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ORIGINAL ARTICLE

Quantifying eroding head cut detachment through flume experiments and hydraulic thresholds analysis

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Abstract Gully erosion is known as one of the most important environmental earth hazards in the world and especially in Iran where it is controlled by both environmental and human factors. This research has attempted to assess the effects of land use (LU) on gully hydraulic flow condition of head cut initiation under similar soil conditions through an experimental field base plot (15×0.4 m). Results reveal that critical shear stresses (τ_{cr}) for head cut initiation in abandoned, dry farming and rangeland, land are 174, 43 and 192 dyne/cm^2, respectively, the remarkable differences being the consequence of soil surface condition (e.g., vegetation cover and micro-relief). Moreover, the flow turbulence and response of soil to an increase in flow condition (rate and depth) indicated a complicated behavior which can be addressed to the influences of surface micro-relief features and LU effects. Although a simple linear equation between τ_{cr} and K_c can be used to estimate the parameter, significant differences of regression coefficients decrease the general equation for whole data sets. The main explanation for dramatic (3–4 times) variations of τ_{cr} is the vegetation cover and soil surface conditions. In fact, the significant decrease in τ_{cr} under dry farming can be linked to the effect of tillage operation on aggregate strength and soil susceptibility. Findings showed that a boundary shear stress of 35 dyne/cm^2 used in some physically based models for predicting erosion is subjected to high uncertainty and not appropriate for estimation of gully development. In addition, the duration of land abandonment has a crucial influence on soil erodibility, a factor given little consideration in erosion models. For the prediction of gully erosion rate, it is recommended that a single erodibility parameter is created from the functional relationship between τ_{cr} and K_c. Due to the interaction of slope, flow regime, shear stress and type of ground cover, the relationship between head cut initiation and surface roughness varies. In addition, the Reynolds number is not a reliable parameter for estimation of surface roughness during head cut initiation. Therefore, for gully erosion modeling other hydraulic parameters should be used to produce a reliable model. For prediction of gully erosion rates a single erodibility parameter from the functional relationship between τ_{cr} and K_c could be used.

Keywords Gully · Head cut detachment · Shear stress · Hydraulic threshold · Land use · Dareh-Kore watershed · Iran

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Introduction

Previous studies have categorized water erosion as rill, stream and gully (Hudson 1995; Boardman and Favis-Mortlock 1998; Refahi 1999), leaving sheet erosion as a

separate category. A gully is an intermittent water course, where processes of channel erosion can be very intense (Torri and Poesen 2014), and due to its effects on sediment supply in watersheds more research is needed to understand the controlling processes as well as mitigation options (Li et al. 2003; Poesen et al. 2003; Valentin et al. 2005; Torri and Poesen 2014). Assessing the impacts of climatic and land use changes on rates of soil erosion by water is the objective of many national and international research projects (e.g., Favis-Mortlock and Boardman 1995; Poesen et al. 1996; Williams et al. 1996; Vandekerckhove et al. 2000; Nearing 2001; Valentin et al. 2005; Knapen et al. 2007; Nazari Samani et al. 2009, 2011; Perroy et al. 2010; Magliulo 2012; Su et al. 2015; Vanmaercke et al. 2015, 2016). The research reported here will add to these efforts.

Land degradation by water erosion is one of the major hazards in the world (Vanmaercke et al. 2016; Varnosfaderani et al. 2016). There are many studies that have developed indicators for separating and identifying the erosion types of rill, stream and gully (Agassi 1996). The first quantitative criteria was introduced by Hauge (1977) as a critical cross-sectional area of 929 cm^2, while minimum width and depth of 0.3 and 0.5 m, respectively, as the other criteria used for distinguishing rills from gullies by Brice (1966), Imeson and Kwaad (1980), and Nazari Samani et al. (2016). Although there is a continuum from rill to gully erosion, Torri et al. (1987) and Slattery and Bryan (1992) used hydraulic concepts to distinguish rills from gullies. Gullies are often the most important source of sediment both spatially and temporally (Rosewell 1996 in Australia; Li et al. 2003 in China; Poesen et al. 2003 in Europe; Nazari Samani et al. 2011 in Iran). However, in most erosion models gullies are not included, leading to significant underestimation of soil erosion rates in catchments (Poesen et al. 2003).

It has been proved that gullying erosion processes are geomorphic threshold phenomenon (Poesen et al. 2003; Katz et al. 2014). Gullies can initiate only if the intensity of effective environmental factors (mostly concentrated overland flow) exceeds a threshold value and flow surpasses the soil resistance (Boardman and Favis-Mortlock 1998). The threshold force required to initiate incision into the ground surface in the concentrated flow zone is termed the 'critical flow shear stress' ($\tau_{cr} = \gamma ds$ with γ and d being the density and depth of water flow, respectively, and s being the gradient of the flow energy). The combination of geomorphic threshold conditions with hydraulic thresholds, produced the $\Gamma_{cr} = (c\gamma)A^{rf}S$ equation, where Γ_{cr} is the τ_{cr} parameter, A is the contribution upslope area (ha), S is the slope gradient (m/m), and rf and c are experimental coefficients (Begin and Schumm 1979; Vandaele et al. 1996). Some researchers have explained the effects of land use/cover on the geomorphic threshold (e.g., Vandekerckhove et al. 2000; Poesen et al. 2003; Nazari Samani et al. 2009, 2011; Jing'e et al. 2010; Price 2011; Peng and Wang 2012; Leh et al. 2013; Sun et al. 2014; Torri and Poesen 2014), but fewer works have been carried out to investigate the hydraulic conditions of head cut initiation in situ. In fact, a key question is: Under what value of T will the gully head cut be initiated? More recently, stream power and shear stress have been used as the two quantitative hydraulic parameters for erosion modeling.

To date, several experiments have been conducted to determine the hydraulic threshold condition for head cut erosion: Nachtergaele and Poesen (2002) in the Belgian loess belt, Prosser et al. (1995) in the grassland of San Francisco and Adelpour (2004) in Iran's loamy-sand area. The diversity of obtained results indicate that more field-based experiments are required to better understand the land use/cover effects on the threshold condition for head cut initiation. Moreover, some physically based erosion models (such as: WEPP, CREAMS, PRORILL and EGEM) established based on the τ_{cr} and the boundary value used in WEPP is 3.5 pa (Stone et al. 1995; Flanagan et al. 2001; Fu et al. 2012). Therefore, it is crucial to create a database for the critical shear stress parameter under various ground surface conditions so as to understand the causal factors and develop a comprehensive erosion model.

More than 60% of Iran is arid and semiarid, and water erosion is pervasive in Iran, but there is little quantification of the rate of this hazard. Research has shown that gully erosion is important in many regions of Iran, particularly in the catchments of the south and southwest Therefore, this research was aimed to investigate land use factors that affect flow conditions (such as status, type and threshold shear stress) and, consequently, determining of threshold value for initiation of head cut erosion. Also, the effect of soil erodibility to concentrated flow and surface roughness on head cut initiation was analyzed by regression analysis.

Materials and methods

Study area

This study was conducted in three land uses (dry farming, rangeland and abandoned) located in southwestern Iran (Bushehr Province) extending between 51°13′ longitude and 29°08′ latitude (Fig. 1). According to the 1:100,000 geological map, all of the study sites are located on the plain with Quaternary alluvium. The long-term average annual temperature and rainfall are 14 °C and 200 mm, respectively. There are no seasonal or annual trends visible in the precipitation data. The dominant vegetation cover
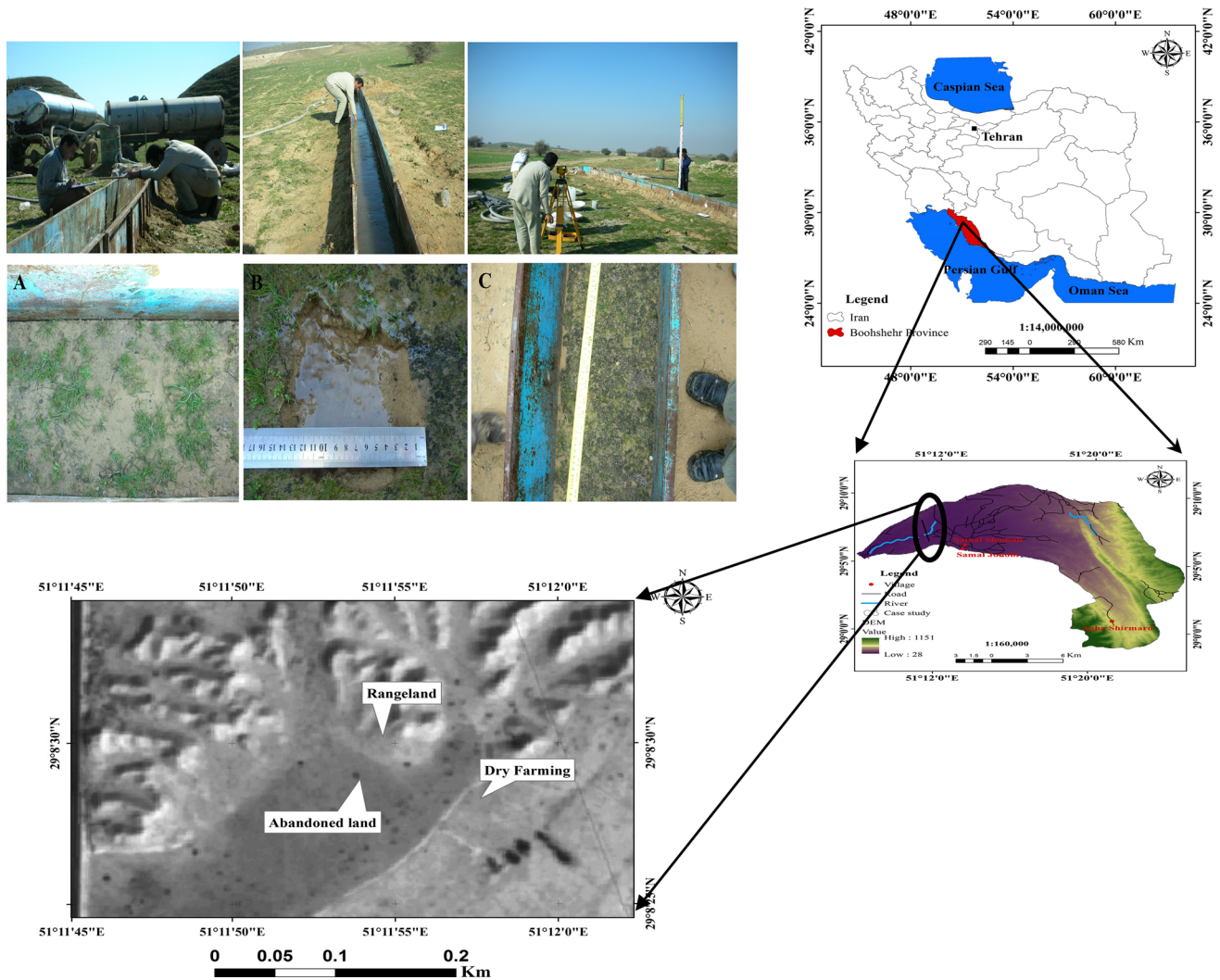
Fig. 1 *Right side* Study area and the location of experimental sites. *Left side* General overview of setting up the flume, **a** abandoned land; **b** measurement of head cut features with step-like feature (2.3 cm height and 13 cm wide); **c** rangeland (grass and lichen 6% slope)

consists of annual grasses and rangeland is the most important land use, on which heavy grazing has had a major impact on the density of vegetation with feedbacks to other ecological factors.

Methods

To measure the hydraulic characteristics of flow, in situ flume experiments were used according to the following stages: construct the flume instruments (wall, Parshall flume and connections) and set them up; design the experiment based on steady and uniform flow; measure flow attributes (depth and velocity and sediment concentration); perform laboratory analysis and final analysis for calculation of hydraulic parameters (Fig. 2).

The erosion plots are $15 \times 0.4 \times 0.5$ m (long, wide and high, respectively) and made of iron plates. The flume parts

were installed so that the ground surface cover of the soil was not disturbed. For each experiment, the parameters of hydraulic flow were measured over the 9 m reach in the middle section of the flume (Figs. 1, 3). The three land uses—dry farming, rangeland and abandoned areas—were chosen. In addition, in order to prevent the effects of spatial variation of soil properties, all tests were conducted at a site consisting of three land uses. The distance between tests locations was about 100 m. The soil characteristics according to the land uses are shown in Fig. 4, which shows that no significant difference between soil attributes. Therefore, all the differences in hydraulic threshold conditions can be addressed by variations of land use/cover. However, slope could not be held constant and the maximum soil surface slope is in the rangeland (5.9%), while the dry farming had the least (0.13%). Therefore, to determine the effect of land slope the shear stress index
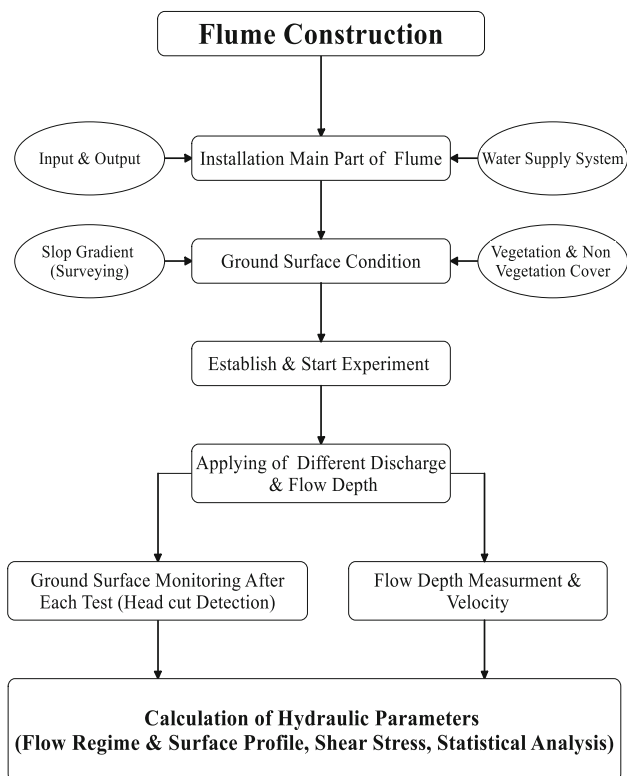
Flume Construction

Fig. 2 Schematic flowchart of methods

$(\tau = \gamma \cdot R \cdot S)$ was used. This index considers both discharge and energy characteristics as well as the slope variability (Prosser et al. 1995; Knapen et al. 2007).

Experimental operation, measurement and parameter calculation

The flume's sidewalls were beaten into the soil and sealed to prevent leakage. After setting up the water supply equipment including a water tank, stilling basin and Parshall flume at both ends of the plot, the experiment was started with low discharge (0.75 L/s) and then increased to high discharge so that the head cut could be observed (Fig. 1). The flow parameters including discharge, depth of flow were measured during the test by using a steel ruler, while the sediment load was determined by sampling at the end of the flume. Finally, through Eq. (1–5) the hydraulic characteristics of flow were calculated.

A: Mean flow velocity: through the flow continuity equation

$$U = \frac{Q}{A} \tag{1}$$

B: To assess the flow condition type and regime: Reynolds (Eq. 2) and Froude numbers (Eq. 3) were calculated.
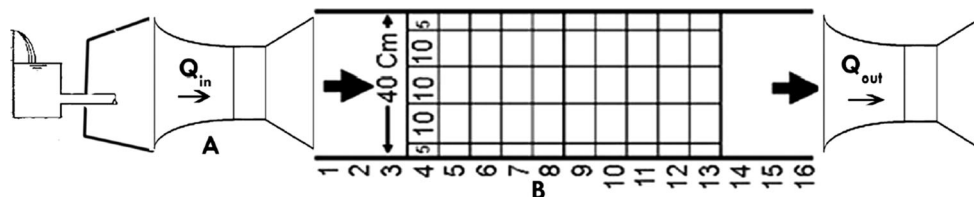

Fig. 3 Sketch of flume including: water supply and pond for decreasing the turbulence of the flow, A Parshall flume, B main section (*dark lines* are the wall with 50 cm height) and the *net* shows the midsection mesh used to measure flow depth and ground elevation
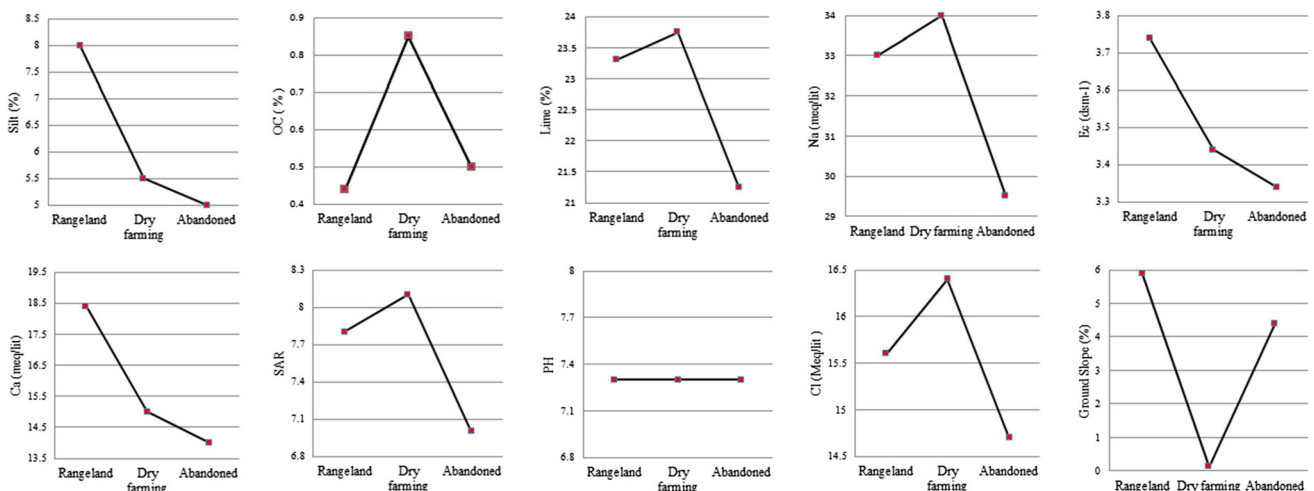

Fig. 4 Soil characteristics according to land uses. No significant difference is obtained between soil attributes of different sites

$$\text{Re} = \frac{U \cdot d}{\upsilon} \qquad (2)$$

$$F = \frac{U}{\sqrt{gy}} \qquad (3)$$

C: Shear stress of flow

$$\tau = \gamma \cdot R \cdot S \qquad (4)$$

D_r: The soil detachment rate

$$D_r = \frac{C_V \cdot Q \cdot t}{6} \qquad (5)$$

Symbols used in the above relations are: Q: discharge, A: cross-sectional area of flow; U: average flow velocity; d: flow depth; υ: kinematic viscosity ($\upsilon = 0.01$ cm²/s); F: Froude number; g: gravitational acceleration; y: mean flow depth; γ: specific gravity (ρg); S: water surface gradient; R: hydraulic radius; C_v: sediment weight concentration; and t: run time.

Critical shear stress (τ_{cr}) and concentrated erodibility (K_c) are predictive parameters used worldwide in soil erosion studies and modeling and are therefore used in this study.

To assess the soil detachment rate based on threshold τ_{cr}, Eqs. (6)–(8) are used (Foster 1982; Nachtergaele and Poesen 2002):

$$D_r = K_c(\tau - \tau_{cr})^B \qquad (6)$$

where D is the flow detachment rate (kg m^{-2} s^{-1}), K_c represents the erodibility of soil to concentrated runoff (S m^{-1}), τ is mean shear stress, τ_{cr} is critical shear stress and B is an empirical coefficient usually equal to 1. Finally,

Equation (6) can be written in a linear mode (Eq. 7).

$$D_r = K_c \tau + b \qquad (7)$$

Finally the τ_{cr} can be calculated by the following equation:

$$\tau_{cr} = \frac{-b}{K_c} r \qquad (8)$$

Consequently, the slope of a linear function between D_r and shear stress is equal to concentrated erodibility (K_c). The Darcy–Weisbach dimensionless coefficient (f) as the surrogate of friction agent was used to assess the flow resistance at the initiated head cut by using Eq. (9):

$$f = \frac{8gds}{u^2} \qquad (9)$$

The initiation of a gully, and the associated threshold shear stress, was obtained by photograph and optical assessing of the flume surface after each run. A small hole or ditch (9 cm³ cross section or 3 × 3 cm size) was considered as a head cut initiation. To prevent scouring, the water was funneled into a second small pond further down-slope which was filled by stone. A total of seven, seven and six runs were conducted on the rangeland, dry farming and abandoned land, respectively, to reach the threshold of head cut initiation.

Equations (1)–(8) are based on the physical processes of water flow and the characteristics of the hill slope, and the coefficients (K_c and b) are critical for erosion modeling. Although most previous work emphasized the description of these parameters, in this research, the regression analyses were applied for better understanding of the relationships between variables. Comparing regression parameters (i.e., slopes) between two groups can be used to assess different patterns of relationships between groups. The regression slope is a representation of erodibility to concentrated runoff and is affected by land use. The statistical difference between the land uses was determined by using an analysis of covariance (ANCOVA) to compare the fitted regression lines for each land use. Also other regression models using curve estimators were tested. All these analyses were conducted using Minitab 13 software. To compare with the 'USLE' soil attributes (silt and very fine sand, organic material, structure and infiltration) were used to calculate the erodibility index K based on the nomograph of Auerswald et al. (2014).

Results

Effect of land use on type of flow

The results of the Froude (Fr) and Reynolds numbers (Re) showed that generally, flow status was turbulent (Re > 2000) through all the run tests. In contrast to other land use, in rangelands, because of the short grass cover and smooth lichen surface and therefore low surface roughness, the effect on the Reynolds number was very low. However, surface roughness induced by land covers in dry farming land and abandoned lands indirectly caused the decrease in Re by declining flow velocity, However, as discharge (flow depth) increased and submerged the vegetation, Re increased to a significant value of 25,000. It is clear that during mean discharge (4 L/s, Table 1), Re in rangelands was lower than in both abandoned lands and dry farming, causing of an increase in flow energy.

The Froude varies from 0.05 to 5.1. (Table 1), and head cut initiation was observed with Fr = 1.61 (Q = 9.2 L/s); Fr = 0.1 (Q = 8.2 L/s) and Fr = 0.6 (Q = 4.3 L/s) for rangeland, dry farming and abandoned land, respectively. In other words, as the soil surface is disturbed by tillage, a flow with less energy is sufficient to initiate a head cut.

Figure 5f depicts an example of surface profiles for various discharge experiments in abandoned land. It can be seen that with low discharge, due to the impact on

Table 1 Results related to the status and type of the flow in different experiments

Land use	Discharge (L/s)	Mean flow depth (mm)	Fr number	Re number
Rangeland	2	13	1.11	5037
	3.9	17	1.46	9860
	6.37	23	1.46	16,190
	9.2	28	1.61	24,178
Dry farming	0.75	50	0.05	1834
	1.21	62	0.06	3065
	3.5	95	0.1	8817
	4.1	101	0.1	10,361
	5.7	129	0.1	14,391
	8.2	165	0.1	20,757
	10	170	0.11	24,969
Abandoned	1.5	15	0.69	3913
	2.9	22	0.72	7299
	4.3	31	0.64	10,937
	5	34	0.65	12,756
	7.2	41	0.67	18,289

roughness of vegetation cover and micro-topography, the profile of the water surface (Run 1 in Fig. 5f) is similar to that of the ground profile. However, as the flow depth increases, the water surface becomes smoother. In fact, vegetation cover can influence both the flow characteristics (e.g., flow resistance, roughness and flow depth) and the hydraulic attributes such as the rating equation of flow depth with discharge and boundary layer depth. Therefore, it is postulated that an alteration of the vertical velocity profile causes turbulent flow as stems and branches are overtopped.

Impact of land use on threshold shear stress for surface erosion

The results of the relationship between the detachment rate (D_r) and τ are shown in Figs. 5a–c in which 1 Pa = 10 dyne/cm^2. As can be observed, in all cases, significant relationships ($P = 0.05$) between D_r and τ were observed (Table 2). The τ_{cr} for each land use [calculated based on Eq. (8)] is shown in Fig. 5 and Table 2. The critical shear stress values are 79, 11 and 80 dyne/cm^2 for rangeland, dry farming and abandoned areas, respectively. Moreover, minimum and maximum soil erodibility for concentrated overland flow (K_c) was obtained for abandoned (0.0005) and dry farming (0.1912).

It is noteworthy that the resistance of the soil to concentrated flow in rangelands is more than 50 times that in dry farming land. Also, the calculated 'USLE' erodibility index showed that the highest and lowest indices are related to rangeland and dry farming (0.385 and 0.341, respectively). However, neither the value nor ordination of the 'USLE' K factor is confirmed by the K_c obtained

from experimental tests. Based on flume analysi,s abandoned land had the highest resistance and lowest erodibility, while the 'USLE' index showed the lowest for rangeland.

Further nonlinear regression models (power, quadratic) were applied between D_r and τ_{cr} and lead to increase in the r^2 about 15 % (Table 3). But the nature of the relationships between lands uses is not similar and for dry farming with lower τ_{cr} the nonlinear form is most suitable by comparison with the other land uses. Also, the results of homogeneity tests for regression of the coefficients for different land uses (Table 4) showed significant F statistics for Land use × X(Tcr) factor.

For the whole data set, a polynomial relationship was fitted between D_r and τ_{cr} with low r^2 (Fig. 5e) and such a third-order polynomial equation form may be explained by the decreasing homogeneity of variance related to the mixing of all data sets.

Effect of land use type on gully initiation threshold

The numbers of head cuts corresponding to τ_{cr} are listed in Tables 5 and 6. The range of average values of τ for head cut initiation in the rangeland is 164–178, for dry farming 34–42, while for abandoned land it is 161–217 dyne/cm^2. Such remarkable differences of τ can be linked to the surface roughness and soil aggregate conditions. Other hydraulic parameters (τ at the initiated gully heads, Fr number and Darcy–Weisbach friction factor (f)) also are shown in Table 5. Comparing the hydraulic parameters indicates significant differences ($P < 0.002$) between land uses. Regression analysis showed a significant direct relation between τ and cumulative number (H_n) of head cuts
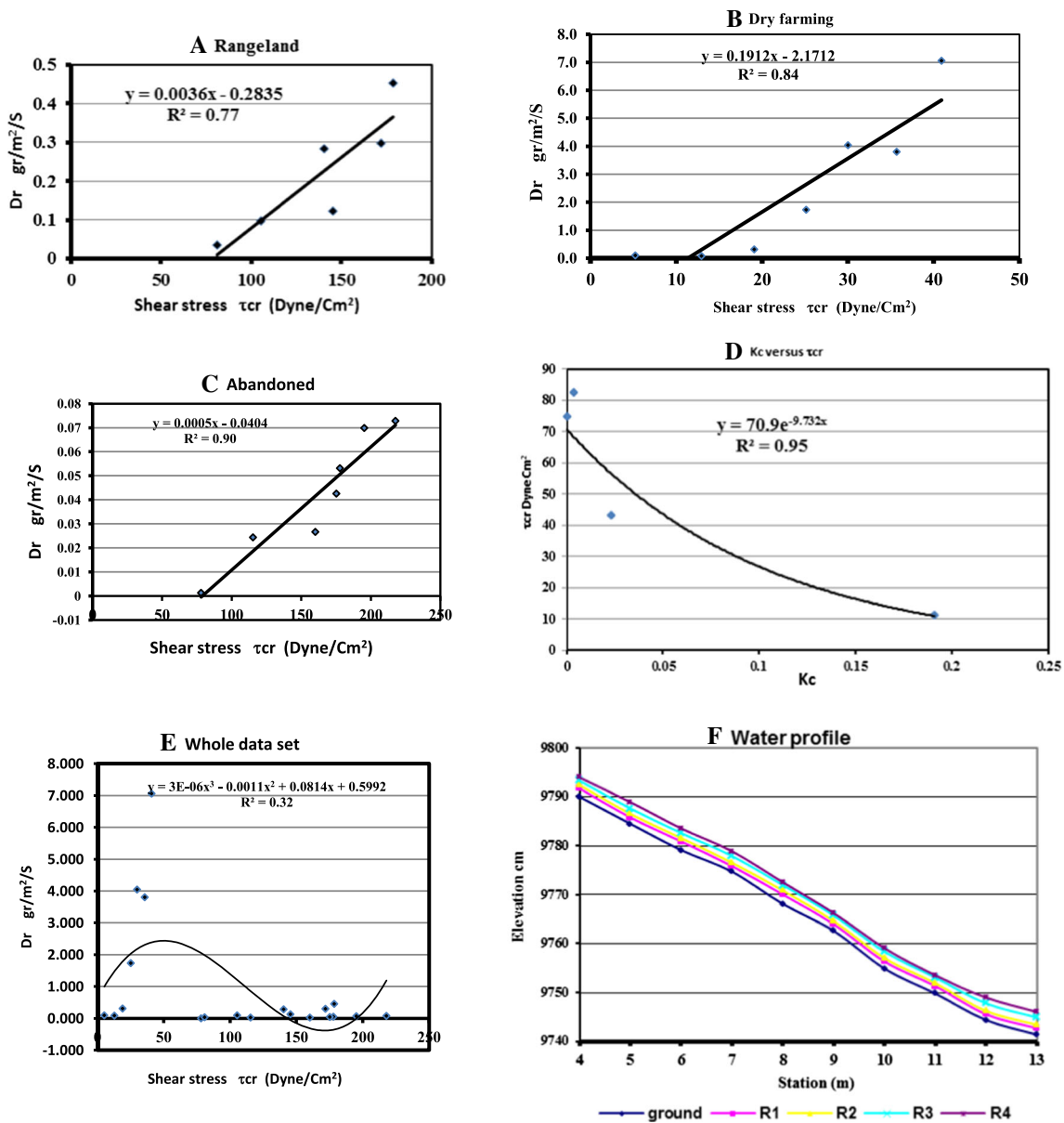
Fig. 5 a Relationships between the critical shear stress (τ_{cr}) and detachment rate for the rangeland; **b** Dry farming land use; **c** Abandoned area; **d** Relationship between K_c and τ_{cr} for head cut initiation; **e** regression of τ_{cr} and D_r for all data sets; **f** profile of water surface and bed of *plot 1* in the undisturbed condition of abandoned land [presence of non-uniform vegetation cover has led to decreased roughness coefficient and increased flow velocity; consequently, flow depth decreased between points 7 and 10 (stations are based on Fig. 3 scheme)]

Table 2 Results of regression analysis between D_r and critical shear stress (τ_{cr})

Land use	R	R^2	Equation	SE of the estimate	Sig. F
Dry farming	0.916	0.838	$0.1912X - 2.171$	1.16368	0.004
Rangeland	0.878	0.771	$0.0038X - 0.284$	0.08375	0.021
Abandoned	0.947	0.896	$0.0005X - 0.040$	0.00916	0.001

($R^2 = 0.97$) and f ($R^2 = 0.49$) for rangeland and abandoned land (Fig. 6) and an inverse relationship between f and Re number ($R^2 = 0.92$). However, for the whole data set the mentioned relationships were neither straightforward nor consistent. The morphology of head cuts in the dry farming field was different from others. The eroded head cuts in the dry farming land were rotating (curvilinear) (Fig. 7c) with inclined face, but the head cuts

Table 3 Different regression models for land uses

Equation	Rangeland		Dry farming		Abandoned	
	R^2	Sig.	R^2	Sig.	R^2	Sig.
Linear	0.771	0.021	0.838	0.004	0.896	0.001
Logarithmic	0.728	0.031	0.613	0.037	0.847	0.003
Inverse	0.673	0.045	0.369	0.148	0.778	0.009
Quadratic	0.811	0.082	0.945	0.003	0.913	0.007
Cubic	0.815	0.079	0.946	0.021	0.915	0.041
Power	0.882	0.005	0.805	0.006	0.887	0.002
Growth	0.867	0.007	0.913	0.001	0.810	0.006
Exponential	0.867	0.007	0.913	0.001	0.810	0.006

Table 4 Results of homogeneity tests for regression coefficients

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
X	1	13.208	30.447	30.447	62.690	0.000
Land use	2	13.587	2.166	1.083	2.230	0.144
Land use × X	2	33.058	33.058	16.529	34.030	0.000
Error	14	6.799	6.799	0.486		
Total	19	66.652				

in the rangeland and abandoned land were step-like with vertical faces.

Results also show that the highest value for f was obtained under dry farming ($f = 2.56$) related to the presence of physical roughness elements caused by tillage operation and vegetation cover. In addition, due to the presence of biological crusts (lichen and mosses) in the rangeland, a uniform and smooth surface leads to the lowest f values (Fig. 5a). However, the surface soil resistance on the rangeland is higher by several times and the exerted force on the soil particles is very much lower than for other land uses (Figs. 6, 7).

ANOVA results indicate that the above mentioned differences are significant ($P < 0.01$) for shear stress, τ, roughness, f, Fr and D_r for the three land use types

(Table 6). The relationship between K_c and τ_{cr} is an inverse exponential function (Fig. 3f) with $R^2 = 0.95$.

The statistical analysis shows that not only the soil erodibility and critical shear stress are affected by land use but also the nature of the relationship as well as the response of land to increased τ is affected.

Discussion

According to the findings, in the rangeland that has a natural cover and biological crust, soil detachment and head cut initiation occurs under a subcritical flow regime. The Fr was between 0.65 and 1.1, values that are consistent with other findings that revealed 0.5–2.8 range as threshold values of Fr for incision (Prosser et al. 1995; Adelpour 2004; Knapen et al. 2007). The main explanation for increasing of Re (turbulence) can be addressed to the micro-topography of the soil surface in abandoned areas and dry farming lands in comparison with smooth surface of rangeland.

The main reason for the low Fr in dry farming areas is the high vegetation cover and roughness. However, soil disturbances caused by previous tillage operations decrease the strength of aggregates dramatically; consequently, flow lines detach and entrain soil particles more easily.

Other research (Prosser et al. 1995; Adelpour 2004) found similar values (0.2 up to 2.1) for Fr and the highest value of which is the result of low vegetation/roughness on the soil surface. In our experiments, the high Fr was also obtained in rangeland with low vegetation cover and a smooth ground surface.

Vegetation cover affects the roughness, soil shear strength, flow regime and the flow profile, with variations depending on the slope gradient. In dry farming and abandoned areas, due to the high vegetation cover and low flow depth, a subcritical regime was observed; however, as the flow depth increased, the overtopping of branches and stalks diminished the impact of vegetation cover. Despite

Table 5 Shear stresses for different runs with observed head cuts for each land use (1 Pa = 10 dyne/cm²). All parameters were calculated at the initiated head cut

	Number of head cuts	Cumulative head cuts (H_n)	Average τ (dyne/cm²)	τ (dyne/cm²)	f	Fr
Dry farming	2	2	34	37.54	2.560	0.079
	5	7	42	57.15	2.340	0.106
Rangeland	1	1	146	148.5	0.229	1.545
	2	3	178	164.56	0.164	1.783
Abandoned	3	3	161	154.2	0.868	0.712
	5	8	178	181.44	0.996	0.672
	8	16	217	208.55	1.006	0.618

Table 6 Comparison of the means of detachment capacity and critical shear stress for head cut initiation between land uses

Variable	F	Sig.
Average T_{cr}	25.41	0.005
T at head cut	25.29	0.005
D_r	57.209	0.000
f at head cut	278.3	0.000
Fr at head cut	153.7	0.000

subcritical flow in dry farming and abandoned lands, D_r is more than twice that in the rangeland that experienced supercritical flow. This can be mainly attributed to the decrease in aggregate resistance produced by tillage operations (Knapen et al. 2007). So, in arid and semiarid climates, where vegetation cover is very low (<10%), any positive or negative change in land cover can dramatically affect the roughness and the type of flow regime, and therefore affects soil detachment and erosion. The

significant difference in τ_{cr} for the three land uses (79, 11, 804 dyne/cm^2) can be related to land use effects.

This finding agrees with previous findings (Knapen et al. 2007) and indicates a linkage between the drag force needed for initiation of head cuts and the increase in soil erodibility rate when the shear stress exceeds the threshold and incises the soil.

Results of homogeneity tests of regression coefficients and curve fits clearly show that the linear form of the equations apply well to medium and high shear stress values, but for low values nonlinear forms are better ones (Tables 3 and 4). Therefore, (boundary) values <40 dyne/cm^2 can be used to determine when nonlinear regressions between D_r and τ can be used. Based on significant differences of beta (β) values between land uses, it can be postulated that the responses of D_r to increasing τ are not similar under various land conditions. Several authors (Zhu et al. 2001; Knapen et al. 2007) found a boundary value of 2.5 Pa. Different regression forms and regression slopes in each data set caused the remarkably scattered plot (Fig. 5)
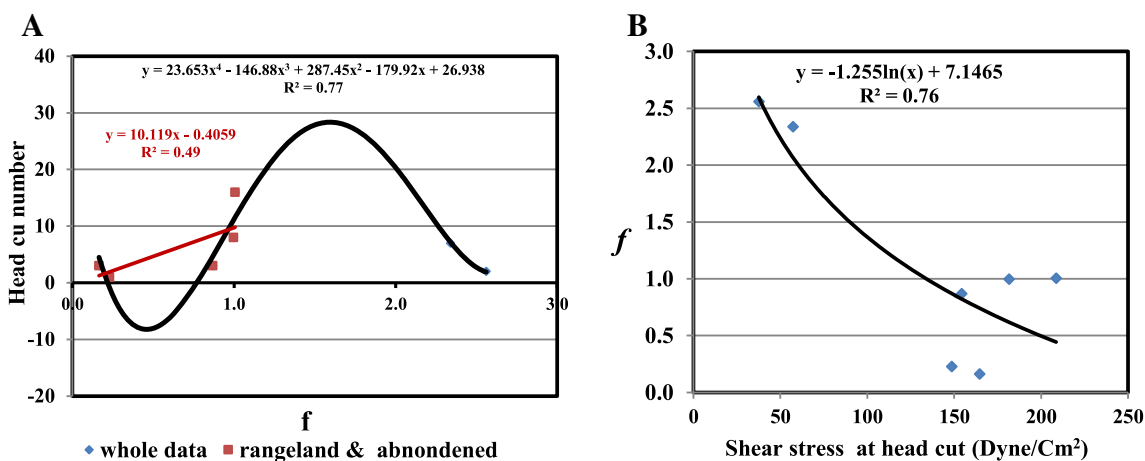

Fig. 6 a Relationship between cumulative head cut numbers and surface roughness for whole data sets (*polynomial curve*) and rangeland and abandoned data (*linear red line*); **b** the inverse logarithmic relationship between τ and roughness
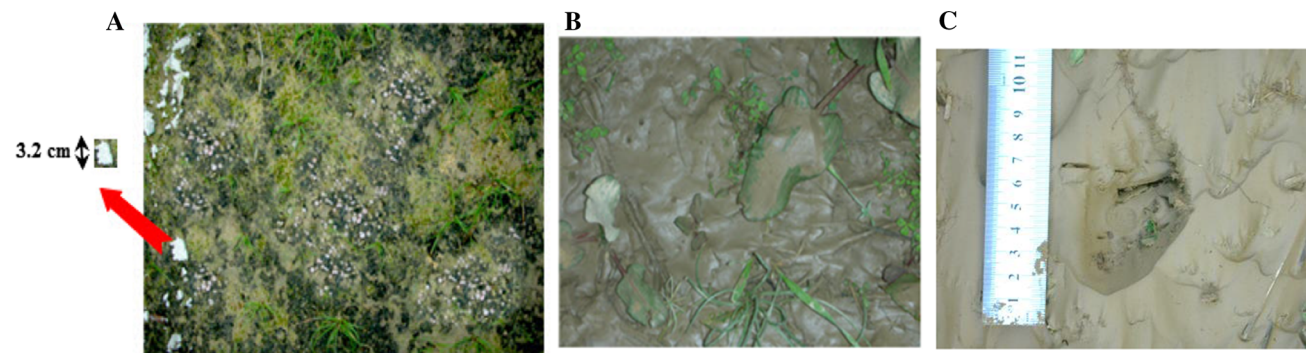

Fig. 7 a Lichens on the rangeland soil (*pale pink* patches). Establishment of biological crust is related to air humidity and soil characteristics (young Entisol). **b** Effects of vegetation cover and micro-relief on sediment trapping in dry farming land. **c** A rotating form of head cut created in dry farming

with weak relationship (third-order and $R^2 = 0.54$) for all data. Therefore, using a single equation for all land use conditions may lead to serious errors of estimation. In contrast, a strong relationship (Fig. 5d) between K_c and τ_{cr} shows that these factors can be used as a single parameter for modeling head cut erosion. This finding provides support for the use of the EGEM model for gully erosion studies.

Dry farming can dramatically increase the soil susceptibility to detachment and transport by tillage practices. Moreover, sudden negative changes in soil erodibility ($K_c = 0.0038$) and τ_{cr} in dry farming land confirm the effect of tillage operations in reducing soil structure and aggregate strength (Léonard and Richard 2004), leading to incision when concentrated water flow occurs. Therefore, to create linear head cuts, runoff must overcome the resistance of soil and must also considerably exceed a critical shear stress. Also the curvilinear morphology of head cut in dry farming can be a result of the unconsolidated soil structure in the arable land but intact soil condition in two others created the step-like with vertical faces.

The relationship between the average τ indicator, contributory catchment area and slope ($T_o = (c\gamma)A^{rf}S$) (Begin and Schumm 1979); it can be postulated that as τ_{cr} increases, upslope area (surrogate for runoff) and slope gradient must increase in order to initiate a gully. Nazari Samani et al. (2009, 2011) reported that when land use changes from rangeland to dry farming land the areas susceptible to gullying increase by a factor of two from 6 to 12% of the total area. Therefore, land use changes not only affected soil stability but also decreased the geomorphic threshold ($S = aA^{-b}$), making more areas prone to gullying.

Previous studies indicate that the soil erodibility and threshold τ_{cr} values are 0.14 and 27 dyne/cm^2, respectively, compared to average values of 0.0651 and 57 dyne/cm^2 from the current study. The surface of rangeland soil is covered by biological crusts (Fig. 7a) with a high critical shear stress of 79 versus 11 dyne/cm^2 in dry farming, and a low susceptibility of soil to concentrated flow could be expected.

In addition, the impact of tillage on aggregate attributes, such as degree of consolidation, weathering, dryness and wetness weathering, can affect the K_c parameter (King et al. 1995). These findings revealed that land use change can increase soil erodibility (K_c) and decrease boundary τ more than 50-fold and sixfold, respectively. It seems that the effect of land use practices on K_c is more significant than on τ_{cr}, reflecting the effect of soil and environmental conditions.

The large differences between 'USLE' K factors and K_c are a result of the variables used for their measurement. The low OM and infiltration rate in the rangeland caused overestimation of K, while in the experimental test the

rangeland had the lowest erodibility. The results for K_c for soil erodibility appear to be more realistic than the 'USLE' K index. The other reason for high K_c for dry farming may be related to low crop residues. Usually in the study area after crop harvesting, the land is used as pasture for local livestock, and trampling together with removal of plant residues leads to a high-level soil disturbance. In most erosion models, erodibility indices are estimated through physical attributes of the soils; however, the results presented here show that these methods will be accompanied by high uncertainty. Numerous indices and methods have been developed to measure or estimate soil erodibility/resistance, but no consensus exists on how to measure or define erodibility. However, for gully erosion the 'USLE' K factor is not suitable. The USLE approach is mostly based on soil attributes while other macro-environmental factors (e.g., root density, soil density, tillage-induced properties and ground cover) are key influences on soil resistance and are neglected by the 'USLE' approach. Therefore, to develop and enhance new physically based models the adoption of a large range of K_r value is essential.

This research mainly focused on head cut initiation, and due to the size of the flume and plot (0.4 × 1.6 m^2), and irregular micro-topography of the soil surface in the dry farming site, head cuts and rills developed freely. The mentioned factors affect the hydraulic characteristics (Bergsma and Farshad 2007) and prevented the establishment of a stable and uniform erosion pattern. In other words, by tillage practices the random roughness and micro-ditches facilitate the formation of head cuts. This result clearly demonstrates the importance of temporal and spatial variation in soil surface resistance along a hill slope (Fig. 7b) [similar to Morgan (2009) and Adelpour (2004)]. Thus, to model erosion over a landscape, a simple sediment transport equation does not give an accurate result regarding detachment and sediment transport.

The difference of regression slopes (K_c) for τ_{cr} and D_r of the abandoned land and rangeland (Table 4; Fig. 5) indicates that for a given soil any change in land use affects the runoff erosion process for many years. The value of τ_{cr} for head cut initiation on the rangeland is five times higher than in dry farming, evidence of high surface and subsoil (10 cm) aggregate resistance in the rangeland that is probably a result of biological crusts. In addition, the mean calculated τ_{cr} of head cut initiation for the whole data set of this research is 121 dyne/cm^2 that is less than that of the global average (150 dyne/cm^2) (Knapen et al. 2007). The main reason for this difference is the variation of test conditions and also local environmental features including the use of a sandy loam soil.

Results of documentation of head cut initiation and associated hydraulic parameters (Table 5) indicate

different behavior between land uses. In dry farming, the initiated head cuts were rotated with gentle inclination that alters their form as discharge and τ increase. Due to a high flow regime (Re > 2000), this form of incision is similar to a chute and plunge pool which traps sediment and consequently hydraulic roughness decreases. Such a condition affects the next run by increasing of τ as the trapped sediments become the sediment source and high detachment rates (D_r) produce a complicated relationship (polynomial) for whole data set (Fig. 5e). The poor relationship between Re and f for the whole data set ($R^2 = 0.18$) demonstrates that Re cannot be a good and suitable predictor for modeling of roughness in head cut erosion and gully initiation. The relationship between cumulative head cut numbers and surface roughness, f, is a complicated polynomial (Fig. 6), but by separating data according to land use (rangeland and abandoned) a simple and significant linear equation can fit the data (Fig. 6a). Moreover, there is an inverse logarithmic relationship between τ_s and f (Fig. 6b). On the other hand, D_r increases with a progressive decrease in physical surface roughness elements due to local scouring on the one side, and the stems are inundated on the other side and consequently, the effects of tillage roughness will be overcome as flow depth increases. These points are in agreement with previous work on rill erosion (Nearing et al. 1997). Therefore, it can be concluded that the same process governs head cuts and rill initiation and both act as break/knick points that convert overland flow into concentrated flow causing hydraulic incision.

Although the cessation of tillage in abandoned land has increased soil resistance and some other parameters, more head cuts were initiated by increasing of τ in comparison with the rangeland (Table 5). Therefore, the effects of land use change on both top and subsoil resistance will be continued for long term.

Based on these results, it is concluded that most physically based models (e.g., WEPP, EUROSEM CREAMS) should use a wider range of both K_c and τ_{cr}. In other words, the use of a single value of $\tau_{cr} = 35$ dyne/cm^2 as the boundary shear stress cannot accurately represent the threshold condition for gully initiation. To obtain a realistic value for K_c, the effect of abandonment duration and other land cover (e.g., lichen and soil stoniness) should also be considered. It is likely that the use of a combined parameter based on K_c and τ_{cr} can include all effects of soil attributes as well as land cover and management practices.

Conclusion

Experimental results of measured soil detachment and head cut initiation, arrived at by simulating concentrated flow on three different land uses with similar soil attributes, indicate a complicated relationship between surface conditions and shear stress. Results indicate that the response of soils to detachment by overland flow is controlled by roughness, vegetation type density and tillage and consequently reflect strong spatial variations of erodibility. Critical shear stress (τ_c), soil resistance to concentrated flow (K_c) and head cut initiation are dependent on land use and soil surface conditions. A comparison of the minimum τ_c for head cut initiation showed a 500% increase from dry farming to rangeland. Soil tillage, compared to rangeland conditions, not only affects the τ_c (79 vs. 11 dyne/cm^2) and K_c (0.192 vs. 0.0005), but also influences the soil's response to increases in runoff depth. Therefore, due to the harsh environmental conditions in dry lands, a longer period is needed for soil to regain its resilience after tillage operation or any land use change. The findings revealed that both equation form and regression coefficients of the relationship between K_c and τ_{cr} are affected by land use.

A combination of hydraulic and geomorphic threshold conditions from previous work on the topographic threshold of gully initiation carried out in the same area indicate that changes in land use would affect both soil erodibility and the topographic threshold condition for gully initiation. Therefore, for effective land protection the conservation practices to prevent gullying should be implemented in the years after land use has changed.

According to the findings of this study, the hydraulic condition for head cut initiation is higher than for micro-rill and surface wash erosion. Actually very high observed D_r was related to micro-rill and inter-rill erosion, and several of these developed into head cuts as the flow depth increased. On the other hand, after the head cut is initiated, the D_r increased most dramatically in rangelands. Also it is noticeable that the 'USLE' K factor is not suitable for assessing soil erodibility to runoff (K_c), and for gully erosion studies it is recommended to use the direct measurement of K_c or optimize it based on real data to make accurate predictions of land use effects on soil erosion.

Our findings strongly show that due to the lack of a full understanding of the interactions between slope, shear stress and discharge, it is not possible to establish a unique equation to estimate surface roughness (f) from an estimate of flow regime (Re). Moreover, the effects of head cut initiation on lands under tillage is different from other land uses as indicated by the effect of head cut shape on flow resistance. Therefore, the use for hill slope processes of hydraulic concepts and equations used for the analysis of rivers is likely to produce major misunderstanding of erosion processes. Unfortunately, there is insufficient data to separate the effect of grain and vegetation roughness on head cut initiation and this should be considered for future research.

Finally, regarding the concentrated erosion threshold and head cut initiation, τ_{cr} is the most widely used parameter for physically based models. In most models, the value of 35 dyne/cm^2 is used as the threshold value for soil detachment. Although this may be suitable for soil detachment and surface incision, it is too small for predicting head cut development and gully erosion. Therefore, the results obtained by models that use this threshold are imprecise. It should be mentioned that to obtain an acceptable result using physically based models (e.g., WEPP, EUROSEM CREAMS, PRORILL, GLEAMS) more effort is needed to consider all erosion processes. Such an approach will enable researchers to completely model erosion in order to prevent over- or underestimation of soil loss.

In regard to K_c, the duration of time that the land has been abandoned should be included as a parameter in the land management data set of erosion models. For head cut initiation, the functional relationship between K_c and τ_{cr} can be used to create single erodibility parameters. Therefore, further experiments similar to those of the current research are needed to ascertain the effects of land use and soil attributes in order to develop a generally applicable model for gully initiation.

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