Factors controlling gully development: Comparing continuous and discontinuous gullies

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Abstract

Gully erosion is a degradation process affecting soils in many parts of the World. Despite the complexity of a series of collective factors across different spatial scales, previous research has not yet explicitly quantified factor dominance between different sized gullies. This factorial analysis quantifies the differences in factor dominance between continuous and discontinuous gullies. First, gullies (totaling 5 273 ha) visible from SPOT 5 imagery were mapped for a catchment (nearly 5 000 km^2) located in the Eastern Cape Province of South Africa. Eleven important factors were integrated into a geographical information system including topographical variables, parent material-soil associations and land use-cover interactions. These were utilized in a zonal approach in order to determine the extent factors differ between continuous and discontinuous gullies. Factors leading to the development of continuous gullies are gentle footslopes in zones of saturation along drainage paths with a large contributing area, erodible duplex soils derived from mudstones, and poor vegetation cover due to overgrazing. Compared to continuous gully conditions, more discontinuous gullies occur on rolling slopes where the surface becomes less frequently saturated with a smaller contributing area, soils are more stable and shallow. Factorial analysis further illustrates that differences in factor dominance between the two groups of gullies is most apparent for soil factors. A combination of overgrazing and susceptible mudstones proves to be key factors that consistently determine the development of continuous and discontinuous gullies.

Key Words: Gully erosion, continuous, discontinuous, factor dominance.

1. Introduction

Gully erosion is a major soil degradation problem, confronting both land and water resource management in many parts of the World (e.g. Descroix *et al*., 2008; Kheir *et al*., 2008; Kakembo *et al*., 2009). It is a process where surface (or subsurface) water concentrates in narrow flow paths and removes the soil resulting in incised channels that are too large to be destroyed by normal tillage operations (Kirkby and Bracken, 2009). Although gully erosion is a natural process, it is most often triggered or accelerated by human activities such as clearing vegetation and overstocking (Valentin *et al*., 2005). Once initiated, individual gullies can expand into a network of active gullies that contribute significantly to soil loss in a catchment (e.g. Martinez-Casasnovas *et al*., 2003). In addition to the loss of arable land, the eroded material leads to sedimentation of reservoirs, as well as lower water tables reducing water available for plant growth or livestock (Kirkby and Bracken, 2009). To prevent these negative impacts and to remediate affected areas (which can be very costly), the spatial extent of the problem and the factors causing it should be established, followed by regional-based erosion control strategies (Poesen *et al*., 2003; Tamene *et al*., 2006).

Most regional studies across the globe emphasize the sheet and rill aspects of the erosion cycle, but few map and/or model gully erosion (e.g. Martinez-Casasnovas, 2003; Vrieling *et al*., 2007). Perspectives on gully factors have typically been obtained from field scale ($<10^{-1}$ km^2) studies and are confined to local conditions (Vrieling, 2006; Ndomba *et al*., 2009). This is probably due to the temporal and spatial complexity at which the phenomenon occurs since several factors contribute to gully development including topographical variables, parent material-soil associations and land use-cover interactions (Valentin *et al*., 2005). Furthermore, gully contributing factors important in a specific area are not necessarily important in other areas (Sonneveld *et al*., 2005). For example, a factorial analysis by Descroix *et al*. (2008) in the subtropical mountain slopes of Western Sierra Madre underline the separation of gullies in two groups. The first group consists of large gullies on gentle slopes with extended contributing/catchment areas where soils are thick and stone-free. The second group constitutes small gullies that occur mainly on hillslopes characterized by steep slopes with thin and stony soils. However, only a qualitative appreciation of the factors influencing their development has been obtained and the factors distinctively controlling small and large gully development remain poorly understood. Differences in factor dominance between large continuous gullies with a branching network that discharges into a stream/river at the base of a slope and small discontinuous that fade out into a depositional zone have not yet been fully resolved.

In this context, the aim of the study is to quantify the differences in factor dominance between continuous gullies (*cgs*) and discontinuous gullies (*dgs*). This will be achieved by accurately mapping gullies in a large catchment (nearly 5 000 km^2) followed by integrating a variety of ancillary information in the form of spatial data layers, also referred to as gully factor maps, into a geographical information system (GIS). A specific catchment located in the Eastern Cape Province of South Africa is used for this purpose coded as tertiary catchment 35 by the South African Department of Water Affairs. The catchment was chosen for its high erosion risk on high potential agricultural land (Le Roux *et al*., 2008a; b). The study highlights gully factors likely to emerge as dominant between *cgs* and *dgs* and provides insight regarding the interplay of eleven important causal factors, collectively disregarded in previous research. The implications of the results are also outlined to assist the design of appropriate strategies targeted at area-specific management of the major causative factors of gully erosion, including the formulation of preventative measures in susceptible areas. Temporal scales are beyond the scope of this research and the study does not distinguish between active and passive gullies.

2. Site description

The catchment lies between 30º 46' 58" and 31º 28' 55" south and 27º 55' 56" and 29º 13' 47" east in the Eastern Cape Province of South Africa, north of the town Mthatha (formerly Umtata) (see Figure 1). Elevation ranges from 168 m at the catchment outlet in the southeast to 2 730 m in the Drakensberg mountains. The catchment area of 4 924 km^2 is drained mainly by the Tsitsa River, which flows into the Mzimvubu River after a flow length of approximately 200 km from northwest to southeast. Landforms are complex, ranging from very steep (40%) mountain slopes of the Drakensberg to gently undulating footslopes (2%) and nearly level valley floors. The climate is sub-humid with mean annual rainfall ranging from 672 mm in the lower plains to 1 327 mm in the mountains. Vegetation is largely influenced by altitude, as well as by grazing and burning. The catchment is mainly dominated by grassland including montane, subalpine and alpine belts with pockets of shrub and woodland or Protea savannah (Killick, 1963 as cited in Flügel *et al*., 2003; Low and Rebelo, 1998). According to the National Land Cover (2000), natural vegetation covers approximately 3 400 km^2 (70%) of the catchment area. The main land use is subsistence grazing (540 km^2 or 11% of the catchment) with minority land uses including forest plantations (4.3%) and commercial agriculture (1.2%). The geology consists of a succession of Beaufort Group sedimentary layers of the Permian Age (Council for Geoscience, 2007). Adelaide mudrock is succeeded by various layers of sedimentary deposits including Tarkastad Mudstones and alternating sandstones of the Molteno, Elliot and Clarens Formations with overlying Drakensberg basaltic lava. Soils from the Tarkastad and Molteno Formations in the central part of the catchment are associated with duplex soils (Land Type Survey Staff, 1972-2008) that are highly erodible with widespread gully erosion evident (Le Roux *et al*. 2008a).

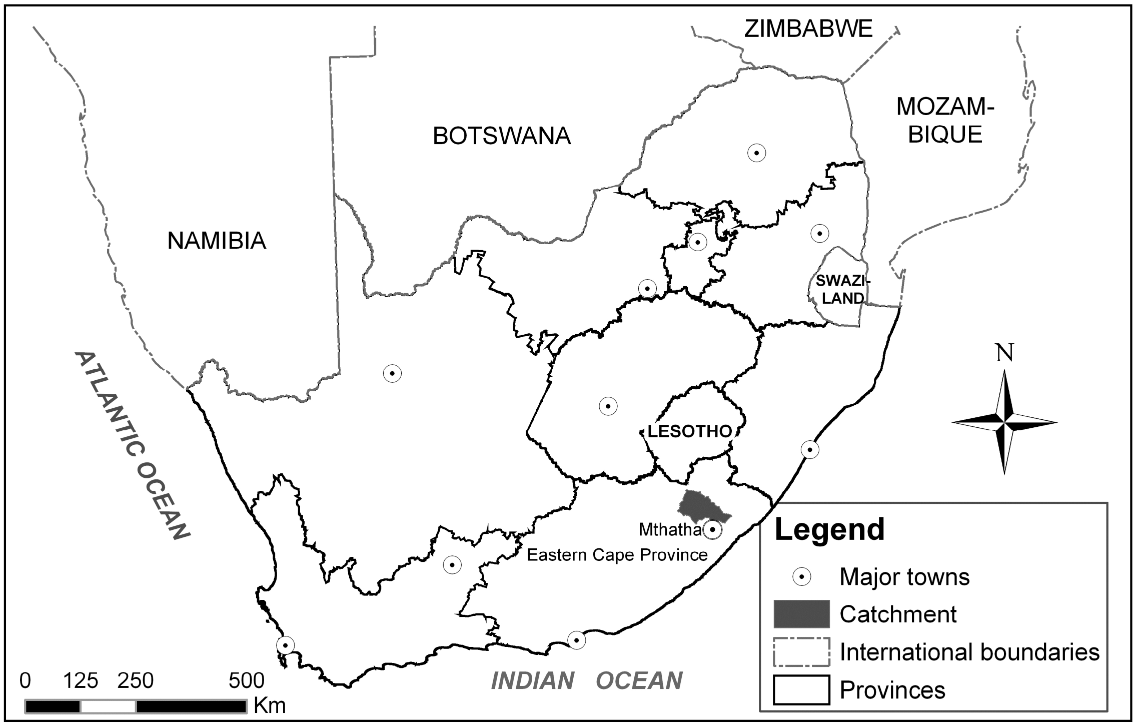

Figure 1: Location map of study area in the Eastern Cape Province, South Africa.

3. Methodology: Gully mapping and factorial analysis

Gully erosion mapping was based on analysis of SPOT 5 imagery from various acquisition dates in 2008. SPOT 5 satellite imagery was utilized because the panchromatic sharpened images at 2.5 m resolution provides high resolution air photo-like quality for gully mapping (Taruvinga, 2008) and was acquired from government agencies for the whole of South Africa. The study resolved to map gully erosion for the whole catchment by means of manual vectorization at a scale of 1:10 000. Although the technique is time-consuming, automated mapping techniques could not express individual gullies with the required accuracy due to their spectral complexity over such a large area. Subsequently, the study effectively distinguished between large continuous gullies (*cgs*) with a branching network that discharges into a stream/river at the base of a slope and relatively small discontinuous gullies (*dgs*) that fade out into a depositional zone.

Several factors contribute to gully development and they have been well described in the literature, including topographical variables (e.g. Desmet *et al*., 1999; Kheir *et al*., 2007; Kakembo *et al*., 2009), parent material-soils interactions (e.g. Laker, 2004; Valentin *et al*., 2005) and cover management (e.g. Boardman and Foster, 2008; Gutiérrez *et al*., 2009). The study considered incorporation of rainfall since it is known to be and important driving factor in gully development (Kirkby and Bracken, 2009). Although rainfall varies from 672 mm in the plains to 1 327 mm in the mountains, it was not integrated in this analysis as it does not vary substantially in the central gullied part of the catchment. Since not all gully factors can be taken into account at a regional scale, the study considered incorporation of the most important factors for which regional data already existed, or that could be readily derived for the whole catchment. Descriptions of the gully contributing factors, methods of derivation and data sources are summarized in Table 1. Furthermore, each gully factor layer was categorized into 5 expert-based rankings or classes that, according to observations, uniquely influence gully development. The soil depth factor was categorized into only 3 classes, mainly due to the unavailability of such spatial data (Van Den Berg and Weepener, 2009). These classes allowed assessment of the separate effects of different factors and spatially weighted comparison of environments with unequal surface areas within the catchment, as well as comparison between numerical (S, AS, TWI, LS, K and VC) and non-numerical (TU, GT, LT, SD and LU) data (see Table 1).

Table 1: Description of gully contributing factors and methods of derivation.

Contributing factor	**Description and method of derivation**				
	Class 1 range (area-km^2)	**Class 2** range (area-km^2)	**Class 3** range (area-km^2)	**Class 4** range (area-km^2)	**Class 5** range (area-km^2)
Slope (S)	Gradient (in %) extracted from 20 m resolution DEMs (GISCOE, 2001) using the Deterministic Infinity (D-Inf) multiple flow algorithm in TauDEM (Tarboton, 2004) in ESRI's ArcGIS				
	0-5.00 (1105)	5.00-10.0 (1105)	10.0-19.0 (989)	19.0-34.0 (873)	34.0-100 (852)
Upslope contributing area (AS)	Upslope area per unit width of contour (in m^2) extracted from above-mentioned 20 m resolution DEMs using the D-Inf multiple flow algorithm in TauDEM				
	0-100 (1598)	100-200 (1297)	200-400 (1037)	400-800 (502)	>800 (462)
Topographic wetness index (TWI)	Using TauDEM, zones of saturation is predicted along drainage paths where AS is high and S is low; assuming steady-state and uniform soil conditions (transmissivity) (Wilson and Gallant, 2000)				
	0-0.36 (866)	0.36-0.39 (939)	0.39-0.42 (984)	0.42-0.46 (1039)	0.46-1.00 (1066)
Sediment transport capacity index (LS)	LS is the spatial distribution of soil loss potential that is equivalent to the length-slope factor in the RUSLE where both AS an S is high; assuming the erosion rate is transport limited with uniform rainfall excess runoff (Mitasova *et al.*, 1996).				
	0-1.02 (1110)	1.02-2.30 (1080)	2.30-3.98 (976)	3.98-6.85 (885)	6.85-12.6 (874)
Terrain unit (TU)	Five terrain morphological areas mapped/modelled from a 90 m SRTM DEM (Rodriguez *et al.*, 2005) interpolated to 30 m, using typical topographical algorithms of Evans (1979) and Schmidt *et al.* (2003) in combination with manual vectorization (Van den Berg and Weepener, 2009)				
	Crest (351)	Convex midslope (2284)	Concave midslope (2062)	Footslope (178)	Valley floor (87)
Geology type (GT)	Stratigraphic/lithologic polygon descriptions at a 1:250 000 scale (Council for Geoscience, 2007)				
	Drakensberg basalt, Karoo dolerite (777)	Elliot mudstones, subordinate sandstone (779)	Molteno sandstones (1571)	Alluvium, mudrock, fine-grained sandstone (595)	Tarkastad mudstones (1204)
Land type (LT)	A class of land over which macroclimate, terrain form, and soil pattern each display a marked degree of uniformity at a 1:250 000 scale (Land Type Survey Staff, 1972-2008)				
	Variety of relatively stable soils (304)	Variety of moderately stable soils (1889)	Variety of moderately erodible soils (1063)	Variety of erodible, shallow soils with minimal development (706)	Highly erodible, strongly structured, duplex soils (574)
Soil erodibility factor (K)	Using the SLEMSA model of Elwell (1976), erodibility units were established and used as a guide to the assignment of USLE (Wischmeier and Smith, 1978) K-factors (in SI units t/ha per unit 'erosivity') to land types at a 1:250 000 scale (Le Roux *et al.*, 2008b)				
	0-0.20 (367)	0.20-0.25 (588)	0.25-0.30 (1530)	0.30-0.35 (1564)	0.35-0.70 (871)
Soil depth (SD)	Soil depth was obtained from existing point (753) datasets of the ARC-ISCW, utilized in scripting rules (outside the scope of the text) to create three soil depth class boundaries at a 1:50 000 scale that spatially correlate with land type data (Van den Berg and Weepener, 2009) clarity				
	Shallow (813)	Medium (2140)	Deep (1930)	n.a.	n.a.
Land use (LU)	National Land Cover database of South Africa derived from Landsat TM imagery with a grid cell resolution of 30 m (National Land Cover, 2000)				
	Natural vegetation and plantations (3884)	Urban / Built-up inc. 'townships' (142)	Cultivated, commercial, irrigated and dryland (76)	Cultivated, subsistence, dryland (282)	Degraded unimproved and natural grassland (541)
Vegetation cover (VC)	Fractional vegetation cover (in %) derived from TSAVI on Landsat TM image with a grid cell resolution of 30 m; delivers reliable vegetation cover results for arid and semi-arid grassveld landscapes in South Africa (Flügel *et al.*, 2003)				
	0-20.0 (897)	20.0-30.0 (987)	30.0-40.0 (1115)	40.0-50.0 (928)	50.0-100 (903)

(R)USLE - (Revised) Universal Soil Loss Equation; SLEMSA - Soil Loss Estimator of Southern Africa; SRTM - Shuttle Radar Topography Mission; TauDEM - Terrain Analysis Using Digital Elevation Models; ARC-ISCW - ARC–Institute for Soil, Climate and Water; TSAVI - Transformed Soil Adjusted Vegetation Index.

A challenge was to assess how factor dominance differs between continuous and discontinuous gullies using the gully factor layers mentioned above. First, an assumption was made that gully factor dominance is associated with the extent of gully erosion within a respective class area. To evaluate differences between these gullies at the large catchment scale, the study postulated that a zonal approach is more appropriate than correlation analyses generally utilized in erosion studies. Multiple regression models, for example, tend to suffer from a limited sample design, subjectivity during factor rating, and a large percentage of variability is usually unexplained (Kheir *et al.*, 2007). Due to the spatially thematic configuration of the gully factor layers it was decided to determine the proportion that each of the above-mentioned 5 classes are affected by continuous and discontinuous gully erosion (by means of zonal functions in the Spatial Analyst extension of ArcGIS 9.3).

4. Results: Gully location map and factor differences

Figure 2 illustrates the spatial distribution of continuous and discontinuous gully erosion in the catchment. Severe gully erosion is identified mainly in the Tsitsa valley located in the central part of the catchment. Table 2 indicates that 4 253 gullies occur in the catchment, directly affecting an area of approximately 5 273 ha (1.1% of the catchment). Only 236 gullies are classified as continuous, yet occupy 2 905 ha (55% of the gullied area). When integrated with drainage networks, gullies reach lengths up to several kilometers and widths up to 100 m. The remaining 4 017 gullies are classified as discontinuous. An error matrix (not shown here) was obtained by comparing the gully vector map with observations in the field (n = 200). In this context, the overall accuracy of the gully map is 93%. Despite the high level of spatial accuracy, however, manual interpretation is incapable of establishing specific erosion process dynamics and spatial information of the driving forces present (Taruvinga, 2008).

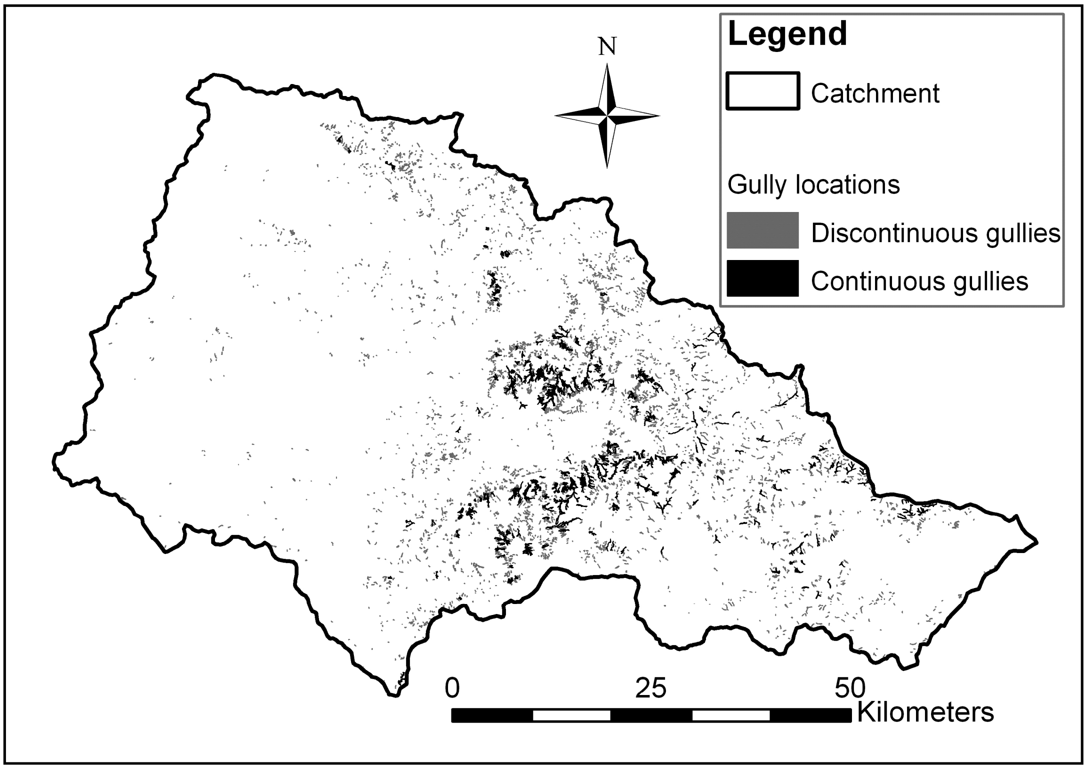

Figure 2: Gully locations map of the catchment in the Eastern Cape Province, South-Africa.

Table 2: Gully erosion information for the catchment.

Type	**Count**	**Area (ha)**	**Gullied area (%)**
Continuous	236	2 905	55
Discontinuous	4 017	2 368	45

The second category of information is presented as a series of graphs (see Figure 3), expressing the fractions each class (1-5) affected by continuous gullies (*cgs*) and discontinuous gullies (*dgs*). Given that the column height is an indication of gully factor dominance, the most prevalent differences between classes are apparent in Graph-LT, signifying predominant gullying in LT5 (duplex soils). More specifically, approximately 0.0% and 0.1% of LT1 (relatively stable soils) is affected by *cgs* and *dgs* respectively, whereas approximately 5.2% and 1.7% of LT5 is affected by *cgs* and *dgs* respectively. Although not as prominent as LT, the other graphs illustrate similar patterns, with fractions affected by gully erosion gradually and almost linearly increasing or decreasing from classes 1 to 5. Furthermore, results indicate that *cgs* exceed *dgs* in the higher gully classes, whereas *dgs* exceed *cgs* in the lower gully classes (except for Graph-S and Graph-LS). These variations between *cgs* and *dgs* warrant further discussion.

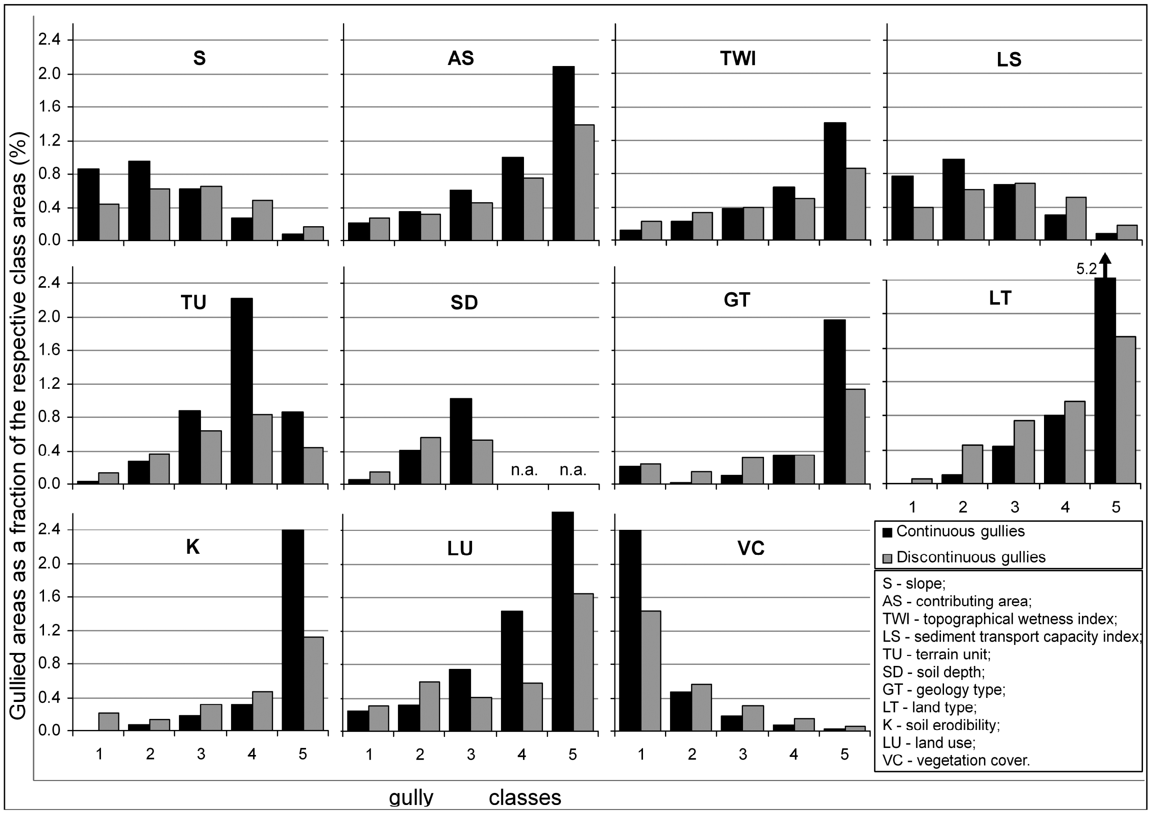

Figure 3: Continuous and discontinuous gullied areas of each class (1-5) as a fraction of the respective class area.

5. Discussion: Differences between continuous and discontinuous gullies

Foremost, the high variability of gullied areas or fractions within each class is not surprising due to heterogeneity of the landscape. Despite this variability, it is possible to distinguish a hierarchy in causal factors for gully erosion between continuous gullies (*cgs*) and discontinuous gullies (*dgs*). The following discussion describes the gully factors individually but draws some attention to their interdependency. Special attention is given to differences between *cgs* and *dgs*.

5.1 Topographical factors

First, gullies in the catchment are mainly located on gentle slopes with gradients less than 10˚ as confirmed in other regions of South Africa (Flügel *et al*., 2003; Kakembo *et al*., 2009). Although *cgs* and *dgs* follow a similar trend in this regard, the current study establishes some significant differences. In particular, *cgs* (0.9% of S1) are more prominent on gentle slopes than *dgs* (0.4% of S1), whereas *dgs* (0.2% of S5) are more prominent on steep slopes than *cgs* (0.1% of S5). The reason that *dgs* (the smallest range of gullies) exceed *cgs* (the largest range of gullies) on rolling slopes is coupled with the reason that gully erosion in the catchment is less severe on steep slopes. Tamene *et al*. (2006) found in Ethiopia that gully erosion is less severe on steep slopes, probably due to steep areas being less accessible and less exposed to human and livestock disturbances. Another possible reason is provided by Poesen *et al*. (2003), explaining that the so-called critical drainage area needed for gully initiation decreases as slope steepens. Likewise, Kakembo *et al*. (2009) observed that gullying in several catchments of the Eastern Cape Province predominantly occurs on gentle slopes where the critical drainage area or upslope contributing area (AS) is high.

Upslope contributing area (AS) is an important topographic variable that is frequently linked with gully development. More specifically, gully development largely depends on high AS values (Kheir *et al*., 2007). Areas with high AS values have high flow accumulation (number of upslope cells that flow into each cell) used to identify drainage areas and flow paths vulnerable to gully erosion (Desmet *et al*., 1999). It is therefore not surprising that gullies in the catchment are mainly located on areas with a large AS (>200 m^2). It is noteworthy here that, opposite to above-mentioned slope pattern, *cgs* (2.1% of AS5) are more prominent than *dgs* (1.4% of AS5) in areas with large AS values, whereas *dgs* (0.3% of AS1) are more prominent than *cgs* (0.2% of AS1) in areas with low AS values. Differences in AS between *cgs* and *dgs* can be explained by slope length since *dgs* have smaller slope lengths with less flow accumulation/concentration of rain water than *cgs*. Areas with low AS values represent local topographic highs/upper-slopes where flow accumulation required for gully development (especially *cgs*) is limited.

Not surprisingly, areas with high AS values also have high topographical wetness index (TWI) values (areas prone to become wet) and vice versa. Similar to the study of Kheir *et al*. (2007), gully formation in the catchment is particularly favoured in areas with high TWI values (>0.4) representing zones of saturation with high surface soil water along drainage paths where AS is high and slope is low. These saturated areas favour gully formation since the surface soils lose their strength as they become wet. The differences between *cgs* and *dgs* are similar to the above-mentioned AS pattern where *cgs* (1.4% of TWI5) exceed *dgs* (0.9% of TWI5) in areas where TWI is high, whereas *dgs* (0.2% of TWI1) exceed *cgs* (0.1% of TWI1) in areas where TWI is low. Therefore, *dgs* occur more frequently than *cgs* in areas where AS is low and slope is high. Areas with low TWI values represent zones with low surface soil water where gully development (especially *cgs*) is limited.

The sediment transport capacity index (LS) also combines the effects of AS and slope. Areas where LS is high (>4) are vulnerable to erosion due to the generation of sufficient runoff (high AS) with a sufficient level of relief energy (high slope) (Desmet *et al*., 1999). However, several studies agree that areas with high LS values do not necessarily represent zones where gullies develop (Kheir *et al*., 2007; Kakembo *et al*., 2009). Here we confirm that a low proportion of gullied areas in the catchment occur in areas where LS is high. It is noteworthy here that Graph-LS provided in the (Results: Gully Location Map and Factor Differences) Section above appears to be markedly similar to Graph-S, highlighting the distinct predominance of gullies on gentle slopes (as mentioned above). Therefore, for LS, it appears as if slope limits the impact of AS. More specifically, in the catchment more *cgs* (0.8% of LS1) than *dgs* (0.4% of LS1) occur in areas where slope is low, yet AS is high, representing zones of saturation with high surface soil water on footslopes and valley floors. In contrast, more *dgs* (0.2% of LS5) than *cgs* (0.1% of LS5) occur where the slope is relatively high, yet AS is low, representing zones with low surface soil water on topographic highs/upper-slopes.

Several studies in South Africa state that gully development is specially favoured in certain terrain units (TUs), namely footslopes and valley floors (e.g. Descroix *et al*., 2008; Kakembo *et al*., 2009). Gully development is favoured in footslopes and valley floors since they represent areas where overland flow is concentrated into preferred pathways of flow

(Beckedahl and Dardis, 1988), especially concave hollows adjacent to drainage lines, as opposed to upland convex hillslope sections (Kakembo *et al*., 2009). The present study indicates that footslopes constitute the preferential gully location zone followed (almost equally) by valley floors and concave midslopes. This pattern is especially noticeable for *cgs* that seems to be expanding from footslopes onto midslopes. More specifically, *cgs* (4.0% of TU3-5) exceed *dgs* (1.9% of TU3-5) in low hillslope and concave sections, whereas *dgs* (0.5% of TU1-2) exceed *cgs* (0.3% of TU1-2) on topographic highs and convex sections. The main reason for this difference is because development of *cgs* is generally restricted to concave areas along drainage paths where soils are deep (whereas *dgs* are not).

Although soil depth (SD) is not a topographical factor *per se*, it is highly correlated with TUs usually increasing downslope or towards the lower hillslope elements (Land Type Survey Staff, 1972–2008). Moreover, gully development also depends on the availability of deep soils (e.g. Descroix *et al*., 2008; Kakembo *et al*., 2009). It is therefore not surprising that *cgs* (1.0% of SD3) exceed *dgs* (0.5% of SD3) where soils are deep, whereas *dgs* (0.2% of SD1) exceed *cgs* (0.1% of SD1) where soils are shallow. As a result, relatively large fractions of deep soils are affected by gully erosion, especially where footslopes and valleys are filled with erodible soils derived from mudstones.

5.2 Lithological and pedological factors

At the regional scale, several authors note that the inherent erodibility of the parent material (geology type - GT) as the overriding erosion risk factor (e.g. Watson and Ramokgopa, 1997; Tamene *et al*., 2006). In particular, Laker (2004) indicates that in South Africa various mudstones are susceptible to gully erosion mainly due to highly erodible duplex soils derived there from (soils are further discussed below). Figure 3 above confirms the preferential development of gullies on Tarkastad Mudstones with 2.0% and nearly 1.1% of GT5 affected by *cgs* and *dgs*, respectively. It is noteworthy here that *cgs*, as well as *dgs*, on the other GTs are markedly limited. One would expect to find higher proportions of gullies in GT4 since it contains a combination of transported/unconsolidated alluvium and weak sedimentary mudrock that usually give rise to erodible soils (Laker, 2004). One possibility for this discrepancy is that gully development on GT4 is counteracted by other factors such as good vegetation cover. Another reason for the preferential development of gullies on Tarkastad Mudstones opposed to the other GTs is linked to the soils derived from these mudstones.

Soils from the Tarkastad Mudstones are notably different from all of the other soils investigated in this study. The most prominent feature of these soils (duplex soils) represented by land types (LTs) in class 5, is a permeable horizon overlying an impermeable one. As a result, water infiltrates and saturates the top layer above the impermeable one where it moves along as subsurface flow causing tunnel erosion (Beckedahl, 1998). In addition, these soils are usually dispersive and easily lose aggregation. The tunnel network is exposed as gullies where their roofs collapsed. Here we confirm the preferential development of gullies on duplex soils with 5.2% and 1.7% of LT5 affected by *cgs* and *dgs*, respectively. In contrast, *dgs* (2.2% of LT1-4) are more prominent than *cgs* (1.4% of LT1-4) on a variety of relatively stable red to yellow apedal and litho soils. Evidently, gullied soils do not always, or simply, correlate spatially with weak underlying geology. If so, then Graph-LT (Figure 3) would have reflected the same pattern as Graph-GT. Instead, it seems as if the variability between *cgs* and *dgs* is largely affected by the high spatial heterogeneity of the LTs and the erodibility of their soils.

It is not surprising that extensively gullied LTs have high soil erodibility (K) values (and vice versa). As expected, the K-graph provided in Figure 3 above is markedly similar to the LT-graph. Once more, the distinction can be made between *cgs* (2.4% of K5) being more prominent than *dgs* (1.1% of K5) on highly erodible soils (duplex and dispersive), whereas *dgs* (0.7% of K1-3) are more prevalent than *cgs* (0.3% of K1-3) on a variety of less erodible soils (that weather more slowly with minimal development). As mentioned above, duplex soils are erodible and favour continuous gully development mainly due to the marked increase in clay content from the topsoil to subsoil horizon. As a result, duplex soils have an abrupt transition between the topsoil and the subsoil with respect to texture, structure and consistence (Samadi *et al*., 2005). These soils limit intrinsic permeability since water does not move readily into the subsurface matrix, which leads to increased subsurface flow causing tunnel erosion (Beckedahl, 1998). In addition, several studies agree that soils prone to tunnel erosion are usually dispersive and easily lose aggregation as a result of high sodium absorption (e.g. Rienks *et al*., 2000; Valentin *et al*., 2005). However, due to the lack of spatial information at a regional scale, the correlation between *cgs*, *dgs* and sodic soils still needs further investigation. Collectively, all the factors discussed above highlight areas that are intrinsically susceptible to gully development. The last two factors discussed below are important to highlight areas where gully erosion is extrinsically triggered or accelerated by land use and human-induced reduction of the vegetation cover.

5.3 Land use and vegetation cover

As indicated by examples worldwide (e.g. Boardman and Foster, 2008; Gutiérrez *et al*., 2009), gully erosion is often triggered and/or accelerated by inappropriate land use (LU). This trend is confirmed consistently for both sets of gullies. However, *cgs* (4.9% of LU3-5) are more prominent than *dgs* (2.6% of LU3-5) in cultivated areas and degraded grassland, whereas *dgs* (0.9% of LU1-2) are more prominent than *cgs* (0.6% of LU1-2) in natural vegetated and urban areas. The trend is not surprising since cultivated areas (LU3 and 4) and degraded grassland (LU5) represent areas where the soil is frequently disturbed and gully development (especially *cgs*) is favoured. Field observations indicate that a relatively large portion of the cultivated and grassland areas in the catchment is affected by gully erosion due to livestock disturbance, including overgrazing and trampling along cattle tracks.

Several studies identify the reduction in vegetation cover (VC) as the main driving factor of gully erosion (e.g. Tamene *et al*., 2006; Descroix *et al*., 2008). Figure 3 above indicates that gullies are mainly located in areas with poor VC. More specifically, *cgs* (2.4% of VC1) exceed *dgs* (1.4% of VC1) in areas with poor VC, whereas *dgs* (1.1% of VC2-5) exceed *cgs* (0.7% of VC2-5) in areas with moderate to good VC. Therefore, Figure 3 above illustrates that more vegetation is present in *dgs* than *cgs*. A probable reason is related to VC calculations being carried out in a grid-based system that depends on grid-cell resolution (Zhang *et al*., 2002). For example, the Landsat TM image used to calculate the TSAVI and subsequent VC grid have a coarse resolution of 30 m^2 and therefore, small gullies with narrow patches of bare soil are incorrectly imbedded in vegetated areas (Taruvinga, 2008). Since *dgs* are frequently less than 30 m^2 in size, the proportion VC inside gullies at field scale could be overestimated, while the proportion bare soil could be underestimated.

Given that all zonal calculations in the study are based on a grid system, one of the main limitations of the study is that all outcomes will be subject to a certain degree of error. However, the variability between *cgs* and *dgs* caused by various grid-cell resolutions of the gully factor layers is outside the scope of current research and remains to be tested. It appears that the variability between scales is mainly affected by the high spatial heterogeneity of the study area itself. Another limitation worth mentioning here is that the study does not investigate land use history and vegetation conditions prior to gully development (since temporal scales are beyond the scope of this research). Therefore, uncertainties remain to what extent poor vegetation cover contributed to initial gully development in relation to other important contributing factors such as the intrinsic susceptibility of the soil. In effect, gully erosion processes itself can reduce the vegetation cover due to the removal of topsoil, as well as by soil tunneling/collapse. Nevertheless, similar to observations in a number of regions of South Africa (Laker, 2004; Le Roux *et al.*, 2008b), it is postulated that a combination of overgrazing and susceptible mudstones proves to be key factors that consistently determine the development of *cgs* and *dgs* in the catchment.

6. Conclusions and recommendations

Factors leading to the development of gullies in the catchment are consistent with other studies. However, previous research has not yet explicitly quantified differences in factor dominance between large continuous gullies (*cgs*) and relatively small discontinuous gullies (*dgs*). This factorial analysis contributes to perspectives on gully development by quantifying the differences or extent in factor dominance between *cgs* and *dgs*. The study indicates the complexity of a series of collective factors that are not identical between *cgs* and *dgs*. Factors leading to the development of *cgs* are gentle slopes in zones of saturation along drainage paths with a large contributing area, erodible duplex soils derived from mudstones, and poor vegetation cover due to overgrazing. When integrated with drainage networks, gullies expand from valley floors and footslopes onto concave midslopes where the soils are deep. Compared to continuous gully conditions, more *dgs* occur on rolling slopes where the surface becomes less frequently saturated with a smaller contributing area and where soils are more stable and shallow. These conditions prevent *dgs* from expanding extensively or from becoming continuous. However, they might still be active, as reported by Ndomba *et al*. (2009) for *dgs* in a catchment northeast of Tanzania. Further refinement will be possible given additional research, including investigation of the effect of land use history and vegetation conditions prior to gully development (e.g. Kakembo *et al*., 2009), distinction between active and passive gullies using a combination of different optical and multi-temporal data (Ndomba *et al*., 2009), and modeling gully erosion rates for representative test gullies and then averaging the results over the areas of active gully erosion (Flügel *et al*., 2003).

Separation of gullies into these two groups is consistent with the findings of Descroix *et al*. (2008). The main difference to previous multi-scale studies such as Descroix *et al*. (2008) and Sonneveld *et al*. (2005) is specific quantification of the differences or extent in gully factor dominance between *cgs* and *dgs*. Some of the most prevalent differences between the two groups are apparent for the terrain unit and soil factors (land types and soil erodibility). A marked distinction can be made between large *cgs* favoured on footslopes with highly erodible soils (duplex and dispersive) and small *dgs* prevalent on a variety of terrain units with less erodible soils (that weather more slowly with minimal development). A combination of overgrazing and susceptible mudstones proves to be key factors that consistently determine the development of *cgs* and *dgs*.

Understanding the significance of gully controlling factors from field to catchment scale enables site– and scale–specific management intervention. For example, due to limited financial resources it will not be feasible to rehabilitate *cgs* with large and expensive structures at the catchment scale. However, it is imperative to minimize their current expansion from footslopes onto concave midslopes with site-specific construction of structures and protecting the vegetation from overgrazing (especially upslope along drainage paths situated on duplex soils). In addition to rehabilitating existing gullies, the identification of currently vegetated or gully-free areas susceptible to continuous and/or discontinuous gully development can also be achieved (not shown here - but estimated at approximately 560 and 6 700 ha, respectively). Appropriate strategies then need to be designed for susceptible areas in order to protect the current vegetation cover.

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References

Beckedahl HR. 1998. Aspects of subsurface erosion phenomena in eastern southern Africa. *Peterman's Geographische Mitteilungen (Supplement)* **245**: 213.

Beckedahl HR, Dardis GF. 1988. The role of artificial drainage in the development of soil pipes and gullies, some examples from Transkei, southern Africa. In: Dardis GF, Moon BP. (eds.). *Geomorphological studies in southern Africa*. Balkema: Rotterdam. pg 229-245.

Boardman J, Foster I. 2008. Badland and gully erosion in the Karoo, South Africa. *Journal of Soil and Water Conservation* **63**(4): 121A-125A.

Council for Geoscience. 2007. *Geological data 1:250 000*. Council for Geoscience: Pretoria, South Africa.

Descroix L, González Barrios JL, Viramontes D, Poulenard J, Anaya E, Esteves M, Estrada J. 2008. Gully and sheet erosion on subtropical mountain slopes: Their respective roles and the scale effect. *Catena* **72**: 325–339.

Desmet PJJ, Poesen J, Govers G, Vandaele K. 1999. Importance of slope gradient and contributing area for optimal prediction of the initiation and trajectory of ephemeral gullies. *Catena* **37**: 377–392.

Elwell HA. 1976. *Natal Agricultural Research Bulletin No 7, Soil Loss Estimator for Southern Africa*. Department of Agricultural Technical Services: Natal, South Africa.

Evans IS. 1979. *An integrated system of terrain analysis and slope mapping*. Final report on grant DA-ERO-591-73-G0040. University of Durham: England. http://www.soi.city.ac.uk/~jwo/phd.

Flügel W, Märker M, Moretti S, Rodolfi G, Sidrochuk A. 2003. Integrating geographical information systems, remote sensing, ground truthing and modeling approaches for regional erosion classification of semi-arid catchments in South Africa. *Hydrological Processes* **17**: 929-942.

GISCOE. 2001. *GISCOE Digital Terrain Models*. GIMS: Midrand, South Africa.

Gutiérrez AG, Schnabel S, Felicísimo AM. 2009. Modelling the occurrence of gullies in rangelands of southwest Spain, *Earth Surface Processes & Landforms* **34**: 1894–1902.

Kakembo V, Xanga WW, Rowntree K. 2009. Topographic thresholds in gully development on the hillslopes of communal areas in Ngqushwa Local Municipality, Eastern Cape, South Africa. *Geomorphology* **110**: 188–194.

Kheir RB, Wilson J, Deng Y. 2007. Use of terrain variables for mapping gully erosion susceptibility in Lebanon. *Earth Surface Processes & Landforms* **32**: 1770–1782.

Kheir RB, Chorowicz J, Abdallah C, Dhont D. 2008. Soil and bedrock distribution estimated from gully form and frequency: A GIS-based decision-tree model for Lebanon. *Geomorphology* **93**: 482–492.

Killick DJB. 1963. *An account of the plant ecology of the Cathedral Peak area of the Natal Drakensberg, Memoirs of the Botanical Survey of South Africa, 32*. Department of Agricultural Technical Service: Pretoria, South Africa.

Kirkby MJ, Bracken LJ. 2009. Gully processes and gully dynamics. *Earth Surface Processes & Landforms* **34**: 1841–1851.

Laker MC. 2004. Advances in soil erosion, soil conservation, land suitability evaluation and land use planning research in South Africa. *South African Journal of Plant and Soil* **21**: 345-368.

Land Type Survey Staff. 1972–2008. *Land Types of South Africa: Digital Map (1:250 000 scale) and Soil Inventory Databases*. ARC-Institute for Soil, Climate and Water: Pretoria, South Africa.

Le Roux JJ, Mashimbye ZE, Weepener HL, Newby TS, Pretorius DJ. 2008a. *Erosion status of priority tertiary catchment areas identified by the Soil Protection Strategy of the Department of Agriculture. ISCW Report No. GW/A/2008/17*. ARC-Institute for Soil, Climate and Water: Pretoria, South Africa.

Le Roux JJ, Morgenthal TL, Malherbe J, Sumner PD, Pretorius DJ. 2008b. Water erosion prediction at a national scale for South Africa. *Water SA* **34**(3): 305-314.

Low AB, Rebelo AG. 1998. *Vegetation of South Africa, Lesotho and Swaziland*. Department of Environmental Affairs and Tourism: Pretoria, South Africa.

Martinez-Casasnovas JA. 2003. A spatial information technology approach for the mapping and quantification of gully erosion. *Catena* **50**: 293-308.

Martinez-Casasnovas JA, Anton-Fernandez C, Ramos MC. 2003. Sediment production in large gullies of the Mediterranean area (NE Spain) from high-resolution digital elevation models and geographical information systems analysis. *Earth Surface Processes and Landforms* **28**: 443–456.

Mitasova H, Zlocha M, Hofierka J, Iverson LR. 1996. Modelling topographic potential for erosion and deposition using GIS. *International Journal of Geographical Information Systems* **10**(5): 629-641.

National Land Cover. 2000. National Land Cover 2000, Unpublished. ARC-Institute for Soil, Climate and Water; Council for Scientific and Industrial research: Pretoria, South Africa.

Ndomba PM, Mtalo F, Killingtveit A. 2009. Estimating gully erosion contribution to large catchment sediment yield rate in Tanzania. *Physics and Chemistry of the Earth* **34**: 741–748.

Poesen J, Nachtergaele J, Verstraeten G, Valentin C. 2003. Gully erosion and environmental change: importance and research needs. *Catena* **50**: 91– 133.

Rienks SM, Botha GA, Hughes JC. 2000. Some physical and chemical properties of sediments exposed in a gully (donga) in northern KwaZulu-Natal, South Africa and their relationship to the erodibility of the colluvial layers. *Catena* **39**: 11–31.

Rodriguez E, Morris CS, Belz JE, Chapin EC, Martin JM, Daffer W, Hensley S. 2005. *An assessment of the SRTM topographic products, Technical Report JPL D-31639*. Jet Propulsion Laboratory: Pasadena, USA.

Samadi M, Germishuyse T, Van der Walt M. 2005. *Understanding South African Soils*. ARC – Institute for Soil, Climate and Water: Pretoria, South Africa.

Schmidt J, Evans IS, Brinkmann J. 2003. Comparison of polynomial models for land surface curvature calculation. *International Journal of Geographical Information Science* **17**(8): 797-814.

Sonneveld MPW, Everson TM, Veldkamp A. 2005. Multi-scale analysis of soil erosion dynamics in Kwazulu-Natal, South Africa. *Land Degradation and Development* **16**: 287–301.

Tamene L, Park SJ, Dikau R, Vlek PLG. 2006. Analysis of factors determining sediment yield variability in the highlands of northern Ethiopia. *Geomorphology* **76**: 76– 91.

Tarboton DG. 2004. TAUDEM. *Terrain Analysis using digital elevation models*. Utah State University. Logan, Utah, USA.

Taruvinga K. 2008. *Gully mapping using remote sensing: Case study in KwaZulu-Natal, South Africa, MSc thesis (Geography)*. Waterloo University: Canada.

Valentin C, Poesen J, Li Y. 2005. Gully erosion: Impacts, factors and control. *Catena* **63**: 132–153.

Van Den Berg HM, Weepener HL. 2009. *Development of spatial modelling methodologies for semi-detailed soil mapping, primarily in support of curbing soil degradation and the zoning of high potential land. ISCW Report No. GW/A/2009/01*. ARC-Institute for Soil, Climate and Water: Pretoria, South Africa.

Vrieling A. 2006. Satellite remote sensing for water erosion assessment: A review. *Catena* **65**: 2-18.

Vrieling A, Rodrigues SC., Bartholomeus, H. and Sterk, G., 2007. Automatic identification of erosion gullies with ASTER imagery in the Brazilian Cerrados. *International Journal of Remote Sensing* **28**(12): 2723-2738.

Watson HK, Ramokgopa R. 1997. Factors influencing the distribution of gully erosion in KwaZulu-Natal's Mfolozi catchment – land reform implications. *South African Geographical Journal*, **79**(1): 27-34.

Wischmeier WH, Smith DD. 1978. *Predicting rainfall erosion losses, a guide to conservation planning*. U.S. Department of Agriculture, Agricultural Handbook No 537.

Wilson JP, Gallant JC. 2000. Digital terrain analysis; In: Wilson JP, Gallant JC. (eds.). *Terrain analysis*. John Wiley & Sons, Inc: New York. pg 1-27.

Zhang X, Drake N, Wainwright J. 2002. Scaling land surface parameters for global-scale soil erosion estimation. *Water Resources Research* **38**(9): 191-199.