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Chapter 3

EPHEMERAL GULLY AND GULLY EROSION IN CULTIVATED LAND: A REVIEW

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ABSTRACT

Soil erosion has been recognized as the major cause of land degradation worldwide. The quantification of soil erosion is an important requirement for representing land degradation processes. One of the crucial points attracting an increased amount of attention in recent years is constituted by the possible discrimination of the different forms of soil erosion. In these contexts, relatively few studies have been conducted on channel erosion that still require improvement and elucidation, though most research and models proved to be very effective in providing useful information about surface erosion rates (rill-interrill).

Erosion due to concentrated flow is severe on many unprotected farm fields across different countries of the world. The presence of various gully types (ephemeral, permanent, etc.) can be observed in different land uses and climatic conditions.

The formation and development of channels, called ephemeral gullies, routinely obliterated by tillage and other farm operations, constitute a severe problem in many cultivated fields. In fact, crops are

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washed out by scour as these small gullies form, and the crops at the lower end of the gully are submerged by the sediments from the ephemeral gullies. These filling operations reduce the long-term productivity of farmlands. Ephemeral gullies rapidly evolve in permanent gullies and contribute to the catchment rill network formation. They constitute effective links for transferring the runoff and sediment from uplands to valley bottoms and contribute to the denudation processes. Ephemeral gullies may also generate new badlands and aggravate the off-site effects of water erosion.

The data available on gully erosion is scarce and usually restricted to small areas in which measurements are carried out over short time periods.

The objective of this paper is to review recent studies on the different aspects of gully erosion, which are:

- the morphological characteristics of gullies in comparison to the characteristics of other erosion channel types, including rills and streams;
- the contribution of the gully erosion to overall soil loss and sediment production;
- the analysis of some controlling factors;
- and the models currently available to predict gully erosion.

1. Introduction

Soil erosion is a severe challenge to the food supply, food security, human health, natural ecosystems, and economic development of countries. Erosional processes are categorised as sheetflow or interrill erosion and linear or channelized erosion. Both kinds of erosion have on-site consequences: soil degradation, declining soil fertility, desertification, and reduced infiltration and water storage capacities. Linear erosion (rill and gully) also shows off-site impacts including eutrophication of water courses and lakes, destruction of wildlife habitats, siltation of dams, reservoirs, rivers, and valley bottoms, as well as infrastructure and property damage by muddy floods (Poesen et al., 1996; Boardman, 2006). Gully erosion contributes to denudation processes and may generate new badlands (Capra et al., 1994; Capra and Scicolone, 1996; Torri et al., 2000; Poesen et al., 2003; Della Seta et al., 2007). Gullies can also change the mosaic patterns between fallow and cultivated fields, enhancing hillslope erosion in a feedback loop. On- and off-site effects of linear erosion may jeopardize the future of natural ecosystems and economic development of societies (Chaplot et al., 2005).

In temperate regions, almost all cases of erosion involve rilling and/or gullying as the dominant process (Boardman, 2006; Chaplot et al., 2005). Gullies don't occur exclusively in marly badlands and mountainous or hilly regions worldwide, as they are found globally in soils subjected to soil crusting, such as: loess (European belt, Chinese Loess Plateau, North America), sandy soils (Sahelian zone, North-East Thailand) and soils prone to piping and tunnelling such as dispersive soils (Valentin et al., 2005). Both the formation and retreat of a gully involves complex processes controlled by a variety of closely related factors such as lithology, soil type, climate, topography, land use, and vegetation cover.

The rill component of the erosion process is due to the channelized transport of the sediment particles, both detached from the interril areas and scoured from the channel-wetted perimeter (Foster, 1982; Nearing et al., 1997). Rill erosion is constituted by the development of numerous, tightly-spaced channels resulting from the removal of surface soil due to the concentrated running water in streamlets (Foster, 1986; Casalí et al., 2006). Rills are considered ephemeral structures with an intermittent plan network and irregular cross-section shape; they can be obliterated by conventional tillage operations (Capra et al., 2009a). Gully erosion is defined as the erosion process where the accumulation of runoff water often recurs in channels, and in short periods, removes the soil from these channels at considerable depths (Poesen et al., 2003); these structures can be ephemeral or permanent.

Valentin et al. (2006) highlighted that gully erosion had been long neglected, and studies on both gullying processes and model development remain scarce because they are difficult to study and predict. The main reasons are: 1) the erosion process is affected by numerous factors and sub-processes, 2) it often results from a long antecedent history that cannot be overlooked, 3) due to a rapid growth into large dimension, many gullies cannot be controlled for both technical and economic difficulty.

On the other hand, understanding linear erosion mechanisms and their controlling factors are fundamental to the identification of possible solutions to environmental issues associated with this kind of erosion (Chaplot et al., 2005). A wide analysis of gully erosion can be found in Poesen et al. (2003) and in Valentin et al. (2005). These issues will be analysed by a review of the more recent studies in literature.

2. GULLY TYPES AND MORPHOLOGICAL CHARACTERISTICS

2.1. Definitions

Gullies are relatively permanent, steep-sided water courses that experience ephemeral flows during rainstorms; they are characterised by headcuts and various steps or knick-points along their course (Morgan, 2005). Some authors used the threshold cross-sectional area or depth to distinguish gullies from rills. According to the criteria proposed by Hauge (1977) and discussed by Poesen et al. (1996a), channels are considered gullies when the cross-sectional area is more than 1 ft^2 (929 cm^2). Besides that, no clear-cut definition exists as why there is a boundary between a gully and an ephemeral river channel.

Different gully types have been described in the literature. According to Poesen et al. (2003), three different gully types can be distinguished: permanent or classic, bank, and ephemeral gullies.

Permanent gullies are landforms created through the incision of alluvial or colluvial deposits by overland or subsurface flow (Rustomji, 2006). They are “channels resulting from erosion and caused by the concentrated but intermittent flow of water usually during and immediately following heavy rains. Deep enough (usually >0.5 m) to interfere with, and not to be obliterated by, normal tillage operations” (Soil Science Society of America, 2001). Some authors distinguish different permanent gully types, e.g. Gábris et al. (2003) cited valley-floor and valley-side gullies.

Bank gullies develop whenever concentrated runoff crosses an earth bank. Due to the very steep local slope gradient, bank gullies can rapidly develop by hydraulic erosion, piping, and eventually mass movement (Poesen et al., 2003). Once initiated, they retreat by headcut migration into the moderate sloping soil surface, and then further into river or agricultural terraces (Poesen et al., 2002). According to Wu and Cheng (2005), bank gullies form over a long period of time and are difficult to control.

An ephemeral gully (EG) is a concentrated type of flow erosion that is larger than a rill, but smaller than a classical gully. Different definitions of an ephemeral gully (EG) have been given in the literature. According to the most common, EGs are channels which occur between two opposite slopes, typically masked, but not completely obliterated, by normal tillage (Laflen, 1985; Foster, 1986; USDA, 1992). According to the Soil Science Society of America (2001), EGs are “small channels eroded by concentrated flow that can be easily filled by normal tillage, only to reform again in the same location by additional runoff events". It's commonly known that rills are more common in planar elements of watersheds, EGs on valley bottoms, or within swales (Haan et al., 1994; Casalí et al., 1999; 2006), but some authors (Poesen at al., 2003; Capra et al., 2009b) highlighted that they observed EGs not only in natural drainage lines, but also along landscape linear elements. Casalí et al. (1999, 2006) defined EGs as incised channels of various sizes, formed in small valleys (swales) on agricultural soils by the scouring of concentrated surface runoff during rain events, which are usually refilled by farmers shortly after the rains, but often reappear in the next rainy season. Capra et al. (2009b) consider an EG as a channel of different sizes, mainly (but not only) located in swales, refilled by tillage equipment normally used on farms in the area where they are observed. Furthermore, the authors used the term EG system to indicate the entire main branch and the interconnected tributaries of an EG (Figure 1).

An EG may not be erased, nor develop towards a permanent gully during subsequent runoff events when it forms in a no-till field or when it forms in the same place year after year, in which case the farmers suspend their efforts to infill the gullies (Nachtergaele et al., 2002). Ephemeral gully erosion generally occurs in cultivated soils during seedbed preparation, and in planting and crop establishment periods, when the soil is scarcely protected by vegetation.

Ephemeral gully erosion is a severe problem in many cultivated fields; crops are washed out in areas where EGs develop and are submerged by the sediments at their lower end; and filling operations reduce the long-term productivity of the farmland (Woodward, 1999). Furthermore, EGs constitute effective links for transferring runoff and sediment from uplands to valley bottoms (Valentin et al., 2005) and can rapidly evolve in permanent gullies. Válcarcel et al. (2003) distinguished EGs located on thalwegs in the valley bottom and EGs associated with linear man-made agricultural features (roads, well tracks, etc.).

Based on field observations, Casalí et al. (1999) described three main types of EGs: classical, drainage, and discontinuity. Classical EGs formed by concentrated runoff flowing within the same field where runoff started; knickpoints (or headcut) due to flowering water migrated upstream, enlarging, and deepening the channel.

Drainage EGs were created by concentrated flow draining areas upstream from the field; drainage flows reached the upstream end of fields and eroded cultivated plots downstream.

Figure 1. Ephemeral gully system (main branch and tributaries).

Discontinuity EGs were commonly found in places where management practices created a sudden change in slope, such as field boundaries adjacent to roads; EG headcuts, probably triggered by these slope discontinuities, later migrated upstream. In Ethiopia, Billi and Dramis (2003) observed two main types of gullies: discontinuous and stream. Discontinuous gullies were commonly found by themselves in isolation, and developed in a single slope stretch. Stream gullies were associated with well-established river systems. They could be considered permanent first order rivers which capture the intermittent flows of a first order catchment in dry climate. Ionita (2003; 2006) described three groups of discontinuous gullies: single (isolated, classical), where aggradation begins immediately below the headcut and moves downstream as the gully floor gets progressively wider, successive (chain, cascade), and batteries of discontinuous gullies, which combine features from the previous groups. Wu and Cheng (2005), on the Loess Plateau of China, checked two main gully types: floor gullies developed on the floor of the valley and occurring immediately down-stream from the convergence of two branches, and slope gullies, which developed in the portion of the interfluves. Clearly, any classification of linear erosion forms into separate classes can be considered, to some extent, subjectively. Poesen et al. (2003) emphasised the difficulty of defining a clear cut between rills and EGs, and also between EG and classic gullies and ephemeral river channels. In fact, the transition from rill to EG to gully to river channel erosion hydraulically represents a continuum. In field surveys in Sicily, Italy (Capra and Scicolone, 2002) and Northeast China (Zhang et al., 2007), the observation of linear erosion elements that could be identified as rills in their top part, EGs in the middle part, and permanent gullies in the bottom part (Figure 2) make further classification difficult (Capra et al., 2009b).

Figure 2. Rills and ephemeral gully (a) and permanent gully (b) in Sicily (Italy).

2.2. Morphological Characteristics

No systematic compilation of the different gully morphological characteristics in a wide range of environments has been made, in spite of the analysis of the gully hydraulic geometry that could contribute to understand the processes acting on their development and also identify the mitigation measures and conservation practices.

The main morphological characteristics of gullies that can be found in literature are length, width, and depth; sometimes cross-sectional area and width/depth ratio are also discussed. The data was collected with different objectives and was obtained using different measurement techniques with different precision: measuring directly the volumes of soil eroded by an EG; using a laser altimeter mounted in an aircraft to measure cross-sections; measuring the change in distance between the edge of the gully head or wall and benchmark pins installed around the gully wall for gully retreat monitoring; applying photogrammetric techniques to sequential aerial photographs in order to estimate the volume of soil lost by gully systems with sufficiently large changes in morphology, etc. (Poesen et al., 2003).

Furthermore, measurements have been conducted at different timescales: event, year, several years. Despite the difficulty of comparing heterogeneous data, an attempt to analyze the main features of gullies deduced from the most recent literature is made here.

Table 1 shows a synthesis of the mean characteristics of different type of gullies. The features of ephemeral gullies, with respect to the other gully types, are described in more detail, probably due to the more recent interest in this type of erosion. The data indicate how the authors distinguished ephemeral from permanent gullies and that the mean depth of the EG is almost 0.20 m, although Capra et al. (2009b) mentions that in Sicily, farmers continue to fill EGs up to 2 m deep when the deeper segments are short in length (few meters). However, neither the length, width nor the soil losses are parameters which allow discrimination between the various kinds of gullies.

The mean area of the cross sections of 181 EG systems in Sicily (Capra et al., 2009b; 2011) was almost 0.2 m^2; 90% of the measured sections showed an area just below 0.5 m^2. The mean cross sections of EGs observed in Sicily were similar to those measured in Northwestern Spain (Válcarcel at al., 2003) and in the black soil regions of Northeast China (Zhang et al., 2007), which the mean values were equal to 0.16 and 0.25 m^2, respectively, but higher than EGs observed in Navarra, Spain (Casalí et al., 1999), which the cross sections ranged between 0.04 and 0.09 m^2. Ǿygarden (2003) described rills and gullies with cross section areas ranging from 0.003 to 4.2 m^2. Large permanent gullies with a mean cross-sectional area from 12.3 to 18.2 m^2 were observed in Southeast Australia (Rustomji, 2006).

Poesen and Govers (1990) proposed the width/depth ratio (WDR) as an index of damage due to gully erosion: gullies showing WDR>1 are more harmful because top soil is lost, and this soil is richer in fertilizers, organic matter and pesticides, causing lost of fertility and non-point source pollution, but they can be easily erased by tillage compared with narrow deep channels. In central Belgium, these authors observed that intense rains of short duration caused the formation of gullies with WDR>1, whereas rains of small intensity produced gullies with WDR<1.

Similarly to Belgium, Casalí et al. (1999) measured in Navarra gullies, showing mean WDR>1 as a result of short and intense rainfall. Ephemeral gullies observed in Sicily showed WDRs ranging between 0.34 and 14, with a mean value of 3.2 (unpublished data measured by the author). These values were similar to those measured in North-Eastern Spain (Válcarcel at al., 2003) ranging between 1.64 and 11.97.

Table 1. Morphological characteristics of gullies

Location	Gully type	Mean lenght (m)	Mean width (m)		Mean depth (m)		Soil losses (Mg ha^{-1} $year^{-1}$)		Source
Australia, Victoria	n.a.						1.4		Whitford et al., 2010
Belgium, Loess belt	Ephemeral	191	1.46		0.19		—		Nachtergaele et al. (2001a)
China, Northeast	Ephemeral	184	1.63		0.22		4-4.3		Zhang et al. (2007)
China, Inner-Mongolian plateau	Ephemeral and hole	214	2.02		0.22		8.8	(1)	Cheng et al. (2006)
China, Loess plateau	Permanent	8	1.33		1.83		—		Wu & Cheng (2005)
Ethiopia, Northern	Discontinuous and stream	53	15.45		2.50				Billi & Dramis (2003)
Iran, Fars province	Permanent	13-28	2.39-6.02	(2)	0.62-3.38	(3)			Kompani-Zare et al. (2011)
Italy, Sardinia	n.a.	54	0.96		0.44		1.35	(1)	Zucca et al. (2006)
Italy, Sicily	Ephemeral	145	0.37		0.17		37.7	(4)	Capra & Scicolone (2002)
Italy, Sicily	Ephemeral	113	0.47		0.19		40.4	(5)	Capra et al. (2011)
Laos, Northern	Rill+gully	78	—		—		13		Chaplot et al. (2005)
Norway	Rill+gully		0.15-10	(6)	0.08-2.0	(6)	0.006-4.1		?ygarden (2003)
Portugal, Alentejo	Ephemeral	86	—		—		—		Nachtergaele et al. (2001b)
Spain, Central Navarra	Rill+gully	—	—		—		0.3		Casalí et al.(2008)
Spain, Central Navarra,	Permanent	32	0.73						Casalí et al.(2006)
Spain, Guadalentin	Ephemeral	22	—		—		—		Nachtergaele et al. (2001b)
Spain, Northwestern	Ephemeral						1.06	(1)	Válcarcel et al. (2003)
Spain, Southern Navarra	Ephemeral	39	—		—		12.3		Casalí et al.(1999)
Spain, North	Permanent	375			>1.0				Ménendez-Duarte et al. (2007)
		123			<1.0				
Tanzania	Permanent		17.9		2.33		630.00		Ndomba et al. (2009)
Tunisia, Souar lithologic formation	Rill+gully						1.66-5.6	(1)	Bouchnak et al.(2009)

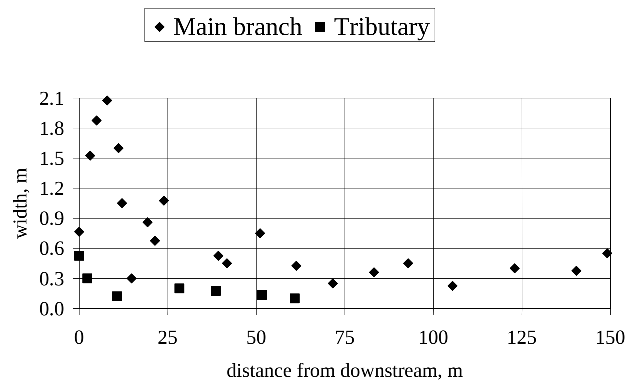
(1) $m^3 ha^{-1} year^{-1}$; (2) top width at middle section; (3) at middle section; (4) mean 1995-2000; (5) mean 1995-2007; (6) maximum values

Figure 3. Simple (on the right side) and branched (on the left side) ephemeral gullies in Sicily (Italy).

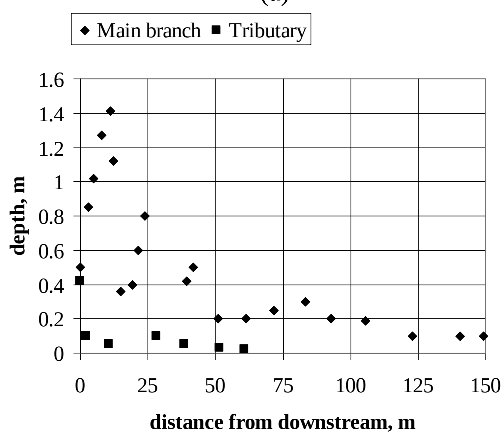
In superficial black soils in Northeastern China, Zhang et al., (2007) observed wide but shallow EGs, with WDRs ranging from 2.48 to 37.31. Gullies monitored in Loess Plateau (China) showed WDRs generally less than 1. In Norway, Ǿygarden (2003) described rills and gullies with mean WDRs generally >1 or >> 1. Capra et al. (2009b), in 12 years of measurements in Sicily, showed that in the different years, both EG systems comprising a main branch alone and those with a main branch and one or more tributaries were active (an example in Figure 3).

The mean number per year of active tributaries in the area was eight, with a minimum of zero and a maximum of 19. The mean number of tributaries per EG system was 0.36, ranging between a minimum of zero and a maximum of seven. The width (*w*) and depth (*d*) of tributaries were lower than those of the main branches: the mean values of *w* and *d* were 0.74 m (*w*) and 0.37 m (*d*) for the main branches and 0.32 m (*w*) and 0.18 m (*d*) for the tributaries. The authors found a significant positive correlation between the length of the tributaries and the length of the main branch.

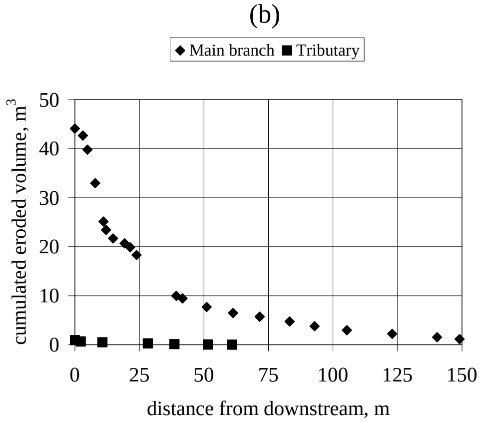
A physical explanation for this correlation could be found by observing that tributaries only appeared when the length of the main EG reached the maximum allowed by the drainage area and length of the catchment. But, as explained before, the tributaries were narrower and shallow than the main branch.



(a)



(b)



(c)

Figure 4. Relationships between mean width (a), mean depth (b), eroded volume (c), and distance from the downstream for an ephemeral gully in Sicily (Italy).

In the same research, the authors showed significant correlation between EG length and eroded volume for both the main branches and the tributaries. That confirmed the feasibility of using EG length to estimate the eroded volumes, as proposed by several authors, and as will be discussed in the following part of this chapter.

Cross-sectional areas and WDRs change along gullies. EGs in Navarrra (Casalí et al., 1999) and Northeast China (Zhang et al., 2007) showed greater sections in the central part and gradually decreasing sections toward the upstream and downstream ends for both the classical and drainage EGs. The variation of cross-sectional areas was smaller in discontinuity EGs, which were more uniform canals (Casalí et al., 1999). On the other hand, cross sections of the EGs observed in Sicily (Capra et al., 2011) generally increased in a downstream direction. Figure 4 shows, as an example, the relationships between depth, width and eroded volume and distance from the downstream for both the main branch and a tributary of an EG.

2.3. Similarity between Morphological Characteristics of Different Types of Erosion Channels

As discussed previously, the transition from an EG to river channel erosion hydraulically represents a continuum. Capra et al. (2009; 2011) and Di Stefano et al. (2013) stated that the evolution of the erosion process determines an imprinted channel, which is geometrically similar at different (rill, EG) scales. The application of the dimensional analysis and theory of self-similarity (Barenblatt, 1987) to both EGs and rills measured in two catchments in Sicily demonstrated that a morphological similarity condition exists between these two erosion types. The analysis (Capra et al., 2009a) allowed to establish Eq. (1), which relates the eroded volume of a channel segment (V_s) to their length (L_s), could be applied for both rills and EGs measured in Sicily (Figure 5) using the same exponent b_s = 1.1956 and a different scale factor $a_{s,}$ which was equal to 0.0423 for the EG systems and 0.0039 for the rills.

$$V = a_s \ L^{b_s} \tag{1}$$

The analysis also showed that the functional relationship (Eq. 2) between the eroded volume and the morphometric characteristics length, L, width, w, and depth, *H*, of the erosion channels developed by Bruno et al. (2008) was valid for both rills and EGs:

$$\frac{V}{L^3} = F\left(\frac{w\,H}{L^2}\right) \tag{2}$$

Applying the incomplete self-similarity theory, the following power relationship was obtained:

$$\frac{V}{L^3} = a_r \left(\frac{w\,H}{L^2}\right)^{n_r} \tag{3}$$

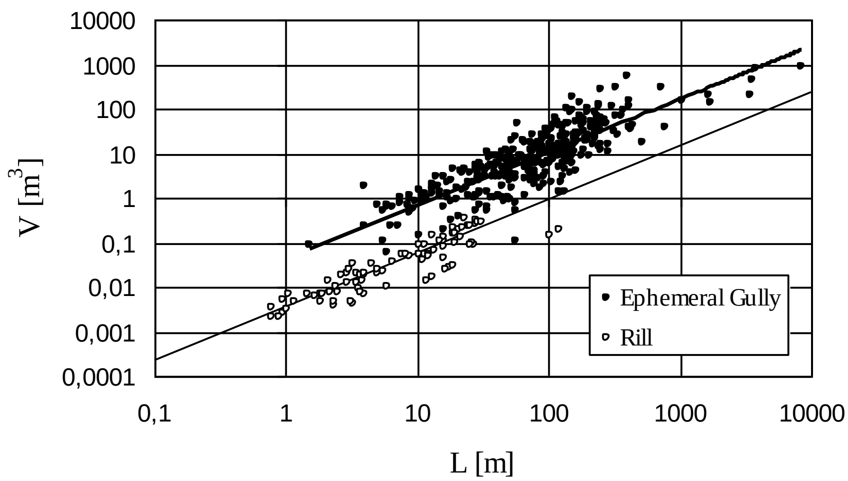


Figure 5. Comparison between the relationship length-volume for rills and ephemeral gullies.

Eq. (3) fitted well for rills and also for EG main channels and tributaries, measured in both humid or dry soil conditions, with a_r= 0.5072 and n_r= 0.9222. In other words, a morphological similarity between rills and EGs was confirmed, and, opposite to the *V*-*L* relationship, a scale-factor depending on channel type (rill or EG) was not necessary.

Capra et al. (2011) compared step-pool structures observed in an EG occurring in the same place from 1995 to 2007 to similar morphological structures observed in evolving streams that tend to maximise their stability

(Abrahams et al., 1995; Chin, 1999; Lenzi and D'Agostino, 2000; Lenzi, 2001; Ferro, 2006).

These structures can be characterised by:

1) wavelength, L_s, e.g. the distance between two successive pool to pool trough points
2) height, *H*, measured by the perpendicular distance between the crest and an imaginary line connecting the troughs of the step–pool unit, and
3) the slope of the bed channel, *S*.

The mean values of *H*, L_s and *S* in the EG were 0.19m, 8.32m and 25%, respectively.

According to Abrahams et al. (1995), the Eq. (4) can be applied to a stream that tends to evolve to a step-pool structure:

$$\frac{H}{L_s} = c\ S \tag{4}$$

where *c* is a coefficient ranging between almost 1.5 (Abrahams et al., 1995; Lenzi and D'Agostino, 2000; Lenzi, 2001) to 2.5 (Zimmermann and Church, 2001).

The analysis showed Eq. (4) could be applied to EG, but with a great dispersion of the *c* values respect streams. The mean value of *c* was equal to 0.19, lesser than the values characterising the streams.

The authors concluded that an ephemeral channel, such as an EG, similarly to a stream, tends, in the environment considered, to reach a step-pool morphology as the structure that maximises its stability.

3. Contribution of Gully Erosion to Overall Soil Losses and Sediment Production

Gully erosion is often the main source of sediment on a catchment scale. In Belgium, gully erosion produced 40 to 60% of the total soil losses with an average value of 5 Mg ha^{-1} $year^{-1}$ (Poesen et al., 1996a). In a study conducted in Sicily (Italy), Capra et al. (1994) and Capra and Scicolone (1996) showed that the gully density was strongly correlated to rill and interrill erosion, and also was the best parameter to use to classify the catchment erosion hazard in eight small catchments. A survey in 22 Spanish catchments (Poesen et al., 2002) indicated that specific sediment yield increased when the frequency of gullies increased. For catchments where no gullies were observed, the mean specific sediment yield was 0.74 Mg ha^{-1} $year^{-1}$, whereas in catchments with numerous gullies, the mean specific sediment yield was one order of magnitude larger, i.e. 9.61 Mg ha^{-1} $year^{-1}$. In the Warragamba catchment (New South Wales, Australia), sediment yields from gullied catchments were at least one order of magnitude higher than ungullied catchments (Valentin et al., 2005). Poesen et al. (2003), in a review of almost 50 field-based studies, evidenced soil losses due to EG erosion ranging between 0.1 and 65 Mg ha^{-1} $year^{-1}$. An update of the data discussed in the paper cited shows annual soil losses ranging between 0.006 and 630 Mg ha^{-1} $year^{-1}$ (Table 1).

Over the past several decades, most research dealing with soil erosion by water focused on interrill and rill erosion operating at the plot scale despite the presence of various gully types in many landscapes under different climatic conditions and land uses (Poesen et al., 2003). Most researchers (e.g. Evans, 1993; Poesen et al, 2003; Boardman, 2006) stressed that interrill and rill erosion at plot scale is not a realistic indicator of total soil losses at catchment scale and it also doesn't indicate the redistribution of soil eroded within a field or catchment. In a recent study, Di Stefano et al. (2013), comparing linear erosion (rill and EG) to interrill erosion measurements at a Sparacia experimental area (Sicily, Italy), showed that linear erosion was larger than the measured total soil loss in almost one half of the events considered. The authors pointed out that this result can be caused by sediment delivery processes, for which a part of the eroded soil mass didn't reach the plot outlet and didn't contribute to the measured total soil loss. Sediment delivery processes were also observed by Rejman and Brodowski (2005) on plots having a length of 10 and 20 m, and was established on a uniform slope of 12%. These authors pointed out that the erosion, as estimated from the volume of all rills and soil bulk density, was larger than the soil loss measured at the plot outlets. On longer plots, they observed that some of the rills remained unconnected to the rill network but connected to the plot outlet. Therefore, they distinguished between the contributing rills, which were connected to this network, and the non contributing rills, and also considered rill erosion only to be related to the contributing rills.

The adoption of monitoring schemes based on field measurement and the estimation of volume of rills and gullies covering several years is an action necessary in order to assess erosion at catchment and landscape scales (Valentin et al., 2005; Boardman, 2006).

Information on the contributions of gully erosion to overall soil loss is scarce, examined over short time periods and obtained for different objectives and by different methods. Sometimes, the data refers to soil losses due to both rill and gully erosion.

A survey conducted by Poesen et al. (2003) showed that soil loss rates by different kinds of gullies may vary considerably representing from 10% to up 94% of total sediment yield caused by water erosion.

Auzet et al. (1993), in the North of France, found that linear erosion during winter accounted for almost 80% of soil loss due to rill erosion. In Normandy (France), two extreme rainfall events promoted considerable erosion damage (Cerdan et al., 2002); the relative importance of channel erosion varied from 21% to 56% out of total erosion.

Vandaele (1993) in the Belgian loam belt observed that the annual EG erosion equaled 70-75% of the mean annual rill erosion. According to Vandaele et al. (1996a), the soil loss due to EG erosion in South Portugal (Alentejo region) was 4 to 5 times higher than the average annual rill-interrill erosion rate, whereas for central Belgium, the ratio varied between 0.4 and 2.3. In actively eroding areas in Navarra (Spain), EGs typically contributed about 30% to the total soil loss, but could reach as high as 100% (Casali et al., 1999). In a comparison of estimated rill-interrill USLE and measured EG erosion values for the same field in 19 U.S. states, the EG erosion rates varied from 21% (in New York) to 275% (in Washington) (Woodward, 1999). In a representative sample of cultivated land in A Coruņa province (Northwest Spain), EG erosion contributes to concentrated flow sediment production between 6% and 76%, with a mean of 26.4% (i.e. 1.06 m^3 ha^{-1} $year^{-1}$) (Valcárcel et al., 2003). For the Loess Plateau in China, Cheng et al. (2007) documented values up to 70%. Capra et al. (2011) evidenced that the ratio between soil loss attributable to EG and total soil loss (rill-interrill + EG) resulted quite variable between erosion events accounting for 23% to 98% of total soil lost.

The soil detached by gullying (EG) accounted for approximately 58% of the total soil detached during an extreme rainfall events in a vineyard plot located in Catalonia (Spain) (Martínez-Casasnovas et al., 2002).

Poesen et al. (2003) showed that the contribution of EG erosion to total soil loss is space- and time-scale dependent. The data reported by the authors clearly indicates that neglecting soil losses caused by EG erosion when changing spatial scales would result in a significant underestimation of soil loss rates, as observed in the field in a range of environments. In a Spanish study, both area rill and EG erosion rates were of equal importance (i.e. 1-2 m^3 ha^{-1} $year^{-1}$) for slope lengths from 0 to 140 m, but EG erosion rates became far more important than rill erosion for slope lengths > 140 m (i.e. up to 20 m^3 ha^{-1} $year^{-1}$, representing 85% of total soil loss) (Poesen et al., 1996a).

Poesen et al. (2003) also showed that the available data indicates that soil loss due to EGs depends on time span considered.

For example, data presented by Poesen et al. (2002) indicate that soil losses caused by EG erosion for a relatively wet winter on the Iberian Peninsula represented 47–51% of total soil loss by water erosion, whereas at the medium time scale (i.e. 3–20 years), this figure rised to 80–83%. Capra et al. (2009b; 2011) confirmed the great temporal variability in the occurrence of EG erosion in an 80 ha Sicilian watershed studied from 1995 to 2007. EG formation occurred 8 years out of 12, with a frequency corresponding to 67% of the years covered by the survey and a return period of 1.5 years. No EG erosion occurred in the rainy seasons 1998–99, 2000–01, 2001–02 and 2002–03. The lowest level of erosion occurred in 1996–97, when a total of four active EGs, 530 m of channels, and about 20 m^3 of soil loss were observed. The maximum number and total length of active EGs, equal to 46 and 6190 m, respectively, were detected in 1999–2000, whereas the maximum total eroded volume, equal to ca. 800 m^3, occurred in 2003–2004, when the EGs were wider and deeper than in 1999-2000.

The space- and time-scale dependence can contribute to explain the high variability of the contribution of gully erosion to total soil loss by water erosion.

4. Gully Erosion Evolution and Controlling Factors

4.1. Gully Erosion Mechanisms

Attempts at evaluating linear erosion mechanisms have been made over several years, but the number of field-based studies on the dynamic process of gully erosion is limited.

Brunton and Bryan (2000) proposed a shear-velocity-based model to explain the rill network development. When shear velocity of the main flow exceeds the threshold value, a channel incision occurs. As the initial knickpoint shifts upslope, reducing the channel thalveg slope, the base level for the side slope is lowered and the effective side slope is increased. Due to increased local slope, shear velocity in tributary areas exceeds threshold value. Headcut of both this main channel and the tributaries continues to shift upslope.

Casalí et al. (1999) described the mechanisms for the appearance and growth of the three types of EG defined in section 2. According to these authors, in the classical EG, the headcut promoted by flowing water probably migrated upstream, enlarging and deepening the channel. The channel incision of drainage EG began in the upper boundary of the field due to the flows concentrated draining areas upstream from the field. For discontinuity EG incision, headcuts, that later migrated upstream, were probably triggered by slope discontinuities due to management practices (e.g. field boundaries adjacent to roads) that create a sudden change in slope. In subsequent years, the hollow that remained after EG filling by ploughing promoted flow concentration and gully development in the same position.

Capra et al. (2011) observed the steps of the EG formation and development during the years from 1999 to 2008 in a wheat field (Figure 3) located in Sicily. In the first rainy season (1999-2000), the first trace of the EG, only a few meters long, appeared at the foot of the slope after the first erosive event at the end of August. The following four events caused a retreat in the upstream direction with an increase in the EG length, width, and depth. Only during the last event of the rainy season, in the middle of January, was the formation of tributaries observed.

The tributaries only appeared when the length of the main EG reached the maximum allowed by the drainage area and length of the catchment. Figure 6 shows the scheme of the EG formation and elongation. The farmers did not move soil or level the EG until the harvest, at the end of May. The EG was erased by filling with soil from areas adjacent to the channel during tillage operations from July to October, before showing.

The farming operations consisted of two tillages (with a cultivator harrow 0.30-0.35 m deep) and one ploughing operation (0.5 m deep). The EG recurred in the same places during the next rainy seasons with the exception of the years 2001-02 and 2002-03, when the precipitation was less than a threshold necessary to create the headcut.

Ephemeral gully formation on the Loess Plateau proceeded as follows (Gong et al., 2011). On sloping farmlands, rainfall led to sheet flow, which initiated sheet and rill erosion and also concentrated flows. The points of initial incision evolved into erosion gullies heading downslope. Since the land was used for agriculture, the gullies were then filled and leveled during plowing. With subsequent rainfall events, the filled gullies were re-initiated at the sites of the original gullies.

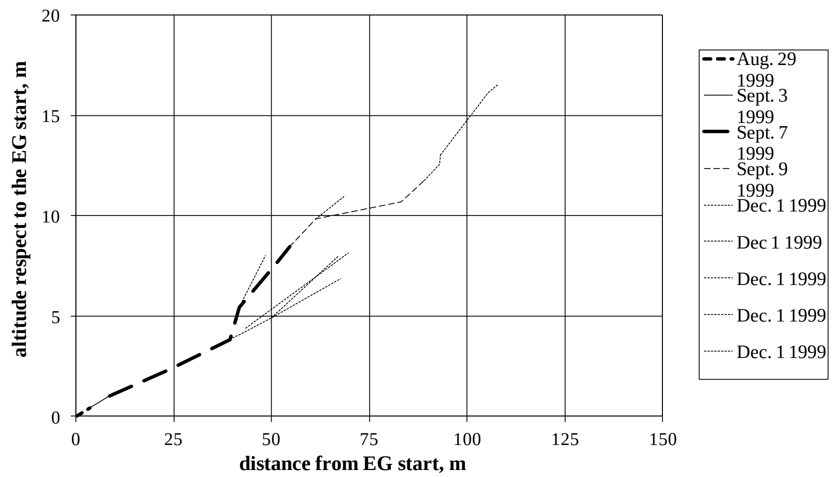


Figure 6. Scheme of an ephemeral gully formation and elongation.

3.2. Controlling Factors

Gullies are threshold-dependent processes controlled by many factors. Poesen et al. (2003) discussed some gully types and environmental controls, such as soil type, land use, climate and weather, and topography. Valentin et al. (2005) focused the attention on topographic thresholds, soil and lithologic controls, and also land use and climate changes. This review is limited to the thresholds widely studied around the world, such as the topographic and rainfall thresholds.

Topographic Thresholds

The kinetic energy of concentrated overland flow depends on runoff and slope. Considering that the drainage area can be used as a surrogate for runoff volume, a critical drainage area (*A*) is necessary for a given slope (*S*) to produce sufficient runoff to concentrate and initiate gullying. The analytical model proposed by scientists can be written in the form:

$$S=aA^{-b} \qquad (5)$$

Or the equivalent:

$$SA^b=a \qquad (6)$$

The constant a and the exponent b depend on environmental characteristics, and have been derived from the field data by different authors around the world. The coefficient a in eq. (6) represents the threshold value for gully initiation.

According to the results of several researches, the exponent b is more or less constant, while the constant a shows important variation and ranges over several orders of magnitude.

According to Morgan (2005), b values <-0.2 indicate that overland flow is the dominant process, while values >-0.2 are associated with subsurface processes and mass movement. That seems to be confirmed by the results obtained in the Northern Iberian Peninsula by Menéndez-Duarte et al. (2007), which showed b values of -0.176 for deep channels and -0.252 for shallow channels where shallow soil could have generated subsurface flow. Zucca et al. (2006), in stony and shallow soils in Sardinia, Italy, estimated a b value of -0.2 and highlighted this value could be due to a subsurface flow that could take place in stony soils, or in soils where Bt horizon was near the soil surface or in shallow soil with a bedrock near the surface.

Montgomery and Dietrich (1994) suggested a b value equal to 2, and a AS^2 ranging between 500 and 4000 m^2 as indicators for gully initiation, but other authors demonstrated that these values are different in different regions and need to be estimated in the different conditions since other factors control this threshold, as well as climate and all other factors controlling the mechanism of incipient gullying, seepage flow and mass movement processes (Poesen et al., 2003). For example, Wu and Cheng (2005) and Cheng et al. (2006) showed that AS^2 for gully headcuts ranged from 41 to 814 m^2 and from 37 to 815 m^2 in the Loess Plateau and Inner-Mongolian Plateau of China, respectively.

Montgomery and Dietrich (1992) stated that, for a given local slope, the drainage area necessary to promote a headcut is greater in dry conditions compared to wet conditions, but Vandekerckhove et al. (2000a, b) observed that this concept did not apply in Mediterranean environments and explained that the trend line was controlled by factors different from climate, such as vegetation cover and geology. Capra and Scicolone (2002) showed the mean channel watershed surface area was higher in years when precipitation was lower and vice versa. Nazari Samani et al. (2009), in a field research on the threshold conditions for gully erosion in Southwestern Iran, found a *b* value of -0.266 and explained that in arid regions with sparse vegetation cover, the intense nature of the rainfall can generate sufficient runoff from small catchments for gully initiation. This *b* value was similar to both in the Sierra Gata (-0.267) and Lesvos (-0.211) in Mediterranean Europe and the Loess Plateau, China (-0.3) estimated by Vandekerckhove et al. (2000a, b) and Cheng et al. (2007), respectively. Vandaele et al., (1996b) derived *b* (almost -0.4) and *a* (almost 0.025) values similar for Portugal and Central Belgium areas despite important differences on climate and soil characteristics between the two regions. The authors explained the different values of *a* (almost 0.35) determined for Oregon and California study areas considering the steeper slope and gully initiation by small land sliding in these regions. Zhang et al. (2007) established *b* values were almost identical (almost -0.14) for ephemeral and classical gullies. The different values of *a* implies that two different relationships could be used to distinguish between the initiation of ephemeral (*a*=0.052) and permanent (*a*=0.072) gullies.

Poesen et al. (2003) indicated that not only the environmental characteristics, but also the methodology used to asses critical *S* and *A* data, affects the topographic threshold conditions for gully initiation. According to Vandaele et al. (1996b), the more accurate data on both slope and drainage area were obtained by field measurements respect to their estimation on topographical maps or GIS. However, the pixel size of the DEM also affects the accuracy of the estimation (Capra at al., 1993; Wu and Cheng, 2005).

The *S-A* relation, in combination with a hydraulic threshold in some cases, have been used to predict, for a given environment, the location in the landscape where gullies may develop by providing a physical basis for the initiation of gullies. Desmet and Govers (1997) and Desmet (1999) showed a *b* value to predict the trajectory of the gullies higher (0.7-1.5) than that (i.e. 0.2) required to identify spots in the landscape where an EG began. Cheng et al. (2006) proposed the relation $S=0.064A^{-0.375}$ for predicting where hole-ephemeral gully heads will initiate in the Inner-Mongolian Plateau (China). This relation was similar to a simple model of channel initiation by overland flow that had been successfully tested in different regions.

Rainfall Thresholds

Channels can only develop if concentrated (overland) flow intensity during a rain event exceeds a threshold value. The threshold force required for channel initiation is often expressed in terms of flow shear stress depending on the density and the depth of flow and also the soil surface gradient (Poesen et al., 2003). This mechanism has been thoroughly studied for incipient rilling, but very few studies deal about the incipient gullying in field conditions mainly due to logistical problems. Therefore, some authors described that rainfall thresholds were easier to measure. However, information on threshold rains are usually restricted to small areas and examined over short time periods.

Threshold rains from 14.5 to 22 mm have been described for EG formation on cropland over loamy or clay soils in various study areas in Belgium, France, Northern Thailand, Spain and the UK (Poesen et al., 2003). In Navarra (Spain), the minimum conditions able to promote EG erosion were a total depth of 17 mm and a peak rate of 54 mm h^{-1} (Casalí et al., 1999). Nachtergaele et al. (2001) analysed EG formation over a 15-year period in central Belgium and found a critical rainfall height of 15 mm in winter and 18 mm in summer. In Normandy (France), a rainfall height of 28.5 mm and a max 6-min intensity of 15 mm h^{-1}, and a rainfall height of 21.6 mm and a max 6-min intensity of 98 mm h^{-1} promoted rill and EG formation in a cropped area in December and May, respectively (Cerdan et al., 2002). Chaplot et al. (2005) observed that the rainfall threshold for linear erosion (rill and gully) in a 0.62 Km^2 catchment in Laos had a total rain amount of about 50 mm with a minimum rainfall intensity of 100 mm h^{-1}.

In addition to rainfall height and intensity, rainfall erosivity indices have been used to show the influence of rainfall in erosion processes. One of the most common rainfall erosivity indices is the R-factor proposed by Wischmeier et al. (1978).

The different threshold rain values are attributed to different states of the soil surface, as affected by tillage operations and previous rains (Poesen et al., 2003). Previous soil moisture before any rainfall event influences runoff generation (Descroix et al., 2002; Castillo et al., 2003) and, therefore, soil erodibility (Morgan, 2005, Casalí et al., 1999). Antecedent rainfall indices can be used as surrogate for soil water content (Descroix et al., 2002; Castillo et al., 2003). The cumulative 24-h rainfall (Woodward et al., 1999) and cumulative 3-day or 5-day rainfall (Capra et al., 2002; NRCS, 2003) have been used as antecedent rainfall indices.

Casalí et al. (2008), in a study on runoff and erosion in two cultivated watersheds in Central Navarra, observed that the erosivity of the rain did not fully account for the total average sediment yield registered, despite average runoff discharges along the year followed a roughly similar pattern than that of precipitations; the explanation furnished by the authors was the soil water content. During winter, the rain erosivity was low but the soil was almost saturated, leading to large runoff rates flowing unprotected and then vulnerable soil. The authors also observed that most of the annual sediment yield was a result of just a few precipitation events, similarly to the EG formation in Southern Navarra (Casalí et al, 1999).

These results have also been supported by Capra et al. (2009b) in a study on the relationships between rainfall characteristics and ephemeral gully erosion in a cultivated catchment in Sicily. Ephemeral gully erosion in the study area was directly and mainly controlled by rainfall events. The height, intensity and erosivity of the rainfall had a role in EG formation and development. An antecedent rainfall index, the maximum cumulative 3-day rainfall (H_{max3_d}), used as a simple surrogate for soil water content, was the rain characteristic which best explained EG erosion in the environment considered. A H_{max3_d} threshold of 51 mm was observed for EG formation. The return period of the H_{max3_d} threshold was almost the same as the return period for EG formation. Although a mean of seven erosive rain events were recorded in a year, EG formation and development generally occurred during a single erosive event. The most critical period for EG formation was that comprised between October and January, when the elevated soil water content facilitated runoff development and the almost bare soil surface with emergent wheat plants eroded most intensely.

5. Gully Erosion Models

Poesen et al. (2003) identified, amongst other things, the need for appropriate models to predict gully erosion. The authors stressed that only few models are currently available and they have not been tested for gully erosion. Boardman (2006) highlighted the scale at which most erosion data for model development has been collected, the experimental plot, is inadequate to consider the effects of long slopes, sediment storage, deposition and gullying. The plot scale is also of limited value in exploring the effects of extreme rainfall events on erosion in the landscape.

Gullying is not simulated in the most widespread models (e.g. USLE, RUSLE). For the latest process-based models (e.g. WEPP and EUROSEM), there is little evidence that they are as useful as expected, compared with statements of original intent (Boardman, 2006). Furthermore, input data for complex models are not always readily available. In many cases, for the above reasons, simple models may be perfectly adequate for the task.

Out of the existing models, the ephemeral gully erosion model (EGEM; USDA, 1992; Woodward, 1999) was primarily intended for use by field, area, and also state personnel in conservation and project planning activity in NRCS (USDA, 1992). The EGEM model has two major components: hydrology and erosion. The hydrology component is a physical process model that uses the NRCS runoff curve number (SCS, 1985), 24-h rainfall, andone of the four standard rainfall distributions developed for the climatic regions of the USA to estimate peak discharge and runoff volume. Estimated peak discharge and runoff volume drive the erosion process. The erosion component is a combination of empirical relationships and physical process equations to compute the width and depth of the ephemeral gully based on the hydrology output. Souchère et al. (2003) developed the model called STREAM Ephemeral Gully. The model was used to estimate erosion rate by the main runoff collector network in a watershed and was integrated in a GRID raster module. The results of an application in four small cultivated watersheds showed the model makes it possible to predict gully erosion from simple information easily recorded by the farmers (e.g. land use, soil surface crusting stage, roughness, plant cover, tillage direction). In some cases, the model tended to overestimate the erosion rate. The authors stressed that it would be necessary to improve the database with the experimental results and the use of a calibration procedure. Casalí et al. (2003) adapted an event-oriented process-based model developed from the river erosion (Alonso and Combs, 1999) to estimate EG erosion. The model computes the gradually varied flow and the channel bed and bank erosion and also simulates the channel shape according to the computed erosion in each reach. The basic equations of the model are the conservation of mass and momentum for water and sediment. A sensitivity analysis showed that particle density and size, and the roughness coefficient were the key parameters. A calibration in a small watershed allowed a proper estimation of soil loss and the gully cross section shapes along the channel.

Nachtergaele et al. (2001a,b) tested the EGEM model in various cultivated areas (Spain, Portugal and Belgium), and concluded that it was not capable of predicting EG erosion properly in the environments studied. They found that an accurate prediction of EG length may be sufficient for accurate prediction of EG volumes by the relationship between the volume (V, m^3) and length (L, m) of an ephemeral gully in the form of eq. (7):

$$V = a\,L^b \qquad (7)$$

in which *a* and *b* are two coefficients.

Similar conclusions were drawn by Capra et al. (2005) in the small watershed of Raddusa (Sicily). The standard version of EGEM was not capable of predicting EG erosion. The adaptation to local conditions of the EGEM hydrological component and EG depth measurements improved the volume prediction, but the cross-section and the width could not be adequately estimated. The reason why EG volumes were well-estimated is because both EG length and depth were measured. Simple and multiple correlation analyses showed that EG length was the true key factor which explained EG eroded volume. Therefore, the authors proposed eq. (7) with a= 0.0082 and b= 1.416 as a good estimator of EG erosion in the environment considered.

The eq. (7) has been tested in different environments. As examples for ephemeral gullies, a=0.048 and b =1.29 have been proposed for EGs developed in the Belgian loess-derived soils (Nachtergaele et al., 2001a, b); 0.10 and 1.04 for winter gullies in Belgium (Nachtergaele et al., 2001a, b), 0.948 and 1.097 in Fars Province (Iran); 0.015 and 1.429 in Northeast China (Zhang et al., 2007).

As described in paragraph 2.3, the analysis performed by Capra et al. (2009a) helped establish Eq. (1), similar to eq. (7) but pertinent to channel segments, could be applied for both rills and EGs measured in Sicily (Figure 7) using the same exponent and a different scale factor a for the EGs and rills.

Di Stefano and Ferro (2013) showed the eq. (1) could be applied to segments of rills measured at Sparacia experimental areas in Sicily (475), to EG measurements obtained by that investigation and those available in literature (330) and also the gully measurements (44) carried out by Ichim et al. (1990), Daba et al. (2003) and Moges and Holden (2008) using the same exponent b_s equal to 1.1 and a different scale factor, a_s, which represents the influence of the channel depth and width (a_s =0.0036 for rills, a_s =0.0984 for EGs and a_s =35.8 for gullies).

Zucca et al. (2006), in a field research, showed that the value of the exponent b nearly to 1 indicates that the cross-sectional area of the channel is almost constant; a value >1 is due to the fact that the cross-sectional area of longer gullies is greater than those of shorter ones. According to these authors, the a and b values varied according to the different substrata: they found a= 0.39 and 0.114 and b= 0.92 and 1.42 for coarse granites and colluvial deposits, respectively. In granites, the gully depth was limited by the presence of bedrock, therefore b was almost 1.

A number of methods are already available to measure (ground techniques and aerial photographs) or estimate EG length (e.g. based on the topographical threshold concept) (Desmet et al., 1999; Nachtergaele et al., 2001a,b).

Zhang et al. (2007) performed stepwise multiple regressions between length (L) and some gully watershed parameters (watershed length, slope and area) for gullies mainly formed in natural drainage lines. They found the watershed length (L_w) was the only significant parameter, but the regression model L-L_w was not successful at predicting the length of a single gully, though the predicted total length was very close to the total measured length.

The topographic thresholds can also be used as models to estimate the location where an EG could start its development, as stated before in the paragraph 4.2.

CONCLUSION

Gully erosion shows both on-site and off-site impacts including loss of fertility, loss of cultivated soils, eutrophication of water courses and lakes, destruction of wildlife habitats, siltation of dams, reservoirs, rivers, and valley bottoms as well as infrastructure and property damage by muddy floods.

Gully erosion isn't limited to badlands and hilly areas; it affects a wide variety of cultivated soils. Though there is considerable evidence to observe more cases of erosion involving ephemeral and/or permanent gully erosion as the dominant processes, gully erosion has long been neglected.

The data available on the contribution of gully erosion to overall soil loss is scarce, usually restricted to small areas, examined over short time periods and obtained for different objectives and by different methods. Most models dealing with soil erosion concern sheet and rill erosion and do not include erosion due to concentrated flow channels. Furthermore, the experimental plot, the scale at which most erosion data for model development have been collected, is inadequate to consider the effects of long slopes, sediment storage, deposition, and gullying. A research effort to better understand gully mechanisms and their controlling factors over a wide range of environmental conditions is fundamental to the identification and adoption of possible conservation strategies.

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