Assessment of Runoff and Sediment Yield from a Small Agricultural Watershed

V. S. Malunjkar, M. G. Shinde, A. A. Atre, V. N. Barai

Abstract— Runoff and soil erosion are very important processes need to be consider during watershed planning and management and are often non-linear and scale dependent, which complicate runoff and erosion modeling at the catchment scale. One of the reasons for scale dependency is the influence of sinks, i.e. areas of infiltration and sedimentation, which lower hydrological connectivity and decrease the area-specific runoff and sediment yield. The simulation models are useful tools for prediction of runoff and soil erosion at plot scale to catchment scale. Various predictive models have been developed by various researchers for predicting runoff and sediment yield from watersheds. The objective of this study was to model runoff and sediment yield for a small watershed using a coupled approach based on Natural Resources Conservation Service Curve Number (NRCS-CN) method and the Universal Soil Loss Equation (USLE). The results showed that the coupled approach of NRCS-CN and USLE model accurately simulate runoff and sediment yield from the study area.

Index Terms—Runoff, erosion, simulation, universal soil loss equation.

I. INTRODUCTION

The upper layer of soil is always exposed to actions of atmospheric forces (water and wind). These active forces continuously tend to remove the top soil layer and transport them from one place to another is termed as soil erosion. Soil erosion is a three phase phenomenon can be defined as, detachment, transportation and deposition of soil particles from one place to another under the influence of erosive agents [1]. During erosion process, the entrained soil material carried by flowing water is known as sediment. Total sediment outflow from a watershed per unit time is called sediment yield and it is obtained by multiplying the sediment loss by a delivery ratio [2]. The transported portion of the eroded sediment (ratio of yield to the total eroded material) is called sediment delivery ratio.

Accurate prediction of the rate of runoff and quantity of sediment load from watershed is difficult, expensive and time consuming. In India, an estimated 175 Mha of land constituting about 53% of the total geographical area suffers from adverse effect of soil erosion and other forms of land degradation [3]. Active erosion caused by water and wind alone accounts for 150 Mha of land, whereas 25 Mha has been degraded due to ravine/gullies, shifting cultivation, salinity/alkalinity, and water logging [3]. National Bureau of Soil Survey and Land Use Planning [4] Nagpur has reported that 146.82 Mha area is be suffering from various kinds of land degradation includes highest share of water erosion (93.68 Mha).

However, availability of accurate runoff and sediment yield data is scarcely available at few selected places. Hence, this necessitates the research in simulation of processes like runoff and transport of sediment from watersheds through hydrological modeling. Estimation of runoff and sediment yield is necessary for developing watershed management plans involving soil and water conservation interventions. Thus, research in hydrological modeling and related watershed planning issues form a strong component of the environmental activities. During the last three decades, researchers have developed hydrological models of empirical or conceptual nature for prediction of different hydrological variables including runoff and sediment yield.

Hydrological models like ANSWERS (areal non-point source watershed environment response simulation, [5]), AGNPS (agricultural non-point source pollution, [6]), WEPP (Water Erosion Prediction Project, Nearing [7]) and SWAT (soil and water assessment tool, [8]) are being extensively used for sustainable development of watersheds. Thus, hydrological models provide the basis for improved understanding of hydrological processes and also for assessing the impact of human activities on environment and agricultural production.

Present study was carried with the specific objective of performance evaluation of the SCS-CN based sediment yield model [9] for estimation of sediment yield by selecting a case study area located North East of Maheshgad hill, Rahuri, Maharashtra state, India.

II. MODEL DESCRIPTION

In 2006, Mishra *et al.* proposed a model for the estimation of the runoff and sediment yield from a watershed by coupling the soil conservation service curve number (NRCS-CN) method with the universal soil loss equation (USLE). The coupling was based on three hypotheses, the runoff coefficient (C) is equal to the degree of saturation (Sr), the potential maximum retention (S) can be expressed in terms of the USLE parameters, and the sediment delivery ratio (DR) is equal to the runoff coefficient.

NRCS-CN method: The Natural Resources conservation service curve number (NRCS-CN) method was developed by the Soil Conservation Service of the USA for determination

Manuscript Received on March 2015.

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of the rainfall excess (surface runoff) of agricultural watersheds. The model balances precipitation, the initial abstraction, and the potential water retention after runoff begins. The empirical model that combines these parameters is as follows,

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \quad P > Ia \tag{1}$$

Where, P is the total rainfall (mm), I_a is the initial abstraction (mm), Q is the direct runoff (mm), S is the potential maximum retention (mm) and calculated as,

$$S = \frac{25400}{CN} - CN \tag{2}$$

The CN is dimensionless ranging from 0 when S tends to infinity, up to 100 when S = 0. Both conditions represent the extremes between total infiltration (runoff = 0) and totally impervious watersheds (rainfall = runoff). To estimate CN values, the NRCS has provided runoff curve number tables for different cover types (agricultural, arid and semiarid rangelands and urban areas), hydrologic conditions (poor, fair and good) and the HSG. The HSG is a standard soil classification (groups A, B, C, D) that depends on soil texture and infiltration rates. The A group includes well-drained soils with a high rate of infiltration, whereas D soils are poorly drained with a permanently high water table [10].

Universal soil loss equation: The universal soil loss equation (USLE) [11] estimates the potential soil erosion (sheet and rill) from upland areas, and it is expressed as,

$$A = R.K.LS.C.P \tag{3}$$

Where, A is the annual potential soil erosion (t ha^{-1} $year^{-1}$); R is the erosivity factor (MJ mm ha^{-1} h^{-1} $year^{-1}$) taken as the long term average of the summation of the product of total rainfall energy (E) and maximum 30 min rainfall intensity (I_{30}), i.e. EI_{30}; K is the soil erodibility factor (Mg ha h ha^{-1} MJ^{-1} mm^{-1}); LS is the slope length and steepness factor (dimensionless); C is the cover management factor (dimensionless) and P is the supporting practice factor (dimensionless). The USLE is the most important, widely used and accepted empirical soil erosion model. It is based on the concept of the separation and transport of soil particles from rainfall in the form of sheet and rill erosion in order to calculate the amount of soil erosion in agricultural areas.

Coupled model of NRCS-CN method and USLE: The sediment yield model is derived by integrating the SCS-CN method with USLE. The integration is based on three hypotheses: (1) The SCS-CN method can be reformulated using the C = Sr concept. (2) The SCS-CN parameter S can be signified using USLE. (3) The delivery ratio (DR) can be equated to C or Sr. It is given as,

$$Y = \frac{A(P - I_a)}{P - I_a + S} \tag{4}$$

Where, Y is Sediment yield (kg/day) and S is calculated by using following equation,

$$S = \frac{n(1 - S_{ro})}{(1 - n)\rho_s} A \tag{5}$$

In which, S_{ro} is degree of saturation, n is the soil porosity (dimensionless) and ρ_s is solid density. For the current study the above models (Eq. 1 and Eq. 4) are used to simulate runoff and sediment yield.

III. MODEL APPLICATION

Study area: For model application, a small watershed was selected based on the availability of rainfall-runoff-sediment yield data of storm events. Maheshgad watershed is located towards south of central campus of Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharshtra (19˚19′ N longitude and 74˚38′ E latitude) and north east of Maheshgad hill having 45.04 ha area divided into four sub-watersheds (Figure 1.).

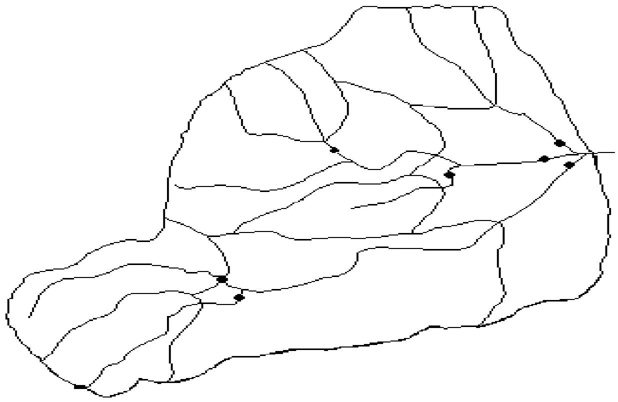

Figure 1. Study area divided in to sub-watersheds.

The topography of the study area is hilly and undulating with an elevation ranging from 511 m above MSL. The general slope of the Maheshgad watershed area varies from 1.95 to 10%. The watershed receives an average annual rainfall of 600 mm and more than 80% of the rainfall occurs during the monsoon season (June-September).

Historical daily rainfall data (1998) was collected from the raingauge station located in the watershed and analyzed to determine the various hydrological parameters. Department of Soil and Water Conservation Engineering of Mahatma Phule Krishi Vidyapeeth, Rahuri under Ad-hoc research project, ICAR, New Delhi, India monitor hydrological data of the Maheshgad watershed. Watershed daily sediment yield were collected for the monsoon season of the years 1998. A set of instruments consisting of continuous recording rain gauge, water level stage recorder and sediment meter were used to record rainfall, stream flow (seasonal) and sediment flow data, respectively. The sediment yield data were measured by manual sampling using sediment meter, which works on the principle of density of water. The sediment concentration was obtained by filtration and evaporation (oven drying) methods. The morphological characteristics of the watershed are presented in Table 1.

In input parameters, Rainfall erosivity factor (R) was calculated by the equation suggested by Atre *et al.* [12] for Rahuri as,

$$R = 1.09 \times P - 5.85 \tag{6}$$

Where, R is daily rainfall erosion factor (metric units) and P is daily rainfall amount (mm). From this equation daily rainfall erosivity factor (R) was computed for the rainfall events of years 1998.

The soil erodibility factor (K) was computed from the soil texture, i.e. sand, silt and clay percentage. The slope length

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and steepness factor (LS) determined from the Eq. (7) and cover management and supporting practise factors were selected from the conservation measures applied in the watershed.

$$LS = L^{0.5}(0.0138 + 0.00974Y + 0.001138Y^2) \quad (7)$$

Where, Y is the gradient (%) over the runoff length and L is the length (m) of slope from the point of origin of the overland flow to the point where the slope decreases to the extent that sedimentation begins.

From the USLE parameters, average annual soil loss (A) was calculated which is next used in Eq. (5) and Eq. (4) for computing potential maximum retention (S) and sediment yield (Y).

IV. MODEL EVALUATION

The model evaluation procedure included calibration, sensitivity analysis and validation. A number of test statistics and techniques can be used for model evaluation and to test the goodness-of-fit of the model to simulate reality. American Society of Civil Engineers (ASCE) Task Committee on criteria for evaluation of watershed management models (1993) recommended that both visual and statistical comparisons between model-computed and measured quantities be made whenever data are presented [13]. In the present case study, the simulated results were evaluated on the basis of following test criteria and statistical indices recommended by the ASCE Task Committee (1993).

Percent deviation (D_V): The percent deviation of sediment yield values, D_V given by the following equation is one of the criterions for evaluation [14].

$$D_v(\%) = \frac{Y_{obs} - Y_{sim}}{Y_{obs}} \times 100 \quad (8)$$

Where, Y_{obs} is the observation for the constituent being evaluated, Y_{sim} is the simulated value for the constituent being evaluated, the smaller the value of D_V, better the model results. D_V should equal to zero for a perfect model.

Nash–Sutcliffe model efficiency (E_{NS}): Another goodness-of-fit criterion recommended by ASCE Task Committee is Nash–Sutcliffe coefficient or coefficient of simulation efficiency (E_{NS}) [15] given by,

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(Y_{obs} - Y_{sim})^2}{\sum_{i=1}^{n}(Y_{obs} - Y_{mean})^2} \quad (9)$$

Where, Y_{obs} is the ith observation for the constituent being evaluated, Y_{sim} is the ith simulated value for the constituent being evaluated, Y_{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations. The E_{NS} values can vary from 0 to 1, with 1 indicating a perfect fit.

Maximum error (E_{MAX}): Maximum error (E_{MAX}) is given as below,

$$E_{Max} = Max|Y_{obs} - Y_{sim}| \quad (10)$$

The value of E_{MAX} shows the maximum difference between the simulated and observed value in series of data.

V. RESULTS AND DISCUSSION

The NRCS CN model and sediment model suggested by Mishra *et al.* was used to estimate runoff and daily sediment yield from the selected study area for the year 1997 and 1998 using the data of monsoon season. The results of calculated and selected variables and input parameters were used for simulating sediment yield using sediment model are presented in Table 2.

The observed daily runoff and sediment yield values were compared with the simulated values to evaluate the model performance. The scattergram of runoff and sediment yield for all the events with 1:1 line (line of perfect fit) is presented in Fig. 2 and Fig. 3.

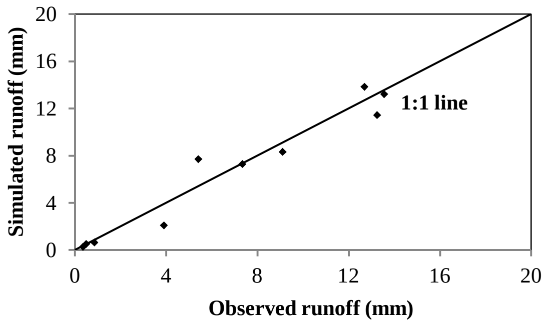

Figure 2. Scattergram for comparison of simulated and observed runoff depth (mm).

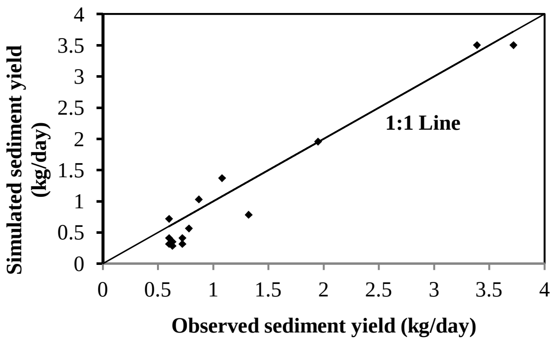

Figure 3. Scattergram for comparison of simulated and observed sediment yield (kg/day).

It is seen from the Figure 2 that, points obtained by plotting simulated and observed values of runoff depth are evenly distributed and near about the 1:1 line indicating a very close agreement between the observed and simulated runoff values. Also Figure 3 depicts the similar results that, points obtained by plotting the simulated and observed values of sediment yield are evenly distributed and near about the 1:1 line indicating a close agreement between the observed and simulated yield values.

The statistical description for the observed and simulated results for all the events is shown in Table 3. The mean, maximum and total value helps to understand the agreement between observed and model simulated runoff and sediment yield for selected rainfall events. The total simulated runoff (65.39 mm) and sediment yield (15.59 kg/day) is slightly less than the total observed runoff (66.92 mm) and sediment yield (17.60 kg/day).

It is observed from the Table 3 that the value of percent deviation (5.71% and 19.49%) indicates almost a close

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agreement between the observed and simulated runoff and sediment yield. The high values of Nash–Sutcliffe model efficiency (0.95 and 0.92) indicates a positive relationship between the observed and simulated values for all the events and shows that the results are close to match perfectly. Further, the values of maximum error are between the limit of 0 to 1, indicating satisfactory validation of the NRCS-CN method and sediment model for the study area.

VI. CONCLUSION

The present study was carried out to evaluate the coupled approach based model for assessment of runoff and sediment yield from a small watershed in Maharashtra (India). The Nash–Sutcliffe efficiency, percent deviation and maximum error, these statistical indices were used for performance evaluation. Higher values of Nash–Sutcliffe efficiency (0.95 and 0.92) and smaller deviation (5.71 and 19.49) indicating satisfactory model performance.

The presented results could be use for erosion based watershed planning, management and for evaluation of conservation management practices in the study area.

ACKNOWLEDGMENT

This study is based on doctoral degree work supported by Department of Science and Technology, Government of India. Also technical guidance from the Department of Soil and Water Conservation Engineering, MPKV, Rahuri has made this project possible

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Table 1. Morphological characteristics of the sub-watersheds

Morphological characteristics	Sub-watersheds							
	W1(a)	W1(b)	W1	W2	W3(a)	W3(b)	W3	W4
Area, ha	3.28	4.4	18.66	2.74	1.09	1.35	9.97	4.75
Stream order	2	2	3	1	1	1	2	2
Average slope, %	9.25	8.02	8.77	3.6	3.97	4.2	4.29	5.84
Main stream channel slope,%	0.062	0.06	0.035	0.019	0.03	0.04	0.025	0.03
Length of overland flow (km)	0.034	0.04	0.047	0.085	0.03	0.04	0.05	0.04
Hydrological soil group (HSG)	C	C	C	C	C	C	C	B

Table 2. Calculated and selected input parameters of sediment model

USLE Parameters	Sub-watersheds							
	W1(a)	**W1(b)**	**W1**	**W2**	**W3(a)**	**W3(b)**	**W3**	**W4**
Rainfall erosivity factor, R	34.84	34.84	34.84	34.84	34.84	34.84	34.84	34.84
Soil erodibility factor, K	0.28	0.35	0.32	0.26	0.27	0.27	0.26	0.20
Slope length and steepness factor, LS	1.17	1.04	1.28	0.59	0.39	0.47	0.54	0.69
Cover management factor, C	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Supporting practice factor, P	0.70	0.70	0.70	0.60	0.60	0.60	0.60	0.60

Table 3. Statistical analysis of observed and simulated runoff and sediment yield

Statistical parameters	Runoff (mm)		Sediment yield (kg/day)	
	Observed	**Simulated**	**Observed**	**Simulated**
Mean	6.69	6.54	1.26	1.11
Maximum	13.55	13.85	3.72	3.51
Total	66.92	65.39	17.60	15.59
Deviation (D_V) (%)	5.71		19.49	
Nash–Sutcliffe efficiency (E_{NS})	0.95		0.92	
Maximum error (E_{MAX})	0.40		0.53	

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