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SCS-CN based modified universal soil loss equation

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Abstract

Modified Universal Soil Loss Equation (MUSLE) is generally used for estimation of sediment yield on storm basis from a small agricultural watershed. To calculate runoff factor of MUSLE, recorded runoff hydrograph are required. In the present study an attempt has been made to develop a sediment yield estimation model based on the curve number and rainfall. The significance and applicability of the developed model is then assessed by comparing the sediment yield estimated value and MUSLE estimated sediment yield values for the different combination of hydrological and the geomorphologic characteristics of the watershed. Also the developed (CN-MUSLE) model is applied by using observed values from two agricultural watersheds. The MUSLE and CN-MUSLE estimated values were then compared with the observed sediment yield. The developed CN-MUSLE model is capable to estimate sediment yield values almost with same estimation accuracy as the MUSLE model for all combinations of input variables. The developed CN-MUSLE model has better adoptability as it does not require recorded runoff hydrograph instead it estimates sediment yield based on storm precipitation and curve number of the area.

Keywords: curve number, modified universal soil loss equation, sediment yield

Introduction

Natural resources such as land and water availability play an important role in the economy of any country. Land degradation, specially, soil erosion affects the soil health badly and hence the accurate determination of sediment yield is very crucial for selecting the proper management/ conservation practices for minimizing soil erosion. The Modified Universal Soil Loss Equation (MUSLE) proposed by Williams (1975) [13] is mainly used for the estimation of sediment yield on storm basis from the small agricultural watersheds. It requires information regarding storm runoff volume and peak rate of runoff. In developing countries where majority of watersheds are un gauged, these information do not generally become available. As recording volume of runoff is easier than peak rate of runoff in an earlier study a model was developed in which peak rate of runoff in MUSLE model was transformed in terms of runoff volume using principles of triangular hydrograph Mockus (1957) [5]. Soil Conservation Service Curve-Number (SCS–CN) method is well accepted and widely used for determining the volume of direct runoff from an area with a known antecedent moisture conditions (AMC) and curve-number of the area Ponce et al. (1996) [6]. The application of the SCS-CN relationship, owing to its simplicity is very useful tool for runoff estimation in un-gauged watersheds Soulis (2008). Remote Sensing and Geographical Information System (RS & GIS) techniques facilitate to obtain crop cover and cropping system of the area required to develop the Curve-Number (CN) of that area. Thus SCS-CN method becomes very convenient to estimate runoff volume and the peak rate of runoff can be obtained based on the principles of triangular hydrograph Mockus, (1957) [5]. Schwab et al. (1993) [18] proposed a model on the basis of Curve-Number for estimation of time of concentration, i.e. runoff volume, peak rate of runoff and time of concentration as the function of rainfall depth and Curve-Number.

Based on the above concepts, in order to further simplify the application of Modified Universal Soil Loss Equation (MUSLE), in the present study it has been conceived that in MUSLE, if the requirement of runoff volume and peak rate of runoff is eliminated by using rainfall depth and curve number technique, it will make its application much easier as rainfall depth data and curve number may be made known at most of the locations.

Keeping above facts in consideration, in this study an attempt has been made to develop a mathematical model which is entirely based on rainfall depth and curve-number of the area to estimate sediment yield on storm basis from agricultural watershed with followings as the

main objectives,
i. To formulate SCS-CN based MUSLE model to estimate storm sediment yield,
ii. To verify and compare performance of developed model with MUSLE model for sediment yield estimation.

2. Materials and Methods

2.1 Hypothesis

The Modified Universal Soil Loss Equation (MUSLE) developed by (Williams, 1975) [13] provides the estimation of sediment yield on storm basis from small (less than 10km^2) agricultural watershed. The mathematical form of the MUSLE is given as,

$$Y = 11.8(Qq_p)^{\beta} K\, LS\, C\, P \text{ ……………………….(1)}$$

where, Y is the sediment yield from an individual storm, metric tons (t); Q is the storm runoff volume, m^3; q_p is the peak runoff rate, m^3/sec; K is the soil erodibility factor (ton/ha)/ (erosive factor R) or t/joules or ton / ha/year; L is the slope length factor; S is the slope gradient factor; C is the crop cover or crop management factor and P is the erosion control practice factor. The value 11.8 is the unit conversion constant and β is the exponent which Williams found to be Equal to 0.56 for the agricultural watersheds of the U.S.A.

The above relationship shows that the sediment loss from a watershed depends on the storm runoff volume and peak rate of runoff as well as soil erodibility, slope length and gradient, crop management and practices being adopted in the area. The application of the MUSLE model under actual field conditions requires the recorded values of storm runoff and peak rate of runoff. With the known value of rainfall amount and the Curve- Number (CN) of the area, runoff from that area can be easily estimated by using SCS-CN method. Similarly, using triangular hydrograph method developed by Mockus, (1957) [5], runoff peak (q_p), converted in terms of runoff volume (Q). The time of concentration is also determined by Curve- Number (CN) Schwab *et al.* (1993) [18], hence the whole relationship for sediment yield estimation could be converted in terms of rainfall and curve-number (CN).

2.2 Problem Formulation

The step by step process of problem formulation is described as below.

1. The runoff volume generated from any area can be obtained by multiplying runoff depth with area and can be represented as,

$$Q_v = d \times A$$
$$\text{Or } Q_v = 10\, d\, A \text{ ……………… (2)}$$

Where, Q_v is runoff volume in m^3, d runoff depth in mm and A is the watershed area in ha. As per SCS-CN method storm runoff depth from any area can be estimated by the following relationship

$$d = \frac{(P_d - I_a)^2}{P_d - I_a + S} \text{ ……………. (3)}$$

where, P_d is the storm rainfall, mm; I_a is the initial abstraction, mm and S is the potential maximum retention, mm. Initial abstraction *'I_a'* is the function of soil type and vegetative coverage present in the field. Potential maximum retention (S) is the maximum possible retention or infiltration during the rainfall. The runoff generation takes place only when the rainfall amount exceeds the initial abstraction *'I_a'*. For generalization 'I_a' can be written as,

$$I_a = n\,S \text{ ……………….. (4)}$$

Accordingly, on substituting the value of *'I_a'* Eqn. 3 becomes as follows,

$$d = \left[\frac{(P_d - nS)^2}{P_d + S - nS}\right] \text{ ……………… (5)}$$

where, n is the regional constant which depends on geographical and climatic factors. The value of n varies in the range of $0.1 \leq n \leq 0.4$ (SCS, USA, 1972). Similarly, the value of potential maximum retention *'S'* being the function of curve number is represented as;

$$S = \frac{25400}{CN} - 254 \text{ ……………… (6)}$$

Substituting the value of S from Eqn 6 in Eqn 5, and simplified it then the Eqn5 can also be written in the following form for runoff depth in terms of rainfall depth *'P_d'* and Curve-Number as follows.

$$d = \left[\frac{[(P_d CN - n(25400 - 254CN)]^2}{[P_d CN^2 - (1-n)(25400CN - 254CN^2)]}\right] \text{ ……………………(7)}$$

Using the principles of triangular hydrograph **(**Mockus, 1957) [5], the runoff volume can be converted in to triangular hydrograph. Area of triangular hydrograph represents the total volume of the runoff generated from a single storm rainfall. As, area of triangular hydrograph is equals to the total runoff volume, hence peak runoff rate can be derived by equating the total runoff volume to the area of triangular hydrograph as follows,

Runoff volume = Area of trinangular hydrograph

$$\mathrm{d} \times \mathrm{A} = \frac{1}{2}\left(q_p \times t_p + q_p \times \frac{5}{3} t_p\right)$$

$$\text{or, } q_p = \frac{0.75\, Q \times A}{t_p} \text{ ……………..(8)}$$

Where, watershed area A in hectare, runoff d in mm and time to peak of runoff t_p, in hour. To find the value of runoff peak, q_p in (m^3/sec), above relationship can be expressed as,

$$q_p = \frac{0.00208 \times Q \times A}{t_p} \text{ ………………..….. (9)}$$

2. The time required to move the surface runoff from remotest point of the watershed to its outlet, is known as time of concentration. For small watersheds the time of concentration has been reported to be assumed as same to the time to peak (Subramanya, 2008) [11]. Thus,

$$t_c = t_p \text{ …………………… (10)}$$

Time of concentration for an area depends on length and average slope of the flow path and the obstacles (vegetation) present on the path of flow. The curve number of the area is also a function of its vegetative conditions. The obstacles thus have been related with curve number and the relationship for time of concentration in terms ofcurve-number (CN) as given below by Schwab *et al.*, (1993) [18] is used in this study.

$$T_c = \frac{l^{0.8}\left(\frac{100}{CN}-9\right)^{0.7}}{4407 \times \sqrt{s}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Where, time of concentration, T_c in h.; length of over land flow path, l in m and over land slope, s in m/m.

2.3 Model Development

The values of runoff volume Q, in m^3 as obtained from Eqn (2) and peak rate of runoff q_p, m^3/sec from Eqn (9) were substituted in the MUSLE Eqn1 and the sediment yield relationship Eqn (1) is written as follows.

$$Y = 11.8\left[\frac{0.00208QA}{t_p} \times 10QA\right]^{\beta} K\ LS\ C\ P \qquad \ldots (12)$$

Considering time to peak equal to time of concentration i.e., $t_p = t_c$ and substituting the relationship for t_p from Eqn (10) and the relationship for runoff volume Q from Eqn 7, the Eqn12 in terms of storm precipitation and curve number can be expressed as,

$$Y = 11.8\left[\frac{0.0208A^2}{\frac{l^{0.8}\left[\frac{1000}{CN}-9\right]^{0.7}}{4407 \times \sqrt{s}}}\left[\frac{P_dCN - n(25400-254CN)^2}{P_dCN^2 + (1-n)(25400CN-254CN^2)}\right]^2\right]^{\beta} K\ LS\ C\ P$$

or,

$$Y = 11.8\left[\frac{91.66}{\left(\frac{1000}{CN}\right)^{0.7}} l^{-0.8} s^{0.5} A^2\left[\frac{P_dCN - n(25400-254CN)}{P_dCN^2 + (1-n)(25400-254CN^2)}\right]^2\right]^{\beta} K\ LS\ C\ P \qquad (13)$$

On simplification, the above relationship can be expressed as;

$$Y = 11.8\Phi^{\beta}\left[l^{-0.8} s^{0.5} A^2\left[\frac{P_dCN - n(25400-254CN)}{P_dCN^2 + (1-n)(25400-254CN^2)}\right]^2\right]^{\beta} K\ LS\ C\ P \ldots (14)$$

where, *(Φ)* is a constant which is a function of 'CN' values and is expressed as,

$$\Phi = \left[\frac{91.66}{\left(\frac{1000}{CN}-9\right)^{0.7}}\right] \qquad \ldots (15)$$

For, Himalayan watersheds of India, the value of the β is reported as 0.257 (Das and Chauhan, 1990) and therefore, substituting the value of β in Eqn 2.14, and solving it, then, the general form of the sediment yield equation on storm basis for Himalayan watersheds is finally expressed as,

$$Y = 11.8\Phi^{0.257}\left[A\left[\frac{P_dCN - n(25400-254CN)}{P_dCN^2 + (1-n)(25400CN-254CN^2)}\right]\right]^{0.514} l^{-0.205} s^{0.1285} KLSCP \qquad \ldots (16)$$

This is the generalized form of sediment yield estimation model which relates storm sediment yield in terms of storm precipitation *'P_d'* and the curve number (CN) of the area. The values of factors KLSCP can be obtained in the same way as is done in case of USLE. Topographic factor (LS*)* is the combined slope length and slope steepness factor and can be obtained for a known value of land slope and length of the watershed and an exponent 'm' by using following relationship (Foster *et al.*, 1981).

$$LS = (l/72.6)^{m}(65.41\sin^2\theta + 4.65\sin\theta + 0.065) \qquad \ldots (17)$$

where, *l* is the slope length in meters and s is the degree of slope in percent. Substituting relationship for L & S in Eqn16, the relationship for sediment yield estimation can be simplified further by expressing it in terms of slope length and degree of slope

Exponent 'm' is also the function of land slope and the value of 'm' varies from 0.2 to 0.5 (Smith, *et al*. 2002) [9]. The value of 'm' is given for three different categories of land slopes, these three different slope ranges are (1) 0 ≤ slope ≤3%, (2) 3≤ slope ≤5% and (3) Slope more than 5%, values of the exponent 'm' for these three slope ranges are as 0.3, 0.34 and 0.5 respectively. Hence, an attempt was made to obtain three different sediment yield models for these three different slope categories. These are as follows,

For case-1: 0 ≤ Slope ≤3%, mean value of exponent m= 0.3, sediment yield Eqn16becomes,

$$Y = 4.66\,\Phi^{0.257}\left[A \times \frac{P_dCN - n(25400-254CN)}{P_dCN^2 + (1-n)(25400CN-254CN^2)}\right]^{0.514} l^{0.0944} s^{1.1285} K\ C\ P$$

or,

$$Y = 4.66\,C^{\beta}[A \times M]^{0.514} l^{0.0944} s^{1.1285} K\ C\ P \qquad \ldots (18)$$

where M is a regional factor which is a function of field curve number and the value of 'n' which represents ratio of initial abstraction to maximum potential retention *(Ia/S)* for the region and is expressed as,

$$M = \frac{P_dCN - n(25400-254CN)}{P_dCN^2 + (1-n)(25400CN-254CN^2)} \ldots\ldots\ldots\ldots\ldots (19)$$

and hence, the general relationship for sediment yield estimation is as follows;

$$Y = 0.56\,\Phi^{0.257}[A \times M]^{0.514} l^{0.0944} s^{1.1285} K\ C\ P \ldots (20)$$

In the same way the sediment yield relationships were developed for other two categoriesof land slopes and are given below.

For case-2: 3≤ slope ≤5% value of exponent m=0.4. Sediment yield Eqn16 as;

$$Y = 0.3095\,\Phi^{0.257}[A \times M]^{0.514} l^{0.1344} s^{1.1285} K\ C \ldots (21)$$

For case-3: Slope more than 5% and the value of exponent m=0.5. Sediment yield Eqn16 for this case becomes as;

$$Y = 0.357\,\Phi^{0.257}[A \times M]^{0.514} l^{0.2944} s^{1.1285} K\ C\ P \ldots (22)$$

3. Results and Discussion

To assess the applicability of the developed model, verification has been carried out by comparing the estimated sediment yield values of the CN-MUSLE with MUSLE model. The comparison and the verification of developed model was made on the basis of,

i. Assumed data ii. Observed field data

3.1 Verification of CN-MUSLE developed model based on the assumed data of different hydrological conditions

In practice the data of different combination of geomorphological and hydrological are usually unavailable, hence sediment yield values were estimated by developed models (CN-MUSLE) and MUSLE models using the assumed data of different combinations of hydrological and watershed characteristics data, like storm rainfall depth, watershed area, curve number, form factor and land slope of the watershed were used for sediment yield estimation and the comparison. Rainfall amount was considered 40 mm to 200 mm in depth for all combinations of land slopes and curve numbers. The watershed area was varied from 10ha to 100ha, with their form factor values from 0.1 to 1 were considered in this study. The slopes of the watershed were taken as 2%, 3%, 5%, 10%, and 15% to evaluate and compare the results of these two models, values of curve number were taken from 50 to 95.

3.1.1 Verification of developed CN-MUSLE model considering different values of curve number and land slopes for an area with specific rainfall depth

Thehigher the curve number value of an area greater the runoff generation potential for a given rainfall amount wich in tern lead to higher sediment generation and transpot from the catchment area to the out let of the watershed. The sediment yield estimation was performed considering 2 %, 3%, 5%, and10% land slopes for different values of curve number with specific rainfall depth 50 mm for AMC-II condition. The percentage error in sediment yield estimation between MUSLE and CN-MUSLE models was found to be -2.34%, 1.85%, 5.35%, and 2.38% for 2%, 3% 5%, and 10% and slopes respectively.The visual comparison of these findings is shown in Fig. 1. The developed model performedwell within 10% error in estimation.

3.2 Verification of developed CN-MUSLE model based on observed field data

The sediment yield data from two small agricultural watersheds of Selakui Research Farm of Central Soil and Water Conservation Research and Training Institute, Dehradun, were obtained for the validation of the developed model. The curve numbers of the study area were generated on the basis of the available crop cover and vegetative cover conditions of the watersheds for antecedent moisture condition (AMC) on the basis of previous 5 days rainfall amount for each rainfall events. Ten storm events of watershed W_2A and seven of W_3A were used for validation of the developed model. The estimated value of sediment yield by MUSLE and CN-MUSLE model for each of rainfall events were calculated and compaired with the corresponding observed sediment yield values as shown in Fig 2. The mean percentage error between estimeted and observed sediment yield values by MUSLE and CN-MUSLE for watershed W_2A were 35.96% and 36.73% respectively and similarlly for watershed W_3A, were 24.57% and 29.50% respectively. The error in estimation though significant but occuring almost same in both MUSLE and CN-MUSLE models.

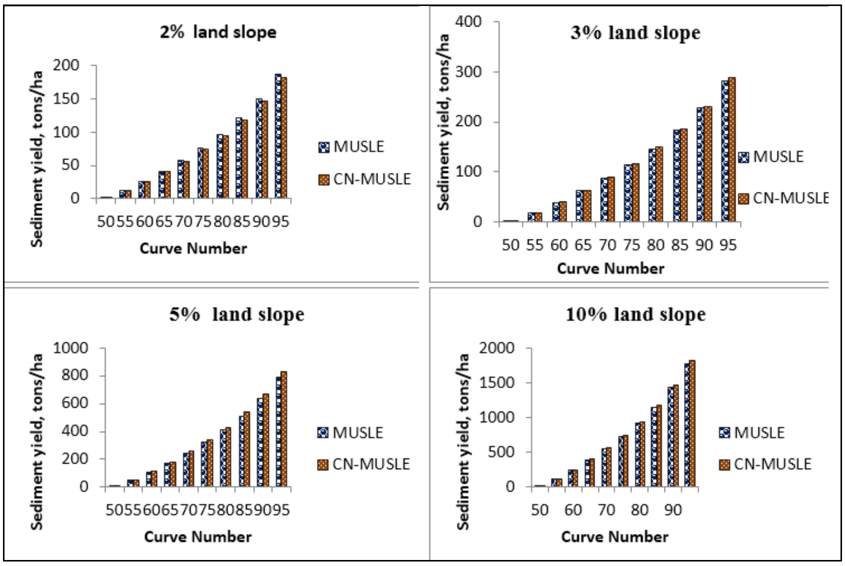

Fig 1: Comparison between sediment yield estimated by MUSLE and CN-MUSLE models for different land slopes and diferrent values of curve number

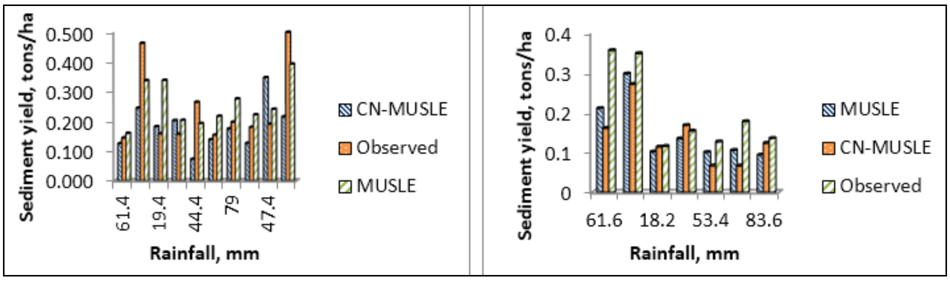

Fig 2: Comparison between observed and estimated sediment yield using MUSLE and CN-MUSLE model, i. W_2A watershed, and ii.W_3Awatershed

4. Summary and Conclusions

To determine the sediment yield from an agricultural watershed, a simplified model (CN-MUSLE) was developed which requires rainfall depth and curve number of the area. The developed model is convenient to apply compared to Modified Universal Soil Loss Equation (Williams, 1975) [13]. On the basis of the present study following specific conclusions could be drawn.

i. The developed CN-MUSLE model is capable to estimate sediment yield values almost with same estimation accuracy as the MUSLE model for all combinations of input variables.

ii. The developed CN-MUSLE model has better adoptability as it does not require recorded runoff hydrograph instead it estimates sediment yield based on storm precipitation and curve number of the area.

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