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Research Paper :

Estimation of monthly surface runoff and sediment yield from a small watershed by using simulation technique

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ABSTRACT

The hydrological and meteorological data from 1991 to 2002 (12 years) observed at the outlet of Nagwan watershed in eastern India were collected for study. For the estimation of the monthly surface runoff and sediment yield from watershed, Soil and Water Assessment Tool (SWAT) model has been tested. The data like watershed and sub-watershed boundaries, drainage networks, slope, soil series and texture maps were generated using GIS utility of EASI-PACE. Supervised classification method was used for land use classification from a satellite image. The standard CN table for the Indian conditions was referred. Sub-watershed wise AMC-II CNs, Manning's roughness coefficient for overland flow and channel flow and the initial soil water storage were calibrated for monsoon season of the year 1996 and the model was validated for monsoon season of the year 1997. Various test criterions are used for calibration and validation of the SWAT model. The test results showed that the mean values of monthly observed and simulated runoff and sediment yield were not significantly different at 95 per cent of confidence level. The per cent deviation values for monthly surface runoff and sediment yield were found to be -6.2 and -13.65%, respectively during calibration, and 9.2 and -6.56 during validation, respectively, indicated the satisfactory prediction of monthly surface runoff and sediment yield by SWAT. Similarly, r^2 values for runoff and sediment yield were found to be 0.991 and 0.981, respectively during calibration and 0.965 and 0.904, during validation, respectively, indicated a good agreement between observed and simulated values of monthly surface runoff and sediment yield from the Nagwan watershed. The attempt was made to test the model performance for prediction of monthly surface runoff and sediment yield for the duration of five years (1998 to 2002). The means of observed and simulated monthly runoff and sediment yield were found to be similar at 95 per cent confidence level. The per cent deviation values obtained in simulation of monthly surface runoff and sediment yield during monsoon season were found to be -8.4 and 7.1 per cent, respectively. In general a close agreement was obtained between simulated and observed monthly values.

Key words : Runoff, Sediment yield, Sub-watershed, SWAT model, Calibration, Validation

The deterioration of natural resources in an area can be controlled effectively by adopting the watershed approach. Watershed, a geographically dynamic unit area that contributes runoff to a common point, has been accepted as a basic unit for planning and implementation of the protective, curative and ameliorative programmes. An accurate understanding of the hydrological behavior of a watershed is important for effective management. The processes like generation and transport of runoff and sediment from watersheds are included in Surface hydrologic modelling. The design of conservation structures require estimation of runoff and sediment yield to reduce the ill effect of sedimentation. This effort can be enhanced by the use of physically based computer simulation models, remote sensing data and GIS technique, which can assist management agencies in both identifying most vulnerable erosion prone areas and selecting appropriate management practices.

Numerous models such as ANSWERS (Beasley and Huggins, 1982), CREAMS (Knisel, 1980), EPIC (Williams *et al.*, 1984), AGNPS (Young *et al.*, 1987), SWARB (Williams *et al.*, 1985) and SWAT (Arnold *et al.*, 1996) have been developed to predict runoff, erosion, sediment and nutrient transport from agricultural watersheds under various management regimes. The management scenarios can also be developed to minimize surface runoff and sediment yield by identifying the critical erosion prone areas of the watershed.

Soil and Water Assessment Tool (SWAT) is the continuation of a long-term effort of non-point source pollution modelling by the USDA-Agricultural Research Service (ARS) at Temple Texas, USA. SWAT was obtained by adding a new routing structure of ROTO (Arnold *et al.*, 1995) to the SWRRB (Williams *et al.*,

1985) so as to remove the restriction of only being able to simulate less number of sub-watersheds as in the case of SWRRB. SWAT allows considerable flexibility in watershed decomposition.

Keeping the above facts in mind, the present study was undertaken with the use of a distributed parameter model 'SWAT', satellite data and a GIS technique. The major objective of this study was calibration and validation performance of the SWAT model for predicting the monthly surface runoff and sediment yield from the Nagwan watershed in eastern India.

METHODOLOGY

Study area:

The Nagwan watershed (92.46 km^2) of Upper Damoder Valley was choosen for the study which is located in Hazaribagh district of Jharkhand state in India. The Nagwan watershed lies between $85^0 25'$ to $85^0 43'$ E longitude and $23^0 99'$ to $24^0 12'$ N latitudes. The topography of the watershed was undulating and the average slope of the watershed was 2.3 per cent. Location map of the study area is shown in Fig. 1. The watershed receives an average annual rainfall of 1256 mm, out of which the monsoon season (June to October) contributes more than 80 % rainfall. The dominant soil of watershed was the silt loam.

Meteorological and hydrological data:

Historical daily and monthly rainfall, maximum and minimum temperature, wind velocity, relative humidity and sunshine hours data from 1991 to 2002 were collected from the Soil Conservation Department, Damoder Valley Corporation (DVC), Hazaribagh (Jharkhand state) for the preparation of weather generator input file of the model. Observed rainfall data of Nagwan watershed for the years 1996 and 1997 was used to prepare precipitation file in DOS editor. Similarly, monthly temperature data file was prepared to facilitate as input data file for the model. Monthly values of runoff and sediment yield observed at the outlet of the Nagwan watershed during the years 1991 to 2002 were also collected.

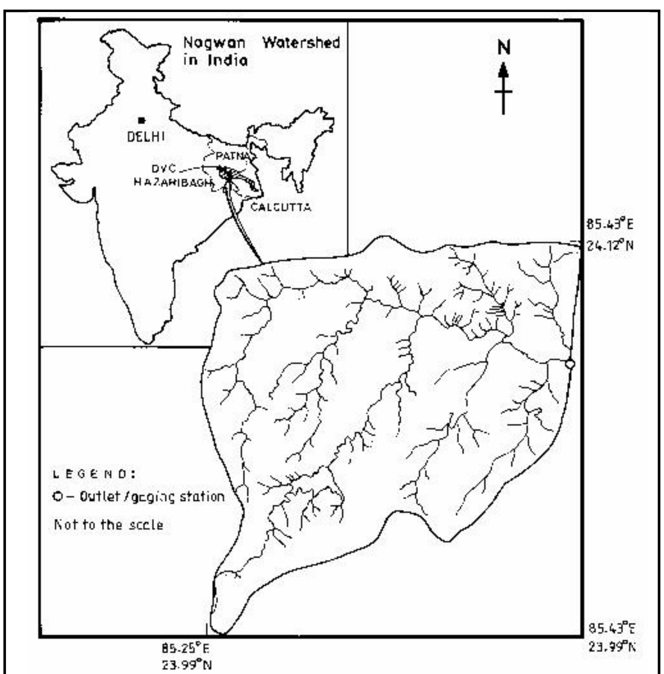

Fig. 1: Location map of the Nagwan watershed

Topographic, soil and land use data:

The Nagwan watershed is covered in the topographic map Nos. 73E/5 and 72H/8 on 1:50,000 scale, which were collected for use from Survey of India, Calcutta. Soil texture and soil series maps and soil resources data for all the soil series were used as reported by Tripathi *et al.* (2003). Land use map of the watershed for the year 1996, which was prepared by Tripathi *et al*. (2003) using a satellite imagery (date of pass: 19.08.1996) of IRS-1B (LISS-II) has been used in this study.

Theoretical considerations:

The model simulates surface runoff volumes, using Soil Conservation Service (SCS) curve number technique (USDA-SCS, 1972).

$$Q = \frac{(R - 0.2s)^2}{R + 0.8s}, R \geq 0.2s \quad (1)$$

Q=0.0, R ≤ 0.2s

where, Q is the daily runoff, R is the daily rainfall and *s* is a retention parameter. The parameter *s* is related to curve number (CN) by the SCS equation (USDA-SCS, 1972):

$$s = 254\left(\frac{100}{CN} - 1\right) \quad (2)$$

The constant, 254, in equation (2) gives s in mm. Thus, R and Q are also expressed in mm. CN is the curve number for antecedent moisture condition (AMC) II.

Sediment yield is computed for each subbasin with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977).

$$Y = 11.8\,(V\,q_p)^{0.56}\,(K)\,(C)\,(PE)\,(LS) \quad (3)$$

where, Y is the sediment yield from the sub-basin in t, V is the surface runoff column for the subbasin in m^3, q_p is the peak flow rate for the subbasin in m^3s^{-1}, K is the soil erodibility factor, C is the crop management factor, PE is the erosion control practice factor and LS is the slope length and steepness factor.

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

$$LS = \left[\frac{\lambda}{22.1}\right]^{\xi}\left[65.41S^2 + 4.465S + 0.065\right] \quad (4)$$

The exponent ξ varies with slope and is computed using the equation:

$$\xi = 0.6\left(1 - \exp\left[-35.835S\right]\right) \quad (5)$$

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

$$C = \exp\left[(-0.2231 - CVM)\exp(-0.00115CV) + CVM\right] \quad (6)$$

where, CV is the soil cover (above ground biomass + residue) in $kgha^{-1}$ and CVM is the minimum value of C. The value of CVM is estimated from the average annual C factor using the equation:

$$CVM = 1.463 \ln(CVA) + 0.1034 \quad (7)$$

The value of CVA for each crop is determined from tables prepared by Wischmeier and Smith (1978). Values of K can be estimated for each subbasin using standard procedure. PE factors can be estimated for each subbasin using information contained in Wischmeier and Smith (1978).

Extraction of watershed parameters for the model:

The watershed and sub-watershed boundaries, drainage networks and slope map were generated using the procedure described by Jenson and Domingue (1988). The area delineated by the algorithm was found to be 90.23 km^2 against the manually judged area of 92.46 km^2. The automatically delineated watershed was used for further study. Since SWAT works on sub-watersheds basis, the delineated watershed was subdivided into ten sub-watersheds on the basis of topography using similar procedure as used for delineation of main watershed. In this study Nagwan sub-watershed were coded as SWS 1 to SWS 10.

Land use map prepared by using satellite data by Tripathi *et al*. (2003) was used in this study. The supervised classification was adopted for classifying the land use of the study watershed. The land use classes used were upland paddy (1905.8 ha), low land paddy (1353.4 ha), orchards (379.3 ha), deep water (12.0 ha), shallow water (160.8 ha), closed forest (30.9 ha), open forest (389.7 ha), fallow land (837.6 ha), grasses/shrubs (1949.3 ha), upland crops (735.5 ha) and settlements (1350.5 ha). Land use classes for each sub-watershed were determined using the sub-watershed as mask.

The soil texture map generated by Tripathi *et al.* (2003) of the watershed was used in this study. Area under different soil textures were reported to be 1100, 1460, 1210, 830, 3900 and 520 ha for silty clay loam, loam, sandy loam, loamy sand, silt loam and clay loam, respectively. There are mainly three series of soil found in the watershed, they are the *Harina*, *Bhushwa* and the *Atia* series, which occupied 1560, 5240 and 2230 ha area, respectively. Areas under each soil texture and soil series in each sub-watershed were also used in this study.

Standard procedures were adopted for extraction of most of the watershed parameters. Watershed parameters such as curve numbers, average slope and slope length, channel length, average channel slope, conservation practice factors and soil erodibility factor are given in the Table 1.

Criteria for model evaluation:

Continuous time series plot of the recorded and simulated series and a scattergram of recorded data plotted against simulated flows were, therefore, used in

Table 1: Sub-watershed wise input data for the SWAT model

Sub- watershed	Area (km^2)	Slope (%)	CN (1996)	Ave. slope length (m)	Channel length (m)	Channel slope (%)	P value	K value
SWS 1	17.19	2.2	83.6	464.3	9.60	0.005	0.60	0.28
SWS 2	9.33	3.0	71.0	493.8	5.28	0.008	0.50	0.19
SWS 3	6.27	2.1	79.7	481.6	1.80	0.001	0.60	0.22
SWS 4	9.89	2.2	55.0	456.4	5.40	0.004	0.60	0.26
SWS 5	14.67	2.1	68.9	395.8	6.00	0.005	0.60	0.21
SWS 6	3.54	2.8	80.1	492.3	2.25	0.001	0.50	0.19
SWS 7	9.46	3.1	69.0	517.0	5.76	0.005	0.50	0.24
SWS 8	7.34	2.6	71.8	574.3	5.19	0.007	0.60	0.21
SWS 9	7.23	3.3	66.5	454.7	5.40	0.009	0.50	0.23
SWS 10	5.31	6.0	73.0	479.4	4.26	0.007	0.50	0.21
WS*	90.23	2.3	72.0	461.7	13.86	0.005	0.55	0.21

* Entire Nagwan watershed

this study. Model performance was also evaluated using recommended statistical and mathematical criterions which are as follows:

Martinec and Rango (1989) recommended that the criteria should be as simple as possible. The per cent deviation of runoff volumes, D_V, is one goodness-of-fit criterion.

$$D_V = \frac{V - V'}{V} 100 \quad (8)$$

where, V is the measured yearly or seasonal runoff volume; V' is the model computed yearly or seasonal runoff volume. D_V can take any value; however, smaller the number better the model results are. D_V would be equal to zero for a perfect model.

The second basic goodness-of-fit criterion is the Nash-Sutcliffe coefficient or coefficient of simulation efficiency (COE) (Nash and Sutcliffe, 1970):

$$COE = 1 - \frac{\sum_{i=1}^{n} (Q_i - Q'_i)^2}{\sum_{i=1}^{n} (Q_i - \bar{Q})^2} \quad (9)$$

where, Q_i is the measured discharge; Q'_i is the computed discharge; Q is the average measured discharge values. The COE values can be varies from 0 to 1, with 1 indicating a perfect fit. A value of COE = 0 indicates that the model was simulating no better than using the average of the observed data.

RESULTS AND DISCUSSION

The manual calibration procedure as described by Sorooshian and Gupta (1995) was adopted. In manual procedure trial-and-error process of parameter adjustments was used. After each parameter adjustment, the simulated and observed hydrographs were visually compared to see if the match had improved. The calibrated parameters were chosen within the prescribed range as suggested in the SWAT user's manual (Arnold *et al.*, 1996).The calibrated values for the model for effective hydraulic conductivity, initial soil moisture storage, Manning's 'n' value for channel flow and overland flow were found to be 6.40, 0.00, 0.025 and 0.060, respectively.

Model calibration:

The model was calibrated for simulation of monthly surface runoff and sediment yield during the monsoon season of year 1996.

Surface runoff:

The model simulated monthly surface runoff was in close agreement with the measured monthly surface runoff (Table 2). There was no difference between the observed and simulated means of monthly runoff because t-calculated was tend to be lower than t-critical at 95 per cent confidence level. Overall per cent deviation (6.26 %) indicated that model was predicting monthly runoff quite accurate. The Nash-Sutcliffe simulation efficiency (0.987) shows that simulated surface runoff was close to the observed runoff during monsoon months.

Sediment yield:

Similar to runoff, the model was also calibrated for the prediction of sediment yield during the monsoon season of 1996. The statistical analysis of monthly values of observed and simulated sediment yield as given in Table 2 shows that the monthly means of observed and simulated sediment yields were similar at 95 per cent level of confidence. Overall deviation (13.65 %) indicated that the simulated monthly sediment yield compared well with observed sediment yield.

Overall prediction of high values of sediment yield by the model might be because of existing tillage practices (country plough), which was included during calibration run. The existing conventional tillage practices loosen the

Table 2: Statistical analysis of the observed and simulated monthly runoff and sediment yield for calibration of the model (1996)

Statistical parameters	Runoff (mm)		Sediment Yield (t/ha)	
	Observed	Simulated	Observed	Simulated
Mean	57.78	61.40	0.864	0.982
Standard deviation	63.16	64.07	1.155	1.238
Maximum peak	151.30	152.39	2.760	2.940
Total	288.90	307.01	4.320	4.910
Count	5	5	5	5
t-calculated	1.339		2.009	
t-critical (two tailed)	2.776		2.776	
r^2	0.991		0.992	
% deviation	(-)6.26		(-)13.65	
COE	0.987		0.975	

soil that is easily eroded from the fields and resulted in high sediment yield during the beginning of the monsoon season. The high sediment yield results might be due to high concentration of sediment in runoff even though runoff volume was also decreased at the beginning of season. Also, since the SWAT operates on a daily time step, it could not simulate sediment rate for an event of smaller duration. A shorter and more flexible time increment may improve the sedimentation rate. Further, the sediment routing equations are relatively simplistic and assume that the channel dimensions are static throughout the simulation.

Based on the above results, it can be inferred that the model was accurately calibrated for predicting monthly surface runoff and sediment yield from the Nagwan watershed specially for the monsoon season.

Model validation:

The calibrated SWAT model was validated using the observed monthly rainfall and temperature data for the year 1997. All the calibrated and known parameters were considered for model validation. Thereafter, the observed monthly surface runoff and sediment yield for monsoon season of the year 1997 was analyzed and compared with simulated results for the evaluation of model validation performance in respect of surface runoff and sediment yield.

Surface runoff:

The model simulated monthly surface runoff was in close agreement with the measured monthly surface runoff (Table 3). The monthly mean values of observed and simulated runoff were not significantly different at 95 per cent of confidence level. The total of observed (429.07) and simulated (389.56) monthly runoff shows a little deviation of 9.2 per cent. Regression analysis between the observed and simulated runoff values (0.965) of the coefficient of determination (r^2) and a high value (0.993) of the Nash-Sutcliffe simulation efficiency indicating a close relationship between measured and simulated monthly runoff.

Based on the above results, it can be said that the model was accurately validated for predicting monthly runoff from the Nagwan watershed for monsoon season of the year 1997.

Sediment yield:

The monthly mean values of observed (0.77 t/ha) and simulated (0.82 t/ha) sediment were not significantly different at 95 per cent level of confidence (Table 3). A close agreement between mean and standard deviation indicated that the frequency distributions of observed and simulated monthly sediment yield were similar. High values of coefficient of determination (0.904) and Nash-Sutcliffe simulation efficiency (0.844) indicating a close relationship between measured and simulated sediment yield. Overall per cent deviation indicated that the model was over predicting monthly sediment yield by 6.56 per cent only.

Based on the above results, it can be concluded that the model was accurately validated for predicting monthly runoff and sediment yield from the Nagwan watershed. On the basis of calibration and validation results, it is inferred that the SWAT model can successfully be used for effective planning and management studies for identified critical sub-watersheds of Nagwan watershed.

Distribution of monthly runoff and sediment yield:
Surface runoff:

Comparison of monthly surface runoff allows us to

Table 3 : Statistical analysis of the observed and simulated monthly surface runoff and sediment yield for validation of model (1997)

Statistical parameters	Runoff (mm)		Sediment Yield (t/ha)	
	Observed	Simulated	Observed	Simulated
Mean	85.81	77.91	0.776	0.828
Standard deviation	67.23	68.77	0.549	0.714
Maximum peak	144.32	151.25	1.29	1.69
Total	429.07	389.56	3.88	4.14
Count	5	5	5	5
t-calculated	1.383		0.440	
t-critical (two tailed)	2.776		2.776	
r^2	0.965		0.904	
% deviation	9.20		(-) 6.56	
COE	0.993		0.844	

examine the accuracy of seasonal phenomenon on a long-term basis. Attempt was, therefore, made to test the model performance on a monthly basis for the duration of five years (1998 to 2002). The results of descriptive statistics between them are given in Table 4.

The scattergram between measured and simulated monthly surface runoff is shown in Fig. 2 along with the 1:1 line. It gives a better feel for the fit between the simulated and observed monthly surface runoff. The means of observed (42.36 mm) and simulated (45.92 mm) monthly runoff were found to be similar at 95 per cent confidence level (t-calculated = 1.167 < t-critical = 2.063), value of COE (0.830) and coefficient of determination (0.841) indicated a good agreement between the monthly frequency distributions (Table 4). Overall deviation indicated that the model is over predicting monthly runoff during monsoon season by 8.4 per cent. In general, the simulated monthly surface runoff compared well with measured monthly runoff. It can be concluded from the above validation results that the SWAT model could predict monthly runoff reasonably well during monsoon season.

Table 4 : Statistical analysis of the observed and simulated monthly surface runoff and sediment yield (1998-2002)

Statistical parameters	Runoff (mm)		Sediment Yield (t/ha)	
	Observed	Simulated	Observed	Simulated
Mean	42.36	45.92	1.576	1.465
Standard deviation	35.14	38.35	1.659	1.417
Maximum peak	142.62	174.37	5.150	4.760
Total	1059.03	1148.11	39.420	36.640
Count	25	25	25	25
t-calculated	1.167		1.120	
t-critical (two tailed)	2.063		2.063	
r^2	0.841		0.921	
% deviation	(-) 8.40		7.10	
COE	0.830		0.910	

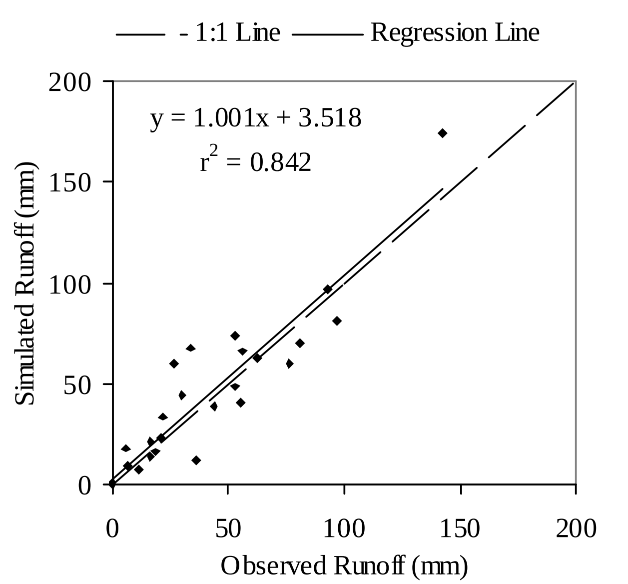

Fig. 2 : Comparison between observed and simulated monthly runoff for model validation (1998-2002)

Sediment yield:

The scattergram between measured and simulated monthly sediment yield is shown in Fig. 3 along with the 1:1 line. It shows that the sediment yield was uniformly distributed about 1:1 line throughout the validation period, which indicated that there was a very good agreement between simulated and observed monthly sediment yield.

The means of observed and simulated monthly sediment yields were statistically similar at 95 per cent confidence level (t-calculated = 1.120 < t-critical = 2.063). Also a high value of r^2 (0.921) and COE (0.910) indicated a very good agreement of monthly distributions of observed and simulated sediment yield (Table 4).

Conclusion:

– Manning's 'n' values for overland flow and channel flow are 0.060 and 0.025, respectively for the Nagwan watershed.

– Both annual runoff and sediment yield are directly proportional to the initial soil moisture storage. (fraction

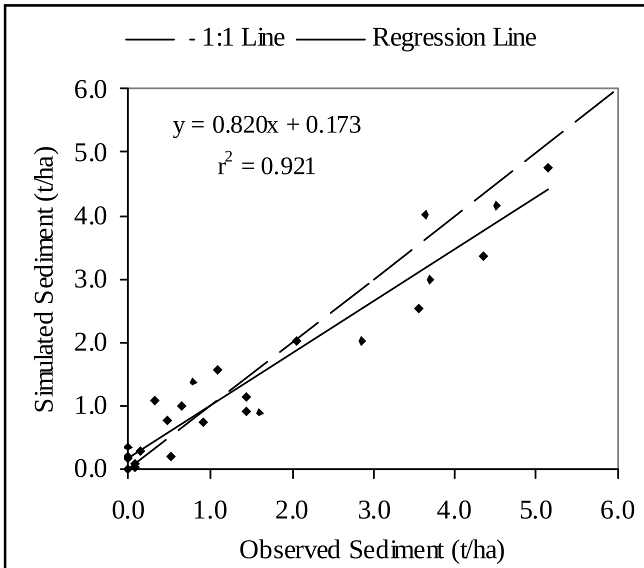

Fig. 3 : Comparison between observed and simulated monthly sediment yield for model validation (1998-2002)

of field capacity, FFC).

– The SWAT model accurately simulates runoff and sediment yield from the Nagwan watershed on monthly basis.

– The baseflow factor does not affect the surface runoff and sediment yield.

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