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Local Factors Controlling Gully Development in a Mediterranean Environment

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Abstract: Gullies contribute very efficiently to soil loss and degradation, particularly in Mediterranean environments. While natural factors are involved in gully formation and further development, anthropic action is almost always an element. Knowledge of formation and development factors are important if soil protection strategies and measures are to be effective. In this paper, we identify the most important factors in the development of gullies in a Mediterranean setting based on a study of the Alva gully (central Portugal). Its development in the last four years is examined, based on a study of the modification of its morphological characteristics. The analysis was based on principal component analysis (PCA) 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.

Keywords: gully development; sediment production; Mediterranean environment

Citation: Martins, B.; Nunes, A.; Meira-Castro, A.; Lourenço, L.; Hermenegildo, C. Local Factors Controlling Gully Development in a Mediterranean Environment. *Land* **2022**, *11*, 204. https://doi.org/10.3390/land11020204

Academic Editors: Gergely Tóth, Eva Ivits and Bozena Smreczak

Received: 30 November 2021
Accepted: 25 January 2022
Published: 28 January 2022

1. Introduction

Water erosion problems are a major factor in causing environmental impacts, including land degradation [1]. This has adverse effects on water quality, ecology, and terrestrial and aquatic habitats. However, in many regions, soil degradation has severe impacts on the economy of the country, the family, and on the individual. The water erosion processes associated with gully formation often lead to considerable agricultural damage as the soil loses productive capacity and water loses quality. The displaced material can end up being deposited in areas of high economic interest where it might destroy more profitable production. In certain circumstances, it can reach watercourses which, in flood peaks, will carry a larger solid load than before [1–5]. The outcome could be to generate massive economic damage to humankind [2–11]. Several authors [12,13] state that in some areas more than 80% of sediment is produced by gully erosion, making it one of the most destructive types [14,15].

A gully is an erosion channel caused by irregular concentrated water flow, often throughout and immediately after a heavy rainfall event (Soil Science Society of America, 2008). Authors such as Foster (1986) [16] and Poesen et al. (2003) [17] consider a classic gully to be a channel deep enough, generally >0.5 m, to interfere with normal ploughing operations. Gullies are often found in mountainous regions [18–29]. But they are even more common in the semi-humid and semi-arid regions of Mediterranean countries [30–38].

The impact of gullies as a factor in soil degradation is very important in these regions. Many causes of gully erosion have been identified and these include natural and human-induced soil erosion processes [13,17]. A number of anthropogenic factors not only help to establish gullies, but very often they contribute to their rapid development and erosive capacity [39–45]. Most notable are forest fires, deforestation, and other causes of erosion, especially inappropriate cultivation and irrigation systems, overgrazing, log haulage tracks, road building, and urbanization. Furthermore, various natural factors are seen as fundamental to the formation of gullies, including topographic thresholds (such as slope gradients and soil crusts), soil and lithologic controls (soil, lithologic and geomorphology factors; soil crusting; piping), land use and climate change (present and past changes in land use) [13,17]. All these drivers together confirm the importance of increasing the urgency for gully erosion research and reinforcing the combined efforts of monitoring, modeling, and managing soil loss processes and landscape degradation [11]. In general, the progress of gullies is monitored by one of two methods. The first approach is based on the measurement of the material at the exit of a gully system [46]. However, this method does not allow the analysis of the gully channel's development. The second method is based on the use of topographic data sets, DEM, digital surface models (DSM) or point cloud (PC) [46–48] and aims to define the evolution of the morphological characteristics of a gully over a period of time.

In most cases, however, the constraint in spatial definition makes topographic variations undetectable for most gullies [47], which implies the use of both very high resolution DEMs [46], and topographic data obtained from photographs using photogrammetric techniques [49]. More recently, a new source of data provided by the LIDAR survey has been used to detect gullies in forested areas [47] that allows measurements of small variations of a few centimeters. However, this approach also has some limitations related to continuous data collection from deeply incised gullies [47]. The number of papers recognizing the problems related to gullies in Portugal, and the repeated impacts on soil and environment, has increased significantly in the past few years, especially related to the quantification of soil erosion rates and, primarily, gully evolution. Nevertheless, works on the monitoring of a permanent gully system are still scarce [38,49], which could perhaps be related to the very time-consuming and labor-intensive nature of the task. Such works are in fact particularly interesting in that they help to identify the main elements in the origin and evolution of gullies. They could thus contribute to developing strategies that are more effective for soil conservation work. The main objectives of this work were (a) to analyze the evolution of a gully located on a granite substratum in a Mediterranean environment, over a 5-year study period between 2015 and 2019, and (b) to identify the main factors responsible for the spatial and temporal differences in erosion rates observed within the specified gully.

2. Materials and Methods

2.1. Study Area

The gully under study is located on the right bank of the River Alva, downstream of the village of Penalva de Alva and opposite Caldas de São Paulo, in the municipality of Oliveira do Hospital (Figure 1). It develops between road bends on a steep incline of between 20 and 30%. This is a forest area that was affected by several forest fires between August 2013 and 2018.

The study area, i.e., where the ravine is located, is part of the Maciço Antigo [Ancient Massif] which lies within the Central Iberian Zone [50]. From the lithological point of view, it is part of the Beira uraniferous province and is essentially composed of granitic rocks, with a predominance of coarse-grained porphyroid granite, calco-alkaline in nature, and sometimes with orientation of megacrystals [51].

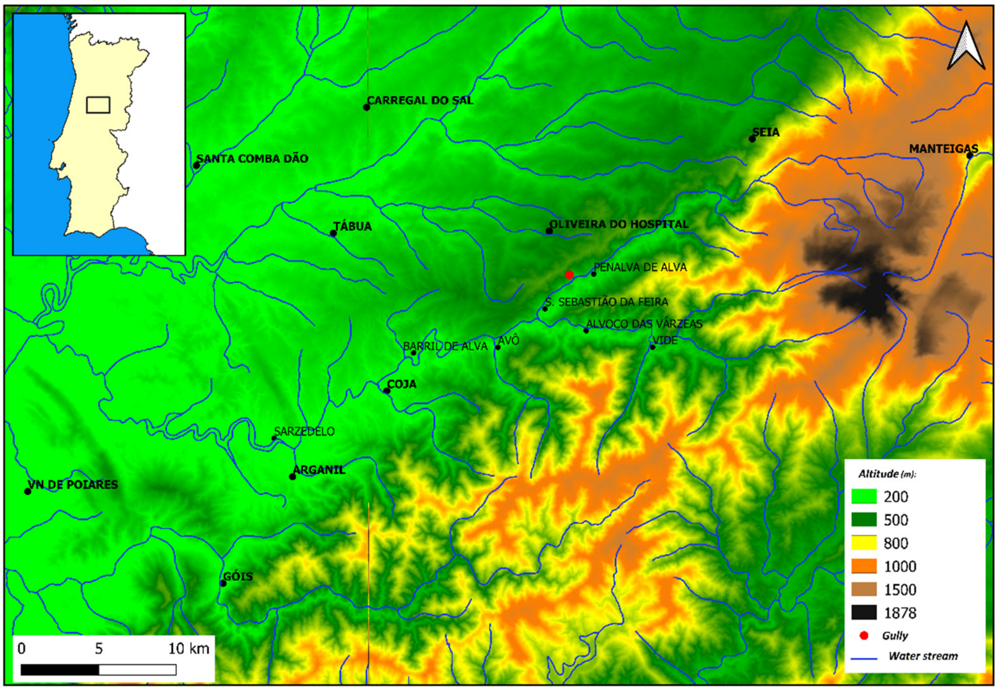


Figure 1. Location of the study area and gully.

The gully is bedded on regolith created by the weathering of granite. From the granulometric point of view, coarse sands predominate over fine sands. The values of the silty-clayey fraction are very small. The modal class corresponds to sands with a diameter of 2 mm, and the central tendency measures (median, mean, and graphic mean) point to values between 1.5 mm, 1.3 mm, and 1.5 mm, respectively. The calibration values confirm the predominance and concentration of sediment in the coarse fractions, revealing the removal of the concentration around the mean. The asymmetry values also suggest an enrichment in coarse relative to fine sediment. The kurtosis value indicates a leptokurtic curve.

As in most of the country, the climate of the study area has Mediterranean characteristics (Cs). The analysis of the temperature-rainfall graphs from the meteorological stations in the official IPMA network [Portuguese Institute of the Sea and Atmosphere] indicates only two dry months (July and August) (rainfall in mm equal to or less than twice the average monthly temperature in °C). The annual rainfall ranges from 1100 mm on the lowest altitude slope to 1300 mm at higher altitudes. Rainfall can sometimes be very heavy and concentrated.

2.2. Monitoring Morphological Changes in the Gully and Statistical Analysis

The gully and slope were split into cross-sectional profiles, separated by 2 m. Depth and width were obtained from a BOSCH GR 240 Professional measuring ruler and a BOSCH GLM 40 laser meter. Depth was determined from the perpendicular distance between the base of the gully and a horizontal bar. Field surveys were conducted in June 2015 and February 2019. Accumulation and erosion areas, as well as volume, were determined during the field surveys using SURFER 8.0 (Scientific Software Corp., Sandy, UT, USA) and ArcGIS 10.2 (Esri, Portugal). The biophysical variables were determined for each section, as follows:

(a) The slope (%) (determined from the use of a graduated iron bar, in order to obtain the difference in level measurements for a distance of 1 m); (b) the slope profile (concave/convex/linear); (c) the average vegetation cover percentage (%) (obtained using a 1 m^2 gridded square, photographed on the ground, digitalized and the percentage value of each plot calculated); (d) the average soil resistance to penetration, in kg cm^{-2} (obtained using a pocket penetrometer, Eijkelkamp©—Giesbeek, The Netherlands); (e) the soil resistance to torsion, in kg cm^{-2} (obtained using an Eijkelkamp© pocket torsor). Total of 402 samples were taken for analysis of the soil penetration resistance and torsional strength obtained at several points of gully wall, or at least, in the topsoil, at the midpoint and at the base of the gully wall and averaged [33,52–56].

The data analysis was carried out using MATLAB (R2020). In order to identify the primary factors influencing denudation/deposition processes at local scale, principal component analysis (PCA) was considered. Before PCA was carried out, the suitability of implementing this multivariate technique was first assessed. A correlation matrix was created to assess possible collinearity among the variables. A correlation coefficient threshold between variables of $|r| > 0.7$ ($p < 0.05$) was considered an appropriate indicator for the point where collinearity begins to severely distort model estimation and subsequent prediction [57].

3. Results

The total length of the studied gully is 116 m, and it influences an area close to 0.03 ha. On average, the gully is about 1.5 m wide and nearly 2 m deep (Table 1).

Table 1. Most important morphological characteristics of gully, sourced in 2019.

Coordinates										
x	Y	Total length (m)	Mean width (m)	Maximum width value (m)	Mean depth (m)	Maximum depth value (m)	WDR *	SSAGH **	Channel slope (m m^{-1})	Plan area (m^2)
40.3337	−7.8471	116	1.33	9.30	2.02	6.65	2.1	0.39	0.36	333.5

* Width depth ratio; ** SSAGH—Surface slope above gully head (m m^{-1}).

A more detailed analysis shows that the gully was formed from the upstream road, first over hard rock, where the incision is incipient and only a few centimeters in depth at its deepest. Then, when it started to develop over altered rock, it quickly gained depth, while its width increased, although with local bottlenecks. The material through which the downstream ravine develops is characterized by the predominance of sandy material, with less of the silty-clayey fraction. The modal class corresponds to sands of 2 mm diameter, and the measures of central tendency (median, mean and graphical mean) point to values between 1.5 mm, 1.3 mm, and 1.5 mm respectively. The calibration values confirm the predominance and concentration of the sandy material (the sum of the sediments of more than 1 mm amounts to more than half of the sediment) revealing a shift of the concentration around the mean. The asymmetry values also suggest an enrichment in coarse versus fine, suggesting a leptokurtic particle size distribution. Given the morphological characteristics of the ravine, two sections are identified, these being gully Section 1 (GS1), which is developed upstream of a bedrock, while gully Section 2 (GS2) develops between the bedrock and the cross-section where the gully enlargement becomes obvious. The main features are described by the variables listed in Table 1. From a morphological point of view, GS1 is essentially a shallow gully sector, with an average width of less than 1 m and a depth close to 0.23 m. Considering the relationship between width and depth, the mean WDR value obtained is close to 3.5. The correlation between gully depth and width is positive and moderate (r = 0.80) and the correlation between WDR and channel slope is 0.09. Sector GS2 is about 78 m long. In terms of width, the average value is more than 1 m, but it is higher than 5 m in many segments of the gully. The average depth is approximately 3 m. The mean WDR value obtained is 1.37. The correlation between gully depth and width is positive and strong (r = 0.93). The correlation between WDR and channel slope is negative (r = −0.34).

3.1. Gully Evolution

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

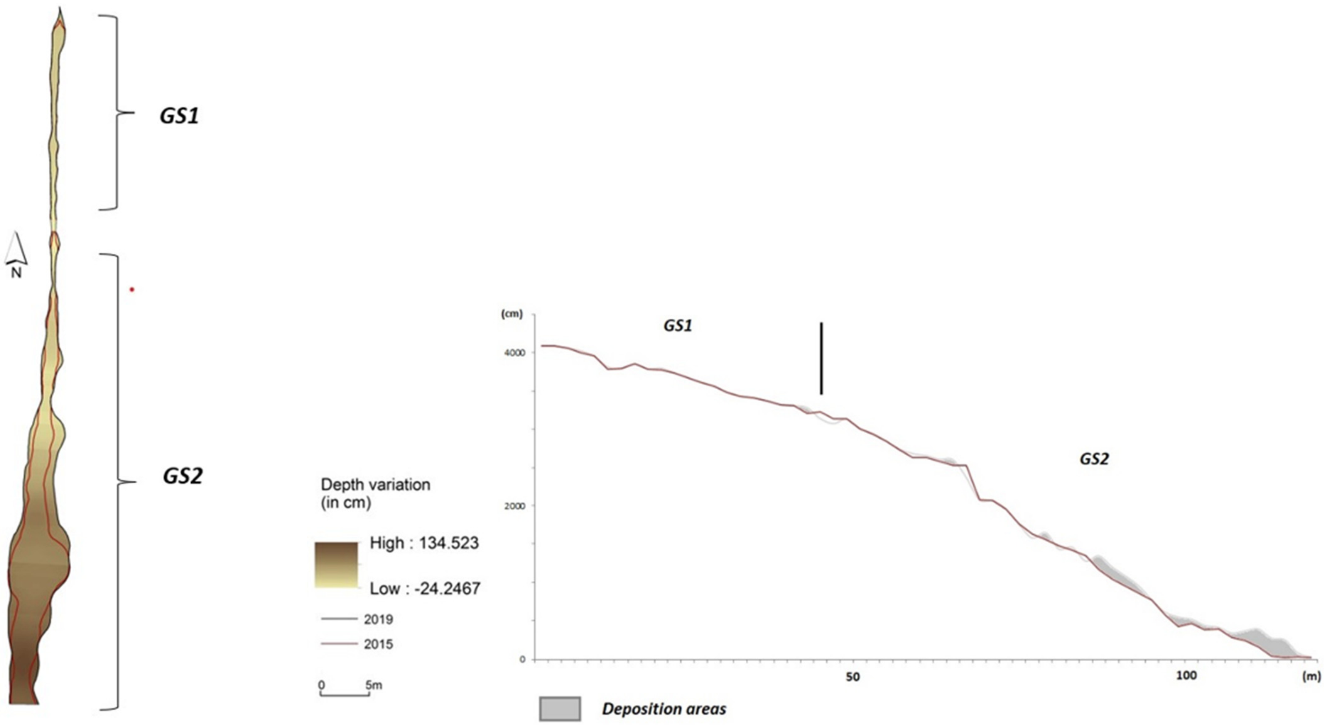


Figure 2. DEM differences between 2015 and 2019 levelling survey. Light where the channel has deepened, dark where there has been accumulation.

3.2. Key Factors of Enlargement and Depth Variation

Table 2 summarizes the exploratory variables best correlated with gully enlargement variation and the independent variables. Slope shape and penetrometer resistance showed the highest correlation values. The correlation of slope shape is positive (r: 0.582; p-value < 0.01) while the penetrometer resistance is negative (r: −0.529; p-value < 0.01). The results also show correlation coefficients that are statistically significant with the depth variation (r: 0.389; p-value < 0.01) and vegetation cover (r: 0.300; p-value < 0.05) variables.

Considering only GS2, where the most significant results were obtained in the variation in depth, WDR, penetrometer resistance, slope shape, slope, and width variation were the ones with the best correlations (Table 3). The WDR and the resistance to penetration has a significant negative correlation with depth variation, r: −0.707 (p-value < 0.01) and r: −566 (p-value < 0.01) respectively. The slope also has a negative correlation but not so significant (r: −0.391; p-value < 0.05). There is a positive correlation with slope shape (r: 0.367; p-value < 0.05) and enlargement variation (r: 0.324; p-value < 0.05).

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

		Depth Variation	Width Variation	WDR	Slope Shape	Vegetation Cover	Slope	Resist. to Penet.	Resist. to Torc.
Width variation	Correlation Coefficient	0.389 **	1	0.229	0.582 **	0.300 *	0.214	−0.529 **	−0.126
	Sig. (2-tailed)	0.003	-	0.084	0	0.022	0.107	0	0.344
Depth variation	Correlation Coefficient	1	0.389 **	−0.586 **	0.391 **	−0.123	−0.182	−0.532 **	−0.152
	Sig. (2-tailed)		0.003	0	0.002	0.36	0.173	0	0.254
	N	38	38	38	38	38	38	38	38

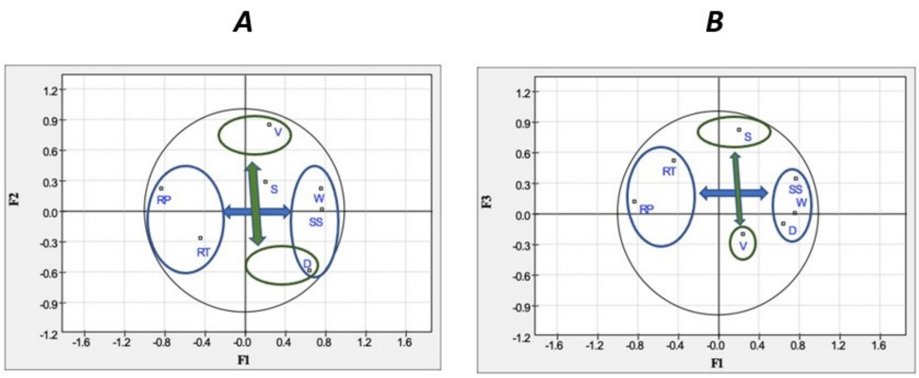
* Correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at the 0.01 level (2-tailed).

Table 3. Correlation between the variables considered and widening of gully section GS2.

		Width Variation	Depth Variation	WDR	Slope Shape	Vegetation Cover	Slope	Resist. to Penet.	Resist. to Torc.
Width variation of GS2	Correlation Coefficient	1	0.324 *	−0.707 **	0.367 *	−0.249	−0.391 *	−0.566 **	−0.166
	Sig. (2-tailed)		0.047	0.000	0.024	0.132	0.015	0.000	0.319
	N	38	38	38	38	38	38	38	38

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

The results of applying PCA suggest that the gully widening and deepening are related both to the physical properties of the soil, notably the strength and torsion, and to the shape of the slope. They confirm that the sectors where the gully widens and deepens more are where the soil shows most change, together with increased slope concavity. On the other hand, it also suggests that the sectors where the percentage of vegetation is lower is where there was even more widening and deepening of the channel (Figure 3A).



	Axis 1		Axis 2		Axis 3	
	% EXP	Related variables	% EXP	Related variables	% EXP	Related variables
Initial data		W, SS, D		V		S
7 variables *58 individuals*	36.9	↕	18.6	↕	16.0	↕
		RP, RT		D		V

Codification:

↕ represents the opposition on the factorial plan. Also represents the strong negative correlation between the variables in opposition.

Variables names: D = depth, W = width, S = slope, SS = slope shape, V = vegetation cover, RP = resistance to penetration, RT = resistance to torsion

Figure 3. ACP output: main correlation between variables according to each factorial axis: (**A**) factorial axis F1 (explaining 36.9% of the variables' variability) and factorial axis F2 (explaining 18.6% of the variables' variability) and (**B**) factorial axis F1 and factorial axis F3 (explaining 16.0% of the variables' variability).

The analysis also suggests that the higher slope sectors are those where the percentage of vegetation cover is lower (Figure 3B). This to some extent reinforces the idea that the steep slope areas are also those where the erosive dynamics is greater, as borne out by the widening of the channel and its greater depth. The results suggest an explanation of about 36.9% when considering the physical properties of the soil, in particular the resistance and the torsion; this figure increases to 55.5% when the slope gradient is considered, and to 71.6% when the slope shape is also taken into account.

The results suggest very significant modifications in the gully channel, particularly with respect to widening, especially in the final section. Although the gully is about 116 m long and the period of analysis relatively short, the steepness of the slope and the friable features of the substrate seem to contribute to this variation. The widening is largely justified by the collapse of material in the gully walls, especially where there is lower resistance to penetration and torsion, and the slope is steeper. Furthermore, forest fires, recurrent over the years, will have aggravated this process.

4. Discussions

Gully erosion is without doubt one of the main environmental problems since it contributes effectively to soil loss and degradation. The recovery of areas affected by gullies is generally costly and difficult. Some studies consider the presence of gullies in about 1–5% of total landscape observation [11], a figure that rises to 10% in Europe [57–60], especially in the Mediterranean area. Given the large number of research works on this topic, one could therefore conclude that knowledge about gully erosion processes, as well as their control, would leave little room for new insights on the topic. This conclusion can be refuted to some extent by some research gaps. More research is certainly needed to understand both the natural and man-made processes of soil erosion, especially their interaction at different spatial and temporal scales. Furthermore, it is critical for us to be able to better predict spatial and temporal scales, to forecast their erosion rates as well as their on-site and off-site impacts, so as to better target erosion control measures. In this study, we have focused on analyzing the evolution of the topographic attributes of the gully and identification of factors which had an influence on the occurrence of erosion (denudation vs. accumulation) between 2015 and 2019. Indeed, the results suggest a very complex spatial distribution of soil erodibility. The results also indicate effective gully dynamics which, although not specifically considered in this work, are certainly expressed as high erosion rates. This conclusion is especially indicated for the gully sector GS2, where a conspicuous enlargement occurred. In recent decades, several gully-erosion models have been developed, usually with the purpose of gully-erosion susceptibility mapping. Most of the time the models resort to the analytic hierarchy process to identify the main factors controlling the process. Examples are probabilistic models, information value, frequency ratio, index of entropy, evidential belief function, weights-of-evidence, certainty factor, and logistic regression. At the same time, remote sensing has enabled the development of high-resolution digital surface models (DSMs) or by photogrammetry that enable detailed morphological analyses of centimeter-order [61–65]. These models are often used for monitoring gullies and measuring erosion rates.

Moreover, the widths, cross-sectional areas, extent, and channel volume of gullies can be obtained from aerial or satellite images. However, gully floor-widths are typically hard to measure from such imagery, often resulting in unreliable results. Furthermore, gully cross-sectional areas are difficult to quantify based on aerial photographs or high-resolution satellite imagery, but are a fundamental prerequisite for estimating discharge volumes. Therefore, they are often obtained through field measurements (e.g., Nachtergaele et al., 2001a, 2001b) [66,67].

Nevertheless, field measurements are also particularly effective, especially in situations where it is hard to identify differences in soil mechanical characteristics using remote sensing. In the study area, the physical characteristics of the soil were identified as part of the fieldwork, making it possible to identify key differences in the evolution of the gully channel in detail. Other factors considered significant in explaining the gully dynamics, such as the shape of the slope and the percentage of vegetation cover, were also acquired from the fieldwork. The shape of the slope is a significant contributing factor to the explanatory model in the evolution of the gully by contributing to the concentration of drainage. The use of DSMs means the shape of the slope can be inferred and so it is often used in hydrological modeling. However, in detailed work, such as the study presented here, the fieldwork allowed the identification of this variable in a very secure way and with a high degree of detail. At the same time, the analysis of the vegetation cover evolution in the field will provide even more reliable results.

In fact, understanding the factors that contribute most to changes in the erodibility of gully is particularly important when it comes to implementing more effective control and mitigation strategies, and for defining the most susceptible areas. However, as Bennett & Wells (2019) [60] report, the temporal and spatial variation in the erodibility of gully sediments can be quite large even without the involvement of strong forces, and there is no consensus on how to predict such erodibility variation. In our study, the main factors that seem to 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 that occurred in both depth and width. Several studies consider a soil penetrometer can be a good screening tool for soil physical conditions [56,57]. Kılıç et al. (2021) [68] states that penetration resistance is dependent on a number of different properties, e.g., bulk density, water content, water potential. In this context, Nunes et al. (2010) [32] also found that soil resistance to penetration follows a similar pattern to bulk density. Erosive processes are in fact determined to some extent by the physical properties of the soil [55–57,69]. According to Olivares et al. (2011) [70], this is because of surface sealing, crusting, soil compaction, poor drainage, impeded root growth, excessive runoff, and accelerated erosion). In this regard, Nunes et al. (2010; 2011) [32,35] found a negative highly significant correlation between soil resistance to penetration and runoff and sediment yield.

The gully development is also favored in footslopes and valley floors since they represent areas where overland flow is concentrated into preferred pathways of flow [68], especially concave hollows adjacent to drainage lines, as opposed to upland convex hillslope sections [69]. Conversely, vegetation cover as offering more protection against overland flow and water erosion show a negative correlation, which agree with the findings of different authors in varied environments [32,35,71–77].

As the model was utilizing a limited set of input parameters based on variables that are easily accessible, the results show a moderate accuracy, meaning that there are several environmental factors related to gully erosion initiation and development that need to be integrated. Although gully contributing factors that are significant in a specific area are not necessarily important in other areas [78–83], local analyses of gullies have nonetheless shown that several environmental factors are related to gully erosion initiation and development. Some are local factors (e.g., soil type), and some depend on the surrounding environment (e.g., land use, climate variability) [33]. The results suggest the importance of local conditions as determinants of gully evolution, which somewhat limits the extrapolation of these results to other areas if these conditions are not considered.

In general, topographic attributes such as upstream drainage area, slope, and plan of curvature are key topographic controls in the formation process [16,80–82]. Soil properties also play an important role in allowing soil particles to detach and travel with overland flow. Soil moisture content can affect the soil critical stress and thus influence the formation and progression of gully erosion [84]. Surrounding land cover and management practices greatly influence vegetation cover and the ability of terrains to slow the overland flow [17].

5. Conclusions, Limitations, and Further Research

Monitoring a permanent gully (Centre of Portugal) over a 5-year period using intensive field topographic surveys has enabled us to understand the morphological evolution of the gully. The gully is similar to most gullies in the Alva catchment; thus, it can be regarded as representative of the main gully processes acting on this catchment. Very contrasted behaviors were observed inside the gully. The main factors affecting the spatial variability of erosion rates on bank slope units were slope gradient and slope profile. The gully was split into two units based on the morphological aspects. Units GS1 and GS2 showed low denudation rates, although they are areas that collect most of the runoff. The absence of regolith did not allow the gully excavation. The main changes occurred in GS3 between 86 m and 94 m. A convex bank slope unit has denudation rates greater than a concave bank slope, especially with regard to the gully widening.

Despite the contributions provided by this study, certain limitations must be recognized, mainly relating to the methodology and research process. The first lies in the fact that, as gullying is a threshold-dependent process controlled by a wide range of factors [13] such as topography, geology, soil type, land use/cover in the drainage areas, and the gully was not gauged, it is difficult to infer how it responds to input (rainfall) and to the combined effects of the mentioned factors. Moreover, although it is assumed that the gully material exposed to erosion is composed primarily of cohesive and non-cohesive clastic sediment, another gap in this research is due to an insufficient understanding of the controlling parameters that could affect denudation vs. accumulation. They can also include physical, geochemical, and biological properties as well as land management practices, all of which can vary in time. In this regard, the numerous fires that have occurred in the study area in recent years, which will certainly have influenced the physical, chemical, and biological properties of the soil, as well as the percentage of plant cover, are therefore essential to understanding the hydrological and erosional response in different sections, and they have not been taken into consideration.

Author Contributions: Conceptualization, B.M., A.N., A.M.-C. and L.L.; methodology, B.M., A.N., A.M.-C. and L.L.; software, B.M., A.N., A.M.-C., L.L. and C.H.; validation, B.M., A.N., A.M.-C. and L.L.; formal analysis, B.M., A.N. and A.M.-C.; investigation, B.M., A.N., A.M.-C. and L.L.; writing—original draft preparation, B.M. and A.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received support from the Centre of Studies in Geography and Spatial Planning (CEGOT), funded by national funds through the Foundation for Science and Technology (FCT) under the reference UIDB/04084/2020.

Conflicts of Interest: The authors declare no conflict of interest.

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