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The development of gullies in a Mediterranean environment: The example of the Corgo gully (central Portugal)

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Abstract

Gullies are the most energy-efficient way to transport excess runoff from the watershed after a landscape disturbance. The diversity of physical factors that are associated with gully formation makes straightforward interpretation difficult and requires well-founded analysis based on local observations. Some gullies have developed in the Alva river basin and some of them reach a spectacular size, especially in areas where forest fires have recurred with greater severity. In this paper, we identify the most important factors in the formation and development of the River Corgo's gully, located in the Alva river valley in central Portugal. The evolution of this gully in the last 4 years is also examined, based on a study of the modification of its morphological characteristics. The analysis was based on the Spearman-Rho correlation coefficient and stepwise multiple regression to estimate the correlation between the quantitative characteristics, geomorphological processes and biophysical variables. The results show that the main factors that seem to control the spatial variation of soil erosion are the soil penetration resistance, slope, slope shape and vegetation cover.

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Keywords: Gully; Soil erosion; Corgo; Centre of Portugal

1. Introduction

Soil erosion is the principal cause of soil degradation worldwide [1], and the off-site impacts of sedimentation can severely affect water quality, ecology, and terrestrial and aquatic habitats. The water erosion processes associated with the creation of gullies often cause significant damage to agriculture, through the loss of the soil's productive capacity and degradation of water quality, especially in rivers, lakes and natural reservoirs [2–7]. Although gullies are mostly found in mountain areas, various situations have been reported in the semi-humid and semi-arid regions of Mediterranean countries [6,8–12].

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Gullies are the most energy-efficient way to transport excess runoff from the watershed after a landscape disturbance [13]. Many causes of gully erosion have been identified, including natural and human-induced soil erosion processes [14,15]. In fact, the presence of gullies is often correlated with anthropogenic factors such as deforestation, wildfires, inappropriate cultivation and irrigation systems, overgrazing, log haulage tracks road building and urbanization. These not only lead to the formation of gullies and their evolution, but also increase their erosive capacity [15–20]. Valentin et al. [15] point out physical factors such as topographic thresholds (like slope gradients and soil crusts), soil and lithologic controls (soil, lithologic and geomorphology factors; soil crusting; piping), and land use and climate change (present and past land use changes). The combination of these drivers increases the urgency of gully erosion research and makes it important to combine efforts to monitor, model, and manage soil loss processes and landscape degradation [7]. In Portugal, although researchers recognize the problems associated with gullies, very few scientific works concerned with the quantification of soil erosion rates and, more importantly, with gullies' evolution have been produced [6,9,12]. This is mainly because the monitoring of a permanent gully system is a very time-consuming and labour-intensive task.

The objectives of this paper are: (a) to study the evolution of a valley bottom gully formed on a granite substratum in a Mediterranean environment, located in the Alva river valley in central Portugal, between 2015 and 2019; and (b) to quantify the main factors responsible for the spatial and temporal differences in the denudation–accumulation processes observed within the Corgo gully.

2. Materials and methods

2.1. Study area

The Corgo gully is on the right bank of the River Alva, downstream of the village of Penalva de Alva and opposite the Caldas de São Paio, in the municipality of Oliveira do Hospital. It lies between bends in the road. The slope varies from 20% to 30% and the area was affected by several forest fires between August 2013 and 2018 (Fig. 1).

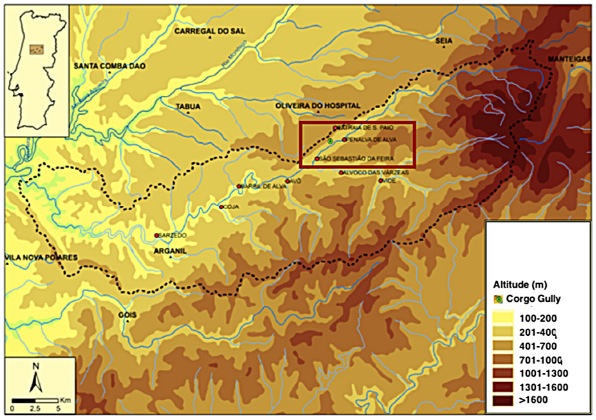

Fig. 1. Location of the Corgo's gully.

The studied area includes autochthonous terrains from the Central-Iberian zone (ITCZ) [21]. From a lithological point of view, it covers part of the Beiras province and is essentially composed of granite rocks, predominantly coarse-grained porphyritic granite that is calco-alkaline in nature and sometimes guided by megacrystals. The regolith where the gully is formed is characterized by weathering granite. The sediments have a very low silt–clay fraction.

The modal class corresponds to sands with a diameter of 2 mm, and the measures of central tendency (median, mean and average) indicate values around 1.5 mm, 1.3 mm and 1.5 mm respectively. The granulometric analysis of the sediments shows a calibration curve that confirms the predominance of coarse fractions. The asymmetry values also suggest the enrichment of the coarse-fraction samples and the kurtosis value indicates a leptokurtic curve. As in most of the country, the climate of the area under study has Mediterranean characteristics (Cs). Thermo-pluviometric analysis in the meteorological stations in the official IPMA [Portuguese Institute for Sea and Atmosphere] network indicates only two dry months (July and August) (rainfall in mm equal to or lower than twice the mean monthly temperature in °C). Annual precipitation ranges from 1100 mm on the lower slope to 1300 mm on the higher slope. Precipitation is sometimes torrential in nature. Although hourly data are sparse, precipitation above 50 mm does give some indication of the occurrence of high-intensity storms. The gully area is 0.03 ha and its main length is about 116 m. The Corgo gully is like most gullies in the Alva catchment and its evolution can be considered typical of the main gully processes acting on this catchment.

2.2. Monitoring gully changes

The first step was to divide the gully into homogeneous units according to the main processes and biophysical factors identified. Two main units were defined and these were then divided into cross sections, 2 m apart. The depth and width of all units were measured using a BOSCH GR 240 Professional measuring ruler and a BOSCH GLM 40 laser metre. The depth was determined by measuring the perpendicular distance between the main bed of the gully and a horizontal bar, supported on and levelled at the gully's bank slope. Good rigour and flexibility are the main advantages of this technique. Levelling surveys were carried out in June 2015 and February 2019. Denudation and deposition surface and volume were finally derived for each unit and each pair of levelling surveys. This work used SURFER 8.0 (Scientific Software Corp., Sandy, UT, USA) and ArcGIS 10.2 software (Esri, Portugal). All the units were also characterized by the following biophysical variables: (a) slope gradient (%), (b) slope profile (concave/convex/linear), (c) average vegetation cover (%), (d) average soil resistance to penetration, in kg cm^{-2}, (assessed using a pocket penetrometer, Eijkelkamp©), and (e) soil torsional vane shear tester (with a Pocket vane tester for measurement, in kg cm^{-2}, Eijkelkamp©).

2.3. Statistical analysis

To understand the factors influencing the denudation–deposition processes, we performed explorative data analysis, correlation analysis and stepwise multiple regressions using IBM SPSS Statistics 22.0. The Spearman-Rho correlation coefficient was selected to estimate the correlation between the quantitative characteristics, geomorphological processes and biophysical variables in the Corgo gully. This rank correlation method is considered robust against outliers and non-normal distribution of data. Stepwise multiple regression is essentially a search procedure with a prime focus on identifying the independent variable that has a strong relationship with the dependent variable(s), while simultaneously removing the weakest correlated variable. At the end we are left with the variables that best explain the distribution.

3. Results

3.1. Gullies morphology

The total length of the studied gully is around 116 m and affects an area of nearly 0.03 ha. The Corgo gully was divided into two main units, according to the morphological aspects. Gully section 1 (GS1) has developed upstream of a bedrock, whilst gully section 2 (GS2) has developed between the bedrock and the cross section where the gully enlargement is particularly striking. The characteristics are described by the variables listed in Table 1. GS1 corresponds to a shallow gully sector, with an average width of less than 1 m and depth close to 0.23 m. The correlation between gully depth and width is positive (r = 0.80).

Table 1. Most important morphological characteristics of gully section (GS).

Gully section ID	Coordinates		Total length	Mean width	SD width	Mean depth	SD depth	Surface slope above gully head	Channel slope	Plan area
	X	Y	(m)		(m)	(m)		(m m^{-1})	(mm^{-1})	(m^2)
GS 1	40.3337	−7.8471	38	0.83	45.2	0.23	15.1	0.22	0.11	32.42
GS 2	40.3338	−7.8467	78	4.06	266.0	2.97	175.6	0.43	2.97	300.63

Sector GS2 has a length of 78 m. Its average value of the width is more than 1 m, and, in some sectors, it exceeds 3 m. The average depth is approximately 3 m. However, in some sectors the values are more than 5 m. The correlation between gully' depth and width is positive (r = 0.93).

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3.2. Gully evolution

The main bed evolution of the gully is presented in Fig. 2 and is based on the two levelling surveys carried out in June 2015 and February 2019. As we can see, the most significant changes have occurred in GS2, although there are areas of deposition and denudation, deposition from the gully banks and the upstream sectors disappears. Deposition occurs mainly between 100 and 104 m and between 118 and 124 m. Denudation occurs between 84 and 94 m (Fig. 2).

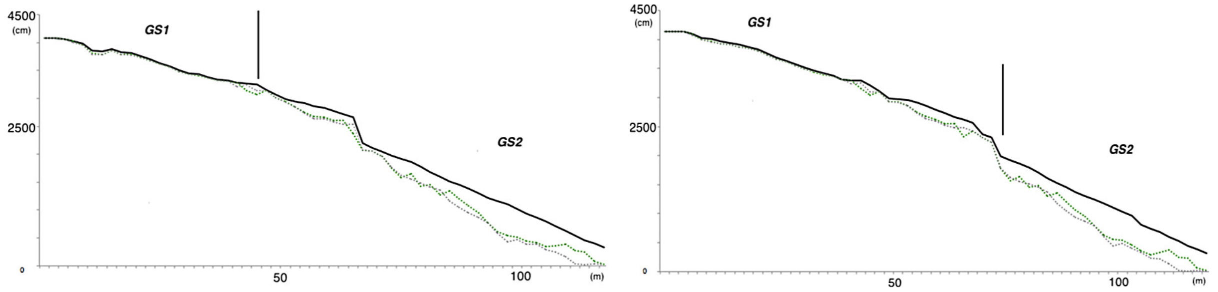

Fig. 2. Gully bed profile (2015 - green dashed line; 2019 grey dashed line) and slope profile taken from NE (left) and SW (right).

3.3. Key factors in depth variation

Correlations between depth variation and geomorphological features are shown in Table 2. According to the results obtained, slope shape and resistance to penetration are the variables most correlated with the depth variation recorded for the Corgo gully during the study period. Both correlations are negative.

Table 2. Spearman correlation between depth variation and some independent variables.

Depth variation		Width variation	Slope shape	Vegetation cover	Slope	Penet. resist.	Soil torsion
	Correlation Coefficient	0.389**	0.391**	−0.123	−0.182	−0.532**	−0.152

* Correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at the 0.01 level (2-tailed); n: 58;.

Stepwise multiple regression models explain between 32% and 45% of the depth variation. Soil resistance to penetration explains about 32% of the predictive model (a). The results also show that adding slope variable, predictive model increases accuracy by about 10% (model b). The best result is obtained when the variables soil resistance to penetration, slope and shape of the slope are considered (model c) (Table 3).

Table 3. Multiple regression, correlation and degree of significance for depth variation.

	Model	R	Explained variance (%)	Std. error of the estimate	Multiple regression equation
Depth variation	Model (a)	0.567a	32.1	60.40	$Dv = 132.18 - 33.99_{rp}$
	Model (b)	0.634b	40.2	57.19	$Dv = 156.89 - 34.39_{rp} - 64.97_{sl}$
	Model (c)	0.670c	44.9	55.44	$Dv = 90.37 - 26.69_{rp} - 78.34_{sl} + 23.04_{ss}$

Dependent variable: Dv-Depth variation (cm); Models: Model (a) predictors: (Constant), soil resistance to penetration; Model (b) predictors: (Constant), soil resistance to penetration and slope; Model (c) predictors: (Constant), soil resistance to penetration, slope and slope shape.

3.4. Key factors of width variation

Table 4 summarizes the results for the relationship between width variation and the independent variables. Slope shape and soil resistance to penetration showed the highest values of correlation. The correlation with the slope shape is positive (r: 0.582) whilst the soil resistance to penetration is negative (r: −0.529). The results also show positive, statistically significant correlations between the width variation and vegetation cover (r: 0.300).

The stepwise regression model explains width variability between 26% and 44.5%, for the three models. The results show explained variance of 26% considering slope shape, and 35.4% when combining slope shape and vegetation cover. Soil resistance to penetration increases the explained variance by 10% (Table 5).

Table 4. Spearman correlation between depth variation and some independent variables.

		Depth variation	Slope shape	Vegetation cover	Slope	Penet. resist.	Resist. to tors.
Width variation	Correlation coefficient	0.389**	0.582**	0.300*	0.214	−0.529**	−0,126

*Correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at the 0.01 level (2-tailed); n: 58.

Table 5. Multiple regression, correlation and degree of significance for enlargement variation.

	Model	R	Explained variance (%)	Std. error of the estimate	Multiple regression equation
Width variation	Model (a)	0.510a	26.0	74.87911	$Ev = -45.81 + 54.09_{ss}$
	Model (b)	0.595b	35.4	70.62715	$Ev = -79.26 + 50.04_{ss} + 50.04_{vc}$
	Model (c)	0.667c	44.5	66.02207	$Ev = 33.72 + 30.89_{ss} + 1.46_{vc} - 25.07_{pr}$

Dependent variable: Width variation (Ev), in mm; Models: (a) predictors: (Constant), slope shape; (b) predictors: (Constant), slope shape, vegetation cover; (c) predictors: (Constant), slope shape, vegetation cover, soil resistance to penetration.

4. Discussion and conclusion

In this study, we examined the evolution of the topographic attributes of the Corgo gully and identified factors which have an influence on the occurrence of erosion (denudation vs. accumulation), between 2015 and 2019. The results show a very complex spatial distribution of soil erodibility, although the differences recorded in the profile evolution were much more significant for GS2, where a significant enlargement occurred.

In fact, as Bennett and Wells [22] reported, despite a great deal of effort, the temporal and spatial variation in the erodibility of gully sediments can be quite large and there is no consensus on how to predict this variation. In our study, the main factors that seem control the spatial variation in soil erosion are the soil penetration resistance, slope, slope shape and vegetation cover. Penetration resistance was the most influential factor for spatial variations found in both depth and enlargement. Several studies consider that a soil penetrometer can be a good screening tool for the soil's physical conditions [23]. Kilic et al. [23] state that penetration resistance depends on many different properties, e.g. bulk density, water content, soil–water potential. In this context, Nunes et al. [24] also found that soil resistance to penetration follows a similar pattern to bulk density. According to [25] it is the soil's physical properties that determine the soil erosion process, because the deterioration of these physical properties is manifested through interrelated problems of surface sealing, crusting, soil compaction, poor drainage, impeded root growth, excessive runoff and accelerated erosion. In this regard, Nunes et al. [24,26]) found a negative, highly significant correlation between soil resistance to penetration and runoff and sediment yield. Conversely, vegetation cover, which offers more protection against overland flow and water erosion, shows a negative correlation. This agrees with the findings reported by different authors in various environments [24,26,27].

As the model used a limited set of input parameters, based on variables that are easily accessible, our results have moderate accuracy, which means that there are several environmental factors related to gully erosion initiation and development that need to be included. Moreover, factors that contributed to gully formation can be significant in one specific area but are not necessarily important in others [28].

Despite the contributions provided by this study, certain limitations must be recognized, mainly relating to the methodology and research process. As gullying is a threshold-dependent process controlled by a wide range of factors [15], and the Corgo gully was not hydrologically gauged, it is difficult to infer how it responds to input (rainfall) and to the combined effects of factors such as topography, geology, soil type, land use/cover in the drainage areas. Moreover, assuming that the gully material to be eroded is composed primarily of cohesive and non-cohesive clastic sediment, another gap in this research arises from an insufficient understanding of the controlling parameters that could affect denudation vs. accumulation. These parameters can include physical, geochemical, and biological properties as well as land management practices, all of which can vary over time.

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