Storm-Wise Sediment Yield Prediction using Hillslope Erosion Model in Semi-Arid Abundant Lands

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Abstract

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Evaluation of soil erosion by existing models is needed as an important tool for managerial purposes in designation of proper water and soil conservation techniques. The present study aimed to assess the applicability of hillslope erosion model (HEM) as one of the newest erosion models for prediction of storm-wise sediment yield in Khosbijan rangeland with 20% slope steepness by using soil erosion standard plots. In order to run the model, runoff depth, land surface cover, soil texture, slope steepness and length were determined for 16 storm events. The results showed that the uncalibrated HEM did not simulate the observed sediment yields properly. Calibration of soil erodibility parameter and developing regression between observed and estimated data indicated that the model was capable of predicting sediment yield in plots by applying soil erodibility parameter of 0.15 with determination coefficient of 0.64 and estimate error of 40%.

Keywords: abundant lands; erosion model; hillslope erosion model (HEM); Iran; Khosbijan Research Centre

Soil erosion and sediment yield from watersheds confine sustainable use of land resources and are supposed to belong among the most critical environmental hazards. Sediment yield also provides an important index of land degradation, severity and trends, and also reflects the characteristics of a watershed, its history, development, use and management. Therefore, the estimation of sediment yield is needed because it not only affects reservoir capacity, sediment transport to the oceans, stream water quality and quantity, aquatic life, stream habitat, channel morphology and in brief environmental health impact assessment but also it is a good indicator for the effectiveness of watershed management conditions (Sadeghi *et al.* 2008; Noor *et al.* 2010, 2012).

The understanding of soil erosion is necessary to determine the environmental impact of erosion and conservation practices by scientific erosion research, development and evaluation of erosion control technology, development of erosion prediction technology and allocation of conservation resources and by the development of conservation regulations, policies and programmes.

Therefore, numerous empirical and process-based models have been developed in the past to predict both runoff and soil loss at a field or watershed level to support decisions on soil management. Computational models are generally used to simulate the amount of sediment yield from watersheds (Sadeghi *et al.* 2008; Noor 2010). These models vary from complex procedures requiring a range of input parameters, e.g. the water erosion prediction project (WEPP), the European soil erosion model (EUROSEM) and the areal non-point source watershed environment response simulation model (ANSWERS), to simple models requiring only a few key parameters, the universal soil loss equation (USLE) and the revised universal soil loss equation (RUSLE) to predict runoff and soil loss. Soil erosion and sediment yield models therefore play a critical role in addressing problems associated with land management and conservation, particularly in selecting appropriate conservation measures for a given field or watershed (Wilson *et al.* 2001; Sadeghi *et al.* 2008). Thus, when evaluating the application of models in an area, it is very important to ascertain how reasonable the predictions are and how sound the assessment is. Soil erosion and sediment yield models can assist in the development of suitable policies and regulations for agricultural, rangeland and forestry practices. Some models, in spite of their strong theoretical base, may not be very suitable in the context of developing country situations such as those in Iran, where the detailed rainfall, topographic and other input data are not often available or are difficult to collect due to resource constraints (Sadeghi *et al.* 2008; Noor *et al.* 2010, 2012).

The hillslope erosion model (HEM) was developed by scientists at the USDA-ARS Southwest Research Watershed Centre to describe erosion and sediment yield on rangelands (Lane *et al.* 2001). It is based on mathematical relationships among sediment yield, runoff, hillslope characteristics, and a relative soil erodibility value. In the USA a large dataset was available to calibrate the model, where it has also had substantial application (Wilson *et al.* 2001; Cogle *et al.* 2003). This model is a time-averaged solution of the coupled kinematic wave equations for overland flow and the sediment continuity equation (Cogle *et al.* 2003).

Thus, the solution emphasizes spatially distributed soil erosion and sediment yield processes averaged over a specified time period. The solution to the sediment continuity equation for the case of constant rainfall excess was integrated through time (Shirley & Lane 1978) and produced a sediment yield equation for individual runoff events as follows:

$$Q_s(x) = QC_b = Q\left\{\frac{B}{K} + \left(K_i - \frac{B}{K}\right)\left[1 - \exp(-k_r x)\right] \Big/ k_r x\right\} \quad (1)$$

where:

Q_s – total sediment yield per unit width of the plane (kg/m)
Q – total storm runoff volume per unit width (m^3/m)
C_b – mean sediment concentration over the entire hydrograph (kg/m^3)
x – distance in the direction of flow (m)
B – sediment transport coefficient ($kg/s/m^{2.5}$)
$K = CS^{1/2}$ – depth discharge coefficient
C – Chezy hydraulic resistance coefficient for turbulent flow ($m^{1/2}/s$)
S – dimensionless slope (slope steepness) of the land surface
K_i – interrill erosion coefficient (kg/m^3)
K_r – rill erosion coefficient (1/m)

The above sediment yield equation for a single plane was extended to irregular slopes (Lane *et al.* 1995; Cogle *et al.* 2003). This extension was accomplished mathematically by transforming the coupled partial differential equations to a single ordinary differential equation (integration through time). As an ordinary differential equation, the solution on a plane could easily be solved for sequential segments of the entire plane. Finally, the extension was accomplished practically by approximating irregular hill slope profiles by a cascade of plane segments. With the extension of the model (Eq. (1)) to irregular slopes, inputs for the entire hillslope model are runoff volume per unit area and a dimensionless, relative soil erodibility parameter. Input data for each of the individual segments are the slope length and steepness, per cent vegetative canopy cover, and per cent surface ground cover (Cogle *et al.* 2003; Sadeghi *et al.* 2008).

The HEM is used to simulate erosion and sediment yield as a function of position on a hillslope and to simulate the influence of spatial variability in hillslope properties (topography, vegetative canopy cover and surface ground cover) on sediment yield and mean sediment concentration. While the simple model may be less powerful than more complex models, the single-event model used has an analytic solution, simplified input, relatively few parameters, and an internal database to relate slope steepness, soil erodibility, vegetative canopy cover, and surface ground cover to the model parameters.

An important component of the HEM is the database it contains. Model calibration results, corresponding relationships from the literature, and expert judgment were used to build a database relating soil properties, slope length and steepness, vegetative canopy cover and ground surface cover with the model parameters. The database was incorporated as a subroutine within the computer program to simulate erosion and sediment yield. As an example, Figure 1a shows how K_i and K_r vary with vegetative canopy cover, and Figure 1b illustrates the variation of K_i, K_r, B, and K with surface ground cover (Cogle *et al.* 2003).

As is apparent in these figures, ground cover has a greater impact on soil erodibility in the HEM than does canopy cover. Default values of the relative soil erodibility parameter used in the HEM were derived, and then grouped by soil textural class, using experimental plot data for over 2000 events in the USA (Lane *et al.* 2001). The HEM application beyond the USA databases where it was calibrated and validated depends on extending the databases and parameter estimation algorithms to additional locations and conditions (Cogle *et al.* 2003).

As land degradation has become more evident with increasing changes in land use and management practices within Iran especially in semi-arid conditions, in the area of the present study, it has become necessary to identify the effects of different treatments on soil erosion and sediment yield. To improve soil and water resources development, achieve sustainable land use and land productivity in the region, an integrated watershed management approach is needed. Development of improved soil erosion prediction technology or calibration of existing models are therefore required to provide conservationists, farmers and other land users with the tools they need to evaluate the impact of various management strategies on soil loss and sediment yield, and plan for the optimal use of the land. The present study aims to assess the applicability and efficiency of the HEM to predict sediment yield from abundant land treatment on a plot scale in central Iran with semi-arid climate.

MATERIAL AND METHODS

The study was conducted at the Khosbijan Research Centre Station (KRCS) on the Zagros Mountain range in the Markazi Province, central Iran. The mean elevation of the study area is 1850 m a.s.l.

According to the data collected at the climatologic station close to the study watershed and applying the Ambrejet method, the general climate of the watershed is semi-arid and cold (Agharazi 1997). The area receives 321 mm of annual precipitation. The mean temperature is reported to be 13.2°C. In this region stockholders convert rangeland to wheat dry land. Because of mismanagement, ploughing on slopes and low productivity of land, land will be abundant. This abundant land will be ploughed only in the farming season (ownership issues).

To run the HEM, we need runoff (mm), soil texture, canopy and ground cover and length and steepness of slope. For performance evaluation we also need sediment yield in the outlet of the plot. In this study canopy cover and soil texture were 0 and clay loam, respectively.

Three standard erosion plots 22.17 m long by 1.83 m wide (Bennett 2001) were also established in each study treatment with three replications. Plots were properly isolated using galvanized sheets 30 cm in height, out of which 15 cm were inserted into the soil. Runoff and soil loss were measured by collecting buckets, which were placed at the

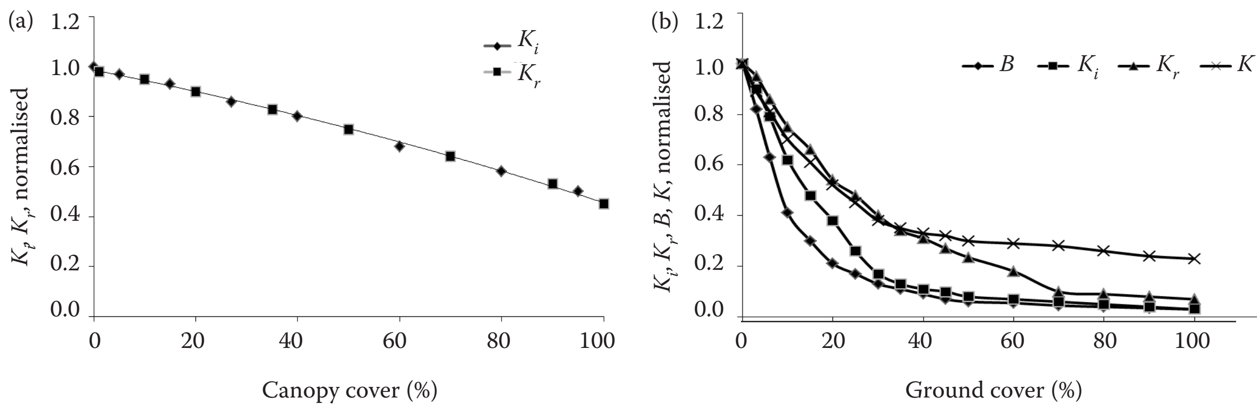

Figure 1. Relationships between model parameters and hillslope characteristics for the hillslope erosion model (HEM): (a) canopy cover vs. K_i and K_r, normalised to 0% canopy cover, (b) ground cover vs. K_i, K_r, B and K, normalised to 0% ground cover (Lane *et al.* 2001; Cogle *et al.* 2003)

bottom of each runoff plot. The collecting buckets were connected to the runoff plots via PVC tubes, which collected both soil sediments and runoff water from the entire 22.17 m by 1.83 m plots after each rainfall event (Agharazi 1997). The sediment concentration was also determined through sampling from the collected runoff at the outlet of each plot. The volume of 1 l was taken for lab analysis from the total runoff after mixing up the entire runoff (Sadeghi *et al*. 2008). Sediment concentration was determined using a drying and weighing method. Because of the small size of the study plots, the amount of sediment yield was assumed to be equal to the rate of soil erosion (Bennett 2001; Sadeghi *et al*. 2008). The runoff and sediment measurements were taken during 16 natural storm events that occurred during the study period (i.e. from 1985 to 1990).

The HEM was then run on a storm basis using the data set collected for each treatment and with the default erodibility parameter. The accuracy of the estimated values was investigated considering the criteria of an estimation error (RE) of below 40% (Das 2000; DeBarry 2004).

The requirement for calibration of the erodibility parameter was investigated by changing the soil erodibility in the model proposed value and running the model to obtain the closest values of sediment yield to those measured in the study plots (Cogle *et al*. 2003; Sadeghi *et al*. 2008).

RESULTS

To estimate erosion and sediment yield from runoff at the hillslope scale, a simple, robust sediment yield model was selected (Lane *et al*. 2001). All required information and data were both collected for the application of the HEM at Khosbijan in Iran. The parameters and runoff data collected for 16 storm events were used to apply the model given in Eq. (1). The soil erodibility was assumed 1.38 in these plot sets, since the soil texture was identical (clay loam).

Therefore, besides rainfall characteristics, the entire input data of slope length and steepness, canopy and ground cover of the three experimental plots were entered into the model using both default and calibrated values of soil erodibility parameter. The corresponding results are summarised in Table 1.

The result of the comparative evaluation between measured and estimated sediment yield data is depicted in Figure 2.

Table 1. Storm properties, observed and predicted sediment yield for the study area, Iran

No.	Rainfall (cm/h)	Runoff (mm)	Sediment (kg/ha)	
			observed	estimated
1	0.374	0.452	9.6	9.75
2	0.84	0.2	2.85	4.25
3	0.452	0.747	3.9	16.25
4	0.33	0.128	0.66	2.75
5	0.16	0.297	2.8	6.50
6	0.6	0.114	2.7	2.50
7	0.19	0.204	2.4	4.50
8	0.09	0.689	2.0	15.00
9	0.28	0.408	2.5	8.75
10	0.32	0.085	8.7	1.75
11	0.23	0.029	2.0	0.75
12	0.23	0.052	1.0	1.25
13	0.14	1.49	5.2	32.25
14	0.34	0.22	1.1	4.75
15	0.24	0.014	0.6	0.25
16	0.6	0.011	0.4	0.25

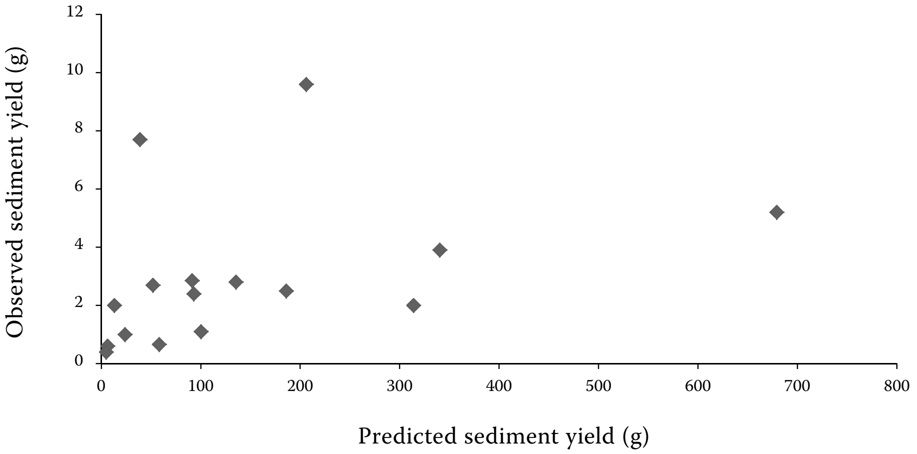

Figure 2. Comparison between observed values and hillslope erosion model (HEM) prediction with default erodibility factor in Khosbian Research Centre Station (KRCS), Iran

According to the results shown in Table 1 and Figure 3, it is simply understood that the HEM has considerably overestimated the sediment yield in the study plots using the default erodibility values. The results obtained during the present study agree with those of Sadeghi *et al.* (2008), who reported the HEM overestimation.

There was a significant difference between the measured sediment yield with mean values of 2.9 kg and that estimated with mean values of 146.4 kg. Along with the mean error of estimation beyond 500% it showed a large difference between each data set indicating the incompatibility of the HEM using the default erodibility values for the study purpose. This agrees with Cogle *et al.* (2003) and Sadeghi *et al.* (2008), who reported the HEM incompatibility using the default erodibility values for sediment yield estimation.

No logical closeness of data points to the prefect line indicates rejecting the model performance for the estimation of sediment yield generated in the plots. These results prove that the HEM does not produce any reasonable estimates of sediment yield under the aforesaid conditions.

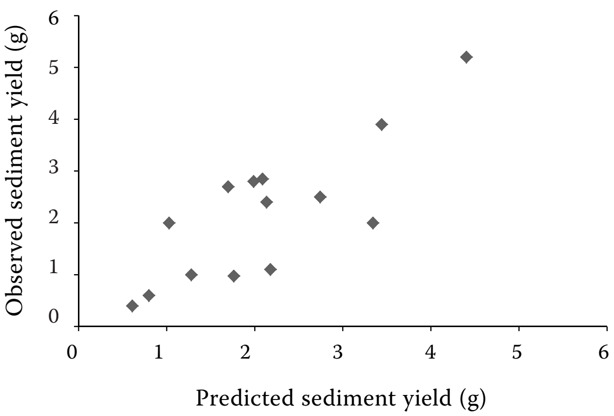

Figure 3. Comparison of observed and predicted sediment yield in the study area

For HEM calibration, modified erodibility factor as supposed by Cogle *et al.* (2003) and Sadeghi *et al.* (2008) was used. In calibration stage, 75% of data were used and 25%, i.e. storms No. 1, 5, 10 and 15, were used in validation stage. Table 2 shows the results of sediment yield prediction for assigning of 1, 0.5, 0.25, 0.2 and 0.15 to erodibility factor. Corresponding estimation errors were 3744, 1319, 461, 327 and 209%, respectively. Using the optimized erodibility value increased the goodness of fit between the calculated and observed sediments. But according to the results shown in Table 2, it is simply understood that the HEM has considerably overestimated the sediment yield in the study plots using the assigned erodibility values. The results obtained during the present study agree with Sadeghi *et al.* (2008) and oppose Cogle *et al.* (2003), who reported that the HEM can be used for sediment yield prediction by adjusted erodibility factor.

Erosion and sediment yield control as stated by Foster *et al.* (1981) Top of Form

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To improve the results of sediment yield prediction, different relationships were then established between measured and estimated sediment yields when regression models were used. Also transformed (i.e. logarithm, inverse, root and cubic) data were investigated (Sadeghi *et al.* 2008). The best-fit models between predicted and observed sediment values were selected based on maximum determination coefficient (R^2), minimum prediction error (RE) and maximum efficiency coefficient

Table 2. Results of sediment yield (kg/ha) prediction by hillslope erosion model (HEM) in calibration process

No.	Erodibility factor				
	0.15	0.2	0.25	0.5	1
1	4.25	6.25	8.25	21.25	57.25
2	16.25	23.25	30.75	79.00	214.00
3	2.75	4.00	5.25	13.50	36.75
4	2.50	3.50	4.75	12.00	32.75
5	4.50	6.25	8.50	21.50	58.50
6	15.00	21.25	28.50	73.00	197.50
7	8.75	12.75	16.75	43.25	117.00
8	0.75	1.00	1.25	3.00	8.25
9	1.25	1.50	2.25	5.50	15.00
10	32.25	46.25	61.75	157.75	426.75
11	4.75	6.75	9.00	23.25	63.00
12	0.25	0.25	0.50	1.25	3.25

Table 3. Relationship between observed (Y) and estimated (X) sediment yield in kg/ha

No.	Erodibility	Equation	R^2 (%)	RE (%)	CE (%)
2	1	$Y = 1.080(\log X)^{1.203}$	61	38	52
3	0.15	$Y = 1.078(\sqrt{X})^{0.803}$	61	37	63
4	0.15	$Y = 0.730(\sqrt{X}) + 0.510$	66	44	66
5	0.15	$Y = 1.493(X^{0.33}) - 0.291$	64	40	64
6	0.15	$Y = 0.532e^{0.731\ (X0.33)}$	56	38	64

RE – minimum prediction error; CE –maximum efficiency coefficient

(CE) criteria. A relationship between observed (Y) and estimated (X) sediment is shown in Table 3.

Because they meet acceptable statistical criteria in calibration stage, Eqs (2)–(6) can be used to describe the relationship between estimated and measured sediment yields in this study. Although the maximum level of estimation error in these models was found to be 44% (Eq. (4)), it was within the acceptable range. However, with these criteria in validation process, Eqs (4) and (6) have above 50% and were not found to have acceptable accuracy because of their high errors of estimation. Finally Eq. (5) was selected, with an estimation error of 40.00%, and coefficients of determination and efficiency of 0.64. Graphical representations of best-fit models for the study area are shown in Figure 3.

It can be concluded from the results of the study that the original HEM did not perform well in the prediction of sediment yield from the study area with default erodibility factor. But the calibration of erodibility factor and regression between observed and estimated values could improve storm-wise sediment yield prediction. The evaluation of HEM has shown that while the model is already a valuable accessible tool, the application of the model to other areas than in the USA and other crop and land treatments requires calibration with observed data as has been carried out in this study. Nevertheless, no specific erosion model is currently available which can simulate sediment yield accurately without calibration.

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