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Predicting the susceptibility to gully initiation in data-poor regions

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ABSTRACT

Permanent gullies are common features in many landscapes and quite often they represent the dominant soil erosion process. Once a gully has initiated, field evidence shows that gully channel formation and headcut migration rapidly occur. In order to prevent the undesired effects of gullying, there is a need to predict the places where new gullies might initiate. From detailed field measurements, studies have demonstrated strong inverse relationships between slope gradient of the soil surface (*S*) and drainage area (*A*) at the point of channel initiation across catchments in different climatic and morphological environments. Such slope–area thresholds (*S*–*A*) can be used to predict locations in the landscape where gullies might initiate. However, acquiring *S*–*A* requires detailed field investigations and accurate high resolution digital elevation data, which are usually difficult to acquire. To circumvent this issue, we propose a two-step method that uses published *S*–*A* thresholds and a logistic regression analysis (LR). *S*–*A* thresholds from the literature are used as proxies of field measurement. The method is calibrated and validated on a watershed, close to the town of Algiers, northern Algeria, where gully erosion affects most of the slopes. The gullies extend up to several kilometres in length and cover 16% of the study area. First we reconstruct the initiation areas of the existing gullies by applying *S*–*A* thresholds for similar environments. Then, using the initiation area map as the dependent variable with combinations of topographic and lithological predictor variables, we calibrate several LR models. It provides relevant results in terms of statistical reliability, prediction performance, and geomorphological significance. This method using *S*–*A* thresholds with data-driven assessment methods like LR proves to be efficient when applied to common spatial data and establishes a methodology that will allow similar studies to be undertaken elsewhere.

1. Introduction

Permanent gullies, i.e. gullies that cannot be obliterated by ploughing, are common features in many landscapes and often, like in Mediterranean and arid environments, they represent the dominant process of soil erosion by water (Vandekerckhove et al., 2000; Poesen et al., 2002, 2003). Gully erosion is responsible for soil degradation, increase in sediment delivery, and reduction of water quality. It is also responsible for a decreased water travel time to rivers (and hence increased flooding probabilities), for the filling up of ponds and reservoirs, and for the destruction of buildings, fences, and roads. Gully erosion is highly sensitive to climate and land use changes (Poesen et al., 2002, 2003).

The initiation and the growth of a gully and gully system is complex (Istanbulluoglu et al., 2002). From field evidence, it is known that gully channel formation and headcut migration are usually very rapid following the initiation of the gully (e.g., Rutherfurd et al., 1997; Sidorchuk, 1999; Nachtergaele et al., 2002; Nyssen et al., 2006; Gómez Gutiérrez et al., 2009a; Seeger et al., 2009). In order to prevent the undesired effects of gullies, there is a need to anticipate the places where new gullies might initiate.

To predict where gully erosion will occur in the landscape by the extension of an existing gully or the formation of a new gully is difficult (Bull and Kirkby, 1997; Poesen et al., 2003, 2011). Gully initiation clearly is controlled by a variety of environmental conditions that can be modelled as threshold phenomena. Montgomery and Dietrich (1988, 1989, 1992, 1994) and Dietrich et al. (1992, 1993) were among the first authors to explore topographic thresholds on the occurrence of erosion channels. From detailed field measurements and the use of high-resolution digital terrain models (DTMs), they found a strong inverse relationships between slope gradient of the soil surface at the point of gully initiation (*S*) and contributing drainage area (*A*, proportional to runoff discharge) for a given environmental condition. The topographic threshold is based on the assumption that in a landscape with a given climate, pedology, lithology, and vegetation, for a given *S*, there exists a critical *A* necessary to produce sufficient runoff for gully initiation (Montgomery and Dietrich, 1988, 1989). For different environmental

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conditions and different gully initiating processes (e.g. Horton overland flow, saturation overland flow, and shallow small landsliding) different topographic thresholds apply (Montgomery and Dietrich, 1988; Dietrich et al., 1992; Montgomery and Dietrich, 1994). Such slope-area thresholds (*S*–*A*) are therefore a useful predictor to forecast the location in the landscape where gullies might initiate (Montgomery and Dietrich, 1992; Dietrich et al., 1993).

Other attempts to map susceptibility to gully initiation through the use of *S*–*A* relationships have been carried out (e.g., Prosser and Abernethy, 1996; Vandaele et al., 1996; Desmet et al., 1999; Vandekerckhove et al., 2000; Istanbulluoglu et al., 2002; Kirkby et al., 2003; Morgan and Mngomezulu, 2003; Vanwalleghem et al., 2003; Hancock and Evans, 2006; Jetten et al., 2006; Pederson et al., 2006; Lesschen et al., 2007; Svoray and Markovitch, 2009; Millares et al., 2012). Although some of these studies were capable of predicting gully location, they require detailed field measurements and high resolution digital elevation data as input; which is in most cases difficult to acquire.

Data-driven assessment methods have also been applied to predict landscape susceptibility to gully erosion. In these methods combinations of environmental factors controlling the occurrence of the existing gullies are statistically evaluated, and quantitative predictions are made for current non-gully-affected areas with similar environmental conditions (e.g. Meyer and Martinez-Casasnovas, 1999; Hughes et al., 2001; Bou Kheir et al., 2007; Geissen et al., 2007; Vanwalleghem et al., 2008; Gómez Gutiérrez et al., 2009b,c; Ndomba et al., 2009; Pike et al., 2009; Kuhnert et al., 2010; Akgün and Türk, 2011; Conforti et al., 2011; Eustace et al., 2011; Luca et al., 2011; Märker et al., 2011; Svoray et al., 2012; Conoscenti et al., 2013). These models are simple in their concept, do not necessarily need to rely on in situ field measurements, and have proved to be capable of predicting gully location even when using predictor variables extracted from common spatial data that are readily available for data-poor regions (e.g. global satellite-derived elevation data, basic topographic and lithological maps, and aerial photographs). A main advantage of these models is that the amount of information they can consider through the use of a potentially large panel of environmental factors can be just as important as the information contained in *S* and *A* alone. However, the spatial resolution of these datasets is often relatively low considering the actual size of the gullies and, when field information is lacking, to distinguish between the gully initiation area and its extension is difficult (Vanwalleghem et al., 2008; Svoray et al., 2012). So far, most of these studies applying data-driven methods did not make this distinction and failed at predicting the actual initiation area of the gullies.

The objective of our research is therefore to develop a quantitative method gathering the advantages of both the threshold and the data-driven approaches for allowing the susceptibility to gully initiation to be predicted with readily available common spatial data. Our attention will be focused on the original point of gully initiation, i.e. before erosion leads to development of the gully. We propose a two-step method that uses published data on *S*–*A* thresholds and a logistic regression analysis (LR) (Fig. 1). LR is a multivariate statistical method widely used for the prediction of the spatial occurrence of surface processes such as mass movements (e.g. Dai et al., 2004; Van Den Eeckhaut et al., 2006; Rossi et al., 2010; Guns and Vanacker, 2012; Bosco et al., 2013), and that has already proved its appropriateness for gully erosion (e.g., Meyer and Martinez-Casasnovas, 1999; Vanwalleghem et al., 2008; Pike et al., 2009; Akgün and Türk, 2011; Luca et al., 2011; Svoray et al., 2012). LR is a low data demanding technique, requiring predictor variables easily extractable from common spatial data, and yields directly a probability of occurrence of the studied process (Hosmer and Lemeshow, 2000). Published *S*–*A* thresholds are used as field measurement proxies.

2. Material

In order to facilitate the method's development and to focus on the *S*–*A* thresholds, a region characterized by a complex topography with a wide range of slope configurations and where environmental conditions such as lithology and soils are favourable to gully development is selected.

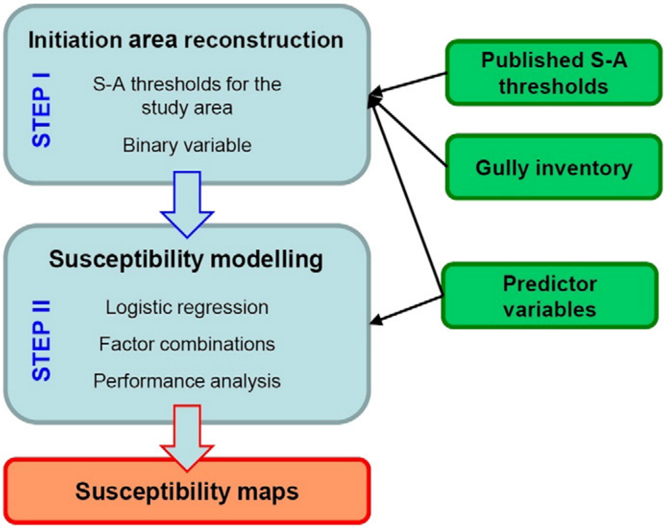

Fig. 1. General framework of the two-step method used to predict the susceptibility to gully initiation.

2.1. Study area

We focus on a 51 km^2 sub-basin of the Isser River watershed in northern Algeria where the environmental conditions are favourable to gullying. The area is located approximately 80 km south east of Algiers in the Tell Atlas (Fig. 2). The climate is classified as Mediterranean close to semi-arid conditions, especially during the driest years. The average annual precipitation is approximately 400 mm. Precipitation is often caused by thunderstorms and is irregularly distributed throughout the year with a maximum in winter (70% of the precipitation between October and March) and a minimum in summer (Touazi et al., 2004).

The elevation of the sub-basin ranges from ~700 to ~1300 m above sea level. The lithology consists mainly of Paleocene–Eocene marls and calcareous marls (~70% of the total area), Cretaceous marls and limestones (~20%), and Quaternary alluvial deposits (~10%) (Fig. 2). These unconsolidated and poorly sorted materials are favourable conditions for gully development (Poesen et al., 2003). The majority of soils in this Mediterranean mountainous terrain are weakly developed Regosols formed on the unconsolidated marls (Daoudi, 2008). The pattern of vegetation and land use forms a mosaic of cultivated lands, rangelands, and scrublands; ninety-five percent of the zone having a sparse vegetation cover (Daoudi, 2008). The road network and building infrastructures are of limited extent.

Gullying is a widespread process in the watershed extending over most slopes (Fig. 2). Gully channels occupy 16% of the study area; which corresponds to a relatively high proportion compared to other watersheds in similar environments (Poesen et al., 2003). The permanent gullies vary in size and in shape. They can extend up to several kilometres in length and several tens of meters in width. In some cases their depth can be up to 10 m (Daoudi, 2008). Some gullies have a basic linear shape with one headcut linear gully (LG); the largest of them extending principally in the Eastern side of the watershed where the slope profiles tend to be more regular and the local relief is higher (Fig. 2C). Gullies develop also into complex gully systems (GS) that divide into several branches and multiple headcuts (Fig. 2B). Some of them have one or several bifurcations that arise either at the gully head or along the channel (Bull and Kirkby, 1997). Geomorphological evidence identifiable in aerial photographs of 1992 (Table 1) and