Prediction of Storm-Wise Soil Erosion in Dryland Farming using a Hillslope Erosion Model

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Summary

Prediction of storm wise soil erosion and sediment yield is very important, especially in arid and semiarid regions due to small numbers and high intensity of rainfall. Sometimes inappropriate use of the model causes very high or low estimate. However, evaluation of soil erosion by existing models is needed as an important tool for managerial purposes in designation proper water and soil conservation technique. 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 Research Center with dryland treatment by using soil erosion standard plots. In order to run the model, runoff depth, vegetation cover density, land surface cover, soil texture, slope steepness and length were determined for 16 storm events. The results showed that the uncalibrated HEM didn't simulate the observed sediment yields, properly. Calibration of soil erodibility parameter between 0.2 – 1 and developing regression between observed and estimated data indicated that the model could successfully predict the soil erosion rate with determination coefficient of 0.91. These findings indicate that calibration of erodibility factor and regression between observed and estimated could improve storm-wise sediment yield prediction using HEM.

Key words

storm-wise soil erosion, Khosbijan Research Center, model calibration, Iran

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Introduction

The design and implementation of improved catchment-based erosion control and sediment management strategies are frequently hampered by the lack of data on both erosion rates and sediment yields, and an understanding of the processes associated with the delivery of fine sediment through the catchment system. Soil erosion and sediment yield from watersheds confine sustainable use of land resources and supposed to be 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, 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 is a good indicator for the effectiveness of watershed management conditions (Sadeghi et al., 2008; Noor et al., 2012).

Understanding soil erosion is necessary to determine the environmental impact of erosion and conservation practices by scientific erosion research, the development and evaluation of erosion control technology, the development of erosion prediction technology and allocation of conservation resources and 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. 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 often not available or are difficult to collect due to resource constraints (Sadeghi et al., 2008; Noor et al., 2010).

As land degradation has become more evident with increasing changes in land use and management practices within Iran especially in semi arid condition, 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 is 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 crop land treatment on plot scale in central Iran with semi arid climate.

Materials and methods

Study Area

The study was conducted in the Khosbijan research center station (KRCS) on the Zagros Mountain range in the Markazi Providence, central Iran. The mean elevation of the study region is 1850 m above the mean sea level.

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 annual precipitation. The mean temperature have been reported to be 13.2°C. In this region stockholders convert rangeland to wheat dry land. Because of miss management, plough in slope and low productivity of land, soil erosion and runoff production are very dangerous in region.

Model description

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. A large dataset was available to calibrate the model, in the USA, 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 and Lane, 1978) and produced a sediment yield equation for individual runoff events as:

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

Where Q_s is total sediment yield per unit width of the plane (kg/m), Q the total storm runoff volume per unit width (m^3/m), C_b the mean sediment concentration over the entire hydrograph (kg/m^3), x the distance in the direction of flow (m), and the model parameters are as are described in the technical documentation. Briefly, B is a sediment transport coefficient (kg/s/$m^{2.5}$), the depth discharge coefficient is $K = CS^{1/2}$, with C as the Chezy hydraulic resistance coefficient for turbulent flow ($m^{1/2}$/s) and S is the dimensionless slope (slope steepness) of the land surface. The inter rill erosion coefficient is K_i (kg/m^3) and the rill erosion coefficient is K_r (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 hill slope 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; Fazli and Noor, 2013).

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.

Application of the HEM 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).

Data collection

To run the HEM we need runoff (mm), soil texture, canopy and ground cover and length and steepness of slope. Also to performance evaluation we need sediment yield in outlet of plot.

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. Runoff and soil loss were measured by collector buckets, which were placed at the 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 every 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 (Morgan, 2005). Sediment concentration was determined using a drying and weighting 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; De Barry, 2004).

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

Results and discussion

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 either 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 soil texture was identical (Silty Clay Loam).

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

According to the results shown in Table 1, it is simply understood that the HEM has considerably over-estimated the sediment yield in the study plots using the default erodibility values. The results obtained during the present study agree with Sadeghi et al. (2008) who reported over-estimation of the HEM with default erodibiity factor.

There is significant difference between the measured sediment yield with mean values of 4.31 kg and those estimated with mean values of 130.8 kg. It along with the mean error of estimation beyond 300% showed a big difference between each data set indicating the incompatibility of the HEM using the default erodibility values for the study's purpose. This agrees with Cogeel et al. (2002) and Sadeghi et al. (2008) who stated

Table 1. Storms properties, observed and predicted sediments for the study area

No	Rainfall (cm/hr)	Runoff (mm)	Ground Cover (%)	Observed Sediment (kg)	Estimated Sediment (kg)
1	0.374	0.368	5	13	167.75
2	0.84	0.214	5	3	97.5
3	0.452	0.788	5	5	359.25
4	0.33	0.132	12	5.1	38
5	0.16	0.234	17	1	50.25
6	0.6	0.076	5	1.5	34.75
7	0.19	0.192	5	1.4	87.5
8	0.28	0.467	10	16	152.5
9	0.32	0.098	20	1.7	17.75
10	0.23	0.078	25	2.5	10.75
11	0.23	0.066	30	1.4	7
12	0.14	1.54	5	9.4	702
13	0.24	0.43	10	2	140.25
14	0.34	0.207	5	3.8	94.25
15	0.24	0.217	5	1.25	99
16	0.6	0.191	20	1.005	34.75

that incompatibility of the HEM using the default erodibility values for sediment yield estimation.

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

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, 4, 8 and 14 used in validation stage. Table 2 sowed the results of sediment yield prediction for assigning of 1, 0.8, 0.5, 0.4, 0.3 and 0.2 for erodibility factor. Corresponding estimation errors were 2613, 1864, 908, 645, 419 and 227% 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 yet, has considerably over-estimated 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 Cogeel et al. (2002) who reported that by adjusted erodibility factor HEM can predict sediment yield.

To improve results of sediment yield prediction, different relationships were 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 RMSE criteria. Because erodibilty factor with value 0.2 has minimum error.

Because they meet acceptable statistical criteria in calibration stage, Eqs. (2) – (7) 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 56% [Eq. (7)], However with these criteria Eq. (2) was selected, with an estimation error of 60% in validation stage.

Table 2. Results of sediment yield predicted by HEM in calibration process (kg)

Erodibility factor / No*	Sediment yield predicted by HEM: 1	0.8	0.5	0.4	0.3	0.2
1	61.25	44.5	22.75	16.5	11.25	6.75
2	225.75	163.5	83.5	61.25	41.25	24.5
3	31.5	22.75	11.75	8.75	6	3.75
4	21.75	15.75	8	6	4	2.25
5	55	39.75	20.25	15	10	6
6	11	8	4.25	3	2.25	1.25
7	6.75	5	2.5	2	1.25	0.75
8	4.5	3.25	1.75	1.25	0.75	0.5
9	441.25	319.25	163	119.5	80.75	47.75
10	88	63.75	33	24.25	16.5	10
11	62.25	45	23	16.75	11.5	6.75
12	21.75	15.75	8.25	6	4.25	2.5

*-12 storms were selected for model calibration and others storms were used for model validation

Table 3. Relationship between observed (Y) and estimated (X) sediment yield in Khosbijan Research Center

No	Erodibility factor	Equation	R^2	RE (%)	RMSE	CE (%)
2	0.2	y = 1.353e 0.042x	74	25	0.49	91
3	0.2	y = 0.168x + 1.012	92	33	0.48	91
4	0.2	y = 0.933e 0.303√x	66	33	0.62	85
5	0.2	y = 1.184√x - 0.401	78	52	0.78	78
6	0.4	y = 1.107e 0.364(log x)^2	62	36	0.78	78
7	0.4	y = 1.404(log x)^2 + 0.291	70	56	0.90	70

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 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, application of the model to areas rather than in the USA and other crop and land treatments requires calibration with observed data as it was carried out in this study. Nevertheless, no specific erosion model is currently available that can simulate sediment yield accurately without calibration.

Conclusions

Throughout the world access to the Internet is growing enormously and this provides access to many people and community groups who have no ready access to erosion prediction technology. The value of HEM is that it introduces the concept, educates potential users and provides a tool for erosion calculations for a diverse group of people. The danger, however, is that inappropriate values can be calculated based on incorrect inputs, or these tools may be applied in inappropriate scenarios. Resource management scientists need to balance these two issues as they promote tools for sustainable management to the broader scientific and general community. This research was showed that uncalibrated HEM didn't simulate the observed sediment yields, properly. But calibration of erodibility factor improves soil prediction of soil erosion. The results could facilitate the application of given methods obtained in the present study to other areas with similar conditions.

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