Environ Geol (2009) 56:993–1008
DOI 10.1007/s00254-008-1201-8

ORIGINAL ARTICLE

Evaluation of effective management plan for an agricultural watershed using AVSWAT model, remote sensing and GIS

V. K. Pandey · S. N. Panda · Ashish Pandey · S. Sudhakar

Received: 15 July 2007 / Accepted: 16 January 2008 / Published online: 5 February 2008

Abstract In the present investigation, an effort has been made to identify the critical sub-watersheds for the development of best management plan for a small watershed of Eastern India using a hydrological model, namely, AVSWAT2000. A total of 180 combinations of various management treatments including crops (rice, maize ground nut and soybean), tillage (zero, conservation, field cultivator, mould board plough and conventional practices) and fertilizer levels (existing half of recommended and recommended) have been evaluated. The investigation reveled that rice cannot be replaced by other crops such as groundnut, maize, mungbean, sorghum and soybean since comparatively these crops resulted in higher sediment yield. The tillage practices with disk plough have been found to have more impact on sediment yield and nutrient losses than conventional tillage practices for the existing level of fertilizer. Sediment yield decreased in the case of zero tillage, conservation tillage, field cultivator, moldboard plough, and conservation tillage as compare to conventional tillage. Lowest NO_3–N loss was observed in zero tillage in all the fertilizer treatments, whereas field cultivator, moldboard plough and disk plough resulted in increase of NO^3–N loss. As compared to conventional tillage, the losses of soluble phosphorus were increased in moldboard plough. The losses of organic nitrogen were also increased as fertilizer dose increased. After zero tillage the conservation tillage preformed better in all the fertilizer treatments as per loss of organic nitrogen and organic phosphorus is concerned. It can be concluded that the sediment yield was found to be the highest in the case of disk plough followed by moldboard plough, field cultivator, conventional tillage, field cultivator and least in zero tillage practices. The nutrient losses were found to be in different order with tillage practices, resulted highest in disk plough tillage practices. In view of sediment yield and nutrient losses, the conservation tillage practice was found to be the best as the sediment yield is less than the average soil loss whereas nutrient loss is within the permissible limit.

Keywords AVSWAT · GIS · NPS pollution · Remote sensing · Watershed management

Introduction

Watershed management implies an effective conservation of soil and water resources for sustainable production with minimum non-point source (NPS) pollutant losses. Agriculture has been identified as the major contributor of the NPS of water resource (Humenik et al. 1987; Duda 1993). Assessment of the environmental impacts of NPS pollutants

---

V. K. Pandey
Department of Soil and Water Engineering,
Faculty of Agricultural Engineering,
Indira Gandhi Agricultural University, Raipur 492006, India

S. N. Panda
Department of Agricultural and Food Engineering, Indian
Institute of Technology, Kharagpur 721302, West Bengal, India

A. Pandey (✉)
Department of Water Resources Development and Management,
Indian Institute of Technology,
Roorkee 247667, Uttarakhand, India
e-mail: ashish_nerist@yahoo.co.in; ashisfwt@iitr.ernet.in

S. Sudhakar
National Remote Sensing Agency,
Indian Space Research Organization,
Government of India, Hyderabad 500037,
Andhra Pradesh, India

at watershed scale is a key component to achieve sustainable agriculture. The NPS pollution from agricultural watersheds can be reduced by adopting sustainable agricultural management practices (Humenik et al. 1987). The effective watershed management plan is a measure or set of measures applied during soil disturbing activities that are intended to prevent or minimize soil erosion and protect water quality. Prescribed measures range from very simple, such as not operating heavy equipment when soils are wet, to the very complex, such as installing specifically engineered structures to collect water and separate soil, grease, and heavy metals. Best management practices (BMP) may also be temporary, intended to last during short periods of disturbance, or permanent, used to prevent water quality degradation over many years.

Non-point source is transported primarily by runoff from watersheds. Runoff carries sediment, organic matter, bacteria, pesticides, and nutrients primarily nitrogen (N) and phosphorus (P). In a particular study conducted in USA, it is reported that agriculture was estimated to be responsible for 60 and 27% of N and P loadings from NPS, respectively (Brannan et al. 2000). The NPS losses from agricultural watersheds can be reduced by adopting sustainable agricultural management practices. Dickinson et al. (1990) revealed that, for many watersheds, a few critical areas are responsible for disproportionate amount of the pollution.

Best management practices are used to control the generation or delivery of pollutants from agricultural activities to water resources and to prevent impacts to the physical and biological integrity of surface and ground water. Because financial resources are generally limited, BMP system implementation should be prioritized. Systems of BMPs should first be implemented at those locations in the critical area that contribute the largest proportion of pollutant(s). Ritter (2000) revealed that protecting water quality, a combination of BMPs, may be more effective than any single BMP.

Due to complexity of the soil–water–plant interactions, the direct up-scaling of results from the singe field scale experiments to regional assessments of losses can be misleading. Therefore, mathematical modeling tools have been developed and modeling strategies are set up to generalize the effect of environmental conditions and agricultural practices on nutrient losses on field and watershed scale. Watershed models serve as a means of organizing and interpreting data while providing continuous water quality predictions proved to be economically feasible and time efficient. Tripathi et al. (2004) and Santhi et al. (2001) validated the SWAT model for flow, sediment and nutrients in the selected watersheds to evaluate alternative management scenarios and estimated their effects in controlling pollution. Turpin et al. (2005) have used a modeling framework to evaluate the impacts of BMPs in terms of hydrological effectiveness, costs for the farmers and society, and their acceptability in several European watersheds. Santhi et al. (2006) used the SWAT model for evaluating the impacts of water quality management plans implemented in a watershed in Texas. The study concluded that current modeling approach would be very useful for decision makers to assess the benefits of BMPs individually and at the watershed level. Several investigations were carried out to predict the extent of NPS pollution with the help of physically based model. Appropriate management alternatives were then implemented to control the NPS pollution of water resources in a basin scale (Mostaghimi et al. 1997; Saleh et al. 2000; Eckhardt and Arnold 2001; Bhuyan et al. 2003).

The hydrologic behaviors of watershed play an important role in its effective management (Shin-Min et al. 2002). Increasing rate of watershed development and utilization for various purposes has focused attention on the application of physically based hydrological models to deal with constantly changing environment. Commonly used agricultural watershed models include AGNPS (Young et al. 1989), ANSWERS (Beasley et al. 1980), MIKE SHE (Xevi et al. 1997), and WEPP (Ghidey and Alberts 1996). Fohrer et al. (1999) have successfully calibrated and validated the SWAT on ‘Aar’ gauged watershed using the land use map derived from satellite images. Srinivasan et al. (1998) calibrated the SWAT model for the period of 1988 through 1994 using the sediment data from the Richland-Chambers (RC) lake and validated for a sub-watershed (Mill Creek watershed) situated on Chambers Creek of RC watershed. They reported that the model was predicting accumulated sediment within 2 and 9% from the observed data for the RC and Mill Creek watersheds, respectively. Weber et al. (2001) used the SWAT model and suggested that land use has a significant influence on the water balance components of any catchment. Previous applications of the SWAT in various parts of the United States have shown promising results (Bingner et al. 1997; Peterson and Hamlett 1998; Manguerra and Engle 1998). SWAT model has been widely used by various researchers in different parts of the globe (Engel et al. 1993; Saleh et al. 2000; Santhi et al. 2001; Fohrer et al. 2001; Arnold and Fohrer 2005). Tripathi et al. (2005) used the SWAT model for the assessment of NPS pollutants and watershed management of Nagwan, watershed of Hazaribagh, India. Behera and Panda (2006) used SWAT model for the evaluation of management alternatives for a small agricultural watershed (Kapagri watershed) of eastern India.

Thus, the planning and implementation of BMPs for effective control of NPS pollutants and development of watershed management can be improved by the use of the SWAT model. Although, the SWAT model have been successfully used in developed countries for simulating the

NPS pollutants of the watersheds, so far little attempt has been made to use them for this purposes in India. However, the research results of SWAT clearly indicated that location-specific testing and wider application of the model are still required. Keeping these facts in view, an adequately tested physically based continuous hydrological model AVSWAT-2000 has been applied to develop an effective management plan for the identified critical sub-watersheds of Banikdih watershed of Gowai river catchment in Eastern India.

Theoretical considerations of the AVSWAT 2000 model

The soil and water assessment tool (SWAT) model is a continuous time model that operates on a daily time step at catchment scale (Arnold et al. 1998, 2001; Neitsch et al. 2001). It can be used to simulate water and nutrient cycles in agriculturally dominated landscapes. SWAT is a process-based model, including also empirical relationships. One objective of such a model is to assess long-term impacts of management practices. It is linked with the raster-based GIS to facilitate the input of the spatial data such as land use, soil maps and digital elevation models (DEM). The SWAT model uses a command structure, for routing runoff and chemicals through a watershed, similar to the HYMO model (Williams and Hann 1973). The model simulates for a basin subdivided into hydrological response units (HRU), grid cells or sub-watersheds. The model simulates surface runoff for daily rainfall by using the soil conservation service (SCS) curve number (CN) method. Sediment yield is computed for each sub-basin with the modified universal soil loss equation (MUSLE) (Williams and Berndt 1977). Sub-basin nutrient yield and nutrient cycling were taken from the EPIC model (Williams et al. 1984). Further, modified as per requirement for inclusion into the model (Arnold et al. 1996). The model allows for simultaneous computations on each sub-basin and routes the water, sediment and nutrients from the sub-basin outlets to the basin outlet.

Materials and methods

Study area and data collection

The study watershed area (Fig. 1) is located at Bokaro district of Jharkhand State and Purulia district of West Bengal State in Eastern India. The watershed receives an average annual rainfall of 1,250 mm, out of which more than 80% occurred during the monsoon months (June to September). Daily mean temperature ranges from a maximum of 44°C (April–May) to a minimum of 4°C (December–January). Daily mean relative humidity varies from a minimum of 40% (April) to a maximum of 95% (July). The region falls within sub-tropical climate with alternate dry and wet periods. The area is dominated by alluvial, colluviums and red soils. Predominant soil properties of the watershed are presented in Table 1. General slope ranging from 0 to 19% is in south and south-west to north and north-east. Topography of the watershed is undulating and much of the naturally incoming water flows out quickly. The entire cultivable land is under rainfed agriculture. Major crops grown in the area are rice (*Oryza sativa*), groundnut (*Archis hypogaea*), maize (*Zea mays*), mungbean (*Phaseolus aureus*), sorghum (*Sorghum bicolor*), and soybean (*Glycine max*) in monsoon season and wheat (*Triticum aestivum*), mustard (*Brassica nigra*), linseed (*Linum usitatissium*) and some vegetables in winter season. Some common species of deciduous trees found in the area are Akashmani (*Acacia auriculforinge*), Babul (*Acacia arabica*), Bamboo (*Bambusa rodesa*), Jackfruit (*Artocarpus integritolia*), Khair (*Acasia catechu*), Mango (*Mangifera indica*), Palas (*Buyea monospermea*), Siso (*Dalbergia sisu*) and Sal (*Shorea robusta*).

Data availability

Observed rainfall, runoff and sediment data of the watershed (recorded at the outlet) were collected from the Damodar Valley Corporation, Hazaribagh, India. Measured data of runoff and sediment yield were available for monsoon season (June–September) for years 1993–2000. The mean value of runoff and sediment yield from the study watershed was observed to be 2.21 and 0.01 t ha^{-1}, respectively. The peak value of runoff and sediment yield from the study watershed was observed to be 276.60 mm and 1.64 t ha^{-1}, respectively. The climatic data were collected from the district seed farm, Hathuara, and the Institute of Wetland Management Kolkata. The soil data and related maps (1:25,000 scale) were collected from All India Soil and Land Use Survey, Department of Agricultural and Cooperation, Government of India, Kolkata. Topographic maps (1:25,000 scale) were collected from the Survey of India (SOI), Kolkata. Digital data (IRS-1D LISS-III pertaining to 29 October, 1998 and 23 October, 2000) were obtained from the National Remote Sensing Agency, Government of India, Hyderabad.

Spatial database generation

The contours of 10 m interval were digitized from SOI topographical map of 1:25,000 scale using ARC/INFO

Fig. 1 Location map of Banikdih watershed

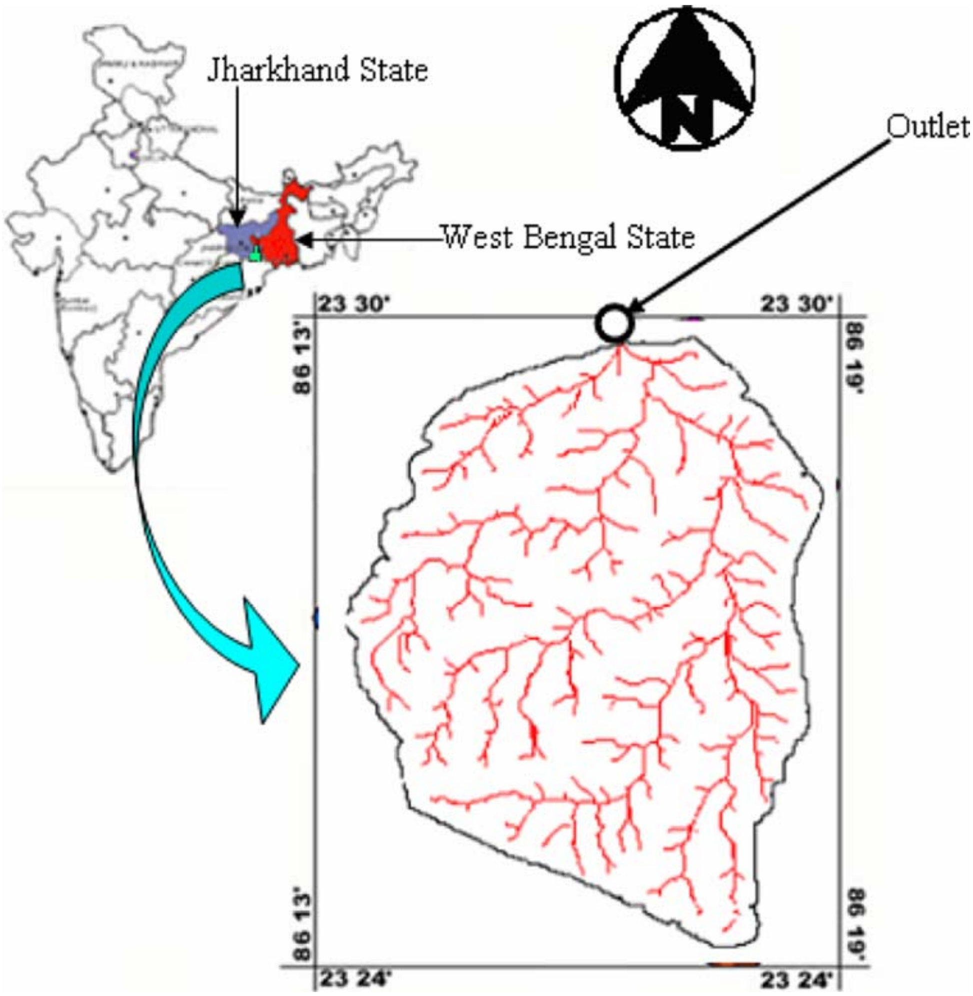

Table 1 Physical and chemical properties of the watershed soils and data for (.sol) input file

Soil properties	Sandy loam			Loamy sand			Sandy clay loam			Clay loam		
	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
Bulk density (Mg/m^3)	1.65	1.60	1.63	1.68	1.59	1.72	1.50	1.40	1.50	1.31	1.35	1.40
AWC (mm/mm)	0.16	0.17	0.20	0.16	0.17	0.18	0.18	0.17	0.18	0.23	0.24	0.22
SHC (mm/hr)	7.25	7.68	6.95	6.95	6.98	5.99	5.88	5.78	5.91	5.10	5.33	4.98
Organic carbon content (%)	0.37	0.38	0.29	0.32	0.36	0.33	0.25	0.23	0.24	0.19	0.18	0.18
Clay (%)	7.69	9.16	7.80	13.36	16.81	14.02	26.25	25.23	27.81	58.35	60.13	59.34
Silt (%)	4.96	5.88	8.65	8.52	9.63	8.86	10.81	10.88	9.81	12.93	14.17	17.00
Sand (%)	87.35	84.96	83.55	78.12	73.56	77.12	62.94	63.89	62.38	28.72	25.70	23.66
USLE K factor	0.18	0.17	0.05	0.20	0.20	0.20	0.23	0.21	0.24	0.26	0.27	0.26
WH (%)	20.40	31.35	37.56	20.00	23.55	27.44	29.30	31.62	30.01	34.24	36.23	37.64
Porosity (%)	40.00	43.32	46.02	41.33	46.32	44.23	45.22	42.35	46.55	46.82	48.66	47.01
pH	5.60	5.36	5.71	5.50	5.47	6.02	6.30	6.21	5.96	6.40	6.56	6.31
N (kg/ha)	249.56	231.88	228.66	228.51	215.53	208.52	254.54	248.74	234.61	289.64	357.24	346.31
P_2O_5 (kg/ha)	19.14	16.58	12.80	15.57	13.74	12.82	19.24	17.86	14.20	17.59	25.72	5.86
K_2O (kg/ha)	139.22	163.55	158.99	125.63	116.55	112.47	172.38	178.85	168.22	235.66	366.41	326.45

AWC available water capacity, *SHC* saturated hydraulic conductivity, *WH* water holding capacity

GIS software (ESRI 1994). The digitized contours were given ID (identity) numbers representing contour elevations. A lattice, that is the surface interpretation of a grid, was developed with the help of digitized contours. Each mesh point contains the z value of that location, and is referenced to a common base z value, such as sea level. Surface z values of locations between lattice mesh points were approximated by interpolation between adjacent mesh points. Finally, the lattice was converted in to digital elevation model (DEM) (cell size 23 m × 23 m) of the watershed using interpolation as shown in Fig. 2. A DEM was developed with 23 m × 23 m spatial resolution using contour (10 m interval) map of 1:25,000 scale (Olivera 2001). Using the input maps and data files for the study area, the model was run through the AVSWAT interface (DiLuzio et al. 2001a, b). Automatically delineated watershed area (88.74 km^2) closely matches with the area delineated manually (89.55 km^2); finally automatically delineated watershed was used for further analysis. The whole watershed was divided into eight subwatersheds (Fig. 3). Supervised classification was performed for classification of satellite data. The overall accuracy of classification for 1998 and 2000 were found to be 92.25 and 90.00%, respectively. The Kappa coefficients (measure of accuracy of satellite image classification) for 1998 and 2000 were found to be 0.91 and 0.90, respectively (Pandey et al. 2005). The maximum likelihood report of landuse classification is also presented in Table 2.

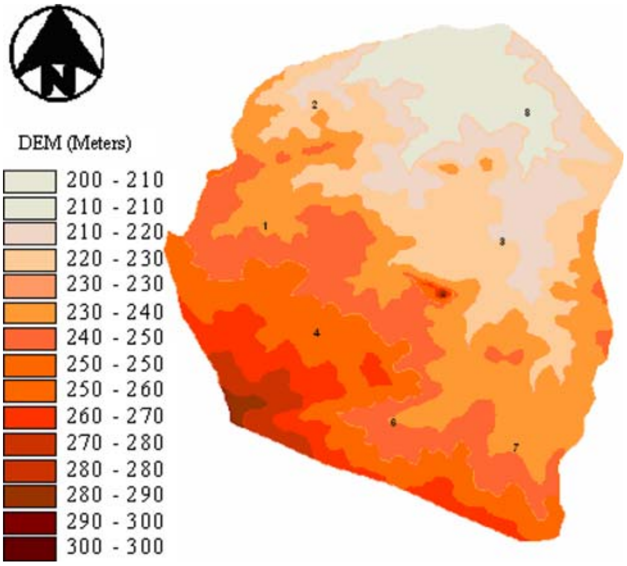

Fig. 2 Digital elevation model (DEM) of the watershed

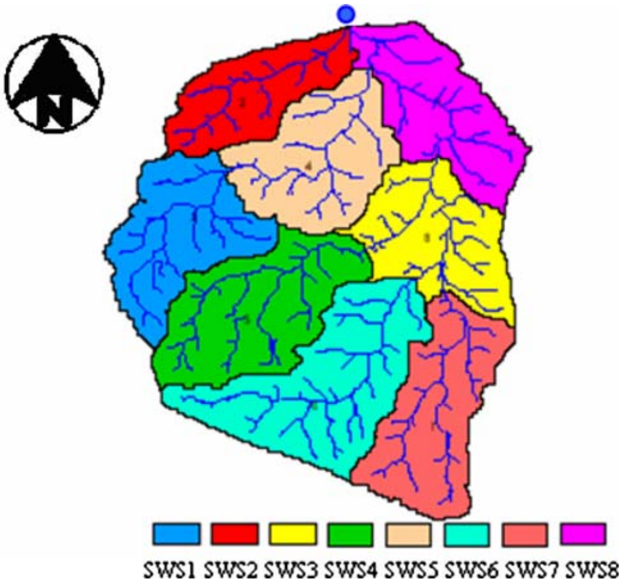

Fig. 3 Sub-watershed map of the watershed

Table 2 Maximum likelihood report for land use classification

Land use classes	1998		2000	
	Area (ha)	Total area (%)	Area (ha)	Total area (%)
Water body	217.94	2.46	229.89	2.60
Lowland paddy	3,344.97	37.45	3,610.29	40.68
Upland paddy	1,887.66	21.51	1,914.37	21.57
Fallow land	1,562.18	17.60	1,366.13	15.40
Upland crops[a]	590.79	6.66	485.77	5.47
Settlement	229.59	2.59	219.65	2.48
Open mixed forest	412.18	4.64	408.72	4.61
Wasteland	628.94	7.09	638.63	7.19
Total	8,874.25	100.00	8,873.45	100.00

*Non-paddy crops

Model input parameter

The input parameters required in the model were generated from various map themes using AVSWAT interface. The weighted average values of curve number and slope were used in the analysis. Daily observed maximum and minimum temperatures, rainfall and relative humidity were used as input to the model. Looking to the availability of meteorological data, Hargreaves method (Hargreaves and Samani 1985) was selected for the estimation of evapotranspiration. Input variables used for model calibration were SCS curve number, available water holding capacity of soil layers, Manning's 'n' for overland and channel flow, soil hydraulic conductivity, erodibility factor, crop cover factor, and soil bulk density.

Sensitivity analysis

The sensitivity analysis was carried out for the calibrated parameters of 1998 using the data set of the selected sub-watershed. Parameters such as Manning's *n* value for overland flow, Manning's *n* value for channel flow, effective hydraulic conductivity of channel alluvium, specific yield, base flow alpha factor, and alpha factor for groundwater were considered for the sensitivity analysis. The base flow alpha factor characterizes the groundwater recession curve. The alpha factor for groundwater is the base flow recession constant or constant of proportionality, which is a direct index of groundwater flow response to change in recharge. It was observed that the sediment yield was very sensitive to both the Manning's *n* value for overland and channel flow, but the surface runoff was less sensitive to Manning's *n* values.

Goodness-of-fit criteria for evaluation of SWAT model

The model performance was evaluated on the basis of test criteria recommended by the ASCE Task Committee (1993), i.e., Nash-Sutcliffe coefficient or coefficient of simulation efficiency (ENS) (Nash and Sutcliffe 1970), and per cent deviation of measured values proposed by Martinec and Rango (1989). The prediction performance of the model was decided based on the criterion suggested by Bingner (1989). Student's *t* test for significance difference at 95% level was also used to test the model simulation results.

Table 3 Parameters used for model calibration

Sl. no.	Calibrated parameters	Values chosen	Prescribed range
1.	Base flow alpha factor	0.080	0.00–1.00
2.	Effective hydraulic conductivity in the tributary channel alluvium	6.750	0.01–150.00
3.	Effective hydraulic conductivity in the main channel alluvium	1.000	0.01–150.00
4.	Mannings '*n*' value for overland flow	0.068	0.06– 0.12
5.	Channel erodibility factor	0.500	0.05–1.00
6.	Channel cover factor	0.800	0.001–1.00
7.	Mannings '*n*' value for the main channels	0.190	0.01– 0.30
8.	Mannings '*n*' value for the tributary channels	0.210	0.01–30.00

Model calibration and validation

The parameters used for model calibration are presented in Table 3. Model was calibrated using land use/land cover data of the year 1998. Statistical parameters of runoff and sediment yield as obtained from calibration of the model are presented in Table 4. It was observed that time of occurrence of simulated and measured peak runoff matched together in the entire season, whereas the peak runoff and sediment rates were slightly over predicted by the model. Daily observed and simulated values of runoff and sediment yield were plotted and their distribution along with 1:1 line presented in Fig. 4a, b. It was observed that simulated values were uniformly distributed about 1:1 line. Regression analysis shows the best-fit relation between the observed and simulated sediment yield values. The coefficient of determination (r^2) was found to be 0.77, which shows close agreement between observed and simulated runoff. Fohrer et al. (2001) also reported that the correlation between measured and simulated stream flow data for the Dietzholze watershed was 0.91 for the calibration period and 0.93 for validation, respectively. Model simulation efficiency (E_{NS}) for observed and simulated runoff

Table 4 Statistical parameters of runoff as obtained from calibration and validation of the model

Statistical parameters	Runoff (mm)				Sediment yield (t/ha)			
	Calibration		Validation		Calibration		Validation	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
Mean	2.21	2.33	2.70	3.11	0.011	0.012	0.01	0.02
Standard deviation	3.59	4.67	6.15	7.60	0.030	0.032	0.04	0.04
Maximum peak	20.74	34.45	43.80	54.84	0.28	0.270	0.31	0.29
Total	268.99	284.12	329.92	378.90	1.30	1.430	1.73	1.84
Sample size	122	122	122	122	122	122	122	122
t calculated	−0.23		−0.45		−0.21		−0.18	
t critical (two tail)	1.97		1.97		1.97		1.97	
D_v (%)	−5.62		−14.85		−7.61		−6.47	
r^2	0.77		0.83		0.89		0.85	
E_{NS}	0.70		0.79		0.87		0.84	

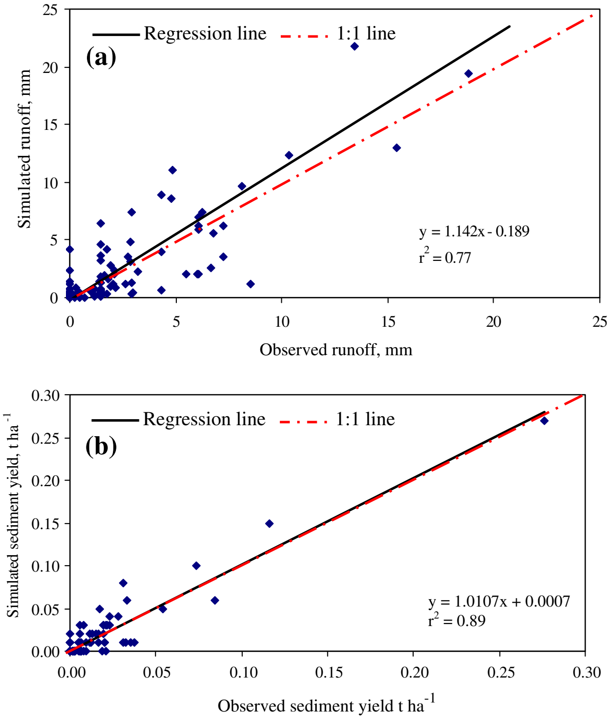

Fig. 4 **a** Comparison between observed and simulated daily runoff for model calibration (June to September 1998). **b** Comparison between observed and simulated daily sediment yield for model calibration (June to September 1998)

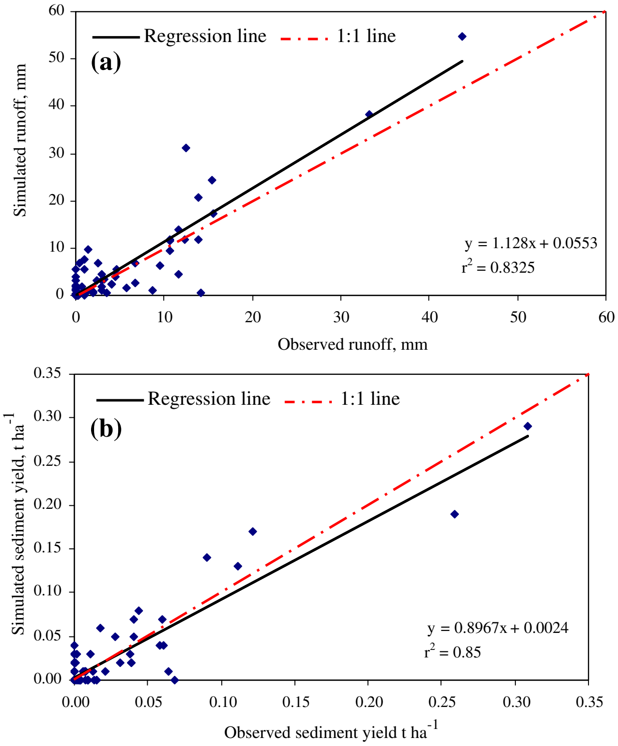

Fig. 5 **a** Comparison between observed and simulated daily runoff for model validation (June to September 2000). **b** Comparison between observed and simulated sediment yield for model validation (June to September 2000)

and sediment was found to be 0.70 and 0.87, respectively. Srinivasan et al. (1998) reported the similar trend of E_{NS} on monthly time step for two American mesoscale watersheds. Comparison of observed and predicted sediment yield using student's t test was not differing significantly at 95% confidence level.

For model validation, rainfall and temperature data of 2000 were taken and remaining input variables were used as such. Statistical parameters of runoff and sediment yield as obtained from validation of the model are presented in Table 4. Observed daily runoff and sediment yield were compared with the simulated values of monsoon season of the year 2000. Distribution of daily runoff and sediment yield along with 1:1 line is presented in Fig. 5a, b. It was observed that the modeled values of runoff and sediment yield are uniformly distributed about 1:1 line. The values of r^2 were found to be 0.89 and 0.85, which show close agreement between the observed and simulated runoff and sediment yield. Comparison of mean using student's t test shows that the mean values of observed and predicted runoff and sediment yield were not differing significantly at 95% confidence level. E_{NS} of 0.79 and 0.84 shows a close agreement between the measured and simulated values of runoff and sediment yield, respectively.

To examine the accuracy of seasonal phenomenon on a long-term basis, the model validation performance was also evaluated on monthly basis for monsoon season of 5 years (1993–1997) using graphical as well as statistical methods. Monthly hydrographs showed that most of the time the model predicted surface runoff and sediment yield matched with its corresponding observed values during monsoon season. A scattergram along 1:1 line between the observed and simulated monthly runoff and sediment yields was uniformly distributed throughout the validation period in Fig. 6a, b. The mean of observed (0.53 t/ha) and simulated (0.59 t/ha) monthly sediment yields was statistically similar at 95% confidence level (t calculated $= -0.40$ and t critical $= 2.02$). The results of the statistical analysis of the measured and simulated monthly surface runoff and sediment yield are summarized in Table 5.

Identification and prioritization of the critical sub-watersheds

The critical sub-watersheds in the present study were identified on the basis of average annual sediment yield and nutrient losses from the sub-watersheds during the period of 1999 to 2001. In this context, annual sediment yields were simulated for each sub-watershed and priorities were fixed on the basis of ranks assigned to each critical

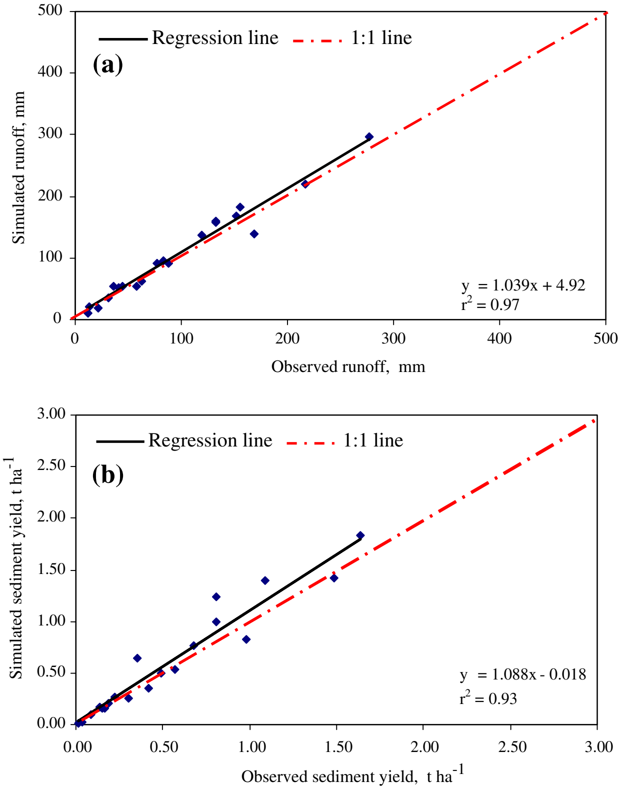

Fig. 6 **a** Comparison between observed and simulated daily runoff for model validation (monsoon season 1993–1997). **b** Comparison between observed and simulated sediment yield for model validation (monsoon season 1993–1997)

Table 5 Statistical analysis of monthly observed and simulated runoff and sediment yield (1993–1997)

Statistical parameters	Runoff (mm)		Sediment (t/ha)	
	Observed	Simulated	Observed	Simulated
Mean	96.12	104.86	0.53	0.59
Standard deviation	071.96	75.94	0.48	0.54
Maximum	276.60	298.29	1.64	1.84
Total	1,922.54	2,097.14	10.60	11.89
Sample size	20	20	20	20
t calculated	−0.37		−0.40	
t critical (two-tail)	2.02		2.02	
r^2	0.97		0.93	
D_v (%)	−9.08		−12.16	
E_{NS}	0.95		0.89	

sub-watershed according to ranges of soil erosion classes described by Singh et al. (1992). From the point of view of nutrient losses, the threshold values 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.

Evaluation of BMPs for prioritized sub-watersheds

For the evaluation of the management scenarios of the prioritized sub-watersheds, the recorded rainfall and temperature data for the year 1999 through 2001 were used. Several simulations were performed considering 180 combinations of six tillage practices, six crops, and five fertilizer doses as management treatments. On the basis of the available field data and existing practices of cultivation, communication with the farmers, scientist and district agricultural development officers, the treatments of watershed were decided for evaluating the BMP.

Tillage implements and crops considered for effective management

Six tillage treatments (zero tillage, conservation tillage, field cultivator, moldboard plough, conventional tillage, and disc plough) were considered in the present study. Tillage treatments and their respective mixing efficiencies were considered as suggested by Neitsch et al. (2001). The mixing efficiency for country plough (conventional tillage) was determined on the basis of other tillage implements. Rice is the predominant crop covering about 59% of the total area of the watershed. Groundnut, maize, mungbean, sorghum, and soybean are some of the other crops grown in few pockets of the up lands during monsoon season. Crops along with their fertilizer levels considered for the evaluation of management scenarios are presented in Table 6.

Fertility status of the soils of the watershed

The fertility status of all the soils in the watershed was low in terms of availability of N, P_2O_5 and K_2O. Aerobic nitrogen is present in the soil predominantly in the form of nitrate (NO_3). In semi-wet situations with intermittent aerobic and anaerobic conditions, leaching and denitrification of NO_3 further deplete N status. The availability of phosphorus is limited due to fixation in acidic soils. Most of the upland soils are inherently poor in fertility. Organic manure in conjunction with different chemical sources of nutrients for various crops was evaluated to identify suitable combinations to maintain soil fertility and productivity on a sustainable basis under various tillage practices.

Results and discussion

Identification and prioritization of critical sub-watersheds

The annual sediment and nutrient losses were simulated for each sub-watershed (Table 7). The critical sub-watersheds

Table 6 Level of N and P of various crops considered for management

Crops	Fertilizer treatment codes and cropwise level of N:P (kg/ha)				
	FR1	FR2	FR3	FR4	FR5
Groundnut (*Archis hypogaea*)	10:20	20:40	20:20	30:60	40:80
Maize (*Zea mays*)	20:15	50:30	75:45	100:60	120:80
Mungbean (*Phaseolus aureus*)	10:20	20:30	25:30	30:40	60:60
Rice (*Oryza sativa*)	25:15	40:30	50:40	80:60	120:80
Sorghum (*Sorghum bicolor)*	10:20	20:20	30:30	40:40	60:60
Soybean (*Glycine max*)	10:20	30:30	45:45	60:60	80:80

FR1 25:15 kg/ha of N:P, *FR2* 40:30 kg/ha of N:P, *FR3* 50:40 kg/ha of N:P, *FR4* 80:60 kg/ha of N:P, *FR5* 120:80 kg/ha of N:P

were identified and prioritized on the basis of actual sediment rate and nutrient losses. All the eight sub-watersheds fell under slight soil loss group of soil erosion classes (0 to 5 t/ha per year) as described for Indian conditions (Singh et al. 1992). None of the sub-watersheds fell under high, very high, severe, or very severe erosion classes. This may be due to the fact that the study watershed is having an average slope of 2.46% only. The study watershed might have got stabilized, as various engineering measures of soil conservation already exist in the watershed. However, the sub-watershed SWS2 yielded maximum sediment. This may be due to more average surface slope of 3.22% with undulating topography as compared to other sub-watersheds. In view of annual soil loss, runoff and nutrient losses, sub-watersheds were considered for execution of the conservation measures as per erosion potential order to reduce the sediment and nutrient losses.

Simulation of nutrient losses

The performance of the SWAT model for its nutrient loss prediction was evaluated through comparison between the observed and simulated values of 11 events. Statistical analyses of the observed and simulated nutrient losses are presented in Table 8. For the selected events of 2000 it was observed that NO_3–N values were over predicted by the model. The observed and simulated mean NO_3–N showed a close agreement at 95% level of confidence since *t* calculated (−0.32) was found to be less than *t* critical (2.09). The close agreement between the observed and simulated NO_3–N was also indicate by coefficients of the determination of 0.82. The observed and simulated values of NO_3–N were evenly distributed about the 1:1 line as presented in Fig. 7a. However, statistical comparisons indicated that model predicts NO_3–N within the acceptable level of accuracy.

The comparison between the observed and simulated values of organic N reveals that the simulated values of organic N were in close agreement with the observed values. It was also noted that the observed and simulated organic N values were uniformly distributed about 1:1 line (Fig. 7b). The observed and simulated mean organic N indicated a close agreement at 95% level of confidence since *t* calculated (−0.29) was found to be less than *t* critical (2.09). The coefficients of the determination of 0.84 also indicated the close relationship between the observed and simulated values of organic N. However, statistical comparisons indicated that model predicts organic N within the acceptable level of accuracy.

The comparison between the observed and simulated values of soluble P revealed that the simulated values of

Table 7 Average annual output of the model for identification of criticalsub-watersheds (1999–2001)

Sub-watershed	Area (km^2)	Runoff (mm)	Sediment (t/ha)	NO_3–N (kg/ha)	Organic N (kg/ha)	Soluble P (kg/ha)	Organic P (kg/ha)
SWS1	10.47	327.04	1.75	0.96	2.02	0.58	1.04
SWS2	07.91	270.72	2.41	0.75	2.70	0.48	1.38
SWS3	10.88	296.48	1.87	0.83	2.15	0.52	1.10
SWS4	11.90	317.77	1.99	0.91	2.28	0.56	1.17
SWS5	10.97	269.79	1.90	0.75	2.18	0.48	1.11
SWS6	15.02	312.93	1.85	0.95	2.13	0.57	1.09
SWS7	11.14	329.55	1.74	0.98	2.02	0.59	1.03
SWS8	10.47	294.26	1.45	0.86	1.69	0.54	0.86

Table 8 Statistical analyses of the observed and simulated nutrient losses

Statistical parameters	NO_3–N		Organic N		Soluble P		Organic P	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
Mean (kg/ha)	0.042	0.046	0.080	0.091	0.026	0.030	0.010	0.009
Std. dev. (kg/ha)	0.032	0.038	0.070	0.104	0.024	0.035	0.008	0.010
Maximum (kg/ha)	0.096	0.120	0.246	0.320	0.083	0.120	0.025	0.030
Sum (kg/ha)	0.458	0.510	0.876	1.000	0.284	0.330	0.109	0.100
Count	11	11	11	11	11	11	11	11
t calculated	−0.320		−0.290		−0.330		0.190	
t critical	2.090		2.090		2.090		2.090	
r^2	0.820		0.840		0.810		0.820	
RMSE (kg/ha)	0.016		0.047		0.017		0.004	
D_v (%)	−11.450		−14.160		−16.360		7.830	

soluble P were in close agreement with the observed values. It was noted that the observed and simulated soluble P were evenly distributed about the 1:1 line (Fig. 7c). The means of observed and simulated soluble P was not significantly different at 95% confidence level, since the *t* calculated (−0.33) was less than the *t* critical (2.09) The coefficients of determination of 0.81 indicated close agreement between the observed and simulated values. However, statistical comparisons indicated that model predicts soluble P within the acceptable level of accuracy. It was observed that the model was over as well as under predicting organic P for the selected events.

The observed and simulated values of organic P were uniformly distributed about 1:1 line as presented in Fig. 7d.

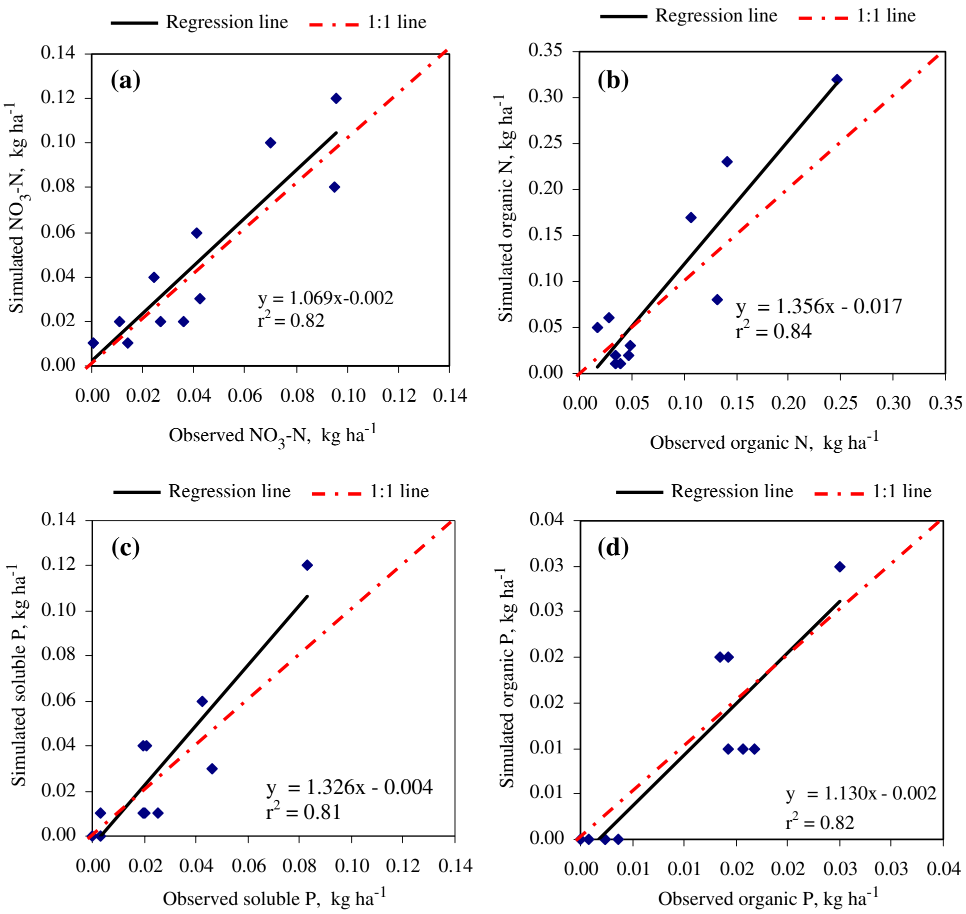

Fig. 7 Comparison of observed and simulated NO_3–N, Soluble P, Organic N and Organic P

The observed and simulated mean organic P were not significantly different at 95% confidence level, since the *t* calculated (0.19) was less than the *t* critical (2.09). The coefficients of determination 0.82 indicated close agreement between the observed and simulated organic P. However, statistical comparisons indicated that model predicts organic P within the acceptable level of accuracy.

The results revealed that dissolved nutrients (NO_3–N and soluble P) losses were within the permissible limit (EPA 1976; Tim et al. 1992). Annual losses of nutrients attached with sediment were found to be more in the case of SWS2 as compare to other sub-watersheds (Table 7). On the basis of annual sediment yield and nutrient losses, the sub-watersheds were prioritized in order to SWS2, SWS4, SWS5, SWS3, SWS6, SWS1, SWS7 and SWS8 and considered for developing best management plan for further conservation of soil and nutrient.

Effective management

It was observed that all the sub-watersheds yielded sediment and nutrients losses within the permissible limit (Mannering 1981; EPA 1976; Tim et al. 1992). However, it was hypothesized that in future it is possible to increase the sediment as well as nutrients losses from all the sub-watersheds if proper conservation measures will not be adopted. It was also hypothesized that agronomic measures would be sufficient enough to further bring down the sediment and nutrients losses. To make sure that the nutrients losses should not exceed the permissible limit in future, the management impact and effect of change of inorganic fertilizer was also analyzed.

Considering six tillage treatments [ZT = zero tillage, CT = conservation tillage, FC = field cultivator, MP = moldboard plough, CP = conventional tillage (country plough), DP = disc plough]; five fertilizer treatments [FR1 = (25:15 kg/ha of N:P), FR2 = (40:30 kg/ha of N:P), FR3 = (50:40 kg/ha of N:P), FR4 = (80:60 kg/ha of N:P), FR5 = (120:80 kg/ha of N:P)] and six crops, a total of 180 combinations of the different treatments were taken for the management evaluation of the sub-watersheds. Various model simulations were performed for the period of 1999–2001 using calibrated and validated SWAT2000. A sample sub-watershed SWS4 located in almost middle of the study watershed was selected to examine the effect of different management treatments. It was assumed that as sub-watershed SWS4 is located centrally, it would be the appropriate representation of the whole watershed.

Fertilizer and tillage effect on crop yield, runoff, sediment yield and nutrients losses

As compared to rice, other crops such as groundnut, maize, mungbean, sorghum, and soybean reduced the runoff by 0.83, 4.34, 1.47, 4.34 and 1.47%, respectively (Table 9). Similarly in comparison to rice, sediment yield was increased by 181.28, 83.96, 108.56, 83.93 and 108.56% from groundnut, maize, mungbean, sorghum, and soybean, respectively. On the basis of these results, it was concluded that rice could not be replaced by any other crops from sediment yield point of view. It was, therefore, decided to consider rice only for further analysis. The effect of different tillage and fertilizer treatments on crop yield, runoff, sediment yield, and nutrients losses under rice crop was also performed. The simulation results are presented in Table 10.

Graphical representation of various tillage and fertilizer treatments and their effects on sediment yield along with runoff and rice crop yield are shown in Figs. 8 and 9, respectively. It was found that runoff and sediment yield were not affected due to change in fertilizer doses, whereas both were influenced by tillage treatments. In comparison to conventional tillage, maximum increase in runoff was obtained in the case of zero tillage (7.83%) followed by field cultivator (5.78%) and maximum reduction in runoff was noticed in the case of disk plough (7.93%) followed by moldboard plough (6.14%) and conservation tillage (3.67%). Disk plough and moldboard plough yielded about 22 and 15% more sediment, respectively, as compare to

Table 9 Effect of crops on average annual yields under existing tillage practices and fertilizer level during monsoon season of 1999–2001

Crop	Runoff (mm)	Sediment (t/ha)	NO_3–N (kg/ha)	Organic N (kg/ha)	Soluble P (kg/ha)	Organic P (kg/ha)	Crop yield (t/ha)
G-nut	299.78	5.26	0.83	5.33	0.40	2.72	1.50
Maize	289.18	3.44	0.82	3.11	0.22	0.49	1.38
M-bean	297.86	3.90	0.82	4.15	0.37	2.23	1.47
Rice	302.32	1.87	0.87	2.15	0.54	1.10	1.89
Sorghum	289.18	3.44	0.83	3.82	0.45	0.45	1.38
Soybean	297.86	3.90	0.82	4.15	0.37	2.23	1.74

G-nut groundnut, *M-bean* Mungbean

Table 10 Effect of various tillage and fertilizer level on sub-watershed (SWS4) yield simulated by model for monsoon seasons of 1999–2001

Treatments	Runoff (mm)	Difference (%)	Sediment (t/ha)	Difference (%)	Rice yield (t/ha)	Difference (%)	NO_3–N (kg/ha)	Difference (%)	Organic N (kg/ha)	Difference (%)	Soluble P (kg/ha)	Difference (%)	Organic P (kg/ha)	Difference (%)
ZT + FR1	342.65	7.83	1.77	−11.06	1.82	−0.55	0.82	−9.89	2.04	−10.53	0.54	−3.57	1.02	−12.82
CT + FR1	306.10	−3.67	1.89	−5.03	1.87	2.19	0.87	−4.40	2.17	−4.82	0.55	−1.79	1.10	−5.98
FC + FR1	336.12	5.78	2.15	8.04	1.84	0.55	0.98	7.69	2.45	7.46	0.60	7.14	1.24	5.98
MP + FR1	298.26	−6.14	2.29	15.07	1.88	2.73	1.04	14.29	2.61	14.47	0.53	−5.36	1.36	16.24
CP + FR1	317.77	0.00	1.99	0.00	1.83	0.00	0.91	0.00	2.28	0.00	0.56	0.00	1.17	0.00
DP + FR1	292.55	−7.93	2.43	22.11	1.86	1.64	1.13	24.18	2.71	18.86	0.67	19.64	1.44	23.08
ZT + FR2	342.65	7.83	1.77	−11.06	2.23	0.91	0.93	−9.71	2.21	−9.43	0.88	1.15	0.98	−14.03
CT + FR2	306.10	−3.67	1.89	−5.03	2.26	2.26	0.99	−3.88	2.33	−4.52	0.88	1.15	1.07	−6.14
FC + FR2	336.12	5.78	2.15	8.04	2.24	1.36	1.13	9.71	2.63	7.78	0.95	9.19	1.21	6.14
MP + FR2	298.26	−6.14	2.29	15.07	2.27	2.72	1.19	15.54	2.75	12.70	0.86	−1.15	1.35	18.42
CP + FR2	317.77	0.00	1.99	0.00	2.21	0.00	1.03	0.00	2.44	0.00	0.87	0.00	1.14	0.00
DP + FR2	292.55	−7.93	2.43	22.11	2.22	0.45	1.34	30.10	2.90	18.84	1.05	20.69	1.42	24.56
ZT + FR3	342.65	7.83	1.77	−11.06	2.43	−0.33	1.08	−10.00	2.40	−7.34	1.31	3.97	0.94	−15.32
CT + FR3	306.10	−3.67	1.89	−5.03	2.45	0.41	1.15	−4.17	2.50	−3.47	1.29	2.39	1.03	−7.21
FC + FR3	336.12	5.78	2.15	8.04	2.44	0.00	1.33	10.83	2.81	8.49	1.39	10.32	1.17	5.41
MP + FR3	298.26	−6.14	2.29	15.07	2.48	1.64	1.40	16.66	2.86	10.42	1.21	−3.96	1.34	20.72
CP + FR3	317.77	0.00	1.99	0.00	2.44	0.00	1.20	0.00	2.59	0.00	1.26	0.01	1.11	0.00
DP + FR3	292.55	−7.93	2.43	22.11	2.47	1.23	1.51	25.83	3.05	17.76	1.31	3.97	1.40	26.13

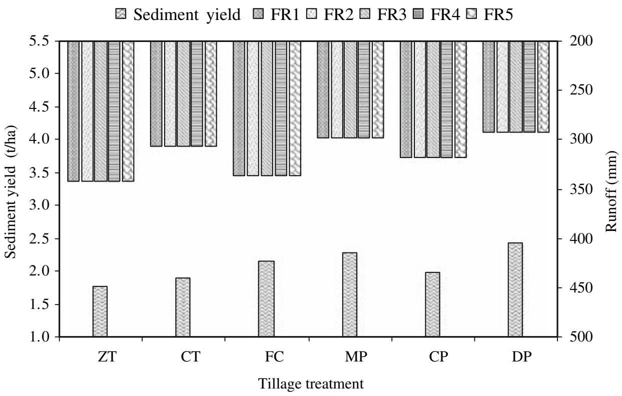

Fig. 8 Effect of tillage on sediment yield and runoff (1999–2001)

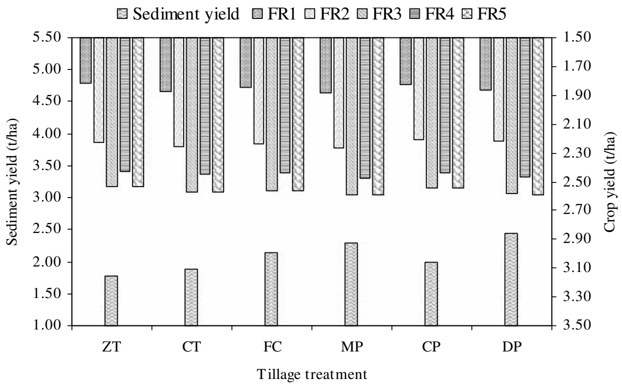

Fig. 9 Effect of tillage on sediment and rice yield (1999–2001)

conventional tillage irrespective of the fertilizer level. As compared to the conventional tillage, the sediment yield for zero tillage and conservation tillage were found to be 11.06 and 5.03% less, respectively, whereas the same was 8.04% more in the case of field cultivator. It was observed that the tillage having higher mixing efficiency produced higher sediment yield. The mixing efficiency plays a major role in mixing-up fertilizer and residue during initial crop growth stage.

It was noted that the yield of rice increased with the increase of fertilizer doses. No difference in the rice yield was observed under fertilizer treatments (80:60 kg/ha of N:P) and (120:80 kg/ha of N:P). While considering tillage treatments, the increase in the maximum rice yield was observed in the case of moldboard plough (up to 2.73%) followed by conservation tillage (up to 2.26%), disk plough (up to 1.97%) and field cultivator (up to 1.36%) as compared to conventional tillage for all the fertilizer levels. The difference in rice yield was not significant among the tillage treatments. Evenly distributed rainfall during the simulation period might have neutralized the tillage impact on rice yield as rainfall distribution is one of the important factors for rice cultivation during monsoon season.

Effect of tillage on nutrient losses

Nitrate nitrogen (NO_3–N) in runoff

An attempt was made to assess the effect of different levels of fertilizer with various tillage options on NO_3–N losses. The results obtained from simulation run were analyzed and presented in Fig. 10a. The increase in fertilizer dose increases the loss of NO_3–N with all the tillage treatments. In comparison to conventional tillage, lowest NO_3–N loss was observed in zero tillage (up to 10.78%) followed by conservation tillage (up to 4.91%) in all the fertilizer treatments, whereas field cultivator, moldboard plough and disk plough resulted increase in NO_3–N loss up to 14.22, 18.96, and 44.79%, respectively. The findings are in conformity with the findings of McDowell and McGregor (1984), Alberts and Spomer (1985), and Tripathi (1999). The researchers reported that the concentrations of dissolved N in surface runoff from soil under conservation tillage often are higher than conventional tillage. In the present study, the NO_3–N losses were found to be lower in the case of conservation tillage and higher in the case of field cultivator as compared to conventional tillage.

Soluble phosphorous in runoff

The effect of fertilizer and tillage treatments on soluble P loss through runoff was also examined using the model simulation (Fig. 10b). Soluble P loss increased as fertilized doses increased. Maximum loss of soluble P was observed in the case of 120:80 kg/ha of N:P followed by 80:60 kg/ha of N:P, 50:40 kg/ha of N:P, and 40:30 kg/ha of N:P fertilizer doses. The minimum soluble P loss was noticed in conventional dose of fertilizer treatment (25:15 kg/ha of N:P). As compared to conventional tillage, the losses of soluble P were increased from 19 to 40% with disk plough and decreased up to 14% with moldboard plough. It shows that moldboard plough inverse and pulverizes the soil properly and mixed up the surface applied phosphorous thoroughly and thereby it is not available on top surface to be dissolved in surface runoff. The availability of phosphorous was limited due to fixation, as the acidic nature of the soils existed in the watershed. The poor availability of phosphorous in the watershed resulted soluble P losses within the permissible limit.

Organic nitrogen and organic phosphorous in sediment

The productivity of the soil can be enhanced by incorporation of organic fertilizers. It also helps in minimizing the requirement of inorganic fertilizers. The effect of different

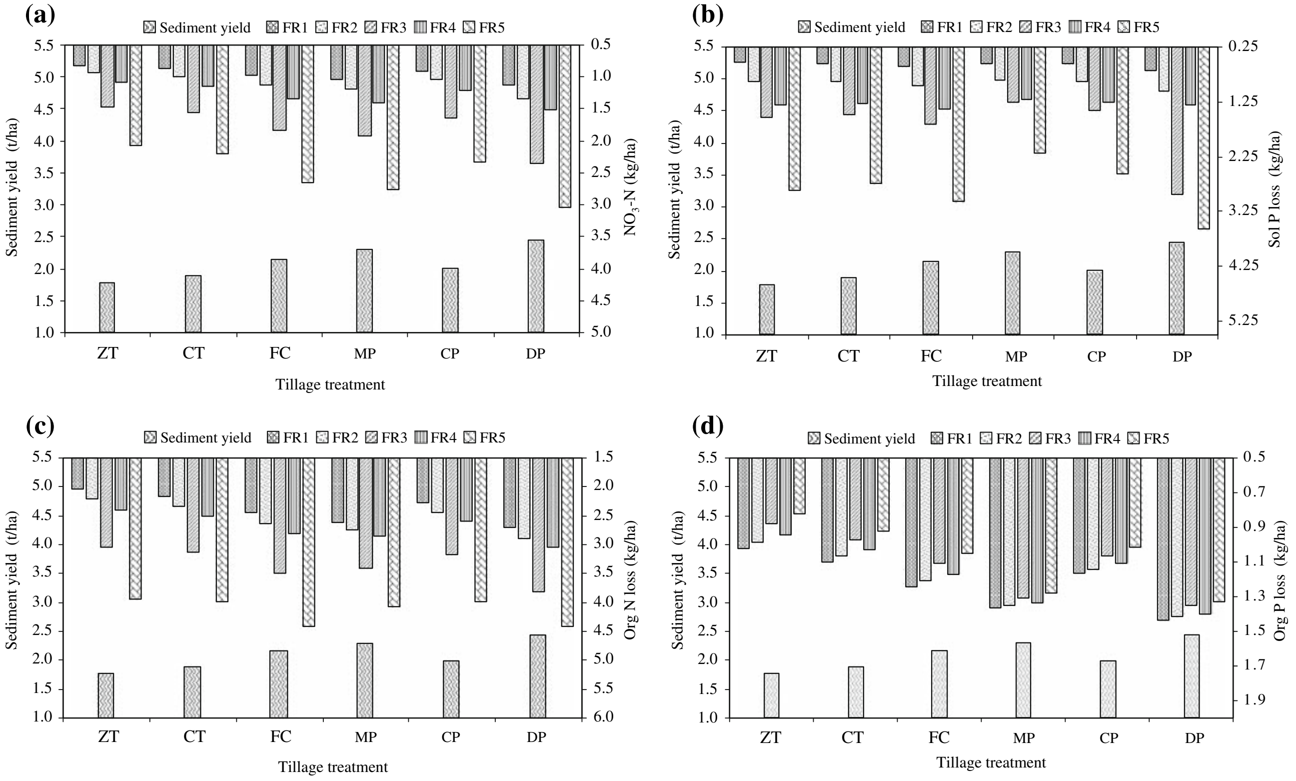

Fig. 10 Effect of tillage on sediment yield for NO3–N, Soluble P, Organic N and Organic P (1999–2001)

tillage implements application on organic N and organic P was analyzed. The amount of N and P in total quantum applied in the form of inorganic fertilizer and obtained from the organic manure was given as input to the model through management file. The initial concentrations of organic nitrogen and phosphorous in the top soil layer of the watershed were given to the model through the chemical file to see the effect of organic N and P on sediment yield.

The similar trend towards losses of organic N and P present in the sediment for different tillage operations was observed and presented in Fig. 10c, d. As the fertilizer does increased, loss of organic N was also increased. As compared to conventional tillage treatment, lowest percent loss of organic N was observed in zero tillage with the conventional does of fertilizer (25:15 kg/ha of N:P), whereas it was found to be highest in the case of disk plough with the application of 80:60 kg/ha of N:P. After zero tillage, the conservation tillage performed better in all the fertilizer treatments. The maximum loss of organic P was obtained in the case of disk plough whereas it was minimum in the case of zero tillage followed by conservation tillage for all level of fertilizer treatments. As the fertilizer doses increased the organic P decreased, this might be because of reduction in immobilization due to additional fertilizer. However, in the case of nitrogen, organic N was found to be enhanced with the increase of fertilizer doses, which might be due to higher rate of mineralization.

It was inferred from overall scenarios of the aforementioned analysis that minimum sediment loss was observed in zero tillage for each fertilizer level. As the framers in the study watershed commonly adopt transplanting system of rice cultivation, zero tillage is hardly practiced. Very small difference in sediment loss in the case of conservation tillage and conventional tillage was observed. The conventional tillage is better from farmers' affordability point of view. The conservation tillage could be used in place of existing conventional tillage, as it reduces the average sediment yield by about 5% as compared to conventional tillage for each fertilizer doses. The conservation tillage considerably reduces losses of NO_3–N, organic N, organic P and soluble P also. Thus, conventional tillage needs to be replaced by improved tillage practices like conservation tillage thereby enhancing overall productivity of the soil. The recommended doses of fertilizer (80:60 kg/ha of N:P) can increase the rice yield satisfactorily as compared to other fertilizer treatments with losses of nutrients within the acceptable limit. The higher doses of fertilizer (120:80 kg/ha of N:P) may not be recommended because it could not produce economically higher yield even the nutrient losses were found to be within the permissible limit.

Conclusions

Physically based model SWAT2000 was calibrated and validated for runoff and sediment yield prediction from Banikdih agricultural watershed in Eastern India. The model's ability to simulate the number of different processes and its link with ArcView GIS have a great potential as a tool for predicting the runoff and sediment yield. The sensitivity analysis of the model input parameters revealed that sediment yield was sensitive to Manning's '*n*' for overland flow, tributary channel flow, and hydraulic conductivity of tributary channel alluvium whereas runoff was not much sensitive to the aforesaid parameters. The model accurately simulates runoff, sediment yield and nutrient losses of the study watershed on daily, monthly and seasonal basis, and can successfully be used for identifying critical sub-watersheds for developing BMP. Keeping nutrient losses within the permissible limit, conservation tillage practice along with 80:60 kg/ha of N:P can be recommended to reduce the sediment yield by about 5% as compared to conventional tillage. The rice crop cannot be replaced by crops such as groundnut, maize, mungbean, sorghum and soybean during monsoon season in view of sediment and nutrient losses. The modeling approach can be extended for hydrologic evaluation of Indian watersheds under similar hydrological conditions.

Acknowledgments The authors express their gratitude to the Ex-Head, Regional Remote Sensing Service Centre (RRSSC) (Department of Space, Govt. of India), Indian Institute of Technology, Kharagpur Center for providing necessary facilities for data analysis using GIS and Remote Sensing techniques. Thanks are also due to the Director of Soil Conservation, Damodar Valley Corporation, Hazaribagh, Jharkhand State for providing necessary data, technical advice and facilities for field survey from time to time.

References

Alberts EE, Spomer RG (1985) Dissolved nitrogen and phosphorus in runoff from watersheds in conservation and conventional tillage. J Soil Water Conserv 40(1):153–157

Arnold JG, Fohrer N (2005) SWAT2000: current capabilities and research opportunities in applied watershed modeling. Hydrol Process 19:563–572

Arnold JG, Williams JR, Srinivasan R, King KW (1996) SWAT: soil and water assessment tool. User's Manual USDA Agriculture Research Service Grassland, Soil and Water Research Laboratory, 808 East Blackland Road Temple, TX 76502, p 190

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment, part I: Model development. J Am Water Resour Assoc 34(1):73–89

Arnold JG, Srinivasan R, DiLuzio M, Neitsch SL (2001) SWAT2000-Capabilities and improvements in watershed modeling. In: Proceeding of the 'international SWAT conference', 13–17 August 2001, SFB 299 and Justus-Liebig-University Giesen, Germany, pp 9–10

ASCE Task Committee (1993) Criteria for evaluation of watershed models. J Irrig Drain Eng 119(3):429–442

Beasley DB, Huggins LF, Monke EJ (1980) ANSWERS: a model for watershed planning. Trans ASAE 23(4):938–944

Behera S, Panda RK (2006) Evaluation of management alternatives for an agricultural watershed in a sub-humid subtropical region using a physical process based model. Agric Ecosyst Environ 113:62–72

Bhuyan SJ, Koelliker JK, Marzen LJ, Harrington Jr JA (2003) An integrated approach for water quality assessment of a Kansas watershed. Environ Model Softw 18(5):473–484

Bingner RL, Murphee CE, Mutchler CK (1989) Comparison of sediment yield models on various watershed in Mississippi. Trans ASAE 32(2):529–534

Bingner RL, Garbrecht J, Arnold JG, Srinivasan R (1997) Effect of watershed sub division on simulation of runoff and finer sediment yield. Trans ASAE 40(5):1329–1335

Brannan KM, Mostaghimi S, McClellan PW, Inamdar S (2000) Animal waste BMP impacts on sediment and nutrient losses in runoff from the OWL Run watershed. Trans ASAE 43(5):155–1166

Dickinson WT, Rudra RP, Wall GJ (1990) Targeting remedial measures to control nonpoint source pollution, Water Resour Bull 26(3):99–507

DiLuzio M, Srinivasan R, Arnold JG (2001a) Application of AVSWAT for a TMDL case in central Texas. In: Proceeding of the 'international SWAT conference', 13–17 August 2001, SFB 299 and Justus-Liebig-University Giesen, Germany, pp 12–13

DiLuzio M, Srinivasan R, Arnold JG (2001b) ArcView interface for SWAT 2000. User's Guide, Backland Research Center, Agricultural Experiment Station Temple, TX

Duda AM (1993) Addressing non-point sources of water pollution must become an international priority. Water Sci Technol 28(3–5):1–11

Eckhardt K, Arnold JG (2001) Automatic calibration of a distributed catchment model. J Hydrol 251(1–2):103–109

Engel BA, Srinivasan R, Arnold JG, Rewerts C, Brown SJ (1993) Nonpoint source pollution modeling using model integrated with geographical information systems. Water Sci Technol 28(3–5):685–690

EPA (1976) Quality criteria for water. Environmental Protection Agency, Washington, DC

ESRI (1994) Arc View GIS Environment System Research Institute. ESRI Inc., USA

Fohrer N, Eckhardt K, Haverkamp S, Frede HG (1999) Effects of land use changes on the water balance of rural a watershed in a peripheral regional. J Rural Eng Develop 40(5–6):202–206

Fohrer N, Haverkamp S, Eckhardt K, Frede HG (2001) Hydrologic response to land use changes on the catchmant scale. Phys Chem Earth B 26(7–8):577–582

Ghidey F, Alberts EE (1996) Comparison of measured and WEPP predicted runoff and soil loss for Midwest Claypan Soil. Trans ASAE 39(4):1395–1402

Hargreaves GH, Samani ZA (1985) Reference crop evapotranspiration from temperature. J Appl Eng Agric 1(1):96–99

Humenik FJ, Semolen MD, Dressing SA (1987) Pollution from nonpoint sources: where we are and where we should go. Environ Sci Technol 21(8):737–742

Manguerra HB, Engle BA (1998) Hydrological parameterization of watershed for runoff prediction using SWAT. J Am Water Resour Assoc 34(3):1149–1162

Mannering JV (1981) The use of soil tolerances as strategy for soil conservation. In: Morgan RPC (ed) Soil conservation problem and prospects. Wiely, Chichester, pp 337–349

Martinec J, Rango A (1989) Merits of statistical criteria for the performance of hydrologic models. Water Resour Bull 25(20):421–432

McDowell LL, McGregor KC (1984) Plant nutrient losses in runoff from conservation tillage on corn. Soil Tillage Res 4:79–91

Mostaghimi S, Park SW, Cooke RA, Wang SY (1997) Assessment of management alternatives on a small agricultural watershed. Water Res 31(8):1867–1878

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models. Part I: a discussion of principals. J Hydrol 10(3):282–290

Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2001) Soil and water assessment tool, theoretical documentation. Soil and Water Research Laboratory, Agricultural Research Service, Grassland, 808 East Blackland Road, Temple, TX, USA

Olivera F (2001) Extracting hydrologic information from spatial data for HMS modeling. J Hydrol Eng 6(6):524–529

Pandey VK, Panda SN, Sudhakar S (2005) Modelling of an agricultural watershed using remote sensing and a geographic information system. Biosyst Eng 90(3):331–347

Peterson JR, Hamlett JM (1998) Hydrological calibration of SWAT model in a watershed containing Fragipan soils. J Am Water Resour Assoc 34(5):531–544

Ritter WF (2000) BMPs to Reduce Nutrient Loads in Delaware's Inland Bays. In: Proceedings of ASCE, EWRI, watershed management 2000: Science and Engineering Technology for the New Millennium

Saleh A, Arnold JG, Gassman PW, Hauck LM, Rosenthal WD, Williams JR, McFarland AMS (2000) Application of SWAT for the Upper North Bosque river watershed. Trans ASAE 43(5):1077–1087

Santhi C, Arnold JG, Williams JR, Dugas WA, Srinivasan R, Hauck LM (2001) Validation of the SWAT model on a large river basin with point a non point sources. J Am Water Resour Assoc 37(5):1169–1170

Santhi C, Srinivasan R, Arnold JG, Williams JR (2006) A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. Environ Model Softw 21:1141–1157

Shin-Min C, Ting-Kuei T, Stephan JN (2002) Hydrologic regionalization of watersheds I: Methodology development. J Water Resour Plan Manag 128(1):3

Singh G, Babu R, Narayan P, Bhushan LS, Abrol IP (1992) Soil erosion rate in India. J Soil Water Conserv 47(1):97–99

Srinivasan R, Ramanarayan TS, Arnold JG, Bednarz ST (1998) Large area hydrologic modeling and assessment part II: Model application. J Am Water Resour Assoc 34(1):91–101

Tim US, Mostaghimi S, Shanholtz VO (1992) Identification of critical nonpoint pollution source areas using geographical information systems and water quality modeling. Water Resour Bull 28(5):877–887

Tripathi MP (1999) Hydrological modeling of effective management of a small watershed. Ph.D. thesis, Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur, India

Tripathi MP, Panda RK, Raghuwanshi NS, Singh R (2004) Hydrological modelling of a small watershed using generated rainfall in the soil and water assessment tool model. Hydrol Process 18:1811–1821

Tripathi MP, Panda RK, Raghuwanshi NS (2005) Development of effective management plan for critical subwatersheds using SWAT model. Hydrol Process 19:809–826

Turpin N, Bontems P, Rotillon G (2005) AgriWaterBMP: systems approach to environmentally sound farming. Environ Model Softw 20:187–196

Weber A, Fohrer N, Moller D (2001) Long term landuse changes in a mesoscale watershed due to socio-economic factors: effects on landscape structures and functions. Ecol Model 140:125–140

Williams JR, Hann RW (1973) HYMO: Problem-Oriented Language for Hydrologic Modelling, User's Manual. USDA, ARS-S-9, p 45

Williams JR, Berndt HD (1977) Sediment yields prediction based on watershed hydrology. Trans ASAE 20(6):1100–1104

Williams JR, Jones CA, Dyke PT (1984) A modeling approach for determining the relationship between erosion and soil productivity. Trans ASAE 27(1):129–144

Xevi EK, Christiaens A, Espino W, Sewanandan D, Mallants D, Sorensen H, Feyen J (1997) Calibration, validation and sensitivity analysis of MIKE-SHE model using Neuenkirchen Catchment Case Study. Water Resour Manage 11:219–242

Young RA, Onstad CA, Bosch DD, Anderson WP (1989) AGNPS: a nonpont source pollution model for evaluating agricultural watersheds. J Soil Water Conserv 44(2):168–173