Scale dependence of gully investigations[1]

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Abstract

Soil erosion causes considerable damage both for the agriculture by soil loss and for the environment by sedimentation via contribution to eutrophication. Disastrous soil erosion events due to extremely high intensity rainfalls have recently posed serious danger to roads, dams, and edifices in Hungary. Gully erosion plays a particular role in rapid and extreme erosion processes. Research at regional, catchment or gully scale may have different objectives. The main aim of this paper is to compare methods from the local to regional scale. Three case studies are presented. The results suggest the following statements to be made. At local scale the processes are determined by gully morphology, material and energy transport as well as by soil properties. The topographical and lithological factors parallel with land use have growing importance with the decreasing scale.

Keywords: gully erosion, scale dependence, GIS

Introduction

Gully erosion is the prevailing soil degradation process under arid and semiarid climatic conditions. Due to the insufficient precipitation amount biomass production is very much restricted, almost inhibited and the low canopy cover cannot stop or slow down surface runoff (Kertész, Á. and Centeri, Cs. 2006; Kertész, Á. 2006; 2009). Rainfall events occur irregularly in time and the increasing probability of heavy rainstorms with extreme intensity generates more frequent gully development (Malzorff, I. and Poesen, J. 2009). As a consequence under arid and semiarid climatic conditions the contribution of gully erosion to total sediment loss can reach 50–80%, meanwhile in humid and subhumid regions it varies between 10–50% (Poesen, J. *et al.* 2006).

Under subhumid climate the biomass production is rather high and the vegetation cover gives a certain protection against the direct impact of the raindrops. In spite of the sheltering effect of the canopy rapidly developing gullies can be found even in forested areas (Kertész, Á. *et al.* 2000). The significance of

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gully erosion under subhumid climate is shown by the results of an investigation carried out in Western Hungary pointing to 50 % of the total sediment amount in a catchment being delivered by gully erosion (Jakab, G. *et al.* (2009).

Gully formation has always been an important geomorphic process in Europe. It is well known that gully development was launched and accelerated by various forms of anthropogenic activities over the last 2 to 3 thousand years (Gábris, Gy. *et al.* 2003; Lang, A. *et al.* 2003; Vanwalleghem, T. *et al.* 2003).

Humans cleared the land in order to obtain new territories for agriculture and land clearing completely changed the hydrological conditions of the field. In many cases in line with land use modifications climatic conditions change, too with the involvement of possible interactions (Poesen, J. *et al.* 2006).

A gully can be filled up because environmental conditions change; however, gully incision is generally faster, than the filling-up of gullies. Gullies affect their surroundings in a relatively long time span (Jakab, G. *et al.* 2005).

Landforms of linear erosion collect surface waters, consequently they are deeply incised into the surface. Insolation into the gully is very limited and almost no wind can reach inside the gully. The consequence is lower evaporation intensity, wetter microclimate conditions and soil moisture surplus inside the gully (Mac Nally, R. *et al.* 2000). Because of the wetter conditions species composition, the number of individuals and even the fertility of the individuals increase (Soderquist, T.R. and Mac Nally, R. 2000).

Measurements performed by Palmer, G.C. and Bennett, A.F. (2006) in forests indicated that on wetter areas the flora composition changes and the diversity of bird species grows. In contrast to this statement Lindenmayer *et al.* (2009) did not find more bird species in forest gullies than in the other parts of the forest. An explanation for these conflicting views can be the scale (size) dependence of various species.

The size of an average gully is large enough to determine the microbiological and non-arboreal composition but in case of vertebrates it is not so direct and evident (Naiman, R.J. *et al.* 1993). The environmental influence of gullies depends on their size, it is scale dependent. The local impact of gullies is manifested in the increase of the number of land mosaics. The role of gullies in soil erosion (Hegedűs, K. *et al.* 2008; Jakab, G. 2006; Kertész, Á. 2004) and in fertilizer and pesticide transport (Madarász, B. *et al.* 2003) is extremely significant at catchment scale.

The main objective of this paper is to analyze the distribution and morphological appearance regularity of gullies from the local to regional scale. The identification of the most important characteristics of a gully is mainly affected by the scale. Research at different scales requires different methods. The case studies presented in this paper apply different methods for gully investigation at different scales.

Methods

At local scale morphometric measurements were carried out in Somogybabod, south of Lake Balaton. A detailed site description of the research area is given by Madarász, B. *et al.* 2003 and in Tóth, A. and Szalai, Z. 2007.

In the winter of 2003 a field survey was carried out using a laser reflectance total station (Trimble 3305 DR). The survey was performed within the framework of the Unified National Mapping System of Hungary. The aim of the survey was to determine morphometric properties of two gullies running next to each other. More than 1000 points were surveyed following a network of 20 by 20 meters grid, plus some representative points of the gullies (Jakab, G. 2009).

For the estimation of the elevation of the surface between the surveyed points the kriging method was used. The digital elevation model (DEM) thus created is far from being perfect in case of banks, sharp relief forms and headcuts. Using the kriging method these forms appear rounded without edges. If the number of surveyed points is sufficient a better representation can be provided via linear interpolation, namely by applying the Triangulated Irregular Network (TIN) method (Marzolff, I. *et al.* 2002). In this case the edges and breaks are better recognizable but the shapes of other parts of the surface are better approched by the kriging method. For a better representation of the terrain a more accurate DEM is needed and this can be achieved by the increase of the surveyed points via remote sensing (Ries, J.B. and Marzolff, I. 2003; Malzorff, I. and Poesen, J. 2009) or surface scanning methods. As these gullies formed under forest remote sensing is hardly applicable. Accuracy without additional measurements can be achieved by the combination of the above interpolation methods. Following this procedure the gullies are well presented and the DEM is useful for the morphometric comparison of the gullies.

In 2009 the faster developing gully was surveyed again using the same method. The creation technique of the DEM was the same as well. With the comparison of the DEMs of various dates the dynamics of gully development can be estimated.

Gully development investigations at field scale were carried out in the Galga River valley next to the town of Galgagyörk to check the field scale investigations at Somogybabod (Jakab, G. *et al.* 2010). Since the cross section of the Galga valley south of Galgagyörk has similar topographic and soil conditions (Marosi, S. and Somogyi, S. 1992) to those at Somogybabod it can be considered as an analogy of the Somogybabod site. Analyzing the available maps and remote sensing databases of the area the dynamics of gully development could be followed.

At regional scale a gully database was created. 1:10,000 topographic maps from the 1980s were digitized. Land use categories were simplified into three classes of forest, pasture and arable land.

Results and discussion

Large scale investigations revealed the morphological differences between the two gullies. The differences are related to spatial and temporal changes of the geomorphic processes in the gullies (Jakab, G. 2008). The DEM shows that the northern gully is a rapidly developing one with quickly eroding vertical slopes and sharp edges *(Figure 1),* meanwhile the slopes of the southern gully are not so steep and covered with vegetation. The latter is less active in spite of having similar topographic and land use characteristics as the northern gully and disposing of a twice larger drainage area.

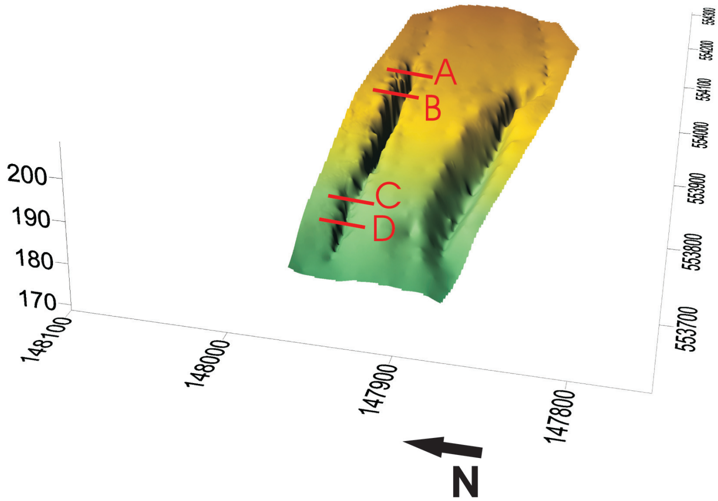

Fig. 1. Digital Elevation Model of the investigated gullies at Somogybabod. The letters refer to the cross section locations in *Fig. 2.*

There are remarkable differences in the development of the two gullies. The topographic survey demonstrates that the southern gully is more or less inactive while the northern one retreats rather rapidly and deepens, too. The morphological changes during the investigated six years can be analyzed on the basis of selected cross sections *(Figure 2).* The heaviest material loss took place along cross section "A", just below the headcut. Here the deepening was roughly 2.5 m and the retreat of the northern slope accounted for 1–1.5 m. Downwards along the gully the sides are less and less eroded while gully incision seems to be constant (ca 2 m). The same tendency can be seen on the soil loss map *(Figure 3).*

Since slope steepness, land use and vegetation cover are the same in both gullies (Jakab, G. 2009) the morphological differences can probably be explained by the variation in lithological properties. Investigating gully development at large scale the interactions of the environmental conditions affecting gully formation and development have to be identified.

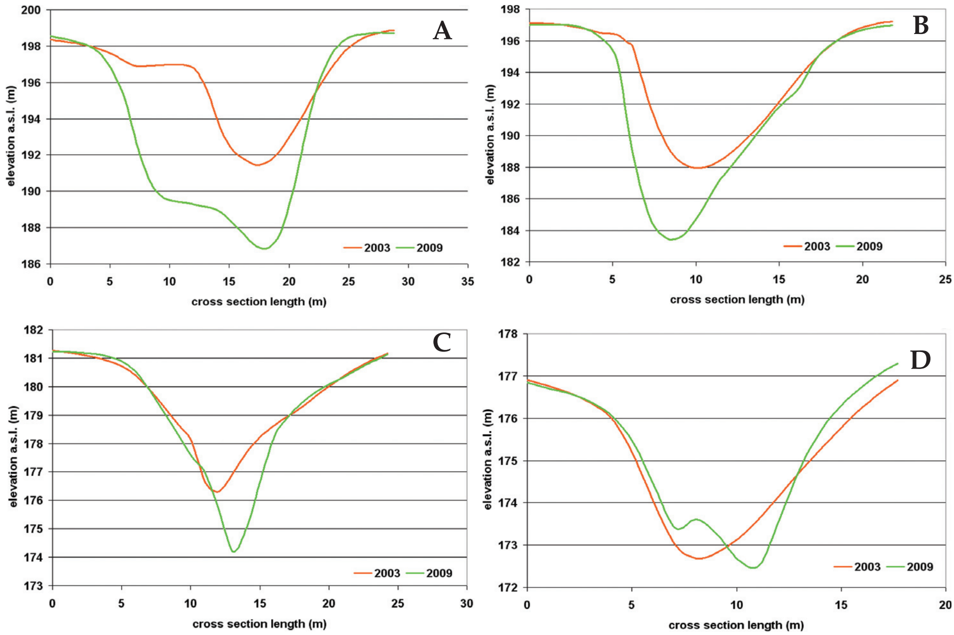

Fig. 2. Four cross sections from 2003 and 2009 of the rapidly developing gully at Somogybabod

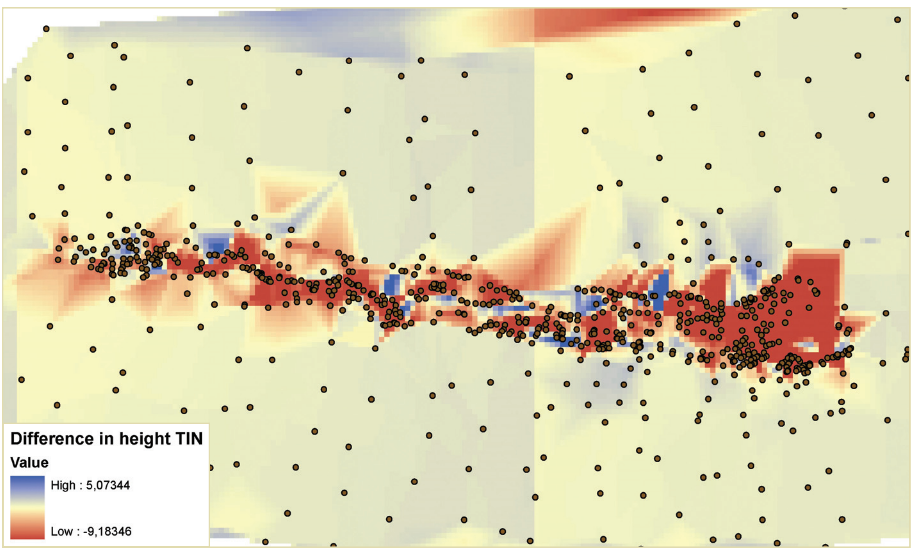

Fig. 3. Soil loss map of the rapidly developing gully at Somogybabod prepared using the TIN method. Decrease in surface height refers to soil loss between 2003 and 2009

The next dimension of the investigations is the catchment scale. At this scale gully development should be investigated in the context of catchment processes. Jakab, G. *et al.* (2010) carried out investigations in a hilly country (Somogybabod, Tolna County) covered by forest at the end of the eighteenth century. The appearance of gullies is due to the forest clearance at the turn of the 18–19th centuries. In those areas where agricultural activities had been carried out prior to 1780 when the first Military Survey of Hungary commenced, gully initiation and development started earlier. The evidence of this can also be detected on the first military maps of Galgagyörk, Northern Hungary *(Figure 4).* In the surroundings of Galgagyörk the valley bottom was occupied by arable fields in the 1780s. On both sides of the river there are roads and gully-like forms running up on the hill slopes towards the divides. On the eastern slope there is a thin forest strip extending to the river bank. This strip used to be probably an abandoned part of the arable field because its cultivation was hindered by the presence of a gully there. At the end of the 18th century huge areas were covered by vineyards mainly on the slopes with western and south-western exposures.

The analysis of the Galgagyörk map drawn during the 2nd Military Survey in the 1840s (B) showed that the arable land/forest ratio of the areas has not changed significantly since the end of the 18th century. The opposite of this is true in Somogy county. Due to the better illustration of topographic forms on the second military survey maps gullies and ditches indicated by the gully bottom line can be well identified. In the investigated section of the Galga valley there are more than ten gullies shown on the map. They must be either ephemeral gullies or deep cut tracks. Two inscriptions refer to gullies developed long before the surveying. In the north-eastern part of the valley a gully name suggests a deep and wide landform. In the other valley of the sample site there are also several gullies in arable fields and vineyards.

On the map of the third military survey (C) gullies are represented by the same symbols as today. Gullies are well recognizable from the contour lines and from the indication of the gully bottom line.

Looking at the map prepared 100 years after the third military survey (D) no major changes can be identified. Gullies are represented more precisely and even the gully bottoms are recognizable on the map. Some of the ephemeral gullies became permanent ones, some of them had transformed into valleys. This development is typical for ephemeral gullies formed on arable fields pointing to the dominant contribution of ephemeral gullies in the total soil loss at catchment scale (Poesen, J. *et al.* 2003; Jakab, G. 2009). The most remarkable land use change is the decrease of vineyards as a consequence of the Viteus vitifolii infection between 1875 and 1890.

On the aerial image (E) the recent status dominated by an extended ephemeral gully system can be seen. Some parts of former ephemeral gullies

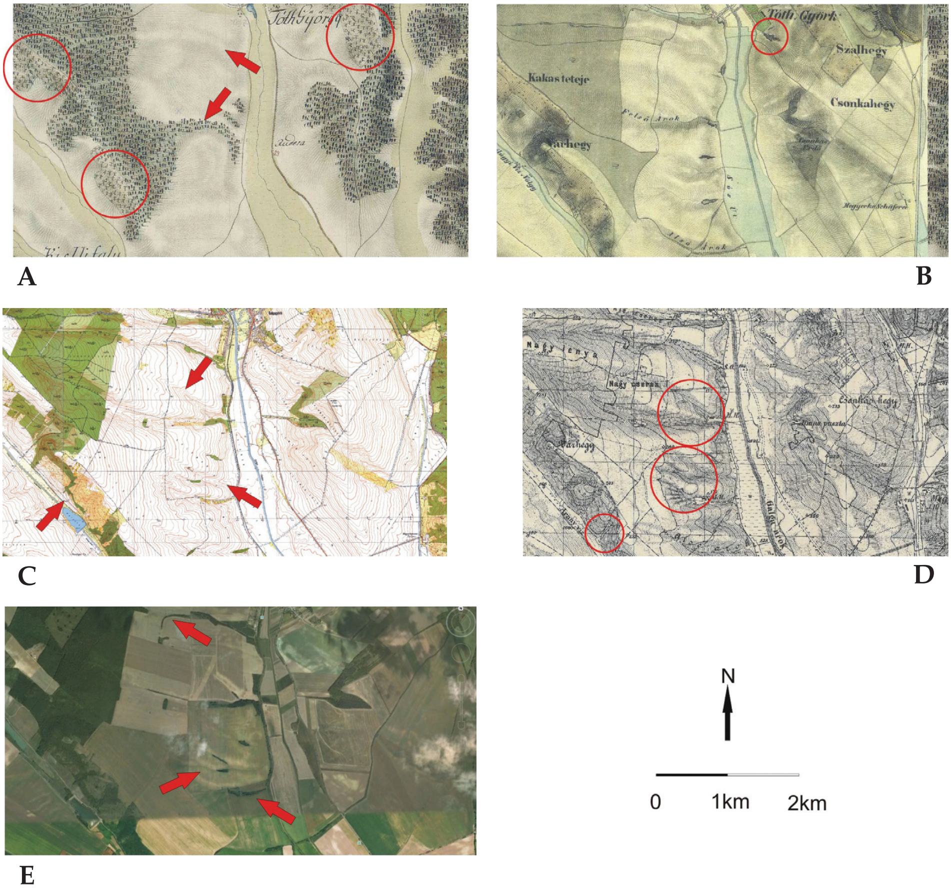

Fig. 4. Changes in topography and land use at Galgagyörk during the last 200 years. A = 1st military survey (1780s), B = 2nd military survey (1850s), C = 3rd military survey (1870s), D = 1:10.000 map (1960s), E = aerial image (2006, Google Earth). Arrows and circles indicate areas of intensive gullying and those of land use change

on certain spots became permanent. In these cases the deepening had been so effective and rapid, that tillage was not possible any more. Accordingly this gully cannot be classified into a definite group as a whole but it has to be divided into parts.

Looking at the Galgagyörk area one could think to deal with a similar situation as in Somogy county, namely that gully initiation started after deforestation when woodland was converted into arable land (Jakab, G. *et al.* 2010). The Galga valley gullies are much older and they are probably active since the arable fields nearby were tilled. Judging from the age of the gullies a huge amount of fertile soil must have been eroded since their appearance.

Land use types are of primary importance from the point of view of erosion (Centeri, Cs. *et al.* 2009). This statement is confirmed by the results obtained at the sites of Somogybabod and Galgagyörk where the main factor of gully initiation has been land use change. If there had not been land use change gully development would have been negligible and new gullies would not be formed. Under such circumstances gully erosion is manifested in a relatively slow development of the existing gullies.

The next dimension is the regional scale and the question arises how the above statements can be generalized at this scale. A national survey of gullies was launched in 2009 in order to build up a gully database. In the 1960s the whole country was surveyed in order to compile an up-to-date 1: 10.000 topographical map series of Hungary.

Gullies and land use were also represented on these maps. The map offers a possibility to analyze the spatial distribution of gullies. A simple ratio, i.e. total gully length/km^2, suggested by Stefanovits, P. and Várallyay, Gy. (1992) can be calculated. The classification system proposed by the authors is applied in this study, i.e.

(a) weakly gullied area: < 200 m/km^2;

(b) moderately gullied area: 200–500 m/km^2;

(c) strongly gullied area: > 500 m/km^2.

Further data layers of the national gully database include topographic parameters (slope gradient, slope exposure, derived from the Shuttle Radar Topography Mission /SRTM/ database), recent land use given in the CORINE database and soil characteristics (soil type, soil texture, parent material etc.) from the AGROTOPO database of Hungary (Várallyay, Gy. *et al.* 1998). The database allows for the identification and analysis of the areas endangered by gully erosion. Sample areas will be selected and temporal change will be revealed based on the database and on remote sensing materials. The detailed investigation of the sample areas allows for the identification of present-day trends in gully development and for the estimation of its rate in the future.

Up to now gullies and land use types of five map sheets of the 1960s were digitized (*Figure 5).*

Preliminary results of the analysis of the database are as follows:

1. Ephemeral gullies are difficult to identify because they are often shown as valleys on the map and the distinction of gullies from valleys is difficult.

2. It is hardly possible to give the exact length of a gully because it is difficult to define independent gullies from those which belong together. The general statement about gully length is that the average gully on arable land is longer than on pasture and in most cases also in forest *(Table 1).*

3. Most of the gullies (85–90%) can be found in forests. The percentage of gullies outside the forest has increased only on less dissected areas.

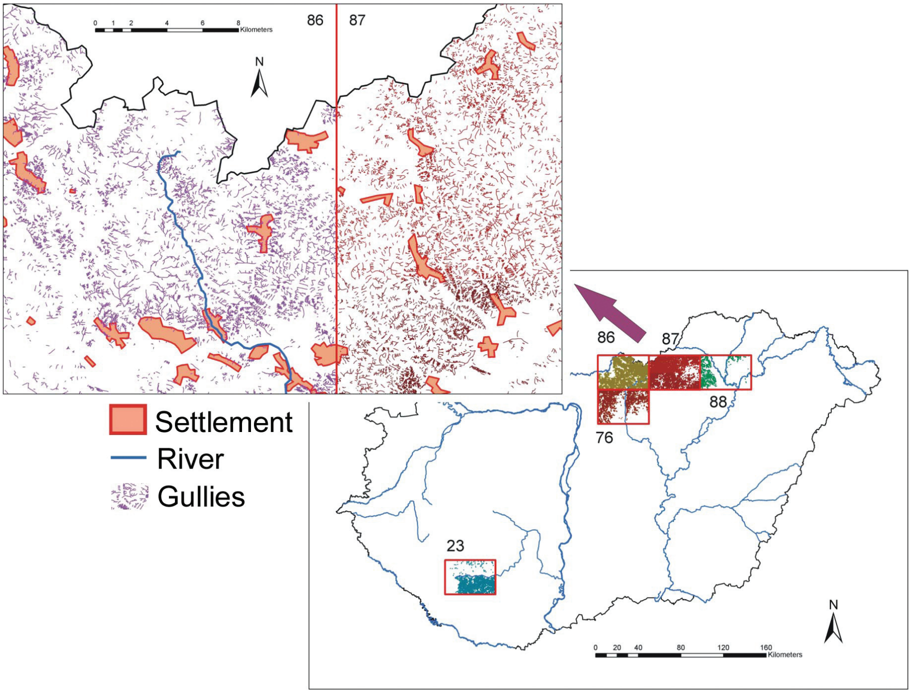

Fig. 5. Digitized map sheets with the indication of the gullies

4. The areas presented in *Figure 5* are highly dissected (500 m km^{-2} <) with the exception of the area shown on map sheet 88 which is partly lowland, i.e. part of the Great Hungarian Plain *(Table 2).*

5. In this study the classification system of Stefanovits, P. and Várallyay, Gy. (1992, see above) was applied. Values within the strongly gullied category vary widely therefore the classification system has to be changed.

Conclusions

Gullies determine the development and material flux of the landscape. Gully formation is triggered by the given environmental conditions, but an already existing gully will remain in the landscape for a long time.

Our investigations carried out at distinct scales had different objectives and the applied methods were different, too. At local scale the role of gully morphology, parent material, soil properties and energy transport determine the processes. Along with the decreasing scale the importance of topographical and lithological factors and of land use increases. The gully classification system has to be improved by adding a new category of "extremely gullied" (1,000 m km^{-2}<).

Table 1. Main statistical parameters of the gully length classified by land use types in the late 1960s

Statistical parameters of gully length (m)	Number of map sheet														
	23	76	86	87	88	23	76	86	87	88	23	76	86	87	88
	Arable land					Pasture					Forest				
Mean	198	258	256	170	220	153	169	127	116	154	292	229	186	222	225
Median	164	180	234	149	180	120	105	76	80	106	154	100	83	104	121
SD	139	214	151	119	240	122	184	211	121	155	431	485	386	402	413
Max.	665	1,015	631	632	1,773	778	1,440	2,994	1,746	1,180	5,970	9,740	7,713	8,636	7,141
Min.	2	34	70	28	27	7	17	8	1	1	3	10	7	1	1

Table 2. Distribution of gullies according to land use types

Number of gullies	Gullies				Land use (late 1960s)								
	Total length	Mean length	Gully density		Arable land			Pasture			Forest		
	m		m km^{-2}	category	No.	Total length, m	%	No.	Total length, m	%	No.	Total length, m	%
3,369	930,930	276	606	strongly gullied	123	24,340	2.6	284	43,335	4.7	2,962	863,255	92.7
4,536	1,023,816	226	667	strongly gullied	86	22,203	2.2	292	49,284	4.8	4,158	952,329	93.0
13,385	2,471,455	185	1,609	strongly gullied	23	5,885	0.2	344	43,743	1.8	13,018	2,421,827	98.0
13,322	2,702,770	203	1,760	strongly gullied	61	10,382	0.4	2392	278,476	10.3	10,869	2,413,912	89.3
1,489	304,788	205	198	weakly gullied	70	15,416	5.1	420	43,335	14.2	999	246,037	80.7

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