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Development of Effective Management Plan for the Critical Sub-Watersheds of Arang Watershed in Chhattisgarh

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ABSTRACT: In this study the SWAT model was verified on monthly basis and used for developing management scenarios for the critical sub-watersheds of a small agricultural watershed (Arang) in Chhattisgarh, India. Various thematic maps including watershed and sub-watershed boundaries, drainage networks, slope and soil texture maps were generated using Arc GIS. Supervised classification method was adopted for land use/cover classification from satellite imageries using ERDAS Imagine. The calibrated values of Manning's 'n' for overland flow and channel flow were referred and used for monthly validation of the SWAT model for the years 2004 to 2005. Validation results revealed that the model was predicting the monthly surface runoff and sediment yield satisfactorily. Comparison between observed and simulated values of organic N and P, NO_3–N and soluble P showed good agreement for several events during the years 2003 to 2005. The model simulated daily rainfall was having close agreement with that of observed rainfall. Also the model predicted and monthly runoff and sediment yield using generated daily rainfall compared well with observed runoff and sediment yield during simulation period of 2003 through 2005. The critical sub-watersheds were identified on the basis of average annual sediment yield and nutrient losses during the study period. Out of ten sub-watersheds only two sub-watersheds (SW5 and SW7) were found to be critical. Several combinations of treatment options were considered which included four crops (rice, maize, groundnut and soybean), five tillage (zero, conservation, field cultivator, M. B. plough and conventional) and three levels of fertilizer (existing, half of recommended and recommended). The existing management practice was considered as the base for evaluating other management practices for rice. The results showed that the other crops could not replace rice since these crops resulted in higher sediment yield as compared to rice. Considering both sediment and nutrient losses collectively the zero tillage, conservation tillage and field cultivator with half dose of fertilizer (40:30 of N:P kg/ha) were found to be better than the other treatments for rice therefore, recommended for the management of critical sub-watersheds of Arang watershed.

INTRODUCTION

Surface hydrologic modelling includes processes like generation and transport of runoff, sediment, and pollutants from watersheds. Prediction of runoff and sediment yield is necessary for the design of conservation structures to reduce the ill effects of sedimentation and to select the priority watersheds for implementing and evaluating the watershed management programs with the limited financial resources. Effective control of soil erosion and sediments requires implementation of best management practices in critical erosion prone areas. This effort can be enhanced by the use of physically based computer simulation models, remote sensing and Geographic Information Systems (GIS) that can assist management agencies in both identifying most vulnerable erosion prone areas and selecting appropriate management practices.

Several computer models are in use to assess various problems related to watershed. Among these models the Soil and Water Assessment Tool (SWAT) is recent one and it has been used most widely for simulating the runoff, sediment yield and water quality of the small watersheds, it has capability to simulate the long-term

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effectiveness of Best Management Practices (BMPs). The SWAT model is one of the more recently developed distributed parameter continuous time model and is a result of the USDA-ARS continuing efforts in non point source pollution modelling and evaluation (Arnold *et al.*, 1996).

Previous application of SWAT has shown promising results (Srinivasan *et al.*, 1993; Srinivasan and Arnold, 1994; Rosenthal *et al.*, 1995; Cho *et al.*, 1995; Tripathi *et al.*, 2003). The review of the research on SWAT model inferred that the model was tested on monthly or annual basis for both runoff and sediment yield by the most of the researchers. Prediction of sediment yield by the model have not been tested widely, work so for has been done was mostly on surface runoff. Very little work has been done to know the impact of management practices on runoff, sediment yield and nutrient losses. Although the model operates on a daily time step and is efficient enough to run for many years, it is intended as a long term yield model.

This study gives an approach to use physically based model (SWAT), GIS (Arc Info) and image processing software (ERDAS Imagine) to estimate the surface runoff, sediment yield and nutrient losses from a small agricultural watershed of Chhattisgarh state. The critical sub-watersheds were identified on the basis of average annual sediment yield and nutrient losses. The adequately verified model was then used for planning and management of critical sub-watersheds.

MATERIALS AND METHODS

Study Area

The Arang watershed is third order watershed and comprises of seven villages. Main channel of the Arang watershed is known as *Sanghari* nala. This watershed is located between 81° 55′ to 82° 0′ E longitude and 21° 12′ to 21° 16′ N latitude and covers an area of 5450 ha. The altitude of the watershed varies from 270 to 290 m above Mean Sea Level (MSL). The watershed is 45 km away from the Indira Gandhi Agricultural University, Raipur towards east. The average slope of the Arang watershed is 1.5%. The predominant soil is loam associated with clayey soils. The characteristics of the major soil of the watershed includes deep, well drained on gentle sloping undulating plateau with mounds and valley with moderate erosion. The watershed receives an average annual rainfall of 1400 mm, out of which the monsoon season (June to October) contributes more than 85% rainfall. The monthly mean temperature ranges from a maximum of 37°C in the month of May to a minimum of 7°C in the month of December. The monthly mean relative humidity varies from a minimum of 38% in the month of April to a maximum of 83% in the month of August. Overall climate of the area can be classified as sub-humid tropical. Major crops grown in the area are paddy, maize and vegetables in *kharif* season and gram, mustered and vegetables in *rabi* season.

The SWAT Model

The SWAT model is a distributed parameter model that operates on a daily time step. Major components of the model include surface hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, ground water and lateral flow and agricultural management. SWAT allows a basin to be divided into hundreds of grid cells or sub-watersheds. The SWAT model simulates the surface runoff using the SCS curve number method (USDA-SCS, 1972). Sediment yield is computed for each sub-basin with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977). The model predicts sub-basin nutrient yield and nutrient cycling using EPIC model (Williams *et al.*, 1984). The SWAT model uses a command structure for routing runoff and chemicals through a watershed similar to the structure of HYMO model (Williams and Hann, 1973). The crop model is a simplification of the EPIC crop model (Williams *et al.*, 1984). Crop yield is estimated using the harvest index concept. The SWAT tillage component was designed to incorporate surface residue into the soil. Fertilizer applications can also be scheduled by the user or automatically applied by the model.

Meteorological and Hydrological Data

A set of instruments consisting of automatic rain gauge, non-recording rain gauge, evaporimeter, maximum and minimum thermometer, wet bulb and dry bulb thermometer were installed at the outlet of the watershed and used for recording the meteorological data for this study. Daily surface runoff at the outlet of Arang watershed was recorded using the traditional water level stage recording method. A silt sampler (USDH-48) was used for collection of runoff samples from the watershed. These runoff samples were analysed to determine the sediment and nutrient losses from the watershed. Daily rainfall, surface runoff and sediment yield recorded regularly at the outlet of the watershed were used in this study for evaluating the performance of the SWAT model and developing the management plan for the critical sub-watersheds of Arang watershed.

Preparation of Thematic Maps and Input Files

Various maps such as contour map, drainage map, soil map and watershed/sub-watersheds boundaries were digitized in the Edit tools of Arc GIS and information available with each map was entered as an attribute value to prepare the database of a particular thematic map. These attribute values associated with each thematic map were used to extract various information and parameters of the study watershed.

Hydrologic behavior of a watershed may be understood by the Digital Elevation Model (DEM), it is the base for generating various information including elevation, drainage, watershed and sub-watershed boundaries in the environment of a GIS. The DEM of Arang watershed was generated using Survey of India topographic map (1:50.000) having 10 m contour interval. Contour map of Arang watershed was digitized using topographic map and then used for preparing the DEM. It shows a continuous surface having elevation information at every point. Various morphological parameters of the watershed required by the model were extracted using DEM, drainage and other thematic maps.

Slope map was generated using DEM on the basis of attribute values of slope. Average slope of each sub-watersheds were determined and then weighted average values of slope were calculated (Table 1). The weighted average slope of the Arang watersheds was found to be 1.5%.

The SWAT model can work on sub-watershed basis, therefore, Arang watershed was divided into number of sub-watersheds on the basis of drainage and elevation information. The watershed was subdivided into 10 sub-watersheds. Sub-watershed boundaries were carefully digitized using GIS and area corresponding to different sub-watersheds of Arang watershed was determined (Table 1).

The land use/cover map of the watershed was generated through ERDAS Imagine using satellite imagery of 5th October 2002. Area covered under each land use classes such as water body, grasses and shrubs, upland paddy, low land paddy, settlement, barren land and fallow land was found to be 126.75 ha, 446.30 ha, 2199.46 ha, 2167.26 ha, 200.81 ha, 278.94 ha and 30.23 ha, respectively. The maximum area (4366.74 ha) was under crop, therefore, watershed was considered as agricultural watershed. Sub-watershed wise land use information was also used in this study.

Soil texture map of the Arang watershed was prepared using soil resource data through GIS. Area covered under different soil texture including loam, sandy clay loam, clay and sandy loam was found to be 711.78 ha, 520.20 ha, 4043.40ha and 174.62 ha, respectively. Sub-watershed wise area occupied by each soil texture was also calculated and used in this study.

The map layers like land use, soil and sub-watersheds were overlaid and statistical information (number of pixels corresponding to various land use and soil textures) were used for calculation of curve numbers of the watershed. Hydrologic condition of the watershed based on the drainage network, hydrological soil groups based on the soil properties, and antecedent moisture condition (AMC-II) were considered. This information was then used to get the weighted average curve numbers for each sub-watershed by referring standard table of curve numbers for the Indian conditions (Narayana, 1993). Weighted average values of CN for the Arang watershed are given in Table 1.

Table 1: Sub-Watershed Wise Data of the Arang Watershed

Sub-Watershed	*Area (ha)*	*Slope (%)*	*Curve Numbers*	*Ave. Slope Length (m)*	*Channel Length (km)*	*Channel Slope (%)*	*K Value*	*P Value*
SW1	345.14	1.3	91.91	136.3	1.50	.001	0.18	0.60
SW2	148.67	1.3	87.98	139.8	1.50	.001	0.18	0.60
SW3	355.17	1.5	83.40	118.6	1.60	.002	0.18	0.60
SW4	934.78	1.6	89.00	142.4	2.10	.003	0.18	0.60
SW5	838.88	2.0	89.74	145.8	2.40	.005	0.20	0.50
SW6	577.55	1.6	90.00	132.3	2.60	.003	0.18	0.60
SW7	385.30	1.7	86.91	117.0	2.50	.004	0..22	0.50
SW8	674.36	1.2	90.64	124.3	2.60	.002	0.18	0.60
SW9	634.48	1.3	89.60	137.8	2.20	.001	0.18	0.60
SW10	555.67	1.3	90.77	124.7	1.50	.001	0.18	0.60

Various morphological parameters of the watershed have been extracted using the standard equations and procedures. The values of some of the important morphological parameters are needed as inputs to the SWAT model. Parameters such as channel length, average slope length, channel slope, soil erodibility factor (*K*) and soil conservation practice factor (*P*) has been calculated for verification of SWAT model (Table 1). All the input data has been entered into the respective files and several model runs were performed. The simulated surface runoff, sediment yield and nutrient losses were compared with their observed counterparts for SWAT model verification.

RESULTS AND DISCUSSION

Model Verification

Calibrated values of Manning's '*n*' for overland flow (0.040) and channel flow (0.025) for Chhokranala watershed which is similar in nature and located near by the study watershed was used for model verification (Shivastava *et al.*, 2004). The simulated values of surface runoff, sediment yield and nutrient losses were compared with their observed counterparts using various methods such as mathematical, graphical, linear regression and statistical tests of significance.

Surface Runoff

The observed and simulated monthly values of runoff for the years 2003 through 2005 were compared graphically. The model simulated both high and low runoff values as compared to the observed values. Monthly simulated runoff values were plotted against the observed values and their distribution along the 1:1 line is shown in Figure 1. The simulated runoff values were distributed uniformly along the 1:1 line for most of the values of observed runoff. A high value (0.94) of coefficient of determination (r^2) indicated a close relationship between observed and model simulated runoff for the Arang watershed (Table 2. Student's t-test showed that the means of observed (163.5 mm) and model simulated (168.6 mm) runoff was not significantly different at 95% confidence level. The overall per cent deviation (Dv) indicated that the model was over predicting surface runoff by 3.1% only for the validation period. It implies that the weighted average CN values determined for each sub-watershed and used for runoff simulation were reasonable.

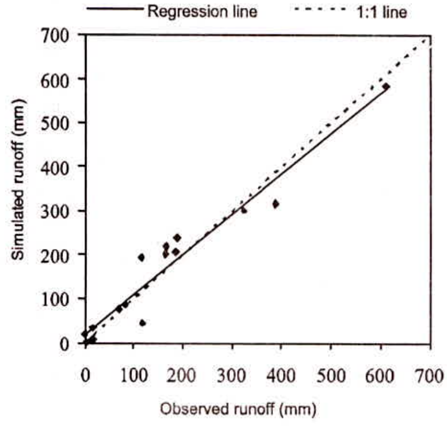

Fig. 1: Comparison between observed and simulated runoff

Table 2: Statistical Results of Surface Runoff and Sediment Yield (2003–2004)

Statistical Parameters	*Runoff (mm)*		*Sediment Yield (t/ha)*	
	Observed	*Simulated*	*Observed*	*Simulated*
Mean	163.50	168.60	1.41	1.60
Standard deviation	167.70	157.70	0.25	0.25
Maximum peak	611.40	584.10	3.55	3.01
Total	2453.00	2528.40	21.20	23.93
Count	15	15	15	15
t-cal	–0.455		–2.023	
t-critical (two tailed)	2.145		2.145	
r^2	0.936		0.874	
% deviation	–3.10		–12.90	

Sediment Yield

Similar to runoff, verification of model was performed for simulating sediment yield at the outlet of the watershed for the monsoon season of the years 2003 to 2005. The simulated monthly sediment yield matched well with the measured sediment yield. However, the model slightly over predicted few values of sediment yield during the validation period. The scattergram of observed and simulated sediment yield along with 1:1 line is shown in Figure 2. The simulated sediment yields were distributed

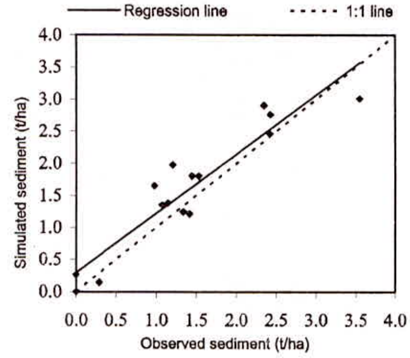

Fig. 2: Comparison between observed and simulated sediment yield

uniformly along the 1:1 line for both lower and higher values of observed sediment yield. A value of 0.87 of r^2 indicated a close relationship between measured and simulated sediment yield (Table 2). Though the model was over predicted sediment yield values by 12.9%, but Student's t-test showed that the means of observed and simulated sediment yield were not significantly different at 95 per cent confidence level.

Nutrient Losses

Similarity in means of observed and simulated organic nitrogen showed a good agreement at 95% level of confidence (Table 3). The Dv value was found to be 6.4% indicated that the model was under predicting organic nitrogen. A value of r^2 of 0.97 indicated very good agreement between observed and simulated organic nitrogen. The coefficient of determination 0.96 also showed good agreement between observed and simulated organic phosphorous. The means were not found statistically similar at 95% level of confidence. The Dv value (12.8%) indicated that the model was predicting organic phosphorous satisfactorily (Table 3).

An r^2 value of 0.78 indicated good agreement between observed and simulated values of nitrate-nitrogen. The Dv indicated that the model was under predicting NO_3–N by about 12.0% (Table 3). However, the difference in means of observed and simulated values at 95% confidence level indicated non similarity between observed and predicted values of NO_3–N. An r^2 value of 0.82 indicated good agreement between observed and simulated values of soluble phosphorous. The Dv value indicated that the model was under predicting soluble phosphorous by about 15.0%. Moreover, the similarity in means of observed and simulated values at 95 percent confidence level indicated similarity in observed and predicted values of soluble *P* for the selected rainfall events of the validation period (Table 3).

Generation of Monthly Rainfall

The SWAT model generates rainfall using first order Markov chain model. In general, the model predicted monthly rainfall values were quite close to the observed rainfall for all the months of monsoon seasons during 2002 to 2005. The t-test showed that the simulated means of monthly rainfall were not significantly different than the observed means at 95% level of confidence. The coefficients of determination were found to be 0.82 and 0.85, respectively, where as Dv values were found to be 14.1% and 10.5%, respectively. It can be inferred from the results that the SWAT could simulate monthly rainfall for these watersheds with reasonable accuracy.

The model performance was also tested for the monthly rainfall, runoff and sediment yield for the monsoon period of the years 2003 to 2005 and the results are given in Table 4. Results showed that the model predicted monthly runoff and sediment yield using generated rainfall were having close agreement with the observed runoff and sediment yield. The differences between the means of observed and simulated rainfall, runoff and sediment yield were not statistically significant at 95% level of confidence. The coefficients of determination were found to be 0.80, 0.88 and 0.67, respectively for monthly rainfall, runoff and sediment yield (Table 4). Dv values of 11.9%, 16.8% and –18.1%, respectively for monthly rainfall, runoff and sediment yield indicated that model was predicted monthly rainfall and thereby runoff and sediment yield satisfactorily (Table 4).

Table 3: Statistical Results of the Observed and Simulated Nutrient Losses

Statistical Parameters	*Organic N*		*Organic P*		*NO_3–N*		*Soluble P*	
	Obs.	*Sim.*	*Obs.*	*Sim.*	*Obs.*	*Sim.*	*Obs.*	*Sim.*
Mean (kg/ha)	0.361	0.338	0.182	0.159	0.164	0.143	0.014	0.012
Standard deviation (kg/ha)	0.630	0.572	0.332	0.290	0.148	0.121	0.019	0.014
Maximum (kg/ha)	3.000	2.280	1.360	1.160	0.650	0.480	0.080	0.060
Total (kg/ha)	23.825	22.290	12.931	12.020	10.789	9.490	0.900	0.765
Count	66	66	66	66	66	66	66	66
t-calculated	1.536		2.604		2.305		1.986	
t-critical (two tailed)	1.997		1.997		1.997		1.997	
r^2	0.968		0.964		0.785		0.816	
% deviation	6.44		12.81		12.04		15.00	

Table 4: Statistical Results of Monthly Rainfall, Runoff and Sediment Yield (2003 to 2005)

Statistical Parameters	*Rainfall (mm)*		*Runoff (mm)*		*Sediment (t/ha)*	
	Observed	*Simulated*	*Observed*	*Simulated*	*Observed*	*Simulated*
Mean	242.59	213.63	163.53	135.99	1.391	1.642
Standard deviation	200.45	174.25	167.68	115.95	0.985	1.148
Maximum	752.20	662.24	611.41	409.4	3.550	3.410
Total	3638.86	3204.51	2452.95	2039.85	20.860	24.630
Count	15	15	15	15	15	15
t-cal	1.274		1.513		–1.460	
t-critical (two-tail)	2.145		2.145		2.145	
r^2	0.808		0.886		0.665	
% deviation	11.9		16.8		–18.1	

Identification of Critical Sub-Watersheds

The critical sub-watersheds were identified on the basis of average annual sediment and nutrient losses from the sub-watersheds during the period of 2003 to 2005. In this context, annual runoff, sediment yields and nutrient losses were simulated for each sub-watershed using SWAT model. Priorities were fixed on the basis of ranks assigned to each critical sub-watershed according to ranges of soil erosion classes described by Singh *et al.* (1992). Also for nutrient losses a threshold value of 10 mg/l for nitrate nitrogen and 0.5 mg/l for dissolve phosphorous as described by EPA (1976) were considered as criterion for identifying the critical sub-watersheds. Identified critical sub-watersheds were arranged in descending order and then priorities were fixed for their management.

Only one sub-watershed (SW5) of Arang watershed was fell under very high soil loss group (20–40 t/ha/yr). Sub-watersheds SW7, SW6, SW4 and SW3 fell under high soil loss group (10–20 t/ha/yr), whereas other sub-watersheds fell under moderate soil loss group (5–10 t/ha/yr). On the basis of annual sediment yield and nutrient losses, sub-watersheds SW5 and SW7 of Arang watershed were found to be critical. As a result the critical sub-watersheds SW5 and SW7 were assigned first and second priority, respectively, to adopt the best management practices in that order.

Development of Effective Management Plan

Adequately verified SWAT model was used for developing the management practices for the critical sub-watersheds. Therefore, several simulations for different treatment combinations were performed for the period of 2003 through 2005. Four crops (rice, maize, groundnut and soybean), three fertilizer doses (existing, half of recommended and recommended) and five tillage practices (conventional, MB plough, field cultivator, conservation tillage and zero tillage) were considered. The management files of these sub-watersheds were taken in to consideration for evaluating the management scenarios. The critical sub-watersheds assigned first priority was considered for evaluating the effect of management. Hence, results of only one sub-watershed (SW5) are presented and discussed in this paper.

Results revealed that none of the crop could replace the rice because maize, groundnut and soybean were yielding high rate of sediment yield as compare to rice in case critical sub-watershed, SW5. Therefore, simulation results given in Table 5 of all the treatments considered for rice were compared with the conventional tillage and existing fertilizer level (25:15 of N:P kg/ha).

The results indicated that the runoff was not much affected by tillage and fertilizer levels. On an average the maximum percent increase in runoff was noticed by the zero tillage with full dose of fertilizer (80:60 of N:P kg/ha). M.B. plough increased sediment yield by about 27.8% as compared to the conventional tillage in case of all the levels of fertilizer. This high sediment yield was due to higher mixing efficiency (0.90) of M.B. plough. The decrease in sediment yield as compared to conventional tillage with existing fertilizer dose was found to be about 63.2%, 35.3% and 26.2%, respectively for zero tillage, conservation tillage and field cultivator. Similar trends of sediment yield were observed in case of all the tillage with half and full dose of fertilizer levels (Table 5).

Considering the existing fertilizer dose, the losses of NO_3–N were found to increase by about 3.9%, 3.8% and 1.9%, respectively for zero tillage, conservation tillage and field cultivator whereas it was decreased by 2.5% in case of M.B. plough. However, NO_3–N losses were found

Table 5: Effect of Various Treatments on Watershed Yield of WS5 (2003–2005)

Treat-ments	*Runoff (mm)*	*Sediment (t/ha)*	*NO_3–N (kg/ha)*	*Soluble P (kg/ha)*	*Organic N (kg/ha)*	*Organic P (kg/ha)*
F1+T1	750.16	9.19	6.62	0.09	09.37	03.77
F1+T2	750.15	15.71	6.58	0.09	11.30	05.47
F1÷T3	750.15	17.85	6.56	0.08	12.52	06.36
F1+T4	750.14	28.02	6.52	0.07	12.94	06.57
F1+T5	750.15	23.34	6.53	0.08	12.71	06.45
F2+T1	750.17	9.20	7.40	0.09	13.09	06.83
F2+T2	750.16	15.72	7.36	0.09	17.07	10.22
F2+T3	750.16	17.86	7.33	0.08	19.31	11.95
F2+T4	750.15	28.02	7.30	0.07	19.95	12.34
F2+T5	750.16	23.34	7.32	0.08	19.60	12.13
F3+T1	750.18	9.20	8.98	0.10	20.54	12.97
F3+T2	750.17	15.72	8.96	0.10	28.61	19.75
F3+T3	750.17	17.87	8.94	0.09	32.89	23.17
F3+T4	750.16	28.02	8.88	0.08	33.97	23.91
F3+T5	750.17	23.35	8.90	0.09	33.39	23.51

to be increased in the range of 12 to 43% for both the cases of fertilizer dose (Table 5). Losses of soluble *P* were found to be similar in case of all the fertilizer levels with respective tillage. For all doses of fertilizer, soluble *P* losses were increased by about 17–50% for both zero tillage and conservation tillage. At all the fertilizer levels organic *N* and *P* losses were found to be higher in case of M.B. plough as compare to other tillage (Table 5).

As far as sediment and nutrient losses concerned, the zero tillage followed by conservation tillage and field cultivator were found to be more suitable than M.B. plough and existing tillage. Considering both sediment and nutrient losses together the zero tillage, conservation tillage and field cultivator with half dose of fertilizer were found to be better than the other treatments considered for evaluating their impact on sediment yield and nutrient losses for sub-watershed (SW5). Therefore, zero tillage, conservation tillage and field cultivator with half dose of fertilizer (40:30 of N:P kg/ha) could be used for the management of the critical sub-watersheds of the Arang watershed. Sediment losses in these cases were found to be less than the conventional tillage and within the average soil loss (16.35 t/ha/yr) of the country. These tillage practices also yielded nutrient losses within the permissible limit. Hence these practices can be recommended to adopt in the critical sub-watersheds of the study watershed.

CONCLUSIONS

The SWAT model accurately simulates monthly runoff and sediment yield from the Arang watershed.

The SWAT model also simulates nutrient losses accurately from the watershed on daily basis. The weather generator can be used to simulate monthly rainfall and thereby runoff and sediment yield. The model can be used for planning and management of the small agricultural watershed on long-term basis using generated daily rainfall. The SWAT model can successfully be used for identifying critical sub-watersheds for management purpose. Crops like maize, groundnut and soybean can not replace the existing rice crop, on the basis of sediment and nutrient losses reduction criteria. Zero tillage, conservation tillage and field cultivator along with 40:30 kg/ha of N:P can be recommended because these tillage practices reduce sediment yield as compared to existing tillage and nutrient losses being within the permissible limit.

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