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Evaluating the RUSLE model and developing an empirical equation for estimating soil erodibility factor in a semi-arid region

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Abstract

Soil erodibility is one of six factors in the revised universal soil loss equation (RUSLE) that reflects the ease with which the soil is detached by splash during rainfall and/or by surface flow. This study was therefore carried out to assess applicability of the RUSLE model in estimating erodibility factor (K) and develop an appropriate equation to predict this factor in soils of the semi-arid region in Iran. Thirty six dry-farming lands were considered in a 900 km^2 agricultural zone in Hashtroud, northwest of the country. Soil loss was measured at 108 unit plots under natural rainfall events for a 2-year period from March 2005 to March 2007. The K-factor was estimated using the mean geometric diameter of soil particles (D_g) and measured based on the mean annual soil loss per unit rainfall-runoff erosivity factor (R). Based on the results, the estimated K values varied from 0.0316 and 0.0485 t h MJ^{-1} mm^{-1} and the measured K values were ranged from 0.0014 to 0.0050 t h MJ^{-1} mm^{-1}. The measured K values were almost 14 fold smaller than the estimated values on average. There was no considerable correlation between the measured K-factor and Dg ($R^2 = 0.05$). Multi-regression analysis showed that the measured K-factor was significantly related to the aggregate stability and permeability ($R^2 = 0.90$, $p < 0.001$). Although D_g was positively correlated with the soil permeability ($R^2 = 0.42$), it did not strongly affect the measured K-factor ($R^2 = 0.05$) because of its negative effect on aggregate stability ($R^2 = 0.64$)
Additional keywords: aggregate stability; permeability; soil loss; unit plot.

Resumen

Evaluación del modelo RUSLE y desarrollo de una ecuación empírica para estimar el factor de erosionabilidad del suelo en regiones semi-áridas

La erosionabilidad del suelo, uno de los seis factores considerados en la ecuación universal de pérdida de suelos revisada (RUSLE), refleja la facilidad con que el suelo se desprende por la acción de la lluvia y/o del flujo superficial. Este estudio se realizó para evaluar la aplicabilidad del modelo RUSLE en la estimación de factor de erosionabilidad (K) y desarrollar una ecuación apropiada para predecir este factor en suelos de la región semiárida de Irán. Se consideraron 36 fincas de secano en una zona agrícola de 900 km^2 en Hashtroud, al noroeste del país. Se midió durante 2 años la pérdida de suelo en 108 parcelas elementales en condiciones de lluvia natural, desde marzo de 2005 hasta marzo de 2007. Se estimó el factor K utilizando la media geométrica del diámetro de las partículas (D_g) basada en la pérdida media anual de suelo por unidad del factor de erosividad lluvia-escorrentía (R). Los valores de K estimados variaron entre 0,0316 y 0,0485 t h MJ^{-1} mm^{-1} mientras que los valores medidos de K variaron entre 0,0014 y 0,0050 t h MJ^{-1} mm^{-1}. Los valores de K medidos fueron casi 14 veces menores de media que los valores estimados. No había una correlación considerable entre el factor K medido y el D_g ($R^2 = 0{,}05$). Un análisis de regresión múltiple mostró que el factor K medido estaba relacionado significativamente con la estabilidad y permeabilidad de los agregados ($R^2 = 0{,}90$, $p < 0{,}001$). Aunque D_g estaba correlacionado positivamente con la permeabilidad del suelo ($R^2 = 0{,}42$), no afectó aparentemente al factor K medido ($R^2 = 0{,}05$), debido probablemente a su efecto negativo sobre la estabilidad de los agregados ($R^2 = 0{,}64$).
Palabras clave adicionales: estabilidad de los agregados; parcela elemental; pérdida de suelo; permeabilidad.

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Abbreviations used: AS (aggregate stability); MWD (mean weight diameter of the stable aggregates); RUSLE (revised universal soil loss equation); SOC (soil organic matter); SP (soil permeability); USLE (universal soil loss equation).

Introduction

Soil erosion is a great threat to long-term agricultural sustainability (Montgomery, 2007). Effective land management strategies depend upon an improved assessment and understanding of soil loss rates from agricultural land (Casalí *et al.,* 2009). Erosion prediction models can help address long-range land management planning under natural and agricultural conditions (Angima *et al.,* 2003). The Revised Universal Soil Loss Equation (RUSLE; Renard *et al.,* 1997) is an empirically based model, founded on the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978), but is more diverse and includes databases unavailable when the USLE was developed (Renard *et al.,* 1997). This model is a practical, flexible and increasingly popular choice to provide soil loss estimates in the preparation of environmental impact assessments, reclamation plans, and post-reclamation site evaluations for land subjected to mining and construction (Toy *et al.,* 1999).

The RUSLE model computes the average annual erosion expected on hillslopes by multiplying several factors together: rainfall-runoff erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and support practice (P) (Renard *et al.,* 1997). The R-factor is measured as the product (EI_{30}) of total storm energy (E) and the maximum 30-min intensity (I_{30}) for all storms over a long time (Brown and Foster, 1987). The K-factor is the inherent susceptibility of soil to be lost to erosion (Renard *et al.,* 1997) and reflects the ease with which the soil is detached by splash during rainfall and/or by surface flow. This factor accounts for the influence of soil properties on soil loss during storm events on sloping areas (Foster, 1982). The LS-factor accounts for the effect of slope length and slope gradient on erosion (Renard *et al.,* 1997). The C-factor measures the effects of all interrelated cover and management variables (Renard *et al.,* 1991). The P-factor is the ratio of soil loss with specific support practice to the corresponding loss with up and down slope tillage (Renard and Foster, 1983).

In the unit/standard plot which is defined as a ploughed-continuous fallow land having a uniform 9% slope steepness and 22.1 m length (Wischmeier and Smith, 1978), values of L, S, C and P factors are equal to one. Therefore, within the RUSLE model framework, the soil erodibility factor (K) can also be defined as the soil loss per unit of erosivity factor (R) from a unit plot. In different unit plots installed in unlike places of a region which receive the same rainfalls, the soil loss rate is only related to the soil K factor. Under these conditions, soil physicochemical properties will have fundamental roles in variations of soil loss in different places of the region. Thus, determining K factor and its effective soil properties is essential to soil erosion predict using the RUSLE model (Zhang *et al.,* 2008).

As direct measurement of the K factor requires long-term erosion monitoring, which is costly and time-consuming (Cantón *et al.,* 2009), techniques have been developed to estimate the K factor values from readily available data on soil properties. Of particular interest to this study, Wischmeier and Smith (1978) and Römkens *et al.* (1977) proposed some equations for soil erodibility estimation under miscellaneous conditions. In the RUSLE model, K factor is commonly estimated based on the mean geometric diameter of soil particles, D_g (Römkens *et al.,* 1977), while in the USLE model, it must be estimated using the nomograph developed based on different soil properties consists of soil particles, organic matter, structure and permeability (Wischmeier and Smith, 1978). Nevertheless, the RUSLE model was only used for soils with less than 10% of rock fragments are considered. The advantage of the RUSLE model is that it has been widely used and tested over many years and the validity and limitations of this model are already known (Renard *et al.,* 1997). The disadvantage of this model is that it was developed using data from the Midwest of the USA, and therefore large variations exist in the estimation of soil erosion in other areas particularly in the semi-arid regions. Thus, the significant adjustments on the erosional factors such as the K factor are required to the algorithms used to derive the key factors before the model can be applied to other areas (Shamshad *et al.,* 2008), particularly the semi-arid regions. Most soils located in the semi-arid regions have high amounts of carbonates such as calcite, aragonite and dolomite (Vaezi *et al.,* 2008). Calcium (Ca^{2+}) is a dominant cation in these minerals which can be effective in flocculation of mineral colloids and accordingly aggregate stability. It is well known that aggregate stability is one main property regulating soil erodibility (Le Bissonnais, 1996). So, in the soils of the semi-arid regions, calcium may play a key role in aggregation and consequently declining the soil's susceptibility to water erosion. Thus, effectiveness of calcium must be taken into account in estimating soil erodibility factor in the semi-arid regions.

About 39% (0.643 million km^2) of the total area of Iran is located in a semi-arid climate (Khaksarfard, 1995). The East-Azarbijan province is one of the semi-arid regions in the north west of the country which mainly has calcareous/limy soils with more than 10% lime (total carbonates). In this area, the farming is mostly done in dry conditions. Soil erosion by water is as a main factor in reducing crop production particularly in sloping fields especially where the fields are cultivated up to down slope. Since estimating the erodibility factor using the RUSLE procedure is easier than the USLE nomograph, it can be used to find out susceptible lands to water erosion in the area. So far, no quantitative study has been reported on assessing the RUSLE model in estimating *K*-factor in the calcareous soils of the semi-arid regions, particularly in Iran. The aims of this study were to assess the RUSLE model in estimating *K*-factor, determine soil properties affecting *K*-factor, and propose an appropriate method to predict the *K*-factor in soils of this semi-arid region.

Material and methods

Study area

The study was conducted in the Hashtroud township of the East-Azarbijan province located in north west of Iran. Field measurements of the soil loss were done in an agricultural region with 900 km^2 in area located between 37° 18' and 37° 35' N latitude, and 46° 46' and 47° 06' E longitude, and about 1,370 m above sea level. Climate is semi-arid with an average annual precipitation of 322 mm. Rainfall mostly comes during two periods (spring season from March to May and autumn season from October to December). Soils are classified as Inceptisols (Hakimi, 1986). Based on field observations, soil erosion by water mainly has occurred as sheet (surface), rill and gully in the study area. In the study area, thirty six grids with a dimension of 5 × 5 km were considered (Fig. 1). The similar lands having a southern slope steepness of 9% were then selected using the Ilwis-3 software (ITC, 2001). In the southern slopes, evaporation rate is higher usually than the northern slopes and so can nearly reduce the effect of antecedent moisture in the runoff generation and soil loss. In these slopes, the lands with 9% slope steepness were considered in agreement with the unit plot conditions as proposed by Wischmeier and Smith (1978). Locations of the selected lands were determined by the global positing system (GPS). Based on the field observations, a dry-farming land having a uniform slope of 9% and under fallow condition was considered to establish three unit erosional plots. Before plowing, crop residues were removed from soil surface. In each dry-farming land, three closed unit plots having 1.83-m width and 22.1-m length and without crop cover with a spacing of 1.2 m were established in slope length on early March 2005. The plots were maintained in a bare condition during the study period using herbicide treatment. At the lower parts of the plots, runoff-collecting equipments consisting of gutter pipes, pipes and 70-L tanks were established (Vaezi *et al.,* 2008).

Soil loss (A)

Soil loss was measured at 108 unit plots (36× 3 plots) in the area under natural rainfall events for a 2-year period from March 2005 to March 2007. After each rainstorm resulting runoff and sediment, total tank contents was measured and accordingly its sediment concentration was determined in a uniform sample of 500 mL. The soil loss in each rainstorm was calculated through multiplying the total tank contents volume by the sediment concentration (Zhang *et al.,* 2008). Annual soil loss value of each plot was computed from the sum of the soil loss values for all rainstorms occurred during 1 year. Based on the annual soil loss values of three unit plots installed in each land, average annual soil loss of each dry-farming land was calculated. Mean annual soil loss of the each land was computed using average annual soil loss values of its three unit plots at the first and second years.

Rainfall-runoff erosivity factor (*R*)

Rainfall properties (depth and duration time) were measured throughout first and second year in the study area with the help of an automatic tipping rain gauge located in grid 17 (Fig. 1) tipping each every one minute. The data were used to calculate the individual total storm kinetic energy (E) in MJ ha^{-1} and the maximum 30-min intensity (I_{30}) in mm h^{-1}. The average rainfall-runoff erosivity factor (R) in MJ mm ha^{-1} h^{-1} yr^{-1} was then calculated by using the following equation (Renard and Freidmund, 1994):

$$R = \frac{\sum_{i=1}^{j} (EI_{30})_i}{N} \qquad [1]$$

where $(EI_{30})_i$ is the erosivity index for storm i, j the number of storms in an N year period. The total storm kinetic energy E, in MJ ha^{-1} was calculated by:

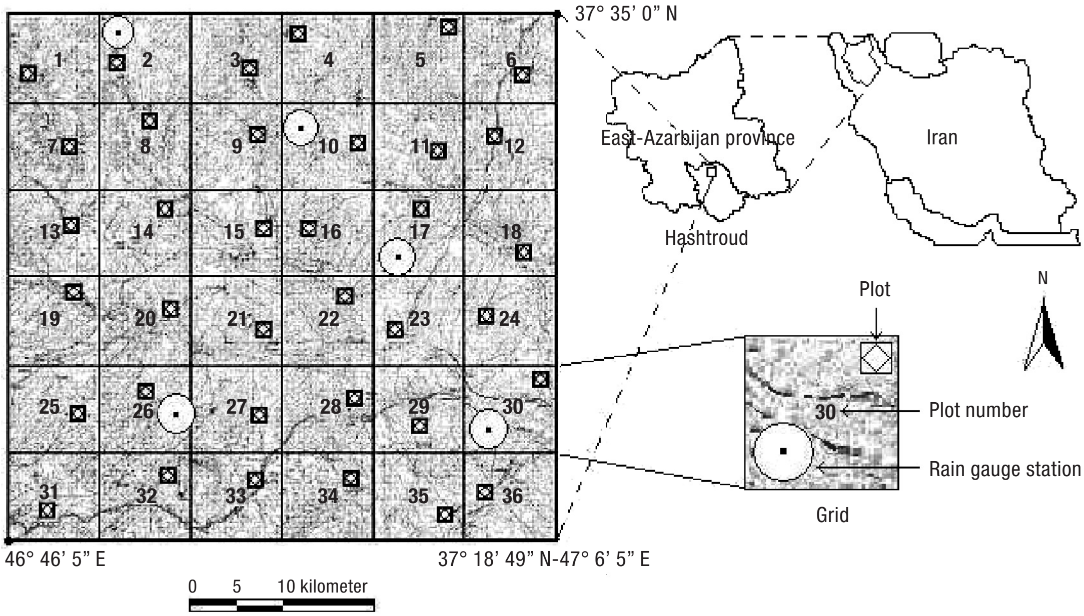

Figure 1. Location of the study area, grids, erosion plots and rain gauge stations in northwestern Iran.

$$E = KE \cdot d \quad [2]$$

$$KE = \sum_{i=1}^{i} e_r \Delta V_r \quad [3]$$

$$e_r = 0.29[1 - 0.72exp(-0.05i_r)] \quad [4]$$

where KE is the rainfall energy per unit of rainfall depth in MJ ha^{-1} mm^{-1}, d is the rainfall depth in mm^{-1}, e_r is is the rainfall energy per unit of rainfall depth and duration in MJ ha^{-1} mm^{-1} h^{-1} (Brown and Foster, 1987), i_r the rainfall intensity for a particular increment in a rainfall event (mm h^{-1}), and V_r the duration of the increment over which i_r is constant in hours (h). The R-factor was calculated as an average of ΣEI_{30} values measured over a-two year.

Since spatial variations of the rainfall influence on runoff generation and consequently soil loss in different places (Wang *et al.,* 2001; Kim *et al.,* 2009), spatial distribution of the rainfalls was tested based on data of the rainfall depth in four different raingauge stations in the study area (Fig. 1). Immediately after each event resulting runoff at the plots, rainstorm depth values were measured in three standard rain gauge stations placed in the grids 2, 10 and 26, and extracted from an automatic recording rain gauge located in grid 17.

Soil erodibility factor (*K*) of the RUSLE model

To determine the soil erodibility factor (K), the average soil loss of each plot (A) per unit area per year (t ha^{-1} yr^{-1}) was also calculated for a two-year period. The K-factor value of each plot was obtained using the RUSLE (Renard *et al.,* 1997; USDA-ARS, 2001) by the following equation:

$$A = R \times K \times L \times S \times C \times P \quad [5]$$

$$K = A / (R \times K \times L \times S \times C \times P) \quad [6]$$

where A is the average soil loss due to water erosion (t ha^{-1} yr^{-1}), R is the rainfall and runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), L is the slope length factor (unitless), S is the slope steepness factor (unitless), C is cover management factor (unitless), and P is the conservation support practice factor (unitless).

Since in the unit plots, values of the L, S, C, and P factors were equal to one, the K-factor value of each plot was calculated using the simple equation as follows:

$$K = A / (R \times 1 \times 1 \times 1 \times 1) = A / R \quad [7]$$

where A is the average soil loss (t ha^{-1} yr^{-1}), and R is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}).

To comparing the measured K-factor values with its estimated values, the K-factor value for each plot was also estimated on the basis of the mean geometric diameter of soil particles using the fallowing equation (Renard *et al.,* 1997):

$$K = 0.0034 + 0.0405exp\left[-0.5\left(\frac{LogD_g + 1.659}{0.7101}\right)^2\right] \quad [8]$$

$$D_g = exp(0.01\sum_{i=1}^{n} f_i \, lnM_i) \quad [9]$$

where D_g is the mean geometric diameter of soil particles (mm), f_i is proportion of soil particle (%), and M is average size of soil particle (mm).

The measured and estimated K-factor values of each dry-farming land located in each grid were calculated from averaging the K-factor values of their three unit plots.

Soil physicochemical properties

Soil physicochemical properties of each plot were determined in a composite soil sample taken from the top 30 cm of the plot, randomly. The soil samples were ground to pass a 2 mm sieve and stored in sealed polyethylene bags in a cool and dry place until the physicochemical analysis in the laboratory. The particle size distribution [coarse sand (0.1-2 mm), very fine sand (0.05-0.1 mm), silt (0.002-0.05) and clay (< 0.002 mm)] was determined by the Robinson's pipette method (SSEW, 1982). Gravel (2-8 mm) was determined using the weighting method (Gee and Bauder, 1980). The total soil organic carbon (SOC) was measured by the Walkley-Black wet dichromate oxidation method (Nelson and Somers, 1982) and converted to organic matter through multiplying it by 1.724. Lime was determined based on consumed volume of acid acetic to neutralize total carbonates in soil sample (Goh *et al.,* 1993). Available potassium was also measured using the ammonium acetate extraction method (Knudsen *et al.,* 1982). Mean weight diameter (MWD) of water-stable aggregates was calculated using the wet-sieving method (Angers and Mehuys, 1993). A 100 g aggregate (6-8 mm in diameter) was pre-wetted overnight to reduce the effect of slaking. The aggregates were then introduced into a nest of oscillating sieves of 8, 6, 4, 2, 1, 0.5 and 0.25 mm immersed in deionized water for 1 minute. Any soil that passed through the 0.25 mm constituted the unstable aggregate fraction for this procedure. The material retained was dried in oven in the sieves at 105°C for 24 h and then weighed. Then material retained on each sieve was gently crushed under running water, allowing the smaller particles to be washed through the sieve, while sand was retained on the sieve. After oven-drying sieves, sand fractal of the material was determined. Soil permeability was determined in the field based on the final infiltration rate for each study plot by measuring the one-dimensional water flow into the soil per unit time by double-ring infiltrometer (Bouwer, 1986) at four to six replications. The infiltration measurements were carried out at the end of the dry season (in July 2005) in order to exclude the influence of different initial moisture contents.

Statistical analysis

To determine spatial homogeneity of the rainstorms resulting runoff-sediment in the study area, a Duncan's parametric test was used at $p = 0.05$ to establish significant differences between rain gauge stations. Difference between the measured and estimated K-factor values was assessed using the t-test. Data of soil physicochemical properties and K-factor were evaluated for normality using the Kolmogorov-Smirnov test prior to the regression analysis. To find out the soil properties influencing the soil erodibility factor in the study area, bivariate relationships between the measured K-factor and soil properties were determined using the Pearson's correlation. A stepwise multiple regression analysis was applied to develop an equation for estimating the K-factor based on the effective soil properties. To evaluate the accuracy of the equation, the standard error of the estimate was determined using the predicted and observed K values.

Results and discussion

Rainfall-runoff erosivity factor (*R*)

Data of the raingauge recording station located in grid 17 showed that mean annual precipitation in the study area was 322 mm for a 2-year study period. Ninety seven rainfall events with a duration beyond 30 min occurred during the 2-year period (Table 1). Rainfall intensity varied from 0.1 to 13.78 mm h^{-1} with an average of 2.76 mm h^{-1}. Values of the rainfall-runoff erosivity index (EI_{30}) were between 0.000822 and 110.8 MJ mm ha^{-1} h^{-1}. Mean rainfall-runoff erosivity factor (R) for a 2-year period was 512.0 MJ mm ha^{-1} h^{-1} yr^{-1}. Soil loss at the plots was caused by 41 rainstorms for a 2-year period. Properties of the rainstorms resulted soil loss in the study area are shown in Table 2. The intensity values of the rainstorms were between 2.11 and 13.78 mmh^{-1}. The rainfall-runoff erosivity index of the rainstorms (EI_{30} in the RUSLE) varied from 0.476 to 110.8 MJ mm ha^{-1} h^{-1}, with an average of 20.2 MJ mm ha^{-1} h^{-1}. The minimum erosivity index (0.476 MJ mm ha^{-1} h^{-1}) was as the threshold erosivity for events that

Table 1. Statistical characteristics of ninety seven rainfall events with a duration beyond 30 min from March 2005 to March 2007

Rainfall characteristics	Minimum	Maximum	Mean	St. D.
Intensity, I (mm h^{-1})	0.10	13.78	2.76	2.55
Maximum 30-min intensity, I_{30} (mm h^{-1})	0.10	25.00	4.88	4.99
Energy, E (MJ ha^{-1})	0.08×10^{-1}	13.24	1.15	2.12
Erosivity index, EI_{30} (MJ mm ha^{-1} h^{-1})	0.08×10-2	110.79	10.34	21.98

caused runoff at the plots due to incensement of the antecedent soil moisture.

Rainfall data analysis showed that the erosivity index (EI_{30}) exponentially and linearly related to rainfall depth with an R^2 of 0.98 and 0.90, respectively (Fig. 2). Regarding strong correlation between the EI_{30} and depth of the rainstorms, depth data was used to analysis spatial homogeneity of the EI_{30} in the study area. The mean depth of the rainstorms in the rain gauge stations located in grids 2, 10, 17 and 30 were 7.22, 6.59, 6.98 and 6.84 mm, respectively. There was no significant difference among the rainstorms depth values of the different rain gauge stations (F = 0.027, p-value = 0.994). In fact, the spatial distribution of the EI_{30} in the study area was uniform. Thus, R-factor values were then supposed to be equal for the entire unit plots distributed throughout the study area.

Soil loss

The mean annual values of the soil loss at the plots varied from 0.674 to 2.43 t ha^{-1} with an average of 1.517 t ha^{-1} (Table 3). The soil loss at the plots was significantly affected by the rainfall-runoff erosivity index (EI_{30}) of the rainstorms as shown in Figure 3 ($p < 0.001$, $R^2 = 0.80$). There was a significant difference in the soil loss values among study plots ($p < 0.001$). Since values of R, L, S, C, and P at the plots were alike, the differences in the soil losses among the plots could be simply pertained to soil erodibility variability.

Soil erodibility factor (*K*)

The mean measured values of the soil erodibility factor (K) varied from 0.0014 to 0.0050 t h MJ^{-1} mm^{-1} with an average of 0.0031 t h MJ^{-1} mm^{-1}. The estimated K-factor values were also between 0.0316 and 0.0485 t h MJ^{-1} mm^{-1} with an average of 0.0388 t h MJ^{-1} mm^{-1} (Table 3). Statistical distributions of data of the measure and estimated K-factor were normal. The measured values of the K-factor were statistically 13.87 fold smaller than their estimated values. This result accords with findings of Hussein *et al.* (2007) who showed that the measured USLE-K factor considerably is smaller than the estimated values. The relationship between the measured and estimated values of the K-factor as shown in Figure 4 was not significant

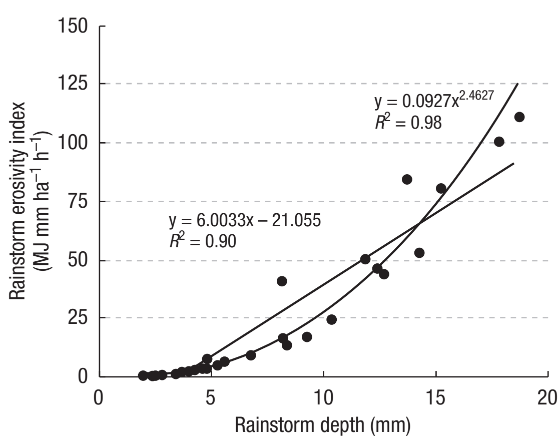

Figure 2. Relationship between the depth and the erosivity index (EI_{30}) of the rainstorms.

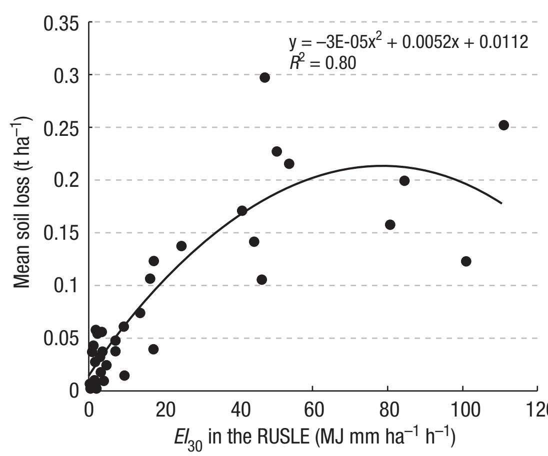

Figure 3. Relationship between the soil loss and rainfall-runoff erosivity index (EI_{30}) of the RUSLE in the study area.

Table 2. Properties of the rainstorms resulted soil loss in the study area from March 2005 to March 2007

Date	h[a] (mm)	D[b] (h)	I[c] (mm h^{-1})	I_{30}[d] (mm h^{-1})	E[e] (MJ ha^{-1})	EI_{30}[f] (MJ mm ha^{1} h^{-1})
March 2005 to March 2006						
April 2	2.55	1.15	2.21	3.0	0.302	0.906
April 3	3.65	1.36	2.68	3.2	0.533	1.706
April 14	13.7	3.40	4.03	15.2	5.557	84.470
April 15	2.70	1.00	2.70	3.0	0.290	0.871
April 16	4.80	1.30	3.70	4.8	0.727	3.488
April 17	3.70	1.10	3.36	5.4	0.462	2.494
April 26	17.85	6.98	2.56	7.6	13.242	100.643
April 27	2.80	0.70	4.00	5.4	0.233	1.260
May 3	8.35	1.50	5.58	8.4	1.654	13.891
May 4	2.00	0.71	2.82	3.8	0.154	0.586
May 5	2.50	0.73	3.42	4.8	0.208	0.999
May 6	4.20	1.15	3.65	5.0	0.560	2.802
May 14	11.90	1.18	10.08	21.8	2.301	50.161
May 15	12.40	0.90	13.78	22.8	2.066	47.115
May 16	8.10	1.60	5.06	25.0	1.657	41.431
May 19	12.50	2.10	5.95	13.0	3.542	46.045
May 20	10.40	1.30	8.00	12.2	2.028	24.748
May 31	3.50	0.50	7.00	7.0	0.250	1.750
Jun 2	1.90	0.77	2.47	3.6	0.154	0.555
August 28	15.30	1.38	11.08	22.4	3.5897	80.409
February 4	4.00	0.65	6.15	6.8	0.355	2.413
February 9	2.40	0.58	4.13	4.6	0.167	0.769
March 8	9.30	4.00	2.32	4.4	3.871	17.034
March 2006 to March 2007						
March 29	5.30	0.84	6.31	8.2	0.613	5.027
April 5	4.25	1.67	2.54	5.2	0.753	3.916
April 7	6.70	3.17	2.11	4.2	2.168	9.108
April 17	12.70	1.61	7.89	14.5	3.052	44.132
April 24	4.20	1.50	2.80	5.0	0.683	3.417
April 25	3.30	1.25	2.64	4.0	0.441	1.766
April 26	5.60	1.83	3.60	6.0	1.185	7.108
May 3	8.10	2.38	3.40	7.4	2.195	16.240
May 4	4.00	1.36	2.94	4.2	0.597	2.507
May 5	3.40	1.34	2.54	4.0	0.483	1.934
May 6	4.80	1.860	2.58	7.6	0.950	7.224
May 10	6.80	1.80	3.78	6.6	1.434	9.464
Jun 29	4.10	0.50	8.20	8.2	0.310	2.545
September 17	18.70	3.50	5.35	13.0	8.522	110.787
October 15	4.60	0.50	9.90	9.8	0.374	3.668
October 20	2.00	0.50	4.00	4.0	0.119	0.476
November 25	14.30	2.15	6.65	12.4	4.312	53.474
November 27	8.10	1.77	4.56	9.6	1.774	17.035

[a] *h* is rainstorm depth. [b] *D* is rainstorm duration. [c] *I* is rainstorm intensity. [d] I_{30} is maximum 30 min intensity of the rainstorm. [3] *E* is rainstorm energy of the RUSLE for each rainstorm. [f] *EI30* is erosivity index of the RUSLE for each rainstorm.

($p < 0.001$, $R^2 = 0.01$). This result revealed that the mean geometric diameter of soil particles (D_g) was not an accurate index to explore soil sensitivity to the rainfall-runoff erosive factors. Thus, the influencial soil properties or the way these properties affected the erodibility factor were not those considered in the RUSLE model. Besides this, the measured *K*-factor values in different dry-farming lands had a significant difference ($p < 0.001$). Spatial variability of the *K*-factor was due to variations of the soil properties in different plots as

Table 3. Mean annual soil loss and the measured and estimated soil erodibility factor (K) of the RUSLE at the plots in the study area

Plot No.	Soil loss ($t\ ha^{-1}$)	RUSLE-*K* factor ($t\ h\ MJ^{-1}\ mm^{-1}$)	
		Measured	Estimated
1	2.431	0.0050	0.0344
2	2.097	0.0040	0.0428
3	2.353	0.0048	0.0347
4	1.476	0.0032	0.0338
5	2.110	0.0043	0.0359
6	0.737	0.0018	0.0337
7	1.131	0.0029	0.0316
8	1.039	0.0021	0.0349
9	1.613	0.0033	0.0384
10	1.950	0.0039	0.0388
11	1.714	0.0034	0.0421
12	0.906	0.0020	0.0405
13	2.358	0.0045	0.0476
14	1.731	0.0034	0.0423
15	1.732	0.0037	0.0360
16	0.722	0.0019	0.0344
17	0.826	0.0016	0.0378
18	1.755	0.0036	0.0351
19	2.034	0.0040	0.0451
20	1.491	0.0033	0.0369
21	0.871	0.0018	0.0419
22	1.235	0.0027	0.0357
23	1.745	0.0035	0.0330
24	1.469	0.0030	0.0363
25	2.193	0.0041	0.0485
26	0.964	0.0019	0.0444
27	0.842	0.0018	0.0408
28	2.165	0.0042	0.0440
29	1.559	0.0032	0.0405
30	1.765	0.0034	0.0349
31	1.350	0.0029	0.0392
32	0.674	0.0014	0.0395
33	1.314	0.0025	0.0416
34	1.273	0.0026	0.0381
35	1.532	0.0030	0.0414
36	1.444	0.0029	0.0404

shown by Wang *et al.* (2001). Thus, there was a need to find out factors affecting the K-factor and accordingly develop a reliable method to prediction of the K factor in the study area.

Modeling RUSLE *K*-factor

Modeling soil erodibility factor is very complicated because the soil loss rate resulting erosive factors is determined not only by its multiple factors, but also by the interaction between the factors. In this reason, proposing a proper index to estimate K-factor would be relatively difficult. However, to remove interaction between the soil properties influencing erodibility factor can group them into two categories: (1) independent soil properties consist of mineral particles, organic matter, carbonates etc.; and (2) dependent soil properties such as structure stability and permeability which affected by the independent properties. Table 4 shows the soil properties related to erodibility factor (K) in the study area. The soils were mostly clay loam having 36.7% sand, 31.6% silt and 32.0% clay and having very little organic matter (1.09%). Mean geometric diameter (D_g) of soil particles was 0.37 mm on average. The soils were calcareous/limy with a moderate carbonates (12.66%). Aggregate stability of the soils was very weak with a mean weight diameter (MWD) of 1.13 mm. Permeability (infiltrability) of the soils varied from

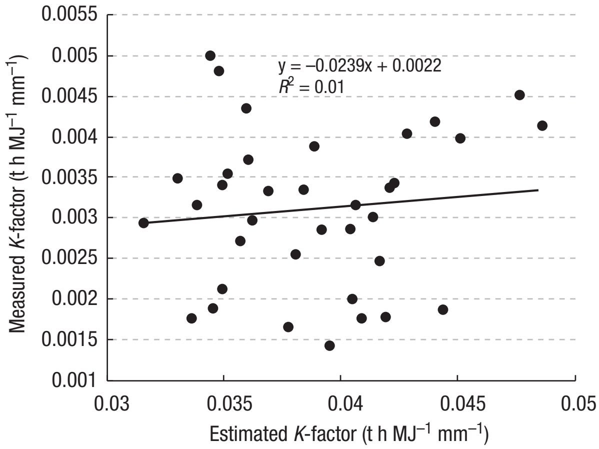

Figure 4. Relationship between measured and estimated RUSLE K-factor in the study area.

Table 4. The soil properties related to erodibility factor in the study area

Soil property	Mean	St. D.
Coarse sand (%)	18.90	5.19
Very fine sand (%)	17.80	3.21
Total sand (%)	36.70	6.91
Silt (%)	31.60	7.12
Clay (%)	32.00	5.75
Mean geometric diameter/D_g (mm)	0.37	0.01
Gravel (%)	9.89	2.37
Organic matter (%)	1.09	0.25
Lime (%)	12.66	5.25
Potassium ($mg\ kg^{-1}$)	314.68	25.41
Structure stability in water/MWD (mm)	1.13	0.44
Permeability ($cm\ h^{-1}$)	3.56	1.16

Table 5. The correlation matrix between the RUSLE *K*- factor and the soil properties

Variable	CS[a]	VFS[b]	Silt	Clay	D_g[c]	Gr[d]	OM[e]	Lime[f]	Pot[g]	MWD[H]	Per[i]	*K*-factor[j]
CS	1											
VFS	0.22	1										
Silt	–0.74***	–0.18	1									
Clay	–0.18	–0.50**	–0.40*	1								
D_g	0.69**	0.66**	–0.25	–0.75***	1							
Gr	0.03	–0.01	0.02	–0.06	0.07	1						
OM	0.27	–0.21	–0.23	0.21	0.04	0.16	1					
Lime	–0.00	–0.56**	0.17	0.03	–0.24	–0.03	0.05	1				
Pot	–0.07	–0.05	–0.18	0.31*	–0.22	0.09	0.06	–0.09	1			
MWD	–0.17	–0.67**	–0.12	0.70***	–0.64**	–0.09	0.29*	0.48**	0.22	1		
Per	0.76***	–0.05	–0.55**	–0.07	0.42**	0.09	0.54**	0.29*	0.08	0.13	1	
K–factor	–0.47**	0.45**	0.44**	–0.32*	0.05	–0.13	–0.55**	–0.56**	–0.16	–0.66**	–0.77***	1

[a] CS: coarse sand. [b] VFS: very fine sand. [c] D_g: mean geometric diameter of the soil particles. [d] Gr: gravel. [e] OM: organic matter. [f] Lime: total neutralized carbonates based on the calcium carbonate. [g] Pot: potassium. [h] MWD: mean weight diameter of water-stable aggregates. [i] Per: permeability (final infiltration rate). [j] *K*-factor: measured soil erodibility factor in the RUSLE. * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

1.4 to 5.8 cm h^{-1}, with an average of 3.5 cm h^{-1}. The soils have a moderate value of gravel (9.89%) and a relatively high value of potassium (315 mg kg^{-1}).

To determine soil properties influencing the *K*-factor, correlation between the measured *K*-factor and the independent and dependent soil properties were computed (Table 5). The measured *K*-factor significantly correlated with the independent soil properties including coarse sand ($p < 0.01$), very fine sand ($p < 0.01$), silt ($p < 0.01$), clay ($p < 0.05$), lime ($p < 0.01$), organic matter ($p < 0.01$). Very fine sand and silt contrary to coarse sand, clay, lime and organic matter, increased the soil erodibility factor (Table 5). The mean geometric diameter of the soil particles (D_g) similar to gravel and potassium had not considerable effect on the *K*-factor. The measured *K*-factor was also considerably correlated with the dependent soil properties *i.e.* the aggregate stability ($R^2 = 0.66$, $p < 0.01$) and soil permeability ($R^2 = 0.77$, $p < 0.001$). With an increasing in the aggregate stability and soil permeability, the *K*-factor remarkably decreased. There was no significant correlation between the aggregate stability and soil permeability. Results indicated that the RUSLE *K*-factor is significantly related to the aggregate stability and soil permeability ($R^2 = 0.90$, $p < 0.001$). Table 6 shows the multiple regression analysis of relationship between the measured soil erodibility factor and the aggregate stability and soil permeability.

Based on the multi-regression analysis, the following equation was developed to predict soil erodibility factor:

$$K = 0.00654 - 0.00122\ \mathrm{AS} - 0.00057\ \mathrm{SP} \qquad [10]$$

where AS is the aggregate stability based on the mean weight diameter (MWD) of the water- stable aggregates (mm) and SP is the permeability based on the final infiltration rate (cm h^{-1}). The standard error of the equation to estimate was 0.000296.

Hoyos (2005) reported that the *K* factor remarkably depends on the aggregate stability and soil permeability. Misra and Teixeira (2001) also showed that the development of cohesive bonds in structural units im-

Table 6. The linear-regression analysis of the relationship between the soil erodibility factor (RUSLE-*K*) and the aggregate stability and permeability in the study soils

Factors	Unstandardized coefficient	Standard error	Standardized coefficient	*t*-value	*p*-level
Constant	0.00654	0.00020		32.754	0.000
AS[a]	–0.00122	0.00012	–0.564	–10.410	0.000
SP[b]	–0.00057	0.00004	–0.694	–12.811	0.000

[a] AS: aggregate stability based on the mean weight diameter of water-stable aggregates, in mm.
[b] SP: soil permeability based on the final infiltration rate, in cm h^{-1}.

proved the stability of soil aggregate and consequently declined the soil erodibility. Some authors have demonstrated that the stability of topsoil aggregates is a valuable indicator to determine soil erodibility (Barthès and Roose, 2002; Cantón *et al.,* 2009). Importance of hydrological soil properties especially infiltration rate on the soil erodibility was well known in several studies (Yu *et al.,* 2006; Zehetner and Miller, 2006). The results showed that soil properties that affect the aggregate stability and soil permeability can control soil erodibility. Coarse sand, very fine sand, silt, clay, organic matter, and lime were important soil properties influencing the *K*-factor in the study area owing to their significant effects on either aggregate stability or soil permeability.

As shown in Table 5, the aggregate stability was affected by several different soil properties. Clay acted as a binding agent, improving the aggregation of soil colloids as shown by Skidmore and Layton (1992). Effect of clay in improving the aggregation and consequently declining *K* factor has been concluded in studies of Loch and Pocknee (1995). Due to negative effect of very fine sand on the aggregate stability, the D_g also significantly decreased the aggregate stability. Contrary to findings of De-Moreno and Heras (2009) in this work no negative considerable correlation was observed between coarse sand and the aggregate stability. Organic matter caused a distinct increase in the aggregate stability (Franzluebbers, 2002) and declined the *K* factor (Rodríguez *et al.,* 2006). Effect of the calcium carbonate (lime) on the aggregate stability also agrees with Al-Ani and Dudas (1988) who showed that addition of calcium carbonate content from 0 to 4% to soil samples increases the MWD of the soil aggregates.

The soil permeability was considerably related to coarse sand ($p < 0.001$), silt ($p < 0.01$), D_g ($p < 0.01$), organic matter ($p < 0.01$), and lime ($p < 0.05$). Silt dissimilar to other soil properties declined the soil permeability (Table 5). Since coarse sand greatly increased the soil permeability, effect of D_g on the soil permeability was positive. Due to the negative influence of very fine sand and silt on one of the two dependent soil properties *i.e.* the aggregate stability and soil permeability, soil erodibility was greatly increased. The effect of organic matter in decline of the soil erodibility was largely related to its main role in enlarging soil permeability. This result agrees with Tejada and González (2006), who reported that SOC plays a key role in increasing the soil permeability and its resistance against water erosion. Although lime increased the soil permeability, but its effect in declining the *K*-factor was largely related to its remarkable role in improving the aggregate stability. Despite D_g significantly increased the soil permeability, due to its negative role in the aggregate stability, it had not remarkable effect on the *K*-factor. The result agrees with Torri *et al.* (1997) who showed that the *K* values obtained from different global studies do not have any detectable relationships with the Neperian (natural) logarithm of the geometric mean of the particle size distribution. The results agree with findings of Wischmeier and Mannering (1969), who concluded that soils having the high amounts of clay and organic matter are resistance to water erosion. Nevertheless, this investigation showed that in the calcareous soils, lime is also a key factor in declining soils susceptibility to water erosion.

Conclusion

Results indicated that the measured values of the RUSLE *K*-factor at 108 unit plots were statistically 13.87 fold smaller than their estimated values. The correlation between the measured and the estimated *K*-factor was not significant ($p < 0.001$, $R^2 = 0.01$). These results revealed that the mean geometric diameter of soil particles (D_g) was not an accurate index to explore the susceptibility of soils to erosion in the study area. Thus, the influencial soil properties or the way these properties affected the erodibility factor were not those considered in the RUSLE model. The multiple regression analysis showed that the *K*-factor was related to the aggregate stability and soil permeability ($R^2 = 0.90$, $p < 0.001$), so that with an increasing in the two dependent soil properties, the *K*-factor remarkably decreased. A linear equation was developed based on the aggregate stability and soil permeability to reliably estimate of the RUSLE *K* factor in the region's soils. Contrary to very fine sand and silt, coarse sand, clay, organic matter and lime were the properties associated with a reduction in soil erodibility. Although D_g was positively correlated with the soil permeability, it did not strongly affect the measured *K*-factor because of its negative effect on aggregate stability.

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