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EVALUATION OF BEST MANAGEMENT PRACTICES FOR SEDIMENT AND NUTRIENT LOSS CONTROL USING SWAT MODEL

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Abstract

The intensive study of an individual watershed is required to develop effective and efficient watershed management plans. Identification of critical erosion-prone areas of the watershed and implementation of best management practices (BMPs) is necessary to control the watershed degradation by reducing the sediment and nutrient losses. The present study evaluates and recommends the BMPs in an agriculture-based Marol watershed (5092 km^2) of India, using a hydrologic model, Soil and Water Assessment Tool (SWAT). After successful calibration and validation, the model simulated daily/monthly discharge and sediment were found satisfactory throughout the simulation period. The model was then applied with a calibrated set of parameters for evaluating the effectiveness of various management practices for sediment and nutrient loss control. Keeping in mind the existing agricultural practices, socio-economic aspects and geography of the study area, the management practices were focused on four crops (Maize, Rice, Soybeans and Ground nut), three fertilization levels (high, medium and low), four tillage treatments (Field cultivator, Conservation tillage, Zero tillage and Mould board plough), and two conservation operations (Contour farming and Filter strips). The simulated annual average sediment yield from the watershed was found to be 12.2 $t.ha^{-1}yr^{-1}$. The water balance analysis revealed that, the evapo-transpiration is predominant over the watershed (approximately 46.3% of the annual average rainfall). Reduction in sediment yield and nutrient loss was observed with alternate cropping treatments of Groundnut and Soybean, as compared to Paddy and Maize cultivation. Overall, based on simulated results, the field cultivator tillage practice and conservation practices viz., contour

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farming and filter strips, could be adopted to reduce sediment yield and nutrient losses in the critical sub-watersheds of the study area and in other watersheds with similar hydro-climatic conditions.

Key words: SWAT Model, Sediment yield, Nutrient loss, Tillage, Conservation operations, Best management practices (BMPs)

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1. INTRODUCTION

Watershed management is an effort to reduce water, soil and nutrient losses from non-point sources (NPS) of the watershed and to ensure sustainable agricultural production (Tripathi et al., 2005; Tuppad et al., 2010; Liu et al., 2016; Wang et al., 2018). NPS pollution has increasingly become a threat to water quality and aquatic ecosystem restoration (Conley et al., 2009; Dong et al., 2018). The main sources of the NPS pollutants are soil erosion and pollutant loads arising from agriculture-related activities (Humenik et al., 1987; Duchemin and Hogue, 2009; Yang and Best, 2015). By adopting sustainable agricultural management practices, land degradation due to soil erosion and pollutant loads from agricultural watersheds can be controlled. Every year about 0.3–0.8% of the world's cultivated land is affected by excessive land degradation, making the soil unsuited for agricultural production (den Biggelaar et al. 2004a). According to den Biggelaar et al. (2004b), there will be an additional requirement of 200 million ha of crop area to feed the increasing population over the next 30 years. Moreover, in agricultural fields, over-fertilization causes deterioration of fresh water resources due to high levels of nitrogen and phosphorus leaching, while some of the dissolved nitrogen and phosphorous also leaves in runoff. It was outlined that about 45% of phosphorus fertilizer and only 30–50% of the applied nitrogen fertilizer is taken up by crops (Tilman et al., 2002). Pradhan et al. (2015) reported that a significant amount of the applied nitrogen and phosphorus is lost from agricultural fields. Therefore, a balanced management approach is needed to prevent soil and nutrient loss, and to protect productive farmland from further

degradation. Implementation of a suitable and practicable management plan for an individual watershed is necessary to control the transport and delivery of NPS pollutants to waterbodies. This kind of management approach will also be useful for other watersheds, with similar hydro-climatic conditions.

In order to implement management programs, prioritization of sub-watersheds is mandatory, so that the critical sub-watersheds can be taken up primarily for treatment considering technical or financial constraints (Prasad et al., 1997; Tripathi et al., 2003; Pandey et al., 2007; Rocha et al., 2012; Gopinath et al., 2016; Lamba et al., 2016). Physically based hydrologic models backed with geographic information systems and remote sensing techniques become popular in identification of the most critical erosion-prone areas of a watershed and selection of a suitable management strategy. Among various physically based models, the SWAT model has been employed under several agro-climatic regimes for different hydrologic applications. The BMPs could be evaluated for critical erosion-prone areas using the SWAT model and recommended for better conservation of soil and moisture (Arnold et al., 1996; Srinivasan et al., 1998).

The SWAT is a physically-based, semi-distributed hydrologic model, and capable of continuous simulation over long time periods (Arnold et al., 1998; Arnold and Fohrer, 2005; Garg et al., 2012; Pandey et al., 2016), developed by the USDA Agricultural Research Service (ARS) to predict the impact of land management practices on hydrology, contaminant and sediment transport in complex, large watersheds (Borah and Bera, 2003). The SWAT hydrologic model has been evaluated by several researchers globally for runoff (Akiner and Akkoyunlu, 2012; Murty et al., 2014; Pandey et al., 2015; Asl-Rousta et al., 2018; Dhami et al., 2018), sediment load (Xu et al., 2009; Oeurng et al., 2011; Qiu et al., 2012; Himanshu et al., 2017, 2018; Brighenti et al., 2019) and

nutrient (Wang et al., 2014; Gildow et al., 2016; Qiu et al., 2018; Uribe et al., 2018) simulation, who reported satisfactory model performance.

BMPs are generally recognized as an effective control measure for agricultural non-point sources of sediment and nutrients (Tripathi et al., 2005; Lam et al., 2011; Jang et al., 2017). The SWAT model is a tool that predicts the impact of BMPs on runoff, sediment and agricultural chemical yields (nutrient loss) in complex watersheds (Ullrich and Volk, 2009; Arnold and Fohrer, 2005, Murty et al., 2014). Site-specific conditions and dimensions of agricultural BMPs as well as the tillage practices can be incorporated in the SWAT model which is often beyond the capacity of most other watershed models (Xie et al., 2015). The effectiveness of BMPs using the SWAT model has been explored by researchers worldwide (McGregor et al., 1999; Pandey et al., 2005, 2009b; Betrie et al., 2011; Zhang and Zhang, 2011; Bossa et al., 2012; Strauch et al., 2013; Rocha et al., 2015; Pare et al., 2015; Lampurlanes et al., 2016; Maharjan et al., 2016; Strehmel et al., 2016; Her et al., 2017; Noor et al., 2017; Merriman et al., 2018; Ni and Parajuli, 2018; Qiu et al., 2018; Wang et al., 2018). These studies revealed that the SWAT model has the ability to evaluate BMPs to reduce NPS pollution (sediment and nutrient load) depending on watershed characteristics, and the type and combinations of applied BMPs. Wei et al., 2018 conducted a study to analyze the influence of BMPs in irrigated watersheds of the Arkansas River valley in southeastern Colorado, which shows that the consideration of individual cultivated fields is necessary to fully capture the hydrologic processes and magnitude of losses. Further, an enhanced paddy simulation module integrated with SWAT (namely SWAT-Paddy) has been applied to an agricultural watershed in Japan, which suggest that the model can simulate management processes realistically in paddy-dominant agricultural watersheds (Tsuchiya et al., 2018). Likewise, other crop specific modules can also be integrated with SWAT to explicitly understand the management processes and control

over losses. Implementation of agricultural BMPs is influenced by a balance of desired economic feasibility and environmental outcomes. Many studies have been conducted to couple multi-objective optimization methods to the SWAT model to optimize the selection and placement of BMPs from both economic and environmental points of view (Chiang et al., 2014; Herman et al., 2015; Pyo et al., 2017). However, in India, very few studies were conducted using the hydrologic and water quality models to evaluate the effects of BMPs on nutrient losses from a watershed (Tripathi et al., 2005; Behera and Panda, 2006; Tripathi et al., 2013).

The literature reveals that rigorous implementation of the SWAT model is required to develop watershed management plans under various hydro-climatic regions. Considering to the aforementioned, a calibrated and validated SWAT model has been adopted for erosion-based prioritization and also for evaluation of BMPs for sediment and nutrient loss control over the agriculture-based Marol watershed of India. Primarily, evaluation of the SWAT model has been carried out for analyzing the spatial distribution of water balance components across the watershed. Soil erosion status in the Marol watershed was also accomplished to provide the priority of sub-watersheds for soil conservation measures. The critical sub-watersheds have been identified based on the SWAT simulated annual average sediment yields for the years 1999 to 2011 (Singh et al., 1992; Dabral and Pandey, 2007; Pandey et al., 2009a, 2009b; Niraula et al., 2013). The critical sub-watersheds which are more prone to soil erosion were also examined for nutrient losses. Further, the SWAT model was employed for assessing the effectiveness of various management strategies in reducing sediment and nutrient loads considering different crops, tillage implements, fertilizer applications and management operations. In this study, calibration and sensitivity analysis for nutrients were not carried out, due to unavailability of observed dataset, which could be a limitation of this study and may have some uncertainties involved in the nutrient simulation results.

2. Materials and Methods

2.1 Study Area

The study area i.e., the Marol watershed, is part of the Krishna River basin, situated along the sub-tributary Vardha River of the tributary Tungabhadra River. **Figure 1** shows location, land use/land cover and soil map of the study area. The study area lies between longitude 74º48'30" E to 75º36'38" E and latitude 14º05'18" N to 15º07'48" N with an elevation of 340 to 848 m above sea level. The total watershed area is 5092 km^2. The mean slope of the watershed ranges from 0 to 8.9% as major part is gently undulating plain and the maximum land slope of the watershed goes up to 31% due to the presence of some hilly areas on the western most part. The temperature of the study area varies from 16º C to 38º C. The average annual rainfall of the watershed is 1624 mm, out of which more than 75% of rainfall occurs during the monsoon season (June to October). Absence of any large storage structures, availability of observed hydro-meteorological datasets, and heterogeneous land use makes this watershed a favorable one for carrying out this study.

Figure 1: Study area description maps a) Location map, b) Land use/ land cover map and c) Soil map

2.2 Datasets used

Relevant information of all the datasets utilized in the present study has been provided in **Table 1**. The improved daily gauge-based gridded precipitation data prepared by the India Meteorological Department (IMD) at a spatial resolution of 0.25° × 0.25° (approx. 27.5 km × 27.5 km) grid (Pai et al., 2014, 2015) were used as standard reference data set for evaluation. The study area is covered under fifteen grid points of precipitation. IMD used the Shepard interpolation method (Shepard, 1968), a simplest form of inverse distance weighted interpolation scheme to interpolate the station point observations into a regular grid after applying severe quality-checks. In this method,

interpolated values were computed from a weighted sum of the observations. The daily temperature data available at a coarser resolution of 1° × 1° (approx. 110 km × 110 km) grid prepared by the IMD were used in the present study (Srivastava et al., 2009). Other meteorological data like relative humidity, wind speed and solar radiation were obtained from the Global Weather Database for SWAT (Dile and Srinivasan, 2014). These datasets are based on the hourly forecast from National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data products (Saha et al., 2010). Except for temperature, all meteorological datasets used are at 0.25° × 0.25° (approx. 27.5 km × 27.5 km) spatial resolution.

The daily stream discharge and suspended sediment load datasets (1998 to 2011) for Marol gauge and discharge (G&D) site (75º36'38" E longitude and 14º55'04" N latitude) located at the outlet of the Varadha River were obtained from the India Water Resources Information System (WRIS) WebGIS portal maintained by the Central Water Commission (CWC), Government of India. However, continuous stream discharge and suspended sediment load data for the years 2005 to 2007 were not available, hence, not considered for simulation in this study. These data are available only for the monsoon period (June to October), therefore, only monsoon data have been used as reference data for evaluation of the SWAT model.

The freely available ASTER Digital Elevation Model (DEM) with 30-m spatial resolution has been used for delineating the watershed and stream networks. The minimum, mean and maximum elevations of the study area were found to be 340 m, 588 m and 848 m respectively. The slope map was reclassified into 4 slopes viz., 0 to 2.8%, 2.8 to 6.3%, 6.3 to 14.2% and more than 14.2%. The soil data utilized in the present study was obtained from the "National Atlas and Thematic Mapping Organization, Department of Science and Technology, Government of India" (Shivaprasad et al., 1998). Seven soil types are prevalent in the study area whose spatial distribution is presented in

Figure 1. The land use/land cover map of the study area was obtained from the "National Remote Sensing Centre (NRSC) Hyderabad, Government of India", and 10 land use/land cover classes were identified within the study area (**Figure 1)**. The map was prepared under the project "National Land Use/ Land Cover Mapping (Second Cycle)" on 1:50,000 scale using temporal Resourcesat-2 terrain corrected multi-spectral linear imaging self-scanning sensor-III (LISS-III) remotely sensed data of 2011-12 (NRSC, 2014).

Table 1: Datasets used in the present study

2.3 Model Evaluation Statistics

The statistical indices viz., percent bias (PBIAS), correlation coefficient (CC), ratio of the root mean square error to the standard deviation of measured data (RSR), Nash-Sutcliffe efficiency (NSE) and Index of agreement (d) have been used for performance evaluation of the SWAT model (Moriasi et al., 2007; Niraula et al., 2011).

PBIAS shows the average tendency of the simulated data to be smaller or larger than their observed counterparts and ranges from -∞ and +∞ (Gupta et al., 1999). CC measures the direction and strength of a linear relationship between observed and estimated data. The value of CC ranges from -1.0 to +1.0, - and + signs have been used for negative and positive linear correlations, respectively. RSR standardizes the root mean square error using observations standard deviation. RSR ranges from the optimal value of 0 to a large positive value. NSE shows how well the plot of simulated and observed data fits the 1:1 line and ranges from -∞ and 1.0. The d is a standard measure of the degree of model prediction error and ranges between 0 and 1.0.

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)*(100)}{\sum_{i=1}^{n} Y_i^{obs}}\right] \quad (1)$$

$$CC = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y^{obs}}\right)\left(Y_i^{sim} - \overline{Y^{sim}}\right)}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y^{obs}}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i^{sim} - \overline{Y^{sim}}\right)^2}} \right] \quad (2)$$

$$RSR = \left[\frac{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y^{obs}}\right)^2}} \right] \quad (3)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y^{obs}}\right)^2} \right] \quad (4)$$

$$d = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(\left|Y_i^{sim} - \overline{Y^{obs}}\right| + \left|Y_i^{obs} - \overline{Y^{obs}}\right|\right)^2} \quad (5)$$

Y_i^{obs}, Y_i^{sim}, $\overline{Y^{obs}}$ and $\overline{Y^{sim}}$ are the observed, simulated, average observed and average simulated values in respective time steps i, and n is the number of observations

2.4 SWAT Model Setup

The ArcSWAT interface has been used to set-up and run the model on a daily and monthly time-scale for the period 1998-2011. Spatial datasets (DEM, land use map, soil map etc.) required for the SWAT model setup were projected into the same co-ordinate system (WGS 1984) using the ArcGIS interface. The land use, soil and slope distribution over the Marol watershed are provided in **Table 2**. The details of land use and soil data was prepared and enlisted in the look up table, which was not included in the default SWAT database. In this study, the Marol watershed was divided into 31 sub-watersheds, based on the user-defined threshold area of 8000 ha along with location of the gauging sites, and outlet points to facilitate precise hydrologic analysis and model simulation. The watershed was then divided into 647 HRUs representing homogeneous hydrological regions defined with unique land use, soil and slope (threshold value of 1% each). The selection of threshold values was based on the desired stream network density, and the connectivity

of drainage network to water reservoirs that mainly affects river channel flow and the outflow at the gauging site. The hydrologic evaluation of the SWAT model was carried out at the HRU level in daily time steps and the outcomes were aggregated to give output at the sub-watershed scale.

Table 2: Detailed land use, soil and slope distribution over the Marol watershed

2.5 Sensitivity and Uncertainty Analysis

The sensitivity and uncertainty analyses were carried out using the SUFI-2 algorithm of the SWAT-CUP program (Abbaspour et al., 2007). A total of 17 sensitive parameters were considered separately for discharge and sediment (**Table 3**). The analysis was carried out on a daily time step in order to accurately preserve the hydrologic characteristics of the watershed accurately. Calibration of the model at monthly/annual time step does not guarantee a good performance at daily time steps (Sudheer et al., 2007). Since the model uses the daily flow dataset to simulate model outputs including sediment and nutrients, it is important that the model-predicted dataset at daily time-scale accurately mimics the actual watershed processes. The sensitivity analysis revealed that discharge is most sensitive to CH_N2 (Manning's 'n' value for the main channel) followed by CH_K2 (Effective hydraulic conductivity in main channel alluvium), whereas sediment is most sensitive to OV_N (Manning's 'n' value for overland flow) followed by USLE_P (USLE equation support practices factor).

Table 3: Discharge and sediment load sensitivity order of the SWAT model parameters for the Marol Watershed

2.6 Effective management of the critical sub-watersheds

To control the sediment and nutrient loss from the critical sub-watersheds, an effort has been made to identify the BMPs for the critical sub-watersheds considering different management operations. Major parts of the study area are under agronomic practices. Therefore, crop based agronomic

measures and management operations were only considered for treatment options in the present study. Based on the available field data and existing agricultural practices, various treatment options were selected for evaluating the BMPs. In this study, different operations were simulated in order to develop an appropriate management strategy suited to the farmers of the Marol watershed. Four crops, i.e., rice, maize, soybean and ground nut at three fertilization levels of N: P (kg/ha) (high, medium and low) were considered. Four tillage practices, i.e., zero tillage (T1), conservation tillage (T2), field cultivator (T3) and mould board plough (T4), and two management operations, i.e., contour farming (CF) and filter strip (FS) were also considered in the present study for evaluation of the BMPs. In the present study, the effects of agronomic measures, tillage practices and management operations on sediment yield and nutrient loss were studied.

2.6.1 Tillage implements for effective management

The conventional tillage practice mostly country plough is used by the farmers of the Marol watershed. The practice of using mould board plough, zero tillage, conservation tillage and field cultivation is relatively less in the watershed area due to farmer's poor knowledge of improved agricultural implements and financial constraints. The tillage treatments were selected based on previous studies (Triphati et al., 2005; Behera and Panda, 2006; Pandey et al., 2009a, 2009b) undertaken in the different Indian watersheds for evaluation of the best management practices. The tillage treatments along with their respective mixing efficiencies and tillage depths (in mm) as suggested by Neitsch et al. (2011) are presented in **Table 4**. The mixing efficiency and the tillage depth determine the fraction of the soil layer that is mixed by a tillage operation (Triphati et al., 2005).

Table 4: Tillage treatments considered for effective management

2.6.2 Crop-fertilization evaluation for best management practices

In the present study, four crops i.e., Rice (*Oryza sativa*), Maize (*Zea mays*), Groundnut (*Archis hypogaea*) and Soybean (*Glycine max*) were considered for developing management scenarios. Rice is the predominant crop of the Marol watershed, grown with low fertilizer doses (25 kg N/ha and 15 kg P/ha) and high seeding rate (140-180 kg ha^{-1}), normally sown during the months of June-July and harvested during the months of September-October. Maize is generally grown in the steeply-sloped lands along the river mainly during monsoon season (June to October). Groundnut is grown in few locations by some of the farmers in the steeply-sloped lands along the river of the Marol watershed. As a cash crop Soybean could be suitable as per prevailing agro-climatic conditions of the watershed, therefore, considered in this study. The crop schedule suggested by Prasad (2002) and Singh et al. (2003) has been adopted in this study.

In terms of phosphorus and nitrogen availability, soils in the study area are mostly low in fertility. Soils are mostly acidic in nature; therefore, phosphorous availability is limited due to fixation in acidic soils. Nitrogen is available in the soil mainly in the form of nitrate (NO_3). Therefore, management practices with different fertilization level for already described four crops were evaluated in all the critical sub-watersheds to identify suitable management practices to maintain productivity and soil fertility on a sustainable basis. In general, farmers of this region use an amount of fertilizer that is lower than the recommended dose. The existing level of fertilizer was categorized as low fertilization level. Fertilization levels for different crops were considered based on studies undertaken by previous researchers (Triphati et al., 2005; Behera and Panda, 2006; Pandey et al., 2009a, 2009b) in the different Indian watersheds and are presented in **Table 5**.

Table 5: Fertilization level with values of N: P (kg/ha) for various crops considered for management

2.6.3 Conservation management operations for best management practices

The SWAT model offers eight options for management operations viz., a) Terracing, b) Tile drainage, c) Contouring, d) Filter strips, e) Strip cropping, f) Fire, g) Grassed water ways, h) Plant parameter update, i) Residue management, and j) Generic conservation practices, to control sediment and nutrient loss from the watershed. Conservation management operations are rarely practiced in the study area. Keeping in mind the socio-economic aspects and geography of the study area, a non-recurring management practice, the contour farming and filter strips were considered in all the HRUs of critical sub-watersheds. Contour farming practices consist of performing the field operations (viz., plowing, planting, cultivating, and harvesting) along the contour which intercepts runoff and reduces the development of rills. When the land slope ranges from 3% to 8%, contour farming can effectively prevent soil erosion (Ng et al., 2008; Guto et al., 2011). Filter strips are densely vegetated areas located between surface water bodies (i.e., lakes and streams) and cropland/grazing land/forestland/disturbed land (Srivastava et al., 1996). Filter strips reduce sediment and nutrients, however, their effect on surface runoff is insignificant in the SWAT water balance (Ullrich and Volk, 2009). This management operation was scheduled at the beginning of the simulation period. The ratio of field area and filter strip area was kept at the default value of 40. The width of the filter strip was taken as 5m.

3. RESULTS AND DISCUSSIONS

3.1 Evaluation of the SWAT model for discharge and sediment

The SWAT model has been evaluated on a daily and monthly basis using observed discharge and suspended sediment load data for the Varadha River at the Marol G & D site. The total available observed data series were divided into two parts, 1998-2004 for calibration and 2008-2011 for validation, out of which the year 1998 was used as a model warm-up period. The performance

evaluation of the SWAT model on the basis of daily and monthly discharge and sediment is shown in **Table 6**. The observed and simulated daily and monthly discharges for the calibration and validation periods are presented in **Figures 2** and **3**, respectively. Similarly, simulated and observed daily and monthly sediment loads for the calibration and validation periods are shown in **Figures 4** and **5**, respectively. Further, the scatter plots of observed versus SWAT simulated daily discharge, monthly discharge, daily sediment load and monthly sediment load are presented in **Figures 6, 7, 8** and **9**, respectively to support the preceding results by visual inspection. The graphical as well as statistical results show that the observed and simulated discharge and sediment yield closely match during the simulation period, except for some high flow events which were mostly underestimated. This may be partially because the curve number technique used by the SWAT model could not accurately predict runoff for a day that experienced several storms (Kim and Lee, 2008). The curve number technique defines a rainfall event as the sum of total rainfall during one day, which might have caused the underestimation (Choi et al. 2002). However, most of the hydrologic models do not simulate extreme events very well. The selection of the SWAT hydrologic model for long term simulation could imply a limitation of this study. Simulation using monthly discharge data has performed better than simulation using daily discharge data. This reveals the fact that in comparison to short term or single storm simulation, the SWAT model performs better for long term simulation (Borah et al., 2007).

Table 6: Performance evaluation of the SWAT model

Figure 2: Comparison of the observed and SWAT simulated discharge for daily calibration (1999-2004) and validation (2008-2011) at the watershed outlet

Figure 3: Comparison of the observed and SWAT simulated discharge for monthly calibration (1999-2004) and validation (2008-2011) at the watershed outlet

Figure 4: Comparison of the observed and SWAT simulated sediment load for daily calibration (1999-2004) and validation (2008-2011) at the watershed outlet

Figure 5: Comparison of the observed and SWAT simulated sediment load for monthly calibration (1999-2004) and validation (2008-2011) at the watershed outlet

Figure 6: Observed versus simulated discharge for daily a) calibration and b) validation

Figure 7: Observed versus simulated discharge for monthly a) calibration and b) validation

Figure 8: Observed versus simulated sediment load for daily a) calibration and b) validation

Figure 9: Observed versus simulated sediment load for monthly a) calibration and b) validation

For runoff simulation, the obtained NSE values of 0.82 and 0.83 for daily and monthly calibrations, respectively; 0.74 and 0.78 for daily and monthly validations, respectively, showed very good simulations (Moriasi et al., 2007). However, PBIAS values of -1.58 and -12.46 for daily and monthly calibrations, respectively; 10.25 and 7.77 for daily and monthly validations, respectively (**Table 6**), indicated that on the average the SWAT model underestimated discharge by 1.58% and 12.46% during daily and monthly calibration, respectively, however overestimated by 10.25% and 7.77% during daily and monthly validation, respectively (**Figures 2** and **3**). Similarly, other performance evaluation criteria showed a very good agreement between observed and simulated hydrographs on both daily and monthly time scales indicating very good performance of the SWAT with IMD gauge precipitation inputs.

Sediment load simulation gave the similar trend like runoff. The NSE values of 0.69 and 0.73 for daily and monthly calibration, respectively; 0.63 and 0.71 for daily and monthly validations, respectively, showed very good performance (Moriasi et al., 2007). However, PBIAS values of -25.16 and -22.69 for daily and monthly calibrations, respectively; 26.24 and 16.59 for daily and monthly validations, respectively (**Table 6**), indicated that on the average the SWAT model underestimated sediment load by 25.16% and 22.69% during daily and monthly calibration,

respectively, however overestimated by 26.24% and 16.59% during daily and monthly validation (**Figures 4** and **5**), respectively. Similarly, other performance statistics indicate very good performance of the SWAT model for sediment load simulation with IMD Gauge precipitation inputs.

The SWAT model was calibrated and validated only at the watershed outlet where observed discharge and sediment load data were available. Though the model calibration performance seems quite good for the calibrated gauging station, multi-site evaluation of the SWAT model should be carried out to achieve a better representation of the physical parameters and to improve the model's predictions. However, due to the limitation of availability of observed data at the watershed outlet only, single site calibration was carried out in this study.

3.2 Evaluation of the SWAT model for the water balance of the Marol watershed

The average annual water balance over the simulation period (1999-2011) has been estimated for 31 sub-watersheds in total using the SWAT model (**Figure 10** and **Table 7**). Evapo-transpiration has been found predominant and accounts for approximately 46.3% of the annual average precipitation (1616.9 mm) falling over the area. Further, as shown in **Table 7**, about 42.0% of the annual average precipitation leaves the watershed as surface run-off. It was observed that almost all the sub-watersheds, converts about 25% of annual precipitation into surface run-off, indicating the need of implementing suitable soil and water management programs to decrease the run-off volume by increasing in-watershed utilization of water in turn minimizing soil erosion.

The monthly break up of average annual water balance (in mm) over the entire Marol watershed is presented in **Figure 11** and **Table 8**. From **Table 8**, it has been inferred that the monthly evapo-transpiration in dry months is higher than total precipitation during that month. This is because the process of evapo-transpiration is continuous which occur throughout day and night at variable rates

whether there is precipitation or not, as the water for evapo-transpiration comes from near surface soil moisture. The rate of evapo-transpiration also depends on the root zone depth and hence can extract water from the deeper soil layers. Moreover, the SWAT model is a continuous model and accounts for change in soil moisture content, which facilitates the consideration of the previous day's soil moisture content too. Therefore, it is possible that in a specific month total precipitation is less than the total evapo-transpiration. However, the annual evapo-transpiration is less than annual precipitation. The evapo-transpiration was found to be highest in the month of April (117.3 mm) and lowest in the month of January (9.1 mm). On the average, about 96% of the total surface flow occurs during the five monsoon months (June to October) compared to about 91% of annual rainfall occurring during the corresponding months. This reveals that, implantation of suitable BMPs demands to reduction of the surface runoff from agricultural areas controlling the sediment and nutrient losses.

Table 7: Sub-watershed wise annual average water balance in the study area

Figure 10: Sub-watershed wise annual average water balance components

Table 8: Monthly break up of average annual water balance

Figure 11: Monthly average values of water balance components

3.3 Soil erosion status in the Marol watershed

In this study, annual average sediment yield from the sub-watersheds not only provides the basis for identification and prioritization of the critical sub-watersheds, but also helps for the planning of agricultural and structural management of the watershed. It could be quite appropriate to utilize the average of the model outputs (sediment yield) from different sub-watersheds for identification and prioritization of critical sub-watersheds, since the simulated sediment yield for the entire simulation period are in close agreement with the observed values. With this in view, the simulated sediment

yields employing IMD gauge data benchmarked SWAT model for all the thirty one sub-watersheds of Marol for the entire ten years of simulation and the average value for each sub-watershed were determined and are presented in **Table 9**.

The annual average sediment yield ($t.ha^{-1}yr^{-1}$) from each sub-watersheds were regrouped into different priority scales according to the guidelines suggested by Singh (1995) for Indian conditions: slight (<5), moderate (5–10), high (10–20), very high (20–40), severe (40–80) and very severe (>80) erosion classes as presented in **Table 10**. The majority of sub-watersheds (69.7%) are falling under slight erosion class. It can be seen from **Table 10**, that high and very high erosion prone areas falling under the watershed are about 24.9%, while severe erosion prone area is about 5.5%. No sub-watershed is falling under moderate and very severe erosion class. The majority of HRUs correspond to barren land and agricultural land use type in the sub-watersheds which are falling under the severe erosion class. It has been observed that sub-watersheds 7, 8, 20 and 22 are falling under severe soil erosion prone areas for which immediate attention is required (**Table 10**). Sub-watershed 22 has been found most severe with an average annual sediment yield of 69.8 $t.ha^{-1}yr^{-1}$ (**Table 9**). Among the slight erosion class category, the majority of HRUs belong to land cover type of forest or water body with different combinations of soil and slope classes. The sub-watershed wise annual average sediment yield ($t.ha^{-1}yr^{-1}$) map is presented in **Figure 12**. The higher rate of erosion might be ascribed to the faulty method of cultivation practices prevalent in the study area, the higher slope in some parts of the area and also the barren land contributing more sediment load. The average annual sediment yield of the watershed was found to be 12.2 $t.ha^{-1}yr^{-1}$,which is high, and if not managed properly it will tend to increase in the future because of ongoing deforestation to provide housing and agricultural land to cope up with the rising population. This

study provides prioritization of sub-watersheds for soil conservation measures. The results were further implemented for evaluating BMPs in the critical sub-watersheds.

Table 9: Average annual sediment yield in the years for identification of critical sub-watersheds

Table 10: Area under different soil erosion classes in the Marol watershed

Figure 12: Sub-watershed wise annual average sediment yield ($t.ha^{-1}yr^{-1}$) map

3.4 Identification and effective management of critical sub-watersheds

A wide variation in sediment yields were observed in various sub-watersheds in different years (**Table 9**). Maximum sediment yield in the most critical sub-watershed was found to be 323.3 t ha^{-1} in the year 2011 when the observed precipitation was highest (2222.4 mm). Similarly, the minimum sediment yield was observed in the range of 0 to 3 t ha^{-1} in the year 2003 when the observed precipitation was at minimum (1030.8 mm). It can be seen from **Table 9** that the sub-watershed numbers SW-22, SW-20, SW-8, SW-7, SW-6, SW-25, SW-18, SW-17, SW-13, SW-27 and SW-3 are belonging to high, very high and severe erosion classes, and are only considered for evaluating BMPs. The maximum sediment yield in all the years of study was observed from sub-watershed 22 (**Table 9**). This may be due to the steep slope of up to 59.1% at many locations in the sub-watershed with an average of 3.2% and undulating topography. Low sediment yield in the majority of sub-watersheds was observed due to the cultivation of rice by bunding and the flat topography with the gentle average slopes. Since the study watershed is already treated with some soil conservation measures, some portions of the watershed might have got stabilized.

Similarly, nutrient losses have also been simulated using the SWAT model for the entire thirty one sub-watersheds of the Marol watershed. The simulated results showed that the nutrient losses were within the tolerable limit in most of the sub-watersheds (EPA, 1976; Tim et al., 1992). Nutrient

losses were found proportional to the loss of sediment from the sub-watersheds. Therefore, the above mentioned 11 sub-watersheds were considered for examining the effect of implementation of BMPs on sediment and nutrient loss in the sequential order of priority. Other sub-watersheds were not considered because they do not yield sediment higher than slight/ moderate erosion classes.

Results showed that nutrient losses usually did not exceed the tolerable limit in different sub-watersheds, however, in all critical sub-watersheds sediment yield was higher than the tolerable limit (Mannering, 1981). It has been assumed that agronomic measures including operation management will be sufficient to control the sediment loss. Although, the nutrient losses were within the tolerable limit, the effect of BMPs on nutrient losses was also considered, so that it can be monitored in the future. Based on the higher sediment yield, critical sub-watersheds were identified and attempt was made to use the SWAT model to evaluate the effects of tillage treatment and change in cropping pattern on sediment yield and nutrient loss. Based on the available field data and existing practices of cultivation, various alternative treatments and operation managements were considered for evaluating the BMPs. Overall, the study revealed that the SWAT model could be used successfully for the evaluation and implementation of BMPs.

3.5 Tillage treatments for effective management

The effects of tillage treatments on sediment and nutrient losses for the rice crop were evaluated for all the critical sub-watersheds and are presented in **Figure 13**. Tillage with mould board plough yielded about 9.5 % more sediment as compared to conventional tillage (country plough) practice. Although, other tillage treatments viz., field cultivator, conservation tillage and zero tillage practices yielded about 9.0 %, 6.8 % and 5.4 % less sediment, respectively, as compared to conventional tillage. This demonstrates that the tillage with higher mixing efficiency generated

higher sediment yield. The mixing efficiency plays an important role in mixing of residues and fertilizer during the initial crop growth stage, and the soil erosion was affected by the mixing efficiency since it is directly related to the residue present on the soil surface (Tripathi et al., 2005).

In terms of nutrient losses, the mould board plough and field cultivator were found better than conservation tillage and zero tillage. Highest reduction in organic N was observed in case of field cultivator (11.5 %) followed by mould board plough (5.7 %). However, maximum reduction in organic P and NO_3 were observed in case of the mould board plough (10.9 % and 16.8 %, respectively) followed by the field cultivator (10.7 % and 13.7 %, respectively) system. Percentage change analysis of sediment yield and nutrient losses helps in evaluating the effectiveness of management practices in the critical sub-watersheds (**Figure 13)**. Overall, the field cultivator tillage practice with proper extension services to the farmers has been found to be the best tillage practice in minimizing the sediment and nutrient losses in the study area.

Figure 13: Percent change in simulated sediment and nutrients after implementing alternate tillage treatments (T1: zero tillage; T2: conservation tillage; T3: field cultivator; T4: mould board plough) as compared to conventional tillage treatment (country plough)

3.6 Evaluation of alternate crop management practices

The SWAT model has been used for evaluation of the BMPs in reducing sediment and nutrient losses by growing four crops viz., rice, maize, soybean and groundnut at three fertilization levels (low, medium and high) (**Figure 14**). The effects of treatments of these combinations were evaluated to develop suitable management scenarios for each of the sub-watersheds by considering economic status and existing agricultural practices being adopted by the farmers (Jang et al., 2017). The average reduction over the entire critical sub-watersheds for sediment loss was found maximum in case of groundnut (18.6 %, high fertilization level) followed by soybean (16.4 %, medium

fertilization level). Similarly, average reduction over entire critical sub-watersheds for organic N, organic P and NO_3 were observed as 20.4 % (groundnut, medium fertilization level), 30.8 % (ground nut, medium fertilization level) and 32.2 % (ground nut, high fertilization level), respectively. Thus, the present study revealed that alternate cropping treatments (Groundnut and Soybean) should be encouraged in the steeply-sloped lands along the river of the critical sub-watersheds. Changing the current cropping pattern of the watershed can be expensive, especially for the low-income farmers, which in turn can hinder the implementation of the alternate crop management practices. Several interviews of the local farmers, agricultural scientists and district agricultural officers also indicated that replacement of rice with other crops could be difficult in low land areas because rice is staple crop in this region. However, it is advisable to replace maize and rice crop in the steeply-sloped lands along the river areas by some cash crops like soybean or groundnut to reduce the sediment and nutrient loss. The impact of crop and fertilization level treatments on the sediment and nutrient losses from the critical sub-watersheds has been presented in **Figure 14**.

Figure 14: Percent change in simulated sediment and nutrients after implementing different crop-fertilization treatments in the critical sub-watersheds as compared to rice cultivation with existing practice of fertilization

3.7 Evaluation of operation managements

The SWAT model has been used for evaluating the effectiveness of different operation management strategies (contour farming and filter strips) in reducing sediment yield and nutrient losses. In this study, existing practice of rice cultivation and conventional tillage practices were considered as a base for evaluating operation management strategies.

Contour farming is similar to terraces in terms of representation in the model and trend in contaminant (sediment, nutrients etc.) reduction. Contour farming reduced the sediment yield by 9.3% to 38.3%, organic N by 7.5% to 26.0%, organic P by 8.0% to 22.4% and NO_3 by 12.4% to 22.4% in the individual critical sub-watersheds (**Figure 15**). The maximum reduction of sediment yield (38.3%) was observed over critical sub-watershed SW-25 after implementation of contour farming practices. Similarly, after implementation of contour farming practices, the maximum reduction of organic N (26.0%), organic P (22.4%) and NO_3 (22.4%) was observed in the critical sub-watersheds SW-27, SW-25 and SW-8, respectively. Conservation practices in the form of vegetative filter strips were introduced in the critical sub-watersheds to reduce sediment and nutrient losses. Filter strips remove the contaminants (sediment, nutrients etc.) by reducing overland flow velocity resulting in the deposition of particulates. The average reduction over the entire critical sub-watersheds for sediment yield, organic N, organic P and NO_3 were found as 25.4%, 31.4%, 34.6% and 28.3%, respectively. The maximum reduction of sediment yield (43.3%) was obtained over critical sub-watershed SW-13 after implementation of filter strips. Similarly, after implementation of filter strips, the maximum reduction of organic N (42.5%), organic P (42.0%) and NO_3 (36.1%) was observed in the critical sub-watersheds SW-18, SW-6 and SW-17, respectively. However, despite good results, the filter strips are difficult to implement because of maintenance issues, and farmers may not be willing to make the vegetation filter strips by reducing their cultivation areas (Jang et al., 2017). Effect of contour farming and filter strips conservation practices on the sediment and nutrient losses from the critical sub-watersheds with percentage change has been presented in **Figure 15**. Overall, the sediment yield and nutrient losses from the critical sub-watersheds after simulation of contour farming and filter strips has been observed to

decline drastically. The present study revealed that the SWAT model can be used to evaluate the effectiveness of agricultural BMPs in the study area efficiently.

Figure 15: Percent reduction in simulated sediment and nutrients after implementing conservation management practices of a) contour farming and b) filter strips in the critical sub-watersheds

4. SUMMARY AND CONCLUSIONS

In the present study, the SWAT model was used for the evaluation of BMPs in the Marol watershed to recommend appropriate soil conservation measures at the sub-watershed level. Soil erosion status for the entire watershed was generated post model calibration, to prioritize critical sub-watersheds for soil conservation measures. Effectiveness of various land management strategies has been evaluated considering different crops, tillage practices, fertilizer applications and management operations, to understand and reduce sediment and nutrient losses. The water balance study was also carried out to analyze various elements of hydrological processes taking place within the area of interest. Model output resulted in the average annual sediment yield of 12.2 $t.ha^{-1}yr^{-1}$, and the water balance study showed that evapo-transpiration is predominant and accounting for about 46.3% of the average annual rainfall falling over the watershed. This study also reveals that the majority of sub-watersheds (69.7%) are falling under the slight class of erosion, wherein SW-22 has been identified as a most critical sub-watershed due to steep slope at many locations and inappropriate cultivation practices. High and very high erosion prone areas falling under the watershed are 24.9%, while the severe erosion prone area is about 5.5%. Results indicated that mould board plough yielded more sediment by 9.5%, while field cultivator, conservation tillage and zero tillage yielded less sediment by 9.0 %, 6.8 % and 5.4 %, respectively as compare to conventional tillage. As far as nutrient losses concerned, mould board plough and field cultivator are better than conservation tillage and zero tillage. Maximum reduction in organic N was observed in case of field cultivator (11.5 %) followed by mould board plough (5.7 %). However, maximum reduction in organic P and NO_3 were observed in case of the mould board plough (10.9 % and 16.8 %, respectively) followed by field cultivator (10.7 % and 13.7 %, respectively) system. Higher reduction in sediment yield and nutrient loss was observed due to alternate cropping treatments of Groundnut and Soybean, as compared to paddy and maize cultivation. Overall, based on simulated results, the field cultivator tillage practice (to replace conventional tillage) and conservation

practices viz., contour farming and filter strips, could be very useful to reduce sediment yield and nutrient losses in the critical sub-watersheds of the present study area. These conservation practices can be applied to watersheds with similar hydro-climatic conditions. However, future studies should be carried out to investigate the cost-effectiveness of the suggested management practices. A multi-objective optimization technique can also be coupled with the SWAT model to optimize the selection and placement of BMPs to a balance of desired economic feasibility and environmental outcomes. In this study, analysis was carried out with the assumption that land use/land cover and other model parameters remain constant with time, however, in reality several parameters change with time/season. Therefore, similar study with incorporation of dynamic land use/land cover and variable model parameters could be carried out in future to develop more realistic and effective management plans.

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Table 1: Datasets used in the present study

Data category	Dataset	Source	Scale/Spatial Resolution	Period	URL/Reference
Weather data	Rainfall	IMD Gridded	0.25° × 0.25°	1998-2011	Pai et al. (2014, 2015)
	Temperature	IMD Gridded	1° × 1°	1998-2011	Srivastava et al. (2009)
	Humidity	NCEP–CFSR	0.25° × 0.25°	1998-2011	http://globalweather.tamu.edu/
	Wind Speed	NCEP–CFSR	0.25° × 0.25°	1998-2011	http://globalweather.tamu.edu/
	Solar Radiation	NCEP–CFSR	0.25° × 0.25°	1998-2011	http://globalweather.tamu.edu/
Hydrological data	Runoff	CWC Gauge	-	1998-2011	http://india-wris.nrsc.gov.in/
	Sediment	CWC Gauge	-	1998-2011	http://india-wris.nrsc.gov.in/
Thematic Data	Topography	ASTER GDEM	30 m	2008	http://earthexplorer.usgs.gov/
	Land use	NRSC, ISRO	1:50,000	2011	NRSC (2014)
	Soil	NBSS&LUP	1:250,000	1998	Shivaprasad et al. (1998)

Table 2: Detailed land use, soil and slope distribution over the Marol watershed

Land use/soil/slope distribution		**Area [ha]**	**% Watershed Area**
Land use	Agricultural Land-Generic (AGRL)	394953.1	77.6
	Forest-Deciduous (FRSD)	54671.1	10.7
	Pasture (PAST)	27364.7	5.4
	Forest-Evergreen (FRSE)	23250.0	4.6
	Water (WATR)	5578.1	1.1
	Forest-Mixed (FRST)	2310.8	0.5
	Residential (URBN)	695.4	0.1
	Range-Grasses (RNGE)	330.4	0.1
	Orchard (ORCD)	30.4	Negligible
	Range-Brush (RNGB)	11.8	Negligible
Soils	Silty Clay	158395.6	31.1
	Sandy Clay Loam	142606.9	28.0
	Clay	77981.1	15.3
	Sandy Clay	57112.9	11.2
	Clay Loam	36013.1	7.1
	Loam	35684.5	7.0
	Loamy Sand	1401.7	0.3
Slope	0-2.8	300602.8	59.0
	2.8-6.3	155211.1	30.5
	6.3-14.2	48832.0	9.6
	> 14.2	4549.8	0.9

Table 3: Discharge and sediment load sensitivity order of the SWAT model parameters for the Marol Watershed

Discharge				**Suspended Sediment Load**			
Sensitivity order	**Parameters[#]**	**Range used for calibration**	**Calibrated value**	**Sensitivity order**	**Parameters[#]**	**Range used for calibration**	**Calibrated value**
1	v__CH_N2.rte	0.01 to 0.3	0.20	1	v__OV_N.hru	0.01 to 30	23.09
2	v__CH_K2.rte	100 to 500	377.20	2	v__USLE_P.mgt	0 to 1	0.81
3	r__CN2.mgt	-20% to +20%	0.11%	3	r__CN2.mgt	-30% to +10%	-23.59%
4	v__ALPHA_BF.gw	0.8 to 1	0.81	4	r__USLE_K.hru	-50% to +30%	0.43%
5	v__RCHRG_DP.gw	0 to 1	0.86	5	v_CH_K1.sub	0 to 300	16.27
6	r__SOL_K.sol	-20% to +20%	-0.17%	6	v__ESCO.hru	0 to 1	0.43
7	v__EPCO.hru	0 to 1	0.98	7	v__RCHRG_DP.gw	0 to 1	0.83
8	r__SLSUBBSN.hru	-20% to +20%	14.68%	8	v__ALPHA_BF.gw	0.6 to 1	0.86
9	a__GWQMN.gw	-1000 to +1000	-798.00	9	v__EPCO.hru	0 to 1	0.48
10	r__SOL_AWC.sol	-20% to +20%	-0.09%	10	r__SLSUBBSN.hru	-20% to +20%	13.65%
11	v__GW_REVAP.gw	0.02 to 0.2	0.15	11	v__SURLAG.bsn	0.05 to 24	16.37
12	a__GW_DELAY.gw	0 to 470	67.21	12	v__GW_REVAP.gw	0.02 to 0.2	0.05
13	v__SURLAG.bsn	0.05 to 24	18.23	13	v__CH_K2.rte	0 to 500	180.87
14	a__REVAPMN.gw	-100 to +300	-13.99	14	V__BIOMIX.mgt	0 to 1	0.46
15	v__ESCO.hru	0 to 1	0.93	15	v__CH_N2.rte	0.01 to 0.3	0.21
16	v__CH_S1.sub	0.0001 to 10	4.19	16	a__GWQMN.gw	-1000 to +1000	-85.50
17	v__CH_COV2.rte	0.5 to 1	0.91	17	v__CH_COV2.rte	0.001 to 1	0.055

[#]The initials represent the method used for defining the parameter range in auto-calibration; r = relative change to initial value, v = replacement of value within given range, a = absolute change with respect to the default value. The extension in the parameter file name represents the processes controlled by the parameter; mgt = crop cover management, gw = groundwater, sol = soil water dynamics, bsn = entire watershed scale, rte = water routing, hru = water dynamics at HRU level.

Parameter description: ALPHA_BF = Base-flow alpha factor (days); BIOMIX = Biological mixing efficiency; CH_COV2 = Channel cover factor; CH_K1 = Effective hydraulic conductivity in tributary channel alluvium; CH_K2 = Effective hydraulic conductivity in main channel alluvium; CH_N2 = Manning's "n" value for the main channel; CH_S1 = Average slope of tributary channels; CN2 = SCS runoff curve number; EPCO = Plant uptake compensation factor; ESCO = Soil evaporation compensation factor; GW_DELAY = Groundwater delay (days); GWQMN = Threshold depth of water required for return flow to occur in the shallow aquifer (mm); GW_REVAP = Groundwater "revap" coefficient; OV_N = Manning's "n" value for overland flow; RCHRG_DP = Deep aquifer percolation fraction; REVAPMN = Threshold depth of water in the shallow aquifer for "revap" to occur (mm); SLSUBBSN = Average slope length; SOL_AWC = Available water capacity of the soil layer; SOL_K = Saturated hydraulic conductivity; SURLAG = Surface runoff lag time; USLE_K = USLE equation soil erodibility (K) factor; USLE_P = USLE equation support practices (P) factor.

Table 4: Tillage treatments considered for effective management

Code	Tillage treatments	Mixing efficiency	Tillage Depth (mm)
T1	Zero tillage	0.05	10
T2	Conservation tillage	0.25	40
T3	Field cultivator	0.30	50
T4	Mould board plough	0.90	150

Table 5: Fertilization level with values of N: P (kg/ha) for various crops considered for management

Fertilization Level	Maize *(Zea mays)*	Rice *(Oryza sativa)*	Soybean *(Glycine max)*	Groundnut *(Arachis hypogaea)*
Low	F1 (20 : 15)	F4 (25 : 15)	F7 (10 : 20)	F10 (10 : 20)
Medium	F2 (50 : 30)	F5 (40 : 30)	F8 (30 : 30)	F11 (20 : 40)
High	F3 (100 : 60)	F6 (80 : 60)	F9 (60 : 60)	F12 (30 : 60)

Table 6: Performance evaluation of the SWAT model

Sr. No.	Parameter	Total stream flow				Suspended sediment load			
		Daily		Monthly		Daily		Monthly	
		Cal	Val	Cal	Val	Cal	Val	Cal	Val
1.	NSE	0.82	0.74	0.83	0.78	0.69	0.63	0.73	0.71
2.	PBIAS	-1.58	10.25	-12.46	7.77	-25.16	26.24	-22.69	16.59
3.	CC	0.90	0.89	0.92	0.93	0.84	0.85	0.91	0.88
4.	RSR	0.43	0.51	0.40	0.46	0.55	0.55	0.42	0.48
5.	d	0.94	0.93	0.95	0.94	0.88	0.86	0.91	0.90

Note: *Cal = calibration; Val = validation*

16 **Table 7:** Sub-watershed wise annual average water balance in the study area

Sub-watershed	Area (km^2)	Precipitation (mm)	Evapotranspiration (mm)	Surface run-off (mm)	Lateral Flow (mm)	Water Yield (mm)
SW-1	149.4	1214.6	746.8	348.0	0.3	453.7
SW-2	181.0	1312.9	754.9	341.3	0.3	541.9
SW-3	228.8	1323.4	757.3	541.0	0.4	772.1
SW-4	87.6	1420.2	736.6	449.8	0.2	667.5
SW-5	131.1	1492.0	751.1	543.9	0.5	719.8
SW-6	111.6	1496.0	791.4	523.4	0.2	778.4
SW-7	85.0	1396.0	857.0	560.1	0.3	750.7
SW-8	83.5	1256.9	797.0	456.7	0.1	570.7
SW-9	111.4	1102.5	785.7	477.6	0.4	566.9
SW-10	48.2	1311.1	783.7	479.6	0.2	570.8
SW-11	139.7	1598.7	744.9	528.3	0.7	775.7
SW-12	188.1	1356.8	758.7	360.5	0.4	510.6
SW-13	204.5	1456.9	772.8	459.4	0.3	696.1
SW-14	266.0	1594.5	749.7	412.9	1.1	768.2
SW-15	170.9	1205.7	788.8	371.7	0.3	560.6
SW-16	235.5	1307.7	792.2	381.7	0.2	501.8
SW-17	201.0	1256.4	792.8	361.4	0.3	510.8
SW-18	196.1	1610.7	692.7	321.1	0.6	594.4
SW-19	137.3	1609.7	711.3	465.7	0.8	674.1
SW-20	61.3	2072.3	717.4	1101.8	1.2	1269.7
SW-21	286.8	1783.7	785.4	528.5	0.7	804.5
SW-22	49.0	2186.5	717.7	1356.9	2.1	1481.4
SW-23	192.2	2051.7	659.3	875.0	1.4	1088.7
SW-24	209.7	1390.7	758.8	514.9	1.4	631.2
SW-25	127.9	2071.9	662.4	925.8	1.1	1196.3
SW-26	194.7	1381.4	808.5	443.8	0.9	574.7
SW-27	196.2	2251.4	678.8	1371.9	2.4	1428.8
SW-28	189.0	2217.6	712.6	1403.7	2.3	1485.9
SW-29	143.1	2116.5	670.0	1441.2	3.0	1582.3
SW-30	174.2	2209.2	721.8	1350.7	3.6	1560.3
SW-31	311.4	2108.7	703.0	1339.7	3.7	1488.2
Watershed, as a whole	5092.0	1618.2	747.1	678.6	1.0	857.3

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Table 8: Monthly break up of average annual water balance

Month	Precipitation (mm)	Evapotranspiration (mm)	Surface run-off (mm)	Water Yield (mm)	Lateral Flow (mm)
Jan	4.2	9.5	0.9	9.3	0.0
Feb	2.9	21.4	0.5	6.8	0.0
Mar	11.1	79.0	0.2	6.3	0.0
Apr	36.2	117.3	2.8	7.2	0.0
May	60.3	68.1	8.3	17.3	0.0
Jun	323.9	77.9	149.8	170.1	0.1
Jul	476.6	86.6	198.2	226.0	0.1
Aug	346.1	96.9	162.2	180.4	0.2
Sep	189.8	70.8	89.2	96.4	0.2
Oct	131.1	67.4	53.0	58.8	0.2
Nov	32.0	41.2	12.7	43.6	0.1
Dec	2.9	12.4	1.3	38.1	0.1
Annual	1616.9	748.4	679.0	860.2	1.0

Table 9: Average annual sediment yield during the years of identifying critical sub-watersheds

Sub-watershed number	Area (ha)	Sediment yield (t ha^{-1})										Average sediment yield (t ha^{-1})	Priority rank
		1999	2000	2001	2002	2003	2004	2008	2009	2010	2011		
SW-1	14935.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	**23**
SW-2	18100.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**23**
SW-3	22878.6	21.7	19.1	12.0	1.1	0.9	5.9	16.2	19.5	3.2	55.6	15.5	**11**
SW-4	8762.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**23**
SW-5	13107.6	0.0	0.0	0.0	0.0	0.0	0.0	0.7	4.1	0.0	0.0	0.5	**18**
SW-6	11154.6	44.5	39.2	24.6	2.3	1.7	12.1	32.1	32.3	6.5	114.3	31.0	**5**
SW-7	8498.0	58.4	51.4	32.3	3.0	2.3	15.9	42.6	45.2	8.6	149.9	41.0	**4**
SW-8	8350.4	60.0	48.9	32.9	3.0	2.3	16.1	39.9	34.7	8.6	189.9	43.6	**3**
SW-9	11143.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**23**
SW-10	4824.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	**20**
SW-11	13969.7	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	**22**
SW-12	18804.8	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	**20**
SW-13	20449.3	24.3	19.9	13.4	1.2	0.9	6.6	16.3	14.1	3.5	77.5	17.8	**9**
SW-14	26596.8	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**22**
SW-15	17089.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**22**
SW-16	23546.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**23**
SW-17	20102.9	24.7	20.2	13.6	1.2	1.0	6.7	16.6	14.4	3.5	99.5	20.1	**8**
SW-18	19611.5	25.3	20.7	14.0	1.3	1.0	6.9	17.0	14.6	3.6	102.0	20.6	**7**
SW-19	13733.2	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.1	**19**
SW-20	6129.1	68.3	62.8	42.5	3.5	2.4	19.6	53.4	40.8	9.8	261.5	56.5	**2**
SW-21	28682.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	**23**
SW-22	4896.4	84.0	77.7	53.2	4.3	3.0	24.4	66.7	49.5	12.0	323.5	69.8	**1**
SW-23	19218.3	1.3	1.0	0.0	0.0	0.0	0.0	0.1	0.8	0.1	2.9	0.6	**17**
SW-24	20965.0	3.7	1.0	0.6	0.2	0.2	0.7	0.2	1.7	0.5	18.9	2.8	**16**
SW-25	12789.0	29.9	28.0	20.4	1.6	1.1	9.3	25.4	17.6	4.4	118.7	25.6	**6**
SW-26	19471.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.1	0.0	0.0	**21**
SW-27	19623.3	18.5	17.4	13.3	1.0	0.7	6.0	16.5	10.7	2.7	74.9	16.2	**10**
SW-28	18897.1	3.7	1.1	0.7	0.2	0.1	0.8	0.2	1.4	0.4	21.0	3.0	**15**
SW-29	14309.3	7.3	2.7	1.3	0.4	0.3	1.9	0.3	2.9	1.1	31.7	5.0	**12**
SW-30	17419.5	4.5	1.5	0.9	0.2	0.1	1.0	0.2	1.6	0.5	20.5	3.1	**14**
SW-31	31135.1	5.8	2.0	1.3	0.3	0.2	1.5	0.4	2.2	0.7	27.9	4.2	**13**

Table 10: Area under different soil erosion classes in the Marol watershed

Sr. No.	Sediment Yield ($t.ha^{-1}yr^{-1}$)	Sub-watershed	Percent Area	Soil Erosion Class
1.	0–5	1, 2, 4, 5, 9,10,11,12, 14,15,16,19,21, 23, 24,26, 28,29,30,31	69.7	Slight
2.	5–10	---	0.0	Moderate
3.	10–20	3,13,27	12.4	High
4.	20–40	6,17,18,25	12.5	Very high
5.	40–80	7,8,20,22	5.5	Severe
6.	>80	---	0.0	Very severe

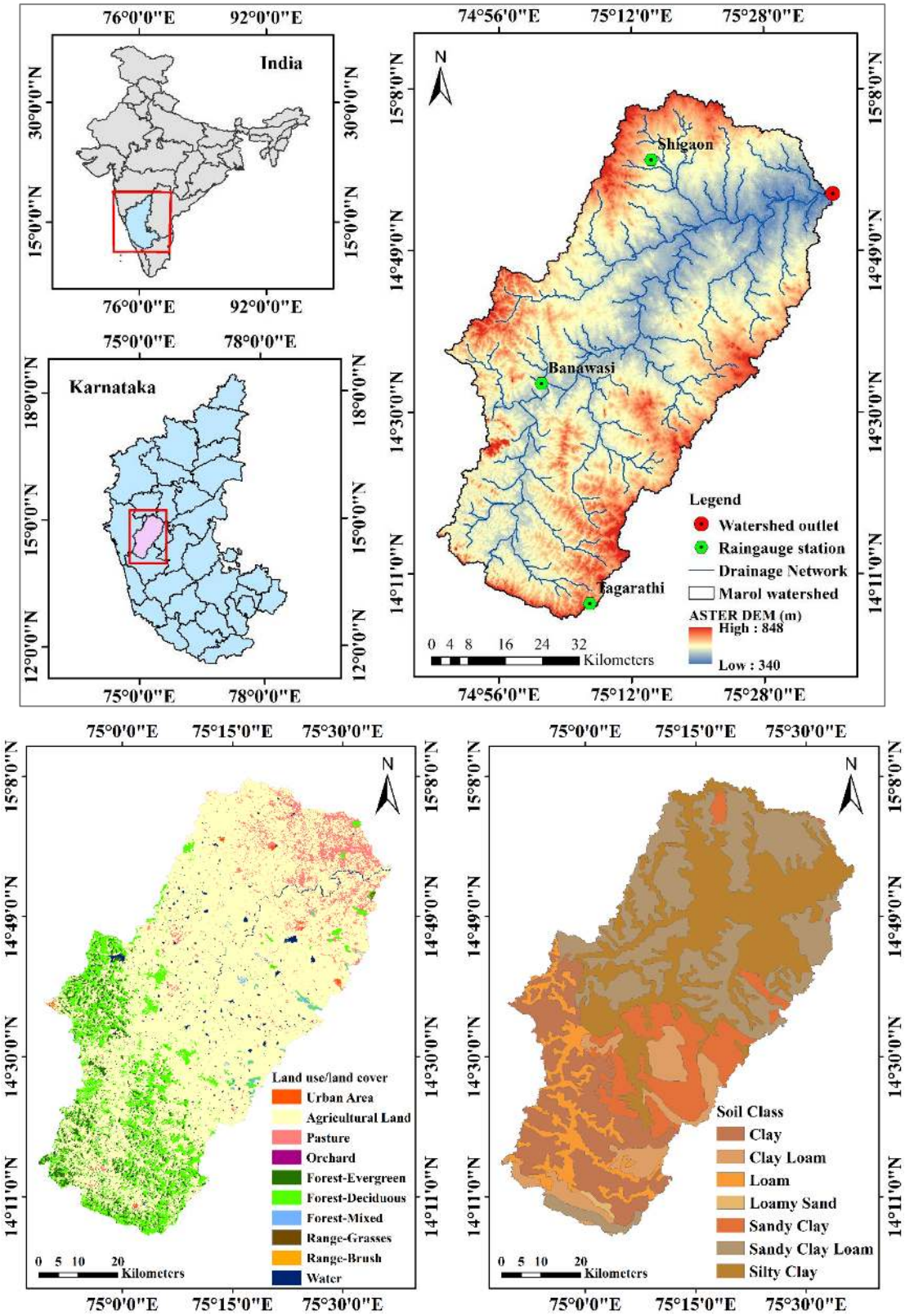
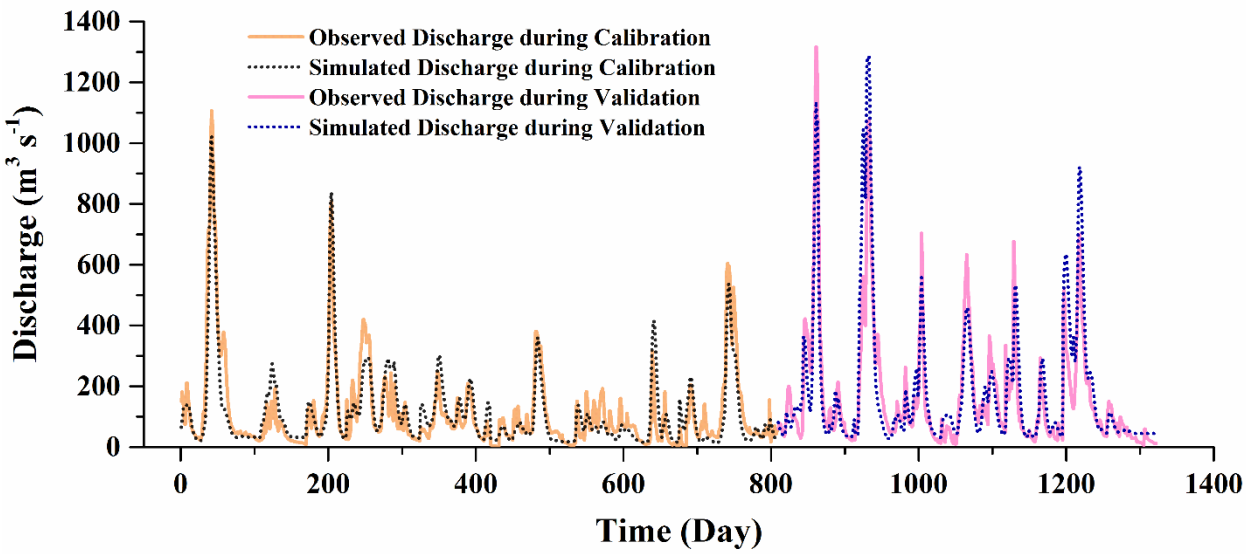


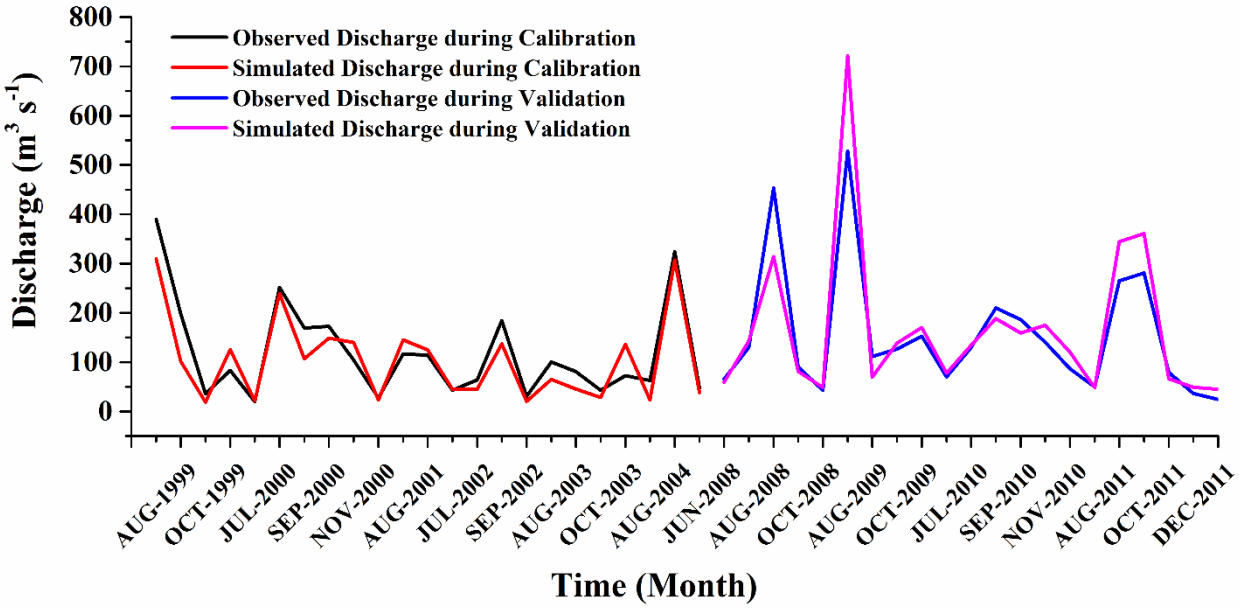
Figure 1: Study area description maps a) Location map, b) Land use/ land cover map and c) Soil map



62

63 **Figure 2:** Comparison of the observed and SWAT simulated discharge for daily calibration
64 (1999-2004) and validation (2008-2011) at the watershed outlet

65



66

67 **Figure 3:** Comparison of the observed and SWAT simulated discharge for monthly calibration
68 (1999-2004) and validation (2008-2011) at the watershed outlet

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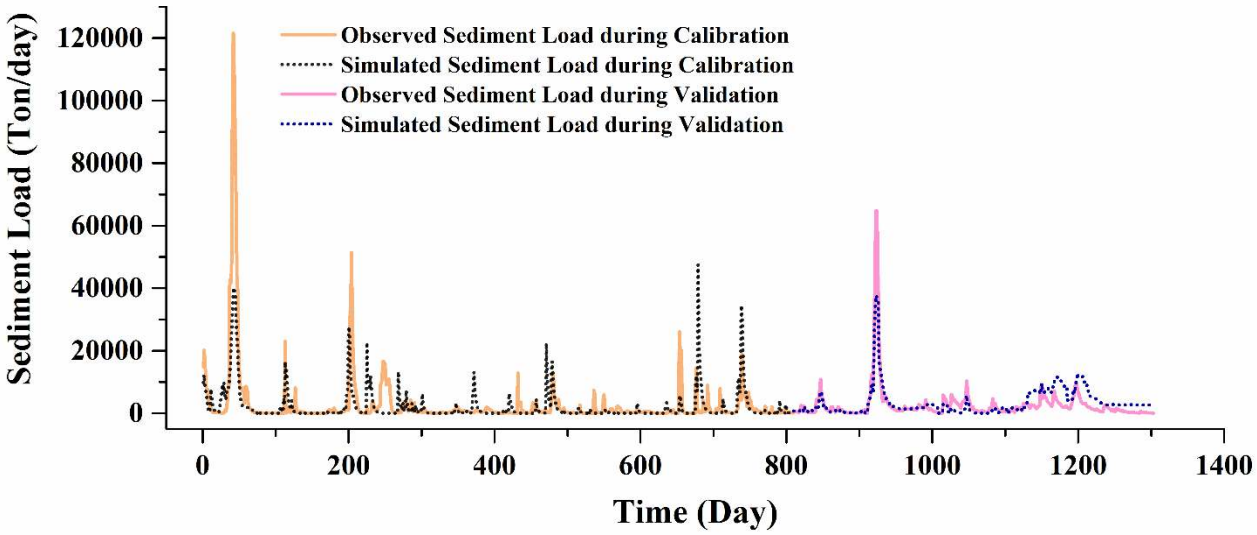

71

72 **Figure 4:** Comparison of the observed and SWAT simulated sediment load for daily calibration
73 (1999-2004) and validation (2008-2011) at the watershed outlet

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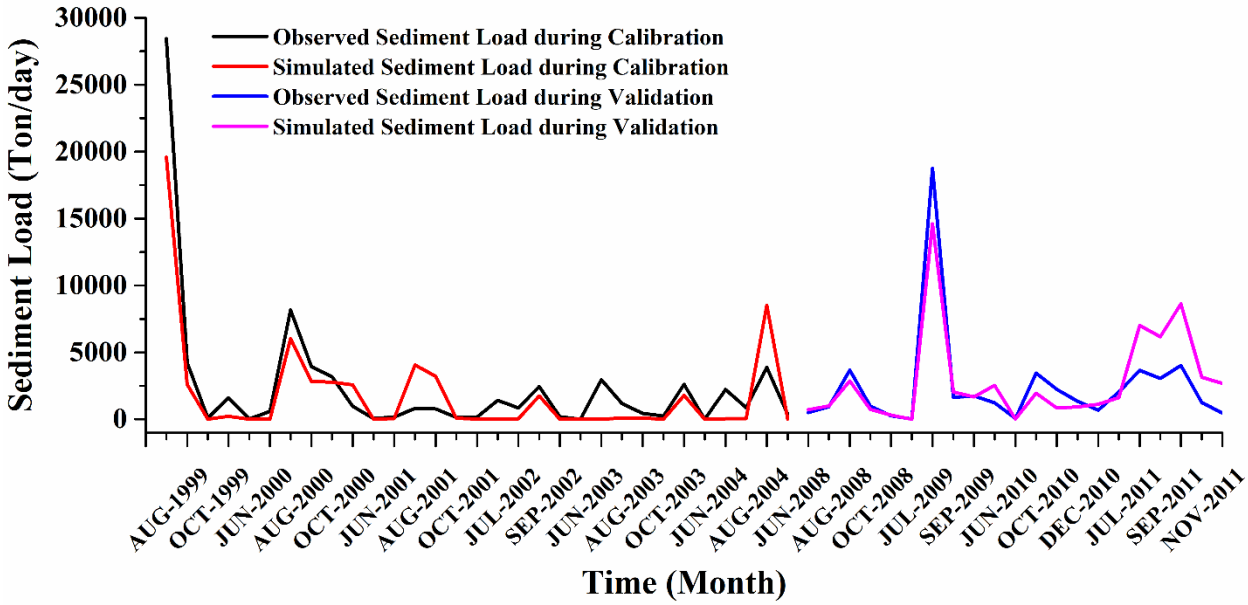
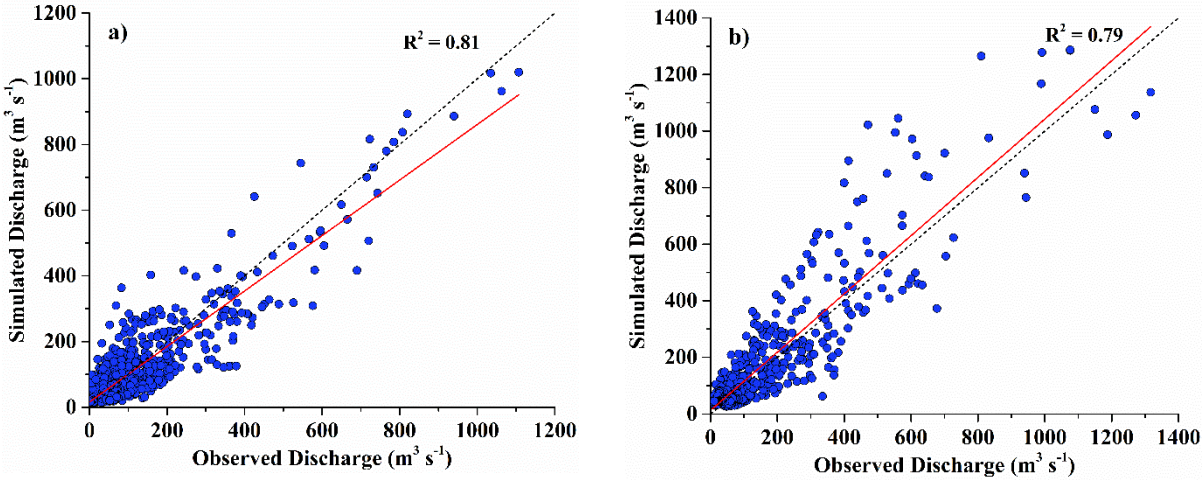


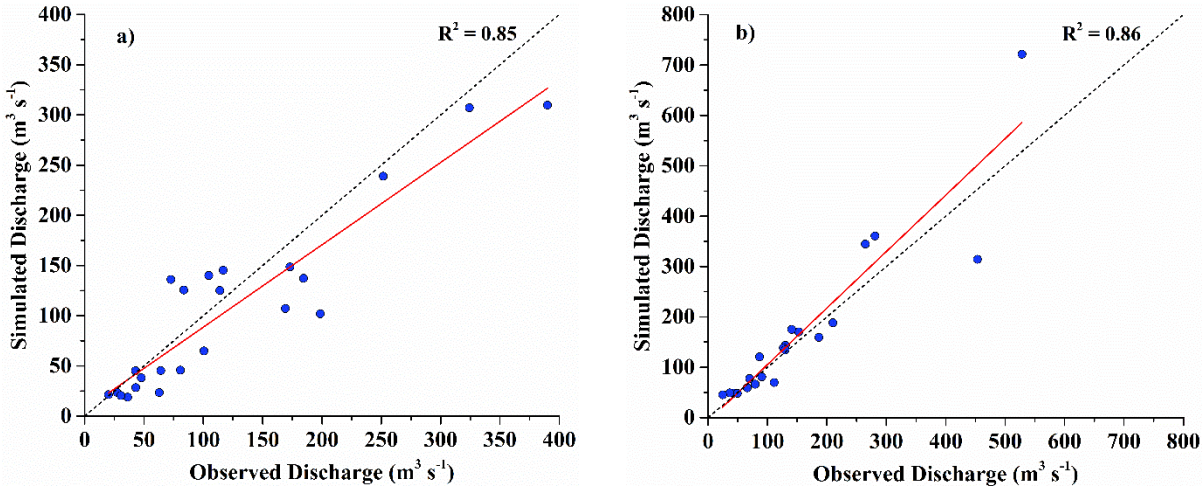
75

76 **Figure 5:** Comparison of the observed and SWAT simulated sediment load for monthly
77 calibration (1999-2004) and validation (2008-2011) at the watershed outlet

78



79 **Figure 6:** Observed versus simulated discharge for daily a) calibration and b) validation



80 **Figure 7:** Observed versus simulated discharge for monthly a) calibration and b) validation

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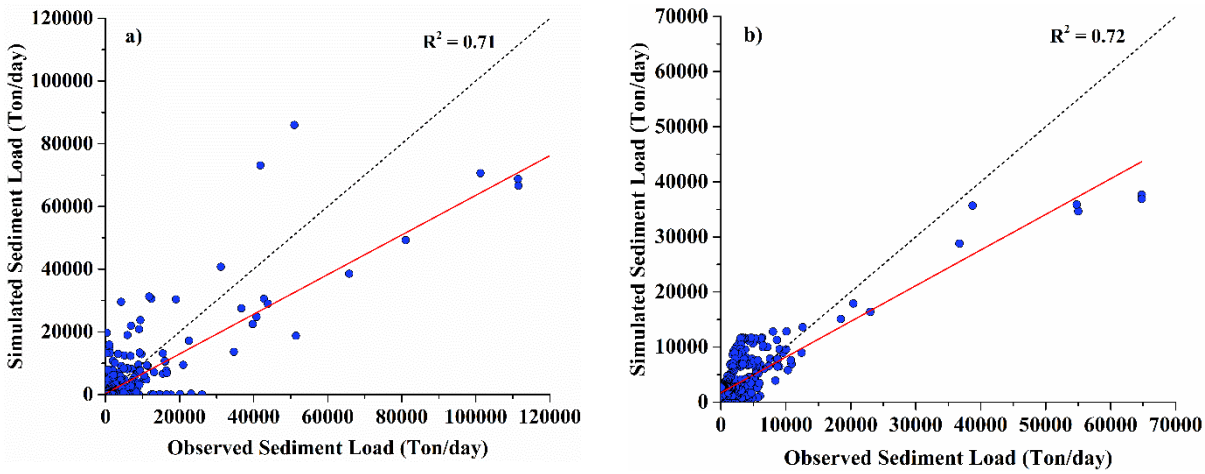
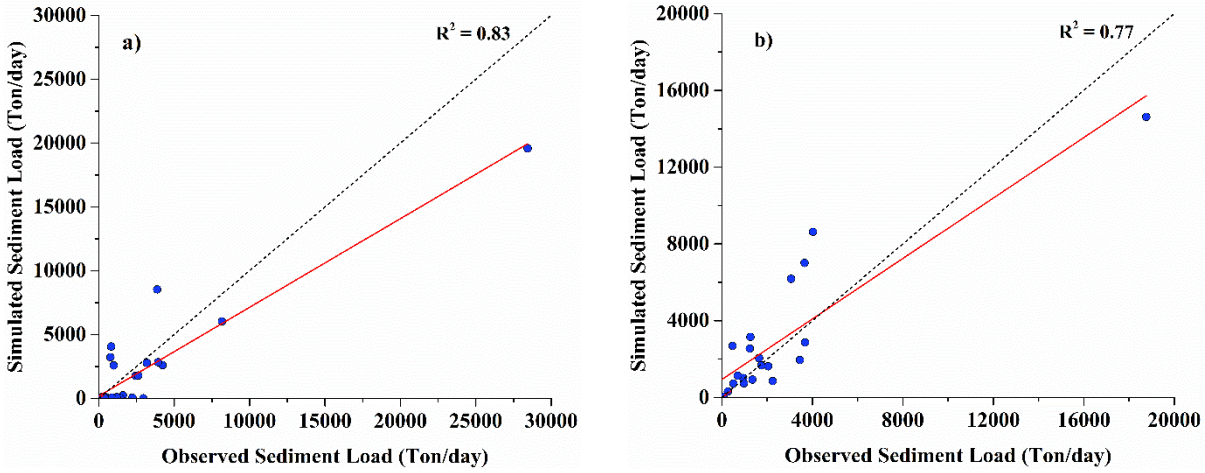


85 **Figure 8:** Observed versus simulated sediment load for daily a) calibration and b) validation



86 **Figure 9:** Observed versus simulated sediment load for monthly a) calibration and b) validation

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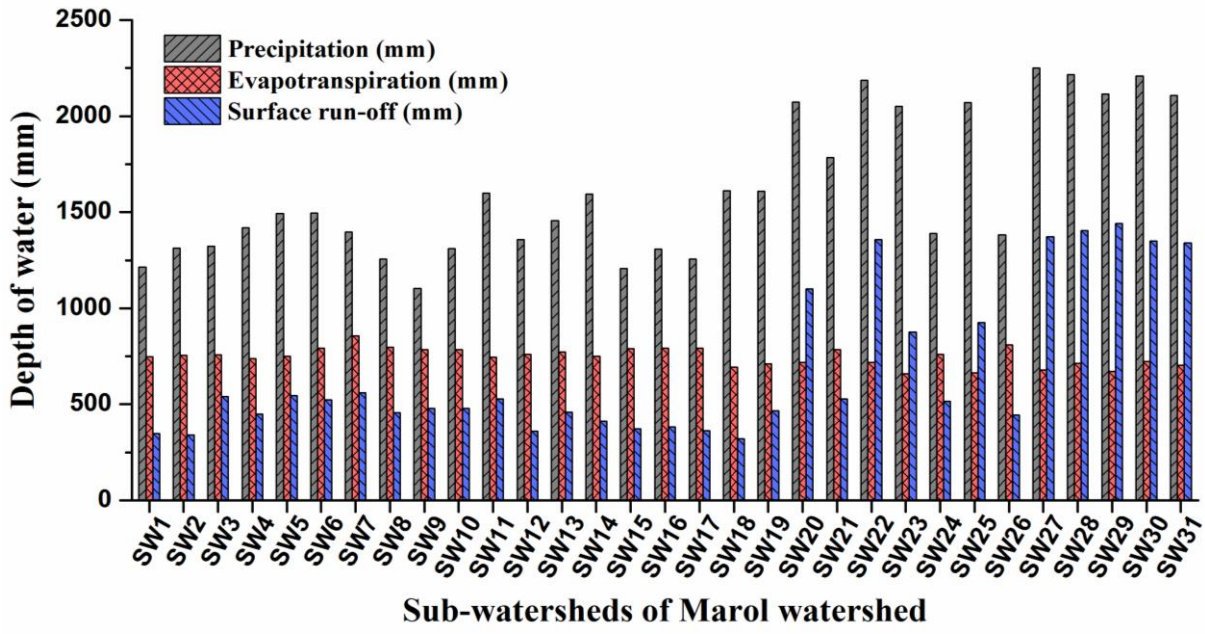


Figure 10: Sub-watershed wise annual average water balance components

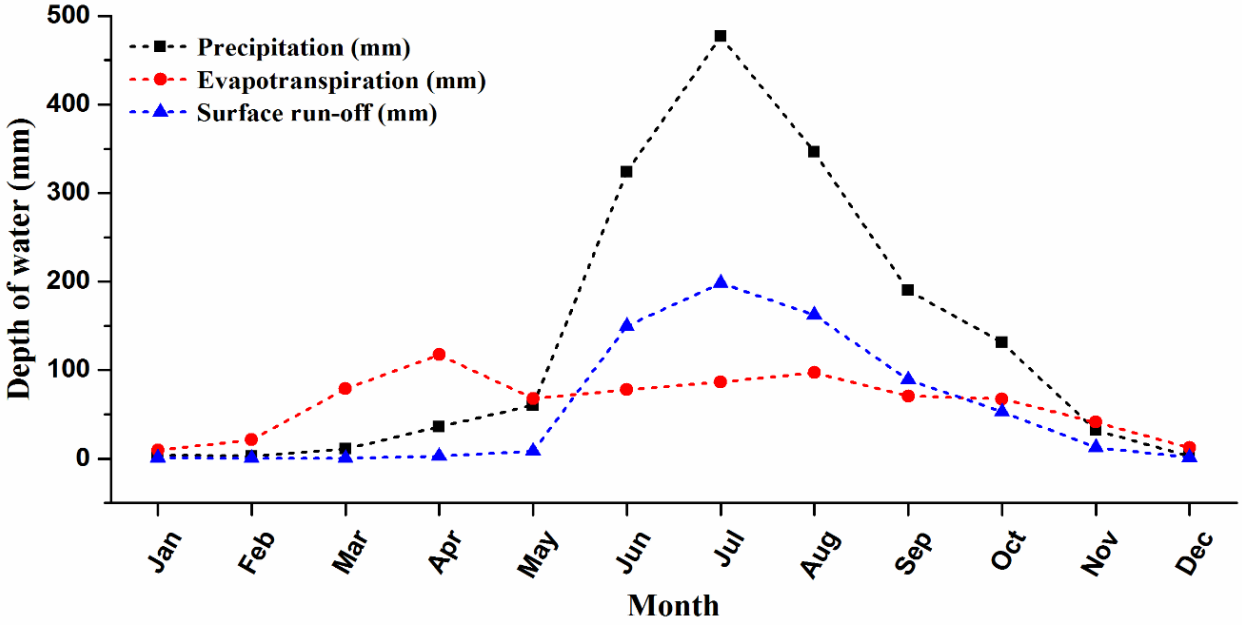


Figure 11: Monthly average values of water balance components

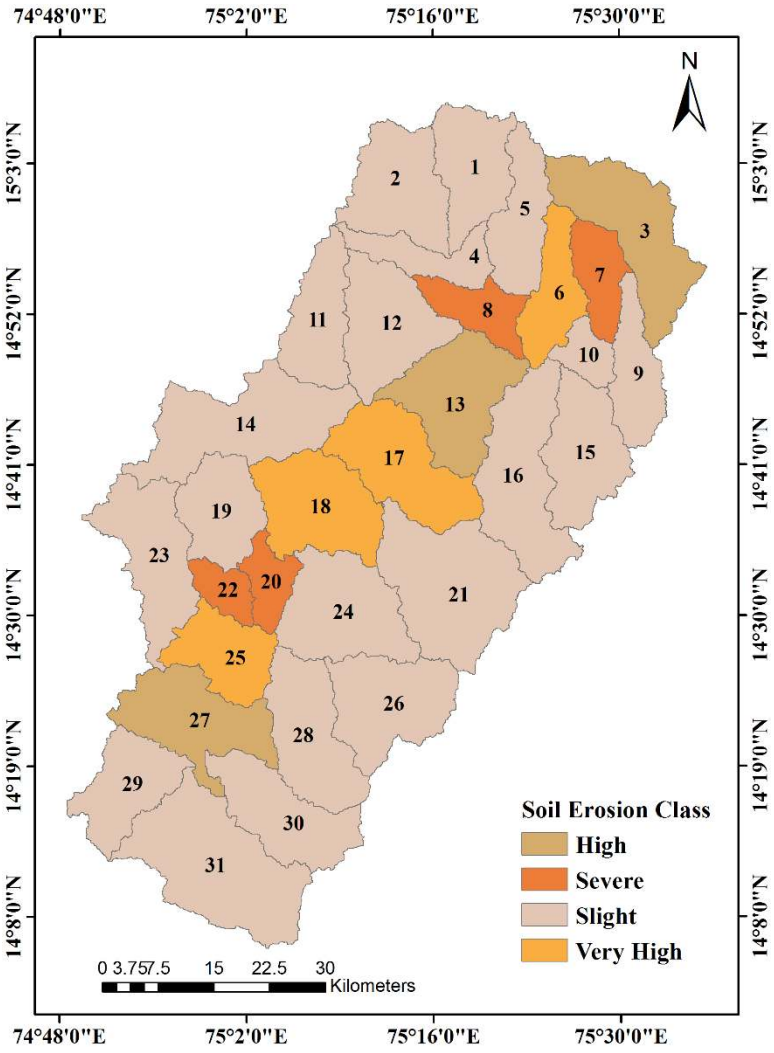


Figure 12: Sub-watershed wise annual average sediment yield (ton/ha/year) map

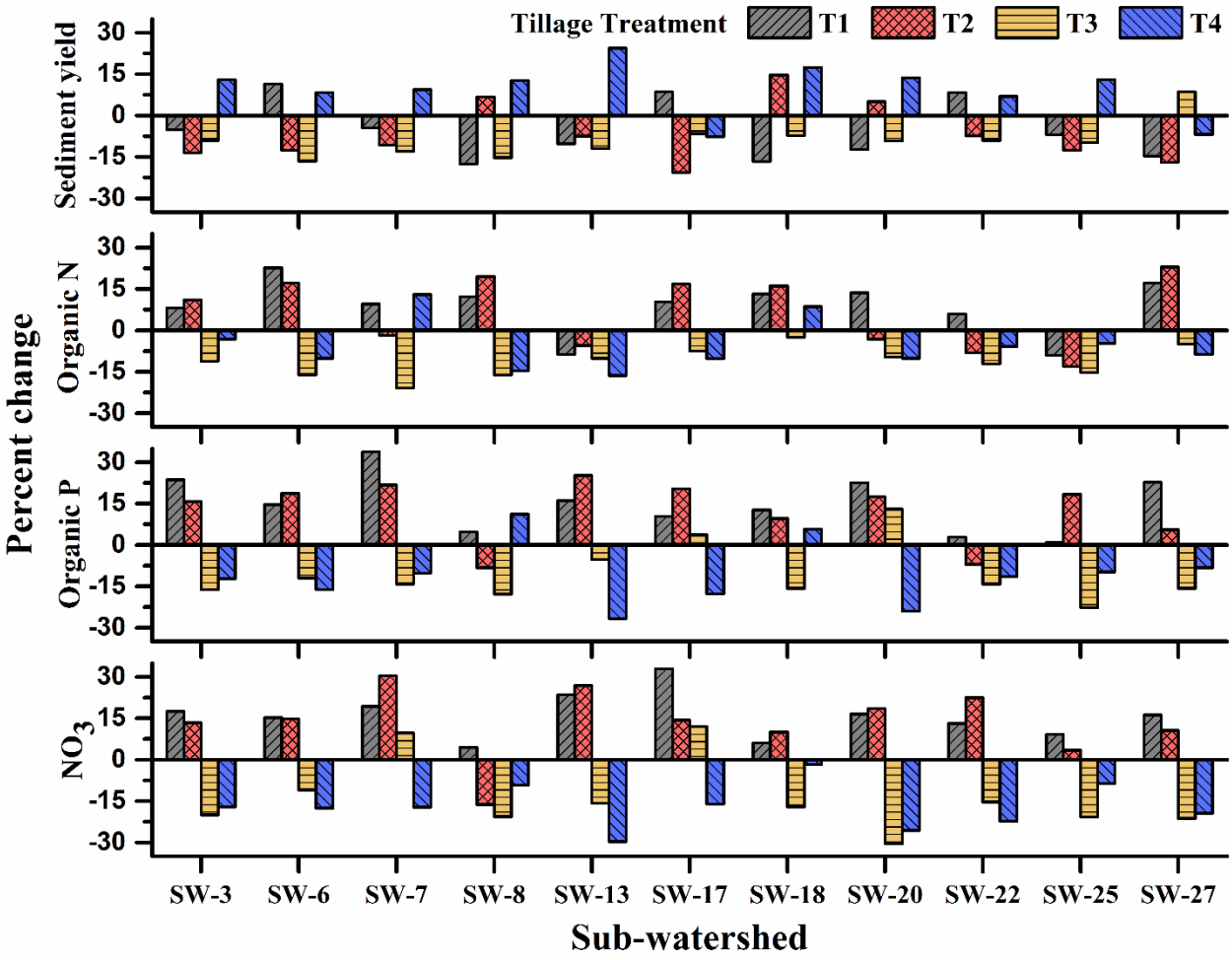


Figure 13: Percent change in simulated sediment and nutrients after implementing alternate tillage treatments (T1: zero tillage; T2: conservation tillage; T3: field cultivator; T4: mould board plough) as compared to conventional tillage treatment (country plough)

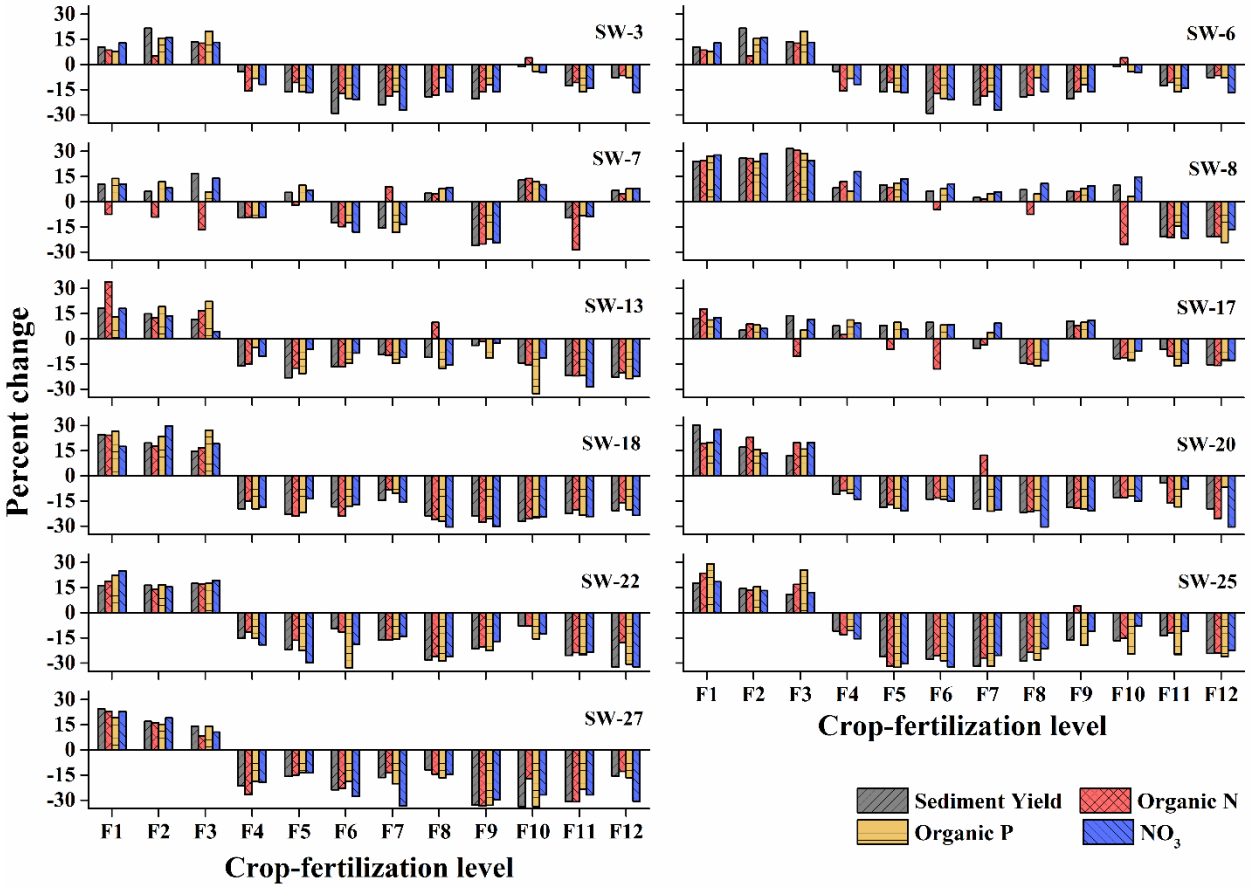
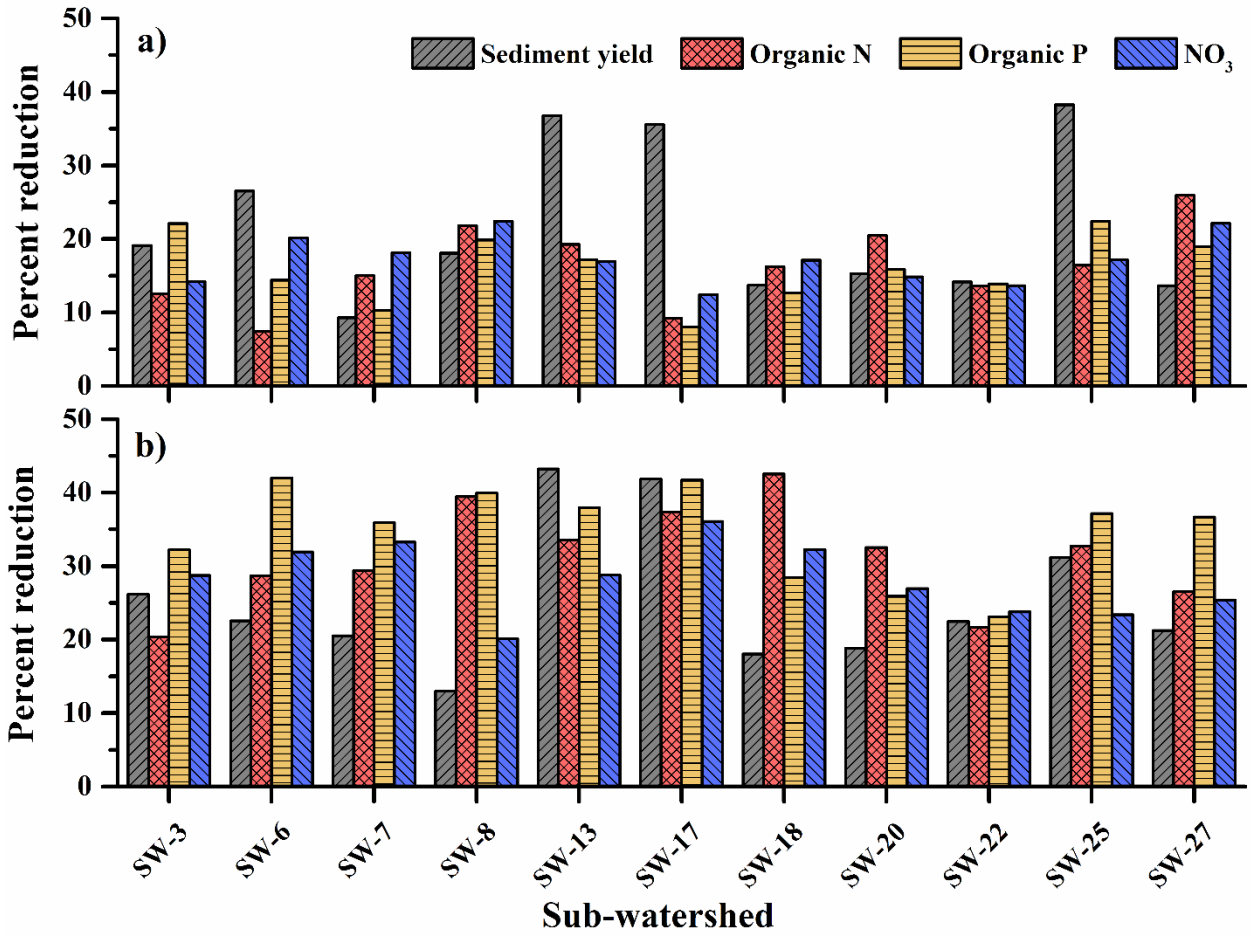


Figure 14: Percent change in simulated sediment and nutrients after implementing different crop-fertilization treatments in the critical sub-watersheds as compared to rice cultivation with existing practice of fertilization



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134 **Figure 15:** Percent reduction in simulated sediment and nutrients after implementing
135 conservation management practices of a) contour farming and b) filter strips in the critical sub-
136 watersheds