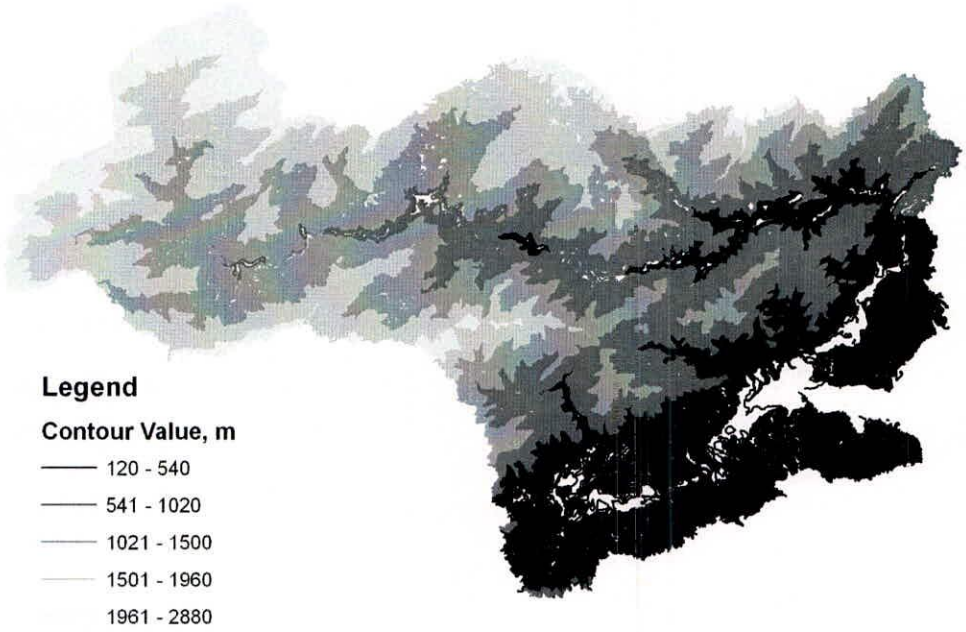


Fig. 5.1 Digitized contour map of the basin

5.1.3 Drainage network

The drainage network map of the study area was collected from NEEPCO PHEP office located at Doimukh, Arunachal Pradesh. This map was scanned, georectified, projected and digitized into an Arc Coverage (Fig. 5.2), which was later burned in to the DEM in AvSWAT to support sub-basin delineation.

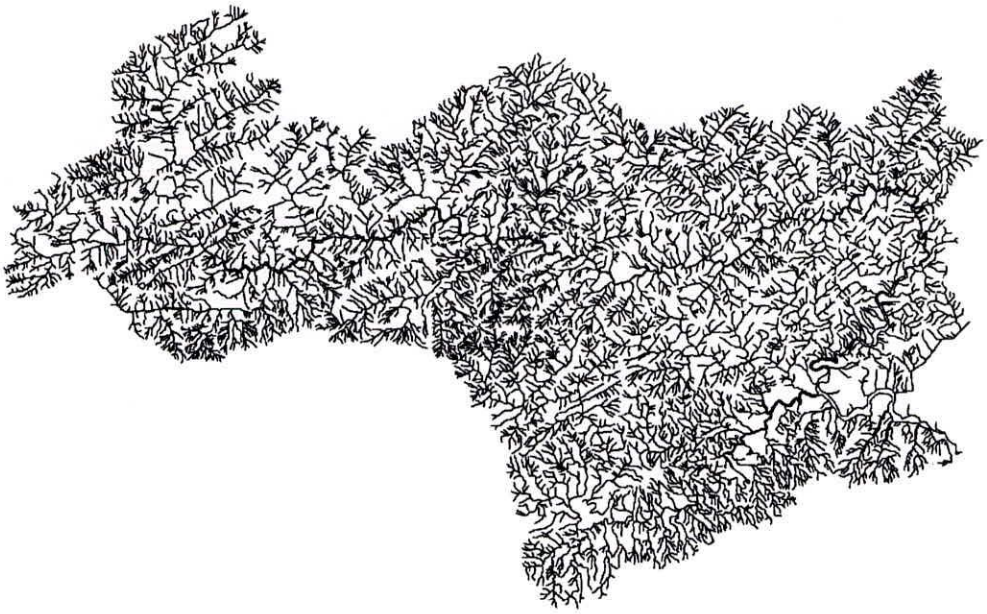


Fig. 5.2 Digitized drainage network map of the basin

5.1.4 Soil

The soils of Dikrong river basin are grouped under loam, silt clay and silt loam which are found to be 80.62, 7.29 and 12.09% respectively of the total area of the river basin (Table 5.1). The maximum area of the river basin falls under hydrologic soil group 'B' (Pandey and Dabral, 2004).

Table 5.1 Soil type and hydrologic soil group of Dikrong River Basin

Soil Type	Area (km^2)	% of total area	Hydrologic Soil Group
Loam	1007.75	80.62	B
Silt Clay	91.12	7.29	C
Silt Loam	151.125	12.09	C

Soil map of Arunachal Pradesh was collected from State Land Use Board of Arunachal Pradesh. This map was scanned, georectified, projected and digitized into a Polygon Coverage (Fig. 5.3), which was later used to overlay soil information on the DEM in AvSWAT. The soil properties were taken from SLUB Publication 18 (Srivastava, 2000) which accompanies the soil map. Primarily three textural soil classes exist in the basin, namely, Silt Clay, Loam and Silt Loam. However, total 10 types of soils varying in other properties were found in the study area, namely, Ar7, Ar9, Ar10, Ar11, Ar17, Ar18, Ar19, Ar20, Ar22 and Ar23. Among these Ar7 is Silt Clay, Ar23 is Silt Loam, and others are Loam.

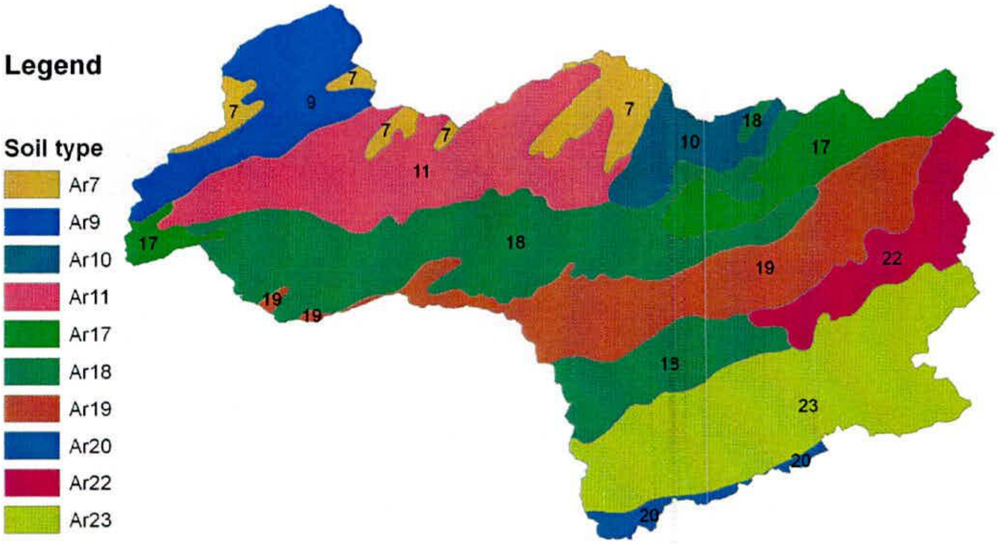


Fig. 5.3 Soil map of the basin

5.1.5 Land use

The land use map in terms of Polygon Coverage (Fig. 5.4) was collected from Department of Agricultural Engineering, North Eastern Regional Institute of Science and Technology (NERIST), Nirjuli, Itanagar (Arunachal Pradesh). This coverage was prepared by land use classification of IRS-1D LISS III geocoded imagery of 16 November 2001 and 14 December 2001. Details of the classification procedure and accuracy of classification are given in Dabral et al. (2008).

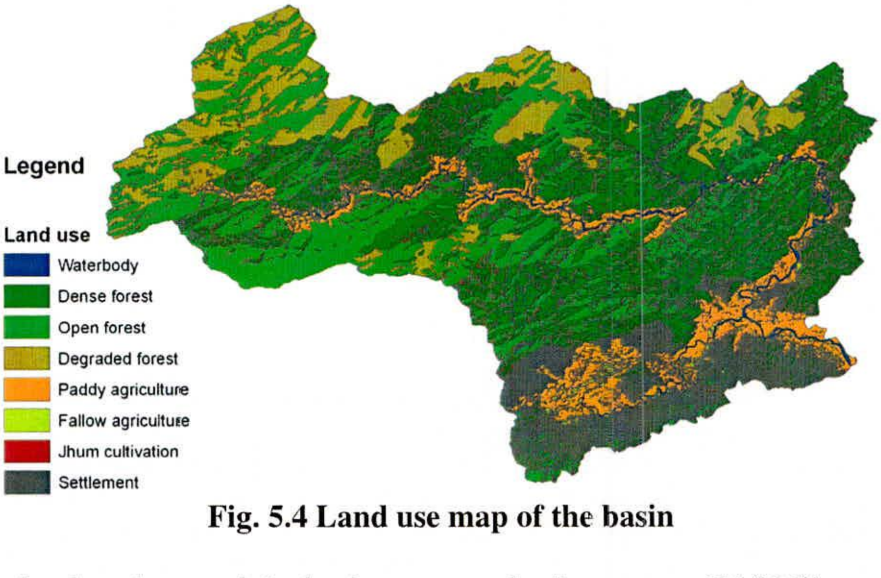


Fig. 5.4 Land use map of the basin

In the developed map eight land uses namely forest area (35.92%), open forest area (48.95%), cultivated land (1.7%), paddy cultivation (1.05%), waste land (3.8%), water body (0.00000796%), habitant (0.46%) and unclassified (8.13%) were identified.

Table 5.2 Land use/Land cover classification of Dikrong River Basin

S.No.	Land Use	Area (km^2)	% of total area
1.	Dense forest	449	35.92
2.	Open forest (Open forest + Scrub + Grass land)	611.775	48.95
3.	Cultivated land (Row crop + Jhum crops)	21.25	1.70
4.	Paddy cultivation	13.125	1.05
5.	Waste land (Abundant Jhum)	47.50	3.80
6.	Water body	9.95×10^{-5}	0.00000796
7.	Habitant (Rural + Urban)	5.75	0.46
8.	Unclassified	101.525	8.13

5.1.6 Digital elevation model (DEM)

As mentioned above, the DEM (Fig. 5.5) of the basin was prepared from the digitized countour map with a cell size of 45m x 45m. This DEM was used as the base information in AvSWAT.

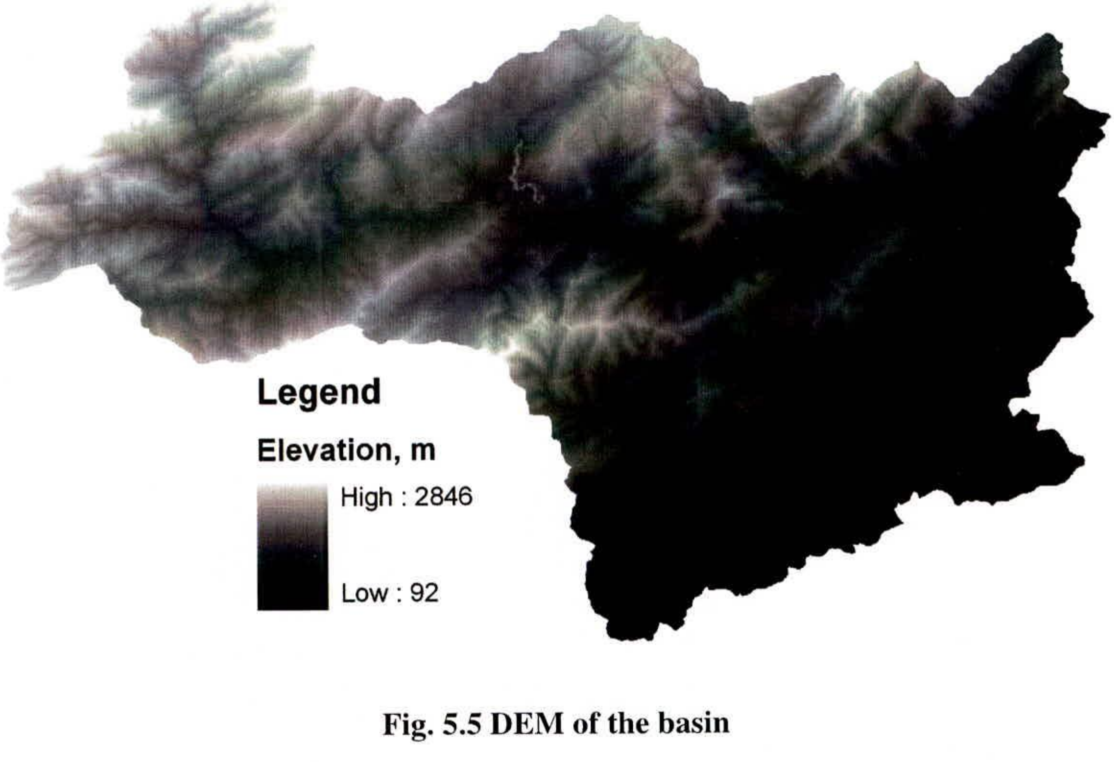


Fig. 5.5 DEM of the basin

5.2 Model Description and Setup

5.2.1 SWAT

SWAT is a long term, physically based, continuous simulation watershed model. It has capabilities of simulating surface runoff, sediment yield and nutrient losses from small, medium and large watersheds. It can be applied to a large ungauged rural watershed with more than 100 small sub-watersheds. Conceptually, SWAT divides a watershed into sub-basins. The use of sub-basins in a simulation is particularly beneficial when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology. By partitioning the watershed into sub-basins, the user is able to reference different areas of the watershed spatially. Each sub-basin is connected through a stream channel and further divided in to Hydrologic Response Units (HRU). HRU is a unique combination of a soil and a vegetation type in a sub-basin and SWAT simulates hydrology, vegetation growth and management practices at the HRU level. Water, nutrients, sediment and other pollutants from each HRU are summarized in each sub-basin and then routed through the stream network to the watershed outlet.

5.2.2 AvSWAT

ArcView GIS, extended and integrated with a hydrologic non-point pollution model SWAT, provides a comprehensive watershed assessment tool (AvSWAT) designed to assist water resource managers. AvSWAT improves the efficiency of analysis for non-point and point source pollutions and control on watershed scale. AvSWAT is a user friendly, unique and single modelling environment based on several user interface tools developed using Dialog Designer extension and able to run on Windows as well as on UNIX platforms.

Within this system (Fig. 5.6) ArcView provides both the GIS computation engine and a common Windows-based user interface. AvSWAT is organized in a sequence of several linked tools grouped in the following eight modules: (1) Watershed Delineation, (2) HRU Definition, (3) Definition of the Weather Stations, (4) AvSWAT Databases, (5) Input Parameterization, Editing, and Scenario Management, (6) Model Execution, (7) Read and Map-Chart Results and (8) Calibration tool. Once AvSWAT is loaded, the modules get embedded into ArcView, and the tools are accessed through pull-down menus and other controls, which are introduced in various ArcView graphical user interfaces (GUIs) and custom dialogs. The basic map inputs required for the AvSWAT include digital elevation, soil maps, land use/cover, hydrography (stream lines) and climate. In addition, the interface requires the designation of land use, soil and rainfall data as well as the simulation period to ensure a successful simulation.

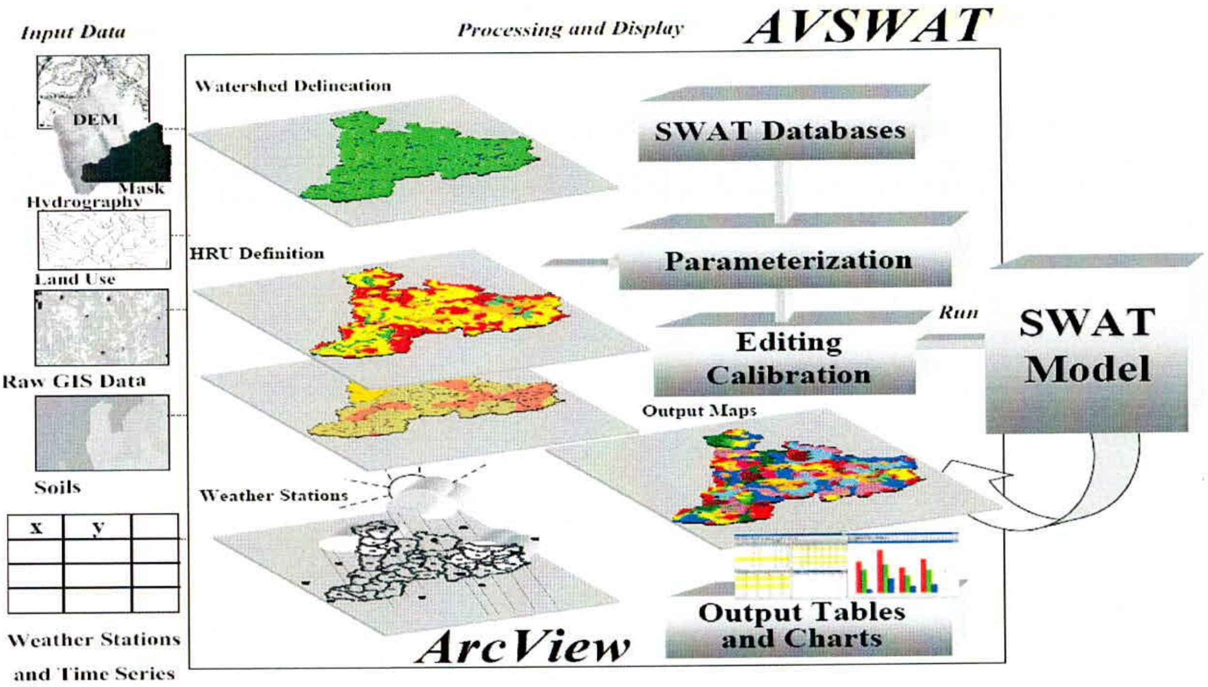


Fig. 5.6 Schematic of AvSWAT model

5.2.3 Model setup

After preprocessing of all necessary collected data as described above, set up for SWAT model was prepared. Details of model set up are discussed below.

5.2.3.1 Watershed delineation

The standard methodology, based on eight-pour algorithm (Jenson and Domingue, 1988) for delineating streams from a raster DEM was applied. Cells are potentially part of a stream network. The stream branches are controlled by the user specified threshold on contributing number of grid cells, which creates the stream branches. The default definition of the sub watershed outlets is accomplished in locating the downstream edge of each stream branch. Once the sub watershed outlet locations are specified, the main watershed outlet can be defined using customized selection tool. At this point, location of Hoz, where observed discharge values are available, was selected as the main watershed outlet, which led to 17 delineated sub-basins (Fig. 5.7). After the watershed and sub watersheds boundaries are delineated, all the geometric parameters of each sub watersheds and stream reaches are calculated by raster-grid functions and stored as attributes of derived vector themes.

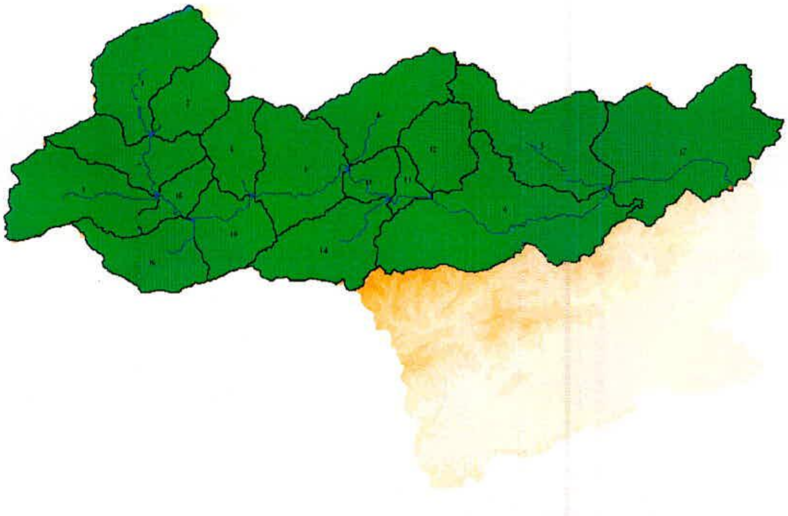
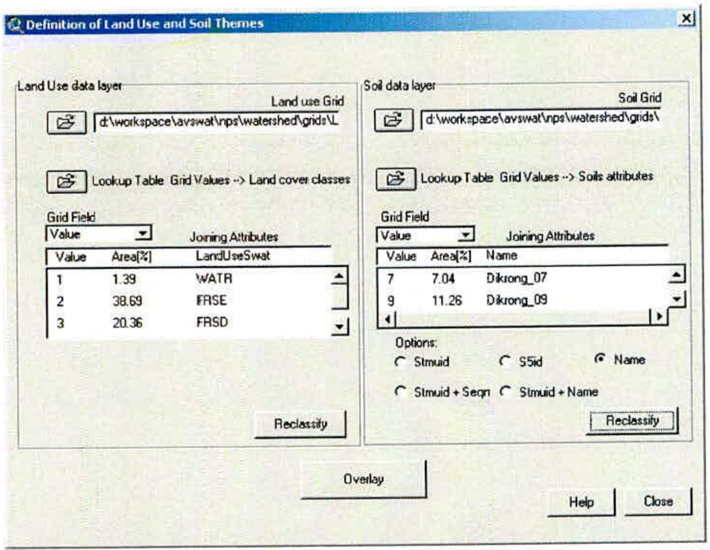


Fig. 5.7 Delineated sub-basins on the DEM of the basin

It can be seen that apart from the southeast part of the basin, which is excluded because it drains to the river downstream of the selected outlet (Hoz), the delineated watershed boundary perfectly matched with the actual DEM boundary. The total catchment area up to Hoz discharge site was 829 km^2.

3.2.3.2 HRU distribution

Soil and land use maps of the study area were converted to grids from polygon coverages and imported to AvSWAT. After importing and linking the soil and land use themes into the SWAT database (Fig. 5.8), hydrologic response units (HRUs) distribution was determined by dominating soil and land use types within each sub-basin. The HRUs are the portions of a sub watershed that possess unique land use, management, and soil attributes. Before the soil theme could be linked to the SWAT database, the properties of each soil type of Dikrong basin were included into the SWAT database usersoil.dbf.



Land Use data layer

Land use Grid: d:\workspace\avswat\nps\watershed\grids\L

Lookup Table Grid Values --> Land cover classes

Grid Field: Value

Joining Attributes

Value	Area[%]	LandUseSwat
1	1.39	WATR
2	38.69	FRSE
3	20.36	FRSD

Soil data layer

Soil Grid: d:\workspace\avswat\nps\watershed\grids\

Lookup Table Grid Values --> Soils attributes

Grid Field: Value

Joining Attributes

Value	Area[%]	Name
7	7.04	Dikrong_07
9	11.26	Dikrong_09

Options:
○ Stmuid ○ S5id ● Name
○ Stmuid + Seqn ○ Stmuid + Name

Fig. 5.8 Definition of land use and soil themes (AvSWAT Window)

5.2.3.3 *SWAT view*

After the HRUs are created by overlaying soil and land use themes over the delineated sub-basins, the SWAT view (Fig. 5.9) is generated within the current ArcView project. The SWAT view allows the user to input the raingauge locations. The rainfall values measured at these raingauges are to be supplied through separate input files made in accordance with the format given in the SWAT user manual. Apart from weather parameters, the SWAT view also allows for changes in a large number of other parameters of the sub-basins which were not used in this study as the scope of this study was limited to rainfall-runoff modelling only.

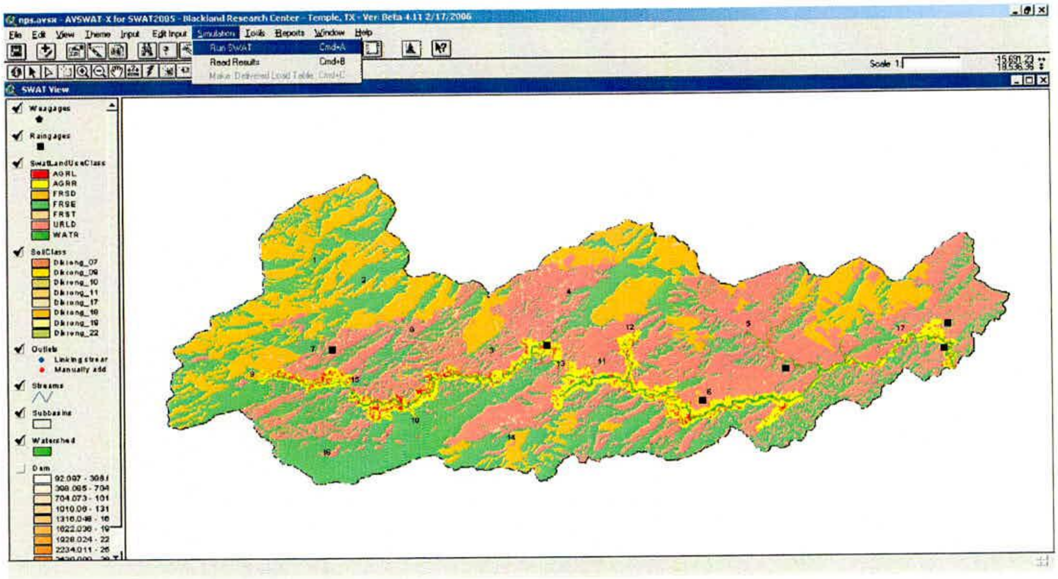
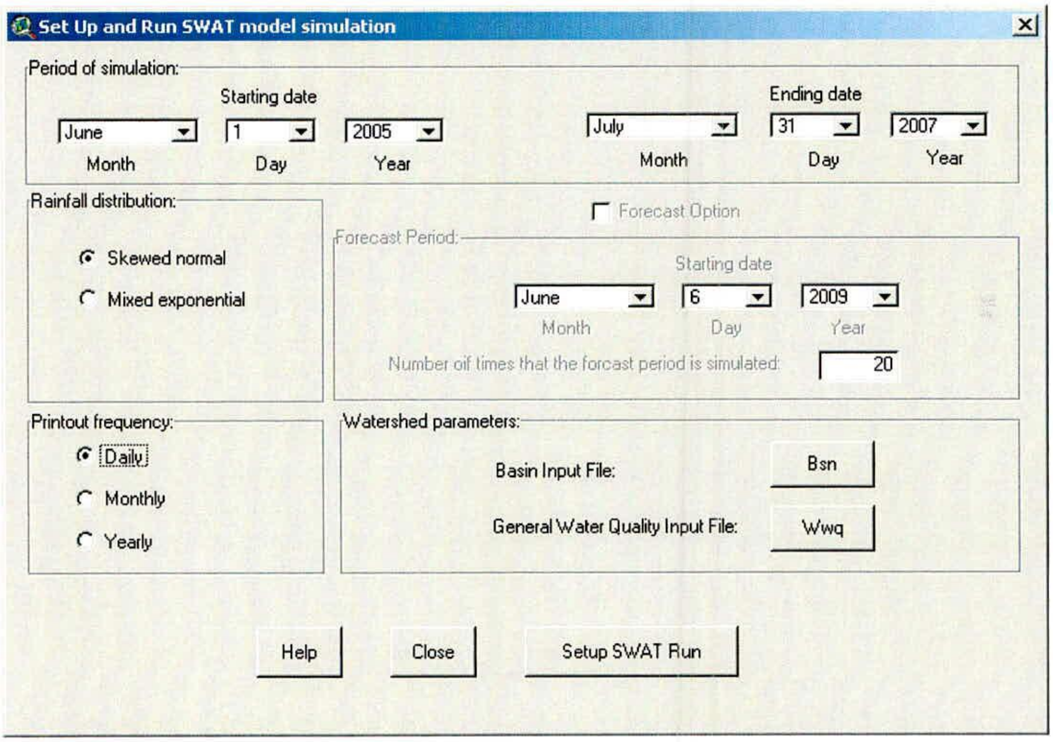


Fig. 5.9 SWAT view

5.2.3.4 Running SWAT and viewing results

The Set Up and Run SWAT model simulation window (Fig. 5.10) provides the option of selection of the time period for which the simulation is to be run among others. The Setup SWAT Run button creates the input files needed by the SWAT2005 executable file (SWAT2003.exe) and executes SWAT2005 (Fig. 5.11). The model also allows the variables to be updated from outside the ArcView interface by asking the user to update the .dbf files of the respective input parameters that have been created by the interface. The simulation was executed a number of times while varying the calibration parameters till the model was calibrated to satisfactorily match the simulated runoff with the observed values. After the model is successfully simulated, all the results of the simulation can be read through the read results option. The outflow from reach 17 was compared to the observed runoff at Hoz site.



Set Up and Run SWAT model simulation

Period of simulation:

Starting date: Month June, Day 1, Year 2005

Ending date: Month July, Day 31, Year 2007

Rainfall distribution:

● Skewed normal

○ Mixed exponential

☐ Forecast Option

Forecast Period:

Starting date: Month June, Day 6, Year 2009

Number of times that the forcast period is simulated: 20

Printout frequency:

● Daily

○ Monthly

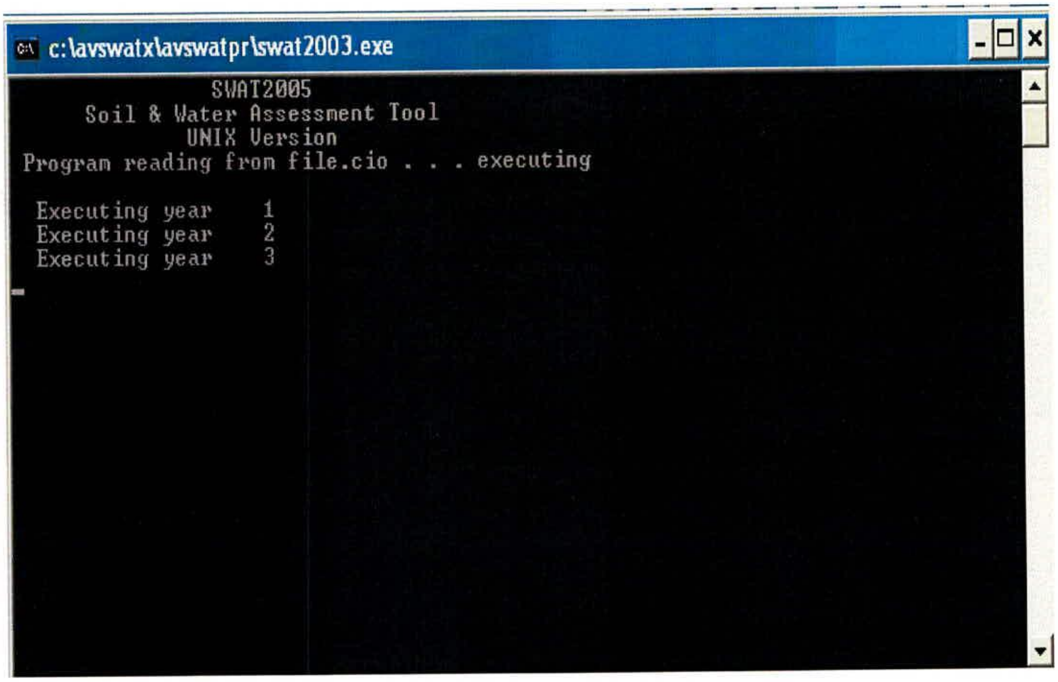
○ Yearly

Watershed parameters:

Basin Input File: Bsn

General Water Quality Input File: Wwq

Fig. 5.10 Set Up and Run SWAT model simulation window



```
                SWAT2005
     Soil & Water Assessment Tool
             UNIX Version
Program reading from file.cio . . . executing

 Executing year    1
 Executing year    2
 Executing year    3
```

Fig. 5.11 SWAT2005 Execution

5.3 Model Evaluation

The performance of the model can be visually interpreted by plotting the simulated data against the observed data simultaneously on a single plot. However, statistical tests can give the quantitative performance of the prediction. Here, three dimensionless statistical performance criteria, viz., Modelling Efficiency (ME), Coefficient of Residual Mass (CRM), and coefficient of determination (r^2) were used for the purpose.

$$\mathrm{ME} = \frac{\left[\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n}\left(P_i - O_i\right)^2\right]}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \qquad \ldots 1$$

$$\mathrm{CRM} = \frac{\left[\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i\right]}{\sum_{i=1}^{n} O_i} \qquad \ldots 2$$

$$r^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \bar{O}) \cdot (P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2 \cdot \sum_{i=1}^{n} (P_i - \bar{P})^2}} \right)^2 \qquad \ldots 3$$

where, P_i = predicted or simulated discharge; O_i = observed discharge; and n = number of data used for evaluation.

For a perfect model, the value of ME is 1.0, i.e., when the simulated values match perfectly with the observed ones. A lower value (close to 0) of ME indicates poor performance of the model and a negative value indicates that the model-simulated values are worse than simply using observed mean. CRM indicates the overall under- or over-estimation of the observed values. For a perfect model, the value of CRM is zero. A positive value of CRM indicates the tendency of the model to under-estimate, whereas, a negative value indicates a tendency to over-estimate the observed data.

6.0 RESULTS AND DISCUSSION

6.1 Hydrological Processes

Hydrological processes are the occurrence and distribution of water over and below the land surface, in the form of precipitation, runoff, evaporation, transpiration, infiltration, percolation, seepage, interception, depression storage, soil water storage and its movement. A precise study of these processes is needed to increase the use efficiency of the resources and improve the watershed environment (Schwab et al., 1981).

Precipitation and interception affect the amount, timing and spatial distribution of the deposition of atmospheric water on the surface of the watershed and, as such, provide the principal input into the hydrologic cycle. Most of the studies on hydrology have focused upon processes including interception and sublimation (Pomeroy et al., 1999), evaporation (Lafleur et al., 1992; Granger, 1999), infiltration, soil storage and runoff (Slaughter and Kane, 1979; Kane et al., 1979; Kane and Stein, 1983; Carey and Woo, 1999, 2000). Few studies have examined the spatial and seasonal variability of the water cycle. Metcalfe and Buttle (1999) analysed sub-basin water balance in a boreal forest catchment with discontinuous permafrost and noted large differences in fluxes controlled by variations in snow conditions, rainfall characteristics, thaw depths and storage properties.

The soils of the watershed have prominent hydrologic role effecting water storage and transmittance properties (McNamara et al., 1998; Carey and Woo, 1999). Topography of the area plays an important role in surface and subsurface runoff. Freer et al., (1997), characterized the topographic controls on subsurface storm flow on small catchments. Carey and Woo (2001), examined the aspect, exposure, vegetation and slope as factors that cause the variation in timing and magnitude of hydrological processes in a subarctic, subalpine environment and presented as spatial variability of hill slope water balance. Generated runoff is highly affected by the soil water content and rainfall characteristics (Seeger et al., 2004) which affect infiltration capacity and the capability of soils to store rainwater as reflected in many physically based hydrological models (Bronstert, 1994; Bronstert et al., 1998). Knowledge of the basic hydrologic processes occurring on watersheds gives us a better understanding of how land use impacts on our soil and water resources. Change in land use/land cover is also considered potential component of hydrology which affects storm runoff generation (Naef et al., 2002) and is often assessed by rainfall-runoff model simulations (Bultot et al., 1990; Parkin et al., 1996).

6.2 Model Calibration

The model is built with state-of-art components to simulate the rainfall-runoff process physically and realistically. Most of the model inputs are physically based. The successful application of model depends on how well the model is calibrated. The model was calibrated for daily discharge at Hoz from 1 June 2005 to 31 July 2007. The calibration tool in the simulation menu of AvSWAT allows performing global changes on input parameters that are commonly modified during the calibration process. The Manning's n value for overland and channel flows were considered for calibration. A range of 0.005-0.085 for channel 'n' value was selected (Neitsch et al. 2001). Different values were chosen within the range and model was run to simulate surface runoff. Similiarly, overland flow 'n' values were considered between 0.006-0.200 and simulation runs were performed. After each parameter adjustment and simulation run, performance indicators were determined. The simulated and the observed hydrographs for the daily runoff were also compared visually to examine the improvement in the match.

The results of calibration run are shown in Fig. 6.1 and the performance indicators are presented in Table 6.1. The best results were obtained for both overland and channel Manning's n = 0.014.

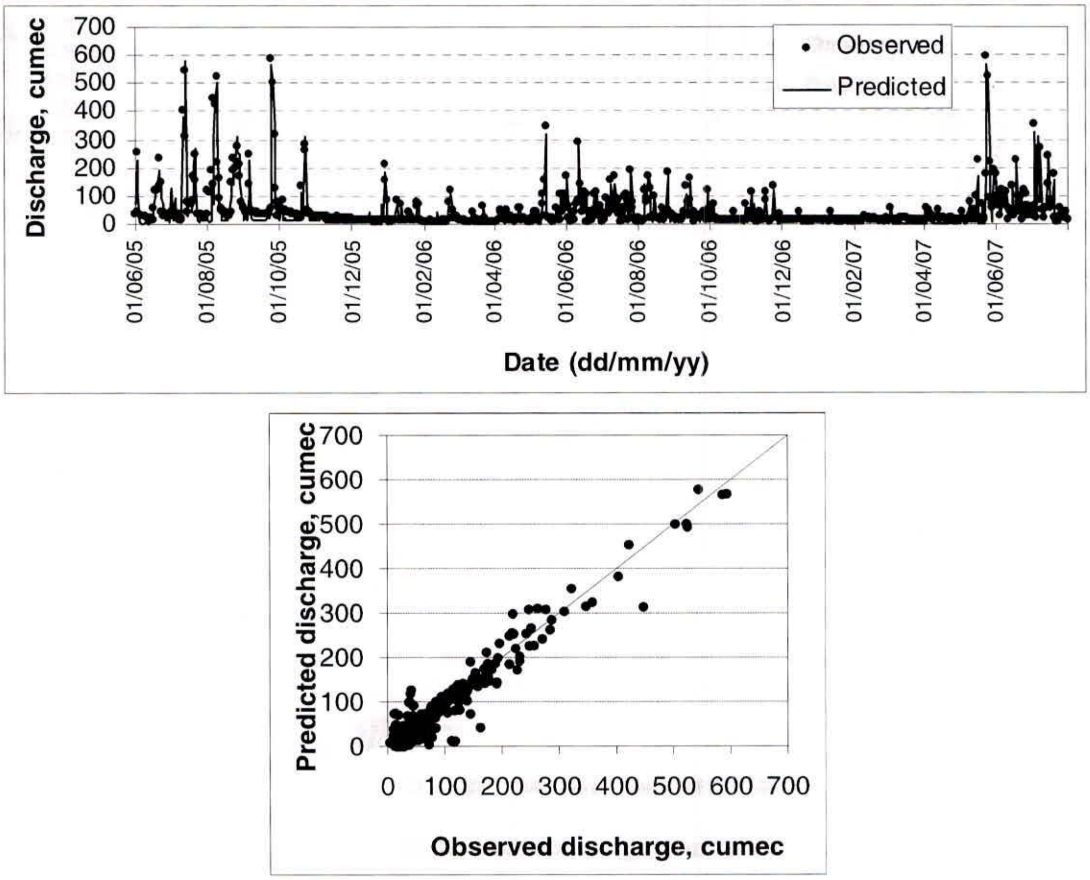


Fig. 6.1 Time series and 1:1 plots of observed vs. simulated discharges at Hoz (Calibration)

Table 6.1 Performance of calibration run (observed vs. simulated discharges at Hoz)

ME	0.932
CRM	0.137
r^2	0.942

It can be observed that the calibrated model has been able to model the peaks quite accurately but has failed to model the low discharges (below 30 cumec) in the river satisfactorily. For low flows, the model predicted discharge was below the observed discharges consistently. A positive CRM also shows that the model slightly under-predicted the discharge which might have arisen out of these low flow under-predictions.

6.3 Model Validation

Proper validation of the calibrated model is essential to understand its performance without any change in the input files except the climatic parameters. The daily values of precipitation for the time period for which the model is being validated is set as the input data for the model. The model was validated for daily discharge at Hoz from 1 September 2007 to 30 September 2008. Daily simulated runoff at Hoz was compared with the observed ones and the results presented below.

The results of validation run are shown in Fig. 6.2 and the performance indicators are presented in Table 6.2.

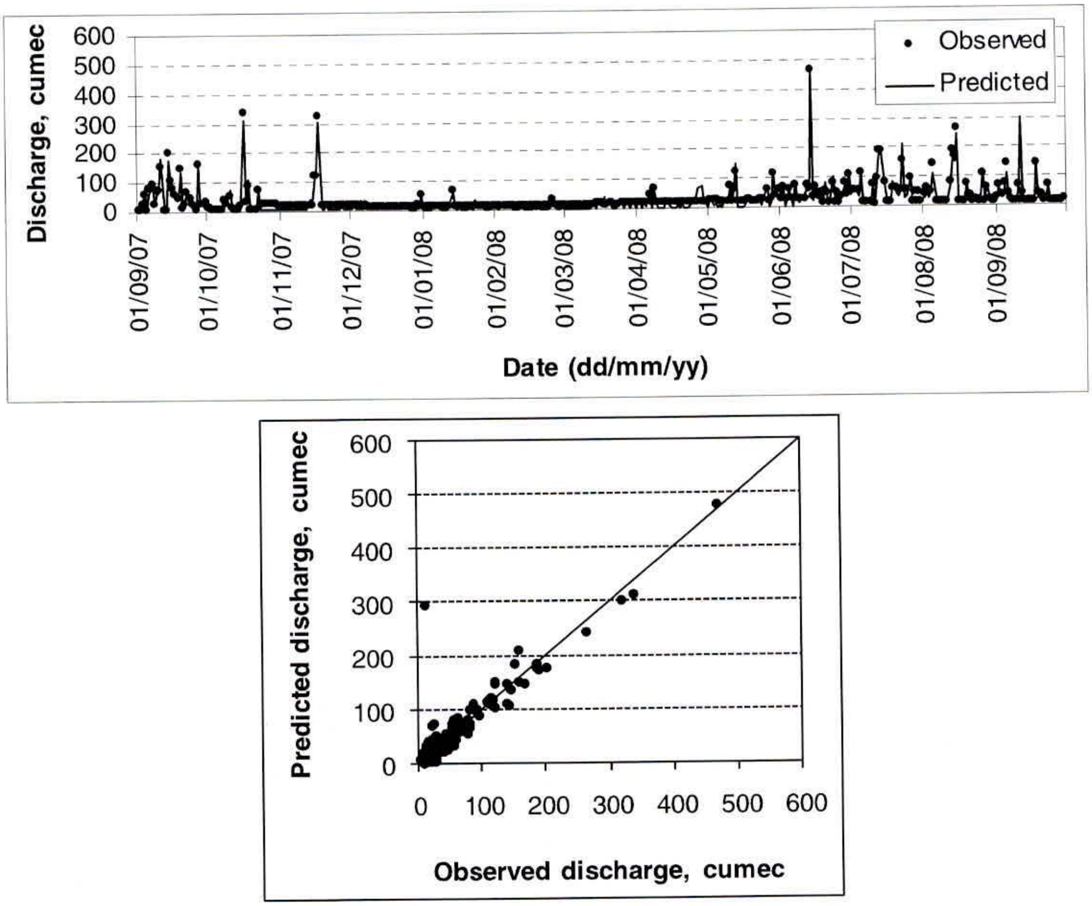


Fig. 6.2 Time series and 1:1 plots of observed vs. simulated discharges at Hoz (Validation)

Table 6.2 Performance of validation run (observed vs. simulated discharges at Hoz)

ME	0.826
CRM	0.133
r^2	0.859

In the validation run, though the performance of the model deteriorated a little, but peaks were still well-matched with observed values. Similar to calibration, in this case also the model under-predicted the low flows in the river during winter months but modelled the peaks really well during the monsoon months. A positive CRM of almost same value shows that the tendency of the model to under-predict observed flow remained unchanged in the validation run also.

7.0 SUMMARY AND CONCLUSION

Large area water resources development and management requires an understanding of basic hydrologic processes and simulation capabilities at the river basin scale. SWAT (Soil and Water Assessment Tool) is one of the recently developed distributed parameter hydrologic models. The model is a physically based continuous time, long-term simulation, lumped parameter and deterministic model. In this study, AvSWAT, an ArcView Extension for SWAT model, has been used for simulating daily surface runoff from Dikrong river basin in Arunachal Pradesh. The major objective of the study was to calibrate and validate AvSWAT for simulating daily discharge at Hoz, the proposed dam site on Pare River under PHEP (Pare Hydro-Electric Project).

The model was calibrated and validated for periods June 2005 to July 2007 and September 2007 to September 2008, respectively. Model was calibrated using the Manning's n parameter for overland and channel flows. Calibration and validation results revealed that model was predicting daily surface runoff in terms of inflow to proposed Pare reservoir of PHEP at Hoz satisfactorily.

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