Assessment of land use impact on hydraulic threshold conditions for gully head cut initiation

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Abstract: Gully as accelerated erosion process is responsible for land degradation under various environmental conditions and has been known as a threshold phenomenon. Although the effects of gullying processes have been well documented, less soil erosion models have taken into account the threshold condition necessary for gully development. This research was devoted to determine the effects of land use change on hydraulic threshold condition and stream power of water flow through an in-situ experimental flume (15m*0.4m). Results indicated that head cut initiation and detachment rates showed a better correlation to stream power indices than shear stress (τ_{cr}). The threshold unit stream power value (ω_u) for head cut initiation in rangeland, abandoned and dry farming were 0.0276, 0.0149 and $4.5*10^{-5}$m/s, respectively. Moreover, the micro relief condition of soil surface and surface vegetation affected the flow regime of discharge and velocity. It is seen that the composite hydraulic criteria of Froude number (*Fr*) and discharge (*Q*) can clearly discriminate the land uses' threshold. In fact, the remarkable decrease of τ_{cr} in dry farming was related to the effect of tillage practice on soil susceptibility and aggregate strength. The findings indicated that using the unit steam power index instead of critical shear stress could increase the models precision for prediction of head cut development. Compared to EGEM's equation for critical shear stress, it is important to point out that for modelling of gully erosion, using of single soil attributes can lead an inaccurate estimation for $\tau_{cr.}$ In addition, based on the findings of this research, the use of threshold value of τ_{cr}= 35 dyne/cm^2 and ω_u=0.4 Cm/S in physically based soil erosion models is susceptible to high uncertainty when assessing gully erosion.

Keywords: Gully erosion; head cut; stream power; threshold; land cover

1 Introduction

Gully erosion as an accelerated erosion phenomena has been known as most effective features in most landscapes. Nonlinear dynamics and complexity of gully erosion have attracted great interests. Researchers have tried to establish different benchmarks to separate gullies from other concentrated water erosion features such as rills and streams. Critical cross-sectional area (Hauge, 1977) introduced a minimum width of 0.3 m and depth of 0.5 m (Brice, 1966) as a criterion to distinguish rill from gully (Imenson and Kwaad 1980). Although the transition from rill to gully erosion is a continuum process, Torri et al. (1987) and Bryon and Slattery (1992) went a step further and suggested a hydraulic concept for rill and gully formation.

In fact the most proportion of sediment yield in a catchment scale is produced by gullies in a wide range of environmental conditions, as described by Nazari Samani et al. (2011) in Iran, Wasson et al. (1996) and Poesen et al. (2003) in Europe, and Li et al. (2003) in China. Many soil erosion models have tried to consider sheet and rill processes; however, fewer attempts have been made to take into account gully erosion at the catchment scale.

Gullying process is an erosion phenomenon, which can develop as soon as the determinant factors (e.g overland flow and rainfall erosivity) exceed a threshold value or resistance force (soil or vegetation) decreases to the critical point. The erosivity of runoff can be defined by hydraulic criteria such as boundary stream power, threshold velocity or shear stress. The required threshold force value to create channel-head incision into the soil surface is mainly a function of soil and land use attributes. In addition, detailed investigation into the relationship between the topographic threshold and shear stress indicated that upslope catchment area and surface slope gradient are linked to stream power index and critical shear stress (Begin and Schumm, 1979). The potential of water flow for erosion can be obtained by combining hydraulic and topographic characteristics (Begin and Schumm, 1979; Conforti et al., 2011).

Although the effects of land use on topographic threshold have been investigated (Vandekcheknov et al., 2000; Poesen et al., 2003; Nazari Samani et al., 2009), there is still great demand to understand head cut initiation and determine threshold hydraulic values when establishing a fundamental knowledge for soil erosion and developing a process oriented gully erosion model. The key question is how large should τ_{cr} be in order to initiate a gully head cut? This question can be further derived as two criteria, namely shear stress and stream power.

Some researchers have investigated the hydraulic threshold of head cut initiation: Prosser et al. (1995, 2000) in the grassland near San Francisco, Nachtergaele and Poesen (2002) in the Belgian loess belt, and Adelpour (2004) in loamy-sands in Iran. However they suggested that more field-based experiments are necessary to effectively analyse effects of land use changes on the threshold situation of head cut initiation. In addition, most physically based erosion models such as WEPP, CREAMS and PRORILL are based on the simplified transport capacity equation Yalin (1977) and soil detachment rate as well as shear stress (Zhang et al., 2014). These models predict the soil erosion through rill and inter-rill concept while neglect gully erosion distribution along a catchment. Meanwhile, it is essential to study the hydraulic thresholds under different environmental conditions and land use patterns when establish a worldwide model for comprehensive erosion predication.

This objectives of this study were to: (1) understand the land use effects on head cut initiation; (2) reveal the relationship between head cut detachment and hydraulic threshold indices (stream power and shear stress); and (3) identify the most determinant factor for gully and concentrated flow erosion.

2 Materials and methods

2.1 Experiment design

The experiments were conducted in the Samal area located in the Dareh-Kore watershed of

Boushehr province in south of Iran. The region has a typical arid to semi-arid climate with an average annual temperature of 14 °C and an average annual rainfall of 200 mm. The main lithological formations include the Miocene Fars Group (Aghajari, Mishigan; consisting of marl, shale, marly and shaly limestone) in the uplands and Quaternary alluvium (consisting of gravels, sands, silt and clay) in the piedmont plain. Gully erosion and bad land formation are two highly destructive processes impacting on the hilly and lowland areas, and are common on the Quaternary formations with slope gradients of less than 20%.

The flume experiments were conducted using an erosion plot that was 15 m long and 0.4 m wide and 0.5 m high, designed to create non-uniform flow resistance. 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 of the flume (Fig. 1 and 2). 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 test locations was about 200 m. The soil attributes according to the land use are presented in Table 1, which show that no significant difference was found between the soil attributes, although a small variation in the samples could be seen in the Ca, organic matter and Na. However, slope could not be held constant. The maximum soil surface slope was in the rangeland (5.9%), while the dry farming land had the least surface slope (0.13%). Therefore, in order to determine the effect of land slope, the shear stress index was used. This index considers both discharge and energy characteristics, which are explained further in the following section. The characteristics of the land cover in the experimental sites were as follows:

a. Rangelands: No surface gravel and uniform cover of lichens and mosses (Fig. 1), with grasses (5%) of *St.cap, St.ar*, and low litter (1%).

b. Dry farming: Ground cover of annual grasses (*Ho. Sp.*; *Br. tec.*), forbs (40%) (*Ch. Ab., As. Sp.,*) and residuals of stalks from previous years and no surface gravel. In contrast to rangelands, the canopy cover of the dry farming land is much greater because of agriculture operations and low slope as well as establishment of weeds.

c. Abandoned areas: This land had been relinquished for 7 years. Vegetation cover of 50% includes annual grasses (*Agi. sp*, *Ma. Sp*, *Fu. sp*, *Br. tec.*) and forbs, low gravel cover (1%) and litter (3%).

[Fig. 1 is here]

[Fig. 2 is here]

[Table 1 is here]

2.2 Experimental operation, measurement and parameter calculation

The flume's sidewalls were beaten into the soil and sealed with plaster, cement and soil to prevent leakage and incursions by animals. To determine the slope of the longitudinal profile with high precision, ground surveying was performed using a Theodolite camera, levelling rod and measuring tape. After setting up the water supply equipment including a water tank, stilling basin and Parshall flume at both ends of the plot, the surface of flume was wetted carefully by a hand sprinkler. The experiment was started with very low discharge (0.75 l/s), and after each run, the discharge was increased. The total number of experiments in dry farming, abandoned and rangeland were seven, five and four respectively. The numbers of runs were different because head cut initiation on different land uses was not similar, and the tests were continued until the threshold condition is reached.

The experiments were done under a steady condition, saying that the discharge was constant in each replicate, and in the consecutive test the discharge was increased. The input discharge was controlled to be constant by a series of pond and storage and a small spill way. The water supply and discharge controller pond were placed at the beginning of inlet before water flowing into Parshall flume.

For every test, the flow parameters including discharge, depth of flow (by a steel ruler) and sediment samples (at the end of the flume) were measured directly, while the water surface velocity was determined by liquid dye tracers (injected once). The soil surface of plots were delaminated and monitored by photos. Any ditch or step like incised erosion feature with size over 3*3 cm was considered as a head cut generation. The experiments were implemented step by step, and after each run the flume was examined for head cut initiation. Through such procedure, the head cut initiation and development could be observed.

The following relations were used to calculate the hydraulic characteristics of flow.

Mean flow velocity: $V = \frac{Q}{A}$ (1)

Shear stress of flow: $\tau = \gamma RS$ (2)

Stream power: $\omega = \tau V = gdSV$ (3)

Total stream power: $\omega_T = \rho gQS$ (4)

Unit stream power: $\omega_u = SV$ (5)

The soil detachment rate: $D_r = \frac{C_V.Q.t}{6}$ (6)

where Q is Discharge (m^3/s), A is cross section area of flow (m^2); V is flow velocity (m/s); d is flow depth (m); υ: kinematic viscosity ($\upsilon = 0.01$ cm^2/s); g is gravitational acceleration (m/s^2); γ is specific gravity (ρg); S is water surface slope; R is hydraulic radius (m); C_V is sediment weight concentration (kg/m^3); t is run time (s). The flow regime was determined based on Froude number equation (F_r).

The basic assumption for this experiment is: the detachment and head cut initiation by water flow occurs when the runoff energy is as large as the soil particle resistance. The validity and generality of this assumption have been verified by previous studies (Yang, 1996; Knapen et al., 2007). Threshold value was calculated by fitting the line of D_r to stream power ω through the equation (7).

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

where D_r is the detachment rate of flow (kg m^{-2} s^{-1}); ω is stream power (Eq. 3-6). The K_c and b are the regression parameters.

To find the effect of land use on flow characteristic condition, the measured detachment rates (D_r) from experimental tests were plotted versus hydraulic indices (ω_u, ω_T, ω and τ). According to the slope of fitted lines, the effects of land use on water flow were assessed.

To compare the findings with a gully erosion model, the procedure of EGEM for critical hydraulic shear stress (Tekwa et al., 2015) was calculated based on equation (8).

$$\tau_{cr} = 0.0065*(\%Clay *10^{0.0182}) \qquad (8)$$

3 Results

3.1 Effects of land use on stream power and flow type

Results of calculated stream power and their relations to detachment rate (D_r) of all land uses were shown in figure 3. The comparison of D_r indicated significant differences of sediment load between three land uses. The parameters of the regression lines (slope and intercept) did not follow the same trend in all land uses and indices. Dry farming land showed the smallest values of total stream power indices.; while rangeland and abandoned lands had smallest value of unit stream power (ω_u). Although all stream power indices could indicate erosion potentials, the ω_u had the highest significant ($p<0.01$) values (R^2=0.99) based on the coefficient of determination. However, the cloud of points for dry farming land exhibited a scattered pattern, which may be explained by the disturbance in agricultural lands.

The Froude Number (F_r) varied from 0.05 to 5.1, and the head cut features developed under sub-critical to supper critical conditions. The lowest F_r values for head cut initiation were 1.61 (with Q = 9.2 l/s) for rangeland and 0.1 (with Q = 8.2 l/s) for dry farming land. The discharge for both dry farming land and rangeland were similar, but the flow types were quite different due to soil disturbance in dry farming land. Therefore, it is expected that by coupling F_r value and flow rate, a composite parameters for head cut initiation could be more meaningful.

[Fig. 3 is here]

3.2 Impact of land use on the threshold shear stress for surface erosion

The results of the relationship between the detachment rate (D_r) and the shear stress are shown in Figures 4, 5 and 6. We preferred to use dyne/cm^2 as the shear stress unit because of the small values obtained in units of Pa (1Pa=10 dyne/cm^2). The significant relationships (P=0.05) between Dr and shear stress were observed. The threshold shear stress for each land use was calculated based on the slopes and intercepts shown in Figures 4, 5 and 6. These values are 83, 11 and 74 dyne/cm^2 for rangelands, dry farming lands and abandoned areas respectively. Moreover, soil resistance to concentrated overland flow (K_c) was obtained for rangeland (0.0038) and dry farming (0.1912). It is notable that the resistance of soil to concentrated flow in rangelands is more than 50 times that in dry farming land.

[Fig. 4 is here]

[Fig. 5 is here]

[Fig. 6 is here]

Through the Eq. 8, the critical shear stress τ_{cr} for dry farming, rangeland and abandoned land were calculated to be 7.53, 6.43 and 8.40 DyneCm^{-2}, respectively. The differences between field data and EGEM were remarkably high. Such inconsistency revealed that the method of estimating τ_{cr} based on single soil attribute could cause unreliable results.

3.3 Effect of land use type on gully initiation threshold

The numbers of head cuts corresponding to mean shear stress for each experiment were listed in Table 2. The critical shear stress for head cut initiation was 174 dyne/cm^2 in rangeland, 35 dyne/cm^2 in dry farming, and 153 dyne/cm^2 in abandoned land. The 3-4 fold difference between the calculated critical shear stresses in the three studied land uses could be linked to the soil surface condition. Although the vegetation cover of rangeland was less than that of dry farming, the biological crust of lichens and mosses made the soil very resistant to detachment. In fact, the presence of biological crusts on the surface of the soil in the rangeland increased the surface soil resistance several-fold (Table 2, Fig. 4 and 5). Table 2 demonstrates that the number of head cuts increased with shear stress. For example, from run 3 to run 5 in abandoned land, the number of head cuts increased more than two-fold while the average shear stress increased just 1.3 times.

[Table 2 is here]

From Table 2 and Fig. 6, it can be found that the relationship between head cuts and shear stress of abandoned land was similar to the dry farming lands, although the critical shear stress for head cut initiation of abandoned land (153 dyne/cm^2) was close to that of rangeland (174 dyne/cm^2).

4 Discussion

From the study, it was found that for the rangeland with no disturbance on soil and cover, both detachment and gully head initiated within a sub-critical flow regime. The threshold value of F_r varied from 0.65 to 1.10. This variation is confirmed by other studies that reported the F_r number in the range of 0.5 - 2.8 as a threshold value for water flow incision (Knapen et al., 2006; Adelpour, 2004; Prosser et al., 1995). One possible explanation to the development of head cut under low F_r number in dry farming land might be the high ground vegetation and micro relief roughness. However, tillage operations and soil disturbances significantly increased the instability and erodibility of soil aggregates; consequently, flow detached and entrained soil particles more easily, which led to the creation of head cuts. Despite sub-critical flow in abandoned and dry farming lands, the detachment rate was more than twice that of rangeland. This could be attributed to the decrease in aggregate resistance produced by tillage operations (Knapen *et al.,* 2007).

Flow discharge and F_r can be used as a composite parameter for discriminant of surface erosion and head cut initiation. The values of this composite parameter ($Q*F_r$) were 14.81, 0.81 and 2.58 for rangeland, abandoned and dry farming land respectively. It can be seen that the composite parameter could clearly rank the flow energy of the three land uses. Therefore, in arid and semi-arid regions with sparse and low vegetation cover, any decreasing of vegetation cover could strongly affect the surface roughness and flow regime, and consequently the soil detachment and erosion (Léonard and Richard, 2004). This finding indicated that the effects of land disturbances and land cover changes on hydraulic threshold of soil detachment and gully erosion were significant, which may not be resilient in a short time scale.

The threshold values for unit stream power (ω_u) were 0.0276, 0.0149 and $4.48*10^{-5}$ m/S for rangeland, abandoned and dry farming respectively. The 100 fold differences could be attributed to the land use effects on water flow energy and the tillage operation effects on soil erodibility. In EUROSEM model, the ω_u was assumed to be 0.4 Cm/S, which is not consistent to our findings. The scattered pattern for dry farming land indicated that when detachment rate was higher than 1(kg/m^2/S), the model prediction was not accurate enough (Fig 3).

The relationship between average shear stress, contributory catchment area and slope proposed by Begin and Schumm (1979) showed the role of a geomorphic threshold on shear stress. Based on the relationship, it is seen that as τ_{cr} increases, upslope area and slope gradient must increase in order to initiate a gully. Nazari et al. (2009) reported that in this study area, when land use changed from rangeland to dry farming land, the areas susceptible to gullying increased 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, causing more areas prone to gullying.

In addition, the impacts of tillage operations on the aggregate attributes such as degree of consolidation, soil weathering, dry and wetness, can affect the erodibility parameter K_r (Franti *et al.,* 1985; King *et al.,* 1995). This study showed that land use change could increase soil erodibility more than 50 times and decrease boundary shear stress about 6 fold. This meant that the effect of land use change on K_r was more significant than on τ_{cr}. Similar results have been reported by other researchers (Nagchtargle and Poeson, 2002; Knapen *et al.,* 2007), who found that using the conventional K in the USLE cannot reflect the spatial variations of erodibility in a landscape scale. With the same soil attributes, both the vegetation cover and the micro relief of the ground surface are the main factors determining the spatial variation of detachment and sedimentation along the flume (Bergsma and Farshand, 2004), preventing the establishment of a stable and uniform erosion pattern. To assess and model erosion over a landscape, a simple sediment transport equation does not give a precise result regarding detachment and sedimentation (Morgan, 2005; Adelpour, 2004). Therefore, the adoption of a large range of K_r values is essential to improve physically based erosion models.

It was noticeable that K_r of the abandoned land and rangeland were similar in low runoff depth (run 1 and 2 in Table 2). However, K_r of the abandoned land in high run-off depth (run 3 in Table 2) was different from that of the rangeland, while it was similar to that of the dry farming land. Such behaviour indicated that for a given soil, a change of land use affected the run-off erosion process for several years. The value of τ_{cr} for head cut initiation on the rangeland is five times higher than that in dry farming land, implying that high surface and subsurface (10 cm) aggregate resistance in the rangeland was probably a result of the biological crust.

The mean τ_{cr} for the whole dataset of this research was 134 dyne/cm^2, which was lower than the global average value of 150 dyne/cm^2 (Knapen et al., 2007). The main reason for this difference could be the discrepancy of ground features and the use of a sandy loam soil. The large differences between τ_{cr} in this research and the result (mean of 7.45 dyne/cm^2) obtained by EGEM's formula (Tekwa et al., 2015) implied that the application of EGEM formula to predicting of gully head cut initiation and gully sediment yield cannot be satisfactory. Previous research (Nachtargale, 2001) held the similar opinion. The main reasons could be the inverse relation of erodibility to τ_{cr}, and the use of a simple soil attribute (clay content) for estimation of threshold shear stress in EGEM.

The relationships between the numbers of observed head cuts and shear stress in the abandoned area and rangeland were the same when τ_{cr}<140 dyne/cm^2. However, in abandoned land, as the τ_{cr} increased, the observed number of head cuts increased by a factor of three (Table 2). This was because land use not only affected the resistance of the surface soil but also affected the resistance of the sub-soil. After seven years of abandonment, the erodibility of sub-soil had not changed significantly. Even though no tillage operations had been conducted on the abandoned land for seven years, the sub-soil had not or even could not return to its original condition and level of resistance.

In most physically based and process based models, D_r is dominated by the shear stress. The regression results of detachment rate (D_r) in this study showed that close relations between D_r and ω_u existed not only in head cut erosion but also in surface and inter-rill erosion. Such validity and generality of power concept for erosion modelling could be related to the fact that all of stream power indices have been derived from the basic concepts of fluid mechanics (Yang, 1996). Many other researches (in situ and in vitro) have also showed that stream power is better than other parameters. Although the hydraulic and erodibility values in this study were within the range of the reported values by the previous researches (Nearing et al., 1999; Knapen et al., 2007; Zhang et al., 2014), the erodibility and threshold values of unit stream power had not been confirm by the WEPP, EUROSEM and

EGEM models (Zhang et al., 2003; Zhang et al., 2014; Tekwa et al., 2015). Together with previous findings (Zhang et al., 2014; Zhang et al., 2003), it is claimed that more efforts should be taken to further investigate the mechanisms of soil erosion and improve erosion models.

5 Conclusions

Experimental results of detachment and head cut initiation indicated that critical shear stress (τ_{cr}), soil resistance to concentrated flow (K_c) and head cut initiation were dependent on land use and soil surface conditions. Critical shear stress has been the most widely used parameter for physically-based models. This study showed that most physically based models should use a wider range of both K_r and τ_{cr} values. In other words, the use of a single value of τ_{cr}=35 dyne/cm^2 or ω_u=0.4 Cm/S as the threshold hydraulic parameters cannot accurately represent the threshold condition for gully initiation. In addition, the duration of farming land abandonment should be taken into consideration in order to obtain a realistic value for K_r.

This study also indicated that more efforts should be taken to obtain a closer insight on the soil erosion mechanisms and erosion modelling. In many physically based and process based models, D_r is dominated by the shear stress; however, the findings of this research revealed that the unit stream power showed stronger correlation to detachment rate. Therefore, new approach based on stream power concept should be considered when developing a process-based model for gully head cut erosion.

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Tables

Table 1: Soil attributes of three land uses selected for experiments

Land use	Texture	Silt (%)	Ec (ds/m)	OC (%)	Lime (%)	Na (meq/lit)	Ca (meq/lit)	SAR	pH	Cl (meq/lit)	Ground slope (%)
Rangeland	Sandy loam	8	3.74	0.44	23.30	33	18.4	7.8	7.3	15.6	5.9
Dry farming	Sandy loam	5.5	3.44	0.85	23.75	34	15	8.1	7.3	16.4	0.13
Abandoned	Sandy loam	5	3.34	0.50	21.25	29.5	14	7	7.3	14.7	4.4

Table 2 Shear stress for different runs with observed head cuts for each land use (1Pa=10 dyne/cm^2).

Land use	Run	Mean shear stress along the flume (dyne/cm^2)	Number of head cuts	Critical shear stress for head cut initiation (dyne/cm^2)
Rangelands	1	70		174
	2	106		
	3	146	1	
	4	178	2	
Dry farming land	1	5	-	35
	2	9	-	
	3	15	-	
	4	19	-	
	5	34	2	
	6	40	4	
	7	42	5	
Abandoned areas	1	78		153
	2	115		
	3	161	3	
	4	178	5	
	5	217	8	

Figures

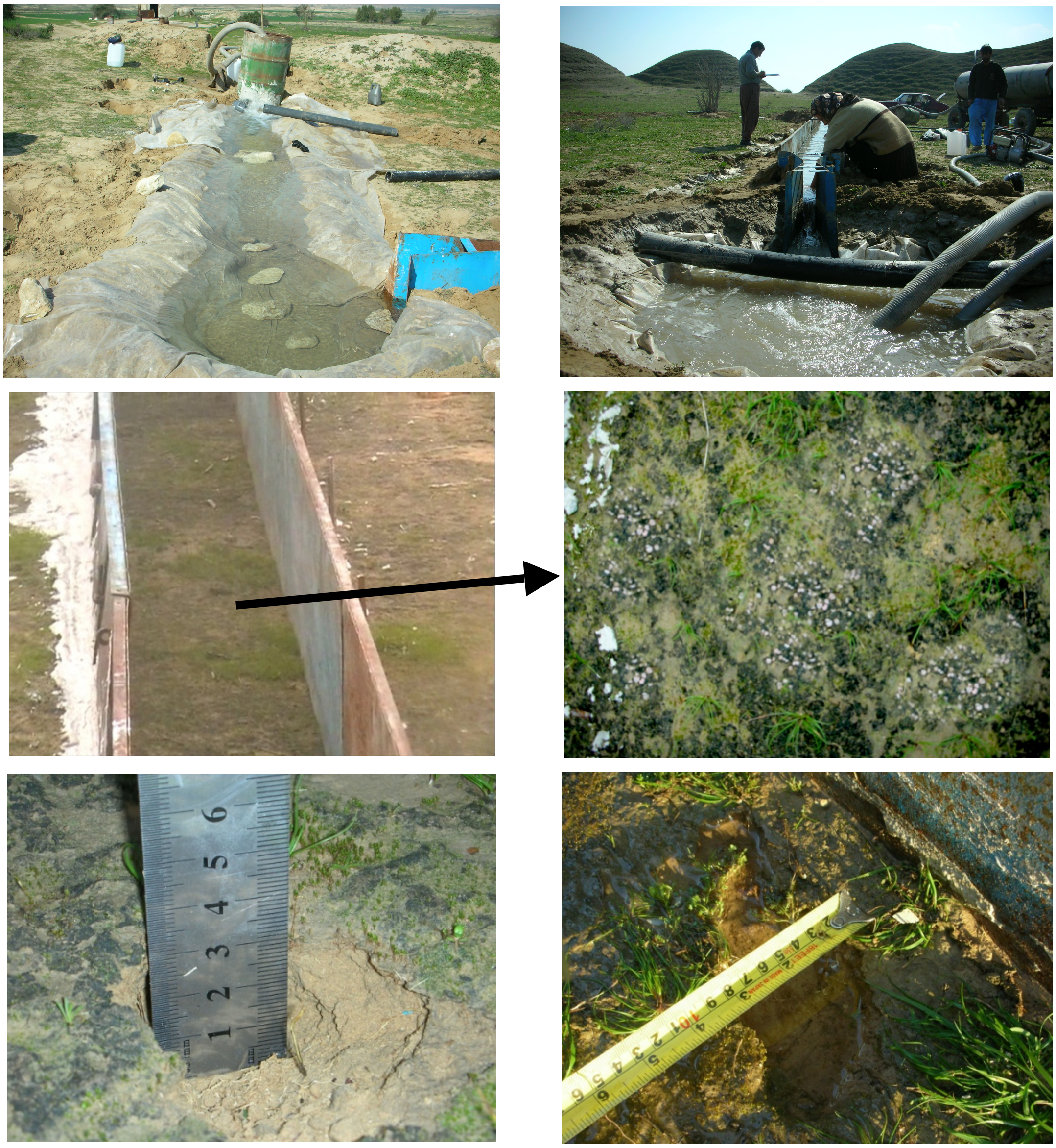

Fig. 1- Flume, water supply, retention pond, overflow pipe and Parshall Flume (Top photos); flume surface and vegetation (grass and pale pink lichen patch) in the rangeland (middle photos); sample of initiated head cut with height of 3 cm in range land (bottom left) and abandoned land (bottom right).

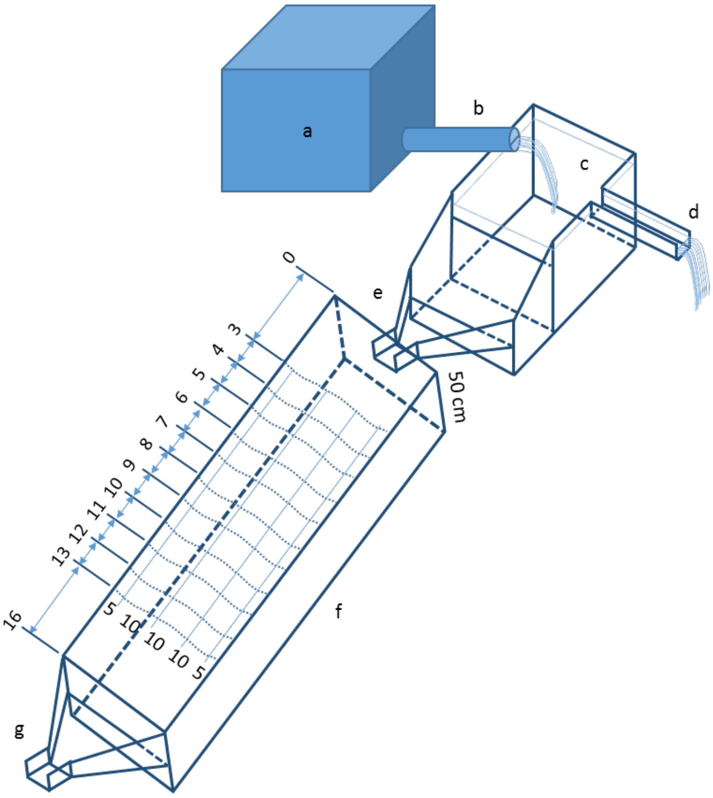

Fig. 2 Schematic of experimental flume. a) Main water supply; b) Input of stilling pond; c) Small retention pond; d) Overflow spillway for constant levelling; e) Inlet Parshall flume;f) Mid-section mesh used to measure flow depth and ground elevation; g) Outlet Parshall flume.

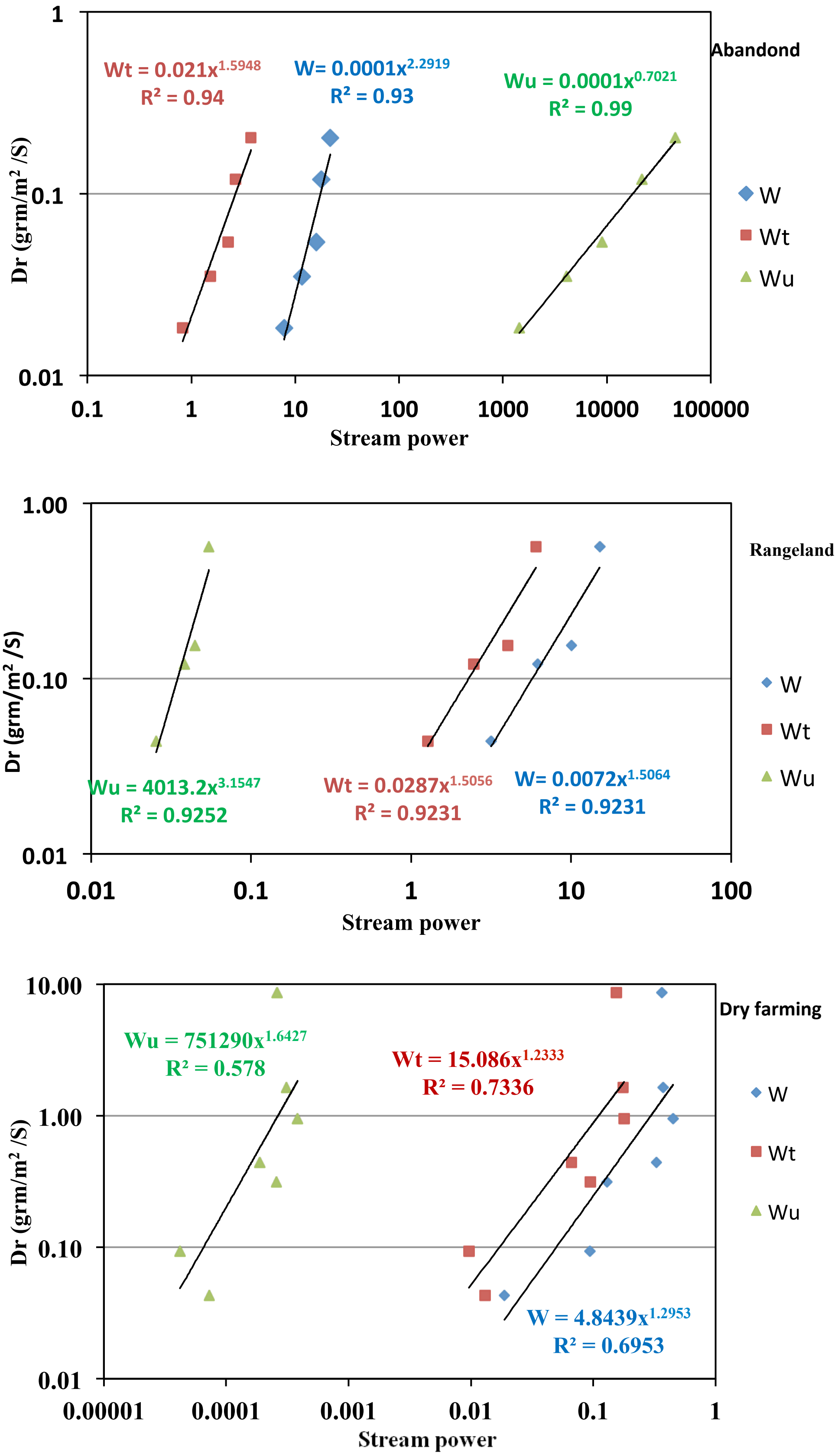

Fig. 3: Relationship between stream power indices and detachment rate in different land use (P<0.001).

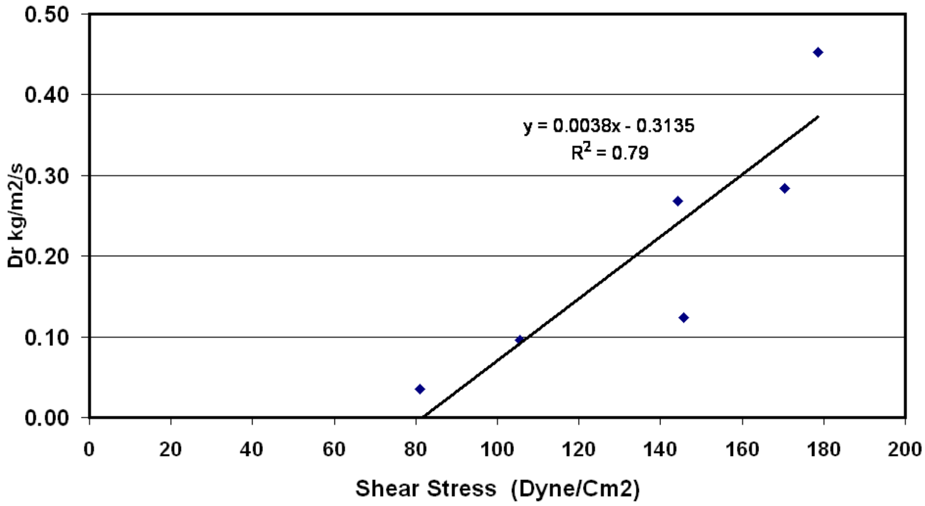

Fig. 4 Relationship between shear stress (τ) and detachment rate in the rangeland (P<0.01)

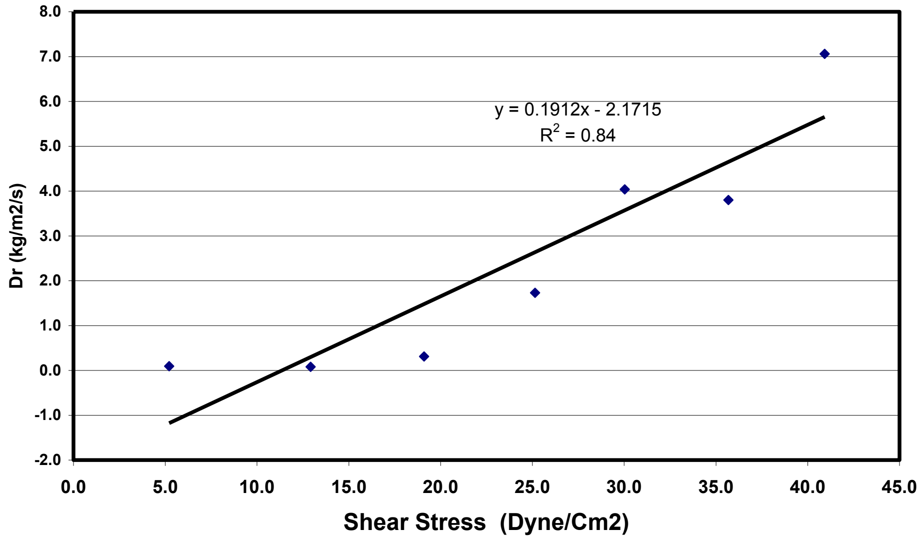

Fig. 5 Relationship between shear stress (τ) and detachment rate in dry farming land (P<0.05)

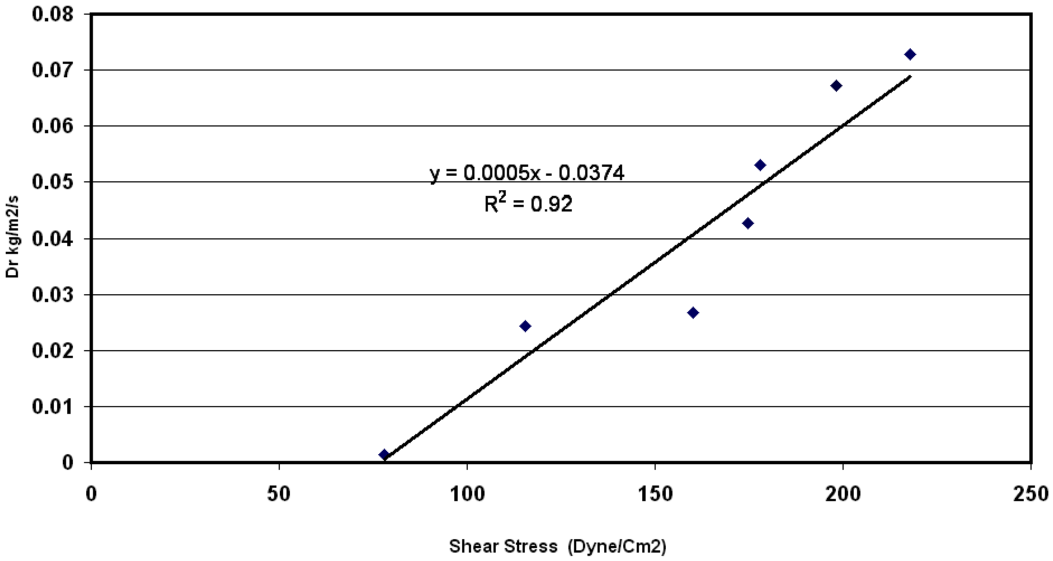

Fig. 6. Relationship between shear stress (τ) and detachment rate in abandoned land (P<0.001)