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A review of topographic threshold conditions for gully head development in different environments

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A R T I C L E I N F O

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A B S T R A C T

Gully head development represents a significant geomorphic process in a wide range of environments. Several studies investigated the critical topographic conditions, expressed by local slope gradient (s) and drainage area (A), controlling the development and position of gully heads in various landscapes. This review examines over 39 publications. After critically analysing the reported threshold data and after standardisation of the procedure to determine the critical topographic conditions for gully head development, i.e., $sA^b > k$ or $s > kA^{-b}$ some data sets were discarded because they were not compatible with the standard presentation of data as reported by the majority of studies. Hence, a detailed analysis was made of 63 reported *s–A* relationships for overland-flow induced gully-heads extracted from data sets collected in various parts of the world. A first examination of the behaviour of both the exponent *b* and the threshold coefficient *k*, which reflects the resistance of the site to gully head development, shows clear effects of land use on the value of k whereas the value of b does not seem to be affected. Further analyses are conducted of the recalculated threshold coefficients k, for two predefined constant values of the exponent *b*. The lowest *k*-values were observed for cropland followed by values for rangeland, pasture and forest. Effects of climate, rock fragment cover at the soil surface and water storage capacity of the gully catchment on *k*-values were also shown. The most interesting result is that for a given and constant *b*-value, the threshold coefficient *k* can be predicted using soil and vegetation characteristics, based on the NRCS Runoff Curve Number values and on surface rock fragment cover.
Furthermore, the underlying physical processes explaining the value of the exponent *b* were analysed. Finally, a physically-based model, well anchored in the established theories, is proposed as a first step to predict gully head development in various landscapes and under changing environmental conditions. The results of this review clearly show that better and more reliable models can be built, including effects of land use, climate changes and natural disasters.

Contents

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1. Introduction

A gully is an intermittent water course, where processes of channel erosion can be very intense. Due to the importance of gullies as a sediment source, lines of preferential connection between upland areas and the main channel network, as well as their capacity to modify water and sediment connectivity during intense rainstorms, especially in cropland, gully erosion needs to be better understood, managed and its effects mitigated (Poesen et al., 2003, 2011; Li et al., 2004; Valentin et al., 2005). The first step requires the development of a standardised system for evaluating site susceptibility to gully erosion, linking the susceptibility to local topography, soil types and management practises. This can be achieved without producing a proper calculation of gully erosion rates, for which the rain event intensity and its spatial and temporal characteristics are needed.

One of the most discussed and data-rich characterisation of gullies is based on the topographic control of the gully head position. A gully head represents the position at which the processes of erosion cannot continue expanding upslope under the given rainstorm intensity and other boundary conditions such as land use, vegetation cover and soil type. Hence, this offers the opportunity of evaluating the relative importance of the various factors influencing gully formation, which is crucial for a better understanding of gully erosion. A significant number of publications have reported field data about gully head positions in a range of environmental settings. Usually the topographic threshold conditions for gully heads are reported as double logarithmic plots of upslope area (A), and slope gradient (s), where A (ha) is the area of the catchment draining towards the gully head (GH) and s (tangent, m/m) is the local slope of the soil surface at the gully heads (Fig. 1, see Eqs. (2a), (2b)). A recent review of studies dealing with topographic thresholds for gully head development by Poesen et al. (2011) suggests a variable exponent (b) for A. Montgomery and Dietrich (1994) proposed a possible interval of variation for b, depending on the degree of runoff turbulence (laminar flow condition – $0.5 < = b < 0.857$ – turbulent flow condition). The majority of the threshold lines appears to suggest almost laminar flow conditions (Montgomery and Dietrich, 1994; Torri and Borselli, 2003) which are rare for concentrated flow conditions in the field (Torri and Borselli, 2003). Moreover, the intercept (k, see Eqs. (2a), (2b)) and exponent (b) values do not follow any proper trend. When the data are plotted all together, they clearly show an increase of the threshold values when passing from cropland through rangeland to forest, as one would expect and which is clearly shown

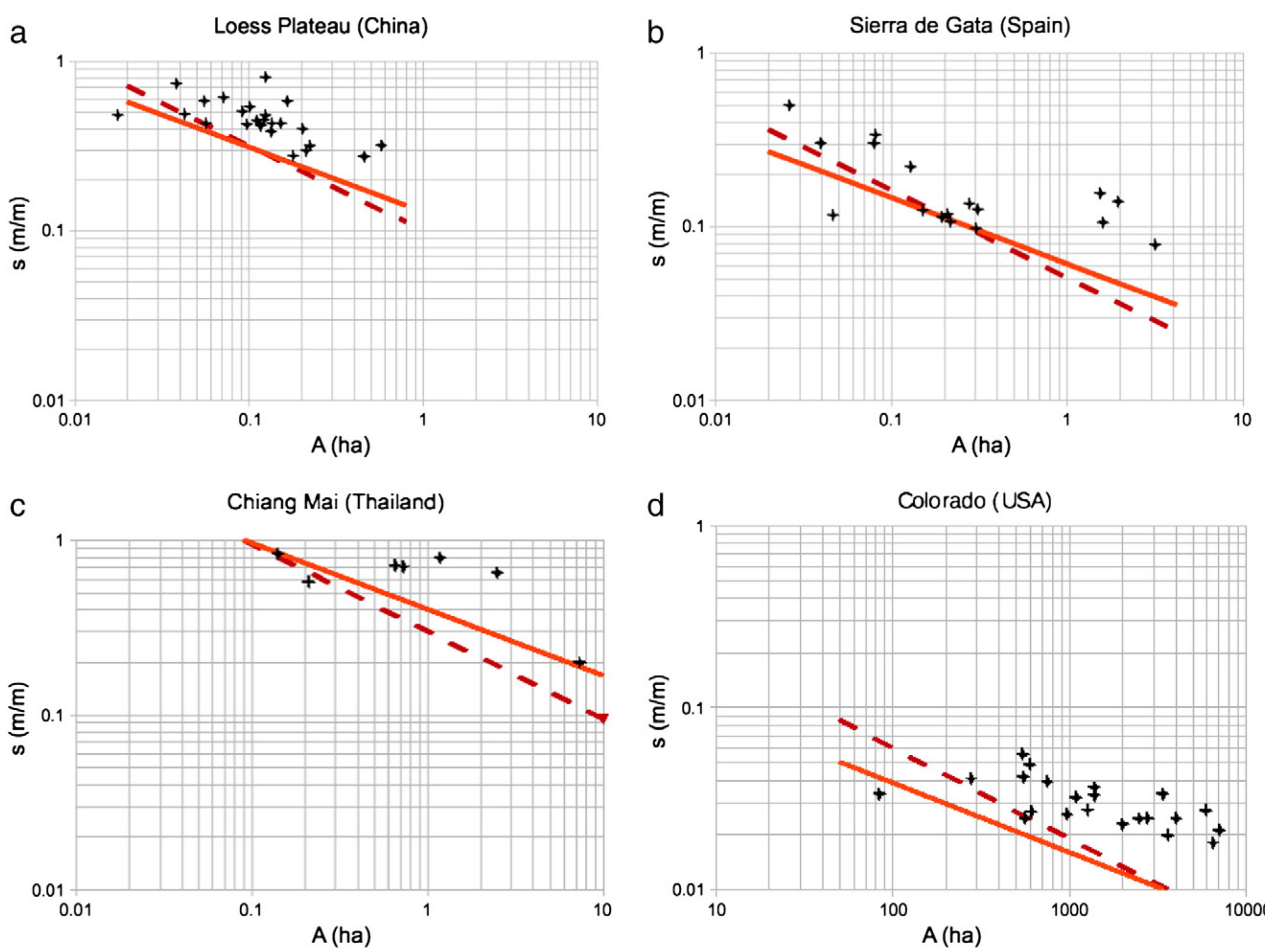

Fig. 1. Illustration of topographic threshold data of gully heads incised by concentrated overland flow, collected in different environments: a) Loess Plateau (Wu and Cheng, 2005), b) Sierra de Gata (Vandekerckhove et al., 2000), c) Chiang Mai (McNamara et al., 2006), d) Colorado (Patton and Schumm, 1975). s is slope gradient of the soil surface at the gully head; A is catchment area. The threshold lines correspond to two exponents (b in Eq. (2): $b = 0.38$ (solid line) and $b = 0.5$ (dashed line).

by the plots presented by Vandaele et al. (1996, Fig. 2, p. 161), Vandekerckhove et al. (2000, Fig. 3, p. 1208) and Poesen et al. (2003, Fig. 8, p. 109). Their figures seem to suggest that there is only one exponent value, which decreases only when landsliding becomes the dominant process of gully head formation. The objective of this paper is to examine all published data for gully head development by concentrated flow erosion, comparing them with the theory proposed by Montgomery and Dietrich (1994) and suggest a way forward to develop a more comprehensive model. This paper does not aim at discussing all-comprehensive models of landscape evolution such as that developed by Willgoose et al. (1991), nor the probabilistic inferences relative to channel initiation discussed by Istanbulluoglu et al. (2002).

1.1. Background

In this section theories, models and equations to which we will refer in the text, are presented as background, including a few notes to underline parts that are important for developing a model.

1.2. Theoretical approach to describe gully head development by runoff

Already in the seventies, Patton and Schumm (1975) and Begin and Schumm (1979) began modelling gully erosion as a threshold process and suggested that an equation defining such threshold could be derived from the fact that concentrated overland flow should produce flow shear stresses in excess of a critical value to erode a gully channel. This approach was further developed by Montgomery and Dietrich (1994). The starting point is that the flow shear stress (τ_f) produced by runoff must exceed a threshold soil shear resistance (τ_{soil}):

$$\tau_f = \rho_f \mathrm{ghsin}\gamma \approx \rho_f \mathrm{ghtan}\gamma \geq \tau_{\mathrm{soil}} \quad (1)$$

where ρ_f is the fluid density, g is acceleration due to gravity, h is flow depth (or hydraulic radius), and γ is slope angle of the soil surface. Note that in the original shear stress equation sinγ is used whereas in many studies flow shear stress is calculated using tanγ which can substitute the sinus only at low slope angles ($\gamma \leq 15°$). At steeper slope angles this may cause significant errors when calculating τ_f.

The final expression was:

$$sa^b \geq k \quad \text{or} \quad s \geq ka^{-b} \quad (2a)$$

where s is the slope gradient of the soil surface near the gully head ($s = \tan\gamma$), α is the area (A) of the catchment draining towards the gully head per unit of contour length and k is a constant which depends on local climate (rainfall), soil and land use (reflecting water infiltration rate, soil shear strength and hydraulic roughness). Eq. (2a) was derived transforming h into Q using the Manning (turbulent case) and Darcy-Weisbach (laminar case) equations. It assumes that runoff discharge (Q) at the outlet of the drainage area is linearly related to A and that Q is at steady state:

$$A\,(R\text{-}I) = Q \quad (3)$$

where R is rainfall intensity (constant) and I is infiltration rate (constant). Eq. (3) is valid only if the entire catchment area is contributing runoff to the gully head, i.e. if the entire area is hydraulically connected to the gully head, which is not always the case particularly for large catchment areas. The term ($R - I$) is obviously implicitly present in Eq. (2a) as it is included in the constant k (which consequently varies with rainstorm intensity or, more precisely, peak runoff discharge).

Montgomery and Dietrich (1994) assumed that the contour line length at the outlet of the catchment equals unity since they did not introduce the concentrated flow width at the gully head explicitly into Eq. (2a). All subsequent studies, apart from a few exceptions (e.g. Prosser and Winchester, 1996), always used A instead of a when defining the topographic threshold for gully heads. This has consequences that will be discussed later. For now we will use Eqs. (2a) and(2b) rewritten by substituting a by A (ha) as this is usually done in most studies:

$$sA^b \geq k \quad \text{or} \quad s \geq kA^{-b} \quad (2b)$$

Montgomery and Dietrich (1994) predicted b to vary between 0.5 and 0.857 corresponding to supercritical laminar flow and rough turbulent flow conditions respectively.

1.3. Interactions between vegetation, soil, soil surface characteristics, sediment load and resistance to soil erosion by concentrated flow

Vegetation is very important in controlling both the forces exerted by overland flow and the resistance to particle entrainment offered by the soil. This was made clear in many studies. Examples are the crop factor of the USLE-RUSLE type of soil loss models (Renard et al., 1997) and the plant architecture routine of the EUROSEM model (Morgan et al., 1998). More general studies evidenced these interactions (Bryan, 2000) while others tried to link the vegetation effects on gully erosion to data extracted from satellite imagery (Anh, 2009). First, vegetation increases the surface storage of rain water because it can more than double the total surface to be wetted before drops can wet the soil and accumulate on the soil surface. Vegetation protects the soil surface from drop impact and retards soil surface sealing. Soil aggregates are more stable if organic matter is present in the soil, which is usually more abundant under (permanent) vegetation cover. Plant roots increase macroporosity and hence also infiltration capacity. Furthermore, vegetation increases friction to overland flow, decreasing runoff velocity and absorbing part of the flow energy. On the other hand, roots increase the resistance of the topsoil to flow detachment (De Baets et al., 2007) which is equivalent to increasing soil cohesion (De Baets et al., 2008; Torri et al., 2013). The increase of soil resistance with root density (0–15 kg/m^3) is initially very close to a power law and corresponds to an increase in soil cohesion at saturation of 4 to 8 kPa (measured using a pocket torvane, see Brunori et al., 1989; De Baets et al., 2008). This brings the soil to an almost non-erodible condition. Hence, with increasing vegetation density and moving from cropland to grassland and further to forest we expect an increase in soil resistance to concentrated flow erosion and a decrease of runoff discharge during a given rainfall event.

In order to study the effects of vegetation on topographic threshold conditions for gully head development we will use the NRCS runoff curve number method (CN method, Hawkins et al., 2009). In the next section we summarise the main equations and units we use in this study.

1.4. NRCS Curve number method

The basic equation for the runoff Curve Number method is:

$$Q = \frac{(P - \lambda S_\lambda)^2}{P + (1-\lambda)S_\lambda} \quad (4)$$

where Q is daily runoff (mm), P is the corresponding daily rainfall (mm), S_λ (mm) is the maximum potential losses to runoff, and λ is the fraction of. S_λ which represents the initial abstraction. S_λ is a storage index, a measure of the catchment hydrological response. It is simply calculated once the Curve Number (CN) is defined using tables describing various field conditions where land use and hydrologic soil groups are the two main inputs. The basic equation was first derived for $\lambda = 0.20$ i.e.:

$$S_{0.20} = 25.4\left[\frac{1000}{CN} - 10\right] \quad (5)$$

More recent studies suggest a much lower value for λ: Hawkins et al. (2009) proposed $\lambda = 0.05$, while Mishra and Singh (1999) suggested $\lambda = 0.00$. We will follow Hawkins et al. (2009) suggestions. Hence $S_{0.20}$ was transformed into $S_{0.05}$ using the equation (where both S-values are expressed in mm):

$$S_{0.05} = 0.819 S_{0.20}{}^{1.15} \tag{6}$$

1.5. Empirical equations governing concentrated flow erosion

Flow width (w) is a variable that will reveal its importance later. An equation is needed for estimating w as it is never given in the various studies relative to the gully head topographical threshold (from Patton and Schumm, 1975, till Verachtert et al., 2010). During the last 20–25 years empirical evidence indicates that a set of equations, similar to the channel geometry equations first proposed for river channels (see Ferguson, 1986, for a review), are also valid for rills and gullies with a few modifications (e.g. Nachtergaele et al., 2002; Salvador Sanchis et al., 2009). Gully channel width (w) can be predicted using the equation (Torri et al., 2006; Salvador Sanchis et al., 2009):

$$w = \chi \left(\frac{Q}{Q_0}\right)^{\alpha} \tag{7}$$

where χ and Q_0 are empirical constants and $\alpha = 0.534(1 - 0.354e^{-2.55w})$. For $w \geq 0.8$m the exponent becomes constant and Eq. (7) becomes:

$$w = k_w Q^{0.534,} \quad with \quad k_w = \frac{\chi}{Q_0^{0.534}} \tag{8}$$

Now we can explicitly write the following relationship linking the catchment area per unit of contour length a to the catchment area A taking Eqs. (3) and (5) into account:

$$a = \frac{A}{w} = \frac{A}{k_w Q^{0.534}} = \frac{A}{k_w [(R-I)A]^{0.534}} = \frac{A^{0.466}}{k_w (R-I)^{0.534}} \tag{9}$$

2. Materials and methods

All papers analysed in this study deal with gully heads produced by concentrated overland flow erosion. Among these subsets of gully heads we have excluded all those whose position in the landscape could have been influenced by the presence of roads (e.g. Nyssen et al., 2002).

The studies examined in this paper are listed in Table 1 subdivided per continent and country. Each study proposed a topographic threshold line (s–A relation, Eq. (2b)) between gullied and non-gullied zones characterised by its own k and b values. The threshold line was then defined in different ways: calculating a best fitting s–A line and then translating it to pass through the lowermost data points, or directly using the lowermost data, proposing a threshold line usually more inclined than the one passing through the data set. This procedure results from the usually small number of data that could be considered to be a good estimation of the topographic threshold situation. This approach is somewhat arbitrary, very close to a by-eye fitting, hence not robust but it is also the only one that can be followed given the scarcity of data. These data are reported in Tab.1 after expressing all of them in the same units (A in ha, s in m/m), with slope (s) as the dependent variable (Eq. (2b)). The most difficult cases occurred when the authors calculated $A = f(s)$ instead than $s = g(A)$, the latter being the most commonly used representation of threshold data and the one adopted here. In some cases we had to recalculate the trend lines after the change of axes. Table 1 also contains two columns reporting the threshold coefficient (k) that we calculated for two pre-defined values of the exponent (b). For achieving all these we re-digitalised the field data for many data sets, for others we used data reported in the papers (in tables). In all cases we positioned the threshold line between the lowermost points.

Examples of a few data sets representing topographic thresholds for gully heads are shown in Fig. 1. Also indicated are examples of threshold lines for the two pre-defined b-values. Fig. 1 illustrates some of the more scattered (weakest) data-sets as well as different environmental conditions, both in terms of location, land use and climate. The discussion of how to analyse these data is given later.

3. Data analysis and discussion

3.1. Critical review of literature

The runoff-generated gully head data reviewed in this paper come from every continent although the majority comes from Europe with only one study from South America (Brazil). Data sets belonging to different studies are heterogeneous because the methodologies used to assess the slope–area relationships were not always the same and because the data are presented in a synthetic way, which usually does not allow for elaborations different from the ones proposed by the authors. Some studies (e.g. Morgan and Mngomezulu, 2003) used the average slope gradient of the gully head catchment (GHC) instead of the slope gradient of the soil surface near the gully head (see Nyssen et al., 2002, for a proper definition). Others used the slope gradient of the valley bottom (e.g. Boardman, 1992). Some used a different approach with different definitions of the variables, such as basin area per concentrated flow width, i.e. area/length (e.g. Prosser and Abernethy, 1996; Prosser and Winchester, 1996). Others used as a measure of slope the local elevation difference divided by the pixel size or the GHC area was reported as number of pixels. In some cases (e.g. Hancock and Evans, 2006) it was possible to transform the data into our units. Slope gradient was also given as the gradient of the channel bed at the gully head, while gullies were caused by seepage and overland flow, giving rise to a scattered threshold plot (Imaizumi et al., 2010). Others had very few data for drawing a threshold line (e.g. Casali' et al., 1999). Hence these papers were not used further and only those studies reporting field data on soil surface slope gradient(s) at or near the gully head versus GHC area (A) were kept and analysed (Table 1a–c). The number of slope–area relationships found or recalculated from the literature is listed in Table 1 (63 (b, k)-couples; Eq. (2b)). Even in this subsets some of the data could not be directly used because the calculated regression line (s–A) was the reverse of Eq. (2), with s as independent variable (e.g. Montgomery and Dietrich, 1994). When possible, regressions were inverted (statistical inverse). Otherwise they were recalculated when it was clear where to draw the threshold line. Descriptions of land use in the GHC were sometimes vague or ambiguous. Also these data were used where appropriate but not in all the elaborations. Hence the number of analysed studies differs for different definitions and elaborations.

When we come to the description of the studied areas, we have a clear picture of the landscape but usually there are no or limited data available to quantify the characteristics of land use type relevant for the processes of overland flow generation and gully incision. The various relevant characteristics, such as rock fragment content in the top soil and vegetation cover, are often impossible to estimate, and only subdivisions between very broad classes (such as low and high) was in some cases possible. When vegetation is made up of different types of plants it is possible to learn that trees are scattered or shrubs are dense but at the same time they may be burnt frequently or overgrazed. Very few papers report these type of data with quantitative details (e.g. Vandekerckhove et al., 2000).

Let us now try to identify the possible sources of scatter in single data sets due to factors not explicitly considered by the authors. The gully-heads which are grouped together are usually spatially close to each other but this is not necessarily ensuring that all the gully heads were

Table 1a
Geographical distribution of the studies reporting topographical threshold data for gully head formation by runoff in a) cropland, b) rangeland and pasture and c) forest and grassland. Also shown are the coefficient *k* and exponent *b* (Eq. (2b)) as given by the authors, as well as the coefficient *k* corresponding to two values of the exponent *b* (0.38, 0.5) as calculated in this study. na = not available, nc = not calculated.

Continent	Country	Location	Source	k	b	k b = 0.38	k b = 0.5
Africa	Uganda	Upper-Rwizi catchment	Hamels (2011)	0.19	0.14	0.10	0.08
	Tanzania	Makonde high Plateau	Achten et al. (2008)	0.07	0.80	0.04	0.05
	Tanzania	Makonde dissected plains	Achten et al. (2008)	na	na	0.02	0.02
	Tanzania	Inland Plateau	Achten et al. (2008)	0.07	0.36	0.05	0.04
Americas	Brazil	Sao Paulo State, Sao Pedro	De Araujo (2011)	0.02	0.38	0.03	0.02
	Brazil	Sao Paulo State, Sao Pedro	De Araujo (2011)	0.01	0.44	0.02	0.01
Asia	China	Inner Mongolia, Baochang	Cheng et al. (2006)	0.06	0.38	0.06	0.06
	China	Loess Plateau	Cheng et al. (2007)	0.06	0.30	0.04	0.02
	China	Loess Plateau	Wu & Cheng (2005)	0.18	0.24	0.13	0.10
	Iran	Boushehr Samal catchment	Nazari Samani et al. (2009)	na	na	0.002	0.001
	Israel	Yehezkel catchment	Svoray and Markovitch (2009)	0.005	0.55	0.01	0.01
Europe	Belgium	Vlaams Brabant	Vandaele et al. (1996)	0.08	0.40	0.08	0.06
	Belgium	Vlaams Brabant	Vandaele et al. (1996)	0.03	0.38	0.03	0.02
	Belgium	Vlaams Brabant	Nachtergaele et al. (2001a)	0.03	0.38	0.04	0.04
	Belgium	Vlaams Brabant	Knapen and Poesen, 2010	0.05	0.40	0.04	0.04
	Belgium	Flemish Ardennes	Verachtert et al. (2010)	0.02	0.12	0.02	0.02
	France	Ligescourt-Somme	IGN (1983)	0.06	0.40	0.06	0.06
	Portugal	Alentejo	Vandaele et al. (1996)	0.02	0.35	0.02	0.02
	Portugal	Bragança, Rio Sabor	Vandekerckhove et al. (1998; 2000)	0.10	0.23	0.03	0.02
	Portugal	Alentejo	Vandekerckhove et al. (2000)	na	na	0.04	0.03
	Portugal	Alentejo	Nachtergaele et al. (2001b).	0.09	0.29	0.04	0.05
	Spain	Cerro Tonosa	Vandekerckhove et al. (2000)	0.23	0.10	0.06	0.03
	Spain	Rambla Chortal	Vandekerckhove et al. (1998; 2000)	0.15	0.14	0.05	0.06
	Spain	Guadalentin	Nachtergaele et al. (2001b).	0.15	0.13	0.03	0.02

Table 1b
Geographical distribution of the studies reporting topographical threshold data for gully head formation by runoff in a) cropland, b) rangeland and pasture and c) forest and grassland. Also shown are the coefficient *k* and exponent *b* (Eq. (2b)) as given by the authors, as well as the coefficient *k* corresponding to two values of the exponent *b* (0.38, 0.5) as calculated in this study. na = not available, nc = not calculated.

Continent	Country	Location	Source	k	b	k b = 0.38	k b = 0.5
Africa	Ethiopia	Tembien highland, area A	Nyssen et al. (2002)	0.26	0.50	0.32	0.36
	Ethiopia	Tembien highland, area B	Nyssen et al. (2002)	0.26	0.50	0.20	0.23
	Uganda	Upper-Rwizi catchment	Hamels (2011)	0.31	0.09	0.43	0.43
Americas	USA	Arizona – Grand Canyon	Pederson et al. (2006)	0.02	0.47	0.02	0.02
	USA	Nevada, Northern Humboldt Range	Montgomery and Dietrich (1994)	0.09	0.50	0.10	0.10
	USA	California, Standford Hills	Montgomery and Dietrich (1994)	0.18	0.50	0.19	0.19
	USA	Colorado	Patton and Schumm (1975)	0.16	0.26	nc	nc
Asia	Iran	Boushehr – Samal catchment	Nazari Samani and al. (2009)	0.03	0.0002	0.01	0.004
Australasia	Australia	New South–Wales	Munoz-Robles et al. (2010)	0.02	0.36	0.02	0.02
	New Zealand	N. Island, Waiapu basin	Parkner et al. (2006)	0.43	0.23	0.32	0.32
Europe	Greece	Lesvos Greece (VC < 0.8)	Vandekerckhove et al. (2000)	0.29	0.14	0.06	0.04
		Lesvos Greece (VC > 0.8)	Vandekerckhove et al. (2000)	0.29	0.14	0.12	0.07
	Italy	Sardinia	Zucca et al. (2006)	0.18	0.20	0.04	0.02
	Portugal	Alentejo	Vandekerckhove et al. (2000)	0.08	0.41	0.07	0.05
	Spain	Sierra de Gata (VC < 0.15)	Vandekerckhove et al., 2000	0.10	0.27	0.05	0.04
	Spain	Sierra de Gata (VC > 0.15)	Vandekerckhove et al. (2000)	0.10	0.27	0.06	0.05
	Spain	Parapapuños catchment, Càceres	Gomez-Gutierrez et al. (2009a,b)	0.09	0.41	0.07	0.09
	Spain	Cantabrian cordillera, shallow channels	Menendez-Duarte et al. (2007)	0.46	0.18	0.31	0.28
	Spain	Cantabrian cordillera, deep channels	Menendez-Duarte et al. (2007)	0.46	0.18	0.38	0.37

Table 1c
Geographical distribution of the studies reporting topographical threshold data for gully head formation by runoff in a) cropland, b) rangeland and pasture and c) forest and grassland. Also shown are the coefficient *k* and exponent *b* (Eq. (2b)) as given by the authors, as well as the coefficient *k* corresponding to two values of the exponent *b* (0.38, 0.5) as calculated in this study. na = not available, nc = not calculated.

Continent	Country	Location	Source	k	b	k b = 0.38	k b = 0.5
Americas	USA	Montana	Gabet and Bookter (2008)	0.60	0.40	0.40	0.48
		Oregon, Coos Bay	Montgomery and Dietrich (1994)	0.25	0.50	0.23	0.22
		California, Southern Sierra Nevada	Montgomery and Dietrich (1994)	0.40	0.50	0.50	0.40
		California, Tennessee Valley	Montgomery and Dietrich (1994)	*0.20*	*0.50*	*0.30*	*0.25*
Asia	Japan	Higashi-gouchi catchment, low terrain roughness	Imaizumi et al. (2010)	0.71	0.43	nc	nc
		Higashi-gouchi catchment, high terrain roughness	Imaizumi et al. (2010)	0.75	1.61	nc	nc
	Taiwan	Shitou	Chen et al. (2009)	na	na	0.41	0.30
	Thailand	Chiang Mai, Pang Khum	McNamara et al. (2006)	0.45	0.50	0.40	0.30
Australasia	Australia	Northen Territory, Tin Camp Creek, Arnhem Land	Hancock and Evans (2006)	na	0.28	0.47	0.40
	New Zealand	N. Island, Waipu basin – gully complex	Parkner et al. (2006)	na	na	0.80	1.03
	New Zealand	N. Island, Waipu basin – forest	Parkner et al. (2006)	na	na	1.10	1.70
	New Zealand	N.Island, Mangaoporo catchment – gully complex	Parkner et al. (2007)	0.79	0.21	1.10	1.30
	New Zealand	N.Island, Mangaoporo catchment – gully strike	Parkner et al. (2007)	0.86	0.20	1.00	1.10
	New Zealand	N.Island, Mangaoporo catchment – gully joint	Parkner et al. (2007)	na	na	0.83	0.90

generated during the same rainstorm and even less that rainfall intensity was the same over all the gully-head catchments. Some gully heads may have been formed in the recorded position by one event or by more events and this certainly makes a difference (Vandekerckhove et al., 2000). Moreover, in cropland the size of the drainage area may change over time due to tillage operations and soil structural changes during rainfall (e.g. Souchère et al., 1998; Takken et al., 2001). Hence, gully-head positions are not always the response of the local topography to a given situation: both local rainfall history and boundary conditions may be different. This explains part of the data scatter.

Fig. 1 shows the usual way in which threshold data are presented: i.e. a double logarithmic plot of slope gradient (s; ordinate axis) at each gully head as a function of the GHC area (A; abscissa). In Fig. 1a the first datum from the left was not used for drawing trends because it was well separated by all the others, i.e. it was considered to be an outlier. Fig. 1b also shows an outlier at about position ($A = 0.045$; $s = 0.11$). Fig. 1b shows data in the region $A > 1$ha: as gully heads were observed at the same slope gradient ($s = 0.1$) for A-values much smaller than 1ha, the s-data for $A > 1$ha are considered to plot above the gully head threshold. The data corresponding to $A > 1$ha plot in a zone of the graph were gully-heads can form (i.e. they plot well above the corresponding threshold line). The same is true for the 4 data plotted in Fig. 1c corresponding to 0.05 ha $< A <$ 3 ha. Hence, threshold lines can be poorly estimated because of the small number of observations. This underlines the main weakness of most data sets and the corresponding threshold relations reported so far which hampers a very detailed analysis. So only if the various characteristics and trends that this review attempts to reveal are coherent and self-sustaining, significant conclusions can be drawn.

3.2. Data analysis

In order to explore the published data on topographic thresholds, land use was subdivided into three broad classes: cropland, rangeland/pasture and forest/grassland (Tab.1). For cropland we did not differentiate between tree crops (e.g. bananas or almond groves) and wheat or vegetables. Some of the pastures could probably be considered more similar to grassland than to rangeland, making the distinction between these two classes vague. Hence, this classification is to some extent arbitrary but the main differences in topographic thresholds corresponding to these classes are reflected by the averages and median of the observed data sets.

Table 2 shows the average coefficient k and the exponent b calculated for the s–A values reported in the literature (Table 1). Let us first limit ourselves to examine the exponent values reported for all the data. At first sight the exponent values are usually lower than the lowermost value suggested by Montgomery and Dietrich (1994; $0.5 < b < 0.857$). As reported in Table 2, the exponent b varies slightly with land use while the median coefficient k increases from cropland to forest by a factor 7. Hence, as a first approximation we can state that k expresses the effects of land use on gully head development, while b is substantially constant and less than that predicted by Montgomery and Dietrich (1994). Such a difference indicates that either the proposed model has some flaws or that the data are not correct. The large scatter in both exponents and coefficients suggests that also on-site observations in the various studies may contain some flaws.

One flaw is due to the assumption that the area draining to the gully head is the area of the entire catchment. Let us suppose that we have a drainage area (A) which receives rains at constant rate R_C for a given time t_C. Be A_C the effective area draining to the gully head at time t_C. As gully head locations are surveyed after the storm, we will measure the right slope gradient s_c but we will attribute the area A (not A_C) to the entire contributing catchment:

$$s_C \geq kA^{-b}, \quad \text{and} \quad A \geq A_C \tag{9}$$

We will plot the datum in a s–A diagram to the right of the position in which it should have been drawn. Actually, we will plot n data points, with $n > 1$, corresponding to n gully heads of area B_j larger than Ac: (Bj, s_C), with $j = 1\ldots n$ (as shown and already discussed for Fig. 1a,b,c), all plotting to the right of the correct position. As this error is not balanced by an error in the opposite direction it causes a bias which decreases the value of the exponent. To reduce the effect of this bias we should use the data corresponding to small GHC areas (A) because those are the areas where the assumption that the entire drainage area is contributing overland flow has a higher probability of being met. Rainfall intensity–duration–frequency curves (Takara and Minh Nhat, 2008) show that the more intense the rain, the lower its chances of falling uniformly over larger areas and lasting long enough to connect the whole drainage area to its outlet (Bracken and Croke, 2007). This is obviously linked to the increased duration of concentration time needed for runoff originating at the catchment divide to reach the outlet (NRCS, 1986; Bracken and Croke, 2007; Reaney et al., 2007). This observation indicates that we should look critically at the reported gully head data corresponding to large A-values. An example is shown by the data plotted in Fig. 1d: the smallest GHC area is larger than 80ha, and all the other gully heads have $A > 250$ha. Therefore, this data set was not included in the analysis. When those precautions are not taken into account the risk of underestimating the exponent b is fairly large. As a consequence, we can expect the true b-values to be somewhat larger than the average ones reported in Table 2. Furthermore, this excludes the use of regression equations using the whole data set because they will be partly based on biassed data.

The exponent b (average and median) does not show a trend with the land use classes, which suggests that b can be represented by a constant value. This offers the possibility of simplifying the threshold Eq. (2b) and develop a simple model based on a constant b-value. Therefore, we explored the collected data sets to see whether a constant b-value allows us developing simple formula for evaluating gully head positions in differently managed landscapes. The decision about which b-values to explore is arbitrary as there are no good reasons to select a particular value. So we decided to use the following two values: $b = 0.38$ and $b = 0.5$. The latter was chosen because this is the lower

Table 2
Topographic threshold values (k) for gully head development under different land use classes. Average coefficient k and exponent b (Eq. (2b)) are calculated for literature values corresponding to various land use classes. All data are reported as gully head catchment areas (A, ha) and slope (s, m m^{-1}). *n obs.* is the number of studies from which a critical s–A relation could be calculated.

	Cropland		Rangeland, pasture		Forest, grassland		All land use classes	
	k	b	k	b	k	b	k	b
Average	0.080	0.329	0.201	0.295	0.557	0.391	0.214	0.327
St dev	0.065	0.164	0.145	0.158	0.241	0.128	0.222	0.156
Median	0.060	0.360	0.180	0.270	0.600	0.430	0.150	0.360
N. obs	21	21	19	19	9	9	49	49

Table 3
Values of the coefficient k (Eq. (2b)), calculated keeping the exponent b constant (i.e. $b = 0.38$; $b = 0.50$), for different land use classes. N. obs. is the number of studies from which a threshold s–A relation could be calculated.

	Cropland	Rangeland, pasture	Forest, grassland
$b = 0.38$			
Average	0.043	0.154	0.628
St dev	0.029	0.139	0.318
Median	0.040	0.085	0.485
N. Obs	24	18	12
$b = 0.5$			
Average	0.037	0.149	0.698
St dev	0.024	0.144	0.491
Median	0.030	0.080	0.440
N. obs	24	18	12

Table 4
Values of the coefficient k (Eq. (2b)), calculated keeping the exponent b constant (i.e. $b = 0.38$; $b = 0.50$), for cropland in the Belgian Loess and the Chinese loess plateau.

	Belgium	China
b = 0.38		
Average	0.048	0.040
St. dev.	0.022	0.016
b = 0.5		
Average	0.040	0.061
St. dev.	0.016	0.055

b-value still compatible with the range proposed by Montgomery and Dietrich (1994). The former is the value proposed by Nachtergaele et al. (2001a) which is larger than the mean and median b-values reported in Table 2 under the heading "all". A b-value of 0.38–0.40 was also confirmed by later studies (e.g. Knapen and Poesen, 2010). The cited studies are based on observations made shortly after the rainstorm that caused the incision of the gully channel.

The results are summarised in Table 3. The k coefficient (i.e. the threshold that needs to be exceeded for a gully head to form) increases moving from tilled soils exposed to runoff (i.e. on cropland) to soils protected by a permanent vegetation cover from erosion (i.e. rangeland, pasture, forest, grassland). Hence, assuming a constant exponent (b) does not change the general trend of the coefficient (k). We can then use subsets of data and compare coefficients to detect further sources of variation.

Initially we began with a subset relative to soils developed on loess: here we have data from Belgium and from China, a temperate cool climate in central Europe versus a semiarid cold continental climate (Table 4). We removed the Verachtert et al. (2010) data from the Belgian set because it was relative to an area where piping was quite active, decreasing the soil resistance to gully-headcut retreat. Nevertheless the Belgian loess appears more prone to gully development than the Chinese loess. This may be an effect of climate (from humid temperate to cold semiarid) or of intrinsic loess properties (e.g. clay mineralogy; Mermut et al., 1995; Römkens et al., 1995). As there are only a few data, we cannot draw final conclusions.

This apparent difference can be examined further by enlarging the comparison to a wider range of studied environments. For this we examine the differences in the threshold coefficient (k) in different climate zones under the same land use class. Only the k-values for cropland are used since we have the largest number of s–A datasets for this land use class. Data are shown in Table 5 and if there are differences in k-values they are not very clear and do not seem to behave as Salvador Sanchis et al. (2008) showed this to be the case for the soil erodibility factor of the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997). Salvador Sanchis et al. (2009) found that the Mediterranean and the tropical soil groups behave similarly among them and differently from the soils in cooler climates. The peak of soil erodibility was found in cooler climates similar to conditions corresponding to regions with loess-derived soils. Here instead, loess-derived soils seem to be more resistant to gully incision than soils in Mediterranean or tropical climates. As already noted, among the loess-derived soils in Belgium one of the studied areas was affected by piping because of an underlying clay layer inducing temporary water tables (Verachtert et al., 2010). The threshold coefficient for piping from this study is actually 0.47 ($b = 0.38$) or 0.5 ($b = 0.5$) times the average gully threshold value for loess-derived soils that are not affected by piping. If this value is included in the calculation of the average k-value, it is enough to make loess soils as erodible as most of the others.

Table 5
Values of the coefficient k (Eq. (2b)), calculated keeping the exponent b constant (i.e. $b = 0.38$; $b = 0.50$), for cropland in different climates. N obs. is the number of studies from which a threshold s–A relation could be calculated.

	Mediterranean	Temperate cool (Central Europe — loess belt)	Semiarid continental (loess plateau — China)	Tropics (Africa and Brazil)
b = 0.38				
Average	0.040	0.050	0.085	0.042
St. dev.	0.016	0.020	0.064	0.031
b = 0.5				
Average	0.033	0.043	0.061	0.036
St. dev.	0.020	0.016	0.055	0.027
N. obs	9	5	3	6

Table 6
Characteristics of Mediterranean study areas reported by Vandekerckhove et al. (2000), and corresponding values of the coefficient k (Eq. (2b)), calculated keeping the exponent b constant (i.e. b = 0.38; b = 0.50), VC is vegetation cover; RFC is surface cover by rock fragments. Cropland is assumed to have been incised by concentrated flow soon after seedbed preparation or when the crop cover was still very small. Cover by almond trees is considered to be ineffective for erosion control as soil erosion is caused by concentrated overland flow and almond roots are kept at more than 10 cm soil depth by continuous tilling (sometimes over 6 times per year).

Study area	Land use	VC (fraction)	RFSC (fraction)	k (b = 0.38)	k (b = 0.5)
Sierra de Gata	Rangeland	0.105	0.56	0.051	0.04
Sierra de Gata	Rangeland	0.425	0.56	0.061	0.051
Lesvos	Rangeland	0.55	0.2	0.06	0.04
Lesvos	Rangeland	0.85	0.2	0.115	0.07
Alentejo	Rangeland	0.68	0.58	0.065	0.05
N. Portugal Bragança	Cropland	0	0.15	0.031	0.023
Cerro Tonosa	Cropland	0	0.93	0.056	0.03
Rambla Chortal	Cropland	0	0.93	0.04	0.062
Alentejo Portugal	Cropland	0	0	0.04	0.03

We then examined a subset of data from different croplands (Vandekerckhove et al., 2000). From this analysis 9 threshold coefficients were calculated for 6 study areas, all belonging to a semiarid Mediterranean climate (Table 6). These data describe a sort of ideal range from cropland through overgrazed to grazed pasture with increasing permanent vegetation cover (VC). Also surface rock fragment cover (RFC) is reported in this study. These data are not associated with particular gully heads but describe the study areas in a more precise way than usual. On the basis of the data in Table 6, models can be proposed in order to define if some significant relations can be found between the threshold coefficients (k) and the reported physical characteristics of the study areas. The general regression model found is:

$$k = c_1 e^{\lfloor c_{v1}(VC - c_{v0}) + c_{r1}(RFC - c_{r0}) \rfloor} + c_4 \tag{10}$$

where c_1, c_{v1}, c_{v0}, c_{r1}, c_{r0} and c_4 are empirical coefficients and the two terms $(VC - c_{v0})$, $(RFC - c_{r0})$ are nil when the differences are negative. The exponential form is accidental: linear or power models gave poorer results. The two subtractive constants at the exponent are based on the fact that in previous studies it was found that rock fragment cover below 10% does hardly affect soil erodibility significantly (Poesen et al., 1994; Borselli et al., 2012). Hence $c_{r0} = 0.1$ was imposed. The same may be true for a very small vegetation cover but vegetation cover in semiarid environments is usually in the form of patches rather than being homogeneously distributed. So $c_{v0} = 0.2$ was arbitrarily imposed.

The results of a simple regression analysis for the two exponents b yield the data reported in Table 7. Given the small number of study sites, the statistics does not produce significant results. This analysis only shows that the threshold coefficient k can be interpreted at a

Table 7
Empirical coefficients for the regression model (Eq. (10)) using data reported in Table 6 and for two b-values (Eq. (2b)).

	c_1	c_{v1}	c_{v0}	c_{r1}	c_{r0}	c_4	r^2
b = 0.38	0.0065	3.5	0.2	0.8	0.1	0.034	0.811
b = 0.5	0.0015	3.5	0	1.8	0.1	0.034	0.474

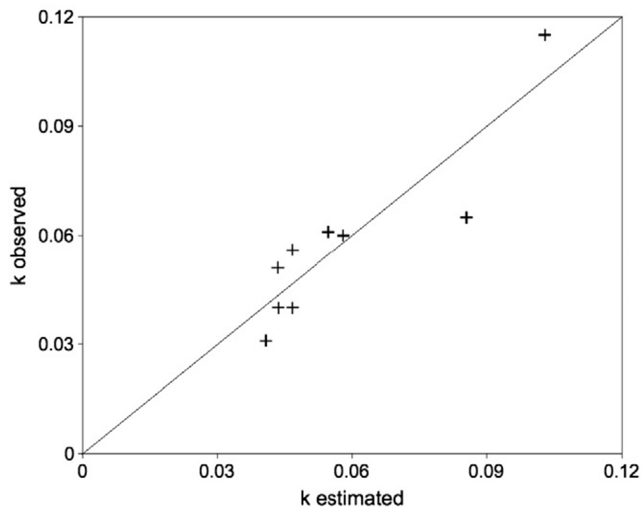

Fig. 2. Observed versus estimated (Eq. (10)) threshold coefficient k at constant exponent $b = 0.38$ for a small subset of gully data collected in Mediterranean environments. (Vandekerckhove et al., 2000).

finer scale than just that of the main land use classes (Table 2). Particularly the results for $b = 0.38$ offers hope that with a better and larger data set, more reliable values for the coefficients can be obtained (see Fig. 2, relative to b = 0.38, which was the most successful of the two b-values investigated). Given the small number of data that can be studied in more detail, it is not worthwhile trying better models because at the moment they can only demonstrate the need for more detailed studies that are worth doing. At this stage, such an analysis cannot produce results adequate for prediction or scenario analysis.

3.3. The overall effects of vegetation, land management and soil

The description of the studied sites is not sufficiently detailed to allow a more in-depth analysis. Yet the analysis is sufficient for a general evaluation of the local situation. Therefore we can draw conclusions about the effects of the overall status of the soil/land use system on the topographic threshold for gully head development. In some study sites we can define the soil hydrological conditions, presuming that infiltration is high, medium or low, probably even deciding something about an expected soil shear strength, may be assessing soil erodibility in terms of low to high. For instance if there is a permanent vegetation cover exceeding 5–15%, then soil resistance to flow entrainment is locally affected positively, and also infiltration is somewhat increased, especially during high rainfall intensities. If the study area has cropland, gullies are generally ephemeral on soils with minimum infiltration and low resistance to erosion as well as low structural stability, especially in arid and semiarid areas. If there is some model that incorporates these considerations into a numerical code, we may attempt a more general analysis than has been done so far. The RUSLE (Renard et al., 1997) and its modifications present several tables that may assist us. Another alternative is the NRCS Runoff Curve Number Method (CN Method; Hawkins et al., 2009). Here we prefer the latter approach because the CN method predicts daily runoff depths, hence its use allows one to predict when it is most probable to have large runoff events, while RUSLE does not. Moreover, application of the RUSLE requires detailed information on crop management which is not provided in the papers on gully thresholds. The fact that the CN method offers immediately a support to our search is evident if we compare the threshold coefficient values (k) reported in Tables 2 and 3 with the average total rainfall abstraction value $S_{0.05}$ (Eq. (6)) for the land use classes. Results are shown in Fig. 3.

Based on this promising result, a careful analysis of land use and soil descriptions presented in the various studies (Table 1) was made and for each of the thresholds coefficients (k) it was possible to calculate a corresponding $S_{0.05}$ value. Before presenting the final results it is necessary to formulate a critical note: the way of classifying soil type and land use when applying the CN method involves some subjectivity which is intrinsic to the classifications. Elements too close to the boundary between successive classes cannot be easily classified. Fuzzy mathematics can help and can be implemented but it too introduces subjective elements in the forms and amplitudes of the fuzzy membership functions. Hence, given the type of data at hand and the uncertainty associated with them, we used averages of curve numbers calculated over the CN-values whose land use could correspond to the given description or the given list of land use types. Descriptions of a study site are often subjective and subjective is the way in which a series of qualifiers (such as "poor", "scarce", "good") are understood by readers. Also the relative importance of trees, bushes and grass are subjective. Only numerical data are sufficiently objective. Furthermore, each combination of land use class and soil hydrologic group does not define one single CN-value but an interval. The consequence is that one must be cautious because of the uncertainty due to the subjectivity that is introduced when attributing a CN-value to a specific k-value. The following results are a suggestion of an approach to follow rather than the production of a final result, which can be easily used for assessment, prediction and control of gully heads. This is something to bear in mind especially when confronted with apparently positive results. This is the reason why we decided to use all the data to demonstrate the possibility of the CN approach instead of splitting the dataset into two parts, one for establishing the relationships and a second for its validation: in both cases the relationships would have been influenced in the same way by our personal interpretation of the gully site descriptions.

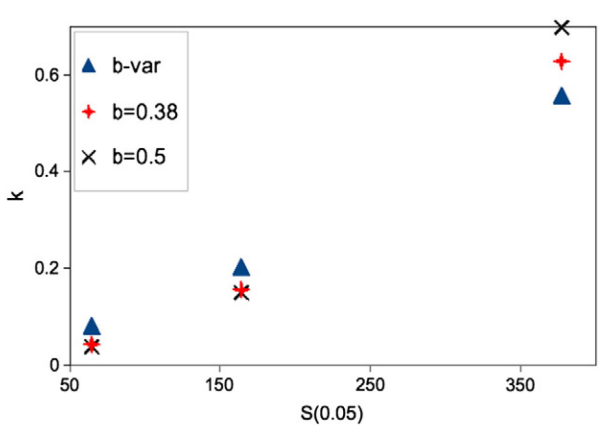

Fig. 3. Threshold coefficient (k; corresponding to three different values of the exponent b in Eq. (2a) and (2b)) varies proportionally to the total abstraction $S_{0.05}$ (Eq. (6)) estimated following the procedures of the NRCS CN method. The k-values correspond to the averages for the three land use classes (Tables 2 and 3).

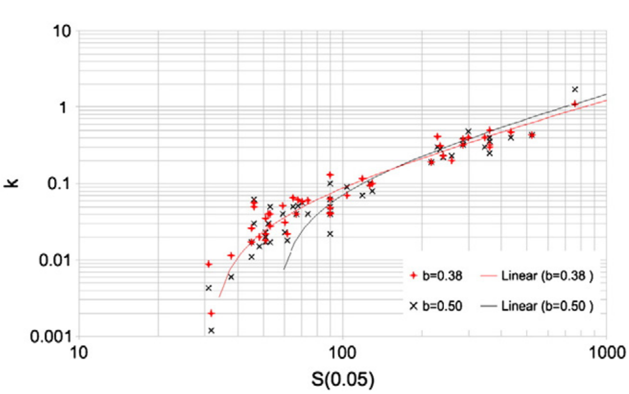

Fig. 4. Threshold coefficient (k; corresponding to two different values of the exponent b in Eqs. (2a) (2b)) as a function of the total abstraction $S_{0.05}$ (Eq. (6)) of the NRCS CN method for two fixed values of the exponent b.

The threshold values (k) corresponding to the variable exponent (b) were not examined because this exponent too needs to be predicted when we want to predict the threshold coefficient. Therefore, the results shown are relative only to the two constant b values. Trends between $S_{0.05}$ and k are plotted in Fig. 4.

The interpolating equations obtained are as follows:

$$b = 0.38, \quad k = 0.00127S_{0.05} - 0.040 \quad with \quad R^2 = 0.917, \quad n = 53 \tag{11a}$$

$$b = 0.50, \quad k = 0.00156S_{0.05} - 0.086 \quad with \quad R^2 = 0.806, \quad n = 53 \tag{11b}$$

The threshold coefficient for $b = 0.38$ can be better predicted than that corresponding to $b = 0.5$ because it is characterised by a larger R^2-value. Therefore we will mainly refer to the case $b = 0.38$ in the following sections.

The topographical threshold equation for gully-heads eroded by concentrated overland flow erosion can be expanded as follows, when k is replaced by Eq. (11a):

$$s \geq (0.00127S_{0.05} - 0.040)cA^{-0.38} \tag{12}$$

where c is a parameter (function of other variables), whose value oscillates around unity. c represents other sources of variation of k which cannot be represented by $S_{0.05}$. We have already observed one situation in which we needed a correction: in the presence of piping (in central Belgium) the threshold value for gully head development is about half its expected value (based on other Belgian data, Table 1a). Piping is not described in the NRCS CN method so it needs to be added explicitly. At present, based on only one study (Verachtert et al., 2010) we might suggest that

$$c = c_p \in [0.1; 0.4] \tag{13}$$

where c_p represents a first evaluation of the effect of piping.

The use of an interval of possible c_p-values is explained by the fact that these gullies were observed in cropland and pasture. The factor c_p, such as any other c-factor, was calculated as the ratio between the measured value and the predicted one using, in this case, Eq. (10). This is only an example and others can be found in Table 1 (e.g., Parkner et al., 2006, 2007 for gully joint and gully complex).

Another soil characteristic which is rarely taken into account in the NRCS CN method is rock fragment cover (RFC) of the soil which appears only in the definition of the texture of one hydrological soil group (group A). RFC affects the infiltration rate (Poesen et al., 1990) so its presence in one hydrologic soil group may be sufficient. This is not the case when we analyse soil resistance to flow detachment and entrainment: rock fragments usually increase the soil resistance to runoff erosion (Poesen et al., 1994, 1999; Borselli et al., 2012). This is an effect that $S_{0.05}$ cannot incorporate. On the contrary, $S_{0.05}$ can represent the effect of roots on increased erosion resistance because root density depends on vegetation type and density from which $S_{0.05}$ too depends. Also the effect of vegetation cover and of vegetation density is related to $S_{0.05}$, hence this parameter can also be a proxy for increased hydraulic resistance and for protection of the soil surface from raindrop impact. It can also be a proxy for expressing the decrease of flow transport capacity due to the reduced drop impact on overland flow (Kinnell and Risse, 1998). Part of the data scatter around the interpolating curve of Eq. (11a) (Fig. 4) can be explained by RFC. We can explore the effects to RFC using the Vandekerckhove et al. (2000) data subset. We compared surface rock fragment cover with the ratio between the measured k-value and the predicted one, which is a measure of the residuals of the interpolation Eq. (11a). Results of this analysis are shown in Fig. 5, where the ratio between the observed and the calculated k-value is shown to vary exponentially with rock fragment cover. This confirms that the NRCS CN method does not reflect this parameter and its effects on the total abstraction $S_{0.05}$.

Data plotted in Fig. 5 can be described using an exponential function which has a maximum when $RFC = 1$:

$$correctedvalue = \frac{observed}{predicted} = 0.69e^{1.2RFC}, \quad R^2 = 0.915, n = 9 \tag{14}$$

The value of the proportionality coefficient 0.69 tells us that generally the observed gully heads correspond to an average RFC close to 0.39 (when observation and predictions coincide).

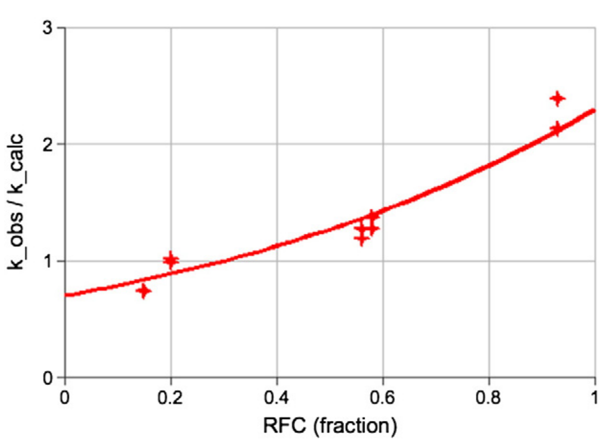

Fig. 5. Ratio between observed and calculated (Eq. (12)) k values (Eq. (2a) and (2b)) as a function of surface rock fragment cover (RFC) for the gully data subset by Vandekerckhove et al. (2000).

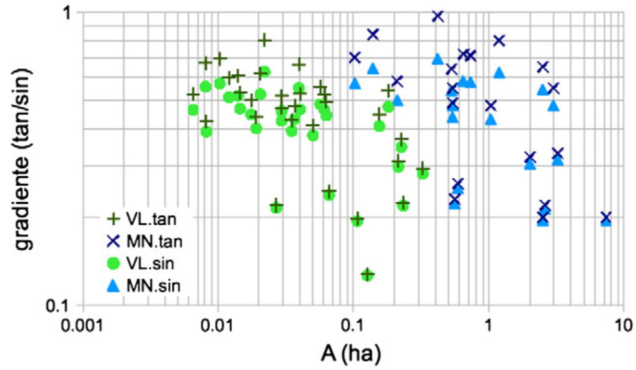

Fig. 6. The effect of using the more correct sinus as a measure of the slope gradient instead than the tangent is shown by the McNamara et al. (2006) data-set (MN) and the Vandekerckhove et al. (2000) Lesvos data-set (VL). As expected only gradients above 30% show differences. The effect on the threshold values is relatively small because it is determined by the locally lowest slope-values.

Table 8
k-values (Eq. (2b); for $b = 0.38$) obtained by using the sinus instead of the tangent of the slope gradient.

b = 0.38	k using tangent	k using sinus
Menéndez-Duarte et al., 2007	0.38	0.33
McNamara et al., 2006	0.40	0.30
Parkner et al., 2006	0.80	0.80
Parkner et al., 2006	1.10	1.05
Parkner et al., 2007	1.10	1.02
Parkner et al., 2007	1.00	0.90
Parkner et al., 2007	0.83	0.75

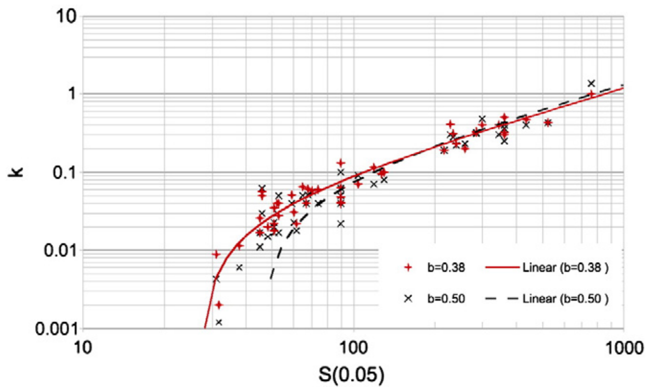

Fig. 7. Threshold coefficient as in Fig. 4. Now the sinus of gradient is used in calculations instead of the tangent.

If we apply this correction (Eq. (14)) to the k-values predicted by Eq. (11a) then the threshold equation can be rewritten as:

$$s \geq 0.69ce^{1.2RFC}(0.00127S_{0.05} - 0.040)A^{-0.38} \tag{15}$$

3.4. Tangent or sinus?

All the topographic data analysed in this study are affected by another bias, a sort of “river hydraulic bias”. In river hydraulics, river channel gradients are usually very small, typically in the order of a few parts per thousand and rarely reaching a few parts per hundred. Hence the local slope angle γ, when expressed in radians, is very close to both its tangent and its sinus. This is still true when the gradient grows close to $\gamma = 0.3rad$ or 16.7° because now the tangent is 0.29 and sinus is 0.287. At $\gamma = \pi/4rad$, i.e. 45° , tangent is 1 and sinus is 0.707. Now they are clearly different and the two will continue to diverge as tangent is infinite at $\pi/2$ while sinus is 1. This means that several basic equations must be rewritten because the approximation done in Eq. (1) does not hold for all the data sets, certainly not for the Parkner et al. (2007) data. Two examples are shown in Fig. 6: the threshold value of the McNamara et al. (2006) data-set is somewhat affected. The threshold condition of the Lesvos data-set (Vandekerckhove et al., 2000) is instead not modified using sinus instead of tangent of the slope angle (°). The effect of the approximation was clearly detectable only for some of the data sets as reported in Table 8.

The data affected by the change from tangent to sinus of the slope angle are all pertaining to the upper values of the k-range, hence they may affect Eq. (11a,b). Using the area (A-sinus) representation of the data (Fig. 7) we obtain even better relationships than Eq. (11a,b)):

$$b = 0.38, \quad k = 0.00124S_{0.05} - 0.037, \quad \text{with} \quad R^2 = 0.923, \; n = 53 \tag{16a}$$

$$b = 0.50, \quad k = 0.00145S_{0.05} - 0.073, \quad \text{with} \quad R^2 = 0.842, \; n = 53 \tag{16b}$$

The better performance of the exponent value $b = 0.38$ is again confirmed, while the use of less approximated values of slope gradient (sinus instead of tangent of slope angle) yields somewhat better results. Using Eq. (16) brings in changes to Eq. (14) because predicted values are now somewhat different than when we used Eq. (11a). The effect of rock fragment cover is now:

$$correctedvalue = \frac{observed}{predicted} = 0.73e^{1.3RFC}, \quad R^2 = 0.927, n = 9 \tag{17}$$

which also improves its R^2 with respect to Eq. (14).

Applying this correction to the k-values predicted by Eq. (16a), results in the following gully head threshold equation:

$$\sin(\gamma) \geq 0.73ce^{1.3RFC}(0.00124S_{0.05} - 0.037)A^{-0.38} \tag{18}$$

whereby s is substituted by the more correct $\sin(\gamma)$ while c indicates that other factors and processes (e.g. piping) still need to be taken on board.

4. Towards an explanation of the *b*-value

The starting point of the explanatory model proposed by Montgomery and Dietrich (1994) was the obvious assumption that the shear stresses produced by the overland flow must exceed the soil strength by which soil particles and rock fragments are bonded to the soil mass (Eq. (1)). Here, for sake of simplicity we will assume that the Manning formula formally holds (i.e. the flow is fully turbulent, the mathematical relationship between mean flow velocity, hydraulic radius h, and roughness n is the usual one). Hence, following the Montgomery and Dietrich (1994) derivation, we need to express h of Eq. (1) as a function of total discharge Q. For this we use the equation:

$$Q = uhw = \frac{1}{n} wh^{\frac{5}{3}} \sin(\gamma)^{\frac{1}{2}} \tag{19}$$

where w is the width of the channel head.

Using this equation, rearranging for h and considering that $Q = (R\text{–}I)A$, it follows:

$$h = \left[\frac{n(R-I)A}{w}\right]^{\frac{3}{5}} \sin\gamma^{-\frac{3}{10}} \tag{20}$$

Substituting Eq. (20) for h into Eq. (1) it follows:

$$\tau_f = g\rho_f \sin\gamma \left[\frac{n(R-I)A}{w}\right]^{\frac{3}{5}} \sin\gamma^{-\frac{3}{10}} \geq \tau_{cr} \tag{21}$$

Now, with a few re-arrangements we obtain:

$$\sin\gamma^{\frac{7}{10}} \left[\frac{n(R-I)A}{w}\right]^{\frac{3}{5}} \geq \frac{\tau_{cr}}{g\rho_f} \tag{22}$$

The area per unit of flow width (A/w; Eq. (3)) can be substituted by Eq. (6), yielding:

$$\sin\gamma^{\frac{7}{10}} \left[n(R-I)\frac{A^{0.466}}{k_w(R-I)^{0.534}}\right]^{\frac{3}{5}} \geq \frac{\tau_{cr}}{g\rho_f} \tag{23}$$

Rearranging it follows:

$$\sin\gamma \, A^{0.4} \geq \left[\frac{k_w^{0.6}\tau_{cr}}{g\rho_f n^{0.6}(R-I)^{0.28}}\right]^{(10/7)} \tag{24}$$

which agrees rather well with the exponent $b = 0.38$ used so far. Actually the difference between 0.38 and 0.4 does not affect the estimations we did of the k-coefficients as only differences in k-values close to 10% start to be detectable given the small accuracy of the used data.

An alternative way to explain this b-value is to use another flow parameter such as the stream power per unit of volume (P), which is defined as follows (e.g. Torri et al., 2012):

$$P = u\rho_f g \sin\gamma \tag{25}$$

where u is mean flow velocity.

Eq. (25) results from the fact that stream power per unit of surface (P_S) is defined as follows:

$$P_s = \tau_f u \quad (26)$$

If we divide Eq. (26) by the flow depth we obtain the stream power per unit of flow volume:

$$P = \frac{P_s}{h} = u\rho_f g \sin\gamma \quad (27)$$

P is used mainly for flow transport capacity evaluation (e.g. Govers, 1990; Morgan et al., 1998) or for evaluating channel bed roughness of rills and gullies (Torri et al., 2012).

P expresses a power, a force that has to accomplish a work in a unit time, e.g. detaching a particle from the soil and then transporting it. For the flow to erode the soil its stream power per unit of flow volume must exceed a critical value P_{cr}.

Hence we can write a threshold condition which is similar to Eq. (1):

$$P_{cr} \leq P \quad (28)$$

Now an equation for the mean flow velocity (u) is needed. Field and laboratory experiments have clearly shown that if the flow is sediment laden than the flow velocity depends on runoff discharge alone:

$$u = k_u Q^{\beta} \quad (29)$$

where k_u is an empirical constant and the exponent β ranges between 0.3 and 0.45 (rills and gullies: Govers, 1992; Govers et al., 2000; Nearing et al., 1999—rivers: Ferguson, 1986).

Substituting Eqs. (25) and (29) into inequality (28) we obtain:

$$P_{cr} \leq \rho_f g k_u Q^{\beta} \sin\gamma \quad (30)$$

Using Eq. (3) for Q and rearranging it follows:

$$\sin\gamma \geq kA^{-\beta} \quad (31)$$

$$\text{where} : k = \frac{P_{cr}}{\rho_f g k_u (R - I)^{\beta}} \quad (32)$$

Torri et al. (2012) suggested $\beta = 0.39$ based on field data. This is a value very close to the b = 0.38 we used since Eq. (11a). Such a coincidence suggests that a different explanation than the one proposed by Montgomery and Dietrich (1994) may be possible.

5. Final remarks and implications

The topographic threshold data sets for gully heads that have been analysed in this paper are affected by a series of problems: generally the number of data that can be used to define the threshold equation is rather small so that it is often not possible to calculate the threshold coefficient in a robust statistical way. The data, here reviewed, can be summarised into a "model" which is represented by Eq. (18). This equation is based on observations made in different environments by different researchers that described the characteristics of the local environment with different level of details. In fact, most studies describe the environment in a qualitative way, thereby providing only a general characterisation of the landscape and not detailed characteristics of each gully head catchment. Each k value calculated from these studies has an uncertainty because the errors introduced both in defining the threshold coefficient k and the other environmental characteristics are large. Even if the coefficients of determination are relatively good for Eqs. (16) and (17), they have been determined separately, hence the model expressed by Eq. (18) is not characterised by its own determination coefficient. Therefore Eq. (18) is a possible model describing gully head threshold conditions in different environments. This model needs to be confirmed or improved using appropriate field data sets. One could have kept some field data aside to use them for validation of the "model" but it is felt that this would not have been correct. The land use descriptions used for estimating CN-values were not the proper, detailed descriptions, pertaining to the particular gully head catchments. Instead, they were general descriptions of the study areas where gully heads developed. Exemplifying, a study area which is prevalently forested, but having overgrazed clearances, some having bare soil spots with a rock fragment cover, does not exclude that one or more of the gully head catchments within this study area had a 100% forest cover while other catchments only had a 50% forest cover, which results in considerable different CN-values. Hence the model is a first approximation suggesting that it is possible to build a gully threshold model in which land use and vegetation can be explicitly taken into account. It is also evident from this example that we need more detailed data sets to improve and to validate this new model. As the model presented above contains subjective judgements in deriving both k and *CN-S* values and as it has not been validated, it is still not a model to be directly applied in field conditions. While this model still needs be re-written in order to interpret and to fit data obtained during more controlled field measurements, it demonstrates that the data collected so far contain much more information when processed all together than when singled out.

There are at least two ways of predicting the value of b, based on current knowledge which are summarised by Eqs. (24), (31), and (32). Both ways suggest a constant b value and exclude the higher exponent (i.e. b = 0.5) we examined. This higher b-value was actually suggested for A before incorporating the effect of channel width. Repeating the discussion developed for obtaining Eq. (24) for the case $b = 0.5$ we would have obtained $b = 0.23$ for laminar conditions. This value contradicts the data presented and the discussion conducted on the bias in data collection which results in an underestimation of the exponent. The interpretation summarised by Eqs. (31) and (32) does not even allow differentiating between laminar and turbulent flow conditions.

The two interpretations predict different relationships between their respective k-values and soil resistance as well as hydraulic friction. So, in principle the best approach to describe gully head formation should be identified. Besides, the processes leading to gully head formation by overland flow need to be revisited: for example, flow velocity and its dependence on sediment load, hydraulic roughness and erosion rate, while the channel bed roughness itself is shaped by the same flow. At the same time, we need a better data base of gully head threshold conditions. We need measurements or good estimations of the relevant soil, land use, land management and rainfall characteristics for each gully-head catchment. Eqs. (18) and (24) suggest that we should measure the width of the gully head as well, which will result in more reliable flow concentration widths compared to those estimated with Eqs. (5) and (6).

In addition, $S_{0.05}$ is a lumped parameter and this should be substituted by more physically-based parameters. To use $S_{0.05}$ with confidence means that we must make it directly measurable at least, otherwise any situation not described by the NRCS Runoff Curve Number Method will be inexplicable and unpredictable. Furthermore, we need to centralise all these gully-head data because no single researcher will be able to collect enough reliable gully head data and to improve, prove or disprove these interpretations of gully-head formation.

If we accept the results obtained from the data presented in this study, then these models (Eqs. (18), (24), (31) and (32)) allow gully head density to be predicted in landscapes under different land use scenarios. Given that we can predict a reliable k-value, we can also predict the minimal catchment area (A) necessary for a gully head to develop at a given slope gradient and under a given rain regime. Then roughly square-rooting A gives an average distance between two gully heads on that slope. Improving on this side can even allow the opposite exercise: given the average distance between gully heads in a given landscape, gully threshold (k) and CN values can also be deduced.

At the same time the published data sets do clearly show that there is a strong effect of land use on k (see Table 1 and Eq. (18)). They also show that the exponent b can be safely approximated by a constant corresponding to rough turbulent flow conditions. The discussions and elaborations of the collected gully threshold data sets demonstrate that there are advantages in assuming the exponent constant because it is possible to build a model. If we assume that Eq. (18) is a good approximation of the way in which gully head position is defined in the landscape, than we have an instrument to start scenario analysis where gully heads can migrate following climate, vegetation, land use and management changes. This makes this approach interesting, simple and easy to use. At present a first application of a previous, rougher version of the model (comparable to Eq. (10)) for identifying gully prone areas in a catchment in Calabria, Italy is discussed by Terranova, 2010. Another attempt, based on this model (Eq. (18)) is presently under development within a European project (BIOSOS) and its results will soon be available.

In conclusion, the dataset on gully head thresholds discussed in this paper is the largest compiled so far. In reviewing these data we have clearly shown that many research aspects are hidden behind these data. We have also shown that the present dataset, as it was extracted from the literature, still failed to answer several questions. However, the analysis of this dataset has allowed us to address these questions in a much more explicit way, suggesting a new avenue for examining unsolved problems.

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