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Prediction the soil erodibility and sediments load using soil attributes

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Abstract

Soil erodibility (K factor) is the most important tool for estimation the erosion. The aim of this study was to estimate the soil erodibility in Sanganeh area located in Naderi Kalat, Khorasan Razavi Province of northeastern Iran. The sediments load collected during the 17 rainfall events were measured at the end of 12 plots during 2009-2012. The K factor was calculated according to the USLE for each plot and rainfall event. The relationships between K factor and measured sediments load with soil attributes were studied. The results showed that calcium carbonate, SAR (sodium absorption ratio), silt, clay contents, and SI (structural stability index) were the most effective soil attributes for estimating the sediments load and OM (organic matter), sand, SI and calcium carbonate, silt, clay contents, and SI for K factor. The results of stepwise regression equations showed that the precision of regression equation derived from PCA for estimating the K factor and sediments load were more than ones derived from correlation test. According to the results of this research, it's recommended that PCA be applied for determination the effective soil attributes for estimating the K factor in USLE and sediments load in studied area.

Keywords: Soil erodibility, soil erosion, sediment

Introduction

Soil erosion is an important problem in agricultural lands worldwide (Kirkby and Morgan, 1980; Jianping, 1999). In many cases, soil erosion causes an almost irreversible decline in soil productivity and other soil functions (Biot and Lu, 1995; Bruce et al., 1995) and leads to environmental damage. Vegetation growth in semi-arid area is relatively slow, while rainfall events can be intense (Govers et al., 2006). In such area a sudden rainfall event may have a particularly large effect on erosion rates and erosion patterns. Rainfall characteristics, management practices, and ground cover are the key factors contributing to soil erosion (Molnár and Julien, 1998; Arnaez et al., 2007). However, very little quantitative information is available regarding the effects of rainfall intensity on soil erosion.

The Universal Soil Loss Equation (USLE) is an empirical erosion model for predicting long-term average annual soil loss resulting from rainfall events from field slopes in specified cropping and management systems and rangelands (Renard et al., 1997).

Many authors have used soil erodibility (K factor) in USLE as indicator of soil erosion (Barthès et al., 1999; Parysow et al., 2001) because soil erodibility is a measure of soil susceptibility to detachment and transport

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by the agents of erosion. The K factor is the integrated effect of rainfall and the resistance of the soil to particle detachment and subsequent transport. These processes are influenced by soil properties, such as particle size distribution, structural stability, organic matter content, soil chemistry and clay mineralogy and water transmission characteristics (Lal, 1994). It was originally derived from five variables, namely the silt plus the very fine sand content, the clay content, the organic matter content, an aggregation index, and a permeability index that have to be combined in a K factor nomograph (Wischmeier et al., 1971). A nomograph to estimate the K factor was derived by Wischmeier et al. (1971) from rainfall simulation experiments.

It was found that the K factor for a particular soil varies considerably on storm, season and year bases. The reason is mainly due to the variation in rainfall and antecedent soil conditions (Kirby and Mehuys, 1987; McConkey et al., 1997). Long term measurements from natural runoff plots are necessary to obtain a representative value for the K factor.

Soil erosion by water is a major problem in Iran. The purpose of this study was to use available data from natural runoff plots in north eastern Iran to have an approximation of soil erodibility and sediments load in the region.

Material and Methods

Description of studied area

Studied area is located in eastern of Kpoe Dagh catchment near the kalat town, is known as Shekar Kalat rangelands. The average annual precipitation and temperature is 257 mm and 15^{oC}, respectively. De Martonne's index for the area is 1.02 reflecting the semi-arid climate (Zangiabadi et al., 2010).

Determination of rainfall erosivity

The sediments load collected during the 17 rainfall events were measured in plots which had been prepared for this work from 2009 to 2012. For each rainfall, the duration of rainfall was divided into small uniform intervals and kinetic energy of each time was calculated following equation 1 (Wischmieir and Smith, 1978):

$$E = 11.87 + 783 \log I \quad (1)$$

Where E is the kinetic energy (J m^{-2} mm^{-1}) and I is the rainfall's intensity (mm h^{-1}) for each time intervals of rainfall. The total E of each rainfall event was determined based on the summation of all time intervals. Then, the maximum intensities of rainfall events for 30 (I_{30}) minute (mm h^{-1}) were calculated using time-height curves of rainfall events. Rainfall's erosivity was then calculated based on Eq. 2 below:

$$R = EI_{30} \quad (2)$$

Where R is rainfall's errosivity (MJ mm ha^{-1} yr^{-1}), E is total kinetic energy of rainfall, and I_{30} is the maximum intensity of 30 minute of rainfall events.

Determination of soil erodibility and soil attributes

USLE computes the average annual erosion on field slopes from the product of six factors representing rainfall erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), cover and management practices (C), and supporting conservation practices (P). Hence the equation:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (3)$$

where A is the computed spatial and temporal average soil loss per unit area (ton ha^{-1} yr^{-1}). Only two of the six components in the equation have units; the rainfall erosivity factor (R, MJ mm ha^{-1} h^{-1} yr^{-1}) and the soil erodibility factor (K, ton ha MJ^{-1} mm^{-1}). The K factor is defined as the rate of soil loss per erosion index unit for a specified soil as measured on a standard plot. For determining the K factor, 12 plots were selected in studied area and it was calculated according to the USLE (equation 3) for each plot and rainfall event. For this aim, R was calculated by Eq. 2 for rainfall events. A (sediments load) as a result of rainfall events was measured at the end of studied plots; L, S and C were calculated in relation to standard plot. Because of no management practices P value was equal to 1. After then, the average of K factor due to the different rainfall events was determined for each plot.

Soil samples were also collected from the 0–10 cm in each plot. Samples were air-dried and passed through a 2 mm sieve before measuring the chemical attributes. Soil physical and chemical attributes included particle size distribution by pipette method (Gee and Bouder, 1986) , organic matter (OM) by Dichromate oxidation (Walkley and Black, 1934), total $CaCO_3$ (TNV) by titration method with 6 M HCl, pH and electrical conductivity (EC) of saturated paste extract (Page et al., 1982), mean weight diameter (MWD) of wet aggregate using 4, 2, 1, 0.6, 0.25 mm sieves (Kemper and Rosenau, 1986), structural stability index (SI; Pieri, 1992) , and sodium absorption ratio (SAR) by Eqs. 4 and 5, respectively.

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (4)$$

$$SI = \frac{(OC\%) \times 1{,}724}{\%\ (silt + clay)} \quad (5)$$

Where Na^{+}, Ca^{+2}, and Mg^{+2} are ionic concentrations in mMole Lit^{-1}.

In order to study the effects of soil attributes on soil erodibility and sediments load, the Pearson correlation coefficient was applied and stepwise regression was used to estimate the K factor and sediments load. For this, the soil attributes had the significant correlation with K factor and A contents in Eq. 3 were used as independent variables. In addition, principle component analysis (PCA) method was applied to select the independent variables for estimating K factor and A values, too. In this method, only the PCs with eigenvalues ≥1 were selected as independent variables. Within each PC, highly weighted attributes were defined as those with absolute values within 10% of the highest weighted loading. When more than one variable was retained in a PC, each was considered important and was retained as independent variables provided they were not correlated ($r < 0.60$) to each other (Andrews et al., 2002). Among well-correlated variables within a PC, the variable having the highest correlation sum was selected for the independent variables (Andrews and Carroll, 2001). Finally, by comparing the precision of regression and PCA method, the best method was introduced for estimating the K factor and A contents. JMP8 software was used for statistical analysis.

Results and Discussion

Statistics of studied soil properties

Some statistics of studied soil properties have been shown in Table 1. According to these data, the sand and silt contents are almost equal and the sand is mostly in the very fine fraction. The silt and very fine sand contents is slightly high, which reflects a higher sensitivity for erosion. Wischmeier and Mannering (1969) found that small increase in silt content has considerable impact on soil erodibility and sediments load. The MWD of soils has a sever limitation. Karimi et al. (2007) reported that soils with MWD value less than 0.5 mm have severe limitations for the formation of stable aggregates. Reasons of instability and sever limitation of aggregates in our soils seems to be the lack of organic carbon and presence of Na^{+} cations. Despite the fact that studied area is conserved against animal grazing and no agricultural practices are applied, but the area is located in an arid region and the vegetation is poor. The positive effects of organic carbon on aggregates stability and soil structure have been reported by Emami et al. (2012), Emami and Astaraei (2012) and Virto et al. (2011). In addition, electrical conductivity is high which may limit crop growth and organic carbon builds up and hence increases soil erosion. The mean value of SAR is also high, so it can degrade the soil structure.

Table 1. The ranges and mean values of studied soil attributes

Soil attributes	minimum	maximum	mean	Standard Deviation	CV (%)
OM (%)	0.52	2.23	1.33	0.56	36.93
Bd (g cm^{-3})	1.3	1.6	1.39	0.12	8.73
TNV (%)	1.5	10	4.3.6	2.47	55.37
EC (dS m^{-1})	2.3	10.4	5.28	2.00	37.62
SAR (-)	0.35	76.28	30.44	21.74	299.55
Sand (%)	25.42	52.24	43.33	5.95	13.81
Clay (%)	20	37	24.95	3.38	13.41
Silt (%)	23.76	51.58	31.72	1.54	17.13
MWD (mm)	0.13	0.74	0.30	0.15	60.04
pH (-)	6.99	7.96	7.36	0.08	4.14

Soil erodibility

The results of soil erodibility (K factor in USLE) calculated in 12 plots of studied area are shown in table 2. There were no conservation practices in the studied plots, therefore in equation 3 P factor was equal 1. In general, the values of soil erodibility in the area are low. This may be due to presence of vegetation, and high content of sand and clay. Vegetation tends to reduce the kinetic energy of rainfall drop impacts and as a result, soil detachment and soil erodibility decreases. With increasing sand content, the infiltration rate increases and runoff decreases (Santos et al., 2003). Furthermore, clay fractions could help decrease particle detachment; hence the soil erodibilty is decreased.

Table 2. The range and average of erodibility factor in studied plots

Plot No.	Average (ton ha MJ^{-1} mm^{-1})	Range (ton ha MJ^{-1} mm^{-1})	Standard Deviation (ton ha MJ^{-1} mm^{-1})	CV (%)
1	0. 37	0.18-0.59	0.002	68.55
2	1.76	0.99-2.3	0.016	111.78
3	2.13	1.47-4.66	0.004	84.47
4	0.41	0.14-0.84	0.003	107.6
5	0.26	0.11-0.39	0.001	87.04
6	0.20	0.12-0.30	0.002	97.76
7	3.03	1.13-5.40	0.022	88.09
8	2.49	0.97-4.69	0.023	93.19
9	1.81	0.94-3.47	0.023	128.53
10	2.75	1.09-3.51	0.022	127.85
11	0.73	0.41-0.96	0.006	104.73
12	0.29	0.12-0.77	0.002	99.76

Relationships between soil erodibility and soil attributes

The correlations between soil erodibility and soil properties are shown in Table 3. Since SAR and K factors had no normal distributions, the data for SAR and K factor were transferred to logarithmic scale and exponential function to get a normal distribution. As seen from the results, exp (K) had a negative and significant ($P < 0.05$) correlation with organic matter content, clay and soil structural stability index. Organic matter by coating the soil particles and creates a water repellent layer that prevents soil detachment and keep soil particles flocculated, therefore it decreases the soil erodibility and erosion. In our study the highest correlation coefficient was observed between K factor and clay content. Wang et al. (1994) indicated that the soil organic matter and clay contents are the principal factors that influenced soil anti-erodibility in the Loess Plateau and that the percentage of water stable aggregates was the best indicator. However, the correlations between OM and SI were also high. Kodesova et al., (2009) reported that presence of organic and clay coatings usually increase soil aggregate stability, hence soil degradation and erodibility is decreased. In our soils, sediments load had a negative and significant correlation with OM ($r = -0.71$), sand contents ($r = -0.72$), SI ($r = -0.71$) value, and calcium carbonates ($r = -0.65$) content. Sediments load and Log SAR ($r = 0.75$), and silt ($r = 0.70$) were also positively correlated.

Bonilla and Johnson (2012) by analyzing 535 soil datasets observed that soil erodibility decreases as the sand content increases ($r= -0.375$). They found no trend between clay content and the erodibility factor ($r=-0.033$) and the correlation coefficient between erodibility and silt content was higher than for the other soil particles ($r=0.607$). Similar to our results, Zhang et al. (2004) found the negative and significant correlation between soil erodibility and clay content ($r = -0.62$, $P<0.05$). According to the literatures the highest vulnerability to erosion by water occurred where soils were predominantly silty (Bonilla and Johnson, 2012; Duiker et al., 2001; Pérez-Rodríguez et al., 2007; Romero et al., 2007; Zhang et al., 2004). Similarly, Di Stefano and Ferro (2002) reported that detachment decreases as particle size either decreases or increases beyond the range of 20–200µm. Above this range, it is more difficult to detach and transport particles because of the particle mass, and below this range, cohesive forces counter particle detachment. Consequently, soil particles with diameters in the size fractions of silt, fine and very fine sand are more easily eroded. The same results were reported by Ampontuah et al. (2006), in two contrasting cultivated hill slopes of England. Their research was performed on fields containing about 67–80% silt, and were highly susceptible to water erosion. Wischmeier and Mannering (1969) found that soil content of the runoff was inversely related to organic matter content. Their analysis on silts, silt loams, loams and sandy loams textural classes showed that the inverse relation of erodibility to organic matter level was strong, but it significantly declined as the clay fraction became larger.

Table 3. The correlation coefficient between soil attributes with sediment content and soil erodibility factor in USLE

Soil attributes	OM	TNV	EC	log^{SAR}	pH	BD	Silt	Clay	Sand	SI	MWD	A	e^K
OM	1												
TNV	-	1											
EC	-	-	1										
log^{SAR}	-	-	-	1									
pH	-	-	-	-	1								
BD	-	-	-	-	-	1							
Silt	-	-	-	**0.71	-	-	1						
Clay	-	-	-	-	-	-	-	1					
Sand	0.60*	0.64*	-	-	-	-	-0.75**	-	1				
SI	0.99**	0.60*	-	-	-	-	-0.72**	-	0.62*	1			
MWD	-	-	-	-	-	-	-	-	-	-	1		
A	-0.71**	-0.65*	-	0.75**	-	-	0.70**	-	-0.72**	-0.71**	-	1	
e^K	-0.60*	-	-	-	-	-	-	-0.62*	-	-0.58*	-	-	1

+ OM: Organic matter, TNV: Calcium carbonate, EC: Electrical conductivity, SAR: Sodium adsorption ratio, BD: Bulk density, SI: Structural stability index, MWD: Mean weight diameter of aggregates, A: sediment content, K: Erodibility factor
++ **: significant at $P < 0.01$, *: significant at $P < 0.05$.

Our results showed that the highest correlation coefficient of sediments load is related to Log SAR. Dexter and Chant (1991) have shown that the amount of clay dispersion increased as SAR increased. In fact, due to sodium impact on clay dispersion and degradation of the soil structure, infiltration rates decreases and leads to more soil erosion. Therefore, the higher SAR in soil solution the more sediments load. Silt particles have low cohesive force and are easily transported by runoff; therefore they are more vulnerable to water erosion. On the contrary, sand content had a negative relationship with sediments load. Due to higher mass of sand particles, runoff cannot transport them. On the other hand, the presence of sand particles in soil cause an increase in macro pores, water infiltration, and consequently decrease in susceptibility to erosion and sediments load (Santos et al., 2003).

The sediments load had a negative but significant ($P < 0.05$) correlation with calcium carbonate ($r = -0.65$). Calcium cations originating from carbonate dissociation linked between organic and inorganic soil components, create cationic bridging effect (Baldock and Skjemstad, 2000), promotes aggregation, increases the soil resistance against rainfall drop impacts, splash erosion, and rainfall erosivity, and consequently, decreases the soil detachment and sediments load. Virto et al. (2011) also, reported that aggregation in many soils in semi-arid land is affected by their high carbonate contents. The role of carbonates, as a source of Ca, in promoting mineral bonds and mineral-SOM interactions through cation bridges has been described responsible for micro-aggregates formation and stability in several studies (Baldock and Skjemstad, 2000).

Estimating soil erodibilty and sediments load

Soil erodibilty and sediments load were estimated by stepwise regression. As mentioned before, soil attributes including structural stability index, sodium adsorption ratio, calcium carbonate equivalent, sand, silt, and organic matter, clay, and SI had significant correlation with sediments load, and erodibilty variables, respectively (Table 3). Therefore, they were regarded as independent variables for the above dependent variables. The results of stepwise regression analysis showed that among the independent variables TNV, log SAR, and silt attributes were effective variables for estimating the sediments load (Table 4). In addition, TNV in this equation is negative, so it has a reductive effect on sediments load, but the sign of SAR and silt contents is positive and by increasing these parameter values, the sediments load increases. Similarly, the clay and SI attributes were selected for estimating the soil erodibilty (exp K) variable (Table 4) and the negative sign shows any increase in both variables decreases that by increasing them, soil erodibility. The determination coefficient (R^2) of regression equations between measured and estimated soil erodibilty and sediments load were 0.6 and 0.74, respectively. Also, the RMSE of soil erodibility and sediment equations were 0.0074 and 0.0022, respectively. In addition the estimated soil erodibility and sediments load were significant at $P < 0.05$ and $P < 0.01$, respectively. As seen in Figure 1, the regression equation of sediments load is under-estimated and that of soil erodibility is over-estimated. The slope of linear equations for sediments load and soil erodibility variables are 0.62, and 0.41, respectively, which demonstrated that the slope of sediment equation is close to 1. In general, based on the R^2, RMSE, significance level and slope of regression line, the precision of sediment regression equation is large enough that can be reliablely predicted by TNV, SAR, and silt contents.

Table 4. Results of regression analsis for estimating the soil erodibility and sediment contents according to correlation test.

Dependent variable	Regression equation	RMSE	Prob. > F
A	A = -0.0008 – 0.0004TNV + 0.0034log(SAR) + 0.0002Si	0.0022	0.0091
Exp K	Exp (K) = 1.068 – 0.0001Cl – 0.002SI	0.0074	0.0148

A: Sediment content (tonha^{-1}yr^{-1}), K: soil erodibility factor (tonhaMj^{-1}mm^{-1}, TNV: equilibrium calcium carbonate, SAR: Sodium adsorption ratio, Si: silt percent, Cl: Clay percent, SI: Structural stability index.

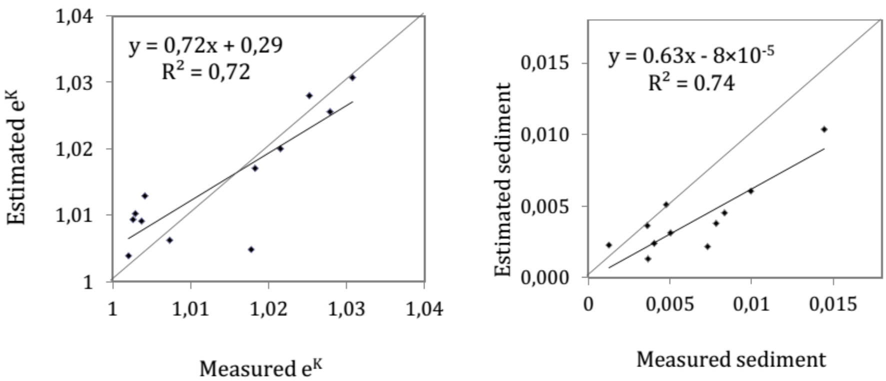

Figure 1. Results of estimated and measured soil erodibilty (left) and sediment content (right).

In addition, A and K factor were estimated based on the principle component analysis (PCA). The results of PCA are shown in Table 5. In this method, 4 principle components (PCs) which had the Eigenvalues more than 1 could explain 83.33 % of variations. The first PC with the highest loading effect and difference of less than10% could explain 44.88% of variations. The attributes of PC_1 consisted of TNV, silt, and SI which had high correlation with each other. Since these attributes had large loading effects, all of them were selected as principle variable at PC1. The second PC had 2 variables i.e. clay percent and bulk density (Bd) with the highest loading effect, which bulk density was chosen as an effective variable. In PC_3 only pH and for PC_4 EC and bulk density had the highest loading effects. Finally, 7 soil attributes i.e. silt, SI, TNV, bulk density, clay, EC and pH were selected as effective variables on sediment and soil erodibilty contents. The regression equations obtained selected based upon PCA is shown in Table 6. The results of stepwise regression equations derived from PCA showed that among the 7 soil attributes, 3 of them were selected for estimating the sediment and K factor. Hence TNV, silt, and clay percents were used for estimation the sediments load but clay and TNV attributes had the negative and silt had the positive effect on sediments load. Also silt, clay, and SI attributes were selected for estimating the K factor and all of them had the negative effect on K factor. Compared to equations of correlation test, The R^2 value of regression equation derived from PCA for estimating the K factor increased to 0.72. R^2 Value for sediment also slightly increased. In addition, RMSE values of these equations for both A and K factor decreased to 0.0068, and 0.0021, respectively. Similarly, the equations derived from PCA method were significant at $P < 0.01$ and 0.05 for estimating A and K factor, respectively. The slope of linear regression equations for both A and K factor were 0.74 and 0.71 and closer to 1. According to R^2, RMSE, and slope of linear regression equations, it can be concluded that PCA method is more precise than correlation test for estimating the A and K factor.

More detailed of regression equations clarified that silt and TNV were used for estimating the sediments load in both PCA and correlation test. TNV and silt had the reductive and incremental effect on A, respectively. Calcium carbonate may improve soil structure and decrease the soil erosion (Duiker, et al. 2001). Silt particles are sensitive to soil erosion (Wischmier and Mannering, 1969). Also clay and SI attributes were applied for estimating K factor in both PCA and correlation test methods and the reductive effect on K factor. Zhang et al. (2004) found that clay content had negative effect on K factor in USLE.

Table 5. The results of principle component analysis

PC4	PC3	PC2	PC1	Component number
1.09	1.48	1.99	4.94	Eigenvalue
9.90	13.42	18.14	44.88	Percent of Variance
83.33	64.43	63.01	44.88	Cumulative percent of Variance
	Communality			
-0.006	0.284	-0.087	0.407	TNV
-0.087	-0.175	0.361	0.333	OM
0.481	-0.290	-0.129	-0.160	EC
0.129	0.462	0.213	-0.304	Log^{SAR}
0.421	0.610	0.255	0.107	pH
-0.433	-0.094	0.571	-0.036	Bd
-0.142	0.116	0.248	-0.397	Silt
-0.385	0.241	-0.562	0.018	Clay
0.389	-0.275	0.121	0.358	Sand
-0.041	0.246	-0.046	0.419	SI
-0.235	0.016	0.106	0.358	MWD

Table 6. Results of regression equations for estimating the soil erodibility and sediment contents obtained according to principle component analysis.

Dependent variable	Regression equation	RMSE	Prob. > F
A	A = -0.0084 – 0.0008TNV + 0.0003Si - 0.0003Cl	0.0021	0.0073
Exp K	Exp (K) = 1.117 – 0.0011Si – 0.0018Cl - 0.0048SI	0.0068	0.0140

A: Sediment content ($tonha^{-1}yr^{-1}$), K: soil erodibility factor ($tonhaMj^{-1}mm^{-1}$, TNV: equilibrium calcium carbonate, Si: silt percent, Cl: Clay percent, SI: Structural stability index.

Conclusion

The results showed that calcium carbonate, SAR, silt, clay contents, and SI were the most effective soil attributes for estimating the sediments load and OM, sand, SI and calcium carbonate, silt, clay contents, and SI for K factor. The results of stepwise regression equations showed that R^2 value of regression equation derived from PCA for estimating the K factor and sediments load increased. In addition, RMSE values of these equations for both A and K factor decreased. According to the results of this research, it's recommended that PCA be applied for determination the effective soil attributes for estimating the K factor in USLE and sediments load in studied area.

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