Published as: Frankl, A., Poesen, J., Scholiers, N., Jacob, M., Haile, M., Deckers, J., Nyssen, J. (2013). Factors controlling the morphology and volume (*V*) – length (*L*) relations of permanent gullies in the Northern Ethiopian Highlands. *Earth Surface Processes and Landforms*, vol. 38 (14), pp. 1672-1684.

Factors controlling the morphology and volume (*V*) – length (*L*) relations of permanent gullies in the Northern Ethiopian Highlands

Short title: Gully morphology and *V* – *L* relations in North Ethiopia

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ABSTRACT: Small-scale aerial photographs and high-resolution satellite images, available for Ethiopia since the second half of the 20th century as for most countries, allow only to determine the length of gullies in detail. Understanding the development of gully volume therefore requires to establish empirical relations between gully volume (V) and length (L) in the field. So far, such $V - L$ relations were proposed for a limited number of gullies/environments and were especially developed for ephemeral gullies. In this study, $V - L$ relations were established for permanent gullies in Northern Ethiopia, having a total length of 152 km. In order to take the regional variability in environmental characteristics into account, factors that control gully cross-sectional morphology were studied from 811 cross-sections. This indicated that the lithology and the presence of check dams or low-active channels were the most important controls of gully cross-sectional shape and size. Cross-sectional size could be fairly well predicted by their drainage area. The $V - L$ relation for the complete dataset was $V = 0.562\ L^{1.381}$ ($n = 33$, $r^2 = 0.94$, with 34.9% of the network having check dams and/or being low-active). Producing such relations for the different lithologies and percentages of the gully network having check dams and/or being low-active allows to assess historical gully development from historical remote sensing data. In addition, gully volume was also related to its catchments area (A) and catchment slope gradient (S_c). This study demonstrates that $V - L$ and $V - A \times S_c$ relations can be very suitable for planners to assess gully volume, but that the establishment of such relations is necessarily region-specific.

KEYWORDS: Ethiopia; gully volume; gully morphology, permanent gullies

1 Introduction

During field surveys, time constraints and difficult terrain allow only partial or local measurements of gully morphology. Gullies may remain unobserved when visually obstructed by vegetation, and recording their dimensions can be quite challenging when gullies are large or when they expand over vast mountainous landscapes. Moreover, field observations only provide limited information on the historical importance of gully erosion. Therefore, several studies explored the potential of (time-series of) remote sensing products to facilitate research on gully erosion (e.g., Patton and Shumm, 1975; Vandaele *et al*., 1997; Betts and Derose, 1999; Nachtergaele and Poesen, 1999; Martinez-Casasnovas, 2003; Ionita, 2006; Parkner *et al*., 2006; James *et al*., 2007; Marzolff *et al*., 2011).

The ability to quantify gully networks and volumes from aerial photographs or satellite images largely depends on their spatial resolution. Considering aerial photographs, the spatial resolution is mainly determined by the scale of the photographs. Large-scale aerial photographs, with a scale exceeding 1:10,000, have a high spatial resolution, generally less than 0.5 m. They allow to accurately map gully networks, but, as they cover small surfaces, their acquisition and processing for large areas is very expensive. Therefore, their usefulness is limited when considering the mapping of gully networks. To compute gully volume, large-scale aerial photographs are more valuable as they allow to precisely resolve gully morphology. This is commonly done through the creation of a Digital Elevation Model (DEM; e.g., Marzolff *et al*., 2002; Ries and Marzolff, 2003; Martinez-Casasnovas *et al*., 2009; Marzolff and Poesen, 2009). The accuracy of the quantification strongly depends on the ratio between the dimension of the gully and the resolution of the DEM (the DEM resolution ought to reflect the resolution of the photographs). Landforms should have dimensions of at least twice the DEM resolution to be defined in a grid-based DEM (Warren *et al*., 2004). In an empirical study, Giménez *et al*. (2009) concluded that, in order to keep the accuracy high, the maximum spatial resolution of aerial photographs should not exceed 15 cm. Medium- to small-scale aerial photographs (scale between 1:10,000 and ca. 1:50,000) have ground resolutions typically ranging between 0.5 and 2 m. They cover large surfaces and thus allow to map gully networks quite rapidly. The precise delineation of gullies can however be challenging, especially when the contrast with the surrounding bare surface is low or when the incision is limited. Computing gully volume from medium- to small-scale aerial photographs has also been done using DEMs (e.g., Betts and Derose, 1999; Martinez-Casasnovas, 2003; Wensheng *et al*., 2005; Parkner *et al*., 2006). Such assessments however suffer from large errors in the positional and vertical accuracy of the DEMs. Moreover, the proposed methodologies are often difficult to adapt as important (and often complex) DEM modifications are required using software that is complex and often difficult to access (e.g., Daba *et al*., 2003). Considering satellite images, the spatial resolution is given by the pixel size. Best resolutions are provided by sensors like IKONOS® (1 m) or GeoEye-1® (0.41 m). Accessing high-resolution images is costly, especially when stereo images for DEM extraction are required. Therefore, few studies use satellite images to quantify gully erosion (e.g., Satter *et al*., 2010). However, with the launch of virtual globes like Google® Earth or NASA World Wind®, the free access to high-resolution images strongly increased, allowing earth scientists to rapidly investigate the Earth's surface, and more specifically, gully networks (Frankl *et al.*, 2012a).

When the spatial resolution of aerial photographs or satellite images only allows to outline gully networks, calculating their volume requires understanding the determinants of gully cross-section shape. In the case of ephemeral gullies, Poesen (1992) reported that the cross-sectional width-depth ratio (determined in the field) is mainly controlled by the thickness and resistance properties of the soil horizons. Knowing the average cross-section of ephemeral gullies for a specific area, in combination with their length, allows to calculate their volume (e.g., Vandaele *et al.*, 1997; Nachtergaele and Poesen, 1999). As ephemeral gullies do not grow subsequently but are erased by tillage (Poesen *et al.*, 1996), the average cross-section can also be applied when using historical photographs or images to assess gully volume. In the case of permanent gullies, because of their continuous increase (or decrease) in size over time, an average cross-section does not allow to calculate historical gully volume. Therefore, several authors explored the relation between gully volume (V) and gully length (L). As a result, a number of power relations of the type $V = \mathrm{a}L^{\mathrm{b}}$ were proposed, that generally closely fit the datasets (e.g., Nachtergaele *et al.*, 2001a; Capra *et al.*, 2005; Zucca *et al.*, 2006; Zhang *et al.*, 2007; Kompani-Zare *et al.*, 2011). Such relations reflect the fact that, when gullies increase in length, their volume increases by a power function, which is the consequence of gullies becoming deeper and wider as their catchment size increases downslope (Graf, 1988; Knighton, 1998; Torri and Borselli, 2003). The coefficients 'a' and 'b' reflect environmental characteristics (soil, lithology, land use, climate) that determine gully cross-sectional shape. To our knowledge, most studies established $V - L$ relations for ephemeral gullies and did not consider permanent gullies. For the latter, larger values for the exponent 'b' can however be expected as ephemeral gullies are often reported as having a more or less constant cross-sectional area (e.g., "winter gullies" in Nachtergaele *et al.*, 2001a). In addition to $V - L$ relations, which allow to calculate gully volume from their length, our interest was also to investigate the relation between gully volume and catchment area (A), as the latter is the only parameter that can easily be derived from a topographical map.

This paper thus proposes a cheap yet comprehensive methodology to assess gully volume over large areas using field data and freely accessible high-resolution satellite images; applied to gully networks of the Northern Ethiopian Highlands – a data-poor region which suffers from severe land degradation (Frankl *et al.*, 2011). The specific objectives are: (1) to demonstrate the potential of small-scale aerial photographs and high-resolution satellite images to study gully development, (2) to determine the controls of gully cross-sectional shape, and (3) to establish $V - L$ *and* $V - A$ relations for gullies in the Northern Ethiopian Highlands that take the regional variability in environmental characteristics into account.

2 Materials and Methods

2.1 Study area

The study area consists of eight catchments that are located in the Northern Ethiopian Highlands and which are representative for the regional variability in environmental characteristics: Ablo (15.2 km^2), May Mekdan (44.7 km^2), May Ba'ati (4 km^2), May Tsimble (8.1 km^2), Atsela (4.9 km^2), Ayba (37 km^2), Seytan (8.2 km^2) and Lake Ashenge

($1.1\ km^2$) (Figure 1). May Tsimble drains to the Rift Valley, Lake Ashenge is an endorheic or marginal graben of the Rift Valley and all other catchments drain to the Tekeze-Atbara river system. Elevations range between 2100 and 3900 m a.s.l. The deeply incised valleys developed over the past 25 million years, as a result of the rapid uplift of the Ethiopian Highlands at the western margin of the Rift Valley (Williams and Williams, 1980). Consequently, Mesozoic limestones, sandstones and Tertiary volcanics were exposed (Merla *et al.*, 1979), and their differential resistance to erosion gave the valleys their typical stepped relief, dominated by flat-topped mountains, called *amba*. The Ablo catchment exposes sandstone; May Mekdan and May Tsimble shale with limestone cliffs and occasionally dolerite at the summits; Atsela, Ayba, Seytan and Lake Ashenge expose volcanics (flood basalt, rhyolites and consolidated volcanic ashes) and May Ba'ati exposes volcanics (= basalt) at higher elevations, while sandstone, limestone and shale occur at lower elevations.

** FIGURE 1 APPROXIMATELY HERE **

The rainfall regime is driven by the position of the Inter Tropical Convergence Zone (Robinson and Henderson-Sellers, 1999). Its passage over the Highlands from March until May announces the beginning of the monsoon-type rainy season, which is intense from June until September. Average annual rain increases from north to south, ranging between 500 and 900 mm y^{-1}, and usually falls as intense showers that seldom last longer than ten minutes (Nyssen *et al.*, 2005). Rain is however highly unreliable and droughts frequently occur.

Due to active geomorphologic processes, most soils are young (HTS, 1976; Nyssen *et al.*, 2008). Leptosols are found in high landscape positions while Regosols or Cambisols occur on steep slopes. In footslope positions, more developed fine-textured soils occur, with Vertisols on basalt (colluvium) and Calcisols on limestone. Under remnant forests, Phaeozems occur (Descheemaeker *et al.*, 2006).

Land degradation is severe in Northern Ethiopia (Virgo and Munro, 1978; Nyssen *et al.*, 2004). Gullies affect nearly all slopes and frequently exceed 2 m in depth and 5 m in top width (Figure 2). Their occurrence is related to the vulnerable environment, which exposes steep slopes, where rainfall intensities are high and where deforestation and overgrazing depleted the landscape of most vegetation. As pointed by Frankl *et al.* (2011, 2012b), improved land management and gully rehabilitation programs are having a positive effect on the stabilization of gullies in Northern Ethiopia. Especially for headwater streams, where hillslope-channel links are strong, reforestation and soil and water conservation programs are beneficial. These measures include the terracing of slopes, the establishment of exclosures, and the construction of check dams in gullies (Nyssen *et al.*, 2004). The implementation of the latter usually started after 1994. Vertisols remain very susceptible to gully erosion (Frankl *et al.*, 2012b).

** FIGURE 2 APPROXIMATELY HERE **

2.2 Data collection

Gully networks were mapped from GeoEye® - 1 (resolution of 0.50 m) images of 2005, Digital Globe (resolution of 0.60 m) images of 2006, and Cnes SPOT® (resolution 2.5

m) images of 2011in Google® Earth (which allows 3D visualization of the images) and subsequently imported into ArGIS® 9.2 according to the methodology of Frankl *et al.* (2012a). Field observations (2008-2010) and Global Positioning System (GPS; Garmin GPSMap 60® with a standard deviation of 5 m) measurements of cross-sections and headcut locations allowed to correct the network maps for errors. As no high-resolution satellite images were available for the May Mekdan study area, gully network maps produced from aerial photographs of 1994 (Frankl, 2012) were updated with field observations and GPS measurements. As shown in Frankl *et al.* (2012a), the positional accuracy of the gully network maps based on the high-resolution satellite imagery accessed in Google® Earth was <5 m, comparable to the accuracies provided by handheld GPS. The positional accuracy of the network map based on the aerial photographs is on average 5.5±3.4 m.

In order to quantify gully volumes and to acquire data on gully cross-sectional morphology, 811 cross-sections were quantified at an equal number of gully segments. This involved measuring the maximum depth (*D*, in m), top width (*TW*, in m) and bottom width (*BW*, in m), of the bankfull channels. Where the gully cross-section shape was trapezoidal or wedge-shaped $((TW + BW) / 2) * D$ gave the cross-sectional area (*CSA*, in m^2). In other cases, additional measurements of the channel dimension were required. For practical reasons, measurements were conducted with a measuring tape. Errors in the calculation of *CSA* are less than 2% (which is equal to a measurement error on *TW* and *D* of 0.01 m for a gully of 1 m deep and wide, and an error of 0.1 m on a gully of 10 m deep and wide). When using the *CSA* to compute gully volume, it is however very important to carefully select the average cross-section of a gully segment, which can imply a much larger error.

Local environmental characteristics that ought to determine the dimensions of the cross-sections were recorded. These included the presence of check dams, gully activity, lithology, gully bank material, the presence of a rock fragment floor in the gully, land use/cover and local slope gradient (S_l, m m^{-1}). When check dams were present in gullies, the cross-section was measured in between two check dams, in order to record the mean gully-filling effect of the structures. Gully activity was assessed visually, by making a distinction between low- and high-active channels. This was based on the cross-sectional shape of the channel, the presence of vegetation in the channel, the occurrence of mobile bed material, bank gullying, and tension cracks or mass failure in the channel banks (Figure 2, Frankl *et al.*, 2011). Considering the lithology, measurements were done in shale-, volcanic-, and sandstone-derived deposits. The effect of gully bank material on gully morphology and size was taken into account in May Mekdan, where shales occur. Based on the FAO guidelines for soil profile description (FAO *et al.*, 1998) and geomorphic field-interpretations, a distinction could be made between Vertisol, floodplain alluvium, colluvium and landslides. Originally, the effect of bank material was also targeted for gullies in volcanics of the Ayba catchment, but due to problems in the texture analysis, this could not be done. For each gully bank material type, a mixed soil sample taken from the gully wall was collected at representative sites in order to examine particle-size distribution. This was done by wet sieving using sieves with 0.063 mm, 0.5 mm and 2 mm openings and by analyzing the fraction smaller than 0.063 mm with a sedigraph (Sedigraph III®). The stoniness (> 2 mm) in the gully wall was also considered separately. As the stoniness had to be assessed visually, rough subdivisions were used: 0-20%, 20-50%, 50-80% and 80-100% volume percent. Many gullies had important deposits of coarse bedload on their floor. The effect of the presence of such a rock fragment floor was therefore analyzed. Assessing the effect of land use/cover on cross-section morphology and size was done by considering gullies that cut through cropland, exclosures, rangeland and grazing land. Cross-sections where land use/cover was different on both sides were not considered. The local slope gradient S_l of the soil surface next to the cross-section was defined between locations five meter upslope and five meter downslope the cross-section.

2.3 Factors controlling gully cross-sections

In order to understand the determinants of gully cross-sectional shape, a first step was to analyze the variability in gully *TW*, *BW*, *D* and *CSA*. This was done by producing boxplots and by computing minima, maxima, the interquartile range and median of the frequency distributions.

Secondly, we assessed the effect of gully and environmental characteristics that were recorded during the field survey on gully cross-sectional area and gully morphology. The latter was explained by using the ratio between gully top width and depth (*TW/D*) and the ratio between gully bottom width and top width (*BW/TW*). Gullies that display a large *TW-D* ratio are much wider then they are deep, and vice versa, while the *BW-TW* ratio, that ranges between 0 and 1, determines whether the gully is V or U shaped. An analysis of variance (ANOVA, $\alpha = 0.05$; Kutner *et al.*, 2005) was performed on the logarithm of the morphologic ratios in order to compare the distributions at different levels of the explanatory variables: check dam (and stabilized cross-sections), lithology, gully bank material, stoniness of the gully bank, rock fragment floor, land use/cover and local slope gradient. The levels of these variables are listed in Table I. Performing a similar analysis for *CSA* did not necessarily mean that that levels of a variable had different distributions. Diverging means between subgroups could also be the result of sampling gullies of a different size. Therefore, obtaining meaningful results required to rescale *CSA* by dividing it with the *TW*, thus correcting for (mostly small) differences in sampled gully size. Normality of the distributions and variance homogeneity was tested with a Kolmogorov-Smirnov test (α = 0.05) and a Levené test (α = 0.01).

Finally, we investigated whether cross-sectional gully properties could be predicted on the basis of catchment characteristics. With the purpose to efficiently transfer water and sediment downslope, channel shape and size mainly adjusts to peak discharges (Knighton, 1998). As a result, channel *TW*, *D* and *CSA* will generally increase downstream. Departures from this trend are caused by variations in slope gradient, gully bank material and vegetation cover (Knighton, 1998).

In order to relate cross-sectional properties to peak discharge, discharge data would be needed for a variety of small gully catchments. Such data is however not available for Northern Ethiopia. Gauging stations are only present at a limited number of large rivers with catchments that range between 121 km^2 and 4592 km^2 (Zenebe *et al.*, 2012). For these catchments, discharge shows a strong positive power relation to catchment area (*A*), indicating that the biophysical setting was similar in the different catchments. Such an assumption can also be made for the basins studied here, and thus the importance of catchment area as a proxy for peak discharge was used to explain the gross variability in cross-sectional properties, without considering variations in rainfall. *A* was mapped from contour lines derived from DEMs (Frankl, 2012).

2.4 Establishing volume – length relations

Establishing relations between the present-day volume of the gully networks and their length was done by selecting 33 mutually exclusive catchments, with areas varying between 0.02 km² and 8.0 km². For these catchments, the length of the gully networks varied between 106 m and 18 366 m. Quantifying volumes was done by summing-up the mathematical products of the length of each gully section and its average cross-sectional area. *V* – *L* relations were produced by taking factors that determine gully cross-sectional size into account.

In addition, the relation between the volume of the gully networks and their catchment area (*V* – *A*) was also explored. The effect of the catchment slope gradient (S_c, in m m^{-1}) on the *V* – *A* relation was also considered. *A* was mapped from contour lines derived from DEMs or from topographical maps (Frankl, 2012), and S_c was calculated from SRTM data (available on http://srtm.csi.cgiar.org); using ArcGIS® 9.2.

3. Results

3.1. Factors controlling gully cross-sectional shape

For the 811 gully cross-sections surveyed in Northern Ethiopia, the gully top width (*TW*) varied between 0.35 m and 31.90 m with a median of 6.34 m. The gully depth (*D*) varied between 0.20 m and 12.77 m with a median of 2.15 m and the bottom width (*BW*) ranged between 0.10 m and 19.50 m with a median of 3.00 m. The median cross-sectional area (*CSA*) was 10.1 m² and ranged between 0.15 m² and 236.5 m². As the boxplots suggest (Figure 3A), the distributions are right-skewed and the variability of the observations, as indicated by interquartile range, is higher for *TW* (5.20) and *BW* (2.70) than for *D* (1.79). The median *TW-D* ratio was 2.7, while the median *BW-TW* ratio was 0.5 (Table I). Note that for *TW/D* and *BW/TW*, median and mean do not differ much as the distributions are nearly Normal. As shown in Figure 3B, plotting *D* over *TW* shows wide scatter around a linear relation purged through the origin (0, 0).

** FIGURE 3 APPROXIMATELY HERE **

In the following analysis, the effect of gully and environmental characteristics that were recorded during the fieldwork on gully morphology (*TW-D* and *BW-TW* ratios) and on *CSA* are presented. In order to reduce the effect of extreme values in the dataset, cross-sections for which the shape was controlled by rock exposure were not considered. For instance, on cliffs edges, rock exposure causes gullies to become very wide and shallow. Omitting these observations did not affect the median of the distributions much, but did increase statistical significance.

The results that are summarized in Table I show median values for the morphologic ratios and *CSA*. The latter were obtained by multiplying the standardized *CSA* of the different subgroups to the median *TW* (= 6.34 m) of the surveyed gullies in Northern Ethiopia, and thus corrects for differences in sampled gully magnitude between the different subgroups. The reported statistics (Table I) apply on the logarithmic transformation of *TW/D*, *BW/TW* and standardized *CSA*.

** TABLE I APPROXIMATELY HERE **

Measurements of cross-sections were made in 376 gullies without check dams and in 294 gullies with (gabion) check dams. In addition, 42 sections that were partly infilled and stabilized without check dams in their immediate proximity were also recorded. As observed in the field, the effect on *TW/D*, *BW/TW* and *CSA* for both gullies with check dams and stabilized gullies is very similar (one-way ANOVA test, $P<0.05$), so that both subgroups were considered together. From a one-way ANOVA ($P<0.05$), we could conclude that the median *TW-D* ratio for gullies with check dams (or stabilized sections) was 32.8% higher than for gullies without check dams and that the median *CSA* of gullies with check dams (or stabilized sections) was 33.5% smaller than for gullies without check dams. This means that the implementation of check dams resulted in the decrease in gully depth by circa one-third. No significant effect could be demonstrated for the effect of check dams and stabilized sections on the *BW-TW* ratio (one-way ANOVA, $P=0.46$). Table I presents median values for *TW/D*, *BW/TW* and *CSA* for the different subgroups.

Assessing the effect of lithology and their derived deposits on *TW/D*, *BW/TW* and *CSA* was done for 322 gully sections where no check dams were present and which were not stabilized: 198 in shale, 94 in volcanics and 7 in sandstone. From a one-way ANOVA Scheffé test ($P<0.05$), we could conclude that the median *TW-D* ratio was 38.2%

smaller in shale than in volcanics, and that the median *BW-TW* ratio was 21.8% larger for shale when compared to volcanics. The combined effect on *CSA* was that cross-sections in shale had a median that was 36.7% larger than in volcanics. This indicates that, for a given *TW*, *D* and *BW* are larger in shale when compared to volcanics. No significant effects could be observed for sandstone versus shale or volcanics.

The effect of the gully bank material on cross-sectional shape and area was analysed by investigating particle-size distribution and rock fragment content of the gully banks. In May Mekdan, where shale occur, a distinction could be made between gullies that developed in Vertisol (n = 41), floodplain alluvial deposits (n = 42), fine colluvium (n = 70) and landslides (n = 30). Sections that developed in weathered travertine or that cut through unweathered rock were not considered. Soil texture properties are given in Table II. Finer particle-size distributions of the gully sidewalls tended to have a positive effect on *CSA* and a negative effect on *TW-D* and *BW-TW* ratios in May Mekdan (Table I). In other words, the finer the particle-size distribution gets, the larger the cross-section tends to be, which is the result of the gully incising deeper while becoming more V-shaped. Although this general trend applies, not all subgroups showed distributions that were significantly different from each other (Table I). When considering the cross-sectional morphology, sections incised in Vertisol had a median *TW-D* ratio that was 31.8% smaller than sections in floodplain alluvium and 39.2% smaller than sections in colluvium (one-way ANOVA Scheffé test, $P<0.05$). For the *BW-TW* ratio, gully segments that incised in Vertisol had a median *BW-TW* ratio that was 50% smaller than sections in floodplain alluvium, 66.5% smaller than sections in colluvium and 61.2% smaller than sections in landslides (one-way ANOVA Scheffé test, $P<0.05$). When considering the median *CSA*, sections that developed in Vertisol were 34.9% larger than sections which were in colluvial deposits (one-way ANOVA Scheffé test, P<0.05). An important anomaly to the trend described here-above is that sections that developed in landslides did not tend to give a smaller *CSA* or a larger *TW-D* ratio when compared sections that developed in finer material (Table I).

** TABLE II APPROXIMATELY HERE **

When considering the stoniness of the gully banks separately for 309 cross-sections, no significant effect could be demonstrated for variations in *TW-D* ratio and *CSA* (one-way ANOVA, P = 0.22 and P = 0.68). However, when considering *BW-TW* ratio, a higher stoniness of the gully wall tends to give higher *BW-TW* ratios (Table I). Stoniness levels 50-80% and 80-100% gave *BW-TW* ratios that where significantly higher than level 0-20%, by 40.5% and 50.72% respectively (one-way ANOVA, P<0.05).

The presence of many rock fragments armoring the gully floor did not have a significant effect on gully cross-sectional morphology or area. Results of the one-way ANOVA performed on 292 sections are P = 0.99 and P = 0.81 for *TW-D* and *BW-TW* ratios respectively, and P = 0.53 for *CSA*.

Analyzing the effect of land use/cover on 251 sections did only yield significant results for the *BW-TW* ratio. This ratio was 34.2% larger in grazing land than in cropland (one-way ANOVA, P<0.05).

The local slope gradient of the soil surface had a positive effect on both *TW-D* and *BW-TW* ratios and a negative effect on *CSA*. Gullies that developed on gentle slopes tend to have cross-sections that are deeper, more V –shaped and larger than gullies that developed on steep slopes. The median *TW-D* ratio of gullies that developed on slopes ranging between 0% and 10% was 21.1% smaller than gullies that developed on slopes ranging between 10% and 20% and 33.2% smaller than gullies that developed on slopes ranging between 20% and 30% (one-way ANOVA, P<0.05). The *BW-TW* ratio was 35.1% smaller for slopes of 0-10% when compared to slopes of 10-20%, and 31.3% smaller for slopes of 10-20% when compared to slopes of 20-30% (one-way ANOVA, P<0.05). The combined effect on the median *CSA* was that on slopes of 0-10%, the *CSA* was 24.7% larger than on slopes of 20-30% and 42.6% larger than on slopes of 20-30% (one-way ANOVA, P<0.05; Table I).

Explaining the variability in *TW*, *D* and *CSA* on the basis of the catchment area (A, m^2) was done for active gullies without check dams and without rock exposure. Figure 4A-C shows the power relations between *TW*, *D*, *CSA* and A respectively. Both *TW*, *D* and *CSA* increase with increasing A. As the trend lines for "all data" show, this increase is more marked for *CSA* than for *TW* and *D*. The rather low r^2 values indicate that the variability on this trend is rather high, as can also be visually observed.

In addition, the effect of local slope gradient of the soil surface (S_l, m m^{-1}) and the lithology on these relationships was analyzed. In contrast to other variables, these can easily be derived from topographical and geological maps, that thus can serve as a basis to predict gully morphology and *CSA*. As can be derived from Table I, these are also the most important factors that control gully shape and size, when no check dams are present. Before investigating the importance of S_l, the relation between A and S_l was analyzed. With an correlation coefficient r equal to 0.71 (n = 60; P < 0.01), A and S_l

showed to be highly interrelated. This is the consequence of catchments becoming steeper and smaller when situated higher in the valley. However, in the stepped relief of the Ethiopian Highlands where a succession of structural flats and steep valley sides is displayed, gentle slopes may also occur in high topographical positions. Adding S_l to the regression analysis did not result in a significant increase in model r^2, and thus, S_l was excluded as a predictive variable.

When looking at the effect of lithology, the analysis yields similar results as those presented in the previous paragraphs (Figure 4A-C). For a given *A*, *TW*, *D* and *CSA* were larger in deposits derived from shale than from volcanics. The effect of sandstone-derived deposits is somehow intermediate.

** FIGURE 4 APPROXIMATELY HERE **

3.2. *V* – *L* and *V* – *A* relations

The relation between network volumes to their length was best described by a power equation of the form $V = aL^b$. From the different parameters that influence gully cross-sectional size, we only considered the lithology of gullied catchments and the presence of check dams in gullies (including the effect of low-dynamic sections). As shown in Section 3.1, these are the most important characteristics that explain the variability in *CSA*, both of which are rather easily observed in the field, or derived from topographic maps. Other parameters, like gully bank material or land use/cover, have similar distributions along gully networks, making different networks difficult to contrast in terms of *V* – *L* relations. Moreover, including such parameters, which are labour intensive to map, would make $V - L$ relations difficult to apply in other areas or periods. The resulting $V - L$ equations for the different lithologies are (Figure 5A):

$V_{\text{all data}} = 0.562\ L^{1.381}$ (n = 33, r^2 = 0.94, with 34.9% of the network having check dams and/or being low-active) (1)

$V_{\text{shale}} = 0.349\ L^{1.465}$ (n = 16, r^2 = 0.96, with 22.2% of the network having check dams and/or being low-active) (2)

$V_{\text{volcanics}} = 0.343\ L^{1.399}$ (n = 12, r^2 = 0.90, with 28.9% of the network having check dams and/or being low-active) (3)

$V_{\text{sandstone}} = 2.94\ L^{1.149}$ (n = 5, r^2 = 0.81, with 90.1% of the network having check dams and/or being low-active) (4)

** FIGURE 5 APPROXIMATELY HERE **

The relations (3.1) – (3.4) are valid for the given fraction of the network which is treated with check dams and/or low-active. For example, the $V - L$ equation that applies for gully networks that developed in shale-derived deposits, is valid for 22.2% of the network having check dams and/or being low-active. From Section 3.1, we know that the median *CSA* of gullies decreases on average by 33.5% when they have check dams and/or are low-active. In our example, the $V - L$ equation established for shale-derived deposits thus takes an infilling of 22.2% x 33.5% = 7.4% into account. This filling is reflected in the a-coefficient of the equation. Thus, simulating the effect of 0% to 100% of the gully network having check dams and/or being low-active, results in a decreasing a-coefficient (Table III). For sandstone, simulating the effect of 0% to 100% of the network having check dams and/or being low-active on the a-coefficient was not done, as the dataset proposed here is limited (n = 5) and covers only a small area (= 1.62 km^2) when compared to the other datasets. Figure 5B displays the resulting equations at 0%, 50% and 100%.

** TABLE III APPROXIMATELY HERE **

As for the relation between gully network volumes and their catchment area, good associations (with high r^2 values) could be established for shale and volcanics (Figure 6A). Due to the limited dataset, the $V - A$ relation for sandstone was weak and not significant. Adding S_c as an explanatory factor to these equations increased the r^2 values, especially for the networks that developed in volcanic deposits (Figure 6B). Note that the $V - A$ and $V - A \times S_c$ relations for all data were not produced, as the catchments in sandstone are of a different order of magnitude and, therefore, should not be merged with those in shale and volcanics.

** FIGURE 6 APPROXIMATELY HERE **

4. Discussion

4.1 Gully cross-sectional shape

As pointed out by Knighton (1998, p. 167), "the cross-sectional form of natural channels is characteristically irregular in outline and locally very variable". Understanding the variability in gully morphology and size therefore mostly requires large datasets to get the general trend. This is well illustrated in Figure 3B, which displays a large scatter around the trend line when plotting gully depth (*D*) over top width (*TW*) for 811 cross-sections of permanent gullies.

Natural channels will adjust their shape and size to the hydrological regime, i.e. the quantity of water delivered to the channel and the characteristics of runoff discharge (Knighton, 1998; Schumm, 2005). Empirical approaches to understand the variability in *TW* and *D* along channels therefore mainly take runoff discharge (annual, peak, bankfull) into consideration. For example, in semi-arid areas, where the hydrological regime is dominated by the occurrence of flash floods, channels tend to develop wider than in humid regions (Knighton, 1998). Hence, *TW* and *D* are explained as a power function ($Y = aX^b$) of runoff discharge. Such relations were essentially developed for rivers, indicating that *TW* varies approximately as the square root of discharge (b-coefficient ~ 0.5; Knighton, 1998; Poesen *et al.*, 2003). For ephemeral gullies, Nachtergaele *et al.* (2002) demonstrated that the equation $W = aQ_{peak}^{b}$ has a b-coefficient of approximately 0.4.

Given the discharge properties, channel shape and size will adjust to the constraints imposed by local controls. As discussed by Knighton (1988) and Schumm (2005), these are especially the gully bank material of the channel, vegetation growing on the banks and the local slope gradient of the soil surface. Numerous studies reported by these authors indicate that the *TW-D* ratio of rivers will be larger for non-cohesive (sand) soils than for cohesive soils (silt-clay), smaller with increasing vegetation cover, and larger when the slope gradient increases. As for gullies, this study and the findings of Muñoz-

Robles *et al.*, (2010) confirm the increasing effect of local slope gradient on the *TW-D* ratio. Regarding the gully bank material, this study also confirms that particle fining causes the *TW-D* ratio to decrease. As gullies become deeper, they also tend to become more V-shaped. Despite our findings, some studies claim that the *TW-D* ratio for gullies in cohesive soils is larger than for non-cohesive soils (Radoane, 1995). The lithology has an important effect of the *TW-D* ratio, with higher ratios in shale when compared to volcanics. The effect of vegetation on the cross-sectional shape could not be demonstrated in this study. This was also not expected for the reason that the free-grazing system restricts the development of dense vegetation and because most gullies are older than the exclosures which they incise.

As mentioned before, the cross-sectional size is mainly controlled by discharge. Regarding the effect of lithology, channel cross-sections in shale are 37.7% larger than cross-sections in volcanics (Table I). An important explanatory variable for this might be the occurrence of incised travertine dams in shale catchments (Figure 7). As they represent the local base-level of gully networks, their deep incision causes the gullies to degrade. The build-up of the May Mekdan travertine dam, which forms the outlet of the studied catchment, occurred at least between 7310 ± 90 y BP and 5160 ± 80 yr BP (Berakhi *et al.*, 1998). The incision of such dams is often related to the deforestation which started some 3000 years ago (Moeyersons *et al.*, 2006). Rainfall variability was not taken into account for the explanation of cross-section variability. However, considering that the average annual precipitation is larger in the volcanics catchments (Atsela, Seytan, Ayba and Lake Ashenge) than in the shale catchments (May Mekdan and May Tsimble) (Jacob *et al.*, 2012), Figure 5A suggests that the effect of lithology is far more important than the effect of average annual precipitation. On average, the volcanics catchment receive 200-300 mm more rain on a yearly basis. More important might be the variability in peak flow discharge, as in dryland environments, high-magnitude low-frequency flash floods accomplish most of the morphologic changes (Graf, 1988; Vanmaercke *et al.*, 2010). This was however beyond the scope of this study.

** FIGURE 7 APPROXIMATELY HERE **

In order to predict the variability in gully cross-sectional shape and size, the use of catchment area as a proxy of discharge was assessed in this study. This shows that indeed, channel *TW*, *D* and *CSA* are positively related to catchment area according to a power relation (Figure 4A-C). However, the large scatter around the trend lines indicates that predicting channel shape and size at a specific location upon these equations can be in gross error.

4.2 $V – L$ and $V – A$ relations

Figure 8 presents the $V – L$ relation for Northern Ethiopia (equation 3.1) as compared to other regions in the world. As can be deduced from Table IV, such relations were especially established in arid to dry sub-humid regions. For humid environments, power relations exist for winter and summer ephemeral gullies in Belgium. The r^2-values of the power equations are relatively high (Table IV). Only for the study considering the Fars Province in Southwestern Iran, the r^2 of the pooled dataset proved to be low. However, clustering gullies according to their morphology gave r^2-values up to 0.86 (Kompani-Zare *et al.*, 2011). The high r^2-values indicate that gully length is a good predictor of gully volume. As pointed out by Nachtergaele *et al.* (2001b) and Capra *et al.* (2005), such empirical relations are more suitable to predict gully volume and simpler to apply than the Ephemeral Gully Erosion Model (Woodward, 1999). Adding the 24-h rainfall as a predictive variable to the $V - L$ equation slightly increased the model fit (r^2 from 0.64 to 0.74) in Sicily (Capra *et al.*, 2005).

Empirical $V - L$ relations reflect the environmental setting (climate, topography, lithology, soil, vegetation) of the area they were developed for, and can thus not easily be applied to wider regions or similar areas worldwide (Graf, 1988). This is especially true when the datasets used to produce these relations are limited or when the area taken into consideration is small. In such cases, the risk exists that the sampled gullies do not reflect the regional variability in gully morphology. The study of the $V - L$ relation, which aims at being representative for the Northern Ethiopian Highlands, covers 5 380 ha and considers 151 767 m of gullies for the establishment of the $V - L$ relation. As can be read from Table IV, the size of the study areas for (a) – (i) is limited in most studies, ranging from 54 ha to 1 199 ha. Whether the gully length range is representative for the area is difficult to assess, but in general, the smaller the study area considered, the larger the risk that the empirical relation does not cover the magnitude of the gullies in the wider region. However, studies (a) – (i) mostly do consider a fairly large total gully length. Total gully length varies from 480 m up to 19 216 m.

The discussed $V - L$ relations can roughly be subdivided in two groups. The first group represents the ephemeral gullies, equations (e) to (i). As ephemeral gullies do not grow subsequently but are erased after tillage, these lines plot lower on the graph. The second group represents the permanent gullies, which increase in size after subsequent rainfall events. These are equations (a) – (c) and this study. Equation (d) includes both ephemeral and permanent gullies and is somewhat transitional.

As observed in Table IV, the b-coefficients for the different equations are very similar, ranging between 1.04 and 1.429. The larger the b-coefficient, the more important the increase in cross-sectional area becomes with increasing length, and thus, the more erodible the incised deposits are. Gullies with coefficients close to 1 will thus display relatively constant cross-sectional areas along their channel. In Zucca *et al*. (2006), b-coefficients close to 1 for a subgroup of gullies that developed in coarse granites was explained by the presence of bedrock at shallow depths limiting the deepening of gullies. The larger b-coefficient for summer gullies than winter gullies in Belgium was explained by the occurrence of higher rainfall intensities during summer months, thus producing stronger floods and creating larger channels (Nachtergaele *et al*., 2001a). As a result of the large similarity for the $V - L$ relations for summer gullies in Belgium and for gullies in Portugal and Spain, Nachtergaele (2001a) presented an equation including both datasets. Given the b-coefficient, the a-coefficient determines the height of the power relation on the Y-axis and therefore reflects the general environmental vulnerability of the area. As can be observed on Figure 8, gullies in Northern Ethiopia plot higher than those in Australia. This can be expected as the environmental setting in the Australian study area is less vulnerable than the Ethiopian context of this study. The study presented by Muñoz-Robles *et al*. (2010) considers an area with undulating terrain for which precipitation is uniformly distributed throughout the year with an annual mean of 441 mm y^{-1} and storms having low to moderate intensities. Considering the power relation that was developed for the Northeastern Iran, the small dataset of only six gullies with a total length of 480 m suggests that the sampling might not be fully representative for the wider region.

** TABLE IV APPROXIMATELY HERE **

** FIGURE 8 APPROXIMATELY HERE **

Applying $V - L$ relations to assess gully volume still requires to map gully networks in the field or to derive them from aerial photographs. For general planning purposes, collecting data on gully lengths might be too labour intensive. Therefore, the value of catchment characteristics that are easy to quantify was assessed in this study. We found that catchment area is a fairly good predictor of gully erosion volume. Including average slope gradient of the catchment yields even better results, as network density proved to increase with S_c. For gullies that developed in deposits derived from shale and volcanics, $V - A \times S_c$ relations (Figure 6B) gave r^2-values of 0.92 and 0.80 respectively. The limited dataset of small gully networks in sandstone catchments did not allow to develop a satisfactory relation. A could be mapped from topographical maps and S_c could be determined from SRTM data. As is the case for the $V - L$ relations, the $V - A$ and $V - A \times S_c$ relations defined here take environmental characteristics into account. Developing such relations was also done elsewhere in the world, for example, by Khosla (1953) in India ($V = 0.00323A^{0.72}$) and by Vandekerckhove *et al*. (2000) for bank gullies in Spain ($V = 1.75A^{0.59}$). Differences in the a- and b-coefficients of such equations are the result of higher gully densities or a higher erodibility of the deposits the gullies developed in (~ $V – L$ relation). The good association between V and A is not surprising, as many studies indicated that A is the major control of gully head retreat (Poesen *et al.*, 2003; Frankl *et al.*, 2012b).

Small-scale aerial photographs of the second half of the 20th century are commonly available for many regions of the world, and are completed with high-resolution satellite images for recent decades. For example, small-scale aerial photographs (~1:45,000) of the years 1963/5, 1974, 1982/6 and 1994 are available for large parts of Ethiopia. They allow to map gully networks quite accurately, and through the establishment of $V – L$ or $V – A$ (x S_c) relations, historical and present-day gully volumes can be calculated as well. Such relations between gully length, catchment area and volume are however region specific, and should take the regional variability in environmental characteristics into account. Fine-tuning the relations is based on *in situ* observations of gully morphology, allowing to order understand to controls of gully size and morphology under specific rainfall and runoff conditions.

5. Conclusions

The spatial resolution of most (historical) aerial photographs or satellite images only allow to outline gullies accurately, while acquiring and/or processing DEMs is time consuming, expensive, and often requires complex methodologies. A cheap yet comprehensive method to assess gully volume is the development of volume – length ($V – L$) relations, which, in Northern Ethiopia, can then be applied for larger areas and different periods with a similar biophysical setting. As for a given L, V varies according to the variability in gully cross-sectional area, the importance of local controls on the latter need to be determined in the field. Local controls that cause gully cross-sectional shape and size to vary in Northern Ethiopia were the presence of check dams, channel activity, lithology, local slope gradient, gully bank material, and to a lesser extent the presence of a rock fragment floor and land use/cover. Considering the effect of lithology, cross-sections in shales were 36.7% larger in than in volcanics (based on median values). This is probably largely explained by the incision of travertine dams. Check dams or stabilized sections caused gullies to fill by a median difference of 33.5%. As a proxy of runoff discharge, catchment area of the cross-sections proved to be a fairly good predictor of channel properties.

As the lithology, the presence of check dams, and the channel activity proved to be the most important controls of gully cross-sectional area, $V - L$ relations that were established account for these controlling factors. Comparing the $V - L$ relations established for ephemeral and for permanent gullies in different regions around the world indicated that for the latter, the increase in V with L is more pronounced. In a comparable study in Australia, the gully volume increase over length prove to be less important when compared to this study, most probably as a result of the higher environmental vulnerability of Northern Ethiopia. As an alternative to $V - L$ relations, which still require to map gully networks, $V - A$ and $V - A \times S_c$ relations were also established. Both catchment area (A) and catchment slope gradient (S_c) could be easily determined and proved to be good predictors of gully volume as well.

6. Figure Captions

Figure 1. Study areas and oro-hydrography in Northern Ethiopia

Figure 2. Examples of high- and low-active gullies in different material. **A**: High-active gully incised in alluvium/colluvium (on volcanics, Ayba), **B**: Low-active gully in a Vertisol (on shale, May Mekdan), **C**: High-active gully in landslide material with large amounts of rock fragments on the gully floor (on shale, May Mekdan), **D**: Gabion check dam in a gully which led to an almost completely filled gully (on sandstone, Ablo). Photographs by Amaury Frankl and Nelles Scholiers.

Figure 3. Cross-section characteristics of the studied gullies in Northern Ethiopia. **A**: Boxplots for gully top width (*TW*), bottom width (*BW*), depth (*D*) and cross-sectional area (*CSA*) for 811 sections. Outliers larger than 20 m and 100 m² are not displayed. **B**: Plotting gully depth (*D*) over gully top width (*TW*) shows a linear relation.

Figure 4. Power relation between **A**: gully top width (*TW*), **B**: depth (*D*), **C**: cross-sectional area (*CSA*, in m²) respectively, and catchment area (*A*). The effect of the lithology on these relations is also shown and trend lines are plotted when significant (*P*-value less than 0.05).

Figure 5. **A**: $V - L$ relations. **B**: Simulating the effect of 0%, 50% and 100% of the networks treated with check dams and/or low-active for networks that developed in deposits derived from shale and from volcanics.

Figure 6. The relationship between gully volume (*V*), catchment area (*A*) and average catchment slope gradient (S_c) (A) **A**: $V - A$ and **B**: $V - A \times S_c$ relations.

Figure 7. Extreme example of the effect of incised travertine dams on gully erosion. **A**: The deeply incised travertine dam near to the town of May Mekdan and gully network upslope. **B**: View from inside the gully before the occurrence of an important flash flood

event on 12/08/2010 when flood marks were recorded at 3.5 m above the gully floor. The arrow indicates where cracks were visible in the land at the time when the photograph was taken. **C**: The flash flood event caused important geomorphic changes as shown here by the occurrence of a slab failure. The arrow indicates the same location as the arrow on B. Photographs by Amaury Frankl. Note that A was taken during the dry season on 28/02/2011.

Figure 8. Gully Volume (*V*) – Length (*L*) relation in Northern Ethiopia as compared to elswhere in the world. For references see Table IV.

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Table I. Median values for the gully top width - depth ratio (*TW*/*D*), bottom width - top width ratio (*BW*/*TW*) and cross-sectional area (*CSA*).

Explanatory variables	Levels	*n*	*TW/D*	*BW/TW*	*CSA* [1] (m²)
All data		811	2,7	0,5	10,1
Presence of (gabion) check dams or stabilized sections	Yes	336	3.7^{a}	0,6	8.4^{a}
	No	376	2.5^{b}	0,5	12.6^{b}
Lithology[2]	Shale	198	2.0^{a}	0.5^{a}	15.6^{a}
	Volcanics	94	3.2^{b}	0.6^{b}	9.9^{b}
	Sandstone	7	2.5^{a,b}	0.8^{a,b}	13.8^{a,b}
gully bank material[2] (case May Mekdan)	Vertisol	41	1.4^{a}	0.2^{a}	20.0^{a}
	Floodplain alluvium	42	2.1^{b,c}	0.4^{b}	15.0^{a,b}
	Colluvium	70	2.3^{b,c}	0.6^{c,d}	13.1^{b,c}
	Landslide	30	1.8^{a,b,c}	0.5^{b,c,d}	17.2^{a,b,c}
Stoniness of the gully bank[2]	0% - 20%	136	2.2^{a}	0.4^{a}	13.7^{a}
	20% - 50%	81	2.3^{a}	0.5^{a,b,c}	13.8^{a}
	50% - 80%	71	2.6^{a}	0.7^{b,c}	12.7^{a}
	80% - 100%	21	2.6^{a}	0.8^{b,c}	12.6^{a}
Presence of a rock fragment floor[2]	Yes	135	2.3^{a}	0.5^{a}	13.9^{a}
	No	157	2.3^{a}	0.5^{a}	13.4^{a}
Land use/cover[2]	Cropland	150	2.0^{a}	0.7^{a}	14.9^{a}
	grassland	93	2.4^{a}	0.3^{b}	13.1^{a}
	Exclosure	8	3.2^{a}	0.7^{a,b}	9.8^{a}
Local slope gradient (S_l)[2]	0% - 10%	112	1.8^{a}	0.4^{a}	16.6^{a}
	10% - 20%	83	2.3^{b}	0.6^{b}	13.3^{b}
	20%-30%	55	2.8^{b}	0.8^{c}	11.2^{b}

[1] Median values were obtained by multiplying the standardized *CSA* of the subgroups to the median *TW* (= 6.34 m) of the surveyed gullies in Northern Ethiopia, and thus corrects for differences in gully magnitude between the different subgroups.

[2] For cross-sections without check dams or which are stabilized

[a,b,c,d] should be read vertically per variable and indicate levels for which the distributions are not significantly different from each other.

Table II. Gully bank material composition of the deposits studied in May Mekdan.

	Soil texture (mass %) Clay (<0.005mm)	Silt (0.005 - 0.063 mm)	Sand (0.063 - 2mm)	Average gully wall stoniness (volume %)
Vertisol	74	23	3	18
Floodplain alluvium	52	32	16	24
Colluvium	54	27	17	22
Landslide	60	28	12	37

Table III. a-coefficients related to a given percentage of the networks treated with check dams and/or low-active for catchments that developed in the lithologies shale and volcanics.

% of gully length treated with check dams or low-active	Shale $V = a\,L^{1.465}$ with a	Volcanics $V = a\,L^{1.399}$ with a
0	0.3746	0.3760
10	0.362	0.3634
20	0.3495	0.3508
30	0.3369	0.3382
40	0.3244	0.3256
50	0.3118	0.3130
60	0.2993	0.3004
70	0.2867	0.2878
80	0.2742	0.2752
90	0.2617	0.2626
100	0.2491	0.2500

Table IV. Overview of the characteristics of the volume – length relations ($V = aL^b$) established in different regions.

Reference on Figure 8	Area	Climate	Lithology	Gully type	Size of the study area (ha)	Total gully length (m)	*n* (gullies or gully networks)	a	b	r^2
this study	Northern Ethiopia	semi-arid / dry sub-humid	shale, volcanics, sandstone	permanent	5 380	151 767	33	0.562	1.381	0.94
a	New South Wales (Australia)	semi-arid	highly metamorphosed sandstone	permanent	1 199	19 216	16	0.43	1.36	0.81
b	Golestan Province (NE Iran)	arid / semi-arid	shale?	permanent	500	480	6	5.64	1.24	0.52
c	Fars Province (SW Iran)	arid	Quaternary sediments and marl	permanent	gullies randomly selected from 5 very large areas (ca. 5-10 10^4 ha)	2 556	146	0.9483	1.097	0.33 (-0.09 - 0.86)
d	Sardinia (Italy)	dry-sub humid	granites and metamorphic rocks	ephemeral / permanent	720	17 405	32	0.235	1.12	0.55
e	SE Spain, SE Portugal	semi-arid / humid	shist	ephemeral	54	4 461	86	0.05	1.27	0.91
f	"summer gullies" Belgium	humid	loess	ephemeral	38	3 221	26	0.1	1.16	0.74
g	NE China	semi-humid	lacustrine and fluvial sand beds and loess	ephemeral	85	9 090	21	0.015	1.429	0.67
h	"winter gullies" Belgium	humid	loess	ephemeral	197	7 885	32	0.1	1.04	0.82
i	Sicily (Italy)	Mediterranean	?	ephemeral	120	13 340	92	0.0082	1.416	0.64

References: (a) Munoz-Robles et al. (2010), (b) Soufi and Isaie (2012), (c) Kompani-Zare et al. (2011), (d) Zucca et al. (2006), (e) Nachtergaele et al. (2001b), (f) Nachtergaele et al. (2001a), (g) Zhang et al. (2007), (h) Nachtergaele et al. (2001b), (i) Capra et al. (2005).