Topographic thresholds in gully development on the hillslopes of communal areas in Ngqushwa Local Municipality, Eastern Cape, South Africa

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Abstract

The relationships between the spatial distribution of gully erosion and topographic thresholds in the form of slope angle, position and configuration, as well as land use change in the form of abandoned lands were examined in several affected catchments of the Eastern Cape Province, South Africa. Land use and permanent gullies were mapped, digitized from orthophoto maps in Arc/info 3.5.2 GIS and converted to shapefiles using ArcView 3.2 GIS. Relationships between the mapped phenomena and topographic variables were sought using a Digital Elevation Model (DEM) in Idrisi Kilimanjaro GIS. A comparison between areas with a high potential for gullying and actual gully erosion was made using the Stream Power Index (*SPI*) as a surrogate for critical flow shear stress. Field surveys were also conducted to assess the present condition of the gullied sites as well as to validate DEM derivations.

Seventy five percent of the gullied area was noted to lie on abandoned lands. A predominance of gullying in concave bottom lands was also identified. The *SPI* values highlighted a distinct preferential topographic zone for gully location. A conceptual model depicting the interaction between land use and topographic parameters to induce gully erosion was developed. This should assist local authorities to develop a policy regarding management of abandoned lands.

1. Introduction

Soil erosion is a widespread environmental problem in South Africa highlighted in several studies (see [Watson and Ramagopa, 1997], [Watson, 2000], [Kakembo and Rowntree, 2003], [Sonneveld et al., 2005], [Keay-Bright and Boardman, 2006], [Keay-Bright and Boardman, 2007] and [Barker and Gauert, 2007]). The Eastern Cape Province is one of the regions where severe erosion in the form of permanent gullies is an endemic form of land degradation, particularly in the communal lands. It is singled out by Le Roux et al. (2008) as one of the three provinces in South Africa with the highest erosion potential. Gully erosion has been widely neglected in erosion modelling (Sidorchuk et al., 2003), and despite its significant contribution to overall soil loss, most research dealing with soil erosion has concentrated on sheet and rill erosion (Poesen et al., 2003). Relatively few studies have taken gully contribution into account when assessing soil losses in upland areas or when quantifying sediment production (Poesen et al., 2002). Gullies are efficient sources and pathways of runoff and sediment from hillslopes to sediment sinks located in stream channels, hence affecting fluvial processes and the ecological functioning therein. Gullies are thus key elements of landscape connectivity, functionality and conversion to dysfunctionality.

Serious gully erosion affects several catchments in the communal villages of the Ngqushwa district, Eastern Cape. Investigations in a number of these catchments have revealed a strong link between land use change in the form of land abandonment and badland gullying ([Kakembo, 1997], [Kakembo and Rowntree, 2003] and [Rowntree et al., 2004]). Similar trends have been identified by Harden (1996) in the Ecuadorian Andes; Sonneveld et al. (2005) in Kwazulu-Natal, South Africa; Sirviö et al. (2004) in Taita, Kenya; and Lesschen et al. (2007) and Gutiérrez and Schnabel (2008) in Southeast Spain. In their evaluation of the effect of land use change on mountain hydrology, Molina et al. (2007) identified abandoned lands as exceedingly important sites of runoff generation. Despite the propensity of abandoned lands to erode severely, this has rarely been addressed in land use modelling studies (Mulligan, 2004). Runoff and erosion mitigation on abandoned lands necessitates an understanding of where land abandonment will most likely occur (Lesschen et al., 2007). This would assist in developing a proactive policy regarding management of abandoned lands.

Topographic thresholds for gully initiation and location have been explained mainly in terms of soil surface gradient and critical drainage area (*S*–*A*) relations ([Vandekerckhove et al., 2000], [Poesen et al., 2002], [Poesen et al., 2003], [Morgan and Mngomezulu, 2003], [Vanwalleghem et al., 2005] and [Parkner et al., 2006]). An exception, however, is the study by Vandekerckhove et al. (1998) which demonstrated that *S*–*A* relations cannot explain gully initiation in isolation, because only a weak correlation was identified between them. Whereas variations in topographic thresholds have been explained by vegetation type and cover in rangelands, soil structure and moisture conditions have also been identified as critical factors in gully initiation on cultivated land (Vandekerckhove et al., 2000). Notwithstanding the emphasis on topographic thresholds, a holistic understanding of gully development necessitates unravelling the interaction between specific topographic attributes and a range of other thresholds related to hydraulics (particularly considerations of critical flow shear stress), rainfall, geology, soil and land use. Long term climatic events, for example wet and dry phases of varying duration are reported by Price-Williams and Watson (1982) as having given rise to locally thick colluvial deposits mantling the landscape throughout Southern Africa. Deeply incised gullies in the colluvia are reported by Price-Williams et al. (1982) and Watson et al. (1984) in Swaziland and Zimbabwe respectively. However, logistical constraints permit only a partial analysis of this interaction, and proxies of some of these thresholds are often employed instead. In this study, the relationship between the spatial distribution of gully erosion and topographic thresholds in the form of slope angle, position and configuration, as well as land use change in the form of abandoned lands is examined. This may serve to highlight a specific topographic zone of high susceptibility to gullying.

2. Study area

The study area comprises the upper sections of several catchments affected by gully erosion in a number of communal villages in the Ngqushwa district. These include the catchments of the Gqora tributary of the Great Fish River and the Bira, Mtati and Mgwalana rivers. Land abandonment is a widespread phenomenon in the study area (Fig. 1). Overgrazing has also been noted from field observations as another major form of land disturbance, as grass biomass is consistently reduced to ground level due to continuous grazing by domestic herbivory.

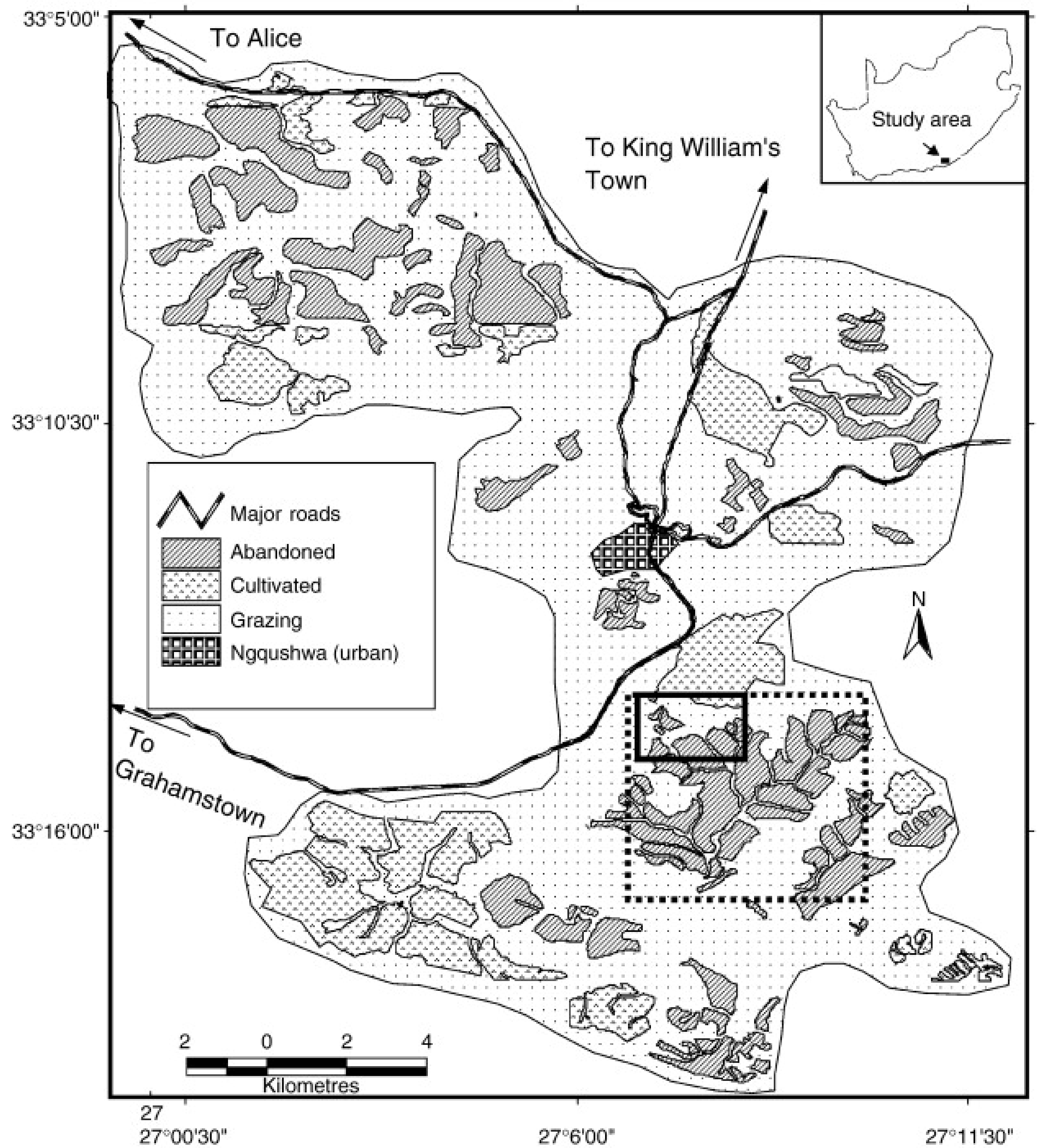

Fig. 1. Distribution of abandoned lands in the study area (Kakembo, 2009). The solid and dotted rectangles indicate the location of gullied areas shown in Fig. 7 and Fig. 8 respectively.

The highly fissile shales occurring in association with red mudstones of the Ecca group of the Karoo supergroup predominantly underlie the study area. The Ecca group rocks give rise to shallow lithosolic soils characterised by stony or rocky phases. Swelling hydrous mica clays with a gross structure similar to that of montmorillonite were identified by Kakembo et al. (2007) as the dominant clay mineral compounds. The local soils are highly sodic with very low organic matter content, rendering them highly erodible. Such characteristics promote chemical dispersion of soil particles and have serious implications for soil surface conditions, particularly crusting. Indeed, soil crusts of up to 1 mm thick are a widespread phenomenon in the study area, particularly in the bare areas that intersperse Pteronia incana, a patchy invader shrub that has colonised most abandoned and other degraded lands.

Whereas extensive gentle interfluves (below 9°) constitute over 70% of the study area, most slopes facing stream channels characteristically rise steeply (10° and above). It is the lower elements of the steeply rising slopes that are extensively affected by severe gully erosion (see Fig. 2). Typically, the study area experiences a highly variable distribution of rainfall with a 70 year mean annual total of 488 mm. It is erratic in distribution and displays a well defined peak during the summer months — October to April. Climatic fluctuations in the form of droughts and extreme rainfall events are a characteristic feature of the area. The coupling between the high soil erodibility and land disturbances is deemed to have interacted with climatic fluctuations and topographic thresholds to promote gully erosion.

Fig. 2. An example of the gully sites mapped in this study.

3. Materials and methods

Seventeen orthophoto maps of 1: 10 000 scale, based on 1998 photography, were used as base maps to identify and map gullies as well as land use. The mapped phenomena were digitized from the orthophoto maps onto the GIS using Arc/Info 3.5.2 version. They were edited, transformed, mapjoined and exported to ArcView 3.2 GIS where they were converted to shapefiles. Gully shapefiles were then exported to Idrisi Kilimanjaro where relationships with topographic variables were established. Notwithstanding the trade-offs associated with exporting data from vector to raster formats and vice versa, a comparison of the area of gullies calculated in both GIS formats corresponded very closely.

Topographic thresholds in the form of slope angle and position, concavity and convexity have a significant influence on gully initiation, as they influence the magnitude and direction of water flow. Areas contributing runoff into individual gully heads are largely determined by hillslope form. In the present study, a 20 m DEM of the study area obtained commercially was used to extract topographic variables at hillslope scale. DEM windows representing specific hillslopes, identified from orthophoto maps and verified in the field as gullied, were generated. Slope angle surfaces were calculated from the windows and slope position was determined in relation to hillslope bottom stream channels.

Gully shapefiles imported from ArcView 3.2 into Idrisi were rasterised and overlaid on the surfaces representing specific hillslope parameters. The overlays provided an indication as to the spatial relationships between specific topographic thresholds and mapped gully sites (n = 120). The relationship between slope angle and gully development was examined by calculating the extent of gullied area on hillslopes represented by eleven DEM windows. The hillslope units were reclassified into five categories: 0°–4°, 5°–9°, 10°–14°, 15°–19° and > 20°. The ‘Curvature’ algorithm was used to derive both profile and plan concavity and convexity surfaces. The percentage of gullied areas was calculated in relation to hillslope position and configuration.

Field surveys were undertaken to assess the present condition of the gullied sites as well as to validate DEM derivatives. Using an Abney level and a GPS, slope angles were measured, and slope configuration (concavity and convexity) and gully positions were recorded at 30 test sites matching the DEM windows. At all the sites, the slope parameters corresponded with DEM derivatives.

Slope characteristics with a high potential for gullying were compared with actual gully erosion using the Stream Power Index (*SPI*) (Moore et al., 1993), a derivative of the TOPMODEL ([Beven and Kirkby, 1979] and [Quinn et al., 1991]), using the formula:

$$SPI=\ln(A_s\tan\beta)$$

where A_s is specific contributing area and β is local slope.

A_s was computed using the one-directional flow routing algorithm in Idrisi GIS. The effectiveness of the algorithm was validated by draping mapped gully sites on *SPI* surface windows and hillshaded images. According to Tagil and Jenness (2008), *SPI* is used to estimate terrain erosive power and indicative of the potential energy available to entrain sediment such that, areas with high stream power indices have a great potential for erosion. A_s and β surfaces for the respective hillslopes were calculated and integrated using the formula above to derive corresponding *SPI* surfaces. This served to highlight areas with high potential for sediment removal and hence prone to gullying. An overlay of gullied areas on *SPI* surfaces served to compare potential and actual gully erosion, as well as identify a preferential topographic zone for gully initiation. A simple conceptual model depicting the interplay of hillslope parameters and land use to induce gully erosion was thus developed on the basis of these relationships.

4. Results

Fig. 3 depicts an overlay of gullied areas on the main land use types. A predominance of gullying on abandoned lands is vividly evident, as 79.4% of the total gullied area lies on abandoned lands. This relationship highlights how low the topographic threshold for gully development is on abandoned lands. However, abandonment alone cannot explain gully threshold conditions. Spatial relationships with specific hillslope parameters would elucidate gully topographic thresholds.

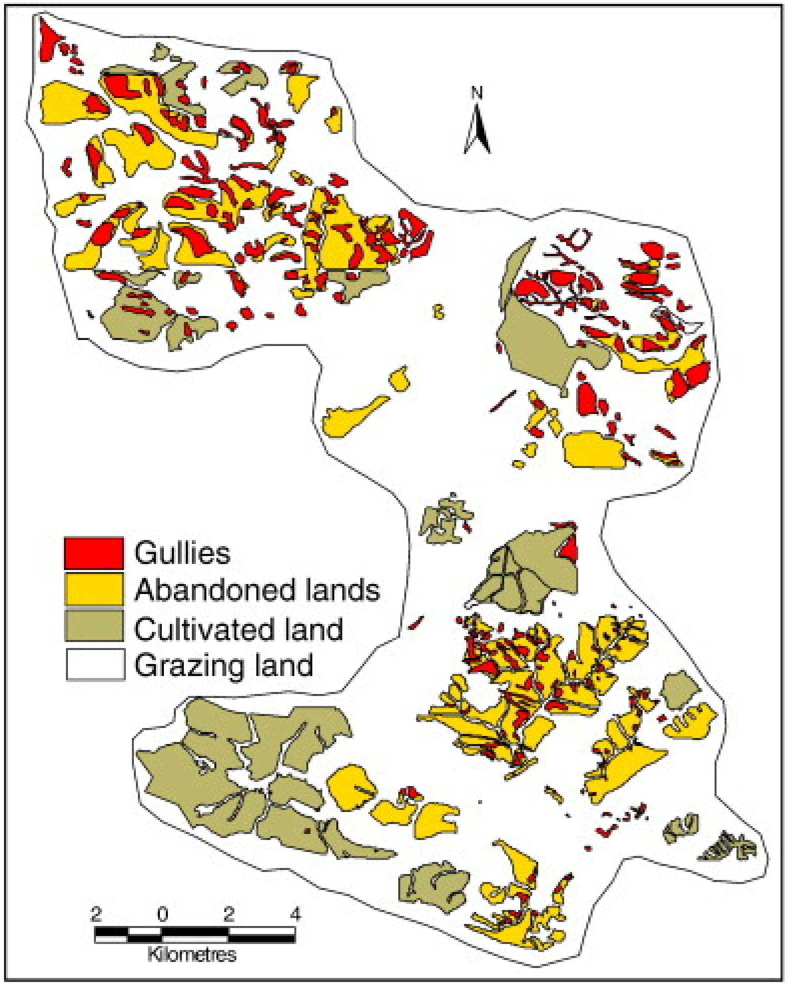

Fig. 3. Predominance of gullying on abandoned lands. Few gullies can be seen on grazing and cultivated land.

The total percentage of gullied area in relation to slope angle is depicted in Fig. 4. The figure shows that gullying is predominant in the slope class 5°–9° (44.4% of gullied area). A considerable amount of gullying can also be seen in the 10°–14° class compared to the steeper slopes of 15°–19° and above 20°. A Chi-square value of 63.29, greater than the critical value of 55.76 at the 0.05 significance level confirmed that there is a statistically significant relationship between the observed gully erosion and specific slope category.

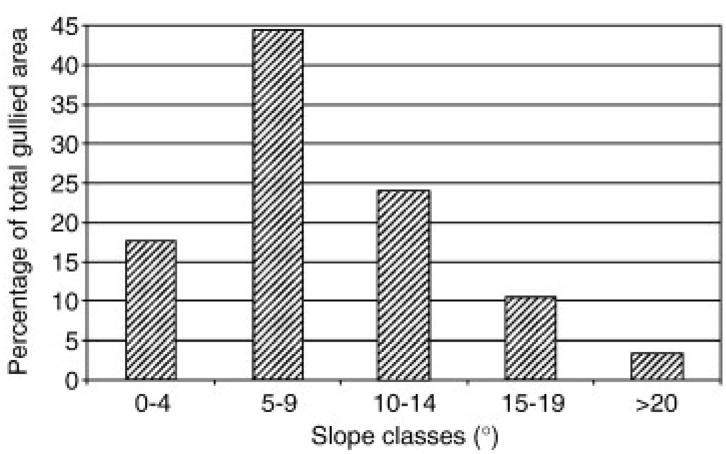

Fig. 4. Percentage of the total gullied area per slope category.

The relationship between hillslope position and gully development was examined on the respective hillslope units. The units were divided into three slope positions viz.: lower, middle and upper, and the gullied area in each position was worked out in the Idrisi GIS database. The total percentage of gullied area in relation to slope position (Fig. 5) shows that the most frequent gullied position is the lower hillslope element. Field observations confirmed that gullies are concentrated in pockets of colluvium located at the foot of hillslopes. Most gullies remain active, deeply incised in colluvium (up to 3.5 m) and assume a gully remnant morphology characterised by collapsed walls (see Fig. 2). Very small proportions of gullied area can be seen in the middle, and almost no gullying occurs in the upper hillslope positions.

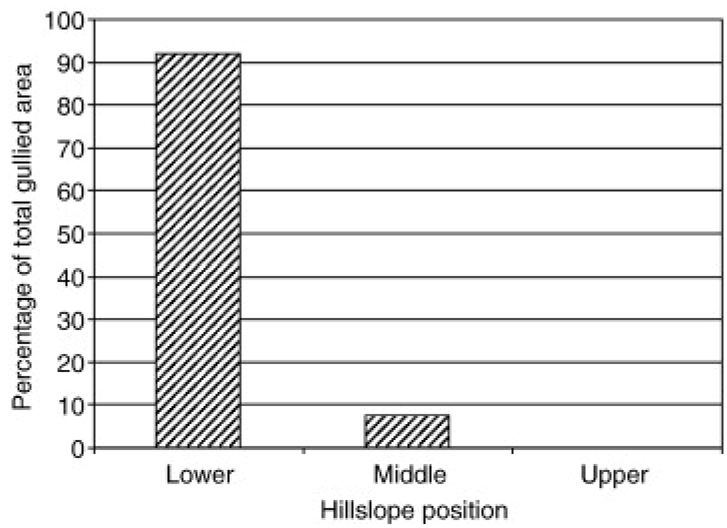

Fig. 5. Percentage of the total gullied area in relation to slope position.

Convex and concave hillslope elements were derived from the DEM windows using the maximum and minimum options of the ‘Curvature’ module in Idrisi GIS, which computes both profile and plan curvature. Rasterised windows representing corresponding gullied areas were overlaid on boolean images representing exclusively convex and concave hillslope elements. It was thus possible to compute the proportion of gullied area on either slope configuration (Fig. 6). It can be noted that gullying is predominantly located on concave hillslope elements. The proportion of gullied area on concave hillslope areas on all 11 hillslope units was more than 70%. The only exception in this trend was hillslope unit *k* where about 60% of the gullied area is on convex hillslopes areas. It was noted that most elements of that hillslope unit are convex, which were previously cultivated and abandoned. The spatial correlation between gullying on abandoned land has already been identified.

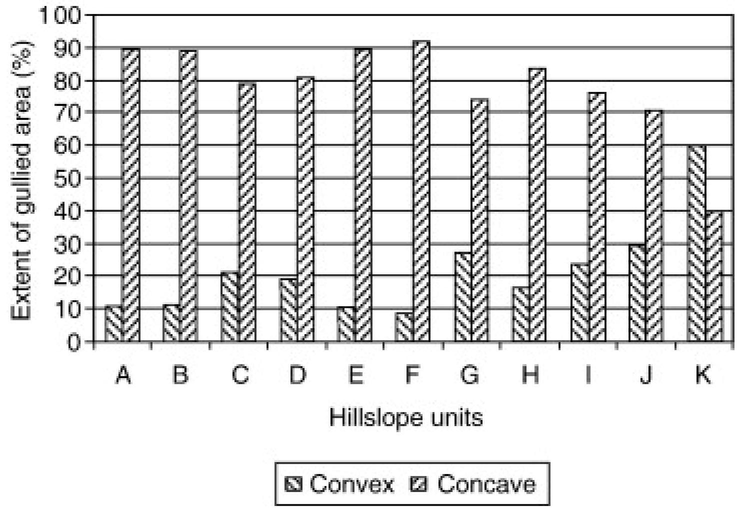

Fig. 6. Gully erosion in relation to slope configuration (concavity and convexity). A–K are hillslope units represented by eleven DEM windows.

An overlay of a vector layer representing gullied areas on the *SPI* surface (Fig. 7) illustrates that gullies lie within areas of high *SPI* values, coinciding with lower elements of slope and bottomland concave hollows adjacent to drainage lines, as opposed to upland convex hillslope sections. This is clearly illustrated further by a hillshaded image of one of the catchments (Fig. 8), with gullied sites draped over it. By implication, a strong spatial correlation exists between the observed gully erosion and areas of high gully potential.

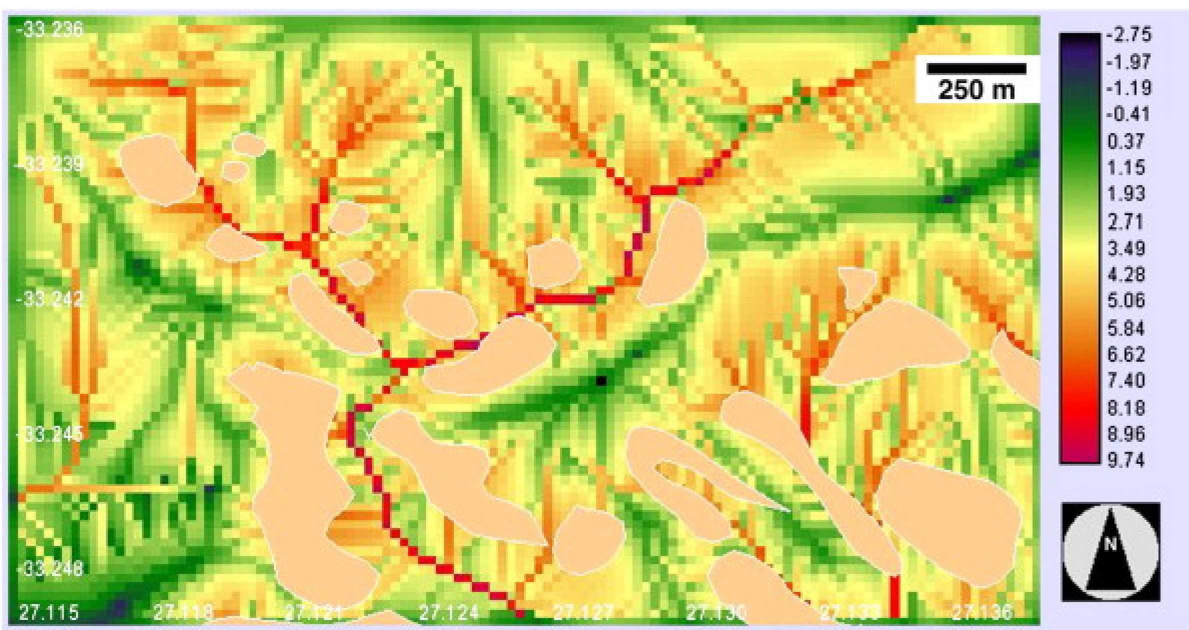

Fig. 7. An example of a gully vector layer overlaid on *SPI* surface. The solid rectangle in Fig. 1 shows the location of this area. Gullies lie predominantly in high *SPI* areas (legend represents *SPI* values).

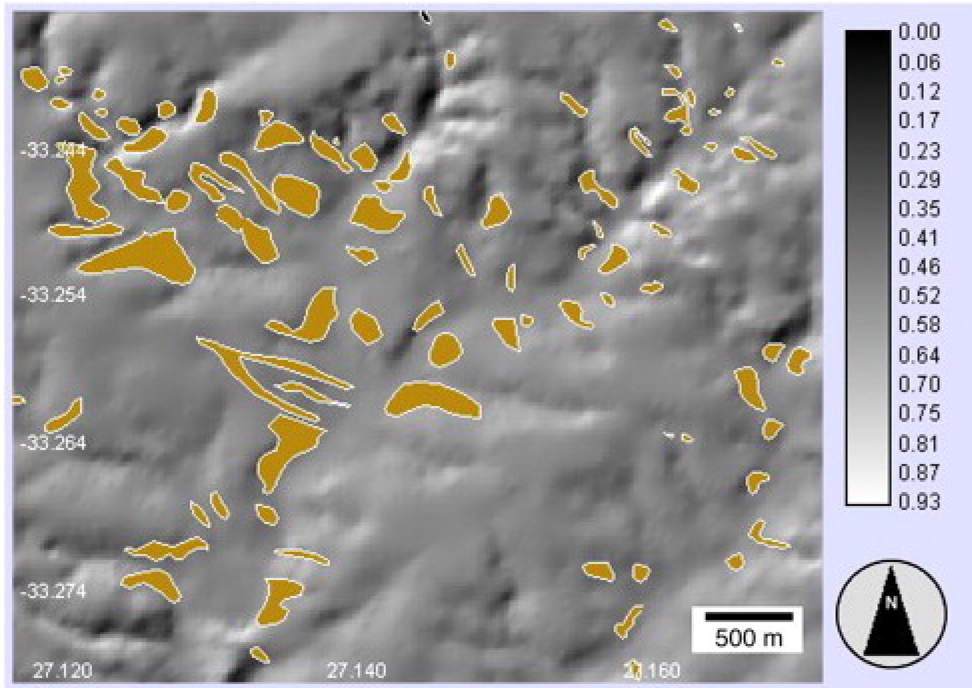

Fig. 8. Hillshaded image of one of the catchments with gullied sites draped over it. The dotted rectangle in Fig. 1 shows the location of this area.

In order to identify the topographic threshold for gully development, average *SPI* values of the gullied areas were extracted from the *SPI* surfaces using the ‘Extract’ module in Idrisi. Average *SPI* values for all individual gully sites (n = 120) were plotted against their area, which would serve to separate out a specific threshold zone for gully development along the *SPI* continuum (see Fig. 9). A distinct cluster of gully sites is noticeable within the range of 2 to 6 *SPI* values, which represent lower slope positions in the vicinity of drainage lines. Upper slope positions with *SPI* of 0–2 are devoid of gullying. Gully sites within the higher *SPI* range of 6.1–8 were identified in the field as hillslope gullies that have linked up with stream channels.

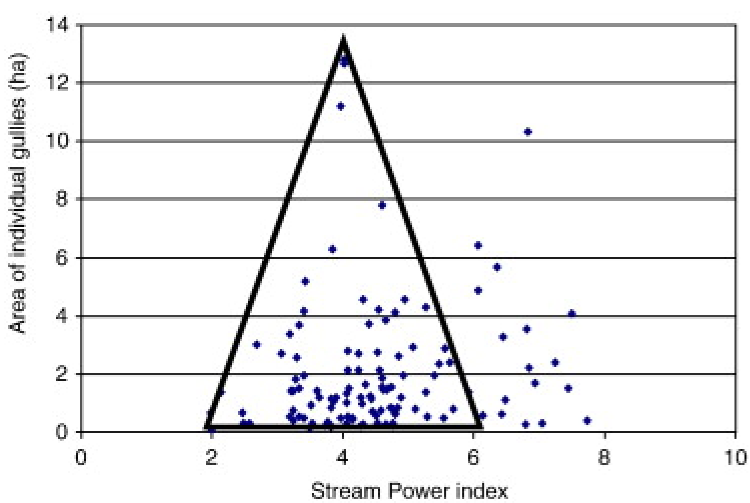

Fig. 9. Distinct topographic zone for gully location in relation to *SPI*. The triangle depicts a preferential zone for gully erosion.

5. Discussion

Fig. 10 shows a conceptual model depicting the interplay between land use and topographic parameters to induce gully erosion. Key factors highlighted are the importance of abandoned lands and the way in which location of gullies on the hillslope profile affects hydrological and geomorphic processes.

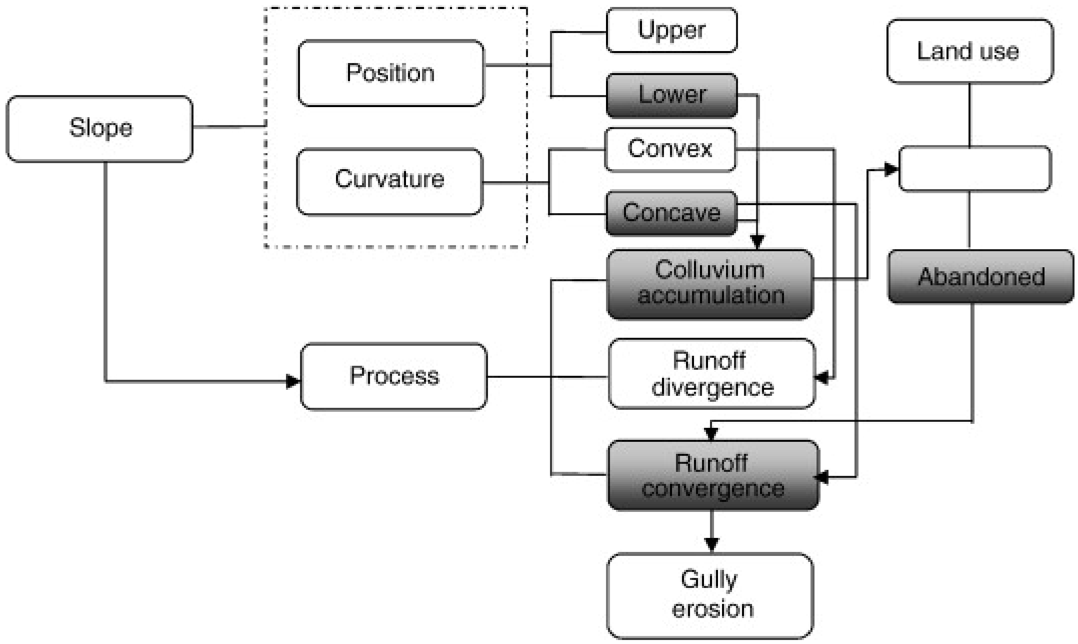

Fig. 10. Conceptual model depicting the interaction among topographic parameters, land use and gully erosion. Shaded boxes show major pathways that lead to gully erosion.

The predisposition of abandoned lands to gully erosion has been highlighted in this paper. Whereas land areas of increasing age of abandonment in the Mediterranean were linked to increasing vegetation cover, improving hydrological conditions, decreasing erosion and an increase in organic matter ([Grove and Rackham, 2001], [Obando, 2002] and [Kosmas et al., 2002]), this is not a universal trend. For example, Koulouri and Giourga (2006) report an opposite tendency — soil erosion intensification as the years of abandonment increased. Similarly, abandoned lands in the present study area were associated with the replacement of indigenous perennial vegetation species by arid condition shrubs, impairment of soil biophysical properties and erosion acceleration (Kakembo et al., 2007), owing to the absence of appropriate management strategies and the high erodibility of the soils (Kakembo and Rowntree, 2003).

The predominance of gully sites in the concave lower hillslope elements, with slope angle and *SPI* values of 5°–9° and 2 to 6 respectively in the vicinity of drainage lines, indicates a markedly preferential topographic zone and hence a topographic threshold for gully location. Deep gullies were noted to develop in a similar zone by Vanwalleghem et al. (2005). This gentle slope angle range for gully location confirms the observation by Poesen et al. (2003) that as slope steepens, the critical drainage area for gully initiation decreases and vice versa. A temporal analysis of gully distribution in the central Karoo, South Africa by Keay-Bright and Boardman (2006) indicated that gullying occurs mainly on footslope areas where colluvial material is available. In the present study, gullying is predominantly on abandoned land situated in footslope positions where the slope tends to be low but the contributing area is large.

Erosion tends to be greater at inflection points in the landscape where hillslope profile form changes from convex to concave (Knighton, 1998). Curvature of a slope largely controls the direction of water and sediment transport (Schaetzl and Anderson, 2005);

soil thickness as well as the rate of soil erosion are also curvature-dependent (Yoo et al., 2006). In the present study, concave hollows in the lower hillslope sections, observed in the field as zones of unconsolidated colluvium, constitute the preferential gully location zone. In such instances where the zones were cleared for cultivation and later abandoned, subsequent extreme rainfall events (see Kakembo and Rowntree, 2003) had a high propensity to initiate and intensify gully erosion. The development of gullies on abandoned lands within the gentle lower concave hillslope elements of the study area is in keeping with the threshold concept which states that “within a given landscape with a given climate, soils and land use, there exist a given drainage area and a critical soil surface slope necessary for gully incision” (Poesen et al., 2002, p. 244). For given environmental conditions, gully heads develop in the landscape where a certain topographic threshold is exceeded. As pointed out earlier, the threshold is an inverse relation between drainage area (runoff discharge) and critical surface slope for incision.

However, it is noteworthy that this threshold cannot be explained in terms of only local slope and contributing area. The present study revealed an interplay between topographic (particularly slope configuration and position) and land-use thresholds as illustrated by the conceptual model (Fig. 9). As pointed out by Vandekerckhove et al. (2000), vegetation type and cover are of utmost importance in explaining topographic thresholds for gully development. Cultivated fields, soil structure and soil moisture conditions are other critical factors affecting A_s–tan β relationships.

6. Conclusion

In this study, topographic thresholds for gully erosion have been noted to be lowest on abandoned lands. Whereas many studies referred to earlier have focused on relationships between upslope drainage area and slope gradient to explain topographic thresholds for gullying, this study has highlighted a distinct preferential hillslope zone for gully initiation and intensification that is augmented by the co-parameter of slope configuration. Concave slope elements in the lower positions of slope do not only enhance runoff convergence but also act as accumulation zones of erodible colluvium. A functional relationship among concave hillslope elements, drainage area and gully erosion is therefore evident. The spatial correlation between gullying and abandoned lands within concave colluvial bottom lands has demonstrated that the topographic threshold for gully erosion is very low where land use, topography and soil characteristics interact, as illustrated by the conceptual model in Fig. 9. Using this model, land managers need to design tailored and elaborate erosion control measures if elements of slope vulnerable to gully erosion are to be opened up for cultivation. A dedicated policy has to be developed by local authorities regarding the management of abandoned lands.

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