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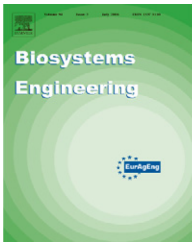

Research Paper: SW—Soil and Water

Field evaluation of the Hillslope Erosion Model (HEM) in Iran

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The development of improved soil erosion and sediment yield predictions technology is required to provide watershed stakeholders with the tools they need to evaluate the impact of various management strategies to plan for the optimum use of the land. In this paper, the Hillslope Erosion Model (HEM) was applied to predict the sediment yield from two sets of plots that represented open grazing and manually harvested treatments in Talesh rangelands, Guilan Province, Iran. The model performance was evaluated by comparing predicted and measured sediment yield in standard plots resulting from 24 natural rainfall events. The results showed that the calibration of the default value of erodibility parameter did not improve the initial efficacy of the model, while the development of an appropriate regression function was required to obtain accurate estimates on sediment yield from the study plots. The results of the analyses showed the potential of the model to predict sediment yield for the open grazing and cultivated treatments with coefficients of determination of 0.96 and 0.98, and estimation errors of 20.78% and 47.00%, respectively. The predicted results therefore showed that the HEM could be used as a major tool to estimate sediment yield at plot scale in rangelands.

1. Introduction

Soil erosion is a natural geomorphic process that can be accelerated by improper land use and management practices. Problems caused by soil erosion and sediment yield include the loss of soil productivity, the degradation of water quality and a reduced capacity to prevent natural disasters such as floods (Aksoy & Kavvas, 2005; Muta *et al.*, 2006; Ahmadi *et al.*, 2006). Recently, soil erosion has been considered as an environmental concern that can lead to a decline in the quality of life. It is well known that the relationship between rainfall, runoff and the processes that result in soil erosion at a given location are usually complex. The prediction of runoff and soil loss is important for assessing the hazard of soil erosion and for determining the suitability of and use and soil conservation measures for a watershed. This in turn can help derive the optimum benefit from the use of the land whilst minimising the negative impact of land degradation and other environmental problems. Soil erosion by water is the result of an interplay between watershed environmental factors such as soil, topography, drainage, rainfall and land-use pattern (Adinarayana *et al.*, 1999). Hence, it is important to

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study soil erosion by analysing these multi-source watershed resources using multi-disciplinary expertise in an integrated manner. After half a century of study, water-induced soil erosion mechanisms still continue to stir controversy. It is widely recognised that upland erosion is largely initiated by the impact of raindrops on the soil surface (Heilig *et al.*, 2001), whereas several studies have demonstrated that the stream power is a simple and good predictor of soil detachment and transport (Siepel *et al.*, 2002; Sadeghi *et al.*, 2004a, 2004b).

Soil erosion, because of its amorphous nature, is difficult to measure on a field scale. It 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 (Toy *et al.*, 2002; Tripathi *et al.*, 2003). 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 (Ahmadi *et al.*, 2006). 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, e.g. Morgan–Morgan and Finney (MMF), productivity erosion runoff functions to evaluate conservation techniques (PERFECT), the universal soil loss equation (USLE) and the revised universal soil loss equation (RUSLE) to predict runoff and soil loss (Moehansyah *et al.*, 2004). Soil erosion 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 (Sadeghi *et al.*, 2007a, 2007b). 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 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.

The need for soil loss estimation at a variety of spatial scales has been well recognised recently. Since measuring hillslope or watershed erosion has historically been a costly and time-consuming practice, modelling and data capture for these scales currently dominate the literature, providing a necessary picture of the physical processes involved (Brazier *et al.*, 2001). The generation of sediment by hillslope erosion is a major environmental problem causing soil infertility, and the transport of particulate nutrients to waterways and the detrimental impacts upon aquatic and estuarine biota (Adams *et al.*, 2004). Since the importance of the inherent resistance of soil to erosion processes (or erodibility) is generally recognised (Hairsine *et al.* 1999; Bryan, 2000), it has to be taken into account in hillslope erosion modelling. Heilig *et al.* (2001) applied Rose's model, developed for rain-induced erosion and sediment transport on hillslopes to a simple experimental set-up, consisting of a small horizontal soil surface (70 mm by 70 mm) under constant shallow (5 mm) overland flow with rain impact. Siepel *et al.* (2002) have developed a physically based water erosion model based on stream power. It handles vegetation in terms of contact cover and considers the settling velocity characteristics of the eroding sediment in hillslope areas. Brazier *et al.* (2001) have applied the MIRSED model, which is a minimum information requirement version of WEPP model to produce an averaged hillslope soil erosion response from each 1 km^2 grid cell in UK. The Hillslope Erosion Model (HEM) developed by scientists at the USDA-ARS Southwest Research Watershed Centre (Lane *et al.*, 1995, 2001) has been applied to a limited extent outside the USA to describe erosion and sediment yield on rangelands; e.g. sandy loam soil in Hyderabad, India, heavy red clay soil in northern Australia and clay loam soil at Pukekohe, New Zealand. The application of HEM (Cogle *et al.*, 2003) showed that the relative soil erodibility values obtained in locations in India and Australia differed from those in the USA. However, the model default values appeared to be suitable for the New Zealand data but with some variability.

As land degradation has become more evident with increasing changes in land use and management practices within northern parts of Iran, 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 water resources development, achieve sustainable land use and land productivity in the most productive northern Iran, 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 open grazing and manually harvested treatments on a plot scale in northern Iran.

2. Hillslope Erosion Model (HEM)

The HEM (accessible at http://eisnr.tucson.ars.ag.gov/hillslopeerosionmodel, 2007) has been developed in USA and it is based on mathematical relationships among a large data set of sediment yield, runoff, hillslope characteristics and a relative soil erodibility value. The HEM model was selected because is a simple and robust sediment yield model that was developed to estimate erosion and sediment yield from runoff at the hillslope scale (Lane *et al.*, 1995, 2001). The model is a time-averaged solution of the coupled kinematic wave equations for overland flow and the sediment continuity equation. The solution emphasises spatially distributed soil erosion and sediment yield processes averaged over a specified period. The sediment continuity equation for overland flow has been considered as summation of interrill and rill erosion rate as presented in Eqs. (1) and (2). The solution to

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the sediment continuity equation for the case of constant rainfall excess was also integrated through time to produce a sediment yield equation for individual runoff events (Shirley & Lane, 1978; Lane *et al.*, 1988, 1995; Cogle *et al.*, 2003):

$$e_i = K_i r, \tag{1}$$

$$e_r = K_r r(T_c - cq) = K_r\left[\left(\frac{B}{K}\right)q - cq\right], \tag{2}$$

$$Q_s(x) = QC_b = Q\left\{\frac{B}{K} + \left(K_i - \frac{B}{K}\right)[1 - \exp(-K_r x)]/K_r x\right\}, \tag{3}$$

where e_i and e_r are interrill and rill erosion rates (kg m^{-1}), K_i is the interrill coefficient (kg m^{-3}). K_r is the rill coefficient (m^{-1}), r is the rainfall excess rate (m s^{-1}), T_c is the transport capacity (kg s^{-1} m^{-1}) and is assumed to be equal to $(B/K)q$, c is the total sediment concentration (kg m^{-3}), q is the discharge per unit width (m^2 s^{-1}), B is the sediment transport-capacity coefficient (kg s^{-1} m$^{-2.5}$), and K is the depth-discharge coefficient which is equal to $CS^{1/2}$, where C is the Chezy hydraulic resistance coefficient for turbulent flow (m$^{1/2}$ s^{-1}) and S is the dimensionless slope of the land.

With the extension of the model to irregular slopes, the inputs for the entire hillslope model are runoff volume per unit area and a dimensionless, relative soil erodibility parameter. The physical processes of detachment are not well understood and so they are usually determined experimentally or empirically as a dimensionless value expressing relative soil erodibility. A soil with a relative erodibility of 2.0 is twice as erodible as a soil with a value of 1.0. 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. Model calibration results, corresponding relationships from the literature and expert judgement 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. 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, 2005).

Since the input data required to use HEM are available, and the prediction accuracy for rangeland areas which occupy some 55% of Iran has been assured in the literature, the efficacy and efficiency of the HEM model to predict storm-induced soil losses from open grazing and cultivated rangeland in the Talesh region, Guilan Province, Iran, were evaluated.

3. Material and methods

The study was conducted in the Matash Mountains summer grazing rangelands on the flanks of the Alborz Mountain range in the Talesh region (45°46′38″E, 37°37′20″N) encompassing some 500 ha. The mean elevation and slope of the study area is 1800 m above the mean sea level and 16%, respectively. The general features and the location of the study watershed are shown in Fig. 1. According to the data collected since 1968 at the climatologic station close to the study watershed and applying the Ambrejet method (Alijani & Kaviani, 1995), the general climate of the watershed is humid and cold. The area receives 1286.5 mm annual precipitation. The maximum and the minimum temperature have been reported to be 30.0 and 19.5 °C, respectively, with a mean value of 8.5 °C. The area is covered by shill, limestone, sandstone, volcanic stones, tuff and conglomerate geologic formations over which shallow deep loamy sand soils exist (GhaderiVangah, 2005). In order to conduct the research, two different rangeland treatments, viz. alfalfa cultivation and open grazing were selected (Fig. 1).

Some areas have been heavily grazed mainly by sheep and goats and to a lesser extent cows and horses, for some 40 years under a free system. The dominant vegetation type in grazing area is *Trifolium*–*Pteridium*, which covers almost 70% of the area. For the past 4 decades some other areas were traditionally sown with alfalfa every few years. Based on the

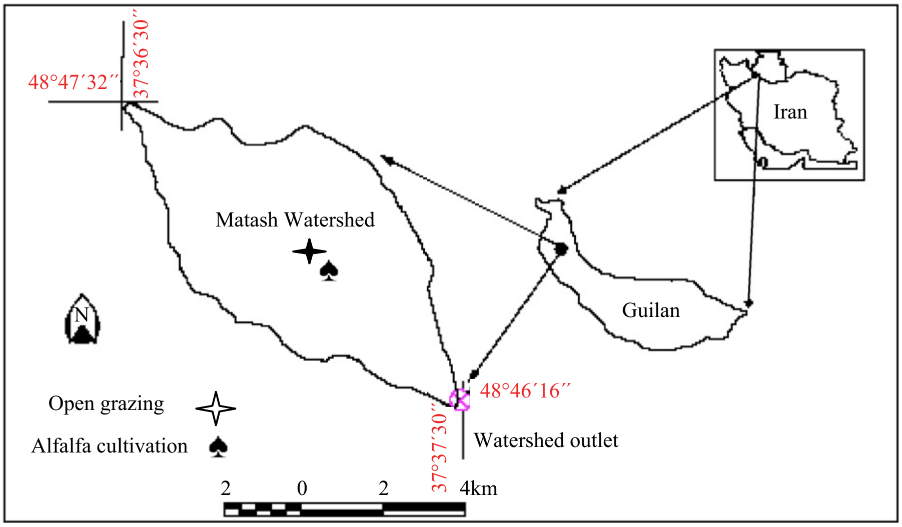

Fig. 1 – Location of the study sites in Iran.

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interviews with local residents, the area was being previously cultivated by wheat and barely. Forage is manually harvested and stocked for animal feed during the winter season and no more tillage occurs. Because stabilised conditions are prevalent in the area, palatable species have extended in area. The dominant vegetation type in the cultivated area is *Medicago–Dactylis* which covers almost 92% of the area (Sadeghi *et al.*, 2007a, 2007b). The detailed information about vegetation and soil characteristics obtained through field and laboratory experiments of the study sites has been summarised in Table 1. Measurements of canopy cover and ground cover were conducted using 1 m^2 plots and through random sampling. Soil texture was also determined based on samples taken form the upper 200 mm of the soil (GhaderiVangah, 2005). The measurements were repeated when any changes occurred in vegetation cover through manual harvesting. The general situations of the study sites are summarised in Table 1.

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 wooden sheets 200 mm in height out of which 100 mm was inserted into the soil. Runoff and soil loss were measured by collecting 20-l-capacity buckets (Khan & Ong, 1997), 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. The details of the study plots are shown in Fig. 2.

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. Sediment concentration was determined using a drying and weighting method (Inbar & Lierena, 2000). 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. The runoff and sediment measurements were taken during 24 natural storm events that occurred during the study period (i.e. from early May to late September 2004). Rainfall measurements were also taken using a manual rain gauge on a storm-by-storm basis.

Table 1 – Vegetation and soil characteristics of investigated areas (Sadeghi *et al.*, 2007a, 2007b)

Variable	Treatment	
	Open grazing	Cultivated area
Vegetation type	*Trifolium–Pteridium*	*Medicago–Dactylis*
Canopy cover (%)	72.00±5.06	92.33±2.18
Stoniness (%)	6.84±3.27	3.29±3.01
Bare soil (%)	17.78±3.34	6.25±1.52
Litter cover (%)	3.83±0.61	4.05±0.87
Organic matter (%)	3.24±0.79	4.62±0.34
pH	6.68±0.16	6.19±0.06
EC (millimhos cm^{-1})	3.33±0.12	3.51±0.47
N (%)	0.24±0.05	0.42±0.04
Production (kg ha^{-1})	613.90±27.30	1600.40±85.90
Range condition	Moderate	Excellent

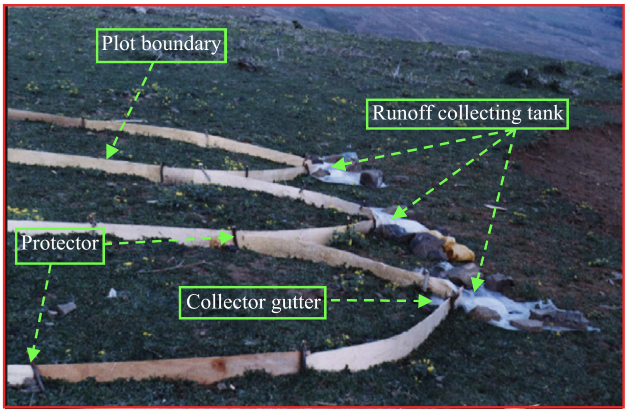

Fig. 2 – Experimental plot with a runoff and sedimentation collection system.

The HEM was then run on a storm basis using the data set collected for each treatment and with the default erodibility parameter of 2.31. The accuracy of the estimated values was investigated considering the criteria of the coefficient of determination, R^2 (Rezaei, 1995), an estimation error (RE) of below 40% (Das, 2000; DeBarry, 2004) and an efficiency coefficient (C_E) of above 60% (Green & Stephenson, 1986). The requirement for calibration of the erodibility parameter was investigated by changing the soil erodibility value and running the model to obtain values of sediment yield closest to those measured in the study plots (Cogle *et al.*, 2003). The susceptibility of model outputs to variations in the input variables and variations in the soil erodibility parameter within the range of ±50% (Jalili, 2003) was assessed using sensitivity analysis. All calculations and statistical analyses were performed using Excel and SPSS software packages.

4. Results

Besides rainfall characteristics, the entire input data of slope length, steepness, canopy cover and ground cover of both the experimental plots were entered into the model using both default and calibrated values of soil erodibility. The corresponding results are summarised in Table 2. The relationship between measured and estimated sediment is also shown in Fig. 3.

It is very clear from Table 2 and Fig. 3 that erosion at both the sites was over-predicted by HEM using the default erodibility values. The mean ratios of predicted to measured sediment yield were found to be 5.56 and 8.32 for open grazing and cultivated treatments, respectively. Using the optimised erodibility value of 1.11, which lies within the range of erodibilities (0.33–4.29) available on the HEM web page (Cogle *et al.*, 2003), increased the goodness of fit between the calculated and observed sediments with a good close agreement in case of open grazing conditions. This is not surprising since the model was originally developed for open grazed areas. The mean ratios of predicted to measured

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Table 2 – Storms properties, observed and predicted sediment for the study area, Iran

	Storm properties						HEM prediction (kg ha^{-1})			
	Date	Depth (mm)	Duration (h)	Intensity (mm h^{-1})	Measured sediment (kg ha^{-1})		Soil erodibility (2.31)		Soil erodibility (1.11)	
					Open grazing	Cultivated	Open grazing	Cultivated	Open grazing	Cultivated
1	05.05.2004	3.31	00:30	6.62	0.068	0.008	1.380	0.000	0.460	0.000
2	10.05.2004	6.94	03:00	2.31	0.704	0.023	5.060	0.460	1.380	0.000
3	13.05.2004	8.66	02:00	4.33	0.993	0.050	5.060	0.460	1.840	0.000
4	13.05.2004	9.93	03:25	2.90	1.795	0.126	8.281	0.920	2.300	0.000
5	14.05.2004	18.94	03:40	5.17	9.082	0.432	18.401	1.380	5.520	0.460
6	15.05.2004	4.55	02:00	2.27	0.261	0.010	2.760	0.460	0.920	0.000
7	17.05.2004	15.28	02:10	7.05	8.258	0.380	17.481	1.380	5.060	0.460
8	23.05.2004	12.29	02:20	5.26	2.966	0.141	11.501	0.920	3.220	0.460
9	30.05.2004	11.62	02:10	5.36	3.479	0.080	11.961	0.920	3.680	0.000
10	31.05.2004	5.79	01:20	4.34	0.814	0.010	5.060	0.010	1.380	0.000
11	04.06.2004	16.24	03:00	5.40	3.761	0.085	13.801	0.920	4.140	0.000
12	12.06.2004	20.20	03:30	5.77	9.336	0.101	18.861	0.920	5.520	0.000
13	19.06.2004	16.78	02:30	6.71	4.389	0.080	14.721	0.460	4.140	0.000
14	29.06.2004	11.05	02:25	4.57	2.594	1.926	10.581	2.760	3.220	0.920
15	03.07.2004	9.01	01:40	5.41	1.797	1.094	11.501	2.300	3.220	0.460
16	12.07.2004	10.85	02:10	5.00	3.713	0.988	11.501	2.300	3.220	0.460
17	20.07.2004	16.43	02:15	7.30	8.205	1.342	17.481	2.760	5.060	0.920
18	04.08.2004	18.15	02:15	8.06	3.625	0.581	15.181	1.380	4.600	0.460
19	06.08.2004	3.78	00:50	4.54	0.106	0.015	1.840	0.460	0.460	0.000
20	13.08.2004	21.65	03:40	5.90	5.628	0.101	17.941	0.920	5.520	0.000
21	06.09.2004	17.70	03:10	5.58	2.559	0.040	14.721	0.460	4.140	0.000
22	12.09.2004	16.30	02:45	5.92	3.157	3.112	14.721	3.680	4.140	0.920
23	13.09.2004	17.00	02:15	7.55	5.251	4.180	17.481	4.600	5.060	1.380
24	17.09.2004	13.21	02:10	6.09	2.350	1.564	11.501	2.760	3.220	0.920

sediment yields were found to be 1.64 and 0.40 for open grazing and cultivated treatments, respectively.

Different relationships were then established between measured and estimated sediment yields when regression models were used. The best-fit models between predicted and observed sediment values that were selected based on maximum determination coefficient (R^2), minimum prediction error (RE) and maximum efficiency coefficient (C_E) criteria have been summarised in Table 3.

As can be seen in Table 3, the results from the HEM model are closer to the experimental measurements in the case of open grazing than for the cultivated areas. Because they meet acceptable statistical criteria, Eqs. (4)–(7) can be used to describe the relationship between estimated and measured sediment yields under open grazing conditions. Either Eqs. (5) or (7) can also be used to achieve accurate values of sediment yield following application of the model because they have similar statistics, although Eq. (5) is probably preferred because it uses the default erodibility value of 2.31. Although the minimum level of estimation error in the cultivated treatment was found to be 64.22% [Eq. (8)], both the coefficients of determination and efficiency were within the acceptable range. The other three equations [Eqs. (9)–(11)] were not found to have acceptable accuracy because of their low efficiency coefficient and high errors of estimation. In order to access an accurate model to regress the estimated values (X) values to the measured values (Y) for cultivated areas, transformed (i.e. logarithm, inverse, root and cubic) data were investigated and Eq. (12) (below) developed. With an estimation error of 47.00%, and coefficients of determination and efficiency of 0.98 it was found to be applicable for the rangeland areas under cultivation

$$Y^{0.5} = 0.4616X - 0.0256. \qquad (12)$$

Graphical presentations of best-fit models for both study areas are shown in Fig. 4. Sensitivity analysis was also conducted to determine the susceptibility of the HEM to the inputs in different levels. The results of this analysis are shown in Figs. 5 and 6.

5. Discussion

The efficacy and applicability of HEM were evaluated for storm-based sediment yield predictions under two rangeland management treatments for open grazing and cultivated areas in the Talesh region, Iran. The results of the study showed that the model could be used successfully to predict results in the case of the open grazed areas which was the type of area used for original development of the model (Lane *et al.*, 2001; http://eisnr.tucson.ars.ag.gov/hillslopeerosionmodel, 2007). It can be seen from the results in Table 3 that the default erodibility value provides good estimates for soil erosion in study treatments as similarly reported by Cogle

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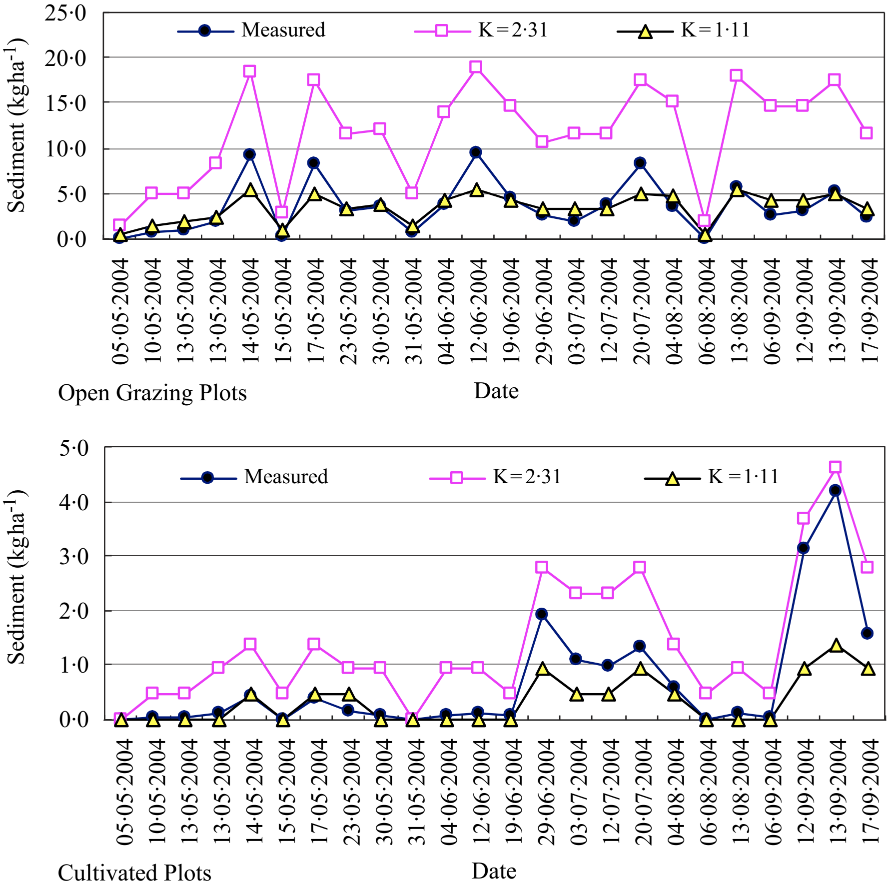

Fig. 3 – Representation of measured and estimated sediment with different erodibilities under open grazing (above) and cultivated (below) conditions.

Table 3 – Relationship between observed (Y) and estimated (X) sediment in kg ha^{-1}

Eq.	Treatment	Soil erodibility parameter	Regression	R^{2**}	RE (%)	CE
(4)	Open grazing	2.31	$Y = 0.4455X - 1.638$	0.77	141.30	0.78
(5)			$Y = 0.0418X^{1.7356}$	0.96	20.78	0.82
(6)		1.11	$Y = 1.5294X - 1.6513$	0.78	38.56	0.79
(7)			$Y = 0.3451X^{1.7558}$	0.96	21.53	0.83
(8)	Cultivated	2.31	$Y = 0.8547X - 0.5100$	0.91	64.22	0.94
(9)			$Y = 0.0215e^{1.4734X}$	0.85	107.69	0.42
(10)		1.11	$Y = 2.3368X - 0.0752$	0.82	105.92	0.81
(11)			$Y = 0.0451e^{4.0531X}$	0.78	108.96	0.49

R^2 is coefficient of determination.
** Significant at the level of 1%.
RE is the relative error and CE is the coefficient of efficiency.

et al. (2003) in New Zealand on clay loam soils. However, the variability of the estimate was high with some regression models, as indicated by the percentage difference between predicted and observed sediments. It was shown that the optimisation of the erodibility value for both areas could in some case increase the accuracy of the predictions. Because there was also substantial variability in the estimates, further optimisation was not found to be possible. This finding contradicts the work of Cogle *et al.* (2003), who used optimisation for experimental studies in India and Australia.

The results of regression modelling (Table 3 and Fig. 4) verified the possibility of applying of the HEM model with high [Eq. (3)] and acceptable [Eq. (10)] levels of accuracy, respectively. However, referring to the scatter plot (Fig. 4), it appears that the model may overestimate the sediment data. This could be due to climatic differences between the study site used here and the study area in the USA, where the model

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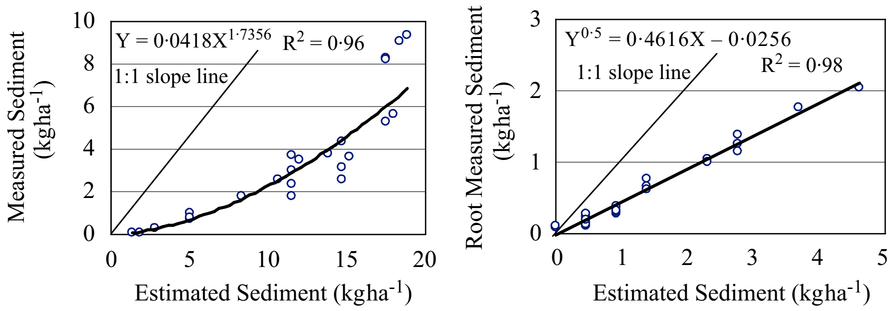

Fig. 4 – Optimal regression equations for application of HEM under open grazing (left) and cultivation treatments (right) with default erodibility value of 2.31.

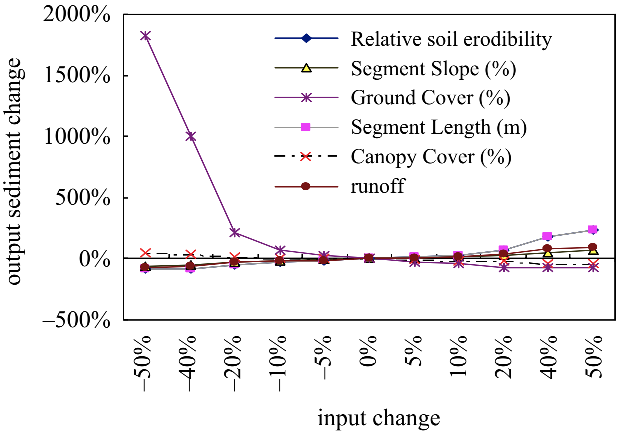

Fig. 5 – Sensitivity analysis of HEM under open grazing condition with default erodibility value of 2.31.

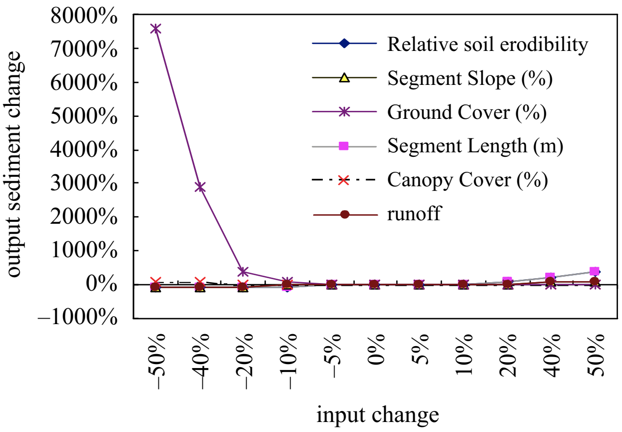

Fig. 6 – Sensitivity analysis of HEM under cultivated conditions with a default erodibility value of 2.31.

was originally developed, the complex and amorphous nature of the model, uncertainty in the input variables, and systematic model errors as mentioned by Stone *et al.* (1996).

The results of sensitivity analysis shown in Figs. 5 and 6 indicate that the model output is very sensitive to variations of ground cover but less sensitive to the slope steepness and canopy cover for both open grazing and cultivated areas. The variation of model outputs resulting from the changes made in model inputs is less in cultivated plots compared to open grazing plots because more consistent conditions occurred in the cultivated plots. The results obtained through sensitivity analysis can be efficiently used for accurate estimation of model inputs.

6. Conclusion

The Hillslope Erosion Model (HEM) was successfully applied on two open grazing and cultivated rangelands in the northern part of Iran. 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 has been carried out in this study. Nevertheless, no specific erosion model is currently available which can simulate sediment yield accurately without calibration. Further work with different datasets and further validation of the model in other crop management and land-use systems are required.

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