Morphometric and hydraulic geometry assessment of a gully in SW Spain

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ABSTRACT

Gully erosion represents one of the most significant types of land degradation in the Mediterranean areas, giving place to important on- and off-site effects. In this paper, a second-order gully located in SW Spain is analyzed. Along the gully, 28 cross-sections were established and measured with a Leica TCRM1102 laser total station, approximately every 6 months from 2001 to 2007. The sections were located at variable distance, placing them in areas where active erosion was evident. In total, 13 field measurements were carried out, and the geometric characteristics of 28 cross-sections were obtained.

Morphometric analyses were carried out in both the main gully and a tributary reach by applying an empirical relationship between channel length and eroded volume. Morphometric variables of the gully sections were combined into two dimensionless groups, and a morphological similarity between different linear erosion landforms (rills, ephemeral and permanent gullies) was obtained. Then, the coefficient of variation of the calculated volumes was used to compare the instability between the main gully and the tributary reach.

Finally, the hydraulic geometry of the gully was assessed by calibrating three empirical power equations, which relate bankfull discharge with mean flow velocity, cross-sectional depth and width. The hydraulic characterization of the main gully and the tributary reach was investigated for each field survey and a different behavior was detected. The hydraulic analysis also demonstrated that higher values of discharge provide better predictions of flow velocity; the size of the main and tributary gullies affects the discharge–width relationship; and that gully depth is the variable which can be predicted with the highest accuracy.

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1. Introduction

According to Schumm (1956), geomorphologists "*have neglected the importance of persistent similarity*" among different landforms, and badland areas can be used as laboratory scale models for studying fully dissected high relief areas with permanent and ephemeral gullies. The study of small areas subjected to rapid erosion could lead to inferences concerning erosion processes operating at larger erosional landform scales. The influence of sediment type can also explain downstream changes in width and depth of a gully (Schumm, 1960; Kirkby and Bull, 2000). Gully erosion is an important land degradation process occurring in different types of environments (Valentin et al., 2005; Zucca et al., 2006; Bou Kheir et al., 2007; Conoscenti et al., 2013, 2014). According to Poesen et al. (2003), its contribution to the total sediment yield increases with the size of the considered study area, varying from 10% to 95%. Gullies are channel incisions triggered by concentrated water flow, mainly formed along natural drainage lines in the landscape

(Gyssel and Poesen, 2003). The depth of permanent gullies typically ranges from 0.5 to 30 m (Soil Science Society of America, 2008), too deep to be obliterated by normal tillage operations and, therefore, hamper the trafficability of the field.

Soil and parental material are usually removed by gully erosion and severe on-site effects take place: loss of soil nutrients and organic matter, breakdown of soil structure, soil moisture reduction, decrease in vegetation cover and overall land degradation reducing crop yields. Gullies represent a link between upland areas and river networks, which allows a rapid water and sediment transport into lowland river systems producing off-site effects such as water pollution, flooding, reduction of dam's lifespan, and changes in river morphology (Daba et al., 2003; Poesen et al., 2003; Capra et al., 2005; Charlton, 2008; Poesen, 2011).

Research on gully erosion needs appropriate measuring techniques, systematic measurements in historical times, and accurate provisional models; it facilitates actions to prevent this type of water erosion process effectively and efficiently (Poesen, 2011). The systematic compilation of morphological characteristics (e.g. length, width, and depth) of different types of gullies and their controlling factors (e.g. topography, soil type, land use, and hydraulics) would allow land managers to

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predict the type of gullies and develop erosion control measures (Poesen et al., 2003; Valentin et al., 2005; Capra et al., 2009; Poesen, 2011).

In the European Union, approximately 15% of the territory is affected by high rates of soil erosion by water. In the southern part of Europe, which is particularly susceptible to erosion (Joint Research Center, 2013), permanent gullies usually develop in abandoned agricultural fields, rangelands or shrublands, occurring on unconsolidated slope deposits, particularly silt-clay deposits and weathered soils (Imeson and Kwaad, 1980; Poesen et al., 2003; Kirkby and Bracken, 2009). Particularly in Spain, soils are severely affected by water erosion due to the extreme environmental variability (Solé-Benet, 2006). Not only highly erodible soils but also non-appropriate land use practices are important factors affecting soil erosion processes in Spain (Faulkner et al., 2003; Romero Díaz et al., 2007; Gómez Gutiérrez et al., 2009). Specifically in SW Spain, gully erosion mainly occurs in valley bottoms, and alluvial deposits are affected (Poesen et al., 2003; Casalí et al., 2006; Gómez-Gutiérrez et al., 2012).

Gully erosion studies have used simple empirical equations for analyzing the morphometric and hydraulic characteristics of gullies (Nachtergaele et al., 2001a, 2001b, 2002; Capra et al., 2005, 2009; Bruno et al., 2008; Di Stefano and Ferro, 2011; Kompani-Zare et al., 2011; El Maaoui et al., 2012; Di Stefano et al., 2013; Frankl et al., 2013; Caraballo-Arias et al., 2014). Since gully erosion processes are often considered similar to those occurring in other types of channelized water flows, many of the empirical equations used for gully erosion assessment have their origins in rills, streams or rivers.

The main goals of this paper are to: a) describe the morphometric characteristics of a gully system in Spain and to apply and analyze an empirical relationship between the length of the main gully and the tributary reach and their eroded volume for 13 field surveys; b) assess a relationship among morphological variables (volume, length, bankfull depth and width) of the main gully and the tributary reach as proposed by Bruno et al. (2008); c) evaluate the morphological similarity to other erosion landforms; and d) assess the hydraulic geometry of the main gully and tributary reach by using three empirical power equations which relate discharge to mean flow velocity and cross-sectional depth and width. The hydraulic characterization of the main gully and the tributary reach is investigated for each field survey.

2. Study area

The study area is located in SW Spain, in the autonomous community of Extremadura, specifically in the Parapuños experimental catchment (99.5 ha) (Fig. 1). The investigated gully is a second order and discontinuous permanent gully incised into alluvial sediments, approximately 1.5 m thick. The main gully and tributary reach have lengths of 833 m and 163 m, respectively. The initiation of the main gully might have occurred between 1726 and 1790, while the tributary reach appeared in 1989 (Gómez Gutiérrez et al., 2009). Important land use changes took place in the study area in the 1700s due to an increased demographic pressure. In 1793 an ordinance allowed the cultivation of large forest areas in the region of Extremadura (Rodríguez Grajera, 2004). Rodríguez Grajera (2004) also determined a strong relationship between gully extension and land use/vegetation cover of the area. More specifically, drastic extension of the gully took place when the land use within the catchment was dedicated to cropland and the vegetation cover was reduced while, on the other hand, the extension of the gully decreased when the land use cover was set back to grassland (Gómez Gutiérrez et al., 2009). During the period 1945–2006, the appearance of several headcuts was also observed within the main gully and tributary reach, probably due to the path traced by livestock crossing the gully. Finally, Gómez Gutiérrez et al. (2009) concluded that the topographic threshold equation seemed to be also related to land use and vegetation cover of the catchment.

The climate of the study area belongs to the Csa Koeppen class, i.e. mesothermal Mediterranean with dry summers. The mean annual temperature is approximately 16 °C, ranging from a minimum value of 3 °C in January and a maximum value of 34 °C in July. The annual rainfall average is around 600 mm, in which October, November and December are the rainiest months. Vegetation and land use vary from treeless pasturelands to savannah-like oak ranges called *dehesas*. The elevation of the study area ranges from 115 to 902 m a.s.l., and its mean slope angle is 7°. The outcropping lithology is heterogeneous, but acidic
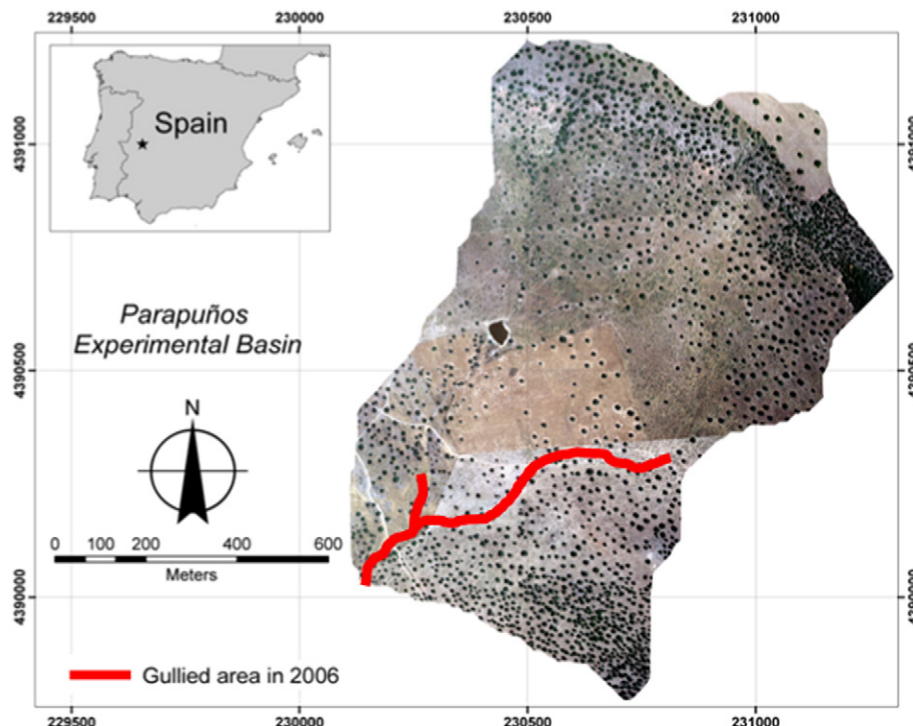

Fig. 1. Location of the study area. The gully is located in the southwest part of the Parapuños experimental catchment.
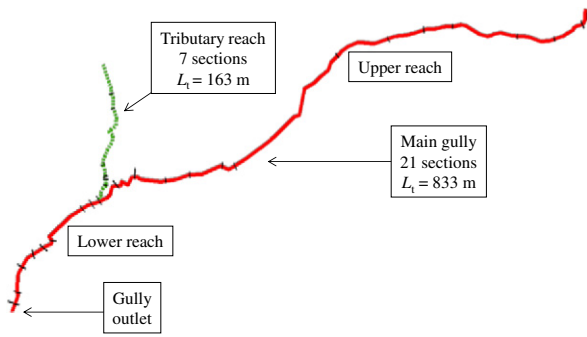
Fig. 2. Location of the measured cross sections along the main gully (21 cross-sections) and tributary reach (seven cross-sections). L_t is referred to the total length.

rocks dominate the area (mostly schists, greywackes and granites). Soils are mainly Cambisols (80%), Luvisols (10%) and Acrisols (5%). Most of the soils have sandy to silty texture and are commonly shallow with very low amounts of organic matter (usually below 3% in the A horizon). Overall erosion processes of the investigated main and tributary gullies occur in the first semester of the hydrological year (Gómez-Gutiérrez et al., 2012).

3. Materials and methods

3.1. Field surveys

Measurements of gully morphology and hydraulic variables were carried out from December 2001 to December 2007, approximately every six months. Along the gully, 28 cross sections were individuated: 21 along the main gully and seven along the tributary reach (Fig. 2). In total, 13 field surveys were carried out, approximately every six months. The cross sections were monitored using a laser total station (Fig. 3). Each field survey allowed the reconstruction of the geometric characteristics of 28 cross-sections by measuring (considering the bankfull stage of the channel) width w, depth h, cross-sectional area A and wetted perimeter W. The field measurement data were analyzed using the AutoCAD 2007 software (Fig. 4).

3.2. Morphometric characterization of the gully

In order to calculate the volume, the main gully and the tributary reach were divided into channel segments and the following equation was applied:

$$V = 0.5(A_u + A_d)L \tag{1}$$

Fig. 3. An example of a measured cross-section with the use of a laser total station. The continuous line indicates the cross-section perimeter and the dotted lines indicate the point of view of the total station.
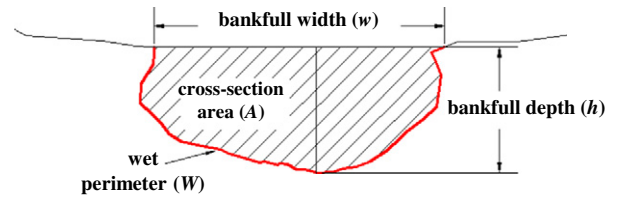

Fig. 4. An example of the geometric characteristics of a gully cross-section, at bankfull stage.

where V (m³) and L (m) are volume and length of the segment, and A_u and A_d (m²) are the areas of the upstream and downstream cross-sections, respectively.

The total volume V_t (m³) of the main gully and tributary reach was obtained by adding the individual V volumes of all segments into which the gully was divided:

$$V_t = \sum V \tag{2}$$

The total channel length L_t (m) was determined by summing up the individual lengths L of the segments into which the main gully and the tributary reach were divided:

$$L_t = \sum L \tag{3}$$

In order to verify whether the length of the gully can be used to predict its volume, the following power relationship was tested:

$$V_t = a_0 L_t^{b_0} \tag{4}$$

where a_0 and b_0 are coefficients determined empirically. Similar empirical volume–length relationships were also successfully tested on rills, ephemeral gullies (EGs), permanent gullies (gullies) and badlands, developed in different environments (Nachtergaele et al., 2001a; Capra et al., 2009; Di Stefano and Ferro, 2011; Kompani-Zare et al., 2011; Caraballo-Arias et al., 2014).

Additionally, in order to verify the morphometric similarity between the studied gully and other linear erosion landforms from the literature (rills, EGs and gullies), a power function between two dimensionless groups of morphometric variables, which was derived by dimensional analysis and self-similarity theory, was tested (Bruno et al., 2008):

$$\frac{V}{L^3} = m_0 \left(\frac{wh}{L^2}\right)^{n_0} \tag{5}$$

where w and h are the mean values of width and depth of the upstream and downstream cross sections, and m_0 and n_0 are two numerical constants to be determined empirically.
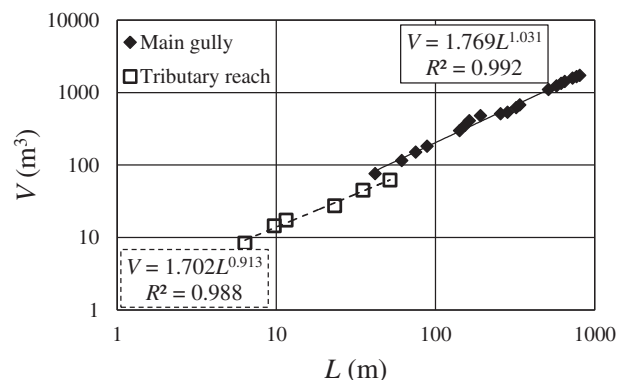

Fig. 5. Volume V_t – length L_t relationship (Eq. 4) of Field Survey 1 (December 2001).

Table 1
Obtained values of a_0, m_0, b_0, n_0 and R^2 when applying Eqs. (4) and (5) to the main gully and the tributary reach of the Parapuños experimental catchment.

Field survey	a_0 Main	a_0 Tributary	b_0 Main	b_0 Tributary	m_0 Main	m_0 Tributary	n_0 Main	n_0 Tributary
1	1.77	1.70	1.03	0.91	0.21	0.55	0.90	0.90
2	2.76	5.48	0.95	0.60	0.56	0.92	0.99	0.98
3	1.66	2.09	1.04	0.76	0.20	0.62	0.90	0.95
4	2.09	2.18	1.01	0.84	0.40	0.58	0.97	0.94
5	2.25	1.82	1.00	0.88	0.45	0.61	0.98	0.96
6	1.98	2.01	1.02	0.87	0.32	0.54	0.94	0.94
7	1.73	1.47	1.04	0.92	0.45	0.77	0.98	1.00
8	1.67	1.87	1.05	0.88	0.38	0.55	0.96	0.93
9	1.92	1.79	1.03	0.88	0.41	0.55	0.97	0.94
10	1.92	1.41	1.02	0.95	0.38	0.60	0.96	0.96
11	2.11	1.65	1.01	0.97	0.37	0.48	0.96	0.92
12	2.14	1.48	1.01	0.96	0.37	0.49	0.96	0.92
13	2.22	1.46	1.00	0.96	0.38	0.41	0.96	0.88

3.3. Hydraulic characterization of the gully

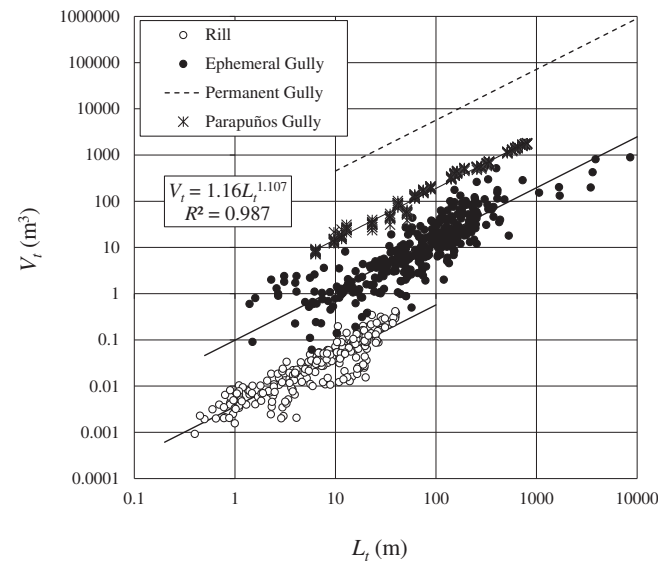The bankfull discharge values along gullies are commonly estimated by using the Chezy's flow equation:

$$Q = A_{u,d} c R_{u,d}^{2/3} s_{u,d}^{1/2} \qquad (6)$$

where Q ($m^3 s^{-1}$) is the bankfull discharge, $A_{u,d}$ (m) is the mean value of the u, d cross-sectional areas, c ($m^{1/3} s^{-1}$) is the Strickler roughness coefficient, $R_{u,d}$ (m) is the mean hydraulic radius and $s_{u,d}$ (m m^{-1}) is the slope within the u,d channel segment.
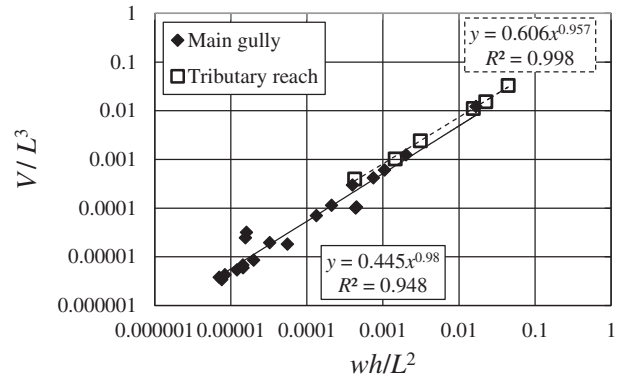
For this study, in order to determine the Strickler roughness coefficient c, the mean geometric characteristics of the lower reach were used (taken from the outlet of the gully upstream to its junction with the tributary reach, Fig. 2) and the following equation was applied:

$$c = \frac{Q_{max}}{A_m R_m^{2/3} i_m^{1/2}} \qquad (7)$$

where Q_{max} is the maximum discharge measured at the outlet of the gully between two consecutive field surveys; the mean area A_m, the mean hydraulic radius R_m and the mean slope of the gully segments s_m were averaged from the morphological characteristics of the lower reach (Fig. 2). The geometric characteristics considered for determining

Fig. 7. Application of Eq. (5) to the geometric characteristics of a cross-section from the Field Survey 5 (January 2004).
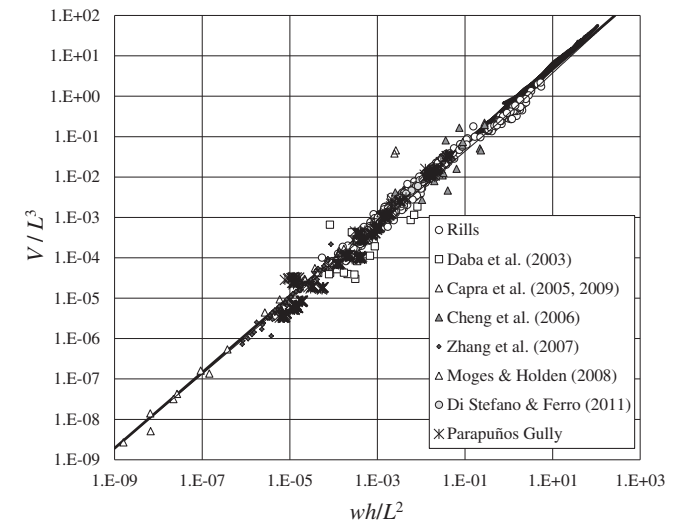
c were those of the field survey carried out after Q_{max} was measured. This choice is related to the assumption that Q_{max} corresponds to the channel-forming discharge, and, hence, it is responsible for the gully geometry observed at the end of the relative time interval.

The hydraulic radius R, A divided by W, was calculated for each gully segment following two different methods: i) R_1, by averaging the upstream and downstream R values, calculated separately, and ii) R_2, by determining R from the mean values of A and W, computed from the upstream and downstream cross sections:

$$R_1 = \frac{R_u + R_d}{2} = \frac{\dfrac{A_u}{W_u} + \dfrac{A_d}{W_d}}{2} \qquad (8)$$

$$R_2 = \frac{\overline{A}_{u,d}}{\overline{W}_{u,d}} = \frac{\dfrac{A_u + A_d}{2}}{\dfrac{W_u + W_d}{2}} \qquad (9)$$

where R_u and R_d are the hydraulic radius of the upstream and downstream channel segment, respectively, W_u and W_d are the wetted perimeter of the upstream and downstream channel segment, respectively, $\overline{A}_{u,d}$ and $\overline{W}_{u,d}$ are the mean cross-sectional area and mean wetted perimeter of the u,d channel segment, respectively.

Fig. 6. Volume V_t – length L_t relationship between rills, EG and permanent gullies from the literature and those for the Parapuños gully.

Fig. 8. Pairs of the dimensionless groups (Eq. 5) taken from the literature and those measured in the Parapuños gully.
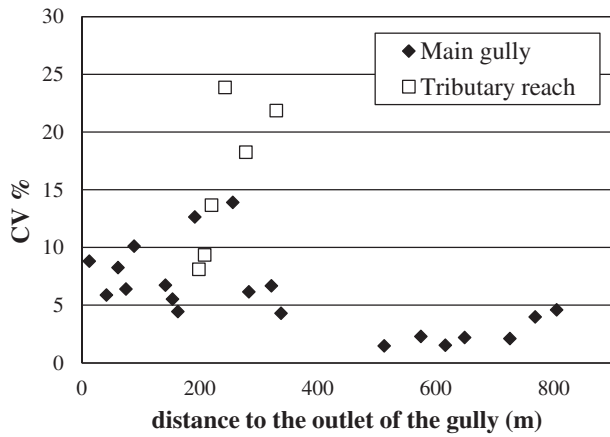
Fig. 9. Coefficient of variation CV of the main gully and tributary reach, taking into account the calculated volume within the gully segments.

The mean slope value of the channel segment s_m, was determined by the following equation:

$$s_m = \frac{q_u + q_d}{L} \qquad (10)$$

where q_u and q_d (m) are the upstream and downstream altitude values (measured at the lowest point of each cross-section).

Finally, the mean velocity v was calculated by dividing the discharge of the u,d channel segment $Q_{u,d}$ by its mean cross-sectional area $A_{u,d}$:

$$v = \frac{Q}{\overline{A}_{u,d}} \qquad (11)$$

The quantitative assessment relating the geometry of stream channels to discharge has been denominated "hydraulic geometry" (Leopold and Maddock, 1953). This approach is mainly focused on the application of three empirical power functions:

$$v = kQ^m \qquad (12)$$

$$w = aQ^b \qquad (13)$$

$$h = eQ^f \qquad (14)$$

where k, m, a, b, e and f are constants. These empirically determined constant should follow the conditions kae = 1 and m + b + f = 1 due to continuity equation ($vwh = Q$). Notice that the condition kae = 1 is strictly applicable for a rectangular cross-section.

Eqs. (12) to (14) have been applied to different types of channels: natural rills, ephemeral and permanent gullies, streams and rivers (e.g. Leopold and Maddock, 1953; Leopold and Miller, 1956; Thornes, 1970, 1974; Graf, 1971; Hamlin and Thornes, 1974; Gilley et al., 1990; Govers, 1992; Foster et al., 1984; Abrahams et al., 1996; Di Stefano et al., 2013) and simulated experiments under controlled laboratory conditions (e.g. Lane and Foster, 1980; Foster et al., 1984; Sidorchuk, 1998; Bennett et al., 2000; Giménez and Govers, 2001). These equations are used as general modelling tools of channel hydraulic characteristics, and some researchers have used them for small ephemeral channels

studies during storm flow events (Rendell and Alexander, 1979; Di Stefano et al., 2013).

The gully was studied in the context of downstream hydraulic geometry, i.e. studying the variation of the geometric characteristics in the downstream direction of the channel (Hickin, 2004). This choice allows us to study the temporal evolution of the segments into which the main gully and the tributary reach were divided. The bankfull discharge stage (channel-forming discharge) was considered when the geometric characteristics of the cross-sections were measured (Fig. 4).

4. Results and discussion

4.1. Gully morphometry

For each field survey, Eq. (4) was applied to both the main gully and tributary reach, by using the cumulative values of L and V, represented in a double logarithmic scale chart (an example is shown in Fig. 5). The estimated a_0 and b_0 coefficients obtained for all 13 field surveys are summarized in Table 1.

Fig. 6 shows Eq. (4) calibrated with L_t–V_t pairs observed for rills, EGs and gullies by Ichim et al. (1990), Daba et al. (2003), Cheng et al. (2006), Zhang et al. (2007), Bruno et al. (2008), Moges and Holden (2008) and Di Stefano and Ferro (2011) together with our measurements of the Parapuños gully. The data plotted in Fig. 6 confirms that Eq. (4) can be applied to rill, EG and gully data using the same exponent b_0 (=1.1), but with a different scale factor depending on the size of the linear erosion landform considered: $a_0 = 0.0036$ for rills, 0.0984 for EGs, 1.16 for the Spanish gully and 35.8 for permanent gullies. These results show that the analyzed gully follows a trend just above that of the EGs. The Parapuños gully has been considered a permanent gully in previous researches (Gómez Gutiérrez et al., 2009; Gómez-Gutiérrez et al., 2012), but according to this morphometric analysis, it fits better to the L_t–V_t relationship for EGs. A reason for this is that, up to now, researchers do not have a uniform criterion when classifying linear erosion landforms and what could seem as an EG for one researcher, could be considered permanent by another researcher. For instance, the size range of permanent gullies is quite large, as attested by a trend fitting channels considerably wider and/or deeper than the Parapuños gully. However, as a general discussion, it can still be affirmed that the exponent of Eq. (4) is independent of the type of channelized erosion while different scale factors hold depending on the size of the erosion landform considered (Di Stefano et al., 2013).

Pairs of the two dimensionless groups contained in Eq. (5), computed for each u, d segment of the main gully and tributary reach, were plotted on a log-log scale. A power relation was derived to obtain the values of the m_0 and n_0 coefficients for all 13 field surveys (Table 1). The results in Fig. 7 demonstrate a morphological similarity between the main gully and the tributary reach.

Fig. 8 plots the values of the two dimensionless groups in Eq. (5), calculated for the Spanish gully and those available from the literature. The diagram shows that the data pairs of the Parapuños gully are well predicted by the same power regression model calculated from data of rills, EGs and gullies. Since Eq. (5) combines different morphometric parameters such as w, h, L and V, this result confirms a morphological similarity of landforms generated by different water erosion processes. Furthermore, considering that the analyzed landforms are cut into different soils and bedrock lithologies, it can be assumed that the morphology of linear erosion features is independent also of the intrinsic
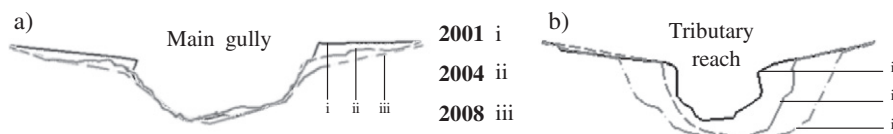

Fig. 10. Temporal variation of a representative cross-section: a) main gully and b) tributary reach.
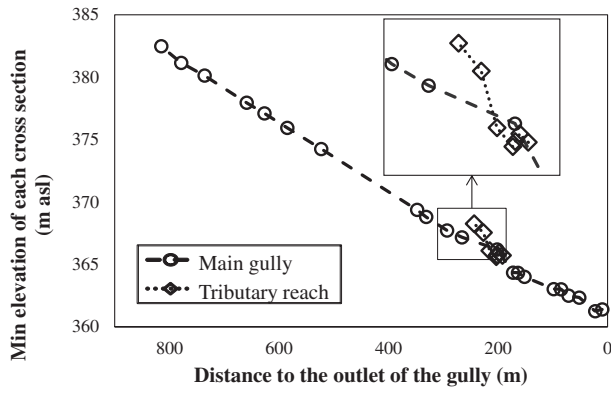
Fig. 11. Longitudinal profile of the main gully and tributary reach. Field Survey 13 (December 2007).

Fig. 12. Comparison between two different methods (R_1 and R_2) for calculating the hydraulic radius.

characteristics of the eroded material (e.g. texture, organic content, and permeability).

Finally, for both the main gully and the tributary reach, the coefficient of variation CV of the volume of the gully segments was calculated (Fig. 9). Higher CV values were found for the tributary reach, especially in its upper part. Conversely, CV in the main gully decreases when moving upstream. However, since the cross-sections were measured on areas with evident erosion activity (e.g. proximity to headcuts, and absence of vegetation cover), marked changes of their geometry were highly expected. In Fig. 10, two representative cross-sections of the main gully and the tributary reach demonstrate a larger variation of the tributary cross-sections than that of the main gully. In general, the higher variability of the tributary reach may be explained considering that it was formed long after the main channel and thus it is in a more juvenile (i.e. unstable) stage. This is also confirmed by higher steepness values of the tributary reach compared to the main gully (Fig. 11). The current incision-deposition phases are controlled by extrinsic factors, mainly land use changes (Gómez Gutiérrez et al., 2009; Gómez-Gutiérrez et al., 2012) and the evolution of the channel, including its longitudinal profile, has been previously analyzed for

medium-term (Gómez Gutiérrez et al., 2009) and short-term (Gómez-Gutiérrez et al., 2012) periods.

4.2. Gully hydraulic geometry

The gully hydraulic geometry, for all 13 field surveys, was first assessed by calculating for every gully segment, the bankfull discharge by means of the Chezy's equation (Eq. 6). The Strickler roughness coefficient used was set to the mean value ($c = 20.86$) of those obtained empirically by applying Eq. (7) to each field survey (Table 2).

The calculated c values vary considerably (0.15–49.48), and higher c values result from the winter measurements in December or January, while smaller values correspond with summer measurements in June or July. For calculating c, Eq. (7) uses the value of Q_{max} measured in a period between two consecutive field surveys; as Eq. (7) suggests, this discharge value is directly proportional to the calculated c values. Consequently, as higher values of Q_{max} were measured in the second semester, higher values of c were obtained for the winter (December/January) field surveys. It is important to note that higher discharge values determine geometric characteristics of the cross-sections which are near to the bankfull condition. However, since we assumed that all discharges are responsible for shaping the channel, we decided to use the mean value of c as the roughness coefficient for the Parapuños gully.

Regarding the hydraulic radius, with the application of Eqs. (8) and (9), similar results were obtained. These are statistically confirmed in Fig. 12, which plots hydraulic radius values calculated with both methods(coefficient of determination $R^2 = 0.96$). For this research, we decided to use Eq. (8), which calculates R as the average between the upstream and downstream values.

Table 2
Q_{max} values measured for each period and the c calculated values for each field survey.

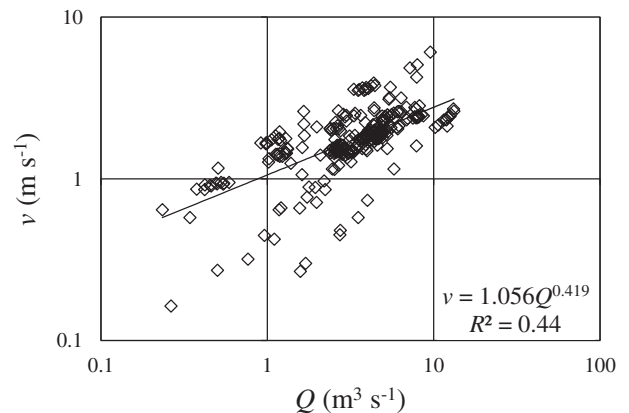| Field survey	Month	Year	Q_{max} (m^3 s^{-1})	$c_{calculated}$
FS 1	December	2001		–
			0.457	
FS 2	July	2002		16.98
			0.457	
FS 3	January	2003		14.44
			0.298	
FS 4	June	2003		9.18
			1.154	
FS 5	January	2004		30.28
			0.328	
FS 6	July	2004		8.14
			1.114	
FS 7	January	2005		32.16
			0.000	
FS 8	July	2005		–
			1.582	
FS 9	December	2005		49.48
			0.269	
FS 10	June	2006		8.17
			1.587	
FS 11	December	2006		39.61
			0.006	
FS 12	June	2007		0.15
			–	
FS 13	December	2007		–
		mean c value		20.86

Fig. 13. Discharge Q – flow velocity v relationship for the Parapuños gully.
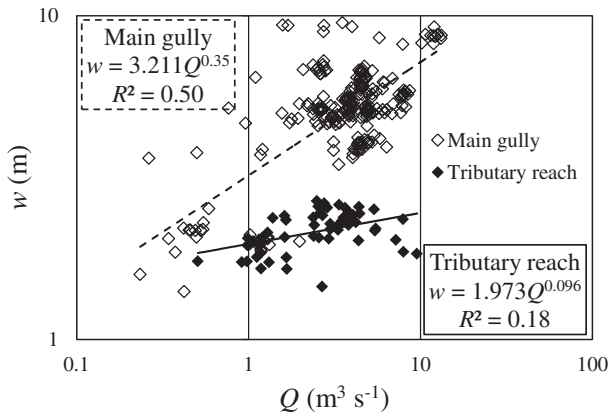
Fig. 14. Discharge Q – width w relationship for the main gully and tributary reach.

In Fig. 13, the estimated Q–v relationship is plotted in a log-log plot. Data for all 13 field surveys yielded the following equation:

$$v = 1.056Q^{0.419} \qquad (15)$$

As a general trend, flow velocity tends to increase with discharge. However, the smallest values of Q provide a more scattered prediction of v, while a better fit of the model is observed for the higher values of Q. Overall, Eq. (15) is able to predict flow velocity and is characterized by a determination coefficient equal to 0.44.

Fig. 14 is the log-log plot of the Q–w relationship for both the main gully and tributary reach. The figure shows a clear distinction between the models of the main and the tributary reaches.

$$w = 3.211Q^{0.35} \quad R^2 = 0.50 \quad n = 243 \quad \text{for the main gully} \qquad (16)$$

$$w = 1.973Q^{0.096} \quad R^2 = 0.18 \quad n = 56 \quad \text{for the tributary reach} \qquad (17)$$

For the Q–w relationship, Nachtergaele et al. (2002) summarized that the b exponent is proportional to the size of the channel considered, that is, b = 0.3 for rills, 0.4 for gullies and 0.5 for rivers. In this research, the determined values of b were 0.35 and 0.096 for the main gully and the tributary reach, respectively. When analyzing the field data separately, b ranges from 0.270 to 0.506 for the main gully and from 0.062 to 0.366 for the tributary reach (Table 3). The values of b obtained for the tributary reach are significantly smaller than those for the main gully. These results are in line with Nachtergaele et al. (2002) who stated that the b value increases with the size of the channel.

The coefficient of determination obtained for the main gully shows that half of the data variability can be explained by Eq. (16), while that for the tributary reach points out that only 18% of the data

variability can be explained by Eq. (17). However, when analyzing the data from each survey, there are some models with high coefficients of determination: for example, Field Survey 1 of the main reach provides b = 0.506, $R^2 = 0.78$, and Field Survey 12 of the tributary reach provides b = 0.176, $R^2 = 0.86$ (Table 3).

Finally, Fig. 15 shows the Q–h relationship Eq. (18) for the main gully and the tributary reach ($R^2 = 0.70$):

$$h = 0.554Q^{0.286} \qquad (18)$$

In this case, the main gully and its tributary reach are well modeled by the same empirical relationship which explains 70% of the data variability. Hence, the depth of the channel segments is the best predicted variable among those considered for the hydraulic geometry analysis.

As regards the continuity equations, the sum of the resulted exponents is 1.8, while the product of the coefficients is 1.05. Stewardson (2005) highlighted that the use of average values, when calibrating Eqs. (12) to (14), may result in obtaining sum and product values different from the unity.

The variation on the coefficients and exponents obtained for the Parapuños gully (Table 3), could be explained by several geomorphological reasons: i) the hydraulic geometry relationships were originally developed for steady state channels, while ephemeral and permanent gullies are characterized by greater variability and, therefore, are geomorphologically more active; ii) the presence of several headcuts along the main gully and tributary reach, which were not directly considered in the models, could influence the hydro-dynamics of the channels; iii) the tributary reach presents fewer data with respect to the main gully, and iv) the tributary reach is discontinuous, with a long interruption (around 100 m) in the middle sector. In other words, the variability of the coefficients and exponents of Eqs. (12) to (14) for the 13 field surveys demonstrates a non-stationary behavior of the main gully and tributary reach. This behavior is mainly due to the temporal variability in discharge which contributes in forming the channel. This discharge modifying effect is more evident for the width variable and determines different power relationships for the main gully and the tributary reach (Eqs. 16 and 17).

5. Conclusions

In this research, a second-order gully with a tributary in SW Spain was studied, focusing on the analysis of morphometric characteristics and the assessment of hydraulic geometry. The morphometric analysis allowed us to verify the applicability of an empirical relationship between the gully length and volume. Moreover, comparisons with morphometric data of other linear erosion landforms described in the literature confirmed that the empirical volume–length power relationship can be applied to rills, EGs and permanent gullies, by using a unique exponent and a scale-factor that varies with the size of the landforms.

Table 3
Values of the constants k, m, a, b, e, f and R^2 obtained with Eqs. (12) to (14).

| Field survey	$v = kQ^m$			$w = aQ^b$ (main gully)			$w = aQ^b$ (tributary reach)			$h = eQ^f$		
	k	m	R^2	a	b	R^2	a	b	R^2	e	f	R^2
1	1.107	0.455	0.56	2.442	0.506	0.78	1.699	0.062	0.09	0.553	0.261	0.73
2	1.064	0.451	0.55	3.091	0.364	0.56	1.626	0.090	0.64	0.553	0.285	0.77
3	1.214	0.280	0.29	3.190	0.370	0.49	2.050	0.091	0.39	0.490	0.342	0.75
4	1.180	0.319	0.28	3.244	0.356	0.43	1.910	0.123	0.31	0.529	0.336	0.78
5	1.167	0.348	0.37	3.064	0.380	0.47	1.778	0.219	0.68	0.610	0.249	0.64
6	1.309	0.294	0.39	2.722	0.447	0.65	2.057	0.085	0.72	0.520	0.343	0.89
7	1.140	0.353	0.46	3.042	0.379	0.58	1.997	0.178	0.59	0.536	0.282	0.71
8	0.870	0.564	0.64	3.536	0.274	0.49	1.767	0.206	0.72	0.612	0.219	0.68
9	0.984	0.467	0.52	3.297	0.329	0.55	1.792	0.229	0.82	0.573	0.258	0.74
10	1.123	0.373	0.50	3.120	0.361	0.64	2.084	0.082	0.50	0.513	0.332	0.86
11	0.874	0.527	0.45	3.652	0.270	0.29	2.162	0.104	0.54	0.622	0.235	0.52
12	0.977	0.448	0.37	3.541	0.300	0.35	1.988	0.176	0.86	0.572	0.280	0.61
13	0.946	0.469	0.40	3.625	0.300	0.40	1.599	0.366	0.52	0.548	0.292	0.65
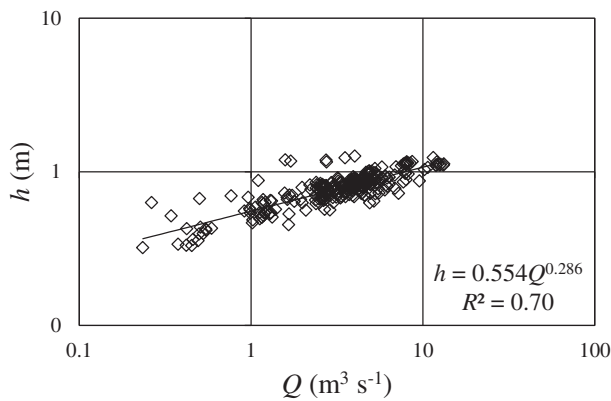
Fig. 15. Discharge Q – depth h relationship for the Parapuños gully.

Furthermore, as a single relationship between two dimensionless groups of geometric variables fits well to the data of the studied gully and those of rills, EGs and permanent gullies in the literature, we conclude that morphological similarity among linear erosion landforms is quantitatively demonstrated. Finally, the coefficient of variation of the volume, calculated for both the main gully and the tributary reach, demonstrated higher variations for the latter, which might be ascribed to the juvenile stage of the tributary reach.

Regarding the hydraulic geometry of the gully, the measurements during the 13 field surveys allowed us to calibrate three empirical relationships for estimating the gully flow velocity, width and depth. Since gullies are intermittently occupied by water, the considered geometric characteristics of cross-sections were those at a bankfull stage. The Strickler's roughness coefficient was determined for the area, and a value characteristic of rough surfaces was obtained. Discharge and flow velocity calculations were combined with the maximum depth and width of the cross-sections, gathering the hydraulic geometry relationships for the Parapuños gully. The Q–v relationship demonstrated that higher values of Q provide better predictions of flow velocity. For the Q–w relationship, two different trends were observed between the main and the tributary channels; additionally, the difference on the magnitude of the b value, obtained for both channels, confirmed that this exponent depends on the size of the channels. This result is due to a different discharge modelling effect between the main gully and the tributary reach. Finally, the Q–h relationship showed that among the variables analyzed, depth of the gully is predicted with the highest accuracy.

In conclusion, our investigation has shown a morphological similarity between the gully characteristic variables measured at different time steps and the applicability of power relationships for estimating the main hydraulic variables of a gully (velocity, width, and depth).

Acknowledgements

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