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Characteristics and controlling factors of bank gullies in two semi-arid mediterranean environments

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Abstract

Bank gullies are gullies that are formed due to a height drop caused by a terrace or a river bank, which develop by headward retreat in erodible hillslopes. This study aims (i) to investigate the morphology of actively eroding bank gullies, i.e., geometrical characteristics resulting from past erosion and active erosion processes shaping the gully, and, (ii), to find relationships with environmental site characteristics, such as topographical parameters, material properties and climate. The ultimate goal is to identify the most important controlling factors of past and present bank gully erosion. Fifty-five active bank gullies formed in different lithologies by various erosion processes have been selected in the Guadalentin basin and the surroundings of Guadix (Southeast Spain). For each bank gully site, geometrical and topographical parameters of both the channel and the drainage basin were measured. Erosion features indicating activity at the gully head, such as tension cracks, plunge pools, undercutting, fluting, piping and rill or sheet erosion on sloping side walls were mapped, and samples were taken from distinct lithological layers that were considered to influence the type and intensity of erosion processes. A relationship could be shown between the presence of piping and fluting and a number of material characteristics, including particle size distribution, dispersion behaviour and electrical conductivity. On the other hand, lithology appeared not to be a differentiating factor on gully development in the long run, as expressed by the total eroded volume (V). This parameter was most strongly related to the drainage basin area in which the entire bank gully had been formed (A_o), explaining 66% of the variance. The relationship is $V = 1.75 * A_o^{0.59}$. No significant difference was found between regression lines through sub-datasets of different soil textural classes. Finally, multiple regression was used to include both topographical parameters and material characteristics in an explanatory and/or predictive equation for the total eroded bank gully volume. The results of the analyses using the entire dataset, including the sites in the Guadalentin as well as in the Guadix area, have been compared with the results for the separate study areas. Differences are not only related to topographical and lithological characteristics, but may also be the consequence of a different climate in the two areas. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: bank gully; piping; fluting; lithology; southeast Spain

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1. Introduction

Bank gullies are gullies that are formed due to a height drop caused by a terrace or a river bank (Poesen and Hooke, 1997), in contrast to hillslope gullies that are formed upon the exceedance of a critical flow shear stress at the soil surface, as described by Montgomery and Dietrich (1988). Bank gullies develop by headward retreat in erodible hillslopes. In this study, they occur as tributary gullies initiated at the bank of an ephemeral river (rambla or barranco) in a semi-arid environment in Southeast Spain (Fig. 1). Eroding bank-gully heads decrease the effective agricultural area of the surrounding land, produce considerable amounts of sediment filling downstream reservoirs, and aggravate floods (Poesen and Hooke, 1997).

Past research concentrated mainly on active gully development in terms of headcut or sidewall retreat and related erosion processes. Many descriptive studies exist on specific processes, such as piping or tunneling (Harvey, 1982; Gutiérrez et al., 1988, 1997; Martín-Penela, 1994), rill formation (Gerits et al., 1987), fluting (Veness, 1980), and badland development (Imeson et al., 1982), relating these phenomena to material characteristics or other factors. Some studies provide an extensive description of the active geomorphological processes by geomorphological mapping of entire gully systems (La Roca Cervigon and Calvo-Cases, 1988) or along a gully wall (Jungerius and van den Brink, 1991). Gullies have been the object of intensive monitoring with respect to headcut retreat and active processes (Leopold et al., 1966; Malde and Scott, 1976; Crouch, 1983; Sneddon et al., 1988; Oostwoud Wijdenes and Bryan, 1991, 1994; Palacio-Prieto and Lopez-Blanco, 1994; Burkard and Kostaschuk, 1995; Archibold et al., 1996). The majority of these studies make links with controlling factors, but in qualitative terms. On the other hand, quantitative prediction equations for gully-head retreat have been established by relating measured gully growth to different environmental

Fig. 1. Illustration of a bank gully in the Guadalentin basin.

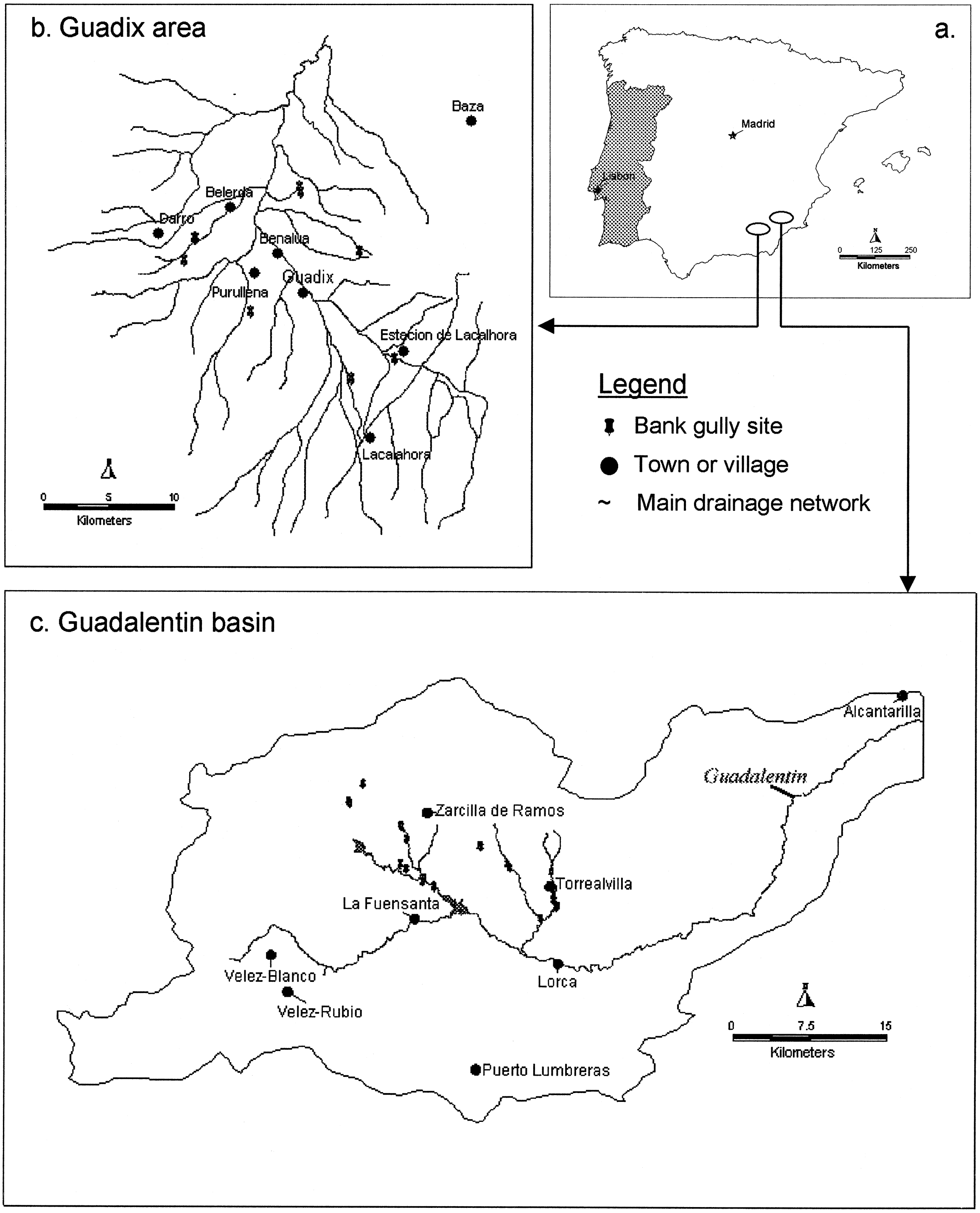
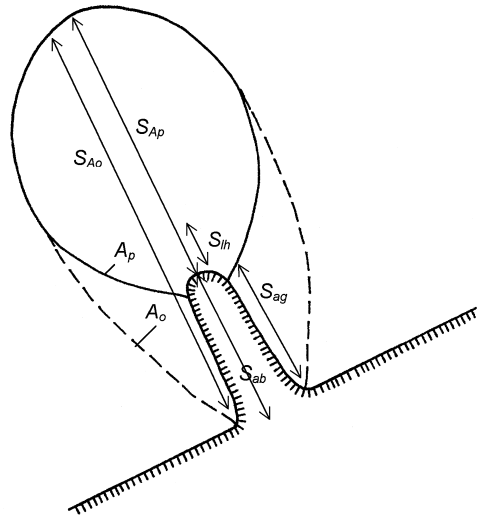


Fig. 2. Location of the study sites in southeast Spain (a); (b) Guadix area; (c) Guadalentin basin.



LEGEND

A_o	Original drainage basin area
A_p	Present drainage basin area
S_{lh}	Local slope at the gully head
S_{Ap}	Average slope of the present drainage basin area
S_{Ao}	Average slope of the original drainage basin area
S_{ag}	Average slope along the gully side
S_{ab}	Average slope along the gully bed

Fig. 4. Topographical parameters measured at a bank gully site.

factors (Beer and Johnson, 1963; Thompson, 1964; Seginer, 1966; Stocking, 1980; Burkard and Kostaschuk, 1997). In fact, these relationships are valid as long as the observed growth mechanisms can be extrapolated in time, which probably represents only part of a gully's life span. Another group of studies uses a classification of gully types (Heede, 1970, 1974; Imeson and Kwaad, 1980) or gully sidewalls (Blong, 1985; Crouch and Blong, 1989) to predict future gully behaviour and sediment production, without providing quantitative estimates. The idea is that understanding gully morphology as a product of past and present gully processes is the basis for predicting future gully events. However, both the quantitative prediction equations and the qualitative assessment of gully erosion hazard are limited to projections to the near future. Measurements and/or observations of *existing* erosion phenomena serve to predict their future evolution, but do not predict nor help prevent gully erosion as such. Consequently, there is a lack of knowledge on the quantitative influence of factors controlling the presence, the prevailing processes and the severity of gullying in a certain environment. This paper presents a contribution to this topic by investigating quantitatively the relationship between the morphology of a number of selected, active bank gullies and some topographical parameters of the catchment as well as some characteristics of the soil material in which they have been formed. Both geometrical characteristics resulting from past erosion, and specific processes shaping the gullies, such as piping and fluting have been investigated. However, the main focus is on the long-term effect of environmental factors on the presence and the final appearance of bank gullies. No detailed process studies have been undertaken, but different gully initiating mechanisms have been considered.

The origin and progression of gullies has often been related to piping or tunnel erosion where high hydraulic gradients occur in dispersive materials. In their gully classification scheme, Imeson and Kwaad (1980) distinguished a U-shaped gully type, in which water is supplied from sub-surface sources in association with piping, usually found on slope deposits and pediments located on gently sloping lower slopes. The dispersive nature of the lower soil horizons is an essential condition for the formation of this gully type. Duplex soils are also susceptible to this type of gullying. Examples are given by Heede (1971) and Crouch (1976). De Ploey (1974) also attributed the generation of gullies in central Tunisia to progressive pipe collapse, and Gutiérrez et al. (1988) considered subsurface pipe networks as the initial cause of gully development in alluvial fans and on debris slopes in

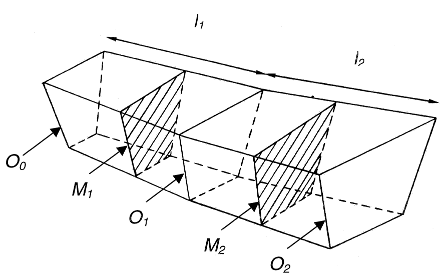


Fig. 3. Measurement and calculation procedure of the total eroded gully volume. O_i represent measured cross-sections. M_i are calculated cross-sections.

the Ebro basin (Spain). Crouch (1983) distinguished three stages in gully-head advance in dispersive duplex soils by a combination of tunnel and overfall erosion, and showed that gully heads advanced most rapidly when tunneling was a dominant active mechanism. Harvey (1982) identified soil conditions in which piping occurs, and showed a strong influence of deep pipes on gully network development, mainly on channel alignment in relation to tension cracks and sub-surface veining. However, the progressive development of piped areas may lead to the development of poorly or non-piped badlands, where surface or near surface processes dominate. No morphometric distinction could be made between badlands where pipe collapse had been important and areas developed by surface or near surface processes. From a study on the litho-structural control of pipe and gully development, Martín-Penela (1994) also concluded that when mature gullies tend to become stabilised, surface processes dominate their evolution. The general reduction of relief and hydraulic gradients implies that piping activity is restricted to small ducts in the sediments deposited in the gully floors or near the heads. Especially in isolated linear gullies, such as the bank gullies investigated within this study, piping gradually decreases and eventually disappears, or can be recognised only in relict morphologies of inactive pipes. Hence, it may become difficult to discern a previous stage of piping interaction in the development of such gullies. In this study, remnants of piping have been related to soil properties and are considered as an important indication of

Fig. 5. Illustration of piping (a), and fluting (b) at one of the studied bank gully heads in the Guadalentin basin.

Table 1
Summary of the measured parameter values for all the studied bank gully sites and for the separate study areas

Variable	Explanation	All sites ($n=55$)					Guadalentin ($n=42$)		Guadix ($n=13$)		Significance level of difference[a]
		Units	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Mean	Standard deviation	
Vol	Volume	m^3	3149	11 994	1.1	65 172	1915	10 016	7138	16 795	(**)
A_p	Present drainage basin area	m^2	359 875	2 140 482	5.1	15 832 950	31 146	146 638	142 192	4 352 455	(***)
A_o	Original drainage basin area	m^2	372 537	2 142 229	11.9	15 845 776	32 630	152 913	147 069	4 342 859	(***)
A_p/A_o	A_p-A_o ratio	%	73.4	22.1	18.2	99.9	72.2	21.1	77.5	25.6	
L_A_p	Length of A_p	m	439.0	1319.0	2.5	8280	145.9	390.3	1386.0	2458.0	*
L_A_o	Length of A_o	m	480.8	1342.0	4.4	8380	175.7	438.9	1467.0	2463.0	*
S_{lh}	Local slope at the gully head	%	12.7	8.8	2.0	38.5	15.4	8.4	4.3	2.0	***
S_{A_p}	Average slope of the present drainage basin	%	14.0	13.6	1.0	58.0	17.0	14.3	4.3	1.8	***
S_{ag}	Average slope of the soil surface along the gully	%	12.2	8.6	1.5	36.0	14.6	8.4	4.4	2.0	***
S_{ab}	Average slope of the gully bed	%	24.5	19.4	2.0	100.0	29.9	19.1	7.1	4.8	***
S_{A_o}	Average slope of the original drainage basin	%	13.8	11.5	1.3	49.1	16.7	11.7	4.5	1.6	***
L	Total gully length	m	41.8	64.3	1.5	350.0	29.7	54.7	80.9	79.0	**
D	Average gully depth	m	3.5	2.1	0.6	10.3	3.3	1.8	4.0	3.0	
W	Average gully width	m	5.0	5.3	0.8	31.6	4.9	5.1	5.6	6.0	
W/D	Width–Depth ratio	/	1.45	0.71	0.23	3.07	1.44	0.70	1.48	0.74	
W/L	Width–Length ratio	/	0.26	0.20	0.03	0.89	0.31	0.19	0.11	0.13	***
Hhc	Height of the headcut	m	2.1	2.2	0.1	12.0	2.2	2.0	1.8	2.6	
Clay	Clay content	%	16.7	10.9	0.6	36.9	15.6	10.4	20.3	12.0	
Silt	Silt content	%	61.8	16.8	17.3	88.4	65.5	14.0	49.7	20.1	**
Sand	Sand content	%	21.5	16.2	2.6	63.1	18.9	12.6	30.0	23.2	
Clay + Silt	Clay + Silt content	%	78.5	16.2	36.9	97.4	81.1	12.6	70.0	23.2	
RFr	Rock fragment content	%	5.2	12.4	0.0	56.9	2.6	6.5	13.7	21.2	*
D_clay	Change in clay content after dispersion[b]	%	13.6	10.3	−4.7	34.8	12.9	10.5	15.8	9.8	
D_Silt	Change in silt content after dispersion[c]	%	−9.0	10.6	−33.1	10.7	−8.4	11.0	−10.7	9.7	
D_sand	Change in sand content after dispersion[d]	%	−4.6	5.8	−36.9	0.6	−4.5	6.2	−5.0	4.5	
EC	Electrical conductivity	mS/cm	3.04	2.71	0.12	13.09	3.78	2.68	0.65	0.63	***
R	Dispersion Ratio	%	94.6	4.4	82.3	100.0	95.2	4.1	92.8	4.9	*

the potential role of this process in the initiation of the respective bank gullies.

2. Study areas

Two study areas have been selected in Southeast Spain, i.e., the Guadalentin basin and an area around the town of Guadix (Fig. 2a). Fig. 2b and 2c show the location of the individual gully sites within each area. The Guadalentin basin is a target area of the Mediterranean Desertification and Land Use (MEDALUS) project. The Guadix area has been chosen to represent different environmental conditions within the same climatic zone. Both areas have a semi-arid climate; however, the area around Guadix is slightly wetter and cooler than the Guadalentin basin. The annual precipitation in the Guadalentin study area, i.e., the average of the measurements over 25 years at 4 locations near the gully sites (Zarcilla de Ramos, Vald'Infierno, Puentes, Lorca), amounts to 276 mm, and the mean daily temperature 16.4°C (Casa Forestal-Zarcilla de Ramos; Andrade, 1990). Near Guadix, 14.5 years' measurements at two meteorological stations (Guadix and Esfiliana) give an annual average precipitation of 325 mm, and a mean daily temperature of 14.9°C (Andrade, 1990). The main differences between the two study areas result from the contrasting geological and lithological situations, and the distinct topographical characteristics of the landscape.

In the Guadalentin, the landscape can be described as a basin and range topography. The inter-mountain sedimentary basins consist of marls and marly limestones of Cretaceous to Tertiary age, covered by Quaternary deposits. These basins were uplifted in the late Neogene and early Quaternary, and consequently, the valley bottoms were incised by ephemeral rivers from which the studied bank gullies developed into the lower hillslopes. The Quaternary sediments consist of alluvial and slope deposits, but they often have an undifferentiated composition, and are difficult to distinguish from each other. Some Tertiary formations contain layers of conglomerate and sandstone, occurring at a minority of the study sites.

The Guadix basin is a wide inter-mountain sedimentary basin between the Sierra Nevada, the Sierra de Baza and the Sierra Arana, uplifted and dissected by an ephemeral river network. The studied bank gullies in this basin are located further from the drainage divide in relatively flat surroundings, compared to the Guadalentin, where the distance from the bank-gully heads to the drainage divides is generally smaller and the slope of the land steeper. In the Guadix area, Quaternary gravel and red clay is the most frequently occurring formation at the studied gully sites. Other formations consist of a combination of Tertiary to Quaternary loams, marls, sands, clays, and conglomerates.

Current land use in both study areas is a mixture of arable land (wheat and almond cultivation) and rangeland.

3. Materials and methods

Screening of aerial photographs covering the study areas, followed by field prospection allowed the identification of a set of 55 apparently active bank gullies. 42 sites have been selected in the Guadalentin, and 13 sites in the Guadix area. The selection aimed at obtaining a representative range of bank-gully types and sizes, and of material properties. Two years monitoring of these gullies allowed the observation of active erosion processes. Processes indicating activity and shaping a gully include the formation of tension cracks at the rim of the head- and the side-walls, promoting mass movements by which the gully extends in length and width, undercutting at the gully head by plunge-pool

Notes to Table 1:

[a] Significance level of the difference between the mean parameter values for both study areas: * = 10%; ** = 5%; *** = 1%; ( ) = significance level of the logged parameter.

[b] % clay measured in dispersed sample − % clay measured in non-dispersed sample.

[c] % silt measured in dispersed sample − % silt measured in non-dispersed sample.

[d] % sand measured in dispersed sample − % sand measured in non-dispersed sample.

activity and fluting, and, in case of sloping side walls, sheet erosion and the formation of small rills and headcuts. Although piping was expected to be an active erosion process, a longer term observation showed that the presence of pipes was not an indication of strong erosion activity. Subsurface flow as a trigger for headcut erosion, e.g., by undercutting, could, in the absence of water, only be assumed at six gully sites. All bank gullies are linked either directly or indirectly with an ephemeral river (rambla or barranco). Only first- or second-order channels were selected. If necessary, the gully length was considered only to the first or second bifurcation instead of down to the outlet in the main river. Most gullies are continuous (some have upstream rills or small headcuts), and both U- and V-shaped gullies were included, as well as combinations of these types. Often, the cross section varied from U-shaped at the head to V-shaped further downstream, due to the dominance of erosion activity at the head and the accumulation and stabilisation of debris against the downstream side-walls.

For each bank-gully site, geometrical and topographical parameters of both the channel and the drainage basin were measured. The total eroded volume of each bank gully was determined by measuring cross-sectional areas, mostly simplified as quadrangles or triangles (areas 'O_i' in Fig. 3), at regular intervals along the entire gully length. This was carried out using measuring tapes. The total bank gully volume (V) was then calculated according to the formula (Tysma et al., 1995)

$$V = \sum_{i=1}^{n} \left(\frac{1}{6} l_i (O_{i-1} + O_i + 4M_i \right)$$

where $n =$ the number of intervals at which a cross-sectional area was measured, $l_i =$ the distance between the measured cross-sectional areas O_{i-1} and O_i; and $M_i =$ the area of the cross section between the measured O_{i-1} and O_i, which can be geometrically derived. A related parameter is the total gully length, $L = \sum_{i=1}^{n} l_i$. From the basic measurements, an average depth (D) and width (W) of each gully, and consequently, a width-depth ratio (W/D) and a width-length ratio (W/L) were calculated.

The present drainage basin area (A_p), i.e., the area draining to the present gully head, the original drainage basin (A_o), i.e., the area draining to the gully mouth (i.e., the original gully head assuming the gully was formed solely by surface processes), and several characteristic slopes of the catchments and along the gully profile were measured (Fig. 4). The drainage-basin area was delineated by visual assessment of local topography and signs of overland flow if these were still present. The area was subdivided into smaller polygons (quadrangles and triangles) that were measured with a measuring tape. The total drainage-basin area was then calculated as the sum of the areas of the individual polygons. The parameter A_p/A_o was calculated to express a relative stage of development of the bank gullies: the greater the difference in present and original catchment area (i.e., the smaller A_p/A_o), the more developed the gully must be. Characteristic slopes were measured with a clinometer and include the local slope above the gully head, measured over a distance of 3 m or less (S_{lh}), the average slope of the present drainage basin (S_{A_p}), the average slope of the original drainage basin (S_{A_o}), the average slope of the soil surface along the gully side (S_{ag}) and the average slope along the gully bed (S_{ab}).

Specific erosion processes in the bank gullies were inventoried by means of geomorphological mapping of the gully head and sketches of characteristic gully-head or side-wall profiles. One to two soil samples for each gully site were taken from distinct soil layers associated with processes such as piping (Fig. 5a) and fluting (Fig. 5b) and/or showing clear differences in texture. As already mentioned, pipes appeared to be relict features of past erosion activity. No changes in shape took place during the monitoring period. Vertical pipes were observed in side-walls (Fig. 5a), but seemed not active anymore. Sub-horizontal pipes, most often formed in slumped and non-evacuated sediment in the gully bed, could still act as ducts for freshly eroded material from the head. However, no roof collapse and consequent deepening of the gully bed was observed.

Flutes are vertically elongated grooves, generally tapering to the top, which furrow into the wall of the gully. They result predominantly from the action of running water (Veness, 1980) or throughflow (Blong, 1985), in combination with raindrop impact and

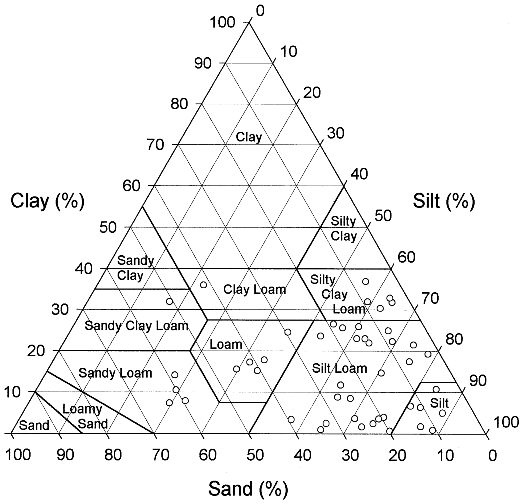


Fig. 6. USDA texture diagram for the fine earth fraction of all studied bank gully sites ($n = 55$).

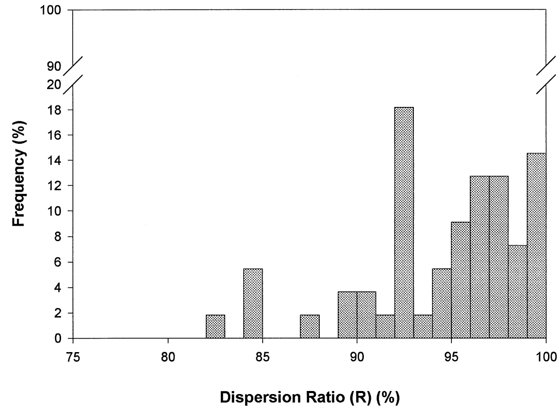


Fig. 7. Histogram of the dispersion ratio (R) for all studied bank gullies ($n = 55$).

splash. In the studied bank gullies, flutes were often found in actively eroding heads, under an apparently more resistant upper soil layer (Fig. 5b). In the Guadalentin, their development and consequent destruction were clearly responsible for undercutting of the headwall as the first trigger of headcut retreat.

The extent of the soil layers with piping and fluting, as well as the location where the samples were taken, was indicated on the profile sketches. From a total of 67 samples, rock fragment content was determined as well as particle-size distribution using the sieve-pipette method without and with addition of a dispersing agent. The difference in clay and silt content before and after dispersion is a measure of the stability of the aggregates in which these particles are 'hidden'. Therefore, Middleton's (1930) ''dispersion ratio'', defined as $R = ((\text{silt} + \text{clay})_{\text{non dispersed}})/((\text{silt} + \text{clay})_{\text{dispersed}})$, was calculated for each sample. This erodibility index expresses the relative amount of total silt and clay content that is easily dispersed by water (without the addition of a dispersing agent). Middleton (1930) classified soils with a ratio below 15% as 'non-erodible soils' and above 15% as 'erodible soils'.

The data of the dispersed samples were used to characterise each bank gully by a USDA soil texture class (Soil Science Society of America, 1996). If more than one sample was taken per gully, a weighted average of the particle-size distribution according to the depth of the sampled soil layers was used. Likewise, a depth-weighted average of the dispersion ratio (R) was determined for each gully from the values of R of the individual soil layers.

The electrical conductivity (EC) was measured from the same soil samples on a mixture of 1:2.5 soil

Table 2
Mean values of soil physical and chemical parameters for soil layers showing piping ($n = 17$) or fluting ($n = 18$) vs. those without (underlined values are significantly different: * 5%, ** 1%*, *** 0.1%)

	N	Clay (%)	Silt (%)	Sand (%)	RFr (%)[1]	R (%)	EC (mS/cm)
Piping	17	17.0	<u>71.2</u>***	<u>11.8</u>***	3.4	93.6	<u>4.7</u>***
No piping	50	16.8	<u>55.4</u>***	<u>27.8</u>***	6.1	93.2	<u>2.1</u>***
Fluting	18	17.6	62.1	20.3	<u>1.7</u>*	<u>96.5</u>**	2.9
No fluting	49	16.6	58.0	25.4	<u>6.6</u>*	<u>92.4</u>**	2.6

and distilled water. This parameter measures the soluble salt content or electrolyte concentration, influencing the dispersion behaviour of the soil.

The relationship between soil material characteristics and the presence of a specific erosion process shaping the gully was studied, in particular for piping and fluting. For this purpose, mean values of the measured soil parameters from the samples taken in soil layers associated with the process were statistically compared with those from the samples taken in soil layers were the process was not observed.

The dataset of all measured geometrical, topographical, and soil parameters for each bank-gully site was statistically analysed. At each step in the

Table 3
Correlation matrix of measured topographical parameters and material characteristics ($n = 55$), Correlation coefficient R = large font, Significance level P = small font

	Log_Vol	Log_A_p	Log_A_o	A_p/A_o	Log_S_{lh}	Log_S_{A_p}	Log_S_{ag}	Log_S_{ab}	Log_S_{A_o}	W/D
Log_Vol	1.000	0.781	0.811	0.029	−0.580	−0.311	−0.376	−0.476	−0.340	0.463
	0	0.0001	0.0001	0.8339	0.0001	0.021	0.0046	0.0002	0.011	0.0004
	Log_A_p	1.000	0.993	0.426	−0.748	−0.428 − 0.668	−0.627	−0.523	0.365	−0.522
		0	0.0001	0.00012	0.0001	0.00011	0.0001	0.0001	0.0001	0.0062
		Log_A_o	1.000	0.319	−0.752	−0.437	−0.660	−0.636	−0.526	0.394
			0	0.0175	0.0001	0.0008	0.0001	0.0001	0.0001	0.0029
			A_p/A_o	1.000	−0.265	−0.104	−0.342	−0.174	−0.194	−0.095
				0	0.0509	0.4498	0.0107	0.2038	0.1563	0.4924
				Log_S_{lh}	1.000	0.661	0.799	0.635	0.759	−0.193
					0	0.0001	0.0001	0.0001	0.0001	0.158
					Log_S_{A_p}	1.000	0.535	0.296	0.958	−0.030
						0	0.0001	0.0283	0.0001	0.8307
						Log_S_{ag}	1.000	0.648	0.701	−0.113
							0	0.0001	0.0001	0.4121
							Log_S_{ab}	1.000	0.409	−0.284
								0	0.0019	0.0354
								Log_S_{A_o}	1.000	−0.045
									0	0.7442
									W/D	1.000
										0
										W/L

analysis, the results for the entire dataset including all the sites in both the Guadalentin and the Guadix area were compared with those for the separate areas. This involves differences in sample size. A correlation matrix was constructed to study the relationships between all the parameters. Meaningful and statistically significant relationships have been selected and interpreted in more detail. Particular attention has been paid to environmental factors explaining the geometrical characteristics of the bank gullies resulting from past erosion, which is mainly reflected in the total eroded volume. Therefore, statistical relationships between these parameters were investigated by simple and by multiple regression.

W/L	Hhc	Clay	Silt	Sand	Rfr	*D_Clay*	*D_Silt*	*D_Sand*	EC	*R*
−0.536	0.450	0.139	−0.245	0.161	0.368	0.146	−0.018	−0.229	−0.334	−0.228
0.0001	0.0006	0.3128	0.0715	0.24	0.0057	0.2866	0.8891	0.0932	0.0127	0.0944
0.222	0.189	−0.239	0.121	0.234	0.171	0.009	−0.322	−0.501	−0.245	
0.0001	0.1029	0.166	0.0788	0.3793	0.0857	0.2111	0.9474	0.0165	0.0001	0.0711
−0.557	0.236	0.187	−0.246	0.130	0.266	0.165	0.016	−0.324	−0.517	−0.263
0.0001	0.0829	0.1708	0.0698	0.3445	0.0495	0.2275	0.908	0.0157	0.0001	0.0525
0.113	−0.001	0.121	−0.021	−0.059	−0.172	0.137	−0.072	−0.111	−0.076	0.066
0.4124	0.9934	0.3805	0.8791	0.6678	0.2081	0.3189	0.5993	0.4193	0.5806	0.6318
0.368	−0.193	−0.251	0.415	−0.263	−0.404	−0.232	0.083	0.261	0.537	0.140
0.0057	0.159	0.0649	0.0016	0.0527	0.0022	0.0888	0.5477	0.0543	0.0001	0.3078
0.145	−0.034	−0.106	0.471	−0.418	−0.507	−0.100	0.095	0.004	0.411	0.090
0.2904	0.806	0.4433	0.0003	0.0015	0.0001	0.4663	0.4887	0.9783	0.0018	0.5122
0.202	−0.030	−0.365	0.387	−0.157	−0.324	−0.325	0.181	0.248	0.497	0.223
0.1397	0.8293	0.0062	0.0035	0.252	0.0159	0.0154	0.1865	0.0678	0.0001	0.1021
0.337	−0.249	−0.174	0.214	−0.105	−0.286	−0.140	0.000	0.251	0.281	0.128
0.0118	0.0673	0.2042	0.1173	0.4456	0.0342	0.3067	0.9991	0.065	0.0378	0.3535
0.132	−0.003	−0.178	0.506	−0.405	−0.482	−0.169	0.131	0.060	0.479	0.139
0.3352	0.9803	0.1936	0.0001	0.0021	0.0002	0.2184	0.34	0.6636	0.0002	0.3109
−0.147	0.104	0.078	−0.233	0.189	0.158	0.096	0.077	−0.312	−0.214	−0.278
0.2836	0.4511	0.5728	0.0873	0.1661	0.2503	0.486	0.5767	0.0203	0.1163	0.0396
1.000	−0.011	−0.041	0.095	−0.071	−0.268	−0.024	−0.043	0.122	0.244	0.153
0	0.9369	0.7679	0.491	0.606	0.0476	0.8603	0.7552	0.3737	0.0727	0.2658
Hhc	1.000	0.122	−0.091	0.012	0.127	0.142	−0.219	0.149	0.092	0.110
	0	0.3768	0.5108	0.9284	0.354	0.3016	0.108	0.276	0.5061	0.4248
	Clay	1.000	−0.379	−0.278	0.152	0.983	−0.803	−0.277	−0.316	−0.124
		0	0.0043	0.0398	0.2667	0.0001	0.0001	0.0405	0.0187	0.3687
		Silt	1.000	−0.783	−0.641	−0.409	0.407	−0.018	0.487	0.298
			0	0.0001	0.0001	0.0019	0.002	0.8982	0.0002	0.0273
			Sand	1.000	0.563	−0.235	0.117	0.204	−0.293	−0.226
				0	0.0001	0.0841	0.3952	0.1344	0.0298	0.097
				Rfr	1.000	0.137	−0.138	0.010	−0.197	−0.256
					0	0.32	0.3143	0.9406	0.1493	0.0588
					D_Clay	1.000	−0.848	−0.226	−0.285	−0.082
						0	0.0001	0.0966	0.0349	0.5502
						D_Silt	1.000	−0.325	0.229	−0.203
							0	0.0155	0.0923	0.1362
							D_Sand	1.000	0.087	0.520
								0	0.526	0.0001
								EC	1.000	0.232
									0	0.0887
									R	1.000
										0

4. Results

A statistical summary of the data is given in Table 1, including the mean values, standard deviation and range of the measured parameters for all the studied bank-gully sites, as well as the values for the Guadalentin and for the Guadix areas separately, indicating significantly different parameters between both areas.

The USDA texture diagram (Fig. 6) shows that most studied bank gullies are characterised by a fine earth texture belonging to the silt, silt loam, silty clay loam, loam and sandy loam class. The rock fragment content in 91% of the gullies is lower than 7%. Only 5 sites, situated in Guadix, have a higher rock fragment content ranging between 20% and 57%. According to Middleton's (1930) erodibility classification, all sites are 'erodible' with very high values of the dispersion ratio R, ranging between 83% and 100% (Fig. 7). Electrical conductivity values (EC) indicate that this parameter is greatly variable with, but not systematically related to the depth at which the sample was taken. This soil parameter also seemed to be dependent on changes in textural composition, and on the topographical position of the bank gully (e.g., distance from the drainage divide). In spite of the variations in EC values within the separate study areas, there is a significant difference between the mean value for the Guadalentin compared to the Guadix area (see Table 1).

Table 2 shows the mean values of the measured soil parameters for the samples taken in soil layers with piping or fluting, in comparison with the results for the samples from horizons where the processes were not observed. This reveals significant differences in silt and sand content, and in EC for the soil horizons showing piping versus those without, and in gravel content and R (dispersion ratio) for the soil layers showing fluting versus those without.

The correlation matrix of the entire dataset is partly shown in Table 3. A significant topographical relationship exists between the local slope at the gully head (S_{lh}) and the present catchment area (A_p), i.e., the area draining to the gully head (Fig. 8). The relationship has a correlation coefficient $R = -0.748$ ($P = 0.0001$), and is significant for the Guadalentin ($R = -0.688$, $P = 0.0001$) but not for Guadix ($R = -0.258$, $P = 0.395$). Hence, the good

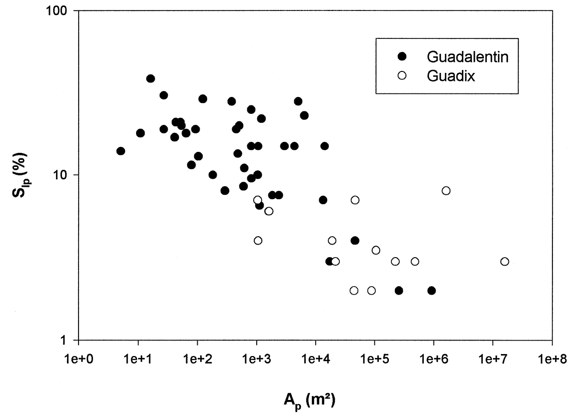


Fig. 8. Local slope (S_{lh})–drainage basin area (A_p) relationship at the head of the studied bank gullies in the Guadalentin basin ($n = 42$) and the Guadix area ($n = 13$).

correlation for the entire dataset is based mainly on that for the Guadalentin and also on the difference between the study areas, i.e., significantly smaller catchment areas and steeper slopes in the Guadalentin compared to the Guadix area. The negative slope-catchment area relationship at the bank-gully heads results from the more pronounced topography of the Guadalentin. In contrast, it is less evident in the relatively flat Guadix basin, where there is little variation in slope with distance from the drainage divide. In addition, the poor significance for the Guadix dataset may also result from its smaller sample size. Nevertheless, this relationship indicates the average topographical position of the studied bank gully heads in the landscape.

Geometrical characteristics of the bank gullies seem to be related to each other and to some environmental parameters. For instance, the total eroded bank-gully volume (V) is positively correlated to the width-depth ratio (W/D) ($R = 0.463$, $P = 0.0004$) and negatively to the width-length ratio (W/L) ($R = -0.536$, $P = 0.0001$). This indicates that in gully growth (increasing bank-gully volume), widening is more important than deepening, but less important than linear gully extension. Width-depth ratio is negatively correlated to dispersion ratio (R) ($R = -0.278$, $P = 0.0396$), indicating that bank gullies in highly dispersive material are rather deep and narrow, and possibly have been formed as collapsed

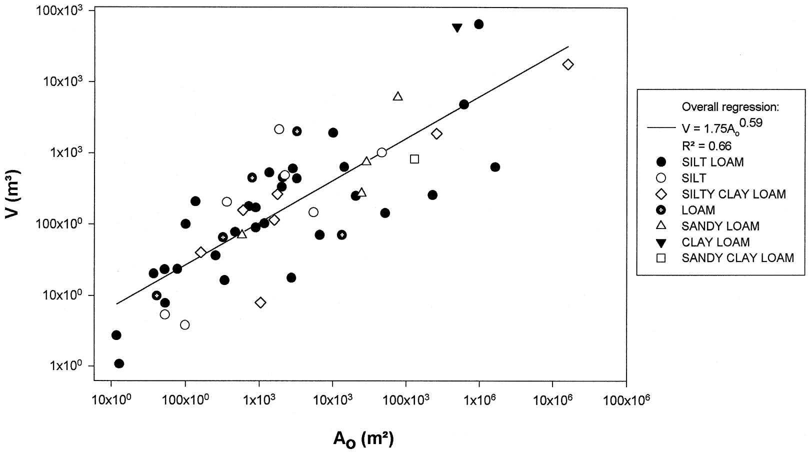


Fig. 9. Bank gully volume (V) vs. original catchment area (A_o) for all study sites ($n = 55$), differentiated by USDA texture class.

pipes. A positive relationship exists between height of the headcut (Hhc) and the present drainage basin area (A_p) ($R = 0.222$, $P = 0.1029$). However, the correlation is significant for the Guadalentin ($R = 0.316$, $P = 0.0413$), but not for the Guadix area ($R = 0.346$, $P = 0.247$). There is also a negative correlation between height of the headcut (Hhc) and average slope of the gully bed (S_{ab}) ($R = -0.249$, $P = 0.0673$), indicating that a steeper bed of a bank gully results in a smaller headcut height. Again, this correlation is significant for the Guadalentin ($R = -0.416$, $P = 0.0062$), but not for the Guadix area ($R = -0.242$, $P = 0.4265$). Also the differences in significance of the correlation between these parameters in the two study areas may partly result from the difference in sample sizes. However, physical causes should not be excluded and are discussed below (see Discussion).

The most significant correlation with total eroded bank gully volume (V) is found with the original

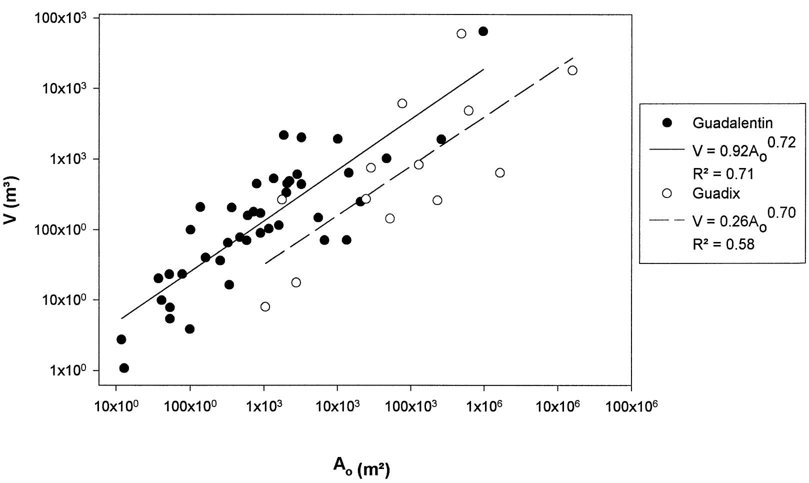


Fig. 10. Bank gully volume (V) vs. original catchment area (A_o) for the Guadalentin basin ($n = 42$) and the Guadix area ($n = 13$).

catchment area (A_o), i.e., the area draining to the gully mouth, explaining 66% of the variance. The relationship is given by

$$V = 1.75^* A_o^{0.59}.$$

This relationship is depicted in Fig. 9, where the USDA texture classes for the individual gully sites are indicated. Visually, points of the same texture class do not cluster in a certain position relative to the overall regression line. This was statistically confirmed as no significant difference was found between regression lines through the sub-datasets of individual USDA texture classes. In contrast, when comparing both study areas (Fig. 10), the V–A_o regression line for the sites in the Guadalentin plots parallel to, but above that of the Guadix area, expressing a significantly higher intercept ($\alpha = 10\%$), but no significant difference in slope. This suggests that, for a given catchment area, smaller gullies are formed in the Guadix study area compared to the Guadalentin.

Multiple regression analysis has been applied to relate the total eroded bank-gully volume (V) to all measured parameters listed in Table 1, apart from

Table 4
Results of the multiple regression analysis for the entire dataset and the sub-datasets of the Guadalentin and the Guadix area, using as input all parameters (A), and only predictive topographical parameters and material characteristics (B), with R^2 = coefficient of determination of the multiple regression equation; R_p^2 = partial R^2; p = p-value of parameter estimate

(A) Input = all parameters							
All gullies							
$R^2 = 0.7872$							
Log_Vol =	−0.34 + 0.80	Log_A_p − 0.02	A_p/A_o + 0.84	Log_S_{ag} + 0.01	RFr − 0.01 D_	*Silt* + 0.047EC	
p	0.5291	0.0001	0.0001	0.0080	0.0671	0.1277	0.1323
R_p^2		0.6095	0.1123	0.0282	0.0203	0.0065	0.0104
Guadalentin							
$R^2 = 0.8236$							
Log_Vol =	0.87 + 0.92	Log_	A_p − 0.02	A_p/A_o + 0.02	RFr + 0.02 D_	*Sand* + 0.04EC	
p	0.0025	0.0001	0.0001	0.0690	0.1361	0.1139	
R_p^2		0.6602	0.1246	0.0166	0.0114	0.0108	
Guadix							
$R^2 = 0.8278$							
Log_Vol =	5.92 + 0.69	Log_A_o − 1.32	Log_A_p/A_o − 2.48	(Clay + Silt) + 0.03	*D_Clay*		
p	0.0277	0.0009	0.1477	0.0793	0.1582		
R_p^2		0.5841	0.1470	0.0445	0.0521		
(B) Input = predictive topographical parameters and material characteristics							
All gullies							
$R^2 = 0.7228$							
Log_Vol =	−0.67 + 1.20	Log_	L_A_o + 0.40	Log_S_{A_o} +	0.02RFr		
p	0.1240	0.0001	0.1193	0.0051			
R_p^2		0.6756	0.0336	0.0136			
Guadalentin							
$R^2 = 0.7510$							
Log_Vol =	−0.51 + 1.41	Log_	L_A_o +	0.02RFr			
p	0.0483	0.0001	0.1873				
R_p^2		0.7395	0.0115				
Guadix							
$R^2 = 0.7647$							
Log_Vol =	0.67 + 0.68	Log_A_o − 0.02	Silt				
p	0.4442	0.0007	0.0198				
R_p^2		0.5841	0.1806				

those directly or indirectly used for the calculations of the volume itself (i.e., total gully length, L, average gully depth, D, average gully width, W, width–depth ratio, W/D, width-length ratio, W/L, depth of the plunge pool, Hhc). The procedure resulted in different but comparable relationships for the entire dataset and the sub-datasets of the Guadalentin and the Guadix area. The result also depended on the combination variables used as input for the stepwise regression procedure. The number of variables in the relationships was further reduced to remove the effect of multicollinearity, which was detected by means of the variance inflation factors of the parameter estimates, and the condition numbers (Freund and Littell, 1991). The equations for both the entire and the separate datasets are given in Table 4, together with the model R^2, the partial R^2 of the selected parameters, and the P-value of the parameter estimates. First, all parameters have been used as input, resulting in the highest R^2 of the fitted relationships (Table 4A). Second, only variables with a predictive value have been used (Table 4B). Therefore, topographical parameters related to or affected by the gully itself, such as average slope along the gully bed (S_{ab}) or along the gully side (S_{ag}), the present drainage-basin area (A_p), the average slope of the present drainage-basin (S_{ap}) and the local slope at the gully head (S_{lh}) were omitted in this input.

5. Discussion

5.1. Piping and fluting in relation to material properties

In our study, piping was observed in only 17 bank gullies, and most pipes appeared to be fossil and relatively inactive. However, the pipe remnants are an indication that these and similar gullies have been initiated from a collapsed pipe or pipe net, or at least developed by a mixture of piping activity with overland flow processes. All bank gullies with pipes were located in the Guadalentin, and no pipes were observed in the studied bank gullies of the Guadix area. Consequently, the initiation of the studied bank gullies by pipe collapse is considered more likely in the Guadalentin than in the Guadix area. Two reasons may explain this unequal distribution: (1) related to soil properties and (2) related to the influence of local topography.

First, the physico-chemical analysis shows that piping occurs in soil layers with a higher electrical conductivity (EC), and a higher silt and lower sand content (Table 2). Although there is no significant difference in dispersion ratio (R) between soil layers with piping and those without (Table 3), EC is positively correlated with R (Table 3), indicating that higher EC values enhance dispersion behaviour in the sampled soil horizons. Swelling and dispersion depend on the relationship between electrical conductivity (EC) and sodium absorption ratio (SAR) (Kamphorst and Bolt, 1976). Dispersion is usually related to high SAR values, but may be inhibited by too high soluble salt contents (i.e., EC values). However, the average EC value of the soil horizons with piping in this study (4.7 mS/cm) is much lower than values reported by Imeson et al. (1982) for saline (EC 10–26 mS/cm) and sodic (SAR 20–35) soils, resulting in a non-dispersive chemical environment. Gutiérrez et al. (1988) reported very high values for both EC (up to 26 mS/cm) and SAR (48–67) in soils showing severe piping. In that case, dispersion was favoured by leaching of the soluble salts whereas high levels of sodium saturation remained. Methods for assessing soil dispersivity include (i) field dispersion tests such as the Emerson test (Loveday and Pyle, 1973), used by Imeson et al. (1982), (ii) dispersion thresholds with respect to the SAR and EC (Agassi et al., 1981; Imeson and Verstraten, 1988; Gerits, 1991), and (iii) dispersion indices such as the Middleton index or variations on this index, used by Imeson et al. (1982), Gerits (1991), Gerits et al. (1987) and Gutiérrez et al. (1988, 1997). Besides chemical characterisation of the soil, several physical properties are also related to its dispersion behaviour. Gerits et al. (1987) used consistency parameters indicating the capacity of material to withstand flow or plastic deformation in terms of its moisture content, such as the plastic and liquid limits to calculate the plasticity index and the activity (Young and Warkentin, 1975), and determined the C_{5-10}-index developed by De Ploey and Mücher (1981). They also measured volumetric properties such as the shrinkage limit, $COLE_{25}$ and the dry bulk density. Most studies relate the presence of pipes to soil texture characteristics. Gutiérrez et al. (1988) report a high silt and clay content and a low sand content of piped soils, and the granulometric fraction smaller than 4 μm was statistically correlated to piping by Gutiérrez et al. (1997). In a study of Harvey (1982), however, silt and clay percentages could not differentiate between piped and non-piped sites. More important was the nature of the material at depth, particularly the presence of differential porosity, solubility and strength, together with surface features allowing concentrated penetration of surface water such as deep tension cracks or desiccation cracks, and surface crusting over less consolidated subsurface layers. According to Martín-Penela (1994), the most decisive factors for piping are the presence of poorly indurated silty–clayey materials containing cracks, fractures or other discontinuities, such as (gypsum-filled) joints and faults.

Compared to these studies, entirely dedicated to piping processes, only a limited number of simple physical–chemical parameters has been determined in this study on bank-gully characteristics, but the relationships found between piping and material characteristics correspond relatively well, i.e., piping was related to the more dispersive, silty soil horizons. Consequently, the first reason for the absence of piping at the study sites near Guadix vs. the exclusive presence in the Guadalentin is also related to the difference in material properties between these two areas. Table 1 shows a lower EC value, a lower silt content, a higher sand and a higher rock fragment content for the Guadix area compared to the Guadalentin, suggesting a lower soil dispersivity.

The second reason is probably related to the difference in overall relief between the two study areas. The wider and flatter drainage basins in the Guadix area, as illustrated by their significantly smaller slope gradients (Table 1), may imply that pipe development was restricted by smaller hydraulic gradients. Consequently, overland flow erosion might have been more important in the Guadix area, whereas in the Guadalentin, more gullies developed from collapsed pipes.

The role of fluting in gully development in dispersible materials, in particular side-wall evolution, has been extensively described by Veness (1980) and Blong (1985). The process of fluting is described in a sequence of stages, starting with rilling in a fresh planar face together with the transport of the dislodged material by the channel, over the initiation and development of flutes, to their destruction (by undercutting or slumping) and eventually complete drowning of the flutes by their own debris when the channel is incapable of collecting and removing the material. In short, gully side-wall development is dominated by the growth, decay and stabilisation of flutes. Whereas these authors stressed the importance of fluting in gully sideward extension, flutes were often observed in the head of the studied bank gullies. In the Guadalentin, this process contributed to headcut retreat by undercutting a more resistant layer on top, when the action of overland flow or plunge pool erosion destroyed the flutes. In the Guadix area, the process appeared to be less active. The frequency of fluting was about the same in the Guadalentin as in the Guadix area, i.e., at 33% and 30% of the sites in the respective areas. Material characteristics of fluted vs. non-fluted horizons (Table 2) show that fluting is related to a higher dispersion ratio (R) and a lower gravel content (RFr), and therefore can be considered to accelerate the erosion process and sediment production from the studied bank-gully heads.

5.2. Topographical and geometrical relationships

The present topographical position of the heads of the studied bank gullies is represented by the relationship between the local slope at the gully head (S_{lh}) and the present drainage basin area (A_p) (Fig. 8). A topographical threshold for the initiation of bank gullies would consist of a similar relationship between topographical parameters at their original initiation point, i.e., at the edge of the rambla banks where the outlet of the present gullies is located. For comparison, the initiation of gullies on hillslopes by overland flow occurs where a critical flow shear stress at the soil surface is exceeded (Montgomery and Dietrich, 1988). This erosional threshold can be expressed by a negative power relation between the local slope and drainage basin area at the gully initiation point (Begin and Schumm, 1979). Applying this concept to the studied bank gullies would provide valuable information on the topographical conditions of bank gully initiation. However, the initiation of bank gullies is somehow different from the incision of a gully into a continuous hillslope (without banks) because of the sudden height drop at the rambla bank. The main trigger for incision of the headcut is more likely to be the overfall depth or the hydraulic gradient at the rambla bank than the shear force at the soil surface near the rambla bank as determined by its local slope. Therefore, the original catchment area (A_o), substituting the runoff volume, should be related to the overfall depth (or the corresponding hydraulic gradient) rather than to the local slope of the soil surface at the original rambla bank where the headcut was first formed. In the field, however, it was impossible to accurately measure these parameters because severe erosion destroyed the original shape of the rambla bank at the outlet of most gully sites, leading to a gradually sloping surface instead of a sharp break. Consequently, the assumed relationships could not be verified. Such a study can only be undertaken at locations where bank gully erosion has just started and the rambla banks are still relatively intact, which was the case at only a few of our study sites.

The positive correlation between height of the headcut (Hhc) and present drainage basin area (A_p) for the bank gullies in the Guadalentin can be interpreted by the positive effect of discharge on plunge pool erosion. A large drainage basin above the gully head generates a large runoff discharge flowing over the headcut, enhancing rapid downcutting and deepening the plunge pool. This correlation is not significant for the Guadix area. The difference between the study areas can be explained by intrinsic differences in channel geometry. Because at most studied bank-gully sites (71%), the average slope of the gully bed (S_{ab}) is steeper than the average slope of the soil surface along the gully (S_{ag}), gully depth generally decreases in upstream direction, i.e. with decreasing drainage basin area. In the Guadalentin, S_{ab} and S_{ag} are significantly steeper than in the Guadix area (Table 1). Hence, comparing gullies of different length within one study area (assuming the respective mean values for S_{ab} and S_{ag} from Table 1), the decrease in headcut height with increasing distance from the rambla, or decreasing drainage basin area, will be much more pronounced in the Guadalentin compared to the Guadix area. The importance of average slope of the gully bed (S_{ab}) in relation to the height of the headcut (Hhc) is once more expressed by the negative correlation between these two parameters, significant for the Guadalentin but not for the Guadix area.

The greater average slope of the gully bed (S_{ab}) compared to the average slope of the soil surface along the gully (S_{ag}) illustrates that the studied bank gullies are situated in the lower part of a concave slope profile, where the slope of the soil surface is flattening out. If the slope of the gully bed (S_{ab}) and the slope of the soil surface along the gully (S_{ag}) would remain constant while a bank gully retreats, both would intersect at a certain point upstream. Hence, it would be possible to predict the point where bank gullies stop growing. However, the concave slope profile of their catchments implies that the slope of the soil surface increases much more than that of the gully bed. Consequently, other mechanisms must be responsible for the future stabilisation of the bank gullies.

Heede (1970) associated low values of width-depth ratio of a channel with a young stage of development, in which all width changes are accompanied by similar changes in depth. In this study, the positive correlation between width–depth ratio (W/D) and gully volume (V) may express the same relationship, as a larger volume can be seen as a further development stage, whereby width increases more than depth. It also implies that for large gully volumes, sidewall erosion becomes more important than linear incision, as suggested by Blong (1985) and Blong et al. (1982).

A positive correlation between total bank-gully volume (V) and the original catchment area (A_o) exists both for the entire dataset and for the sub-datasets of the Guadalentin and the Guadix area. As the original catchment area is a substitute for runoff volume entering the entire bank gully, this relationship expresses the physical effect of discharge as an erosive force. The importance of drainage basin area for gully growth has been shown by several authors investigating the effects of catchment characteristics and hydrologic variables (Beer and Johnson 1963; Thompson, 1964; Seginer, 1966; Stocking, 1980; Burkard and Kostaschuk, 1997). In most studies, headcut retreat occurs by the action of overland flow. Stocking (1980), however, made a distinction between gully growth by waterfall erosion (overland flow), piping, or a combination of the two. Multiple regression analysis pointed out that catchment area was highly significant for all heads that migrated at least partly through waterfall erosion, but this parameter was not selected for headcut retreat by piping alone. Also, Imeson et al. (1982) pointed out that where piping occurs due to swelling and dispersion, very high denudation rates can be expected that are not just a function of mechanical laws, i.e., the eroded volume may be extremely large compared to the volume of water draining it. In contrast, where interflow is responsible for undercutting by seepage erosion, the progression of gully heads and sidewalls is again related to contributing drainage area by Sneddon et al. (1988). Hence, the good correlation of total bank-gully volume (V) with original catchment area (A_o) resulting from this study suggests that in the long run, the total amount of water that has reached the gully during its lifespan, through either surface or sub-surface sources, determines its total eroded volume. Differences in growth rate between the first stages of development, possibly dominated by piping and hence less related to catchment area, and later stages when surface process become dominant, are averaged out at this time scale. The final extent of the gullies is determined by the volume of overland flow that can still reach the head after piping activity has disappeared. This explains the nonlinear increase in total eroded volume with drainage basin area, suggesting that gully growth is limited by water transmission losses in the catchment.

In the study of Seginer (1966), the area draining into the gully head (A, km^2) appears as the single most important factor explaining average annual gully head retreat, (E, m/year), measured over 15 years. He obtained a relationship of the form $E = aA^b$ with b ranging from 0.36 to 0.75 for 3 different areas in Southern Israel. Higher values for the exponent b were associated with samples of smaller catchments both within and between locations. This illustrates the higher efficiency in surface runoff production for smaller drainage basin areas. Finally, the average value of 0.50 for the exponent b is proposed for use in a practical prediction formula, valid for catchment areas ranging between 0.01 and 1 km^2. This b value is very close to the exponent of the relationship between original drainage basin area (A_o) and total eroded bank gully volume (V), found in this study ($b = 0.57$). Apparently, the cumulative effect of the original drainage basin area on gully growth, resulting in a certain eroded volume, is about the same as the short-term effect of the drainage basin area entering the gully head on linear gully growth. Burkard and Kostaschuk (1997) found a similar power relation between gully area growth rate (G_A, m^2/year) and drainage basin area (D, m^2), $G_A = 0.4D^{0.59}$ ($R^2 = 0.77$) from measurements over 62 years. The authors defined watershed area as the area that flows into the gully through the headcut and over the side slopes, because they measured the increase in planimetric area of the entire gully, including both headcut retreat and sidewall erosion. This parameter corresponds to the original drainage basin area (A_o) used in this study, and the relationship expressing the short-term effect on gully growth (in the order of decades) corresponds very well with our relationship expressing the long-term effect on total eroded volume (in the order of centuries, based on extrapolation of actual gully retreat rates measured in the study areas).

The difference in regression lines between the two study areas indicates smaller eroded volumes per unit catchment area in the surroundings of Guadix. Assuming that the gullies in Guadix are roughly the same age as those in the Guadalentin, this can be explained by topographical, lithological and climatic factors. Table 1 shows that average catchment slopes (S_{A_p} and S_{A_o}) as well as local slopes above the gully heads (S_{lh}) are steeper, on average, in the Guadalentin. Consequently, larger bank gullies can be formed with the same drainage basin area, because not only runoff volume, but also the flow velocity influences the erosivity of concentrated overland flow. Comparing material properties between the two study areas (Table 1), the Guadix area is characterised by less dispersive soils compared to the Guadalentin (see 5.1), and hence by an increased stability and erosion resistance of the material in which the studied bank gullies developed. Statistically, however, soil parameters were only poorly correlated with bank-gully volume. This shows that differences between the two study areas can only partly be attributed to different material properties and the main control of gully development in the long run is topography. In addition, erosion activity also depends on climatic factors. Although both areas have a semi-arid climate, the more humid conditions in Guadix allow a higher vegetation cover providing a higher erosion resistance.

5.3. Multiple regression

The multiple regression equations in Table 4 integrate the effects of both topographical parameters and soil material characteristics on the total eroded bank-gully volume. If all parameters are used as input, they provide a good reflection of the controlling factors (A), whereas limiting the input to predictive parameters provides a somewhat less accurate but more simple and useful tool to predict the future volume of bank gullies in a non-affected area (B). Drainage-basin area, A_o or A_p, or its length, L_A_o, is represented in all equations, and explains the main proportion ($>58\%$) of the total variation. The parameter A_o appeared to be the most significant by simple regression both in this study and in previous studies (Seginer, 1966; Burkard and Kostaschuk, 1997). In other studies using multiple regression to estimate future rates of gully head retreat, drainage basin area is always investigated as an input parameter. Drainage basin area above the gully head was represented in the equation proposed by Thompson (1964) with an exponent of 0.49. It was also highly significant in equations obtained by Stocking (1980) for gully heads that migrate at least partly through waterfall erosion. The exponent varies from 0.38 to 1.00 with an average of 0.68. In this study, exponent values for A_o are between 0.68 and 1.20.

The contribution of the remaining parameters varies from about 1 to 18%. Although the parameter A_p/A_o was not significantly correlated to V, neither for the entire or the separate datasets, it explains the second largest proportion of the variation in the multiple regression equations (in A) for all datasets. Obviously, this parameter is not predictive as it involves the present catchment area (A_p). Its negative coefficient in the equations corresponds to the idea that, when bank gullies retreat and hence increase in volume, the catchment at the headcut (A_p) becomes smaller compared to the original catchment (A_o). Thus, smaller values for A_p/A_o imply greater bank gully volumes. The average slope along the gully, S_{ag}, and of the original drainage basin, S_{A_o}, are represented in both types of equations (A and B) for the entire dataset. Its positive coefficient reflects decreasing transmission losses and increasing flow velocity with steeper catchment slopes, resulting in greater eroded volumes. In comparison, Thompson (1964) and Stocking (1980) tested the slope above the gully head (equivalent with our S_{lh}) as an input parameter for their headcut retreat model, but obtained rather poor results. The parameter was represented in the equation of Thompson with an exponent of 0.14, but with a low significance. Stocking did not withhold the parameter in his equations as it was insignificant at the short-term while it improved with longer-term measurements.

Material characteristics appearing in the equations include clay, silt and rock fragment content, change in clay, silt and sand content after dispersion, and electrical conductivity. Clay and silt appear in the equations (both A and B) for the Guadix area with a negative coefficient. The cohesive influence of clay contributes to the erosion resistance of the soil material, and hence clay content has a negative effect on the total eroded volume. Although silt can be considered as highly erodible, its negative coefficient is due to the fact that the largest bank gullies in the Guadix area were found in lithologies with a low silt content but high gravel and sand content. This also explains the positive coefficient of rock fragment content in the equations. It can be concluded that, if bank gullies in the Guadix area occur in gravels or lithologies with a high rock fragment content, they tend to be large, whereas in silty soils with few rock fragments, relatively small gullies develop.

Changes in particle-size distribution upon addition of a dispersing agent reflect the influence of soil dispersivity on the total eroded gully volume. A low negative value for *D_silt* (a great reduction in silt content after dispersion) has the same relative effect as a high positive value for *D_clay*, and a negative value for *D_sand* closer to zero (a small reduction in sand content after dispersion), i.e., increasing the total eroded volume. A great reduction of silt content after dispersion implies that (i) a relatively large proportion of the silt fraction consists of water-stable aggregates that disintegrate into clay particles upon addition of a dispersing agent, and (ii) a relatively small proportion of the sand fraction disintegrates into silt particles upon addition of a dispersing agent. The latter is confirmed by the negative correlation between *D_silt* and *D_sand* (see Table 3), and indicates that there are few water-stable aggregates of sand size, which can be considered as the least erodible. In contrast, particles or aggregates of silt size are generally considered to be highly erodible. Hence, the parameters *D_silt*, *D_clay* and *D_sand* in the multiple regression equations reflect relatively well the effect of aggregates of silt and sand size on the erodibility of the soil material in the estimations of total eroded volume. Finally, electrical conductivity (EC) also represents its influence on soil erodibility in some multiple regression equations. High EC values may enhance dispersion of the soil material in water, and therefore have a positive effect on bank gully volume.

6. Conclusions

This study focused on the morphology and geometrical characteristics of bank gullies resulting from present and past erosion processes in two semi-arid environments in Southeast Spain and revealed the following conclusions.

(1) Erosion processes shaping the bank gullies are related to soil material characteristics. Piping occurs in soil layers with a higher silt content, a lower sand content and a higher electrical conductivity, whereas horizons with fluting show a lower rock fragment content and a higher dispersion ratio.

(2) Correlation analysis of all measured bank-gully parameters showed a negative relationship between local slope at the gully head (S_{lh}) and the present drainage basin area (A_p), i.e., the area draining to the gully head, indicating the average topographical position of the studied bank gully-heads in the landscape. A similar relationship indicating the topographical threshold conditions for bank-gully initiation could not be determined because erosion of the original surface of the rambla banks inhibited accurate measurement of the necessary parameters. Some geometrical characteristics of the bank gullies, such as total eroded bank gully volume (V), width-depth ratio (W/D), width-length ratio (W/L) and depth of the plunge pool (Hhc) are related to each other. The overall result of bank gully erosion over time, expressed by its total volume (V), seems to be best related to the topographical parameter 'original drainage basin area' (A_o), explaining 66% of the variance of the relationship $V = 1.75 * A_o^{0.59}$. Soil texture had little impact on this relationship. The difference between the two study areas, indicating greater eroded volumes for a given drainage basin area in the Guadalentin compared to the Guadix area, may be due to steeper drainage basin area slopes, a lower erosion resistance of the soil material, and a higher degree of degradation due to drier and more extreme climatic conditions in this area. The implication of these findings is that, in order to reduce the eroded volume over time, conservation measures should focus on reducing the amount of overland flow draining into active gully heads. This could be achieved either by mechanical structures diverting the flow away from the headcut into stabilised channels, or by adopting land-use practices which increase surface roughness and depression storage (Oostwoud Wijdenes and Bryan, 1994).

(3) The effect of both topographical parameters and soil material characteristics on total eroded bank gully volume was integrated in multiple regression equations. The models based on all measured parameters explain up to 83% of the variation in V. R^2 is limited to 76.5% for the strictly predictive models, but these are more useful tools for erosion risk assessment studies in potentially vulnerable areas.

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References

Agassi, M., Shainberg, I., Morin, J., 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. Soil Sci. Soc. Am. J. 45, 845–851.

Andrade, J.L.A., 1990. Atlas Fitoclimatico de España, Taxonomias. Instituto Nacional de Investigationes Agrarias, Ministerio de Agricultura Pesca y Alimentacion, Madrid, 66 pp.

Archibold, O.W., De Boer, D.H., Delanoy, L., 1996. A device for measuring gully headwall morphology. Earth Surf. Proc. Landforms 21, 1001–1005.

Beer, C.E., Johnson, H.P., 1963. Factors in gully growth in the deep loess area of western Iowa. Trans. ASAE 6, 237–240.

Begin, Z.B., Schumm, S.A., 1979. Instability of alluvial valley floors: a method for its assessment. Trans. ASEA 22, 347–350.

Blong, R.J., 1985. Gully sidewall development in New South Wales, Australia. In: El-Swaify, S.A., Woldenhauer, W.C., Lo, A. (Eds.), Soil Erosion and Conservation. Soil Conservation Society of America, Ankeny, IA, pp. 574–584.

Blong, R.J., Graham, O.P., Veness, J.A., 1982. The role of sidewall processes in gully development; some N.S.W. examples. Earth Surf. Proc. Landforms 7, 381–385.

Burkard, M.B., Kostaschuk, R.A., 1995. Initiation and evolution of gullies along the shoreline of lake Huron. Geomorphology 14, 211–219.

Burkard, M.B., Kostaschuk, R.A., 1997. Patterns and controls of gully growth along the shoreline of lake Huron. Earth Surf. Proc. Landforms 22, 901–911.

Crouch, R.J., 1976. Field tunnel erosion — a review. Journal of Soil Conservation Service NSW 35, 98–111.

Crouch, R.J., 1983. The role of tunnel erosion in gully head progression. Journal of Soil Conservation 30 (2), 148–155.

Crouch, R.J., Blong, R.J., 1989. Gully sidewall classification: methods and applications. Z. Geomorph. N.F. 33 (3), 291–305.

De Ploey, J., 1974. Mechanical properties of hillslopes and their relation to gullying in Central semi-arid Tunisia. Z. Geomorphology Suppl. Bd. 21, 177–190.

De Ploey, J., Mücher, H.J., 1981. A consistency index and rainwash mechanisms on Belgian loamy soils. Earth Surf. Proc. Landforms 6, 319–330.

Freund, R.J., Littell, R.C., 1991. SAS System for Regression. 2nd SAS Institute, Cary, NC, 210 pp.

Gerits, J., 1991. Physico-Chemical Thresholds for Sediment Detachment, Transport and Deposition. PhD thesis, University of Amsterdam, Faculty of Environmental Sciences, Dept. of Physical Geography and Soil Science.

Gerits, J., Imeson, A.C., Verstraeten, J.M., Bryan, R.B., 1987. Rill Development and Badland Regolith Properties. In: Rill Erosion. Bryan, R.B. (Ed.), Catena Supplement 8 pp. 141–160.

Gutiérrez, M., Benito, G., Rodriguez, J., 1988. Piping in badland areas of the Middle Ebro Basin, Spain. In: Harvey, A.M., Sala, M. (Eds.), Geomorphic processes in environments with strong seasonal contrasts. Geomorphic Systems, Catena Supplement 13 II, pp. 49–60.

Gutiérrez, M., Sancho, C., Benito, G., Sirvent, J., Desir, G., 1997. Quantitative study of piping processes in badland areas of the Ebro Basin, NE Spain. Geomorphology 20, 237–253.

Harvey, A., 1982. The role of piping in the development of badlands and gully systems in Southeast Spain. In: Bryan, R., Yair, A. (Eds.), Badland Geomorphology and Piping. Geo Books (Geo Abstracts), Norwich, pp. 317–355.

Heede, B.H., 1970. Morphology of gullies in the Colorado Rocky Mountains. Bulletin of the International Association of Scientific Hydrology XV (2), 79–89.

Heede, B.H., 1971. Characteristics and processes of soil piping in gullies. USDA Forest Research paper RM-68, 15 pp.

Heede, B.H., 1974. Stages of development of gullies in Western United States of America. Z. Geomorphology N.F. 3, 260–271.

Imeson, AC., Kwaad, F.J.P.M., 1980. Gully types and gully prediction. K.N.A.G. Geografisch Tijdschrift XIV 5, 430–441.

Imeson, A.C., Verstraeten, J.M., 1988. Rills on badland slopes: a physico-chemically controlled phenomenon. In: Imeson, A.C., Sala, M. (Eds.), Geomorphic Processes in Environments with Strong Seasonal Contrasts. Geomorphic Processes, Catena Supplement 12 1, pp. 139–150.

Imeson, A.C., Kwaad, F.J.P.M., Verstraeten, J.M., 1982. The relationship of soil physical and chemical properties to the development of badlands in Morocco. In: Bryan, R., Yair, A. (Eds.), Badland Geomorphology and Piping. Geo Books (Geo Abstracts), Norwich, pp. 47–70.

Jungerius, P.D., van den Brink, J.W., 1991. The Geomorphology of a gully wall. An example of the application of geomorphological mapping to process research. In: Bork, H.-R., De Ploey, J., Schick, A.P. (Eds.), Erosion, Transport, Deposition Processes, Catena Supplement 19, pp. 57–69.

Kamphorst, A., Bolt, G.H., 1976. Saline and sodic soils. In: Bolt, G.H., Bruggenwert, M.G.M. (Eds.), Soil Chemistry A. Basic Elements. Elsevier, Amsterdam, pp. 171–191.

La Roca Cervigon, N., Calvo-Cases, A., 1988. Slope evolution by mass movements and surface wash (Val d' Alcoi, Alicante, Spain). In: Imeson, A.C. Sala, M. (Eds.), Geomorphic Processes in Environments with Strong Seasonal Contrasts. Geomorphic Processes, Catena Supplement 12 1, pp. 95–102.

Leopold, L.B., Emmett, W.W., Myrick, R.M., 1966. Channel and hillslope processes in a semi-arid area, New Mexico. United States Geological Survey Professional Paper 352-G, 192–243.

Loveday, J., Pyle, J., 1973. The Emerson dispersion test and its relationship to hydraulic conductivity. In: Division of Soils Technical Paper 15 CSIRO, Australia, pp. 1–7.

Malde, H.E., Scott, A.G., 1976. Observations of contemporary arroyo cutting near Santa Fe, New Mexico, U.S.A. Earth Surf. Proc. Landforms 2, 39–54.

Martín-Penela, A.J., 1994. Pipe and gully systems development in the Almanzora basin (Southeast Spain). Zeitschrift fur Geomorphology 38 (2), 207–222.

Middleton, H.E., 1930. Properties of soils which influence soil erosion. US Dept. Agr., Tech. Bull. 178, 16 pp.

Montgomery, D.R., Dietrich, W.E., 1988. Where do channels begin? Nature 336, 232–234.

Oostwoud Wijdenes, D.J., Bryan, R.B., 1991. Gully development on the Njemp Flats, Baringo, Kenya. In: Bork, H.-R., De Ploey, J., Schick, A.P. (Eds.), Erosion, Transport, Deposition Processes — Theories and Models. Catena Supplement 19, pp. 71–90.

Oostwoud Wijdenes, D.J., Bryan, R.B., 1994. Gully headcuts as sediment sources on the Njemps Flats and initial low-cost gully control measures. In: Bryan, R.B. (Ed.), Soil erosion, land degradation and social transition — geo-ecological analy-

sis of a semi-arid tropical region, Kenya. Advances in Geoecology 27, pp. 205–229.
Palacio-Prieto, J.L., Lopez-Blanco, J., 1994. Using video imagery for gully erosion evaluation. Z. Geomorph. N.F. 38 (1), 33–43.
Poesen, J.W.A., Hooke, J.M., 1997. Erosion, flooding and channel management in Mediterranean environments of southern Europe. Progress in Physical Geography 21 (2), 157–199.
Seginer, I., 1966. Gully development and sediment yield. J. Hydrol. 4, 236–253.
Sneddon, J., Williams, B.G., Savage, J.V., Newman, C.T., 1988. Erosion of a gully in duplex soils. Results of a long term photogrammetric monitoring program. Aust. J. Res. (26), 401–408.
Soil Science Society of America, 1996. Glossary of Soil Science Terms. Soil Science Society of America, Madison, WI, USA, 134 pp.
Stocking, M.A., 1980. Examination of factors controlling gully growth. In: De Boodt, M., Gabriels, D. (Eds.), Assessment of Erosion. Wiley, Chichester, pp. 505–520.
Thompson, J.R., 1964. Quantitative effect of watershed variables on rate of gully-head advancement. Trans. ASAE 7, 54–55.
Tysma, Sj., van Herwijnen, F., Leijendeckers, P.H.H., 1995. Poly-Technisch Zakboekje. 47ste druk. Koninklijke PBNA, Arnhem.
Veness, J.A., 1980. The role of fluting in gully extension. J. Soil Cons. Serv. NSW 36 (2), 100–107.
Young, R.N., Warkentin, B.P., 1975. Introduction to Soil Behaviour. Elsevier, Amsterdam, 489 pp.