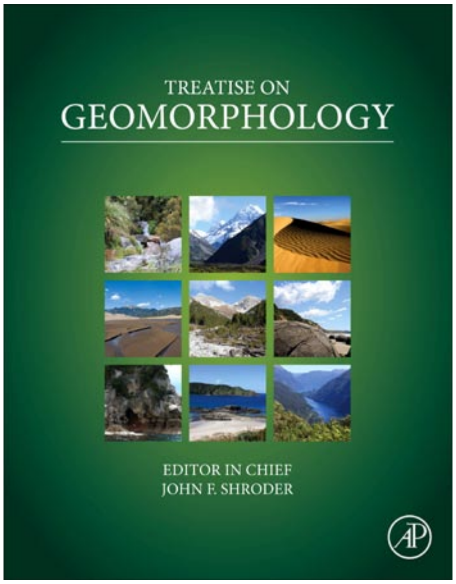

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7.11 Rill and Gully Development Processes

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Glossary

Ephemeral gullies Small, linear (either continuous or discontinuous) channels formed during one rainfall event but may be filled in subsequent events or artificially.

Headcut An erosional process at the head of rills or gullies that causes rills and gullies extending upstream.

Permanent gullies Big channels that permanently locate in the same locations where they were initiated.

Piping An erosional process caused by subsurface flow traveling through the pipes within soil structure. It is a common process giving rise to the initiation of gullies.

Rills Rills are micro-channels that are formed by concentrated surface runoff during rainfall events.

Abstract

Rills and gullies are common and generally companion geomorphological features on hillslopes, but they are different both morphologically and mechanically. By introducing the concepts and classifications of both rills and gullies, this chapter describes the physical processes causing the development of rills, followed by an overview of research methods for characterizing the mechanics of rill erosion and modeling rill development. Compared with rill erosion, gully initiation and erosion are more complex as they are controlled by both surface and subsurface processes. As a result, much more diverse approaches have been developed both to quantify gully headwall retreat and sidewall erosion and to characterize gully development.

7.11.1 Concepts and Classifications

Rills and gullies are common geomorphological features on hillslopes. Rills consist of microchannels that have undergone erosion and/or deposition by concentrated surface runoff (Bull and Kirkby, 1997; Knighton, 1998) (**Figure 1**). Gullies are linear channels formed where upland soil and parent materials are removed by concentrated ephemeral flows during rainstorms (Kirkby and Bracken, 2009). Rills are generally smaller than gullies in size. Typically, rills are 0.05–0.3 m wide and up to 0.3 m deep (Knighton, 1998), whereas gullies have a minimum width of 0.3 m and a depth typically ranging from 0.5 to 30 m (Poesen et al., 2002; Charlton, 2008). The threshold cross-sectional area that distinguishes rills from gullies is 929 cm^2, which is often referred to as 'square foot criterion' (Poesen, 1993). Large gullies may have dimensions of 500-m width and 300-m depth (Derose et al., 1998). These gullies have permanent incised channels caused by intense soil erosion. Larger gullies are referred to as 'arroyos', which are continuous entrenched channels with steeply sloping or vertical walls in cohesive valley-floor alluvium (Cooke and Reeves, 1975; Bull, 1997). In arid and semiarid regions, gullies are associated with badlands, intensively dissected high-relief areas unusable for agriculture (Charlton, 2008). Morphologically, gullies ostensibly differ from stable channels, which have relatively smooth, concave-upward longitudinal profiles. Gullies have steep sides, low width/depth ratios, and a stepped profile, characteristically having a headcut and various steps or knickpoints along their courses (Knighton, 1998). These rapid changes in slope alternate with sections of very gentle gradients, either straight or slightly convex in a gully longitudinal profile (Morgan, 2005). Rills exist only on hillslopes, whereas gullies commonly occur at the valley bottom and in swales (Casali et al., 2006). On hillslopes, rills are formed with gentle slopes of 2–5°, whereas

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Figure 1 Rills on a roadside in central New York, USA.

Figure 2 An ephemeral gully in central Belgium. Reproduced from Poesen, J., Vanwalleghem, T., de Vente, J., Knapen, A., Verstraete, G., Martinez-Casasnovas, J.A., 2006. Gully erosion in Europe. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley, Chichester, pp. 515–536, with permission from Wiley.

gullies tend to have steeper slopes ranging from 8° to 16° or even steeper (Savat and De Ploey, 1982; Li et al., 2004).

The morphological distinction between rills and gullies is attributed to different processes controlling their formation and development. Rills formed during one rainfall event tend to have higher resistance than their neighboring areas and hence may be subsequently filled by sediment deposition when new rills are formed during the following event (Bull and Kirkby, 1997). This means that rills are negative-feedback or self-stabilizing systems. As such, rills vary in lateral positions from year to year over slopes of fine-grained material (Bull and Kirkby, 1997). By contrast, gullies, once formed, maintain their positions as permanent channels. The wide variation of gully morphology has led to attempts of gully classification based on physical and land-use factors, planforms, locations, and parameters representing gully cross-sectional shapes (Bull and Kirkby, 1997; Poesen et al., 2002; Golosov and Panin, 2004; Brooks et al., 2009). A simple, physically based classification distinguishes gullies as ephemeral or permanent (Poesen et al., 2002). Ephemeral gullies are impermanent channels that are obliterated periodically by cultivation (e.g., deep tillage or land-leveling operation)

Figure 3 A permanent gully in Spain. Reproduced from Poesen, J., Vanwalleghem, T., de Vente, J., Knapen, A., Verstraete, G., Martinez-Casasnovas, J.A., 2006. Gully erosion in Europe. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley, Chichester, pp. 515–536, with permission from Wiley.

or natural processes (i.e., deposition) (**Figure 2**) (Poesen et al., 2006). Their infilling generally leaves topographic depressions or swales, which assure the return of new gullies developed subsequently to the same position (Bull and Kirkby, 1997; Poesen et al., 2002). Permanent gullies are channels that have cross sections permanently recognizable without flowing water and have identifiable banks (Bull and Kirkby, 1997) (**Figure 3**). Although deposition can occur, erosion is generally more intensive such that these gullies may enlarge (Poesen et al., 2002). It follows that permanent gullies are self-perpetuating systems and ephemeral gullies fall between self-stabilizing and self-perpetuating systems. Ephemeral gullies tend to develop in intensively cultivated areas, whereas permanent gullies typically develop on abandoned fields or rangelands (Poesen et al., 2002).

Because rills and gullies directly relate to agricultural activities where they occur, distinguishing them from the practical perspective is useful. Rills are intermittent water courses that present no impediments to tillage using conventional equipment (Grissinger, 1995). Once filled, they normally do not re-form in the same locations (Foster, 1986; Vandaele and Poesen, 1995). Ephemeral gullies are small channels that can be filled by normal tillage and can re-form in the same location by additional runoff events (Foster, 1986; Soil Science Society of America, 2001). Permanent gullies are steep-sided channels that are too deep to easily ameliorate with ordinary farm tillage equipment (Soil Science Society of America, 2001). Geomorphologically, rills and gullies may be regarded as different morphological stages of a continuum of incised channels, including microrills, rills, megarills, ephemeral gullies, permanent gullies, and arroyos (Bocco, 1991; Poesen et al., 2003). However, the transition from one stage to another is gradual and no quantitative equation exists to discriminate these classes (Grissinger, 1995).

A special type of permanent gully is bank gullies, which form where a washline, a rill, or an ephemeral gully crosses an earth bank (e.g., river, gully, or terrace bank) (Poesen et al., 2002). They typically occur as tributary channels initiated at the bank of an ephemeral river or at a terrace bank from where gully heads retreat into low-angled pediments, river, or agricultural terraces (**Figure 4**). Gullies may be discontinuous or continuous. If gullies occur on valley floors, a section of a discontinuous gully is characterized by a vertical headcut, a channel immediately below the headcut with depth greater than its width, a bed gradient less than that of the original valley floor, and a decreasing depth of the channel downstream. Where the gully floor intersects the valley floor, the gully depth becomes zero and a small gully fan occurs (Leopold et al., 1964; Bocco, 1991). If gullies occur on valley sides, a discontinuous gully refers to the channel fading out into a depositional zone but not reaching the valley floor (Morgan, 2005). Discontinuous gullies are isolated from the rest of the draining network. Continuous gullies discharge into streams at the bottom of the slope and hence form part of a drainage network (Poesen et al., 2002; Morgan, 2005).

7.11.2 Rill Development and Erosion Processes

Rills are formed by overland flow on hillslope surfaces. The processes of rill initiation and development generally involve four stages: unconcentrated overland flow, overland flow with concentrated paths, microchannels without headcut, and microchannels with headcut (Merritt, 1984; Knighton, 1998). The second stage is critical for a rill system to initiate (Morgan, 2005). Concentrated flow may be caused by microtopography, vegetation, animal tracking on natural hillslopes, or tillage on agricultural soils. However, flow concentration alone does not necessarily cause rill incision (Bryan, 2000). This is because rill initiation is theoretically characterized by detachment capacity – the ability of the water to detach soil particles, which is related to not only flow hydraulics but also soil properties.

Figure 4 A bank gully in Spain. Reproduced from Poesen, J., Vanwalleghem, T., de Vente, J., Knapen, A., Verstraete, G., Martinez-Casasnovas, J.A., 2006. Gully erosion in Europe. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley, Chichester, pp. 515–536, with permission from Wiley.

The hydraulic concept related to rill initiation was first proposed by Horton as the threshold tractive force in his theory on slope erosion owing to overland flow (Horton, 1945). The threshold tractive force will not be reached until flow depth, which increases with distance from the drainage divide as flow accumulation increases, reaches a critical value. Therefore, no rilling occurs within this distance even if a concentrated flow exists. This zone was termed by Horton (1945) as the belt of no-erosion. Since then, mathematical equations using various hydraulic indices (including shear velocity, bed shear stress, stream power, unit stream power, and unit or total discharge) have been proposed to describe the initial condition of rilling (see detailed citation in Bryan (2000)). These equations are not comparable with each other, suggesting that the critical condition of rill initiation cannot be characterized by a single hydraulic variable for different settings such as field plots and flumes with different designs and dimensions, slope intensities and shapes, pedological material types, water conditions, and rainfall characteristics. A more fundamental problem in these equations is that they ignored the influence of soil properties on rill initiation (Bryan, 2000; Cerdan et al., 2002). Although the ratio of flow shear stress to soil shear strength has been used to describe rill initiation (Torri et al., 1987), it is unlikely to develop a universal equation to quantify rill initiation because of diverse soil types and properties, and variable disturbance from agriculture.

The development of rills involves at least the interaction between raindrop and flow, the influence of interrill erosion to rill, and the sediment transport in rills. Once concentrated flow exceeds a threshold value, it creates rills by detaching and transporting soils downslope. On the other hand, raindrops on interrills move detached soil particles into rills (Dunne and Aubry, 1968), and those in rills attenuate the strength of the concentrated flow (Dunne, 1980). These raindrop impacts cause a negative-feedback mechanism to limit rill development. Consequently, rills generally exhibit discontinuous and ephemeral features. Rills formed during one rainfall event are generally obliterated during the next event if sediment supply from interrill surface or rill-wall collapse exceeds transport capacity (Knighton, 1998). These processes assure that rills are self-stabilizing systems with limited dimensions.

Originally formed (near) parallel rills may become integrated into a rill network by cross-grading and micropiracy (i.e., the robbing of a small channel's drainage system by a large channel) (Horton, 1945). This occurs when overland flow is sufficiently deep to overtop and breaks down the ridges that initially separate adjacent rills (Leopold et al., 1964). The confluence of small rills into bigger ones changes local hydraulic conditions and leads to different rill network geometry for slopes of different soil types (Bryan, 2000). Confluence zones tend to form well-defined knickpoints or headcuts from intense scouring. New rill tributaries can develop either because localized rill bank collapses or because of shear stress of interrill flow increased above the critical value (Bryan, 2004). However, fully understanding rill network evolution requires the development of physically based models.

7.11.3 General Approaches on Rill Erosion

Rill erosion contributes higher soil loss than sheet erosion (Zhu and Cai, 2004). Sediment transport through rills accounts for about 50–70% of total soil erosion (Morgan, 2005). In cultivated lands, rill erosion can lead to significant reduction of soil fertility and reduces annual agricultural revenue up to 30% (Valentin et al., 2005). Processes of rill erosion have been studied in two ways: (1) treating rills as channels wherein rill erosion is characterized by the relationship between rill morphology and rill channel hydraulics or by its transport capacity, and (2) treating rills as linear features and studying rill erosion at different spatial scales. For example, rill width, W, has been characterized by a bivariate power relation between W and flow rate, Q, $W = aQ^b$ wherein the exponent b ranges from 0.3 to 0.4 (Abrahams et al., 1996; Nachtergaele et al., 2002; Torri et al., 2006). This exponent is less than that of river channels (b is typically around 0.5), suggesting the general smaller widths of rills. Mean flow velocity can also be related to Q by a power function with an exponent of 0.294, suggesting that bed slope and bed roughness have no effect on flow velocity (Govers, 1992; Giménez and Govers, 2001). However, rill hydraulics may be significantly affected by soil types, land use, and land cover (Mancilla et al., 2005). For example, flow velocity is generally lower in rills with soil cover, incorporating rock fragments, vegetation, or vegetation residue (Nearing et al., 1999; Govers et al., 2000; Giménez and Govers, 2001, 2008). Rill erosion relies on sediment transport in rills, which mechanically has no difference from that on interrill surface. Therefore, many popular sediment-transport equations have been used to estimate sediment-transport capacity in rills (Aksoy and Kavvas, 2005).

Rill cross section and length have been measured to estimate the rill volume, which represents the amount of rill erosion (Govers, 1991; Valcarcel et al., 2003; De Santisteban et al., 2006). Three common methods exist for determining rill morphology (Casali et al., 2006). The first is microtopographic profile determination using a pin profiler consisting of 50 stainless steel pins spaced 20 mm apart to photograph rill channel geometry. The cross-sectional area of the rill can be calculated subsequently. The second is detailed characterization of cross sections with a tape and ruler. In this method, each cross section is assimilated to a simple geometric form. A tape is used for directly measuring horizontal distances in the field and a ruler is used for measuring the vertical distances (depths). The third method is the approximate characterization of cross sections with a tape. This method assumes that a rectangle reflects all cross sections and allows quick measurement of many cross sections. The measured total volume of rills can be used to estimate total amount of soil erosion with known or field-measured soil bulk density. Measuring rill morphology provides a convenient way of assessing relative contribution of rill erosion to the total soil erosion (Govers and Poesen, 1988; Cerdan et al., 2002; De Santisteban et al., 2006; Kimaro et al., 2008).

The above-mentioned approaches provide necessary theoretical bases and data for modeling rill erosion at both plot and catchment scales. Generally, soil erosion models relevant to rill erosion are either empirical or physically based. The most popular empirical model, Universal Soil Loss Equation (USLE), accounts for soil erosion at the plot scale (Wischmeier and Smith, 1978) and characterizes soil erodibility using a single parameter for both rill and sheet erosion. The model relates variation of erosion rates to various environmental factors such as topography and land use (Auerswald et al., 2009; Cerdan et al., 2010). Those similar to USLE are the Sediment Delivery Distributed (SEDD) model (Ferro and Porto, 2000) and (revised) Morgan–Morgan–Finney (MMF) model (Morgan et al., 1984; Margan, 2001).

Because the negative-feedback mechanism assures that new rills form in different locations from old rills, the cumulative effect of rill development is to lower the hillside more or less uniformly (Bull and Kirkby, 1997). Therefore, using a single parameter to reflect the overall effect of rill and interrill erosion is reasonable, especially when these models are used to estimate annual or decadal soil loss.

By contrast, physically based soil erosion models can distinguish between rill and sheet erosion. The Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989) divides runoff between rills and interrill areas and requires the input of both interrill and rill erodibility factors that are empirically determined (Moffet et al., 2007; Romero et al., 2007). Other models that separate interrill and rill erosion are the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) and the European Soil Erosion Model (EUROSEM) (Aksoy and Kavvas, 2005). For microrills and the associated rill network, the rill initiation and subsequent rill network development have been successfully characterized by a simple physically based model, RillGrow (Favis-Mortlock et al., 1998).

7.11.4 Gully Development and Erosion Processes

Gully initiation and development, in contrast to rills, generally involve multiple episodes of channel erosion: downward scour, headward cutting, rapid enlargement, and stabilization (Ireland et al., 1939; Harvey et al., 1985). The first three processes form gully headwalls and create gully channels, which may be further characterized by four stages (Morgan, 2005). In the first stage, surface water concentrates in small depressions caused by localized weakening of vegetation cover and then enlarges until depressions coalesce to form an initial channel. In the second stage, the supercritical flow (i.e., the flow with Froude number greater than 1) formed at the heads of the depressions creates near-vertical scarps, the initial headwalls. In the third stage, headwalls are undermined by concentrated scouring at their base. The scouring is caused by the dissipation of kinetic flow energy of the dropping water at the base. Concentrated flow can also cut down the initial channel bed to form the incised gully floor. In the fourth stage, headwalls collapse (i.e., headcut) and retreat upslope, and the gully floor further develops with bank slumping.

The fundamental difference between rill and gully development is that the latter is controlled by a positive-feedback mechanism, which may be described as follows. The erosion initiated in the depressions creates smoother depression bottoms than the surrounding surface. Thus, velocities in these depressions are relatively higher (Hudson, 1985), providing greater stream power to cause more erosion. The greater stream power also assures that sediment-transport downslope is greater than that supplied from the surrounding surface and banks, leading to the enlargement of the gullies. This hydraulic nature provides a positive-feedback mechanism to sustain gully development. The positive-feedback mechanism can be amplified when the downcutting induced by flowing water reaches the lower soil layer that has a much lower shear strength (Morgan, 2005). As gully development continues, the positive-feedback mechanism may be attenuated by the plunge pool formed at the base of the headwall by the concentrated scouring (van der Poel and Schwab, 1988). The formation of the plunge pool indicates that erosion at the base of the headwall is faster than that along the gully floor. Thus, the development of a plunge pool serves as a mechanism to gradually reduce the slope of the gully floor, which gradually decreases the magnitude of the positive feedback. As the gully floor slope reaches a degree at which sediment transport in gullies is balanced overall by sediment supply from headwall retreat and possible bank collapse, gullies are stabilized. Gully stabilization may occur in the entire gully or in part of it (e.g., the downslope section of a gully where sediment deposition also contributes to the stabilization).

The positive-feedback mechanism is essential to create a sizable channel of a gully that cannot be filled during one or subsequent rainstorms. However, gullying is not controlled only by the fluvial processes. For example, Leopold et al. (1964) found that headward extension of gullies in the American southwest is more effectively caused by sapping (i.e., the entrainment of material as individual particles or in bulk because of water flowing through and emerging from permeable soils; Knighton, 1998) at the base of headwall, although the subsequent erosive action of water flowing over the vertical face of a gully head contributes to the headward progression. The headwall retreat from groundwater seepage was also discovered in Africa (Okagbue and Uma, 1987). Thus, although gullies may be developed from enlarged rills (Knighton, 1998; Poesen et al., 2003; Morgan, 2005), gully erosion is much more complex than rill erosion. This complexity is highlighted by piping and mass movement involved in gully initiation and development (Knighton, 1998; Morgan, 2005).

Piping involves the removal of subsurface soils by subsurface flow in soil pipes to a free or escape exit (Masannat, 1980). The subsurface flow is mainly caused by high seepage pressures. If soil entrainment is caused by shear stress because of water flow and involves progressive expansion of an existing conduit or macropore, it is termed 'tunnel' erosion (Bryan and Jones, 1997). Pipe and tunnel collapses triggering gully initiation occur widely (Morgan, 2005; Valentin et al., 2005). Piping and tunneling also cause the most rapid gully erosion (Bocco, 1991, 1993; Knighton, 1998; Morgan, 2005) and account for 25–30% of the catchment sediment yield (Zhu, 2003). Pipe formation and development are controlled by the interaction among climate conditions (e.g., irregular heavy storms or prolonged drought), soil/regolith characteristics (e.g., the presence of silt-clay material containing cracks, fissures, and other discontinuities), and local hydraulic conditions (Bull and Kirkby, 2002). For example, where secondary pores created by biological processes (e.g., roots) provide efficient drainage in the form of concentrated flow, pipes can emerge because of sapping and downslope erosion via inertia. Pipes may be formed by the creeping of wet soil below peat or sod, caused by heterogeneities in the underlying soils and bedrock. Pipes can also be produced by sinking where open-textured soil is compacted and settled by water percolating downward to the level of permanent saturation (Bull and Kirkby, 2002). The necessary high hydraulic gradients required for pipe development are commonly achieved by the opening deep cracks upslope of the eventual pipe outlet (Bull and Kirkby, 2002).

Gully initiation and development can also be caused by mass movement. In general, gully heads and sidewalls are subject to three forces: (1) the weight of the soil, (2) the weight of water added by infiltration or a rise in the water table, and (3) seepage forces of percolating water (Bull and Kirkby, 2002). When the resultant driving force is greater than the resultant resistance, gully heads or sidewalls fail. One common failure is rotational slip along a deep-seated circular arc. Another is slab failure, caused by tension-crack development (Bradford and Piest, 1985). Gullies with homogeneous, cohesive banks may expand by progressive, continuous failure through creep over long time periods or by catastrophic shear failure of the bank (Poesen et al., 2002). Although mass failure can be mechanically characterized by the safety factor, F_s, defined as the ratio of driving to resistant shear strength along the shear surface (Bradford and Piest, 1985), determination of F_s can be complicated because many factors, such as change of water content, freeze–thaw, and wetting–drying cycles, may affect driving and resistant shear strength. Thus, mass failure is essentially a composite and cyclical process that can be achieved by the combination of downslope creep, tension-crack development, crack saturation by overland flow, and the removal of collapsed debris to facilitate the next failure (Poesen et al., 2002).

Gully erosion and development can also be caused by fluting and channel bifurcation (Poesen et al., 2002). Fluting at headwalls and on gully banks is mainly caused by differential erosion between ridges and depressions. The resultant flutes are vertically elongated grooves, generally tapering toward the top that furrows into the gully wall. Fluting can result in pronounced gully wall retreat. Gully channel bifurcation is a process of lateral budding that extends the gully head or along a gully channel (Bull and Kirkby, 1997).

7.11.5 Gully Erosion Approaches

7.11.5.1 Threshold Approaches

Gully initiation is essentially a threshold process that requires certain threshold conditions to be exceeded (Wells et al., 2005). For gullies created by the concentrated overland flow, a hydraulic threshold may be quantified by the critical flow shear stress, τ_c, which tends to be inversely related to the width of concentrated flow in gullies (Poesen et al., 2002, 2003). However, values of τ_c vary widely from about 3 to 74 Pa, depending on soil types. Values of τ_c also change with vegetation types and may be as high as 260 Pa in grassed irrigation canals (Poesen et al., 2003). Since τ_c values for rill initiation may range from 1 to 11 Pa (Govers, 1985; Poesen et al., 2003), it can seen that (1) larger τ_c values generally are associated with gully initiation and (2) the range of τ_c values for gully initiation overlaps with that for rill initiation. The first indicates that more rills may develop than gullies during one rainstorm. The second suggests that rills and gullies can develop under similar critical hydraulic conditions. Therefore, the threshold conditions of gully and rill initiation cannot be purely characterized by the critical shear stress. For instance, the observation that rills tend to occur on gentle slopes and that gullies incline to exist on steep slopes requires not only the critical shear stress but also other processes to interpret. One of these processes is soil crusting. The soil-crusting rate is lower on steep slopes than on gentle ones because of (1) the lower impacting kinetic energy resulting from raindrops and (2) a continuous erosion of the surface seal (Poesen et al., 2003). Consequently, small rainstorms can generate a sufficient depth of concentrated flow on gentle slopes such that the threshold condition for rill initiation is reached and rills develop. On steep slopes, bigger rainstorms are required to produce the necessary depth of the concentrated flow that exceeds the threshold condition. The reason that gullies rather than rills develop subsequently is because steep slopes favor high-runoff velocity, which leads to higher stream power to trigger the positive-feedback mechanism for gully development.

Gully erosion does not occur everywhere on hillslopes, but is controlled by a topographic threshold, represented by a critical soil surface slope, S, required to initiate gully incision for a given drainage-basin area, A (Poesen et al., 2002). This topographic threshold is mathematically expressed as an inverse relationship between A and S, $S = aA^{-b}$, where a and b are environment-specific coefficients. Values of a and b change with not only different environmental characteristics (e.g., climate, soil, and land use) but also different methods used to measure both S and A (e.g., local S derived from a topographic map usually underestimates that measured in the field) (Poesen et al., 1998). Vegetation type and cover are the most important factors determining the topographic threshold. For example, the same drainage-basin area of uncultivated lands requires a steeper soil slope than that of the croplands. In cultivated fields, topsoil structure and soil moisture condition, which are controlled by antecedent rainfall distribution, are more important than daily rain in affecting the power function (Poesen et al., 2003). The S–A relationship for a given land use can be used to predict the locations where gully channels may develop on a hillslope (Desmet et al., 1999; Kirkby et al., 2003). Nonetheless, this relationship primarily applies to gullies formed by concentrated surface runoff. If gully development is significantly influenced by the subsurface flow, the negative trend of the relationship is weakened (Poesen et al., 2002).

7.11.5.2 Gully Headwall Retreat and Sidewall Erosion

Headwall retreat is an essential process of gully development. Flume experiment studies have shown that turbulent flow within the plunge pool of a headwall is analogous to plane turbulent reattached wall jets, and erosion processes at headwalls are controlled by the characteristics of these wall jets and overall nappe (Alonso et al., 2002; Bennett and Alonso, 2006). This idea is termed as jet impingement theory (Alonso et al., 2002), which further indicates that headwall retreat rate may be significantly different for walls of different soil textures (Wells et al., 2009). A deterministic model based on the interaction of runoff and seepage has been established to predict headwall retreat by incorporating fluid dynamics and material properties (De Ploey, 1989; Robinson and Hanson, 1994, 1995). Simplified dynamic equations based on the principles of energy conservation have also been developed to predict headcut-migration rate (Prasada and Romkens, 2003). In addition to the process-based studies, headwall retreat has also been studied by establishing empirical relationships between headcut retreat measured in the field and various parameters such as basin area, rainfall depth, erodibility, and headwall height (Poesen et al., 2003).

Gully sidewall erosion can be treated as a two-stage process: (1) gravity-induced mass failures provide bank-derived slough materials to the active transport area of the gully channel and (2) materials are subsequently entrained into the flow and transported downslope (Grissinger, 1995). The mechanics controlling sidewall collapse at least include the development of undercut hollows from stress release at the base, the existence of tension cracks to promote high throughflow velocity, and piping (Martinez-Casasnovas et al., 2004). Thus, the stability of sidewall depends not only on bank slope angle but also on height (Poesen et al., 2002).

Because gully erosion involves both hillslope (e.g., rainsplash and mass movement) and channel (e.g., sediment transport) processes that may be affected by many environmental factors, such as topographic threshold, land-use change, and climate change (Valentin et al., 2005), quantifying the mechanics controlling gully initiation and development is extremely difficult. For example, the role of piping on headwall retreat and sidewall collapse of gullies has been well known. However, determination of shear stress and thus erodibility of preferential flow in pipes are still challenging because the enlargement of the internal dimensions of the soil pipe with time still cannot be accurately measured (Wilson, 2009). An alternative approach to quantifying gully sidewall erosion is comparing the change of gully morphological perimeters for given time intervals (e.g., years) based on the digital elevation data reconstructed from detailed aerial photographs of different dates (Betts and DeRose, 1999; Martinez-Casasnovas, 2003; Ries and Marzolff, 2003; Svoray and Markovitch, 2009). Studies based on this technique revealed that (1) the intensity of sidewall erosion is most related to rainfall characteristics; (2) vegetation cover on gully sidewalls does not affect sidewall retreat, although it protects the exposed materials against the direct impact of rainfall, reducing splash and overland-flow erosion; and (3) tension-crack development in the vicinity of the walls with steep slopes promotes sidewall retreat (Martinez-Casasnovas et al., 2004, 2009).

7.11.5.3 Estimation of Gully Erosion

The contribution of gully erosion to the total soil loss from water erosion ranges from 10% to 94% worldwide (Poesen et al., 2003). In agricultural watersheds, gully erosion can account for as high as 80% of the total soil erosion (Capra and Scicolone, 2002). The total amount of annual gully erosion has for years been calculated by measuring gully width, depth, and length using a steel tape and global positioning system (GPS) (Rowntree, 1991; Oygarden, 2003; Cheng et al., 2007; Capra et al., 2009). It can be more effectively estimated using process-based soil erosion models. Generally, the physically based models described previously for estimating rill erosion can also evaluate gully erosion on hillslopes. In these models, gully erosion is represented as a channel-erosion process in which erosion occurs where transport capacity of flow is greater than sediment load in the channel (Poesen et al., 2003). Additionally, the Ephemeral Gully Erosion Model (EGEM) was specially developed for estimating the volume from gully erosion (Merkel et al., 1988). However, independent model testing showed that EGEM failed to predict gully cross-section areas for the studied cropland environments (Poesen et al., 2003). By specifically considering the gully headcut effect, Casali et al. (2003) developed an event-based model to estimate ephemeral gully erosion. A common limitation of these models is that they lack routines to predict the location of gullies (Poesen et al., 1998). This limitation is overcome by a recently developed data-mining technique, Multivariate Adaptive Regression Splines (MARS). MARS is a nonparametric statistical technique that can be used to construct a model capable of predicting the location of gullies (Gomez Gutierrez et al., 2009).

7.11.6 Conclusions

Rills and gullies are ephemeral channels with variable sizes on hillslopes. Although rills generally have smaller sizes than gullies, there is no sharp boundary between rills and ephemeral gullies. The fundamental difference between rills and gullies is that rills are self-stabilizing systems in which the location and size of rills change from rainstorm to rainstorm, whereas gullies are self-perpetuating systems in which they remain at the locations where they are initiated. Rills are predominately formed by overland flow and can be studied by field morphology measurement and process-based modeling. Gullies may be created by either surface or subsurface flows and hence their initiation and development involve both hillslope (e.g., pipe flow and mass movement) and in-channel processes (e.g., sediment transport and deposition), which vary widely with environmental factors such as climate, soil, and land use. Therefore, characterizing gully initiation and development is still a challenging task.

References

Abrahams, A.D., Li, G., Parsons, A.J., 1996. Rill hydraulics on a semiarid hillslope, southern Arizona. Earth Surface Processes and Landforms 21, 35–47.

Aksoy, H., Kavvas, M.L., 2005. A review of hillslope and watershed scale erosion and sediment transport models. Catena 64, 247–271.

Alonso, C.V., Bennett, S.J., Stein, O.R., 2002. Predicting head cut erosion and migration in concentrated flows typical of upland areas. Water Resources Research 38, 1303–1317.

Auerswald, K., Fiener, P., Dikau, R., 2009. Rates of sheet and rill erosion in Germany – a meta-analysis. Geomorphology 111, 182–193.

Bennett, S.J., Alonso, C.V., 2006. Turbulent flow and bed pressure within headcut scour holes due to plane reattached jets. Journal of Hydraulic Research 44, 510–521.

Betts, H.D., DeRose, R.C., 1999. Digital elevation models as a tool for monitoring and measuring gully erosion. International Journal of Applied Earth Observation and Geoinformation 1, 91–101.

Bocco, G., 1991. Gully erosion: processes and models. Progress in Physical Geography 15, 392–406.

Bocco, G., 1993. Gully initiation in Quaternary volcanic environments under temperate subhumid seasonal climates. Catena 20, 495–513.

Bradford, J.M., Piest, R.F., 1985. Erosion development of valley bottom gullies in the upper Midwestern United States. In: Coates, D.R., Vitek, J.D. (Eds.), Thresholds in Geomorphology. Allen and Unwin, London, pp. 75–101.

Brooks, A.P., Shellberg, J.G., Knight, J., Spencer, J., 2009. Alluvial gully erosion: an example from the Mitchell fluvial megafan, Queensland, Australia. Earth Surface Processes and Landforms 34, 1951–1969.

Bryan, R.B., 2000. Soil erodibility and processes of water erosion on hillslope. Geomorphology 32, 385–415.

Bryan, R.B., 2004. Gully-scale implications of rill network and confluence processes. In: Li, Y., Poesen, J., Valentin, C. (Eds.), Gully Erosion Under Global Change. Sichuan Science and Technology Press, Chengdu, pp. 73–95.

Bryan, R.B., Jones, J.A.A., 1997. The significance of soil piping processes: inventory and prospect. Geomorphology 20, 209–218.

Bull, L.J., Kirkby, M.J., 1997. Gully processes and modelling. Progress in Physical Geography 21, 354–374.

Bull, L.J., Kirkby, M.J., 2002. Channel heads and channel extension. In: Bull, L.J., Kirkby, M.J. (Eds.), Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channels. Wiley, Chichester, pp. 263–298.

Bull, W.B., 1997. Discontinuous ephemeral streams. Geomorphology 19, 227–276.

Capra, A., Porto, P., Scicolone, B., 2009. Relationships between rainfall characteristics and ephemeral gully erosion in a cultivated catchment in Sicily (Italy). Soil and Tillage Research 105, 77–87.

Capra, A., Scicolone, B., 2002. SW – soil and water: ephemeral gully erosion in a wheat-cultivated area in Sicily (Italy). Biosystems Engineering 83, 119–126.

Casali, J., Loizu, J., Campo, M.A., De Santisteban, L.M., Ivarez-Mozos, J.A., 2006. Accuracy of methods for field assessment of rill and ephemeral gully erosion. Catena 67, 128–138.

Casali, J., Lopez, J.J., Giraldez, J.V., 2003. A process-based model for channel degradation: application to ephemeral gully erosion. Catena 50, 435–447.

Cerdan, O., Govers, G., Le Bissonnais, Y., et al., 2010. Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. Geomorphology, doi:10.1016/j.geomorph.2010.1006.1011.

Cerdan, O., Le Bissonnais, Y., Couturier, A., Bourennane, H., Souchere, V., 2002. Rill erosion on cultivated hillslopes during two extreme rainfall events in Normandy, France. Soil and Tillage Research 67, 99–108.

Charlton, R., 2008. Fundamentals of Fluvial Geomorphology. Routledge, New York, NY.

Cheng, H., Zou, X., Wu, Y., Zhang, C., Zheng, Q., Jiang, Z., 2007. Morphology parameters of ephemeral gully in characteristics hillslopes on the Loess Plateau of China. Soil and Tillage Research 94, 4–14.

Cooke, R.U., Reeves, R.W., 1975. Arroyos and Environmental Change in the American South-West. Clarendon, Oxford.

De Ploey, J., 1989. A model for headcut retreat in rills and gullies. Catena Supplement 14, 81–86.

De Santisteban, L.M., Casalí, J., López, J.J., 2006. Assessing soil erosion rates in cultivated areas of Navarre (Spain). Earth Surface Processes and Landforms 31, 487–506.

Derose, R.C., Gomez, B., Marden, M., Trustrum, N., 1998. Gully erosion in Mangatu Forest, New Zealand, estimated from digital elevation models. Earch Surface Processes and Landforms 23, 1045–1053.

Desmet, P.J.J., Poesen, J., Govers, G., Vandaele, K., 1999. Importance of slope gradient and contributing area for optimal prediction of the initiation and trajectory of ephemeral gullies. Catena 37, 377–392.

Dunne, T., 1980. Formation and controls of channel network. Progress in Physical Geography 4, 211–239.

Dunne, T., Aubry, B.F., 1968. Evaluation of Horton's theory of sheetwash and rill erosion on the basis of field experiments. In: Abrahams, A.D. (Ed.), Hillslope Processes. Allen and Unwin, London, pp. 31–53.

Favis-Mortlock, D., Guerra, T., Boardman, J., 1998. A self-organizing dynamic systems approach to hillslope rill initiation and growth: model development and validation. IAHS Publication no. 249, 53–61.

Ferro, V., Porto, P., 2000. Sediment delivery distributed (SEDD) model. Journal of Hydraulic Engineering 5, 411–422.

Foster, G.R., 1986. Understanding Ephemral Gully Erosion. National Research Council. Board on Agriculture, Washington, DC, pp. 90–118.

Giménez, R., Govers, G., 2001. Interaction between bed roughness and flow hydraulics in eroding rills. Water Resources Research 37, 791–799.

Giménez, R., Govers, G., 2008. Effects of freshly incorporated straw residue on rill erosion and hydraulics. Catena 72, 214–223.

Golosov, V., Panin, A., 2004. Methods of monitoring of bottom gullies development, the centre of the Russian Plain. In: Li, Y., Poesen, J., Valentin, C. (Eds.), Gully Erosion Under Global Change. Sichuan Science and Technology Press, Chengdu.

Gomez Gutierrez, A., Schnabel, S., Felicisimo, A.M., 2009. Modelling the occurrence of gullies in rangelands of southwest Spain. Earth Surface Processes and Landforms 34, 1894–1902.

Govers, G., 1985. Selectivity and transport capacity of thin flows in relation to rill erosion. Catena 12, 35–49.

Govers, G., 1991. Rill erosion on arable land in central Belgium: rates, controls and predictability. Catena 18, 133–155.

Govers, G., 1992. Relationship between discharge, velocity, and flow area for rills eroding in loose, non-layered materials. Earth Surface Processes and Landforms 17, 515–528.
Govers, G., Poesen, J., 1988. Assessment of interrill and rill contribution to total soil loss from an upland field plot. Geomorphology 11, 343–354.
Govers, G., Takken, I., Helming, K., 2000. Soil roughness and overland flow. Agronomie 20, 131–146.
Grissinger, E.H., 1995. Rill and gullies erosion. In: Agassi, M. (Ed.), Soil Erosion Conservation and Rehabilitation. Dekker, New York, NY, pp. 153–167.
Harvey, M.D., Watson, C.C., Schumm, S.A., 1985. Gully Erosion. USDI Bureau of Reclamation, Fort Collins, CO, 181 pp.
Horton, R.E., 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Bulletin of the Geological Society of America 56, 275–370.
Hudson, N.W., 1985. Soil Conservation. Batsford, London.
Ireland, H.A., Sharpe, C.F., Eargle, D.H., 1939. Principles of gully erosion in the piedmont of South Carolina. Technical Bulletin 633. US Separtment of Agriculture, Washington, DC.
Kimaro, D.N., Poesen, J., Msanya, B.M., Deckers, J.A., 2008. Magnitude of soil erosion on the northern slope of the Uluguru Mountains, Tanzania: interrill and rill erosion. Catena 75, 38–44.
Kirkby, M.J., Bracken, L.J., 2009. Gully processes and gully dynamics. Earth Surface Processes and Landforms 34, 1841–1851.
Kirkby, M.J., Bull, L.J., Poesen, J., Nachtergaele, J., Vandekerckhove, L., 2003. Observed and modelled distributions of channel and gully heads – with examples from SE Spain and Belgium. Catena 50, 415–434.
Knighton, D., 1998. Fluvial Forms & Processes. A New Perspective. Arnold, London.
Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial Processes in Geomorphology. W.H. Freeman, San Francisco, CA.
Li, G., Klik, A., Wu, F., 2004. Gully erosion features and its causes of formation on the (Yuan) land in the Loess Plateau, China. In: Li, Y., Poesen, J., Valentin, C. (Eds.), Gully Erosion Under Global Change. Sichuan Science and Technology Press, Chengdu, pp. 131–142.
Mancilla, G., Chen, S., McCool, D.K., 2005. Rill density prediction and flow velocity distributions on agricultural areas in the Pacific Northwest. Soil and Tillage Research 84, 54–66.
Margan, R.P.C., 2001. A simple approach to soil loss prediction: a revised Morgan–Morgan–Finney model. Catena 44, 305–322.
Martinez-Casasnovas, J.A., 2003. A spatial information technology approach for the mapping and quantification of gully erosion. Catena 50, 293–308.
Martinez-Casasnovas, J.A., Ramos, M.C., García-Hernández, D., 2009. Effects of land-use changes in vegetation cover and sidewall erosion in a gully head of the Penedès region (northeast Spain). Earth Surface Processes and Landforms 34, 1927–1937.
Martinez-Casasnovas, J.A., Ramos, M.C., Poesen, J., 2004. Assessment of sidewall erosion in large gullies using multi-temporal DEMs and logistic regression analysis. Geomorphology 58, 305–321.
Masannat, Y.M., 1980. Development of piping erosion conditions in the Benson area, Arizona. U.S.A. Quarterly Journal of Engineering Geology and Hydrogeology 13, 53–61.
Merkel, W.H., Woodward, D.E., Clarke, C.D., 1988. Ephemeral gully erosion model (EGEM). In: ASAE (Ed.), Modeling Agricultural, Forest, and Rangeland Hydrology. American Society of Agricultural Engineers Publication, St. Joseph, MI, pp. 315–323.
Merritt, E., 1984. The identification of four stages during microrill development. Earth Surface Processes and Landforms 9, 493–496.
Moffet, C.A., Pierson, F.B., Robichaud, P.R., Spaeth, K.E., Hardegree, S.P., 2007. Modeling soil erosion on steep sagebrush rangeland before and after prescribed fire. Catena 71, 218–228.
Morgan, R.P.C., 2005. Soil Erosion and Conservation. Blackwell, Malden, MA.
Morgan, R.P.C., Morgan, D.D.V., Finney, H.J., 1984. A predictive model for the assessment of erosion risk. Journal of Agricultural Engineering Research 30, 245–253.
Nachtergaele, J., Poesen, J., Sidorchuk, A., Torri, D., 2002. Prediction of concentrated flow width in ephemeral gully channels. Hydrological Processes 16, 1935–1953.
Nearing, M.A., Foster, G.R., Lane, L.J., Finkner, S.C., 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. Transactions of the ASAE 32, 1587–1593.
Nearing, M.A., Simanton, J.R., Norton, L.D., Bulygin, S.J., Stone, J., 1999. Soil erosion by surface water flow on a stony, semiarid hillslope. Earth Surface Processes and Landforms 24, 677–686.
Okagbue, C.O., Uma, K.O., 1987. Performance of Gully Erosion Control Measures in Southeastern Nigeria. IAHS Publications, IAHS Press, Wallinford, vol. 167, pp. 163–172.
Oygarden, L., 2003. Rill and gully development during an extreme winter runoff event in Norway. Catena 50, 217–242.
Poesen, J., 1993. Gully topology and gully control measures in the European loess belt. In: Wicherek, S. (Ed.), Farm Land Erosion in Temperate Plains Environment and Hills. Elsevier, Amsterdam, pp. 221–239.
Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. Catena 50, 91–133.
Poesen, J., Vandaele, K., Van Wesemael, B., 1998. Gully erosion: importance and model implications. In: Boardman, J., Favis-Mortlock, D.T. (Eds.), Modeling Soil Erosion by Water. Springer, Berlin, pp. 285–311.
Poesen, J., Vandekerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G., van Wesemael, B., 2002. Gully erosion in dryland environments. In: Bull, L.J., Kirkby, M.J. (Eds.), Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channels. Wiley, Chichester, pp. 229–262.
Poesen, J., Vanwalleghem, T., de Vente, J., Knapen, A., Verstraete, G., Martinez-Casasnovas, J.A., 2006. Gully erosion in Europe. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley, Chichester, pp. 515–536.
Prasada, S.N., Romkens, M.J.M., 2003. Energy formulations of headcut dynamics. Catena 50, 469–487.
Ries, J.B., Marzolff, I., 2003. Monitoring of gully erosion in the Central Ebro Basin by large-scale aerial photography taken from a remotely controlled blimp. Catena 50, 309–328.
Robinson, K.M., Hanson, G.J., 1994. A deterministic headcut advance model. Transactions of the American Society of Agricultural Engineers 37, 1437–1443.
Robinson, K.M., Hanson, G.J., 1995. Large-scale headcut erosion testing. Transactions of the American Society of Agricultural Engineers 38, 429–434.
Romero, C.C., Stroosnijder, L., Baigorria, G.A., 2007. Interrill and rill erodibility in the northern Andean Highlands. Catena 70, 105–113.
Rowntree, K.M., 1991. Morphological characteristics of gully networks and their relationship to host materials, Baringo District, Kenya. Geojournal 23, 19–27.
Savat, J., De Ploey, J., 1982. Sheetwash and rill development by surface flow. In: Bryan, R.B., Yair, A. (Eds.), Badlands Geomorphology and Piping. GeoBooks, Norwich, CT, pp. 113–126.
Soil Science Society of America, 2001. Glossary of Soil Science Terms. Madison, WI.
Svoray, T., Markovitch, H., 2009. Catchment scale analysis of the effect of topography, tillage direction and unpaved roads on ephemeral gully incision. Earth Surface Processes and Landforms 34, 1970–1984.
Torri, D., Poesen, J., Borselli, L., Knapen, A., 2006. Channel width-flow discharge relationships for rills and gullies. Geomorphology 76, 273–279.
Torri, D., Sfalanga, M., Chisci, D., 1987. Threshold conditions for incipient rilling. Catena Supplement 8, 97–105.
Valcarcel, M., Taboada, M.T., Paz, A., Dafonte, J., 2003. Ephemeral gully erosion in northwestern Spain. Catena 50, 199–216.
Valentin, C., Poesen, J., Li, Y., 2005. Gully erosion: impacts, factors and control. Catena 63, 132–153.
van der Poel, P., Schwab, G.O., 1988. Plunge pool erosion in cohesive channels below a free overfall. Transactions of the American Society of Agricultural Engineers 31, 1148–1153.
Vandaele, K., Poesen, J., 1995. Spatial and temporal patterns of soil erosion rates in an agricultural catchment, central Belgium. Catena 25, 226–313.
Wells, R.R., Alonso, C.V., Simon, A., 2005. Gully study revisited. In: Walton, R. (Ed.), Impacts of Global Climate Change World Water and Environmental Resources Congress. Proceedings. Anchorage, Alaska, USA. American Society of Civil Engineers, Reston, VA.
Wells, R.R., Bennett, S.J., Alonso, C.V., 2009. Effect of soil texture, tailwater height, and porewater pressure on the morphodynamics of migrating headcuts in upland concentrated flows. Earth Surface Processes and Landforms 34, 1867–1877.
Wilson, G.V., 2009. Mechanisms of ephemeral gully erosion caused by constant flow through a continuous soil-pipe. Earth Surface Processes and Landforms 34, 1858–1866.
Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall Erosion Losses – A Guide to Conservation Planning. US Department of Agriculture, Washington, DC.
Zhu, T.X., 2003. Tunnel development over a 12 year period in a semi-arid catchment of the Loess Plateau. China. Earth Surface Processes and Landforms 28, 507–525.
Zhu, Y., Cai, Q., 2004. Rill erosion process and its factors in different soils. In: Li, Y., Poesen, J., Valentin, C. (Eds.), Gully Erosion Under Global Change. Sichuan Science and Technology Press, Chengdu, pp. 96–106.

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