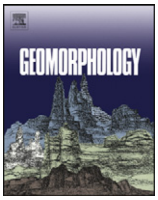
Geomorphology 186 (2013) 1–11

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



Impact of terrain attributes, parent material and soil types on gully erosion

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ARTICLE INFO

Article history:
Received 24 March 2011
Received in revised form 9 October 2012
Accepted 25 October 2012
Available online 9 December 2012

Keywords:
Soil erosion
Land degradation
Water movement
Digital mapping

ABSTRACT

Gully erosion is a worldwide matter of concern because of the irreversible losses of fertile land, which often have severe environmental, economic and social consequences. While most of the studies on the gullying process have investigated the involved mechanisms (either overland flow incision, seepage or piping erosion), only few have been conducted on the controlling factors of gully wall retreat, an important, if not the dominant, land degradation process and sediment source in river systems. In a representative 4.4 km^2 degraded area of the Drakensberg foothills (South Africa) the main objective of this study was to evaluate the relationship between the rate of gully bank retreat (*GBR*) and parent material, soil types and selected terrain attributes (elevation, specific drainage area, mean slope gradient, slope length factor, stream power index, compound topographic index and slope curvatures). The survey of gully bank retreat was performed during an entire hydrological year, from September 2007 to September 2008, using a network of pins ($n=$ 440 from 110 pits). Both the gully contours and pin coordinates were determined, using a GPS with a 0.5 m horizontal accuracy ($n=20{,}120$). The information on the parent material and the soil types was obtained from field observations complemented by laboratory analysis, while terrain attributes were extracted from a 20 m DEM generated from 5 m interval contour lines. The average *GBR* value for the 6512 m of gully banks found in the area was 0.049 ± 0.0013 m y^{-1}, which, considering bank height and soil bulk density, corresponded to an erosion rate of 2.30 ton ha^{-1} y^{-1}. There was no significant difference in *GBR* between sandstone and dolerite and between Acrisols and Luvisols. Despite a weak one-to-one correlation with the selected terrain attributes ($r<0.2$), a principal component analysis (PCA), the first two axes of which explained 68% of the data variability, pointed out that *GBR* was the highest at hillslope inflexion points (profile and plan slope curvatures close to zero), in the vicinity of the head cuts and for drainage areas up to 500 m^2, as both situations experience a high removal rate of the soil material produced from the gully bank collapse and protecting gullies from laterally retreating. These results could be used to digitally map the more active gully banks for the improved implementation of preventive measures of gully growth, if high resolution DEMs are available. There remained, however, a certain amount of unexplained variability in the data, that further research studies on the mechanisms and associated factors of control of *GBR* could help to address.

1. Introduction

Soil erosion is a natural phenomenon. However, when the removal of the soil is faster than soil formation through bedrock weathering, it becomes problematic, often resulting in the reduced ability of the terrestrial ecosystems to perform their functions, such as those of food and biomass production, storage and filtering of water (FAO, 2008).

There are three main types of water erosion (Wischmeier and Smith, 1978). The first type is splash erosion, which is the detachment and airborne movement of small soil particles caused by the impact of raindrops on the soil surface. The second type, sheet erosion, corresponds to the detachment of soil particles by raindrop impact and their removal down-slope by sheet flow (Chaplot and Le Bissonnais, 2003; Chaplot et al., 2007), while the third type is linear erosion, where the soil material is detached and transported by overland flow (Kinnell, 2004). Rills correspond to the shallowest forms of linear erosion, while gullies are sufficiently deep not to be filled by tillage operations, thus resulting in irreversible losses of agricultural land. In light of ecosystem management, it is important to understand the spatial distribution of gullies and gullying (the process of gully formation and evolution) in agricultural landscapes (Poesen et al., 2003).

Overland flow is thought to be the main cause of gully erosion. When the flow velocity overcomes a threshold resistance of the soil material, overland flow induces scouring, which initiates macro channel formation. Because of the topographic control of flow velocity, several topographical thresholds have been used for spatially predicting gully formation (Nachtergaele et al., 2002; Poesen et al., 2003). In addition, linear erosion by subsurface water movements is often overlooked. Preferential flow paths through pipes are considered as a major process

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http://dx.doi.org/10.1016/j.geomorph.2012.10.031

of linear erosion (Fox and Willson, 2010), as well as of landslides (Uchida et al., 2001). Gullies may build-up, when soil pipes erode underlying soil horizons to the extent that tunnel collapse occurs. When the sediment concentration in the pipe flow exceeds its transport capacity, pipe blockage may happen, causing a build-up of soil water content and water pressure, which is responsible for mass movements and landslides. Once the depression forms, the changed soil surface morphology collects and concentrates overland flow, which may increase the export of sediments. Lateral seepage is another process by which the enhanced soil pore water pressure causes undercutting, which, in turn induces wall failure and depression enlargement (Fox and Willson, 2010).

The literature on the prediction of gully head cut location, based on the role of topography, is abundant (Poesen et al., 2003). The topographic thresholds for gullying, which are based on Horton's (1945) concept of overland flow generation and concentration, may vary from site to site. However, Bocco (1991) suggested that rather than be caused by Hortonian flow, gully initiation might often to be due to saturated overland flow and piping. According to various authors, the topographic parameters, mean slope gradient (S) and upslope contributing area per unit length of contour (As in m^2 m^{-1}), are critical to assess the location and the size of gullies. It is indeed assumed that gullying occurs as the flow velocity exceeds the soil shear stress, which is mostly a function of As, as it controls the amount of overland flow and S, which determines its level of energy (Vandaele et al., 1996; Vandekerckhove et al., 1998; Desmet et al., 1999). Based on this concept, there is an inverse relationship between S and As, the upslope contributing area for gully initiation decreasing, as the mean slope gradient increases. Several topographic thresholds for gullying were found in the literature. In the US, Moore et al. (1988) found that $S \times As$ should be over 18 or $\ln As/\tan S$ up to 6.8 to initiate gully erosion. In the Belgian loess belt, the threshold was found to be between $S \times As^{0.4} = 0.025$ (Vandaele et al., 1996) and $S \times As^{0.4} = 0.72$ (Desmet and Govers, 1997). Predictions based on topographic thresholds have successively allowed the spatial prediction of gully erosion headcuts in some areas of the world, such as the West European loess belt (Poesen, 1989; Desmet and Govers, 1997) and the steep slopes of South East Asia (Chaplot et al., 2005), but in many other areas, the concept of topographic control of gullying is flawed.

For this reason, several authors established thresholds of upslope contributing area to account, not only for gullying by saturation overland flow, but also pore pressure induced landsliding and piping (Montgomery and Dietrich, 1988, 1989, 1994; Dietrich et al., 1993; Montgomery, 1994, 1999), two frequently overlooked mechanisms, operating at low flow velocities. Montgomery and Dietrich (1992) and Dietrich et al. (1993) showed that a single $S \times As^{a}$ threshold was insufficient at predicting gully initiation in Tennessee, USA. They further demonstrated that the "a" exponent should be between 1 and 2, with a threshold between 25 and 200 to account for the different gullying processes.

While most of the studies have investigated the factors of control of gully head cut location, only few have been performed on the controlling factors of gully side wall retreat, an important – if not the dominant – land degradation process (Daniels, 2002; Krause et al., 2003). Based on the fact that environmental factors are much easier to obtain than measurements of gully wall retreat, especially when large areas are considered, establishing a link between wall retreat and some key environmental factors, such as relief and soil type, will allow the spatial prediction of lateral gully growth and will improve the implementation of preventive measures that will reverse the growth of existing gullies.

From the available literature, gully side walls can either retreat rapidly in width during single storm events or change little over long periods of time (5000–10,000 years) (Kirkby and Bracken, 2009). The reason for such discrepancies seems to be related to the detachment of soil material from the gully walls and its evacuation possibilities. By wetting the soil, rainfall acts mainly through the slaking and spalling of the soil at gully banks (the wetted soil part breaks off from the drier material underneath and drops), but with the detachment of single particles by splash being a minor process (Chaplot et al., 2011). Moreover, during rainfall events, overland flow can infiltrate in between soil aggregates and natural vertical cracks, fostering the collapse of gully banks, a process that may be accelerated by seepage undermining erosion. As the gully walls sap, the collapsed material produces a talus slope close to the angle of repose, that may eventually protect the gully bank from further retreat. The capacity of the gully to grow laterally thus depends on the ability of runoff in the gully channel to evacuate this material. It is the premise in this paper that bank retreat processes are correlated to the bank environment. The question of whether environment factors, such as terrain morphology (mean slope gradient, terrain curvature and upslope drainage area), parent material and soil types may allow the prediction of the retreat rate of gully walls, remains to be asked. To this end, this study investigated the link between gully evolution and selected environmental factors in an active gully system of South Africa. The study was performed in the foothills of the Drakensberg, where preliminary observations have shown that gullying is an active process (Martin, 1987; Yaalon, 1987; Botha et al., 1994; Wintle et al., 1995; Rienks et al., 2000; Morgan and Mngomezulu, 2003; Chaplot et al., 2011).

In a representative 4.4 km^2 degraded rangeland, the main objective was to assess the relationship between gully side wall retreat over an entire year and selected factors of the environment, such as terrain morphology, parent material and soil types. Here the focus is on permanent gullies, not ephemeral gullies and rills.

2. Study area

The study site is a 2×2.2 km^2 area (longitude: 29.36°; latitude: 28.82°) of the foothills of the Drakensberg mountains (KwaZulu-Natal Province, South Africa) (Fig. 1). This area under rangeland is included in the Thukela Basin (30,000 km^2), a river system highly modified by humans with a high density of dams and reservoirs to fulfill the needs of the agriculture and of large cities.

The altitudes in the area range between 1237 and 1467 m (Fig. 1). Higher altitudes occur in the north-east and in the south-west, separating two hydrologic networks, one flowing to the North and one flowing to the East. The relief in the area is relatively gentle with a mean slope gradient of 0.16 m m^{-1}, but with values reaching 0.9 m m^{-1} in the southern or northern escarpments.

The most commonly found parent material in the area is composed of sedimentary rocks in horizontal alternate layers of fine grained sandstones. Luvisols and Yellow Acrisols (WRB, World Reference Base for Soil Resources, 1998) are developed from this geological substrate. Few intrusions of dolerite with typical weathering features of rounded boulders were found in the area. This parent material, associated with Red Acrisols, was found mainly in the south, north and north-east of the study site (Fig. 1C).

Following the classification of Köppen (Peel et al., 2007), the climate of the area is temperate with cold dry winters and rainy warm summers. The mean thirty year annual precipitation at the Bergville meteorological station, situated 10 km north, is 684 mm. The mean potential evaporation is 1600 mm and the mean annual temperature is 13 °C (Schulze, 1997). Summer rainfall occurs between October and March and frosts are common in winter, especially in June and July. In the area, a 30-min rainfall has a 2-year return period intensity of 49 mm h^{-1}, with 1st and 9th deciles at 37 and 61 mm h^{-1}, respectively. The intensity is 76 mm h^{-1} for a 10-year return period and 115 mm h^{-1} for 100 years.

The rainy season under study (2008–2009) was characterized by a total rainfall amount of 762 mm, which was close to the 2007–2010 average of 747 mm, but 11% higher than the thirty year value. Using