Investigation of Nutrient Transport in A Semi-arid, Tropical, Agricultural Watershed Using A Process Based Model

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Declaration

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Dedication

To my father, mother and younger sister

Abstract

The contribution of agriculture and its allied sectors to Indian GDP has continuously decreased from 18.26% in 2007 to 14.10% in 2012. One of the three reasons attributed by World Bank to this decrease includes lack of adopting innovative agricultural practices by analyzing the soil-crop-water relations specific to the region. Nitrogen and Phosphorous dominant fertilizers are extensively applied by farmers of India for increased crop yield with no proper attention given to the amount applied, timing of application, and effect on ecosystem balance. Excessive application of nutrients results in leaching, eutrophication and pollution of surface and groundwater bodies. The Manjeera-Singur Catchment is one of the agriculturally intensive watersheds in Telangana, where in, nitrate surface loadings have substantially impacted groundwater nitrate concentrations of the aquifer. Also, Singur Reservoir is catering to about 40% drinking needs of the Hyderabad city. A careful assessment of nitrates movement in surface and groundwater sources can help water managers of the region in practicing water conservation practices and establish guidelines on water use specific to the study area.

Hydrologic models can simulate either whole or part of the hydrologic cycle in response to various natural or anthropogenic activities. Process based models (such as SWAT) can reasonably predict the impact of various land management and water use activities on flows, sediment, nutrient, and biologic movement either within, or, out of the system. Application of SWAT to Indian catchments has received less attention, compared to the watersheds of the rest. Major reasons for this might include lack of monitoring (and access to) intense datasets (meteorological, flow, groundwater), lack of historical data for running steady state simulation, and absence of region specific regulations on water withdrawals that can severly affect the quantity and/or quality of the source.

The conceptual model of the Manjeera-Singur Catchment in Sadasivapet

Mandal, Medak District, Telangana was developed in the present study using SWAT. The catchment (area: $57km^2$) is draining between Singur and Manjeera reservoirs. A total of 260 hydrological response units (HRUs), 15 sub basins, and 15 reaches were identified. The model was simulated on daily time step for the irrigation year 2013-14. Data on meteorological, soil, land-use, crop, irrigation, and management practices was provided using geographical interface ArcSWAT. The model was calibrated for catchment outflows and PET estimates at two weather stations. The SWAT was observed to over predict the observed groundwater nitrates ($NO_3 - N$) by a factor of more than 3. This is mainly attributed to the ignorance of nitrate leaching mechanism in the un-saturated zone by the SWAT model.

The performance of the SWAT model to simulate nitrate leaching was improved by modifying the source code. The nitrate concentration in the irrigation water was considered as one of the surface loads, and nitrate leached past the root zone was assumed to depend (exponentially decaying) on various factors. These include, nitrate leaching coefficient, depth below the surface, water available for leaching, and soil porosity. SWAT simulates nitrates leached (or, available in ground water) in load (kg/ha) units. However, the measured concentrations of groundwater nitrates are in mg/l (ppm). To simplify the comparison process, mass balance of nitrates for the shallow aquifer was developed in the present study, considering the aquifer mixing volume (AMV) as the system boundary.

Performance of modified SWAT code to simulate nitrate leaching past the root zone was evaluated for the sub-basins 6 and 15. A significant improvement in the model performance was observed using the modified code. It was observed that, the effect on exponential decay of nitrates with depth (past the root zone) is significantly high. This is particularly true for the Manjeera-Singur basin due to the higher depths of the aquifer, and greater availability of water for leaching. The modified code also evaluates the model sensitivity to leaching coefficient, and initial concentration of nitrates in the soil layer. Results of the statistical analysis conclude that, a leaching coefficient of 2.0 and initial soil nitrates of 20 mg/kg is reasonably predicting the groundwater nitrates. Spatial distribution of Nitrate leaching map for the watershed was prepared using GIS, which can be co-related with the existing cropping system and depth to groundwater to comment on the management practices that are suitable for the region.

Contents

Chapter 1

Introduction

1.1 Introduction

Agriculture and allied sectors including forestry and horticulture plays a significant role in Indias financial security since ages. The direct contribution of the agriculture sector to national economy is reflected by its share in total GDP, its foreign exchange earnings, and its role in supplying savings and labor to other sectors. Agriculture and allied sectors like forestry and fishing accounted for 18.26 percent of total Indian Gross Domestic Product (GDP) in 2007 and employed about 58 percent of the country's workforce (CSO, 2007). It accounted for 10.95 percent of Indias exports in 2005-06 (GoI, 2007) and about 46 percent of India's geographical area is used for agricultural activity. Total food grains production of the country during 2012-13 has reached an all-time high of 259.3 million tonnes (MT), where in, rice and wheat production stood at 105.3 MT and 94.9 MT respectively. Agriculture is unquestionably the largest livelihood provider in India, more so in the vast rural areas.

Contribution of agriculture sector to Indias GDP has been consistently decreased from 18.26% in 2007 to 14.10% in 2012 (source: World Bank). The three major reasons attributed to this decrease include:

1. Inconsistent and unevenly distributed monsoon assisted with extreme natural calamities (such as floods, droughts, cyclones);
2. Inadequate finance and marketing services; and
3. Lack of adopting innovative agricultural practices by analysing the soil-crop-water relations specific to the region.

Nitrogen and Phosphorous dominant fertilizers are extensively applied by farmers of India for increased crop yield, with no proper attention given to the amount, timing, and ecosystem balance. Application of nutrient dominant fertilizers in excess of crop uptake results in leaching, eutrophication of water bodies, and pollution of surface and groundwater bodies. Fertilizers enhance the natural fertility of the soil or replace the chemical elements taken from the soil by previous crops. Nitrogen is a primary plant nutrient that plays a major role in achieving the maximum economic yields from the agricultural areas. Phosphorus (P) is vital to crop growth as it is involved in several key functions, including energy transfer, photosynthesis, transformation of sugars and starches, nutrient movement within the plant and transfer of genetic characteristics from one generation to the next. And Potassium (K) increases crop yield and improves quality. It is also required for numerous plant growth processes. The Nitrogen-Phosphorous-Potash (NPK) consumption (by weight) for the state of Andhra Pradesh during 2007-12 is given in Table 1.1 (source: Department of Agriculture and Cooperation, Government of India). It is evident that, nitrogen rich fertilisers are being used extensively in the agriculture.

It can be observed that, in spite of increased use of fertilizers in the recent years, there is a consistent decrease in the agriculture output. The reasons for this include, imbalanced use of fertilizers, improper timing of fertilizers, and absence of site and crop specific fertilizer application.

Table 1.1: N-P-K consumption for the State of Andhra Pradesh, India during 2007-12

Irrigation Year	2007-08	2008-09	2009-10	2010-11	2011-12
NPK ratio	3.8 : 1.7 : 1	3.5 : 1.7 : 1	3.6 : 1.8 : 1	3.9 : 2.1 : 1	6.1 : 3.2 : 1

Ministry of Environment and Forests (MoEF), Government of India (GoI) in an attempt to conserve the critical environmental resources, has sought to improve the water quality by encouraging the optimal utilization of fertilizers, and pesticides as they are the main non-point source of pollution of groundwater and surface water (National Environment Policy 2006). This mission also promotes efficient water use techniques, including sprinkler and drip irrigation, among the farmers. The Policy further laid down a plan to take explicit account of groundwater pollution in pricing policies of agricultural inputs. In addition to the actions taken at National level towards sustainable agriculture development, Andhra Pradesh State Water Policy (2008) aims at undertaking efforts to control point and non-point source pollution from industrial, domestic and agricultural sources that pose threat to public health and ecosystems. Integrated pest and nutrient management practices along with organic farming are encouraged to ensure that sustainable agricultural practices are undertaken without compromising on public and ecosystem health.

Although the concerns related to water pollution have been adequately addressed both at the Central and the State levels, provisions for generation of resources for prevention of pollution, treatment of polluted water and ecological restoration of polluted water bodies are not adequate (source: Comptroller and Auditor General of India, Report No. 21 of 2011-12). Standards for agricultural practices and runoff pollutant levels for ground water had not been set either by MoEF or Central Ground Water Board (CGWB). No monitoring of pollution caused by agricultural practices and runoff pollutant levels were being done by MoEF / Central Pollution Control Board / CGWB. Though a few states including Andhra Pradesh, had framed programmes for tackling agricultural non-point source pollution of rivers, the extensive use of fertilizers applied by farmers for increased crop yields had worsened the situation. The Manjeera-Singur Catchment in Telangana is one of such agriculturally intensive watersheds, where in, nitrate surface loadings have substantially impacted groundwater nitrate concentrations of the aquifer. Also, Singur Reservoir is catering to about 40% of drinking needs of the Hyderabad city. Nitrates in drinking water affects health in many ways. Infants below six months who drink water containing nitrate in excess of the maximum contaminant level (MCL) could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue baby syndrome. Prolonged intake of high levels of nitrate by healthy adults are linked to gastric problems. Thus it is necessitates the need for controlling the nitrate concentration in water. A careful assessment of nitrates both in surface and groundwater sources can help irrigation engineers and water managers of this region towards implementing water conservation strategies and establishing guidelines on water withdrawals.

1.2 Description of Study Area

The study area exists between the Singur and Manjeera Reservoirs in Sadasivapet Mandal of Medak District, Telangana. The Manjeera-Singur sub watershed has an area of 57 square kilometres (km^2) and is existing between 77.906^0 to 78.015^0 East longitudes, and 17.577^0 to 17.7^0 North latitudes. The watershed contains four villages namely Nizampur, Sadasivapet, Machireddy Palli and Maddikunta in the Medak District of Telangana. Figure 1 represents the Index map of the study area delineating road network, land use characteristics, water bodies, and major land marks. The elevation of the region ranges from 503 m to 592 m above mean sea level. The climate of the region is mainly semiarid tropical with mean annual precipitation of 873 mm. Major crops grown in the region include cotton (60-65%), rice (15-20%), sugarcane

(10-150%), Jowar and Bengal gram (3-5%). Groundwater in this region occurs under unconfined to confined conditions in both hard rock (Archean and Deccan traps) and soft (Alluvial) formations (CGWB, Medak district, Andhra Pradesh, July 2007). In the Archeans, groundwater occurs under phreatic conditions in shallow weathered mantle and under semi-confined conditions in the fractured zones. Basalts and laterites occupy about 20% of the area of the Medak District and ground water occurs in joints, fractures and crevices of massive and jointed basalts under semi-confined conditions. Alluvial aquifers are very limited in extent and the development of ground water in these alluvial tracts is through shallow dug wells and filter points. The common groundwater abstraction structures in this region include dug wells, dug-cum-bore wells and bore wells and their yields mainly depending on the recharge conditions in the area. Depth to groundwater in the study area varies from 4 to 20 m below ground level (bgl) during pre-monsoon, and from 1.8 to 14.5 m bgl during post-monsoon period. The ground water in the District is in general suitable for both domestic and irrigation purposes. The electrical conductivity ranges from 610 to 3200

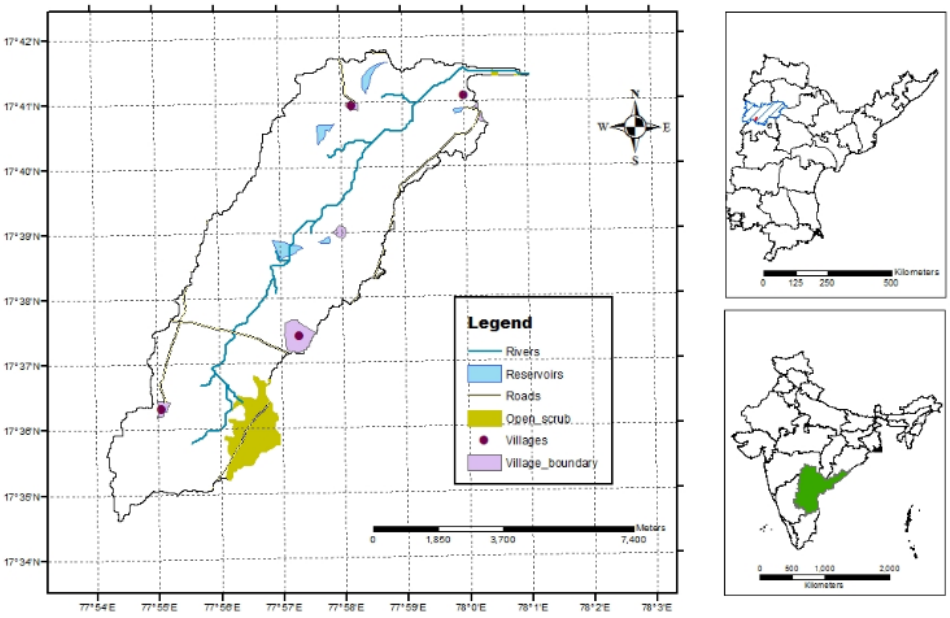


Figure 1.1: Index Map of the study area delineating roads, river network, and land marks

micro Siemens/cm at 250 C. Nitrate values in general ranges from 4 to 340 mg/l and Fluoride values are within the potable limits of 1.5 mg/l.

1.3 Objectives of the Research

The objectives of this research include:

1. Prepare base map, land use and land cover, hydro-geologic, and watershed maps of the study area in GIS environment at field scale resolution.
2. Estimate various components of hydrologic cycle and soil parameters specific to the study area using field/lab techniques.
3. Develop comprehensive hydrologic model of the Manjeera-Singur watershed using ArcSWAT.
4. Modify the source code of SWAT to incorporate nitrate leaching dynamics and nitrogen mass balance studies within the unsaturated zone.
5. Simulate spatial and temporal movement of nutrients (NO3 N) on daily step for the existing agricultural conditions using SWAT.
6. Evaluate the model performance to the potential parameters (including leaching index) that can effect nitrogen transformation and transport processes.
7. Calibrate and validate the model for watershed outflows and potential evapotranspiration measurements.
8. Generate the nitrogen (NO3-N) leaching index map of Manjeera-Singur watershed, and quantify the nitrates leached to groundwater at sub-basin level.

1.4 Organization of Thesis

The thesis is organized into SIX chapters which is as follows:

Chapter One provides the motivation behind this research, followed by agricultural scenario in India, and a brief description of the study area. Objectives of this work are presented at the end.

Chapter Two presents a comprehensive literature on general hydrologic models, hydrologic modeling with SWAT, calibration and uncertainty analysis with SWATCUP, nutrient modeling at watershed scale, and evaluation of BMPs.

Chapter Three details the collection, analysis, and processing of the data used with the hydrologic simulation and calibration. Model framework and data processing was discussed using ArcSWAT tool.

Chapter Four provides the mechanism of nutrient transport and mass balance in the unsaturated zone considered in this research. Modifications to the existing nutrient transport mechanisms were elaborated in this chapter.

Results of simulation (for groundwater nitrates) and calibration (for catchment outflows and PET estimates) were provided in Chapter Five. Groundwater vulnerability (in terms of NO3-N) to leaching index and components of nitrogen cycle was discussed in detail.

Summary and conclusions, followed by limitations and future scope of the work was presented in Chapter Six.

Chapter 2

Literature Review

2.1 Introduction

This chapter summarize research findings or methods available in literature on hydrologic modelling (specific to nutrient transport) using process based modes. A comprehensive overview of the structure and applications of SWAT (used directly, or, in conjunction with other models) was well documented by Gassman et. al. (2007). This chapter mainly focuses on application of SWAT to simulate hydrological processes, nutrient transport, and evaluate best management practices, that have been reported in the peer-reviewed literature after 2007. Application of SWAT model to simulate basic hydrological processes for different watersheds across the globe (with varying topography, climate, drainage area, and cropping patterns) was reviewed initially. Model calibration (for streamflows), sensitivity, and uncertainty analysis using SWATCUP and other tools was discussed in brief. Application of SWAT and other process models to simulate nutrient transport through un-saturated zone was reviewed in detail. At the end of the chapter, methods and measures for the evaluation of best management practices (BMPs) for controlled pollutant loads to the water bodies and increased crop yields was reviewed in detail.

2.2 SWAT Overview

SWAT is a basinscale, continuous time model that operates on a daily time step. SWAT is designed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in ungauged watersheds. The model is physically based, computationally efficient, and capable of continuous simulation over long time periods. The model input components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. In SWAT, a watershed is divided into multiple sub-watersheds, that are further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the sub-watershed area and are not identified spatially within the SWAT simulation. The overall hydrologic balance is simulated for each HRU, where in the surface runoff from each HRU is estimated Curve Number (CN) or GreenAmpt method. Storage routing techniques are used to calculate redistribution of water between layers in the soil profile. Sediment yield is calculated with the Modified Universal Soil Loss Equation (MUSLE). The transformation and movement of nitrogen and phosphorus within an HRU are simulated in SWAT as a function of nutrient cycles consisting of several inorganic and organic pools. Bacteria surface runoff losses are simulated in both the solution and eroded phases. Catchment outlows, sediment, nutrient, pesticide, and bacteria loadings or simulated at HRU level, and then summed at the sub watershed level, and the resulting losses are routed through channels, ponds, wetlands, depression areas, and/or reservoirs to the watershed outlet.

2.3 Hydrologic Modeling with SWAT

Setegn et al. (2008) applied SWAT2005 model to Lake Tana Basin, Ethiopia for modeling of the hydrological water balance with an aim of testing the performance and viability of the SWAT model for prediction of streamflows. The results obtained from SWAT simulation were good in spite of data uncertainty. The sensitivity analysis of the model indicated that streamflows are sensitive to the HRU definition thresholds than subbasin discretization. The hydrological water balance analysis showed that, baseflow forms an important part of the total discharge (40% - 60%) within the study area than surface runoff. More than 60% of the losses were attributed due to evapo-transpiration.

Abbaspour et al. (2006) applied SWAT tool to test its performance and feasibility of using this model for simulating flow and transport processes at watershed scale in the Thur River basin located in the north-east of Switzerland. SWAT is assessed to be a reasonable model for water quality and water quantity studies. They concluded the necessity of a large amount of measured data for proper model calibration and the effectiveness of large-scale watershed models in simulating watershed processes and watershed management studies.

Rostamian et al. (2008) performed SWAT simulation to model runoff and sediment in the Beheshtabad (3860 km^2) and Vanak (3198km^2) watersheds in the northern Karun catchment in central Iran. The calibration and uncertainty analysis of the model were carried out with the help of Sequential Uncertainty Fitting (SUFI-2) algorithm, a package in SWATCUP. It was observed that the simulated runoff values were better than those of sediment. The poor prediction of surface runoff for some months was attributed to poor characterization of snowmelt processes in these mountainous watersheds, lack of sufficient discharge data, and lack of input data for simulation of groundwater recharge and groundwaterriver interaction. The weakness of the model to simulate sediment was observed due to the improper peak runoff simulation and the nature and accuracy of the measured sediment data. This developed model could help to assess different land management options and in studying the effect of climate change on soil erosion.

Stehr et al. (2008) used SWAT model to examine the impacts of land-use and climate changes on the hydrology of the Biobio basin, which is an area of critical importance to Chile due to its rich biodiversity, forestry activities and agricultural lands. They used ParaSol algorithm for calibration. The model was calibrated for monthly runoff values where the Nash-Sutcliffe index ranged from good to satisfactory while during validation, the model performance remained good. The model underestimated the runoff over the long term and for the peak flows which can be explained by inadequate description of rainfall input field caused by limited availability of meteorological stations. The application of SWAT model under conditions of limited data availability for this study area proved to be successful as it moderately helped in assessing the potential impact of land-use and climate changes on the hydrology of this basin.

Srinivasan et al. (2010) applied the physically based, spatially distributed SWAT model for hydrologic budget and crop yield predictions to the Upper Mississippi River basin (UMRB) in USA from an ungauged perspective. They proposed a framework for developing spatial input data, including hydrography, terrain, land use, soil, tile, weather, and management practices. For watershed delineation, the eightdigit USGS hydrologic unit codes (HUCs), stream dataset, and a 90 m digital elevation model (DEM) were provided. The Land-use maps were generated by combining both National Land Cover Data (NLCD) and Cropland Data Layer (CDL). The STATSGO (USDA) 1:2,50,000 scale soil map was used for soil definition and the associated soil properties AT were extracted from the national STATSGO layer. The thresholds for land-use, soil and slope classes were defined in order to create unique combinations of Hydrological Response Units (HRUs). The tillage and management practices were also incorporated followed by preparation of weather data. They tested the uncalibrated SWAT model for streamflow, base flow, and crop yield simulation and observed that SWAT was able to capture the annual streamflow very well while its performance for monthly streamflow simulation was slightly degraded. Crop yields were also satisfactorily simulated. In addition, the uncalibrated SWAT model developed in this study produced similar evaluation statistics to those calculated using calibrated SWAT models from the previous studies. Overall, they concluded that, SWAT model could satisfactorily predict the UMRB hydrologic budget and crop yield without calibration. This necessitates the use of accurate input datasets for the process based SWAT model.

Xie and Cui (2010) focussed on the simulation of hydrological processes in areas irrigated with paddy rice and proposed developments to the current SWAT framework. The actual evapo-transpiration of paddy fields was estimated to depend on water storage conditions and a scheme of controlling irrigation was introduced where three critical water depths were used to adjust the irrigation and drainage operations in paddy fields. Ponds and reservoirs, as local sources of water storage objects, could provide water to paddy fields in a timely manner to compensate for canal water transfers. An agronomic model was also adopted to estimate crop yields. This developed framework was then tested in Zhanghe Irrigation district, China. The simulated runoff exhibited good agreement with the measured runoff, estimation of crop yield was satisfactory and the water balance components resembled the nature of water movements present in the fields thus suggesting that the developed framework is adequately representing the hydrological processes in this district.

Impact of the mesh size of the digital elevation model (DEM) (ranging from 20 to 500 m) and the soil map scale (1/25,000; 1/250,000 and; 1/500,000 scale) within SWAT to simulate runoff, sediment, and NO 3N loads at the outlet of the Lower Walnut Creek watershed in Central Ohio, U.S.A. was determined by Chaplot (2005).

SWAT model was run and the results suggested 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 ux but generated prediction errors for nitrogen and sediment yields. Chaplot also suggested on the need for a detailed soil map to accurately estimate the loads.

Accurate simulation of hydrologic processes in mountains terrais at large scales is important for water resource management and for watershed management planning. Streamflow simulation in mountainous watersheds is often challenging because of irregular topography and complex hydrological processes. Noor et al. (2014) used the SWAT to model daily runoff in the Taleghan mountainous watershed (800.5 km^2) in west of Tehran, Iran. Most of the precipitation in the study area takes place as snow, and hence, modeling daily streamflow in this river is very complex and involves large uncertainty. Model performance was evaluated and found to be reasonably good. The model was calibrated and found to be most sensitive to snowmelt parameters and Curve Number (CN2). Results indicated that, SWAT can provide reasonable predictions of daily streamflow from Taleghan watersheds.

The original SWAT model performs poorly for daily streamflow simulation in small-scale farmland catchments in two ways: (1) the streamflows are usually underestimated for high-flow events while overestimated for low-flow events, and (2) there is an obvious time lag between the simulated and observed peak times. The SWAT model is modified by recalculating the peak flow rate and peak time based on the physical mechanism by Meizhao et al. (2014). The daily simulation of the modified model is validated with observed streamflows and also compared with the results of the original SWAT model based on a case study of the Pengjiahe Irrigation District, China, during the 1987-1991 flood seasons. Results show that a better match of the peak times and peak streamflows was captured between the modified predictions and the measurements. It is also found that the modified model presents more actual and faster water recession rates than the original model. Meizhao et al. concluded that the modifications improved the the applicability of SWAT in small-scale farmland catchments.

Impact of land use and cover change on hydrological conditions (water discharge and sediment load) of the Hulu Langat basin, a strategic watershed in Malaysia, were investigated using the SWAT by Memarian et al. (2014). Four land use scenarios were defined for land use change impact analysis. These include, past, present (baseline), future and water conservation plan. Model calibration and uncertainty analysis was performed using the Sequential Uncertainty Fitting (SUFI-2) algorithm. The model robustness for water discharge simulation during the period 1997-2008 was observed to be good. However, due to uncertainties, mainly resulting from intense urban development in the basin, its robustness for sediment load simulation was only acceptable for the calibration period 1997-2004. The optimized model was run using different land use maps over the periods 1997-2008 and 1997-2004 for water discharge and sediment load estimation, respectively. In comparison to the baseline scenario, SWAT simulation using the past and conservative scenarios showed a significant reduction in monthly direct runoff and monthly sediment load, while SWAT simulation based on the future scenario showed a significant increase in monthly direct runoff, monthly sediment load and ground water recharge.

Non-point source pollution in river basins has resulted in water contamination, aquatic ecology deterioration and eutrophication. SWAT was applied to assess the non-point source pollution of Xin'anjiang catchment in China and its effect on drinking water (Zhai et al., 2013). Water discharge, sediment, total nitrogen and total phosphorus load processes from 2000 to 2010 were simulated, and the spatial distributions of non-point source pollutants were evaluated at the catchment and administrative county levels. Sensitivity analysis of model parameters was carried out using the Sequential Uncertainty Domain Parameter Fitting 2 technique. Hydrological parameters (such as CN2, RCHRG_DP, ALPHA_BF, SOL_AWC, ESCO and SOL_K), characteristic parameters of sub-basins (such as HRU_SLP and SLSUBBSN) and water quality parameters (viz. CH_EROD, NPERCO, RSDCO and PPERCO, PHOSKD, etc.) have a significant effect on nutrients. The model performance was very satisfactory, especially for runoff, sediment and total phosphorus simulation. The non-point source pollutant load increased from 2001 to 2010 in the whole catchment. This study was expected to provide a method and reference for non-point source pollution quantification and to support water quality management implementation in China.

2.4 Calibration and Uncertainty Analysis

Abbaspour et al. (2007) developed SWATCUP , an extension to SWAT that offers model parameterization, sensitivity, calibration and uncertainty analysis for use with SWAT developed models. The various calibration/uncertainty analysis procedures described in SWATCUP include Generalized Likelihood Uncertainty Estimation (GLUE), Parameter Solution (ParaSol), and Sequential Uncertainty FItting version 2 (SUFI-2). They applied SWATCUP to the Thur watershed in North-West Switzerland. The watershed was calibrated based on the discharge, sediment, nitrate, and total phosphorous loads at the watershed outlet and produced very good results for each parameter during both calibration and validation periods. Abbaspour et al. inferred that, SWATCUP framework can be used for calibration and uncertainty analysis of the watershed models.

Arnold et al. (2012) presented a comprehensive over-view of all key facets required for an ideal SWAT calibration and validation process. SWAT is a semi-distributed river basin model that requires a huge number of input parameters and that complicates model parameterization and calibration. Several calibration procedures including manual and automated, have been developed for SWAT. Further, SWATCUP was also developed to serve as a decision-making framework that incorporates sensitivity, calibration and uncertainty analysis. In SWATCUP, the parameters and ranges can be manually adjusted iteratively between auto-calibration runs. Parameter sensitivity analysis focus the calibration and uncertainty processes. Also, SWATCUP calibration helps the user in better understanding of the overall hydrologic processes and of parameter sensitivity. Arnold et al concluded that all the model input parameters must be kept within a realistic uncertainty range and there is no substitute to the actual physical knowledge of the watershed.

Tang et al. (2012) used SWAT to set up hydrological model in the Chao River Basin in Beijing. Being one of the most important sources for drinking water in Beijing, the Chao River faces water scarcity owing to human activities and climate change. This called for an effective management of water resources. The aim of their study was to simulate hydrological process of the Chao River basin using SWAT and also perform model calibration and uncertainty analysis using Sequential Uncertainty Fitting algorithm. A total of 12 parameters such as CN2, ALPHA_BF, SOL_AWC, SOL_K, et al., were found to be more sensitive from the sensitivity analysis results. While large uncertainties were found for validation period in the SWAT model, the simulation results for monthly runoff during calibration period was acceptable.

Reduction of modeling uncertainty is required to set up a well performing model for water balance simulations. Pluntke et al. (2014) focussed on the reduction of uncertainty that results from precipitation observations and parameter estimation during the calibration process. SWAT was applied and a calibration and uncertainty reduction strategy was set up that consists of time- and spatial-scale dependencies as well as alternative precipitation inputs. The single models that were set up and calibrated with alternative precipitation inputs are treated as an ensemble and were averaged with different methods. The calibration strategy revealed the benet of applying a complex bottom-up calibration that starts with sub-basins and ends with the entire basin, that not only improved the performance significantly but also identified and reduced the water balance gaps. Simulations improved and parameter uncertainty was reduced applying the SWAT model variants. But this approach had some drawbacks since differences between modeled and observed runoff are large in some occasions and cannot be balanced completely by the applied methods. The chosen uncertainty measures are not optimal and indicate that parameter uncertainty is still high. Despite its limitations, it was demonstrated that, simulations can be improved and modeling uncertainty can be reduced with an appropriate calibration strategy, with extended precipitation information and the application of an ensemble approach.

2.5 Nutrient Modeling at Watershed Scale

Ferrant et al. (2011) analysed the outcomes of using different modeling approaches on the simulation of Nitrogen dynamics in small agricultural catchments. Two models , TNT2 and SWAT, that were designed with a focus on N processes and with similar levels of spatial and temporal resolution for the simulation of field scale processes, were tested on a small agricultural catchment in South of France. The simulated results were found to be reasonably good estimators of water and N fluxes at the outlet when large observed dataset, detailed agricultural information and long time series of hydrological and hydrochemical data were used for calibrating the models. While the water yield was accurately estimated, flood events were poorly predicted. TNT2 performs better than SWAT in simulating base flow. SWAT simulates more infiltration, TNT2 simulates more leaching, more N transfers through the aquifer and less overland flow. Hence, the differences in the simulated stream nitrate concentration can be explained. Even if simulated annual water and N yields are very close, major differences were found regarding mineralization and denitrification dynamics. The authors emphasised the need to either refine mineralization and denitrification modeling or use of more generalized simplified approaches.

De Paz et al (2009) implemented the GIS NIT-1 approach in a GIS environment, based on quantitative Nitrogen(N) mass balance and qualitative rankings, to assess N management practices across the nitrogen vulnerable zone (NVZ) of the Mediterranean region of Valencia. The new GIS NIT-1 assessment tool developed by them was able to simulate N uptake, hydrology characteristics (water leaching), N dynamics and NO_3N leaching across several sites of the NVZ. This study suggested that the GIS NIT-1 is very useful to separate management practices with potential for very low to moderate N losses from those with potential for high to very high N losses to the environment.

Wang et al. (2014) modeled the water movement and soil nitrogen cycle of the Baiyangdian Basin of the North China Plain in order to quantify the risk of nitrate contamination arising from highly intensive farmland. The modeling results showed that the fertilizer application is the major source of soil nitrogen in the study area, which resulted in loss of nitrate by leaching or runoff. This increased the risk of surface water and groundwater contamination. The modeling analysis also indicated that nitrate leaching was the main approach of soil nitrogen movement due to strong percolation, with the largest amount leached from surface soil layers and the smallest amount leached from lower soil layers. Thus, it demonstrated that the nitrate concentration was very low at soil layers lower than the root zone of crops (of 1.2m). The groundwater pollution by nitrate had not reached a critical level due to the presence of thick unsaturated zone. But concluded that the magnitude of risk of groundwater contamination would increase, if precipitation increased.

Jamshidi et al. (2010) used SWAT model to simulate the impacts of different point source and non-point sources of nitrate pollution in the Jajrood river watershed in northern Iran. While the simulated monthly discharge and daily nitrate load were in good agreement with the observed data, the model performed poorly for daily data. The modeling results implied that the major point source of nitrate load in the watershed was untreated wastewater along with leaky septic systems. Runoff from orchards also contributed to nitrate loading. Further, observations indicated that maximum discharge and nitrate load occur from February to June, which suggests that at high flow rates, the nitrate concentration in the river increases.

Almasri and Kaluarachchi (2007) have demonstrated a framework for modeling the effects of land use practices and protection alternatives on nitrate pollution of groundwater in agricultural watersheds. The framework employs a soil nitrogen dynamic model to estimate nitrate leaching to groundwater and finally develop a groundwater nitrate fate and transport model. Both point and non-point sources of nitrogen were considered across different land use classes. The model was applied to the SumasBlaine aquifer of Washington State in USA. The authors concluded that proper estimation of on-ground nitrogen loadings and nitrate leaching to groundwater is necessary to develop the nitrate fate and transport models in groundwater. The denitrification process in groundwater helps in higher reduction of nitrate mass in groundwater when compared to advection and mechanical dispersion. They also concluded that, the reduction of manure loading has a high impact on reducing nitrate mass build-up in the aquifer compared to fertilizer loading reduction in areas dominated by dairy farms.

Akhavana et al. (2010) employed SWAT to model the amount and dynamics of nitrate leaching from Hamadan-Bahar watershed which lies in an intensive agricultural region in western Iran. Source code of SWAT was modified specific to the irrigation module to estimate percolation and the consideration of spring discharge to predict base flow. The SWAT model was then calibrated and validated with uncertainty analysis using SUFI-2 based on measured daily discharge data from 7 hydrometric stations, wheat and potato yield, and measured daily nitrate at the outlet of the watershed. The nitrate leaching rate was observed to be higher than 100 kgN$ha^{-}1$ $year^{-}1$ .The model performance was found to be satisfactory and hence the authors concluded that the model could serve as a strong base for considering different scenarios to reduce nitrate leaching and suggest alternate BMPs in the HamadanBahar watershed.

Phosphorus loading from residential onsite wastewater systems (OWSs) into neighbouring surface waters is a poorly understood process in rural watersheds, which becomes further challenging when rural residential dwellings are intermixed with agricultural land use. Sinclair et al. (2014) designed a Phosphorous onsite wastewater simulator (POWSIM) to assess P loads from individual or clusters of residential OWSs typically used in Nova Scotia, Canada. He simulated OWS P loads in a mixed agricultural watershed (Thomas Brook Watershed [TBW], NS) using SWAT model in conjunction with POWSIM, to predict and compare the P loading from agricultural and residential sources. The combination of POWSIM and SWAT modeling approach produced a better simulation of baseflow total P (TP) loads in both a predominantly residential subcatchment and the one dominated by agriculture, when compared to SWAT model without POWSIM. The residential sub catchment had 48% of its average annual land use TP load (simulated) contributed by OWSs, whereas the agricultural sub catchment had 39%.

2.6 Evaluation of BMPs

Chaubey et al. (2010) evaluated the effectiveness of 171 various BMPs in controlling nutrient losses from a pasture watershed, and impacts of uncertainty in weather conditions on water quality improvement and BMP performance. The SWAT model along with detailed farm and watershedscale data, and combined with 250 different possible weather realizations was simulated for a 25-year period. The authors concluded that the total nutrient losses increased with grazing intensity and litter application rates and more so, during fall. They concluded that, overgrazing of pasture areas must be avoided since it resulted in huge losses of nutrients for all litter application rates, timings, and buffer management. Variability in weather conditions had a significant impact on BMP performance. Under certain weather conditions, an increase in pollutant losses can be greater than reductions due to BMPs implemented in the watershed. Buffer strips and grazing management were two important BMPs affecting the losses of total nitrogen and total phosphorus from the pasture areas.

Kannan et al. (2014) focussed on modelling of BMPs that affect water quality and assessed the extent of pollution mitigation by each BMP on a cultivated watershed in South Texas, USA. The SWAT model was applied with recent datasets and the simulated results were compared with the observed counterparts. The conclusions drawn from the study were that, the model performance was reasonably good, thus could be used for analysing various scenario trials. The outcome of the study also indicated that, the agricultural BMPs pursued in the watershed have improved the dissolved oxygen (DO) in the tidal section of the river though the non-tidal section suffered from poor DO which required to be mitigated. It was also observed that the point source pollution is the major concern for the watershed. The binomial method was found to be a reliable method for analysing water quality trends.

Ouyang et al. (2013) applied SWAT to model the non-point source (NPS) nitrogen loading in a freezethaw area in northeast China and determined the responses of NPS nitrogen loading to different land-use and soil for a period of 30 years (1979-2009). The study considered synergistic impacts of soil and land-use on NPS nitrogen loading and conducted F-tests to identify their significance. The results demonstrated that watershed NPS nitrogen loading was more sensitive to soil change than to land-use change. The loading also decreased after the latest soil and land-use data were used in the simulation, thus suggesting the need for strict controls on the NPS nitrogen loading. Temperature was also observed to have significant effects on nitrogen yield as it caused twin peaks in the temporal scale.

Jiang et al. (2013) simulated the impacts of conservation tillage and fertilization based on soil test, an agricultural policy promoted by the Chinese government, on non-point source pollution using SWAT for the Liuxi River watershed in China. The model results pointed that total nitrogen and total phosphorus loadings could be reduced by implementing suitable conservation tillage systems for agricultural lands in the study area. Optimal fertilization could also lead to significant effects in nutrient loads reduction at the expense of minor impacts on crop yield. Further, the modelling approach used in the study can serve as a cost-effective and reliable tool to quantify the benefits of BMPs and to devise pollution control strategies for watersheds.

Amon-Armah et al. (2013) investigated the effects of crop rotation sequence, tillage type, and nutrient N application rate on crop yield and the associated groundwater $NO_3^- - N$ leaching and sediment loss by applying SWAT model to the Thomas Brook Watershed located in the intensive agricultural region of Canada. The cropping systems studied were seven fertilizer application rates and two tillage systems (conventional tillage and no-till) and reflected the cropping systems practised by the farmers in the study area. ANOVA models were developed and used to evaluate the impacts of crop management choices on crop yield and two water quality parameters ($NO_3^- - N$ leaching and sediment loss). The modeling analysis indicated that significant reduction in $NO_3^- - N$ leaching and sediment loading can be achieved by lowering the existing recommended N-fertilizer rate, while optimising the crop yield.

Changes in land-use or management practices affect water outflow, sediment, nutrients and pesticides loads. Chaplot et al. (2003) evaluated the impact of farming practices and land-use changes on water discharge, sediment and NO3-N loads at the outlet of a 51.29 km^2 watershed of central Iowa in USA by applying SWAT model over a simulated period of 30 years. With varying N application rates from 60% to

+40% of the reference, flow discharge and sediment loads showed no variations though NO3-N exponentially decreased with decreasing N inputs from 60 to 20%. No-tillage practices did not significantly affect the water resource and sediment loads. When replacing corn-soybean rotation by winter wheat, N outputs greatly increased in early fall, immediately after the harvest. Also, the generalization of pastures significantly decreased flow discharge, $NO_3 - N$ and sediment delivery. Such predictions would help policy-makers to take optimal decisions for a sustainable management of watersheds under similar environmental conditions.

The SWAT model was applied to the Medjerda river basin in Northern Tunisia to study the potential impact of land management scenarios (Bouraoui et al., 2005). The region is experiencing an intensification of agriculture and the irrigated area is increasing rapidly. The developed model was able to represent the hydrological cycle even though some discrepancies were observed, probably due to a lack of sufficient rainfall data, and due to the lack of representation of reservoirs. It was also predicted that converting all agricultural land to irrigated crop introduced significant changes on nitrate concentration in surface water. However, the concentration was still below the limit of potability. Drastic reduction in the load of ammonium and phosphorus could be achieved by collecting and treating wastewater from major urban areas.

To assess relationships between land use changes and nonpoint pollutant indexes upstream of the Three Gorges Reservoir, SWAT model was used (Yang et al., 2014). Results indicated that SWAT model, calibrated with the adjusted parameters, could successfully reproduce the nonpoint indexes at the water quality monitoring sites in the two rivers. The different land use change types were shown to be sensitive to nonpoint pollutants in the study area. The land use change type from upland to water was the strongest influence on changes in total nitrogen and total phosphorus. An empirical regression equation between nonpoint indexes and different land use change types was developed for the study area by partial least squares regression.

This regression equation was useful for evaluating the influence of land use change types on changes in nonpoint pollutants over a long time period.

Use of more inorganic fertilizers and pesticides has become essential for farmers to produce enough food for the increasing population in China. Additionally, rural areas were heavily populated and a large number of domestic sewage were discharged widespread. This makes agricultural land and residential land two of the major sources of nonpoint source pollution. Thus, the SWAT model was utilized to evaluate the individual and combined impacts of various management practices on total nitrogen (TN) and total phosphorus (TP) loads in the Changle River watershed (Liu and Lu, 2014). The simulated results indicated that model performance was good. For those tested watershed management scenarios, no-tillage (NT) offered more environmental benefits than moldboard ploughing. In terms of reducing fertilizer rate or treating domestic sewage, they were also able to reduce TN and TP loads. When the combined effects of the three practices were examined, it was found that the scenario of NT and reducing fertilizer rate by 30% without domestic sewage inputs could greatly restrain the loss of nutrients to waters and basically met the II grade water quality target, meanwhile it was also the best management practice that could be easily accepted by local farmers and government.

Chapter 3

Hydrologic Modeling

3.1 Introduction

Quantification of various processes of the hydrologic cycle and their complex interaction can be best achieved using hydrological models. Hydrologic models are the simplified and conceptual representations of a whole or part of the hydrologic cycle. Variations in climate, topography, land characteristics, as well as various man-made interferences within the system make it very difficult to construct general models that are applicable to any catchment across the globe. Most of the existing models simulate only a part of the cycle, e.g. rainfall- runoff, infiltration, floods, groundwater flow and transport. Models developed in a certain climatic or geologic region often have difficulties when directly used in a different setting.

Models are simplified systems that approximate the real conditions. In the case of hydrological models, the real system may be an entire river basin, a groundwater basin, or parts of it (e.g., a small headwater catchment, or a soil column). Primary components of a hydrologic model include

1. A processing mechanism, similar to a control device in the model, can be of various types that can model and control soil, land, climate and flow properties

2. Input, the datasets processed by the model (meteorological, hydrological, geological, soil-crop-water specific information)

3. Output data, are the results of the processing (flood water levels, hydraulic heads)

Hydrological models have become increasingly important tools for the management of water resources. They are used for flow forecasting to support reservoir operation (Walter Collischonn et al., 2005), flood protection and mitigation (P.Y. Julien et al., 2009), in the design of hydraulic structures (S. Erpicum et al., 2004), sediment transport studies (Joris de Vente and Jean Poesen, 2005), groundwater flow and transport phenomena (Xu Xu et al., 2012), climate change impacts on water resources (H.J. Fowler et al., 2007). Applications of hydrological models find have multiple dimensions. During the event of a flood, hydrologic and/or hydraulic routing models may help to predict when and where there is a risk of flooding and which areas should be evacuated. After the event of the flood, probabilistic/economic models may be used to quantify the risk associated with a flood of similar or larger magnitude for use in the design of hydraulic structures. Moreover, models may help to analyse the reasons behind the flooding events such as increase of human activities in the catchment. Hydrological models can be classified into two categories.

1. Stochastic models: These are black-box models and deals with the collection which is a collection of random variables, representing the evolution of some system of random values over time. There is some indeterminacy involved here such that, even if the initial condition is known, there are several directions in which the processes may evolve. The stochastic models use the measured data and apply on mathematical and statistical theories. Examples of these include Regression based models, Neural Networks, and Transfer functions.

2. Process based models: These models represent physical processes observed in

the real world. They describe a process that can evolve in only one way provided the initial condition is given. Also known as deterministic hydrologic models, they are basically of two types viz., Lumped and Distributed model. Lumped model describes a watershed as a single entity, whereas distributed model divides the watershed into smaller units where in each unit has fairly homogeneous characteristics. Lumped model is based on the concept of unit hydrograph with single rainfall (mean) input and single discharge output. Process based hydrological models can also be of semi-distributed type, which has the attributes of both distributed and lumped models. They comprise of hydrological response units (HRUs) which are unique combinations of various datasets like land-use, soil, and slope unlike the distributed models, where the model is spatially discretised into equally sized grids.

Hydrologic modeling tools that are widely used across the globe include HEC-HMS, SWAT, and HSPF.

HEC-HMS

The Hydrologic Modeling System is designed to simulate the precipitation-runoff processes of dendritic watershed systems. Developed by The Hydrologic Engineering Center, the latest version of HEC-HMS being used is version 3.5. It is designed to be applicable for a wide range of problems including large river basin water supply , flood hydrology, and small urban or natural watershed runoff. It is capable of performing physical representation of a watershed, hydrologic simulation, parameter estimation, simulation analysis, forecasting future flows and compute sediment and water quality in natural streams.

HEC-HMS uses deterministic mathematical models, where the boundary conditions, initial conditions and parameters of the models are assumed to be known. Moreover, the parameters are assumed to be stationary in time domain. During long periods of time, it is possible for parameters describing a watershed to change as the result of human or other processes at work in the watershed. These parameter trends cannot be included during the simulation. There is a limited capability to break a long simulation into smaller segments and manually change parameters between segments. Also, the mathematical models included in the HEC-HMS program are uncoupled. For example, the program first computes evapotranspiration followed by infiltration. In the physical world, the amount of evapotranspiration and infiltration depends on the amount of soil water. However, evapotranspiration removes water from the soil while infiltration adds water to it. In order to solve the problem properly, both the processes should be simulated simultaneously with the mathematical equations for both processes numerically linked.

SWAT

Soil and Water Assessment Tool is a river basin or watershed scaled, semi-distributed model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields. SWAT is generally applied to large complex watersheds with varying soil, land use and management conditions over a long period of time. The Soil and Water Assessment Tool (SWAT) is a public domain model jointly developed by USDA Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research, part of The Texas A&M University System, USA. ArcSWAT 2012.10.15 is the latest version being used. SWAT is a continuous time (long-term yield) model and operates on a daily time step. In addition to simulating the fate and transport of sediment, nutrients, pesticides, and bacteria, the model has the capability to simulate crop growth, tile drainage, wetlands, reservoirs, and carbon dynamics, broadening the models utility and appeal.

SWAT is physically based model. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling etc. are directly incorporated in SWAT. The benefits of this approach is that, watersheds with no monitoring data (eg. stream gauges) can be modeled and the relative impact of alternative input data (eg. changes in management practices, climate, vegetation etc.) on water resources can be quantified. SWAT is also computationally efficient as simulation of very large basins can be performed without excessive investment of time or money. SWAT enables the users to study long term impacts of climate change and management practices on the water resources of the watershed under consideration.

The main weakness of the model is the non-spatial representation of HRU inside each sub catchment. This kept the model simple and supported application of the model to almost every catchment. Land use, soil and slope heterogeneity of the model is accounted through sub-catchments. This approach ignores flow and pollutants routing between HRUs. Wide range of different input datasets needs to be obtained to run the model and numerous parameters needed to be modified during the calibration. This discourages modelers to use SWAT, by compromising on the model performance to predictions. More extensive use of the model would be expected with adding more groundwater routines and algorithms or with permanent coupling of the model with groundwater flow and transport models. SWAT ignores the movement of nitrate concentration as the recharge as it moves through the vadose zone.

HSPF

Hydrological Simulation ProgramFortran, popularly known as HSPF, is a watershed model that simulates runoff and nonpoint pollutant loads leaving a watershed and performs the fate and transport processes in streams and one-dimensional lakes. It is developed and maintained by U.S. Environmental Protection Agency and U.S. Geological Survey. HSPF version 12 is currently being used worldwide. It is comprised of three main modules (PERLND, IMPLND, and RCHRES) and five utility modules. For simulation with HSPF, the watershed has to be represented in terms of land segments (pervious and impervious lands) and reaches. The PERLND module represents hydrology and water quality processes that occur on pervious land segment, while the IMPLND may be used for impervious surface area where little or no infiltration occurs. The RCHRES module simulates the processes that occur in a single reach of an open channel or well-mixed impoundment. HSPF is extremely data intensive and over-parameterised model that requires a large amount of site information to accurately represent hydrology and water quality processes in a watershed.

HSPF includes routines to simulate runoff, suspended solids, nutrients, water temperature, pesticides, biochemical oxygen demand, pH, and dissolved oxygen. In addition, HSPF allows the user to simulate selected water quality constituents by specifying their sources, sinks, chemical properties, and transport behaviour.

Advantages of HSPF model include:

1. Comprehensive representation of watershed land and stream processes.
2. Comprehensive representation of watershed pollutant sources, including non-point sources (by multiple land uses), point sources, atmospheric, etc.
3. Flexibility and adaptability to a wide range of watershed conditions.
4. Well-designed code with modularity and structure.
5. Companion database and support programs to assist model users.

Limitations of HSPF model include:

1. Extensive data requirements (eg., hourly rainfall)
2. No comprehensive parameter estimation guidance is available
3. Limited spatial definition (i.e., lumped parameter approach)
4. Hydraulics limited to non-tidal freshwater systems and unidirectional flow

5. Simplified representation of urban drainage systems (eg., culverts, pipes, CSOs)

SHETRAN

SHETRAN is a physically-based, spatially-distributed modelling hydrologic system that can simulate the entire land phase of the hydrologic cycle including surface water flow and groundwater flow. It is a model for water flow, solute and sediment transport in river catchments. In the 1980s, the Systme Hydrologique Europen (SHE) model was developed by a consortium of three European organizations: the Institute of Hydrology (the United Kingdom), SOGREAH (France) and DHI Water.Environment.Health(Denmark). The SHE model was renamed SHETRAN at School of Civil Engineering and Geosciences, Newcastle University, after the introduction of the sediment and solute transport component. Since then it has undergone further improvements. The latest version of SHETRAN being used these days is Version 4.4.1. The development of SHETRAN has taken river basin modeling a step beyond previous models. SHETRAN has a substantial capability for addressing environmental and water resources problems that span the traditional disciplines of river basin and ground water modeling. Spatial discretization can be done using rectangular grid cells (typically of 200 to 300 m).

3.2 Data Processing with ArcSWAT

SWAT requires comprehensive datasets of weather, soil, topography, vegetation, and land management practices of the watershed at hru level provided on daily time steps. Figure 3.1 represents the land-use map of the study area featuring the measurement stations.

3.2.1 Collection of Data

1. Weather data: SWAT requires daily meteorological data that can either be read from a measured data set or been generated by a weather generator model. The weather variables used for this study for driving the hydrological balance include precipitation, minimum and maximum air temperature, wind speed, relative humidity and solar radiation, all on daily scale for the period May 2013 April 2014 (to account for one complete irrigation year). These data were obtained from two Automatic Weather Stations (AWS) located at Nizampur (17.685^0, 78^0) and Mominpet (17.6^0, 77.93^0). AWS captures the data at 30 minute intervals, which was accumulated / averaged for the day.

2. Soil data: SWAT requires soil textural and physicochemical properties such as available water content, hydraulic conductivity, bulk density, porosity, and organic carbon content for different layers of each soil type. The undisturbed soil samples were collected from six locations (Figure 3.1) distributed over the study area and was used to determine various soil parameters in the laboratory.

3. Nitrate data: The groundwater samples were collected on a weekly scale from three locations (Figure 3.1) for determination of nitrate ($NO_3 - N$) concentration.

4. Topographical data: Terrain characteristics and slope parameters are derived from the digital elevation model (DEM) of the study area. A 90 m DEM (Figure 3.1) was downloaded from Shuttle Radar Topography Mission (SRTM) website on 16 September 2013 and re-sampled to 30 m using cubic interpolation method. ArcHydro tool was used to delineate the watersheds and drainage patterns of the region. Sub-basin parameters such as slope, sinks, and stream network characteristics were also derived from the DEM.

5. Land-use data: IRS-P6 CartoSAT-II image was procured from the National Remote Sensing Agency, Hyderabad (resolution: 5 m, LISS IV FMX). Supervised classification of the image was performed to represent the land use pattern of the study area.

6. Management practices: The various details on land management practices such as tillage, planting, irrigation, fertilizer application, harvesting operations, were gathered from the officials in Agricultural Department, Mominpet.

7. River discharge: Daily outflows from the Singur Reservoir and inflows to the Manjeera Reservoir were obtained from the AP Irrigation Department office at Sangareddy. The daily flows were used during model calibration and validation.

3.2.2 Processing of Data

1. Weather data: Meteorological parameters obtained at 30 minutes interval were changed to daily scale by adding the corresponding values of rainfall, computing the averages of solar radiation, wind speed, relative humidity, and considering the minimum and maximum values of temperatures of the day.

2. Soil data: The undisturbed soil samples were used to find the soil texture and organic content (Table 3.1) as below.

    (a) Soil texture: Textural classification of the soil was performed as per the US specification. Soil texture defines the composition of the soil particles expressed as the percentage of sand, silt, and clay of total volume. The soil is first spread on a newspaper to dry. Then all stones, trash, and roots, were removed. Lumps and clods are then crushed, and the soil is pulverized. A tall, slender jar is filled with a one-quarter full of soil. Water is added until the jar is three-quarters full. A teaspoon of sodium hexa-meta phosphate is then added and shaked hard for 10 to 15 minutes. This shaking breaks apart the soil aggregates and separates the soil into individual mineral particles. The jar is then un-disturbed for 2 to 3 days and the soil particles are allowed to settle down according to size. After 1 minute, the depth of the sand is marked on the jar. After 2 hours, the depth of the silt is marked. The clay level is labeled when the water clears off, which took about 1 to 3 days. The total thickness of the sand, silt and clay layers is measured followed by the calculation of the percentage of each layer. Finally the soil texture class is found out from the soil texture triangle (as specified by the Food and Agricultural Organization of the United Nations).

(b) Organic content: Total organic carbon (TOC) is determined by treating an aliquot of dried sample with sufficient phosphoric acid (1:1) to remove inorganic carbon prior to the experimentation. Total organic carbon is analyzed by placing approximately 0.350 g of dried, ground and homogenized sample into a clean, carbon-free combustion boat. Each sample boat is treated with phosphoric acid drop by drop until the sample stops bubbling and the sample is completely moist with acid. The sample is then placed into an oven at 40^0 C for 24 hours and then transferred to an oven at 105^0 C. Once the sample is dry, the boat is placed on the auto sampler rack assembly and loaded onto the carbon analyzer.

Remaining soil properties like moist bulk density, saturated hydraulic conductivity , available water capacity, moist soil albedo, USLE equation soil erodibility factor were determined by applying Pedo-Transfer functions, developed by Saxton and Rawls (2006), to the already determined soil parameters, and are given in Table 3.2.

Table 3.1: Soil textural and organic parameters observed at the sampling stations

Sampling Station	Geographical Location	% Sand	% Silt	% Clay	% Organic content
A	N 17.64^0 ; E 77.954^0	35	43	22	1.038
B	N 17.6729^0 ; E 77.973^0	30	50	20	1.015
C	N 17.622^0 ; E 77.9198^0	38	41	21	1.031
D	N 17.583^0 ; E 77.906^0	60	30	10	0.972
E	N 17.587^0 ; E 77.932^0	60	30	10	1.004
F	N 17.657^0 ; E 77.94^0	35	42	23	1.043

Table 3.2: Soil parameters derived using pedo transfer functions

Sampling Stn	Bulk density(g/cc)	Hyd. conduct.(mm/hr)	AWC(%)	Albedo	USLE factor
A	1.518	8.2638	0.1434	0.25	0.1627
B	1.5161	8.5205	0.1561	0.25	0.1713
C	1.528	9.4529	0.1386	0.25	0.1623
D	1.5658	37.6039	0.1015	0.25	0.1688
E	1.5635	37.7748	0.1016	0.25	0.1676
F	1.5142	7.6675	0.1423	0.25	0.1612

3. Nitrate analysis:

   Reagents required: Deionized water of highest purity to prepare all solutions and dilutions, Stock nitrate solution, where potassium nitrate (KNO_3) is dried in an oven at 105C for 24 h and 0.7218 g is dissolved in water and diluted to 1000 mL; 1.00 mL = 100 microgram $NO_3^- - N$, Intermediate nitrate solution where 100 mL stock nitrate solution is diluted to 1000 mL with water, 1.00 mL = 10.0 microgram $NO_3^- - N$, Hydrochloric acid solution (HCl), 1 N.

   Treatment of sample: To 50 mL clear filtered sample, 1 mL HCl solution is added and mixed thoroughly.

   Preparation of standard curve: $NO_3^- - N$ calibration standard chart is prepared in the range of 0 to 7 mg $NO_3^- - N/L$ by diluting to 50 mL following volumes of intermediate nitrate solution as $0, 1.00, 2.00, 4.00, 7.00, \ldots, 35.0$ ml.

The $NO_3^- - N$ standard is treated in the same manner as samples.

Spectrophotometric measurement: Absorbance is read using distilled deionized water as the reference. A wavelength of 220 nm is used for the analysis

Calculation: A standard curve is constructed by plotting absorbance due to NO_3^- against $NO_3^- - N$ concentration of standard. Using corrected sample absorbances, sample concentrations are directly obtained from the inter/extrapolation of the standard curve.

Groundwater nitrates were estimated using spectro-photometric analysis at three well locations (Figure 3.2) and were accordingly used in calibration.

4. Land-use: The CartoSAT-II image of the region is classified using supervised classification algorithm in ERDAS Imagine (version 2011). It involves a preliminary examination of the image where in the features are identified and distinguished using digital numbers (DN). Training sets were defined and delineated by selecting specimen polygons of existing land-use categories including agricultural, fallow, built-up areas. Un-classified pixels are assigned to one of several known informational classes. This resulted in the classification of the image into categories based on land-use characteristics.

5. Management practices: Management operations used in this study include timing and amount of irrigation water, fertilizer, and crop operations (including tillage, planting, harvesting), and are specified for each spatial entity. Information specific to each unit is provided after discussions with farmers, and village revenue officers (VROs).Figure 3.3 provides the temporal distribution of management parameters considered for simulation.

3.3 Modeling Framework

SWAT is a comprehensive, semi-distributed river basin model that requires a large number of input parameters. SWAT operates on a daily time step and is designed to predict the impact of land use and management on water, sediment, and agricultural chemical yields in ungauged watersheds. The model is process based, computationally efficient and capable of continuous simulation over long time periods. Major model components include weather, hydrology, soil properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. In SWAT, a watershed is divided into multiple sub-watersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, topographical, and soil characteristics. The HRUs are represented as a percentage of the sub-watershed area and may not be contiguous or spatially identified within the SWAT simulation. A HRU is the least spatial entity having uniform soil, slope, and land use characteristics.

Water balance is the driving force behind all the processes in SWAT because it impacts plant growth and the movement of sediments, nutrients, pesticides, and pathogens. Simulation of watershed hydrology is separated into i) the land phase, which controls the amount of water, sediment, nutrient, and pesticide loadings to the main channel in each subbasin, and ii) the in-stream or routing phase, that simulates the movement of water, sediments, etc., through the channel network of the watershed to the outlet. Hydrologic processes simulated by SWAT include canopy storage, surface runoff, infiltration, evapo-transpiration, lateral flow, tile drainage, redistribution of water within the soil profile, consumptive use through pumping (if any), return flow, and recharge by seepage from surface water bodies, ponds, and tributary channels. SWAT uses a single plant growth model to simulate all types of land cover and differentiates between annual and perennial plants. The plant growth model is used to assess the removal of water and nutrients from the root zone, transpiration, and biomass/yield production. In addition, SWAT models the movement and transformation of several forms of nitrogen and phosphorus, pesticides, and sediment in the watershed. SWAT allows the user to define management practices taking place in every HRU.

Datasets used for simulation include:

1. Weather data: Rainfall, relative humidity, minimum and maximum temperatures, solar radiation, wind speed at daily scale.
2. Soil data: The soil texture and total organic content of the soil samples were determined and the other properties of the soil were derived from the Pedo Transfer functions.
3. Land-use map: This was obtained from supervised classification of the CartoSAT image.
4. Management practises: This was obtained after the discussions with local farmers and VROs.

Datasets used for calibration include:

1. Change in streamflows between Singur and Manjeera Reservoirs on a daily scale.
2. Potential evapotranspiration at the two AWS stations on a daily scale estimated using ASCE standardized reference equation (Final Report , Environmental and Water Resources Institute of the American Society of Civil Engineers, January 2005).
3. Groundwater nitrates observed at three sampling stations on weekly scale.

ArcSWAT is the geographic information system (GIS) interface to SWAT, and was used as the pre-processor to input the spatial and temporal data sets. SWAT was run on daily step for the irrigation year 2013-1 (1 May 2013 to 30 April 2014) covering both Kharif and Rabi seasons.

The first step involved in the modeling is to delineate the watershed. Arc Hydro tool was used to process the DEM of the study area, and analyze for flow direction and accumulation. A threshold area of 250 hectares was specified for stream network and catchment delineation. A total of four watersheds were identified that are draining into the Manjeera Reservoir. However, due to the lack of monitoring data and other constraints, only one watershed was considered for the analysis. This watershed was further divided into 15 sub-basins.

The second step is HRU analysis that involves landuse, soils and slope map representation using GIS. Probabilistic interpolation techniques (Kriging) using Geostatistical Analyst in GIS was used to generate the continuous surface of various soil parameters. This soil grid is then reclassified into six classes and using quantile method. A total of 3 slope classes (0 to 2; 2 to 4; and 4 to 6) were derived by processing the DEM for use with HRU analysis. The threshold values considered for each parameter in the HRU analysis are given below.

1. Landuse % over sub-basin area= 5
2. Soil class % over landuse area= 20
3. Slope class % over soil area = 20

This has resulted in the generation of 260 HRUs across the study area.

Meteorological data from the two AWS stations, and the management data from the field visits was accordingly inputted to the model on daily steps. The SWAT model was then run for a period of one year and the corresponding output datasets (catchment outflows, nitrates leached, PET, etc.) were generated at subbasin, reach and HRU scales. Figure 3.4 and Table 3.3 provides the spatial distribution of modelling units and their details respectively.

Table 3.3: Description of datasets considered in SWAT simulation and calibration

Data type	Format	Scale/Res	Source	Remarks
Topography	DEM (Grid)	30 m	SRTM DEM data	Resampled from 90m
Land use	Satellite Image	5 m	NRSA, Hyderabad	IRS P-6, LISS-IV FMX
Meteorologic	Point data	30 min.	AWS (Watchdog)	2 weather stations
Soils	Point data	5 m (kriging)	Un-disturbed soil samples	Permeability, density, gradation, …
Stream network	DEM (Grid)	30 m	SRTM DEM data	From DEM using ArcHydro
Management practices	Distributed	seasonal	Discussion with farmers / VROs	Crop, watering, tillage, fertilizers, …
Stream Flows	Point data	Weekly	AP Irrigation Department	Weekly discharges at inlet / outlet of basin
GW Nitrate conc.	Point data	Weekly	Lab measurement (UV-VIS)	8 groundwater samples
ET	Point data	Daily	ASCE Standardized	2 weather stations

3.4 Calibration and Uncertainty

SWAT input parameters are process based and must be held within a realistic uncertainty range. The first step in the calibration and validation process is the determination of the most sensitive parameters for a given watershed. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs. It is necessary to identify the key parameters and the parameter precision required for calibration. This helps in determining the predominant processes for the component of interest. Global sensitivity analysis was performed, and the parameters sensitive to streamflows and PET were analysed. Model parameters sensitive to catchment streamflows include curve number under moisture II condition (CN2) , base flow alpha factor (ALPHA_BF), groundwater delay coefficient (GW_DELAY), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), saturated hydraulic conductivity (SOL_K), moist bulk density(SOL_BD), average slope length (SLSUBBSN), baseflow alpha factor for bank storage(ALPHA_BNK), effective hydraulic conductivity in main channel (CH_K2), soil evaporation compensation factor (ESCO) and plant uptake compensation factor (EPCO).

Calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty. Model calibration is performed by carefully selecting values for model input parameters (within their respective uncertainty ranges) and then by comparing model predictions for a given set of assumed conditions with observed data for the same conditions. The final step is validation for the component of interest (streamflow). Model validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations.

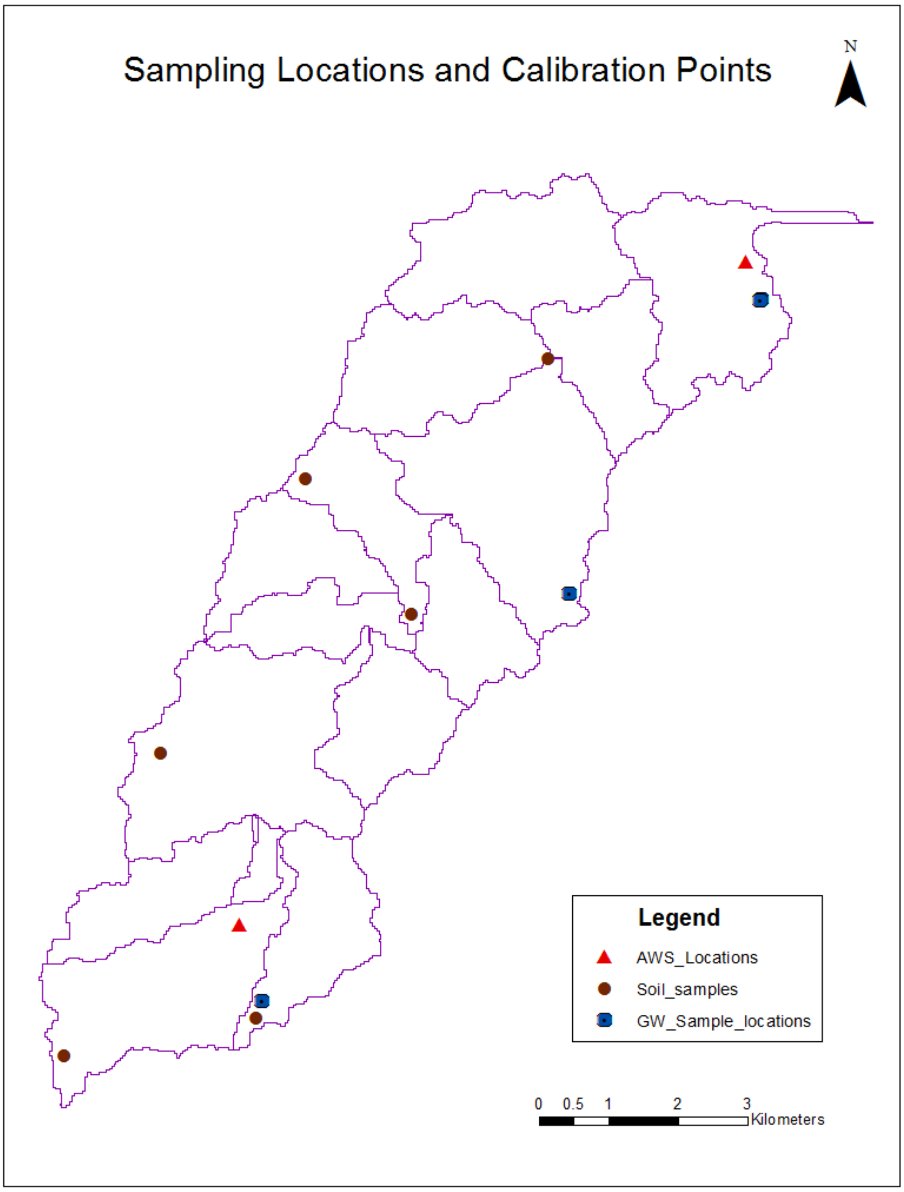


Figure 3.1: Map of the study area representing sampling / monitoring stations

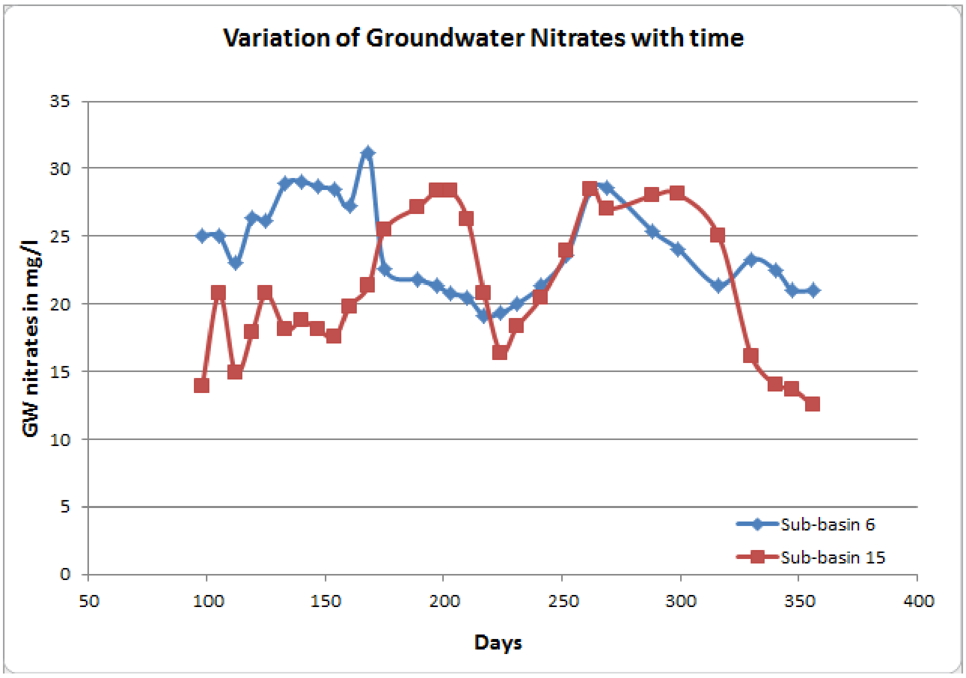


Figure 3.2: Variation of groundwater Nitrates with time at the monitoring wells

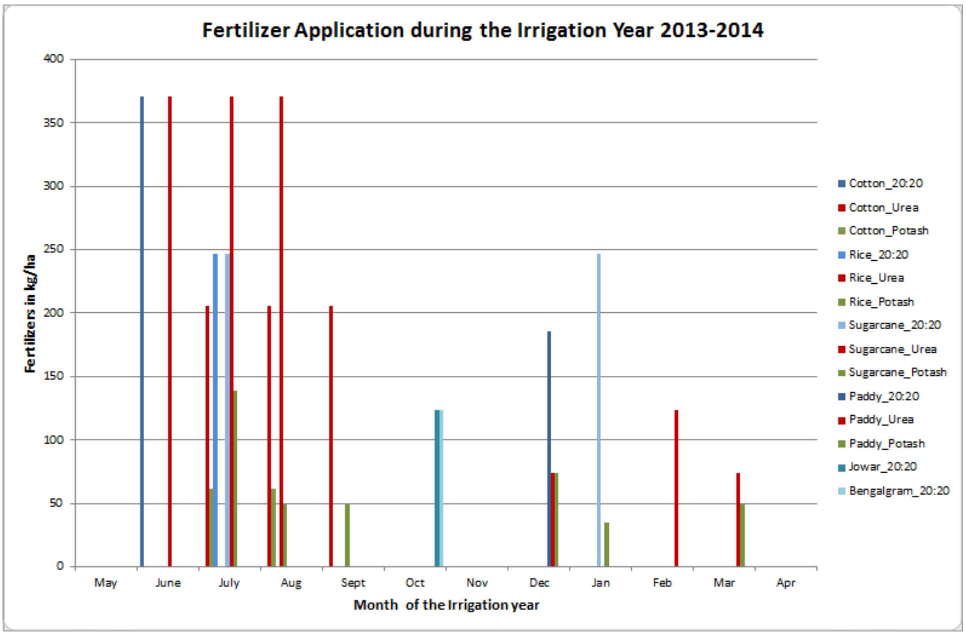


Figure 3.3: Temporal application of fertilizers

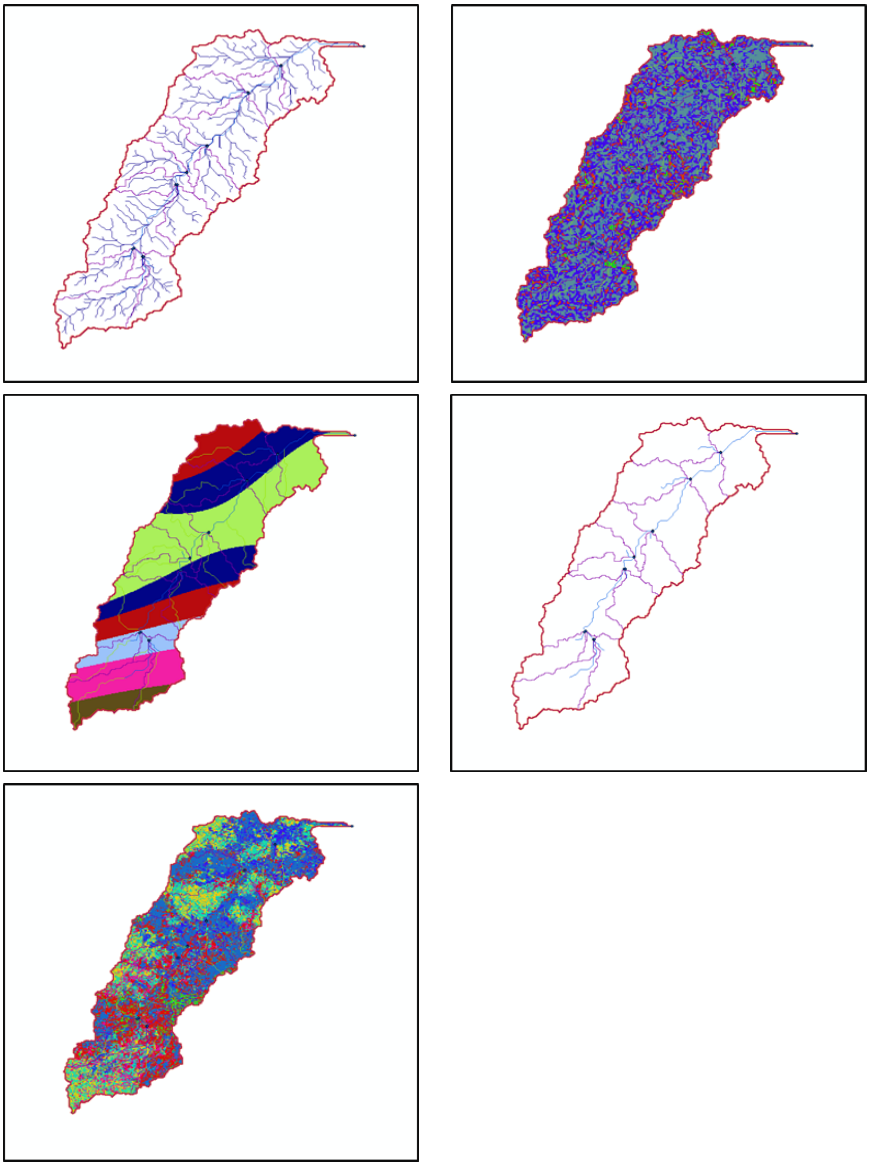


Figure 3.4: Representation of stream network, slopes, soils, sub-basin and land use characteristics

Chapter 4

Modeling Nitrate Loads

4.1 Introduction

Nitrogen is highly reactive with water due its existence in a number of valence states ranging from Nitrate (highly oxidized) to ammonium (highly reduced). Nitrogen is added to the soil by fertilizer, manure or residue application, fixation by symbiotic and nonsymbiotic bacteria, and rain. Nitrogen is removed from the soil by plant uptake, leaching, volatilization, denitrification and erosion.

4.2 Nitrogen Transformation

Nitrogen cycle (Figure 4.1) is the process by which nitrogen is converted between its various chemical forms. This transformation can be carried out through biological and/or physical processes. SWAT is capable of modeling the components of nitrogen cycle in both soil profile and shallow aquifer. Major processes involved in the nitrogen cycle that are applicable to soil zone are given by:

1. Mineralization and Decomposition/ Immobilization: Decomposition is the breakdown of fresh organic residue into simpler organic components. Mineralization

is the microbial conversion of organic, plant-unavailable nitrogen into inorganic, plant-available nitrogen. Immobilization is the microbial conversion of plant-available inorganic soil nitrogen to plant-unavailable organic nitrogen. Mineralization and decomposition are highly dependent on water availability. SWAT is capable of simulating nitrates added by mineralization and/or removed by immobilization at HRU level for each soil layer.

2. Nitrification and Ammonia Volatilization: Nitrification is the oxidation of ammonium (NH4+) to nitrates (NO_3^-). Ammonia volatilization is the gaseous loss of ammonia (NH_3) that occurs when ammonium, at the surface is applied to a calcareous soil or when urea ($NH_2\ 2CO$), is applied at the surface to any soil. SWAT simulates nitrification and ammonia volatilization by calculating the total amount of ammonium lost, and then portioning between the two processes.

3. Denitrification: It is the bacterial reduction of nitrate (NO_3^-) to nitrites (N_2) or nitrous oxide (N_{2O}) gases under anaerobic conditions. Amount of denitrification from the soil layer is a function of water content, temperature, presence of a carbon source and nitrate. SWAT simulates nitrates lost to denitrification at HRU level for each soil layer.

4. Atmospheric deposition: Atmospheric deposition is the processes of settling down of airborne chemical onto the surface. Nitrogen compounds can be deposited onto water and land surfaces through both wet and dry deposition mechanisms. Wet deposition occurs through the absorption of compounds by rain particles as it falls, and carries mainly nitrate (NO_3^-) and ammonium (NH_4^+). Dry deposition is the direct adsorption of compounds to water or land surfaces and involves complex interactions between airborne nitrogen compounds and plant, water, soil, rock, or building surfaces. Amount of nitrates and ammonia added to the soil through rainfall are given, respectively by:

$$NO3_{rain} = 0.01.R_{NO3}.R_{day} \tag{4.1}$$

$$NH4_{rain} = 0.01.R_{NH4}.R_{day} \tag{4.2}$$

5. Nitrogen Fixation: Legumes are able to obtain a portion of their nitrogen demand through fixation of atmospheric nitrogen. Legumes have symbiotic nitrogen-fixing bacteria in their root nodules. In exchange for nitrogen, the plant supplies the bacteria with carbohydrates. SWAT simulates nitrogen added by fixation as a component of plant biomass instead of adding to the soil layer.

6. Nitrogen Assimilation: Plants require nitrogen more than any other essential element. Plants take nitrogen from the soil by absorption through their roots in the form of nitrate or ammonium ions. If nitrate is absorbed by the plant, it is first reduced to nitrite ions and then ammonium ions for incorporation into amino acids, nucleic acids, and chlorophyll.

7. Nitrate Leaching: The majority of plant-essential nutrients are cations (positively charged) which are attracted and sorbed to negatively-charged soil particles. As plants extract these cations from soil solution, the soil particles release bound cations into soil solution to bring the ratio of nutrients in solution and on soil particles back into equilibrium. In contrast to the other nutrients, nitrate is an anion and is not attracted to or sorbed by soil particles. Because retention of nitrate by soils is minimal, nitrate is very susceptible to leaching. In addition to leaching, SWAT also simulates the upward movement of nitrate in water resulting from soil evaporation. Water from the lower saturated profiles will move upward (following the gradient) in response to the gradient, carrying dissolved nutrients with it.

4.3 Nutrient transport

Most soil minerals are negatively charged, and hence, repulse the nitrate ions resulting from the transformations. The end result of nitrogen cycle in a given soil layer is the addition and/or removal of nitrates from that layer. Once nitrogen enters the soil, it undergoes several physical and biochemical transformations before leaching to groundwater mostly as nitrate. SWAT simulates the amount of nitrates carried by a given phase of the hydrologic cycle (such as surface runoff, lateral flow, leaching, and groundwater flow) by multiplying the nitrates concentration with corresponding flow. Nitrate removal coefficient (such as percolation coefficient) is added to this as a calibrating parameter, to adjust the nitrate movement values.

This study estimates the amount of nitrates added to the soil from irrigation water pumping as:

$$NO3_{irr} = 0.01.R_{NO3}.Irr_{day} \tag{4.3}$$

where NO_{3irr} is the nitrate added by irrigation water (kg N/ha), R_{NO3} is the concentration of nitrate in irrigation water and Irr_{day} is the amount of irrigation water applied to the field on a given day. Major limitation of SWAT in transporting nutrients is that SWAT assumes no change in nitrate concentration of the recharge as it moves through the vadose zone. This assumption is valid under following conditions:

1. When depth to groundwater below the plant root zone is relatively less
2. When leaching coefficient is sufficiently high
3. When nitrates concentration in groundwater has no practical significance (for analyzing fate of nitrates / coupling with groundwater models)

In reality, nitrates carried away from the plant root zone via leaching will either be lost to other forms, or, sorbed to the soil particles. Hence, nitrates reaching the groundwater are dependent highly on depth to groundwater table, factors that effect the leaching process, and the amount of water being percolated. SWAT simulates nitrates leached at the root zone depth. However, $NO_3 - N$ concentrations of samples are observed at the groundwater (aquifer) level. It is difficult to correlate N leaching at rooting depth with the NO_3N contents in the aquifer because other factors, such as groundwater depth, lateral flux and denitrification in the vadoze zone are difficult to simulate (Hallberg and Keeney, 1993). Many mathematical models are available in the literature to simulate soil nitrogen movement through the vadose zone (Pierce et al., 1991; de Paz, J.M. et al. 2009; Almasri and Kaluarachchi, 2007).This research aims at implementing the nitrogen leaching (movement) process happening in the vadose zone into SWAT simulation.

The main reactions and pathways that the nitrogen undergoes in the soil layer include mineralization, immobilization, nitrification, denitrification, volatilization,crop uptake, and leaching from the soil zone. The final output from most of the soil nitrogen models (including SWAT) is the spatial and temporal nitrate leaching at the plant root zone level. Nitrate available for leaching (NAL) in HRU level for each soil layer is calculated from the nitrate balance equation, given by

$$NAL = NAL_0 + NO_3^{So} - NO_3^{Si} \tag{4.4}$$

Where NAL_0 is the nitrate available for leaching at the beginning of the time step; NO_3^{So} is the summation of all sources of nitrates (includes nitrate that enters the soil from the ground surface, nitrate from nitrification, and the initial nitrate mass); and NO_3^{Si} is the summation of all sinks of nitrate (includes nitrate losses in runoff, immobilization, denitrification, and plant uptake).

The flux of nitrates leaving the soil profile (NL) is computed in the modified SWAT code as (reference:de Paz, J.M. et al. 2009; Almasri and Kaluarachchi, 2007)

$$NL = NAL \times [1 - exp((-K \times WAL)/w)] \tag{4.5}$$

where K is the nitrate leaching coefficient, WAL is the water available for leaching (L^3); and w is the volume of voids of the soil (L^3) that can be determined as (Pierce et al., 1991)

$$w = [1 - BD/PD] \times soil\ depth \times surface\ area \tag{4.6}$$

where BD is the bulk density (ML^{-3}) and PD is the particle density (ML^{-3}). The value of K depends largely on the soil characteristics. It is evident that, Nitrates leached are exponentially decreases with depth from the root zone.

The potential impact of NL on underlying aquifers depends on several additional factors including travel time to the aquifer, presence or absence of a confining layer, initial concentration of NO3-N in the aquifer, mixing volume of the aquifer, volume and quality of water moving out of the aquifer, (agricultural pumping), and permeability of the aquifer. Major limitation with SWAT is that, the nitrates available for leaching at the root zone level are in Kg/Ha units, where as the observed concentrations of nitrates in groundwater are in mg/l, making it difficult to compare. Also, nitrate balance for the aquifer / groundwater system is not considered in SWAT. Considering these SWAT limitations, an aquifer risk index (ARI) for NO3-N entering the aquifer is proposed in this research (NLEAP:Model description and Application, Shaffer et al., 1991).Mass balance to nitrates for the aquifer systems is applied to generate the ARI (in mg/l) at HRU level for all time steps. ARI can serve as an important parameter to be compared with the observed groundwater nitrate concentration (NLEAP:Model description and Application, Shaffer et al., 1991;Arzu Firat Ersoy and Fatma Gltekin, 2013).

The risk of moving recently leached $NO_3 - N$ and deep residual $NO_3 - N$ (if any) located in the vadose zone below the root zone to an underlying aquifer can be estimated using an expression,

$$Depth = WAL/AWHC_d/12 \tag{4.7}$$

where depth is maximum depth of water penetration below the root zone (ft), $AWHC_d$ is water-holding capacity of the material underlying the root zone (in.fin.), WAL is water available for leaching below the root zone (in.), and 12 converts in. to ft.

The potential impact of NL on underlying aquifers depends on several additional factors: travel time to the aquifer, presence or absence of a confining layer, volume of water moving with the NL, initial concentration of $NO_3 - N$ in the aquifer, mixing volume of the aquifer, volume and quality of other water moving into the aquifer, volume of water leaving the aquifer (pumped be computed at the present or a future time T (days, months, or years) by applying the following equation under steady-state water flow conditions. A present-day calculation would require historical information on aquifer conditions and $NO_3 - N$ leaching.

$$ARI = 0.369[N_0 + (NL)(A) + N_{sl}N_l]/AMV \tag{4.8}$$

where AMV is the aquifer mixing volume (acre-ft), N_0 is the initial $NO_3 - N$ content of the AMV (lb), NL is soil $NO_3 - N$ leached to the aquifer (lb/[acre-time step]), A is the area of the field or farm (acre), N_sl is $NO_3 - N$ entering the AMV from sources outside the farm or field of interest (lb/time step), N_l is $NO_3 - N$ leaving the AMV in pumped wells, tile drains, and other flows (lb/time step), and 0.369 converts lb/acre-ft to parts per million (ppm). This equation assumes that the upper portion (usually a few feet in depth) of a shallow aquifer (called the AMV) can be defined where an approximate complete mix is occurring with respect to the sources and sinks of $NO_3 - N$. Nc is calculated using,

$$N_0 = 2.7l(N_c)(AA)(W) \tag{4.9}$$

where Nc is the initial $NO_3 - N$ concentration in the AMV (ppm) (mg/L), AA is the surface area of the aquifer (acre), W is thickness of the AMV (ft) multiplied by its porosity, and 2.71 converts ppmacre-ft to lb/acre-ft. N_{sl} is calculated by multiplying associated flows (acre-ft/time step) times their concentration of $NO_3 - N$ (ppm) times 2.71. N_l is computed in a similar fashion by multiplying N_c times the corresponding discharge volumes (acre-ft/time step) times 2.71. For steady-state conditions, aquifer discharge volume equals input volume.

Source code of SWAT was modified in the present work to effectively simulate nitrogen leaching past the plant root zone, and create a rational base for comparison of groundwater nitrate concentrations. Workflow of nutrient transformation and transport considered in this research is provided in Figure 4.2. Following are the major revisions to the existing nutrient leaching dynamics (nlch.f) simulated using SWAT.

1. Incorporate nitrates present in the irrigation water (pumped out of the aquifer) into SWAT simulation (for selected HRUs and time steps)

2. Simulate nitrates leaching past the plant root zone considering leaching coefficient, water availability, and depth to the aquifer

3. Develop an index for converting the flux of nitrates reaching the aquifer into concentration, considering the mass balance of the aquifer system

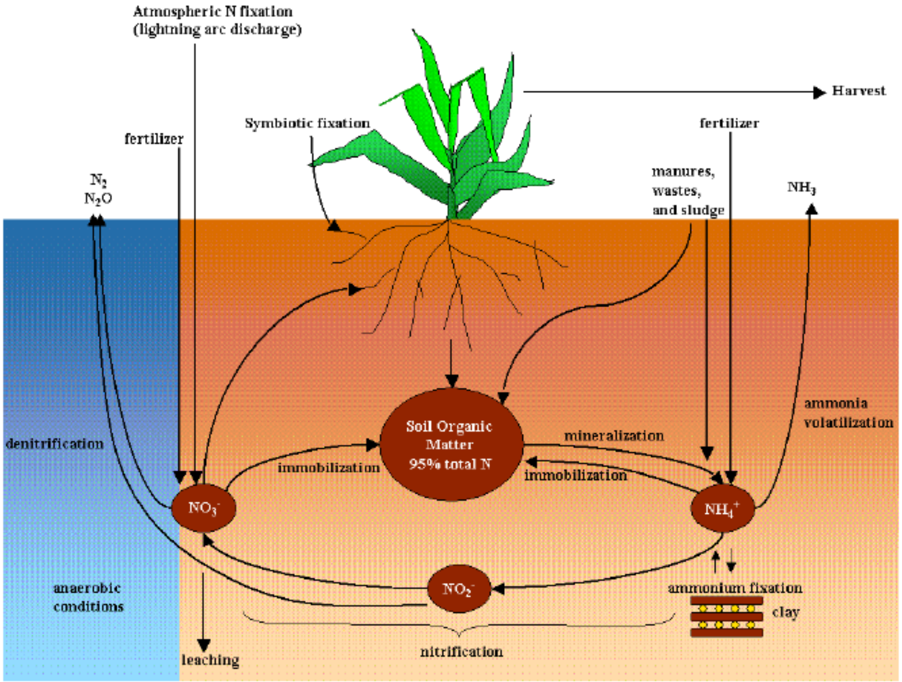


Figure 4.1: Schematic representation of nitrogen flow

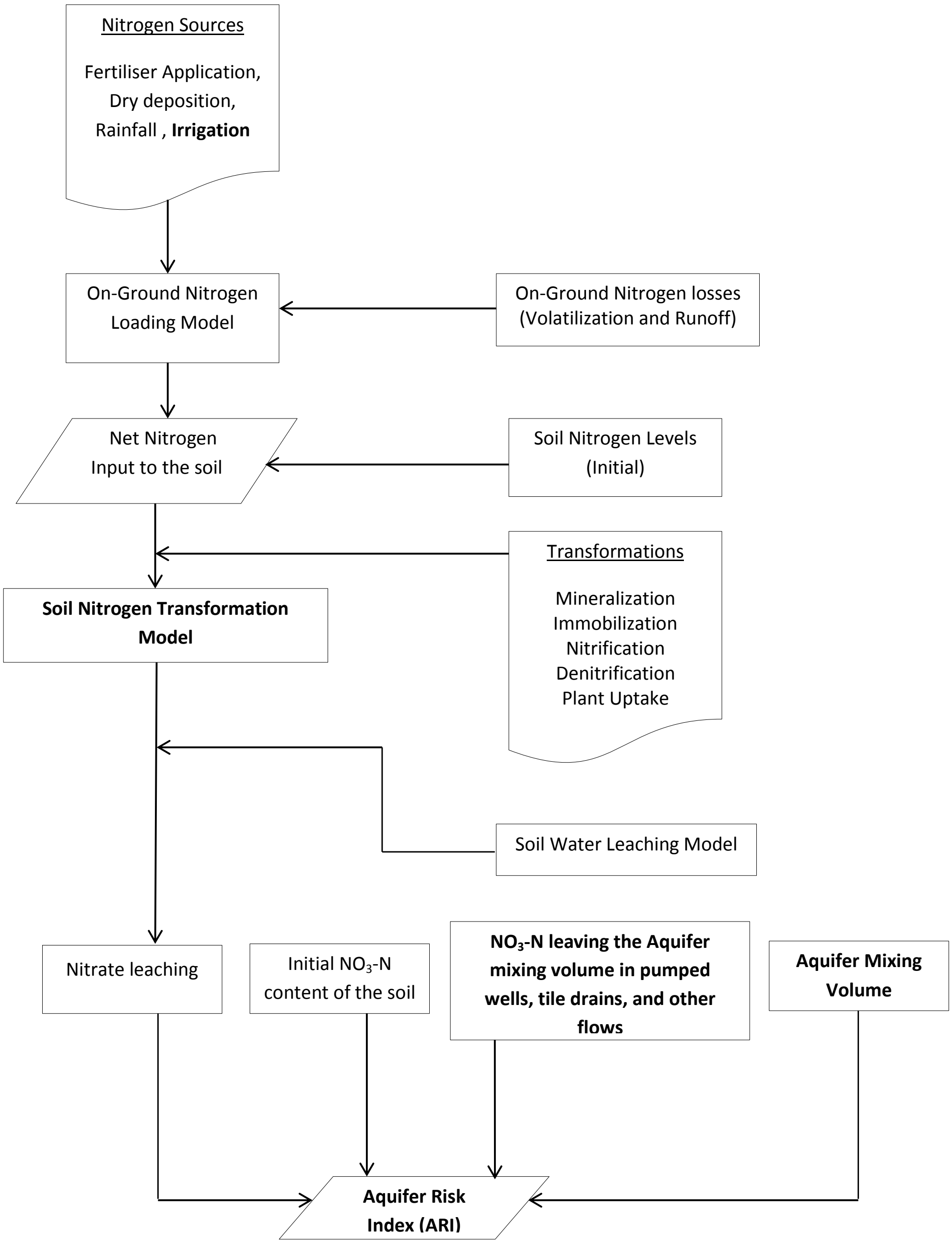


Figure 4.2: Flow-chart describing the modeling framework for assessment of groundwater nitrates using the modified code

Chapter 5

Results And Discussions

5.1 Introduction

This chapter presents the results of model simulation and calibration for catchment outflows and PET estimates. Simulation results on nutrient transport using the modified SWAT code were discussed in detail. Effect of leaching coefficient and initial soil nitrates on the groundwater nutrient loads was also investigated. Groundwater vulnerability (in terms of NO3-N) was discussed in detail by developing the mass balance of nutrients for the aquifer system.

5.2 Model Simulation

The modified SWAT model was run for the Kharif and Rabi seasons of the irrigation year 2013-1 4 (May 2013- April 2014) on daily scale. The model setup includes delineation of watershed using a 90m DEM, analysis of HRUs that employs landuse grid, soil data and slope definition followed by the threshold values for each class. This resulted in the development of 260 HRUs and 15 sub-basins. The daily weather data was then provided to the model. Management practices ranging from tillage operations, fertilizer and irrigation applications were provided for the agricultural lands (after consultation with the farmers and VROs).

5.3 Simulation Results

The simulated model yields hydrologic budget outputs for each HRU / sib-basin specific to each time step. The components of the budget include: stream outflows, evapo-transpiration, infiltration, nitrate leached from the root zone, groundwater nitrate loads, etc. Of these, catchment outflows PET estimates, and groundwater nitrate loads were used for further analysis.

5.3.1 Simulation of Catchment Outflows

The streamflows out of the catchment (outlet of sub-basin 2) were calibrated using the observed data. The observed streamflows for the entire catchment were obtained by subtracting the infows of Manjeera reservoir from the outflows of Singur reservoir for each day. Considering the mass balance for the entire watershed, the observed flows were indirectly estimated using the inflows and outflows to the system. However, inflows to Manjeera reservoir were zero for most of the days, particularly during the non-monsoon times. These data points were ignored from the calibration. The sensitivity analysis was then performed for the model by varying the ranges of few parameters. These parameters include: curve number for moisture condition II (CN2), baseflow alpha factor (ALPHA_BF), groundwater delay time (GW_DELAY), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), saturated hydraulic conductivity (SOL_K), moist bulk density (SOL_BD), average slope length (SLSUBBSN), baseflow alpha factor for bank storage (ALPHA_BNK), effective hydraulic conductivity in main channel (CH_K2), soil evaporation compensation factor (ESCO), and plant uptake compensation factor (EPCO). The model was found to be sensitive to parameters such as CN2, ALPHA_BF, GW_DELAY, GWQMN, SOL_K, SOL_BD, CH_K2 and EPCO . The model sensitive parameters along with their best fitted values, initial and final ranges used in simulation are given in Table 5.1.

Table 5.1: Model parameters sensitive to catchment outflows, and their ranges

Sensitive Parameter	Fitted Value	Initial Range	Final Range
A_CN2.mgt	9.5	-10,10	-0.88, 19.88
V_ALPHA_BF.gw	0.175	0,1	-0.2625, 0.6125
V_GW_DELAY.gw	9.75	0,10	4.638,14.862
V_GWQMN.gw	0.75	0,2	0.07, 1.43
V_SOL_K(..).sol	0.25	0,10	-4.95, 5.45
V_SOL_BD.sol	1.44	1.1,1.9	1.185, 1.695
V_SLSUBBSN.hru	111.5	10,150	57.16,165.84
V_ALPHA_BNK.rte	0.08425	0.01,1	-0.401, 0.569
V_CH_K2.rte	3.75	0,150	-73.885, 81.385
V_ESCO.hru	0.28225	0.01,1	-0.105, 0.67
V_EPCO.hru	0.62875	0.01,1	0.2926,0.964

In Table 5.1, V denotes that the existing parameter value is to be replaced by the given value, A denotes that the given value is added to the existing parameter value. The file extensions of .mgt, .gw, .sol, .hru and .rte represent Management, Groundwater, Soil, HRU and Channel physical characteristics respectively. Model sensitive parameters were represented using the dotty plots in Figure 5.1. The model was calibrated using SUFI2 algorithm. Simulated flows were in congruence with the observed flows. Calibration results along with the 95 ppu plot is represented in Figure 5.1.

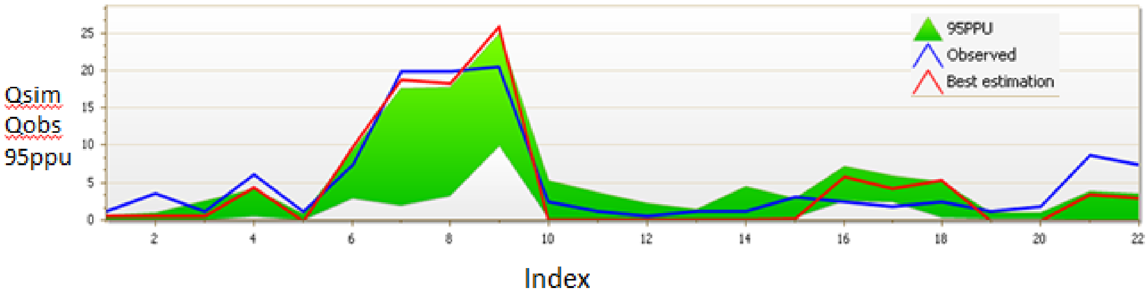


Figure 5.1: Comparison of simulated and observed streamflows at the outlet of catchment

Model performance to replicate the catchment streamflows was evaluated using statistical parameters including coefficient of determination (R^2), Nash Sutcliffe Coefficient (NSE) and Mean Squared Error. Results of the statistical analysis are provided in Table 5.2

Table 5.2: Evaluation of model performance using statistical parameters

p-factor	r-factor	R^2	NS	br^2	MSE	SSQR
0.45	0.6	0.88	0.83	0.8344	6.77	2.9543

5.3.2 Simulation of Potential Evapo-transpiration

The ASCE standardized Penman Monteith method was used for determining the potential evapo-transpiration (PET) at the two weather stations from the observed meteorological data. These values were compared with the corresponding PET values simulated by SWAT, that employs the Penman Monteith (PM) method. The advantage of using ASCE Standardized Penman-Monteith method includes, provision of simplified numerator and denominator coefficients that are crop-specific. Comparison of ASCE and P-M estimated PET values at the two AWS locations are given in Figure 5.2 and Figure 5.3

5.3.3 Simulation of groundwater nitrates at Sub-basin level

The calibrated model was applied to estimating nitrates load on groundwater. Observed groundwater (GW) nitrates at two sampling stations (sub-basins 6 and 15) on every week were used for comparison. Figures 5.4 and 5.7 represents the comparison of observed GW nitrate concentration with original (ignoring leaching) and modified (considering leaching) SWAT simulated ones. Since the soil depth specific to the study area was assumed to be constant, and water available for percolation in this region is also invariably the same, the effect of leaching coefficient on the nitrate leaching process was studied by varying within a defined range of 1 to 2. Effect of leaching coefficient on the groundwater nitrate loads using the modified SWAT code for the sub-basins 6 and 15 is represented in Figures 5.5 and 5.8 respectively. The nitrates concentration in the soil layers, at the start of simulation, were difficult to estimate, and hence varied from (20mg/kg to 50mg/kg) during the sensitivity analysis. No tests performed to measure the nitrate content in the soil, Model simulated GW nitrate loads for different assumed initial soil nitrates for the sub-basins 6 and 15 is represented in Figures 5.9 and 5.10 respectively.

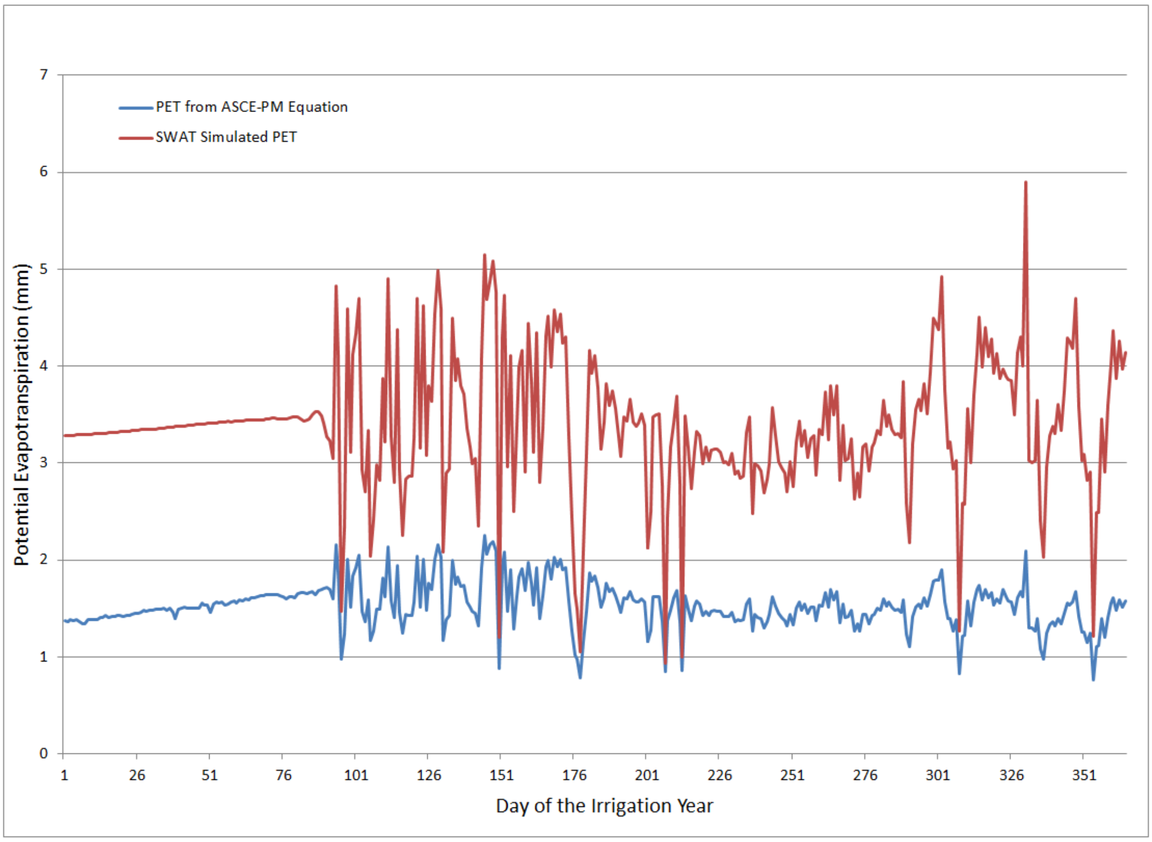


Figure 5.2: Comparison of ASCE and SWAT simulated PET values at AWS-1

The observed and best simulated (leaching coefficient of 2.0 and soil nitrates of 20 mg/kg) groundwater nitrates were compared for the sub-basin 15, and evaluated using statistical parameter R2 (Figure 5.3.3)

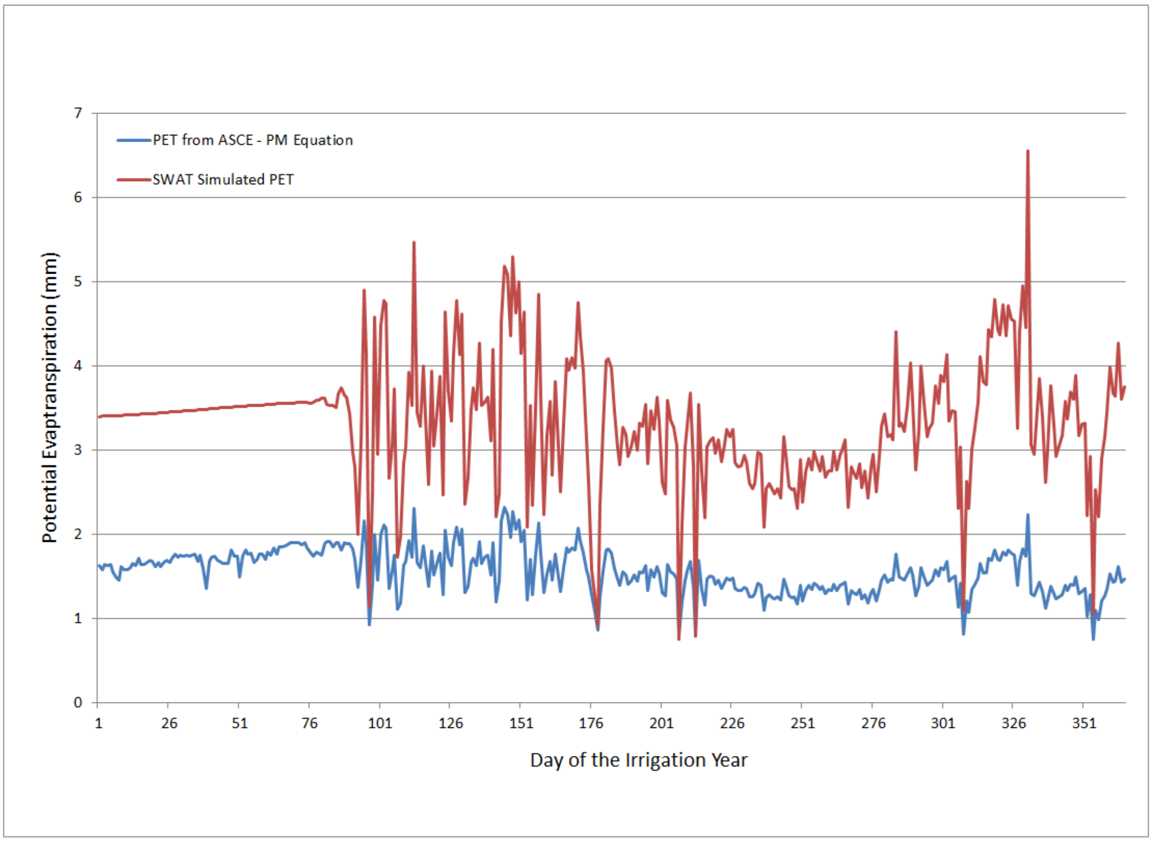
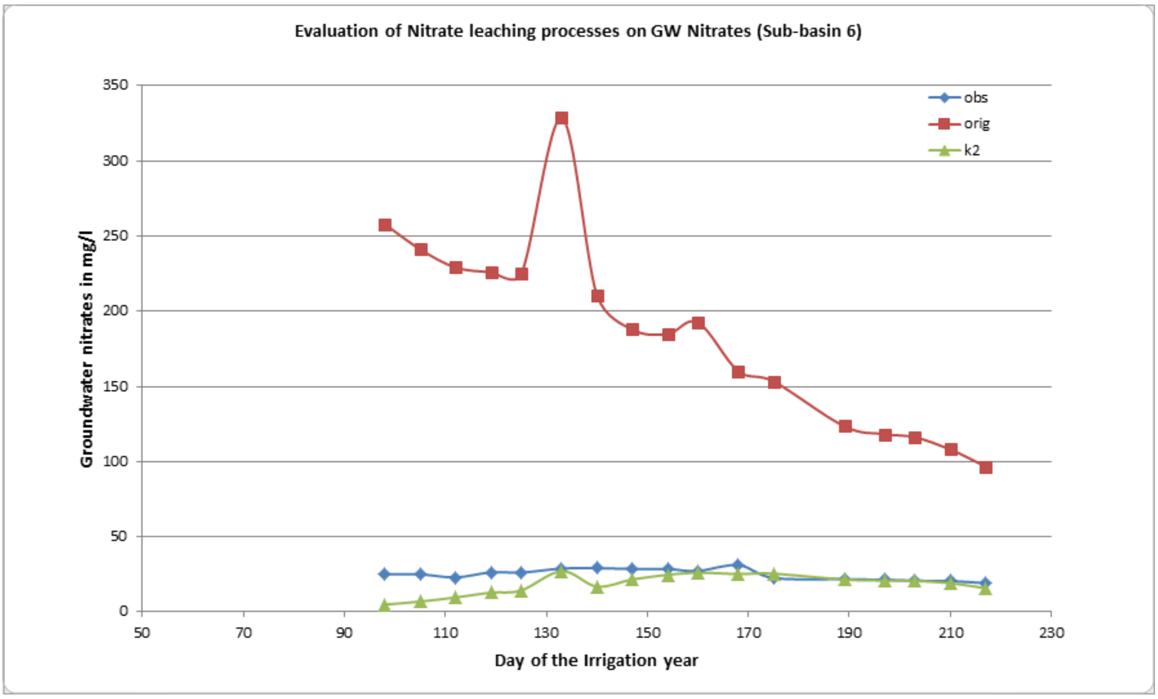


Figure 5.3: Comparison of ASCE and SWAT simulated PET values at AWS-2

5.4 Discussion of results

The groundwater nitrate concentration for various leaching coefficients was determined for both sub-basins 6 and 15. It was observed that the model prediction was reasonably accurate when the leaching coefficient was taken as 2. Further, the soil nitrates was varied in order to check its impact on the model prediction. This showed that, the nitrate concentration of 20 mg/kg in the top two layers of soil produced fairly good results.

The coefficient of determination between the modeled and observed values was found to be 0.2735. The model can be considered to be reasonably good as inferred from Chu et al. (2004), Grizzetti et al. (2005), Du et al. (2006) since the simulation was performed for a short duration of one year and on a daily step.

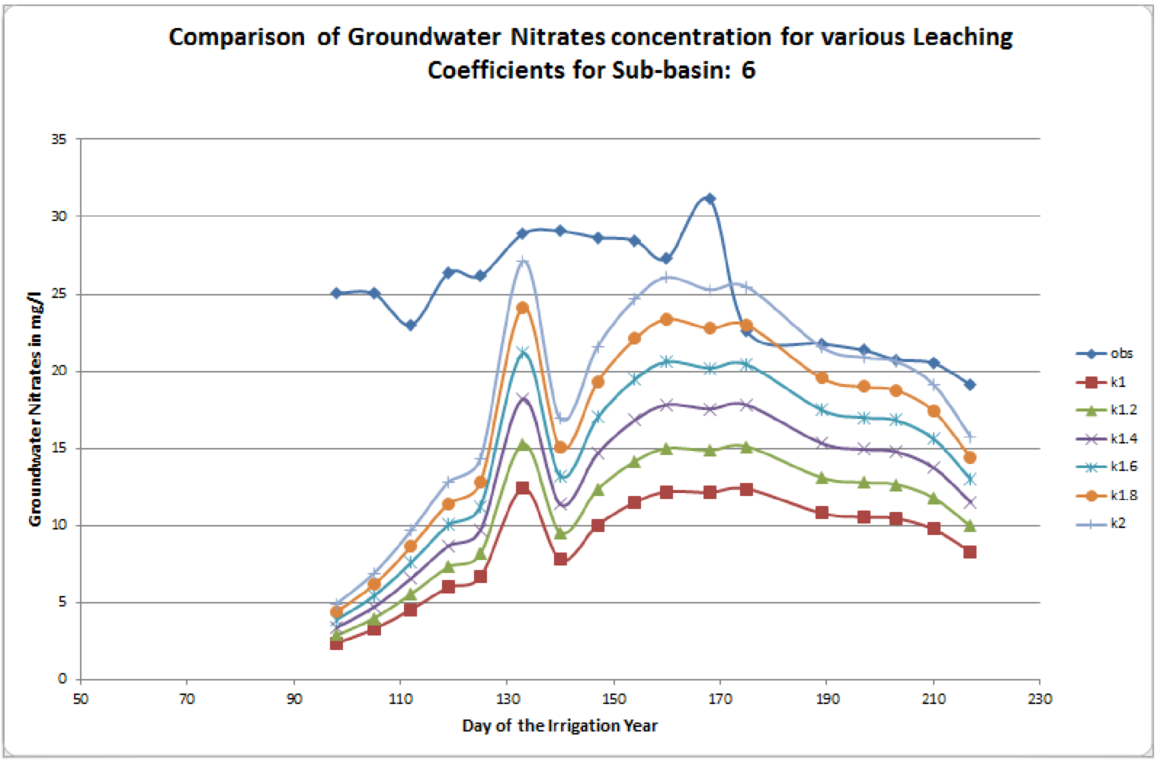


Additionally, the graphical comparison of the PET estimated by ASCE standardized Penman-Monteith method and the Penman Monteith method indicated that they both follow the same trend. While SWAT overestimates the PET obtained on a daily scale from the model, the ASCE Penman Monteith method predicts lower values of the same.

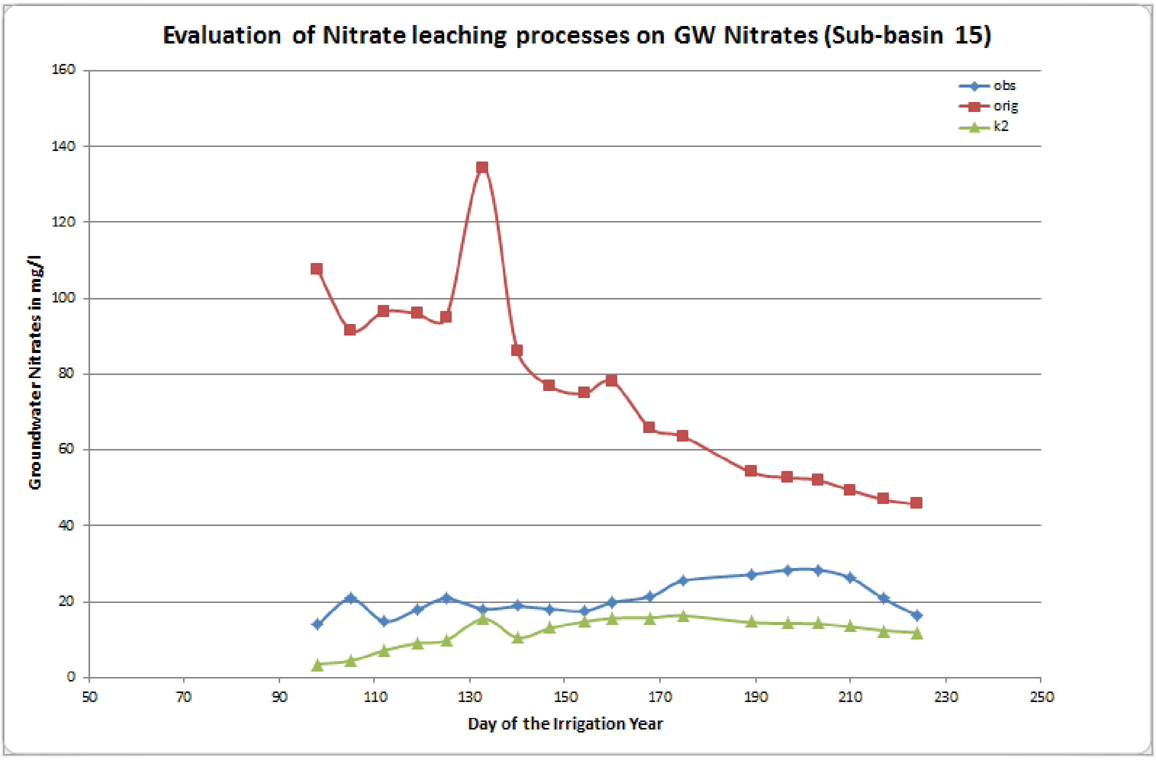
5.5 Nitrate leaching maps

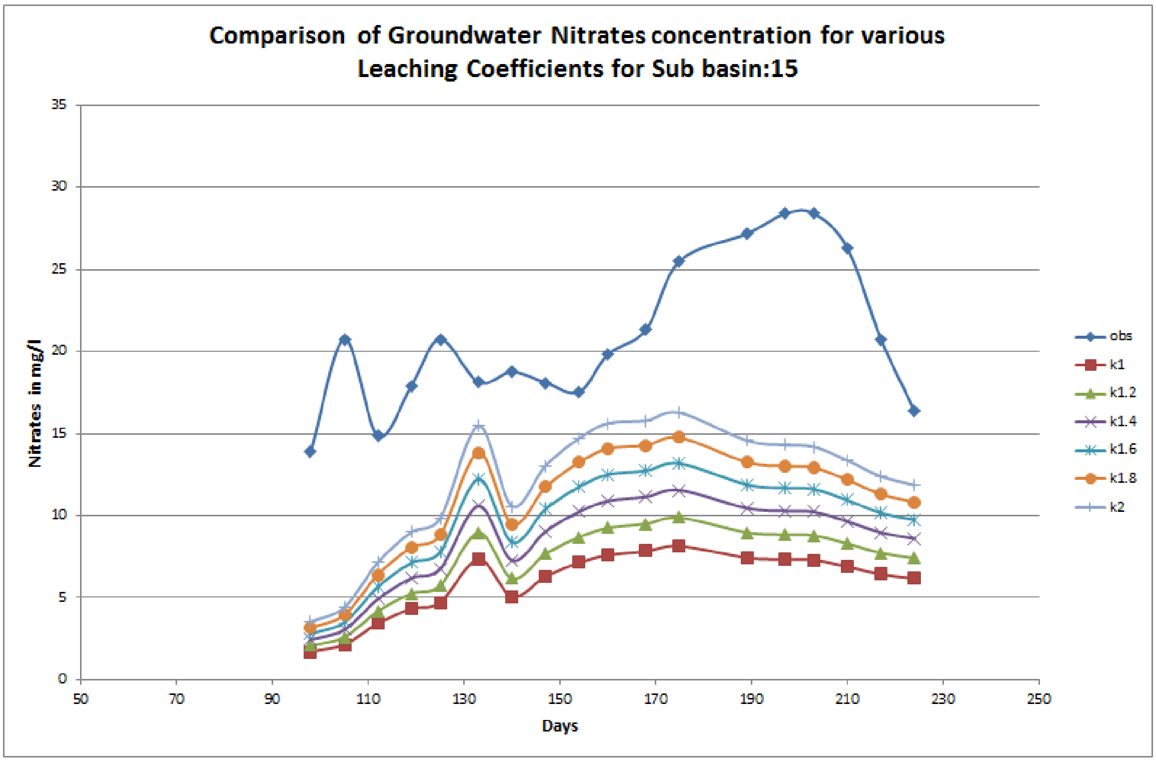
Nitrate leaching map (Figure 5.11) represents the spatial variation of groundwater nitrates at the end of the simulation in different sub-basins for the study area. The nitrates transported to groundwater were reported in terms of kg per hectare.

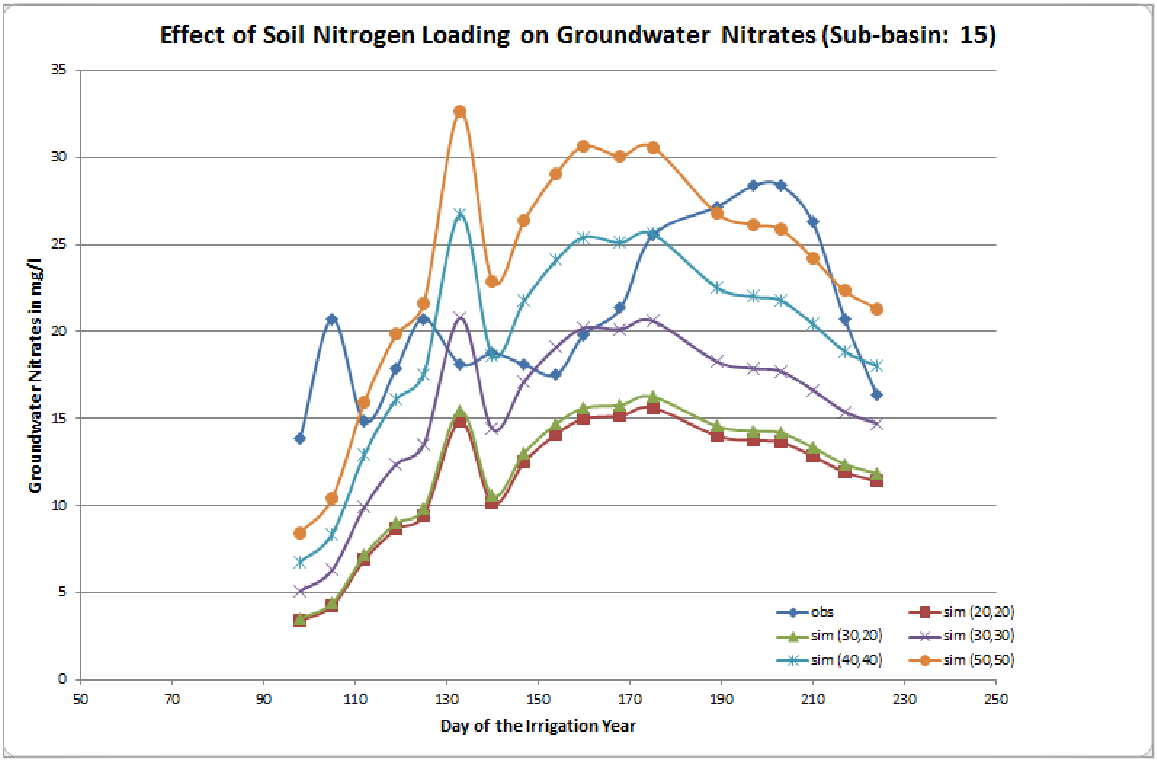
Aquifer risk index map (Figure 5.12) demonstrates the spatial distribution of nitrate risk to groundwater for all the sub-basins present in the study area. It is a measure of groundwater vulnerability to the various components of nitrogen cycle and soil nitrogen dynamics. As evident from this map, the sub-basins 6, 8 and 9 have

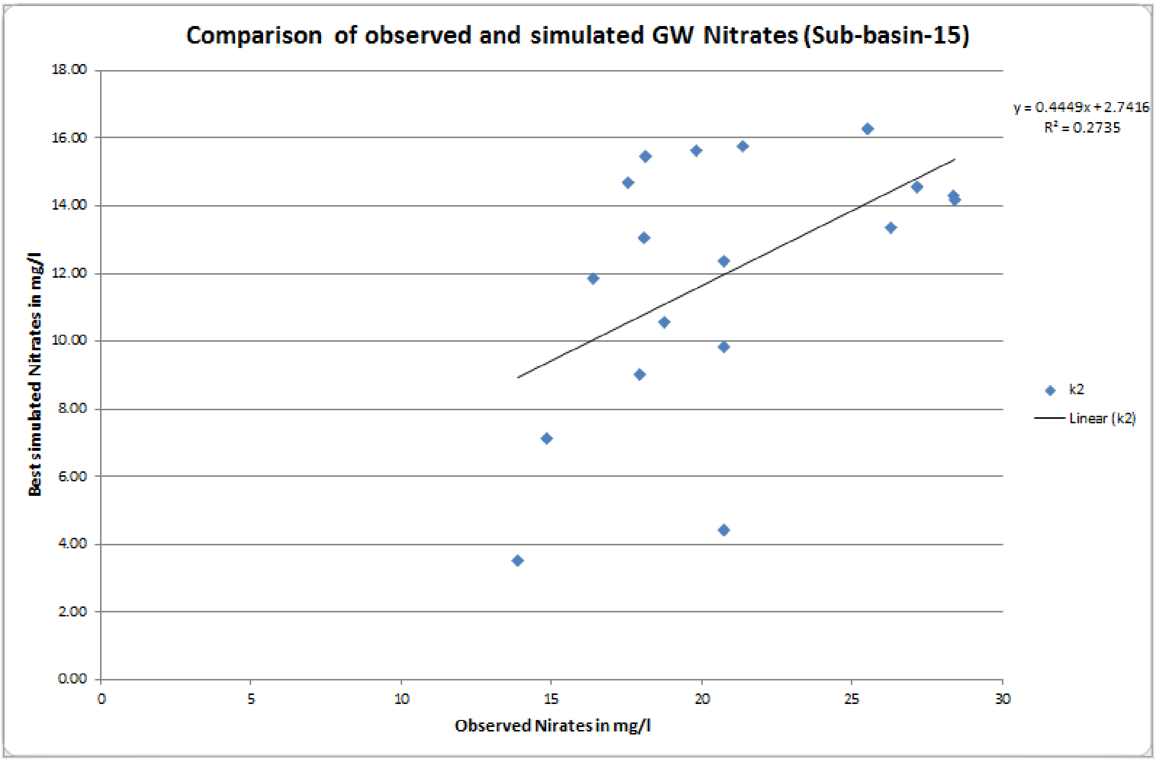


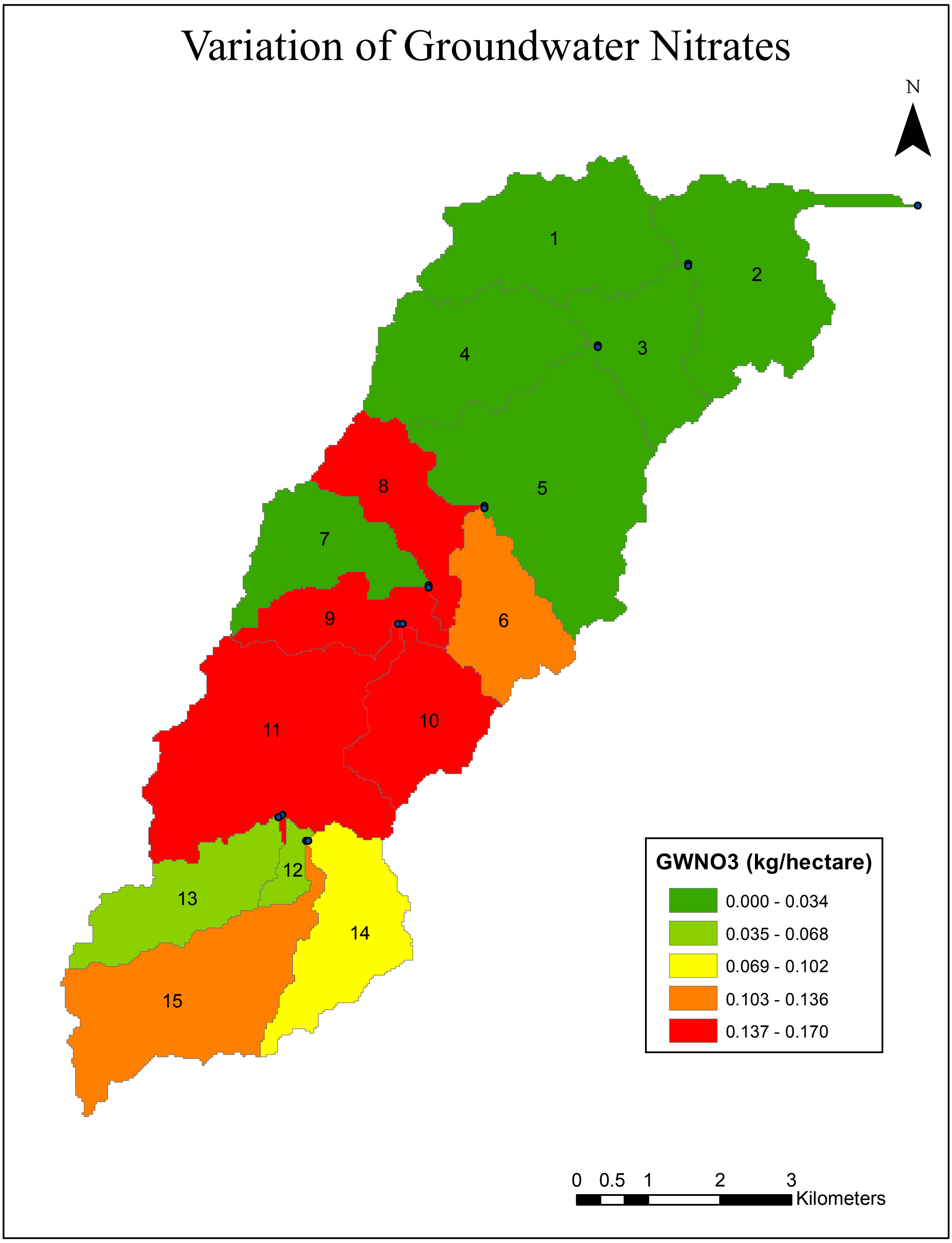
greater values of ARI. Cotton fields are dominant in these sub-basins, and this crop also requires a huge amount of fertilisers in addition to the water for its growth and yield, which explains the higher values of nitrate leaching in these regions.


Evaluation of Nitrate leaching processes on GW Nitrates (Sub-basin 15)
Groundwater Nitrates in mg/l
Day of the Irrigation Year
obs
orig
k2
0
20
40
60
80
100
120
140
160
50
70
90
110
130
150
170
190
210
230
250

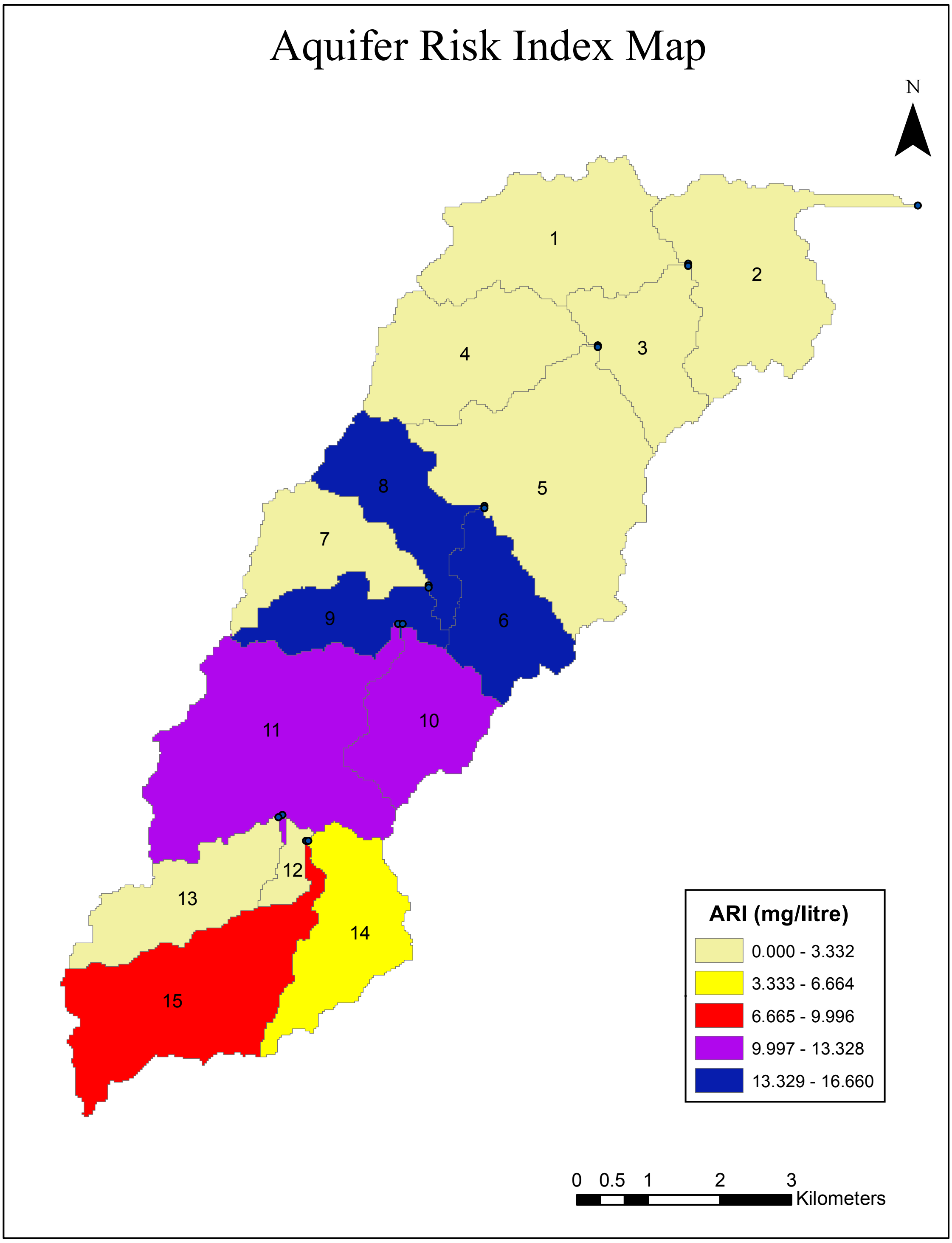

Comparison of Groundwater Nitrates concentration for various Leaching Coefficients for Sub basin:15
Nitrates in mg/l
Days
obs
k1
k1.2
k1.4
k1.6
k1.8
k2
0
5
10
15
20
25
30
35
50
70
90
110
130
150
170
190
210
230
250


Effect of Soil Nitrogen Loading on Groundwater Nitrates (Sub-basin: 15)
Groundwater Nitrates in mg/l
35
30
25
20
15
10
5
0
50
70
90
110
130
150
170
190
210
230
250
Day of the Irrigation Year
obs
sim (20,20)
sim (30,20)
sim (30,30)
sim (40,40)
sim (50,50)


Comparison of observed and simulated GW Nitrates (Sub-basin-15)
Best simulated Nitrates in mg/l
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0
5
10
15
20
25
30
Observed Nirates in mg/l
y = 0.4449x + 2.7416
R² = 0.2735
k2
Linear (k2)



Variation of Groundwater Nitrates


Aquifer Risk Index Map
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
ARI (mg/litre)
0.000 - 3.332
3.333 - 6.664
6.665 - 9.996
9.997 - 13.328
13.329 - 16.660
0 0.5 1 2 3
Kilometers

Chapter 6

Summary and Conclusions

6.1 Summary

The objective of this research is to improve the performance of process based hydrological models by effectively simulating nutrient leaching resulting from agricultural activities. Soil and Water Assessment Tool (SWAT) was applied to develop the semi-distributed hydrologic model of the Manjeera-Singur Catchment in Sadasivapet Mandal, Medak District, India. The catchment (area: 57 km^2) is draining between Singur and Manjeera reservoirs, the major drinking water sources for the needs of Hyderabad city. A total of 260 hydrological response units (HRUs), 15 sub basins, and 15 reaches were identified. The model was simulated on daily time step for the irrigation year 2013-14. Data on meteorological, soil, land-use, crop, irrigation, and management practices was provided using geographical interface ArcSWAT. The source code of SWAT was modified to consider nitrates in irrigation water and properly simulate the nitrate leaching. The nitrate leached past the root zone was assumed to depend (exponentially decaying) on various factors such as nitrate leaching coefficient, depth below the surface, water available for leaching, and soil porosity. Stream-flows at the outlet of the catchment, and nitrates ($NO_3 - N$) concentrations in the percolated groundwater were used in calibration. Model performance is evaluated using statistical parameters including coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) coefficient. A significant improvement in the model performance was observed using the modified code. It was observed that, the effect on exponential decay of nitrates with depth (past the root zone) is significantly high. The sensitivity of the model to leaching coefficient and initial concentration of nitrates in soil layer was also evaluated with the modified code. Spatial distribution of Nitrate leaching map for the watershed was prepared using GIS, which can be co-related with the existing cropping system and depth to groundwater to comment on the management practices that are suitable for the region.

6.2 Conclusions

Following are the conclusions of this research.

1. The SWAT model was successfully employed to simulate streamflow and groundwater nitrate for Manjeera-Singur watershed.
2. The results of the calibrated SWAT model were quite satisfactory ($R^2 = 0.88$, $NS = 0.83$) at the outlet of the watershed.
3. Two important modifications were made in SWAT setup, by considering of nitrates in irrigation water and implementing nitrate leaching dynamics in the vadose zone.
4. The revised SWAT code was used to evaluate the model performance by varying leaching coefficient and initial nitrate concentration in soil layer.
5. Results of the statistical analysis conclude that, a leaching coefficient of 2.0 and initial soil nitrates of 20 mg/kg is reasonably predicting the groundwater nitrates.

6. Spatial distribution of Nitrate leaching map for the watershed was prepared using GIS. This map represents the aquifer risk index for all the sub-basins present in the study area. It is a measure of the potential impact of nitrate leaching on underlying aquifer.

7. Sub-basins 6, 8 and 9 have higher values of nitrate leaching due to the presence of cotton fields which consumes a huge amount of fertilizers required for its growth and yield.

6.3 Future Scope

1. The spatial nitrate leaching map prepared from the modified SWAT model using GIS can be further used to suggest best management practices specific to the study area by analyzing the effects of changed land use pattern, time and amount of fertilizer loading.

2. The SWAT model, if coupled with a groundwater model, can yield effective results and track the transport of the non-point source pollutant in the groundwater, both spatially and temporally. This can further serve as a very promising hydrologic model.

3. Another modification made to the model that will help in reasonable prediction of nitrate loading on the aquifer is the incorporation of initial concentration of nitrates in groundwater.

6.4 Limitations

Following are the limitations of using the modified SWAT algorithm developed in the present research.

1. The presence of nitrates in soil was not estimated but it was used as a sensitive parameter to the model.
2. Factors affecting the leaching coefficient were not analyzed.
3. SWAT CUP was not used for calibrating nitrates in groundwater.
4. The simulation period of the model is one year which is very less.
5. Warm-up period was also not considered for the SWAT model due to the absence of contiguous data.

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