Soil erosion and the influenced factors: A review article

Shereen Adnan, Asad H. Aldefae* and Wissam H. Humaish
Department of Civil Engineering, University of Wasit, Iraq, Wasit, Kut.

* Corresponding author: asadaldefae@uowasit.edu.iq

Abstract. Unacceptable rates of soil erosion are one of the main important factors that the hydrologists and the water engineers should keep in their mind to prevent soil detachment and increasing of the sediment yields from occurring. Unnoticed soil erosion due to slow process may lead to serious problems with the time due to wash of soil surface that leads to decrease the shear strength and building failure may occur. This review paper focuses on the forms of soil erosion, the affecting factors and prediction of the soil erosion. Forms of soil erosion are presented clearly and the formations of the rills, inter-rills, gullies due to steam flow are explained. Historical sequence of main important equations of the soil erosion determinations from art-of-literature is presented. Hydraulic, topographical and soil critical condition for the erosion with empirical equations are explained in details. Finally, the sedimentation which is the results of the soil erosion, sediment transport and the sediment yields process has been considered in this paper.

Keywords: Erosion, Rills, Gullies, Rainfall, Sedimentation

1. Introduction
Soil erosion is one of the most influential problems of land degradation worldwide [1]. It is a separation and movement of soil particles [2]. Estimation of soil wearing away is often found by models derived from measurements of soil loss from normal runoff or heavy rain drops. The Universal Soil Loss Equation (USLE) has been considered as the best example for an estimation tool, which was lately improved to Revised Universal Soil Loss Equation (RUSLE). Water Erosion Prediction Project (WEPP) model, which depends on a large list of observed and experimental data and were considered a strong tool to estimate rates of soil corrosion as a function of rainfall, land surface, topography, and management factors [2]. The forms of soil erosion have included four main kinds: sheet, gully, rill, and stream [1]. The intensity of rainfall and slope gradient are more important factors that influencing to soil erosion [3]. There are two main factors of rainfall characteristics that control the hydrologic reaction, duration and intensity of rainfall. Higher runoff peak is generated by longer duration and/or higher intensity rainfall [4]. When the rainfall has high intensity, soil corrosion can evolve quickly from sheet to rill even gully erosion [5]. In a corroding rill, the flow focuses and produces in hydrodynamic characteristics with rising washing out power, and consequently drives to fluent increase in soil erosion [6]. The effectiveness of raindrops water appears as an energy source causing separation and as wetting source, increasing wetness causes decreasing in shear strength of soil [7]. The surface runoff generation and the processes of sediment have been affected oppositely by previous content of subsurface water and water pressure for soil [8-11]). Therefore, a reduced detachability by raindrops effect and shear forces of runoff can take place because of increasing cohesiveness, which
is caused by a lower soil content of water and a raised negative pore water pressure. Moreover, enhancement of soil detachment by raindrop effect and dependent transport by surface flow may happen because of increasing time of aggregate saturation and collapse due to air fleeing upon quick wetting, which is caused by lower water content because of previous events of rainstorm [2]. The concentrated runoff caused higher soil erodibility and transport ability than that caused by raindrops [1].

This review paper focuses on the forms of erosion soil, the affecting factors and prediction of the soil erosion. Forms of soil erosion are presented clearly and the formations of the rills, inter-rills, gullies due to steam flow are explained. Historical sequence of main important equations of the soil erosion determinations from art-of-literature is presented. Hydraulic, topographical and soil critical condition for the erosion with empirical equations are explained in details. Finally, the sedimentation which is the results of the soil erosion, sediment transport and the sediment yields process has been considered in this paper.

2. Forms of soil erosion
The erosion can be classified according to the formation along the stream flow and the nature of soil surface. Figure 1 shows most of these forms and it can be summarized as follows:

2.1 Sheet erosion
It is the transportation of soil particles by sprinkles of rainfall and overland flow, it often happens equally on regular slope until it becomes unnoticed when the top layer of soil has been eroded [7].

2.2 Rills erosion
Soil can be moved indirectly by rainfall, by overland flow in forms of tiny channels, it’s called rills, they do not have continual features that means: rills created in one tempest can disappear before the happening of the next tempest [7]. It has a noticeable V-shape [12]. All of the hydraulic, morphological, and geometric parameters that affect both of soil settlement and angle of failure are summarized in Table 1 whereas the parameters that related to the appearance of tension cracks (i.e., angle of failure, angle before failure, the width of failure block, and depth of tension cracks) only affect the angle of failure.

2.3 Inter-Rills erosion
Separation of soil particles is caused by raindrops impact on the catchment area of inter-rill. Surface runoff moves these particles to the rill collection. Inter-rill erosion is equivalent to the sheet erosion; it may be called soil regular elimination, without evolution of distinguished channels of water [7].

2.4 Gullies erosion
Gully forms due to erosion produced by water running leading to soil removal along drainage lines by surface water runoff. Gullies have carry ephemeral flow [7] with a more U-like shape. Many gullies and rills did not have a form of straight lines, gully erosion is produced by flow not by impact raindrops [12].
3. Factors Affecting Soil Erosion

The soil erosion is strongly influenced by many distinguishable factors. Schematic diagram as shown in figure 2 explains these factors and it can be summarized as follows:

3.1 The topography
Area of the catchment and the density of drainage are some of the factors linked to topography of catchment. Overland flow velocity and consequently shear stress of particles on the surface of the land and capacity of transport are also remarkable factors [7]. The slope also impacts soil erosion. Slope impacts including shape, gradient, and length of slope [17]. The results of many studies revealed that the value of erosion have been increased by rising in slope gradient [18].

3.2 The soil
Soil has many aspects that impact erosion, such as soil crust, soil resistance, soil water content, infiltration capacity, etc. Soil erodibility is defined as the susceptibility of soil to the erosion factors, which is linked with soil properties, containing chemical properties, physical properties, soil structure and texture [15]. Soil physical properties including the soil bulk density, water-stable aggregates, water content of soil, and composition of particle may affect soil infiltration capacity and shear strength of soil and hence impact on rill erosion [16]. Soil oxides content and organic carbon content may change tightness of soil which impact soil erodibility [17]. Factors of soil erodibility can be obtained immediately from data of soil loss found from costly and time exhaustion process, or in a worst way, by absolutely measured properties for soil, containing clay content, aggregate stability, texture of soil, shear strength of soil, and cohesion strength [1]. The result from some studies showed that the shear strength of soil may be applied as an index for erodibility for soil [18].

Stability of aggregate have used as factor of soil erodibility by many researchers. They believed that it is more workable and easier to model of erosion prediction [1].

3.3 The land use
Soil erosion can be reduced by vegetation. Its activity has shown during increasing of the density of roots continuity, rising of canopy and ground cover density. Reduced rate of soil erosion can be affected effectively by roots through restricting the mass of soil to raise strength of soil to flow [7]. Vegetation recuperation has been utilized extensively for reducing the velocity of water flow and increase the strength of soil since it may increase soil anti-erodibility, soil infiltration, and stability of soil and decrease the erosivity due to rainfall, velocity of flow, and discharge of runoff [1].

3.4 The rainfalls
Raindrops impact is the main function of rainfall effects on erosion. The Corrosion-ability of soil because of rainfall has realized as the latent energy onto soil erosion. Rainfall affects soil erosion during many related parameters, like: intensity of rainfall, amount of rainfall, and duration of rainfall.

Figure 1. Landform variation and soil erosion potential [7].
[1]. The different functions of rainfall have affected different amounts of erosion [2]. After falling of raindrops on the surface of soil, the impact of raindrops quite increased detachment of soil and transported it, because of the conversion of raindrops kinetic energy to the potential energy of flow [19].

3.5 The runoff
Sediments can erode and move directly by runoff. It is not difficult to study the effects of runoff functions on soil erosion from view point of dynamics of overland flow, containing pattern of flow, flow discharge rate, flow depth, flow velocity, flow shear stress and flow resistance. Many efforts have been made for estimating erosion amounts by means of using the hydraulic parameters of flow, like Froude number and Reynolds number. When rills stand out, significant changes have been shown in hydraulic characteristics of over land, so the flow of rills is different from both river flow and overland flow [1].

3.6 The tillage system
Many actions of tillage have effects on the processes of erosion on cultivated soils. Tillage implement using different cutting tools and the type of equipment can change the situations of soil and has potential to trigger rill. Processes of tillage have contained tillage speed; tillage depth and frequency have effects on erosion during alteration runoff discharge, soil erodibility, and the infiltrations of soil [1].

Figure 2. Relationships of influencing factors on erosion process [1].

4. Predicting of Soil Erosion
The first introduction of mathematical equation for predicting the losses of soil erosion was by Eq. 1 [20]:

\[ A = C'' S^{1.4} L^{0.6} \]  \hspace{1cm} (1)

Where A refers to soil loss, \( C'' \) is a constant, \( L \) is the slope length factor and \( S \) is slope steepness factor.

Later on, this equation is modified by introducing a conservation factor \( P \) as shown in Eq. 2 [21]:

\[ A = C'' S^{1.4} L^{0.6} \ P \]  \hspace{1cm} (2)
A modification for equation (2) is introduced by [22] and management of soil erodibility factor is added to this equation.

Empirically derived model called the universal soil loss equation (USLE) was developed to estimate sheet and rills erosion with allocated conditions [19]:

\[ A = RKLSCP \]  

(3)

Where \( A \) soil loss per unit area in unit time, \( R \) rainfall erosivity factor, \( K \) soil erodibility factor and \( C \) cover management factor. This model estimating the soil loss as an annual average caused by water erosion based on many factors such as: topography, rainfall, management practices, crop system and soil type [24].

(USLE) model to derive universal soil loss equation (RUSLE) is improved by [20]. A new version of (RUSLE) was improved also by [21] for estimating soil loss by adjusting factors of soil loss erosion. Later on, and based on model of (USLE), RUSLE 1.06c and RUSLE 2 are developed containing extra features that resolve specific aspects of the processes for soil erosion [25]. Comparison of models (USLE, RUSLE 1.06c, and RUSLE 2) to discover their inadequacies in determination of the soil loss is made. According to this comparison, USLE model did not calculate the deposition, RUSLE 1.06c calculate deposition as a function of the texture of soil, but RUSLE 2 products changes of sediment characteristics by deposition along the slope, which impacted calculated deposition [32]. For rills and inter-rills erosion, RUSLE 2 model have been estimated as easier as and more powerful than the other models to employ model of erosion prediction [25].

4.1 The rills initiation

The processes of rill initiation were classified by many researchers. These processes contained separation, petrification and transmitting of soil particles [29]. Processes of rill initiation have been defined as stages of knick-points, head cut extension, discontinuous rill, continued rill and rills networks [30]. The rill initiation can be divided into; sloping split and horizontal expansion over the moist perimeter for rill, regional erosion by the debris in a rill, rills wall collapse, side transmigration of rill [30]. Rills are complex and random and this is the viewpoints of why the rills initiation reasons inconsistent [1]. The crust of land surface was importance for rills initiation [31]. Firstly, it can pettishly decrease the infiltration of soil [31], On the other hand, soil crust can raise shear strength of the soil and decrease soil detachment then prevent rill erosion [32]. Some researchers accepted that the roles of interflow are more significant than the crust of land surface in the directness of rills. Through rainfall, when the water content for soil at the range of saturation, the interflow focused and way out to the surface of land to the down point of slope, and thus, streams are evolved over the way out of interflows. In this time, knick-points take place at the upper place of streams follow and lead to breakdown of the upper soil surface, and then rills are evolved [31]. Rills have been excited by surface flow [31]. Rill head cut form when the soil resistance force is smaller than shear stress, this great shear stress occurred because of increased local water depth from upper to lower slope in the flowing processes due to the superimposition of rolled waves [31]. Inter-rill erosion mainly caused by detachment of the particles by raindrops impact, but rills caused by soil particles detachment due to surface flow land [34]. Inter-rill erosion is basically occurs at the top regions of slope whereas on the steepness and slope length, rills is occurring [35]. Figure 3 shows the rills geometry [36].
4.2 Critical conditions for erosion

Hydraulic indicators of rill directness contain Froude number (Fr), Reynolds number (Re), runoff shear velocity, runoff discharge, and runoff energy [1].

The indication threshold of initiation of rills is indicated by [37] as shown in eq. 4:

\[ F_{rc} > 1 + 0.0035d \]  \hspace{1cm} (4)

Where \( F_{rc} \) is the Froude number at critical state and \( d \) is the mean diameter size of sediments.

The threshold conditions of rill directness might equal equations (5) & (6) together, and the basic conditions for overflow are firmly related with the gradient of slope [38].

\[ F_{rc} > 1 \]  \hspace{1cm} (5)

\[ q_c = 0.8547 \left( \sin \theta \right)^{-7/6} \]  \hspace{1cm} (6)

Where \( \theta \) Can be defined as the slope gradient and \( q_c \) is the critical discharge of runoff.

A few specialists did not accept Froude number as appropriate marker for the limit state of rill directness. Reynolds number is more proper for describing the critical condition for the directness of rills after comparing the indices of runoff cross section energy \( (E) \), Reynolds number \( (Re) \), and Froude number \( (F_{rc}) \) [39]:

\[ Re \geq 1.486 \]  \hspace{1cm} (7)

\[ F_{rc} \geq 6.51 \]  \hspace{1cm} (8)

\[ E \geq 1.387 cm \]  \hspace{1cm} (9)

Some studies have been shown that the good indices to depict the crucial conditions for rill initiation are flow shear velocity and flow shear stress [1].

The values of critical shear velocities of flow are between (3- 3.5) cm/s as investigated by [40], furthermore, the properties of soil have been considered with the conditions of flow, and established the critical shear velocity of flow which is firmly related with the surface saturated viscosity as shown in eq. 10:

\[ V_{cr} = 0.89 + 0.56C \]  \hspace{1cm} (10)

Where \( C \) is the saturated viscosity of surface in (kPa) and \( V_{cr} \) is the threshold of flow shear velocity of rill directness in (cm/s).
The energy consumed may be considered as a critical indicator for the initiation of rill erosion, and when it exceeds 7.38 J, the rills happen [31].

4.2 Critical topographic conditions

Many investigations have been made to find the threshold topographic conditions. The inception of the rills critical slope gradient depends on dynamics of sediment as shown in eq. 11 [41].

\[
\frac{\partial \left( \frac{q^{0.25} J^{0.026}}{0.68 V_c} \right)}{\partial \beta} = 0
\]  

(11)

Where \( J \) is the gradient for rills, \( q \) can be defined as the width flux as a unit, \( \beta \) is the slope gradient and \( V_c \) is rills initiation sediment velocity.

The value of the slope critical gradient for rills is constant value; it is a function of the properties of soil [1]. The calculated values of critical slope gradients are between 21.3 to 50.4 [41].

The critical slope gradient from 60 to 120 of sandy soil as indicted by [31]. Equation 12 shows that there is a good relation between soil shear stress \( (K_r) \) and critical slope gradient \( (A_c) \) [42].

\[
A_c = -16.16 + 2.84 K_r
\]  

(12)

The length of critical slope for rill initiation is pointed to the lower length of slope for the diversion from sheet or rill flow, it’s provided flow distance of runoff enough to make it gain adequate energy and power for triggering rills [37].

The critical slope length decline with rising of the rainfall intensity and slope gradient, comparing slope gradient with rainfall, gradient of slope is played more important role [27]. A nonlinear correlation equation is presented between the slope gradient and the critical rill length as shown in eq. 13 [44]:

\[
L_c = af^2 + bf + c
\]  

(13)

Where \( L_c \) is defined as the length of the critical slope whereas \( J \) is the slope gradient.

We conclude that the topographic conditions play an important role on the initiation of rills during their influence on other factors which they are indirect factors [1].

4.2 Critical topographic conditions

Soil shear stress have been used by many researchers as an indicator to show the critical soil states of rills directness quantitatively [42]. From art-of-literature, critical shear stress has predicted by soil shear strength during contradictory and limiting products were completed [48].

The critical shear stress of soil ranges from 1.33 to 2.63 Pa (i.e. 1.94 Pa as an average) as determined by [22]. The tracing method for scarce earth element to investigate the critical shear stress for the initiation of rills and found it range from 1 to 2 Pa with 1.13 Pa as an average [40]. The shear strength is strongly influenced by the slope gradient [27]. It was found that increasing of the slope gradient from (50 -250) conducted to a little increase in critical shear stress (3.2 -4.6 Pa) by using a rational method for this study.

The values of critical shear stress are from 0 Pa to 15 Pa depends on surrounding conditions and soil [41]. It was noticed also that the critical shear stress ranges between 2.08 Pa to 6.30 Pa and it was significantly affected by land uses [36]. Typical limits of critical shear stress should be from 0 Pa to 10 Pa mostly [47].

In Water Erosion Prediction Project (WEPP), the critical shear stress is considered as an important parameter, and it can be estimated utilizing the parameters of soil such as organic matter content, dry bulk density and texture [1].

A linear connection among soil shear strength and critical shear stress of runoff have been produced as in Leonard’s and Richard’s equation [49-52]:

\[
\tau_c = \beta \sigma_s
\]  

(14)
Where $\tau_c$ is previously termed as critical shear stress, $\sigma_s$ is the strength of the soil. The value of $\beta$ estimated as $2.6 \times 10^{-4}$ and it has standard error around $1.2 \times 10^{-5}$.

A linear relationship among critical soil shear stress and slope gradient is presented by [33] and shown in eq. 15:

$$\tau_c = A + BS$$ (15)

Where $S$ is the slope gradient.

The critical shear stress was estimated for head cutting to be as shown in eq. 16 [48]:

$$\tau = c' + (\sigma - \mu_a) \tan \theta^f + (\mu_a - \mu_w) \tan \theta^b$$ (16)

Where $\tau$ is the soil shear stress at critical condition for rill initiation in (kPa), $c'$ is the soil cohesion parameter at effective status in (kPa), $\sigma$ is the positive soil stress, $\mu_a$ is term of air pressure in the soil pore, $\mu_w$ is the pressure of water in the soil pore, $\theta^f$ is the angle of internal friction at effective state and finally, $\theta^b$ is the rate of soil shear stress increasing with the increase of soil suction.

5. Conclusions

According to the previous investigations concerning with the soil erosion and how different factors effect on its formation, main conclusion can be summarized as follow:

1- Formation of rills, inter-rills and gullies are strongly influenced by the rainfall intensity whereas indirect effects for other factors. Kinds of the soil are very effective in both the formation erosion and the discharge of the sediments.

2- Many empirical equations are produced to determine the soil erosion, but the best one is the universal soil loss equation (USLE) in which topography, rainfall, management practices, crop system and soil type are considered in this model.

3- Froude number (Fr), Reynolds number (Re), runoff shear velocity, runoff discharge, and runoff energy are effect directly on the sediment discharge.

4- It is highly recommended to perform more investigation related to the critical condition for erosion formation. Principles of physical modeling in hydraulics and sedimentation transport should be further understood and critical relationships values of different factors should be considered.

5- Precise and ease of the mathematical model of predicting the sediments yields and soil erosion is the main reason that keeps the researchers use it widely around the world.

Acknowledgement

The authors would like to thank the staff of the main library of the University of Wasit, Iraq. The second author would like also the Ministry of higher education and scientific research (MOHESR) in Iraq for supporting the postgraduate students in the engineering faculty at University of Wasit and giving them a chance to complete their higher studies.

6. References

[1] Sun , Fang H, Qi D, Li J and Cai Q 2013 A review on rill erosion process and its influencing factors Chinese geographical science 23 389-402

[2] Römkens M J, Helming K and Prasad S N 2002 Soil erosion under different rainfall intensities, surface roughness, and soil water regimes Catena 46 103-123

[3] Haiou S, Fenli Z, Leilei W, Yong H and Wei H 2016 Impacts of rainfall intensity and slope gradient on rill erosion processes at loessial hillslope Soil and Tillage Research 155 429-436

[4] Qingquan L, Jiachun L and Li C 2004 Dynamics of overland flow and soil erosion (II)-soil erosion Advances in Mechanics 34 193-506

[5] Haiyan F, Liying S and Zhenghong T 2015 Effect of rainfall and slope on runoff, soil erosion and rill development: an experimental study using two loess soils Hydrological processes 29 2649-2658
[6] Wang Y C and Lai C C 2018 Evaluating the erosion process from a single-stripe laser-scanned topography: A laboratory case study Water 10 956
[7] Mahabaleshwara H and Nagabhushan H M 2014 A study on soil erosion and its impacts on floods and sedimentation International Journal of Research in Engineering and Technology 3 443-451
[8] Aldefae A H, Al-Khafaji R A, Shamkhi M S and Kumar H Q 2020 Erosion, Sediments Transport and Riverbank Stability: A Review. IOP Conf. Ser.: Mater. Sci. Eng. 901 012014
[9] Almeida W S D, Carvalho D F D, Pereira F A and Rouws J R 2019 Sediment production and soil water infiltration under different simulated rainfall characteristics Revista Brasileira de Engenharia Agrícola e Ambiental 23 572-578
[10] Luo J, Zhou X, Rubinato M, Li G, Tian Y and Zhou J 2020 Impact of multiple vegetation covers on surface runoff and sediment yield in the small basin of Nverzhai, Hunan Province, China Forests 11 329
[11] Rodrigo-Comino J, Senciales-González J M, Terol E, Mora-Navarro G, Gyasi-Agyei Y and Cerda, A 2020 Impacts of weather types on soil erosion rates in vineyards at “Celler del Roure” experimental research in eastern spain Atmosphere 11 551
[12] Øygarden L 2003 Rill and gully development during an extreme winter runoff event in Norway Catena 50 217-242
[13] McCool D K, George G O, Freckleton M, Papendick R I and Douglas J C L 1993 Topographic effect on erosion from cropland in the northwestern wheat region. Transactions of the ASAE
[14] Liu B Y, Nearing M A and Rise L M 1994 Slope gradient effects on soil for steep slopes Transactions of the ASAE 37 1835-1840
[15] Vrieling A 2006 Satellite remote sensing for water erosion assessment: A review Catena 2-18
[16] Li JL, Cai Q G and Sun L Y 2010 Reviewing on factors and threshold conditions of rill erosion Progress in Geography 29 1319-1325
[17] Emmett W W 1978 Overland flow. In: Kirkby M J (ed). Hillslope Hydrology John-Wiely and Sons 145-176
[18] Nearing M A and Bradford J M1985 Single waterdrop splash detachment and mechanical properties of soils Soil Science Society of America Journal 49 547-552
[19] An J, Zheng F, Lu J and Li G 2012 Investigating the role of raindrop impact on hydrodynamic mechanism of soil erosion under simulated rainfall conditions Soil Science 177 517-526
[20] Zingg AW 1940 Degree and length of land slope as it affects soil loss in run-off Agric. Engng. 21 59-64
[21] Smith D D and Wischmeier W H 1957 Factors affecting sheet and rill erosion Eos, Transactions American Geophysical Union 38 889-896
[22] Browning G M, Norton R A and McCall A G 1948 Investigations in erosion control and the reclamation of eroded land at the Missouri valley loess conservation experiment control station, Clarinda, Iowa USDA Tech Bull 1931
[23] Wischmeier W H and Smith D D 1978 Predicting rainfall erosion losses: a guide to conservation planning (No. 537) Department of Agriculture, Science and Education Administration
[24] Dutta S 2016 Soil erosion, sediment yield and sedimentation of reservoir: a review. Model Earth Syst. Environ. 2 123
[25] Kinnell P I A and Risse L M 1998 USLE-M: Empirical modeling rainfall erosion through runoff and sediment concentration Soil Science Society of America Journal 62 1667-1672
[26] Foster I D L 2006 Lakes in the sediment delivery system. Soil erosion and sediment redistribution in river catchments: measurement, modelling and management CAB Int. Wallingford 128-142
[27] Yao C T and Lei W J 2008 Critical conditions for rill initiation Transaction of the ASABE 5 107-114
[28] Turkelboom F, Poesen J and Trébuil G 2008 The multiple land degradation effects caused by land-use intensification in tropical steeplands: A catchment study from northern Thailand Catena 75 102-116.

[29] Wang G 1998 Summary of rill erosion study Soil and Conversation in China 8 23-26

[30] Ding W, Li Z and Lu K 2003 The elementary study of the reason of rill erosion on slope. Acta pedologica Sinica 40 822-828

[31] Cheng Q, Cai Q and Li J 2005 Summarization on study of soil surface crust or sealing and its effects on erosion Progress in Geography 24 114-122

[32] Lei T W, Zhang Q W and Yan L J 2008 A rational method for estimating erodibility and critical shear stress of an eroding rill Geoderma 144 628-633

[33] Consuelo C R, Stroosnijder L and Guillermo A 2007 Interrill and rill erodibility in the northern Andean Highlands Catena 70 105-113

[34] Govers G and Poesen J 1998 Assessment of the interrill and rill contributions to total soil loss from an upland field plot Geomorphology 1 343-354

[35] Shit P K, Bhunia G S and Maiti R 2016 An experimental investigation of rill erosion processes in lateritic upland region: A pilot study Eurasian Journal of Soil Science 5 121

[36] Savat J and PLOEY D 1982 Sheetwash and rill development by surface flow

[37] Zhang G H, Liu G B and Tang K M 2008 Flow detachment of soils under different land uses in the loess Plateau of china Transaction of the ASABE 51 883-890

[38] Lei T and Nearing M A 2000 Laboratory experiments on rill initiation and critical shear stress in loose soil Transactions of the Chinese Society of Agricultural Engineering 16 26-30

[39] Rauws G and Covers G 1988 Hydraulic and soil mechanical aspects of rill generation on agricultural soils Journal of soil science 39 111-124

[40] Yang J R, Shi Z T, Cao S Y and Liu X N 2008 Study on the Critical Erosion Gradient by the Hydrodynamics [J]. Journal of Arid Land Resources and Environment 5

[41] Cai Q 1998 Research of rill initiation condition on loess hillslopes. Journal of sediment Research 1 52-59

[42] Lei T W, Zhang Q, Zhao J and Tang Z 2001 A laboratory study of sediment transport capacity in the dynamic process of rill erosion Transaction of the ASAE 44 1537-1542

[43] Fenli Z 1989 Relation between critical slope length of occurring rill erosion and slope gradient Soil and Water Conservation in China 8 23-25

[44] Leonard J and Richard G 2004 Estimation of runoff critical shear stress for soil erosion from soil shear stress 233-249

[45] Johannesson K H, Tang J, Daniels J M, Bounds W J and Burdige D J 2004 Rare earth element concentrations and speciation in organic-rich blackwaters of the Great Dismal Swamp, Virginia, USA Chemical Geology 209 271-294

[46] Knapen A, Poesen J, Govers G, Gyssels G and Nachtergaele J 2007 Resistance of soils to concentrated flow erosion: A review Earth-Science Reviews 80 75-109

[47] Collison A and Simon A 2001 Modeling gully head-cut recession processes in loess deposits. In Soil Erosion (p. 87). American Society of Agricultural and Biological Engineers.

[48] Ran Q, Su D, Li P and He Z 2012 Experimental study of the impact of rainfall characteristics on runoff generation and soil erosion Journal of Hydrology 424 99-111

[49] Renard K G, Foster G R, Weesies G A, McCool D K and Yoder D C 1996 RUSLE user's guide Soil Water Conserv. Soc.

[50] Shit P K, Bhunia G S and Maiti R 2016 An experimental investigation of rill erosion processes in lateritic upland region: A pilot study Eurasian Journal of Soil Science 5 121

[51] Timothy J R, Chih T Y and Joseph D 2006 Erosion and sedimentation manual U.S. Department of the Interior Bureau of Reclamation.

[52] Yunyun H, Shufang W, Hao F and Lifeng Y 2011 Dynamic process of slope rill erosion based on three-dimensional laser scanner Science of Soil and Water Conservation 9 32-37
[53] Zejun T, Tingwu L and Qingwen Z 2004 A method for determining critical shear stress of soil in eroding rill with ree tracers ACTA Pedologica Sinica 41 28-34