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Controlling factors of the size and location of large gully systems: A regression-based exploration using reconstructed pre-erosion topography

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ABSTRACT

The role of different factors potentially affecting the size and location of large gully systems is explored in two tributary basins of the Tagus River (S Portugal). The hillslopes of these basins, corresponding to tertiary sedimentary formations, are affected by hundreds of large gully systems, varying in extent from somewhat <200 m^2 to >3 ha. A study set of 90 gully systems were vectorized from aerial ortophotos and analysed in relation to a set of potential control variables, obtained by reconstructing the pre-erosion topography. Multiple linear regression and logistic regression were combined in order to investigate controls over the general morphometry of these landforms (area, perimeter and sinuosity) and their location in the respective basins. Results indicate that gully systems initiated as bank gullies in response to an incision by the drainage network in both basins and then evolved as a function of upslope contributing area, developing progressively more sinuous outlines as a result of headcut bifurcation. Pre-erosion topographic form was shown to have only a marginal effect, with results suggesting gully systems have grown essentially through mass movements in headcuts and sidewalls, influenced by subsurface water.

1. Introduction

Landforms resulting from the erosive action of concentrated flow present enormous variability, not only in terms of size and configuration, but also of evolutionary processes (e.g. Bocco, 1991; Poesen et al., 2003; Bergonse and Reis, 2011a, 2011b).

From their initiation, either through downcutting of a linear channel (ephemeral gully) or the erosive action of surface and subsurface flow on the depression left by a mass movement (bank gully), gullies frequently evolve through successive bifurcations, thus originating channel systems. These may show a network-type configuration (channels are separated by undegraded portions of the topographic surface), a complex-type configuration (channels are separated by interfluves resulting from the degradation of the original topography), or a combination of both, with sectors dominated by each of these modes of organization. Gully evolution may be marked by changes in process dominance as different geomorphic thresholds are crossed. For example, Betts et al. (2003) described the evolution of large gullies in a New Zealand study area as being dominated by fluvial incision in an initial phase, after which mass movements become the main source of sediment. Blong et al. (1982) described a similar pattern in Australia. Hicks et al., 2000 and Vandekerkhove et al. (2003) both described situations (respectively a gullied hydrographic basin in New Zealand and a study area in SE Spain) in which mass movements are critical in making easily entrained material available for removal by concentrated flow. The relevance that mass movements frequently have in gully dynamics led Collison (2001) to propose that a traditional conceptual erosion model of the kind:

$$\text{Erosion} = f(\text{erosivity},\ \text{erodibility})$$

should be replaced by:

$$\text{Erosion} = f(\text{head and wall strength},\ \text{head and wall shear stress},\ \text{erodibility},\ \text{erosivity})$$

The many studies dedicated to gully erosion have tended to focus on relatively incipient, active channels, frequently in agricultural contexts (e.g. Auzet et al., 1995; Vandekerkhove et al., 1998; Belyaev et al., 2006). Upon development, however, these erosive features remain for long periods in the landscape, crossing successive phases of growth, infilling or stability. As examples, Parkner et al. (2006) studied the evolution of numerous gullies in New Zealand throughout the period 1939–2003, defining phases of expansion and inactivity spanning intervals of several years. For a single gully in Belgium, Vanwalleghem et al. (2005)

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have defined four cycles of cutting and infilling occurring over <100 years.

Published studies on large gullies and gully systems have frequently consisted in the establishment of chronologies using different dating methods (Dotterweich et al., 2003; Lang and Mauz, 2006; Vanwalleghem et al., 2006; Panin et al., 2009) and photogrammetry-based quantifications of change across multi-decadal periods (De Rose et al., 1998; Betts et al., 2003; Parkner et al., 2006), sometimes with the purpose of exploring relations between these changes and potential control factors (Martínez-Casasnovas et al., 2004; Bouchnak et al., 2009; Martínez-Casasnovas et al., 2009). Whereas the relations between topographic setting and the incidence of ephemeral gullies have been frequently considered, similar enquiries are made more difficult with regard to large gullies and gully systems because of the expression these features have in the topographic base data. In these cases, investigating the possible link between pre-erosion topography and gully erosion requires either a generalized approach, such as dividing study areas into homogeneous geomorphological units and comparing these as to the presence of erosive features (Bacellar et al., 2005) or, in order to consider individual gullies, some form of reconstruction of the pre-erosion surface. Past approaches to this topographic reconstruction are few, and have included the interpolation of linear surfaces in eroded areas, assumed to represent the original surface (Buccolini and Coco, 2010; Buccolini et al., 2012; Cappadonia et al., 2016).

In parallel with the above mentioned studies, evolution models have been employed with promising results to simulate the initiation and development of gullies. Used models include those developed specifically for gully landforms (Sidorchuk, 1999; Flügel et al., 2003) and landscape evolution models such as the SIBERIA model employed by Hancock et al. (2014).

Two promising research opportunities seem apparent when considering published works focused on the relations between pre-erosion topography and large gullies. The first derives from the fact that real topography frequently presents some degree of curvature, either in plan or in profile. A linear approach to its reconstruction will thus very likely overlook the possible role played by curvature regarding the concentration, diffusion, acceleration and deceleration of surface and subsurface runoff (Summerfield, 1991; Olaya, 2009). Although spline-based interpolation methods can produce curved surfaces and are readily available in commercial GIS packages, some form of validation is necessary in order to meaningfully compare the capacity of different methods to reproduce real topography. In a recent article, Bergonse and Reis (2015) compared Spline and Triangular Irregular Networks methods as to the capacity to reproduce portions of the actual topography extracted from 1:10,000 topographic maps. Comparing a total of 24 parameterizations for both these methods using ArcGIS 10.1 and using as a measure of success the Mean Absolute Error (MAE) between the interpolated surfaces and the topographic contours, they concluded that in situations where contour data are available, the optimal method will be the Topo to Raster interpolator available in ArcGIS 10.1 (based on the ANUDEM method by Hutchinson, 1988, 1989), with the default parameterization (roughness penalty parameter $R = 0$). Noticeably, they observed that the linear TIN method produced the third highest MAE among all the 24 interpolations performed, a likely result of its inability to reproduce curved surfaces. It must be underlined that the above mentioned article is based on the same study area as the present one, as the results described could vary in other topographic settings.

The second limitation is one of scope, as past research has been solely focused on relating the properties of currently large gullies (namely the Italian *calanchi*) to the pre-erosion hillslopes wherein they evolved (e.g. Buccolini et al., 2012; Buccolini and Coco, 2013). Although extremely relevant, this focus could be complemented by investigating whether reconstructed pre-erosion hillslopes are morphometrically distinct from other, ungullied hillslopes in the same study area.

In other words, a more encompassing approach to large gullies may be adopted wherein two main questions are investigated:

(1) To which degree did pre-erosion hillslope form determine the current location of gullies?
(2) To which degree did it determine the morphometric evolution of gullies, culminating in their present state?

Investigating both these questions is the main objective of this article. In parallel with pre-erosion topography, the potential role of hillslope orientation and base level change as potential control factors over gully location and morphology are considered.

2. Study area

The Ulme and Vale do Casal Velho river basins (UL and VCV) are situated on the left margin of the lower Tagus basin (Fig. 1), occupying 138.4 km^2 and 12.9 km^2 respectively. Climate is temperate with a warm and dry summer (*Csa* in the Köppen system) with annual precipitation between 600 and 800 mm (Brito, 2005). Altitudes vary between minimums of 7 m (UL) and 20 m (VCV) and maximums of 200 and 198 m, reached in the headwaters sectors.

The essential morphologic units of both basins are shown in Fig. 1, together with the lithologic map. Hillslopes (average slope of 12° for UL and 11.4° for VCV) are dominated by a succession of Miocene to Pliocene sands, clays and sandstones, with frequent gravel and conglomerate levels. In contrast, interfluves show a markedly flat relief (2.8° for the UL and 3.6° for the VCV), corresponding to extensive conglomerate and sandstone beds (Pliocene). Apart from these two main formations (representing 91% and 87.5% of the areas of the UL and VCV), lithologic setting includes four levels of fluvial terraces (Pleistocene), frequently occurring as relatively smooth-sloped sectors on the hillslopes (2.5% of the UL and 6.2% of the VCV) and alluvial deposits (Holocene) along the valley bottoms (6.5% of the UL and 3.3% of the VCV). The remaining formations, consisting of Holocene sand deposits and Paleozoic granites, have a merely residual expression.

Landcover in both basins is characterized by eucalyptus stands, dominating the interfluves and part of the hillslopes, and by spontaneous bush formations among disperse cork-oaks (*Quercus suber*), occurring in the hillslopes and resulting from the abandonment of prior *montado*-type agro-forestry. It is important here to make reference to the fact that although land use is potentially a major factor on gully initiation and evolution, the focus of this article is on the possible control exerted by antecedent topography. Land use was therefore given no further consideration.

The hillslopes of both basins are affected by hundreds of large gullies, predominantly organized in complexes (as opposed to networks: Bergonse and Reis, 2011a), with sizes varying from c.200 m^2 to >3 ha. Some examples are shown in Fig. 2. They are partially stabilized, with bottom sectors dominated by vegetation. Present activity is visible only in walls and headcuts, where steep, unvegetated sectors, frequently large fluting features, basal deposits and trees with exposed root systems signal mass movement-based retreat. In spite of their size, these landforms mostly drain towards incipient, decimetric channels, and frequently have their outlets completely disconnected from the present drainage network, with no outflow channel whatsoever. In their present state, these gullies seem therefore to be either weakly coupled to the fluvial system or completely discoupled from it as a result of deposition. Although there are no published works dedicated to their evolution, visual inspection of black and white aerial photos taken in 1958 (when the land use was dominated by cork oak agroforestry) has shown that the studied gullies were already present in much the same state as today.

3. Methodology

The applied methodology may be divided into three phases.