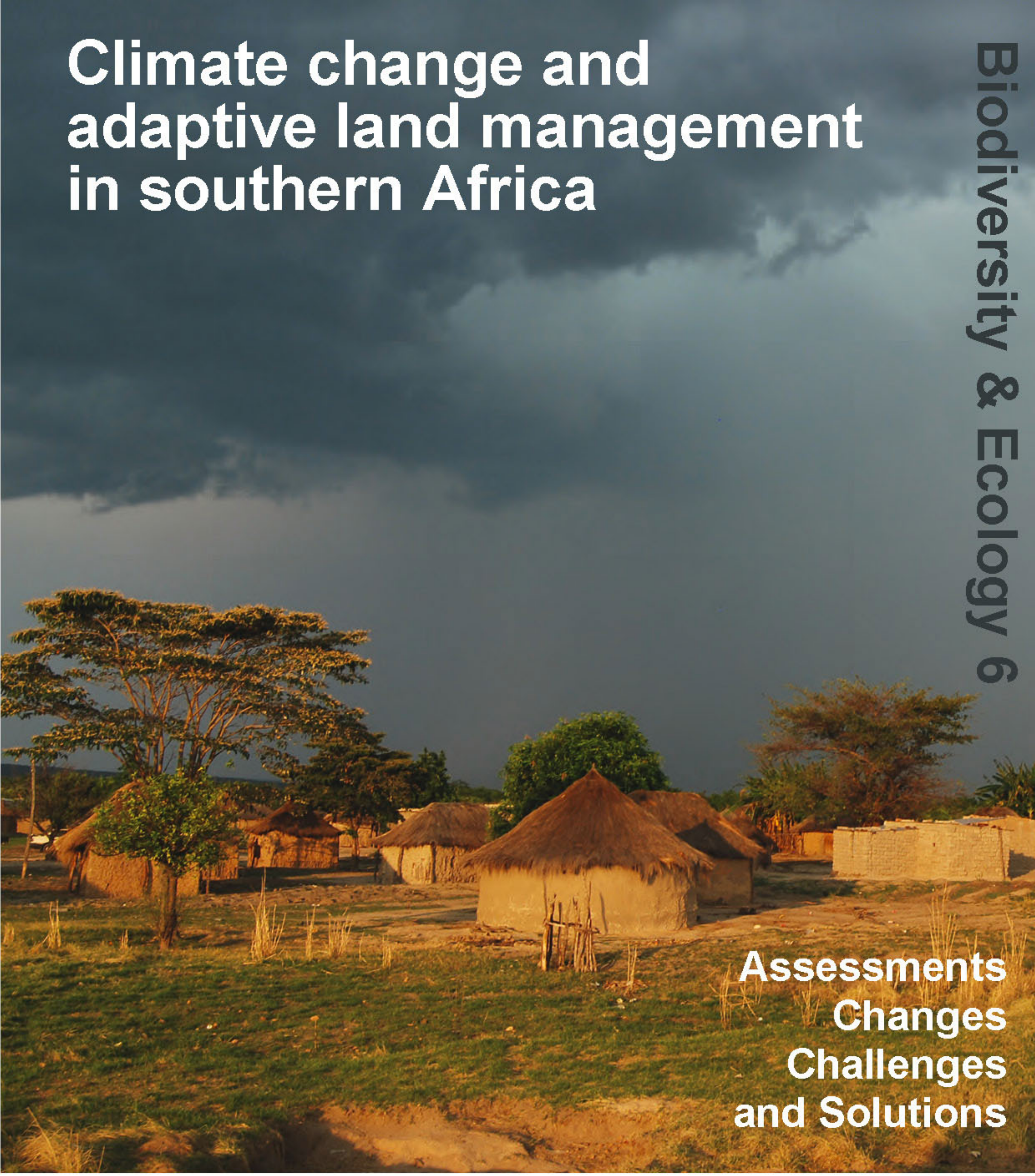
# Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6



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Changes
Challenges
and Solutions

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# Climate change and adaptive land management in southern Africa

## Assessments, changes, challenges, and solutions


Edited by

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# Are large classical gully systems inactive remnants of the past? A field-based case study investigating sediment movement

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**Abstract:** The Swartland region in the Western Cape of South Africa is situated in a Mediterranean climate zone, affected by large gullies that are widespread in occurrence on commercial farms. Despite gully erosion being recognized as a major land degradation process, especially in Mediterranean climates, these large gully scars in the Swartland are believed to be inactive remnants of the past. Due to this belief, gully erosion research in the Swartland is a topic that has long been ignored. To address this research shortfall, a field-based case study of a classic, discontinuous gully system in the Swartland was done. Sediment movement was measured at hillslope scale and discussed in the context of rainfall data and field observations of gully activity. The results showed that the gully system was an active sediment source, but also a conduit for sediment from hillslopes. Notably, ploughed contour banks, a measure introduced to curb gully erosion, are causing the expansion of the gully network, in addition to delivering sediment from hillslope sources to the gully system. Vegetation cover was found to reduce gully erosion temporally by up to 91.6% during the case study period. This case study illustrates that large gully channels are not mere relics of the past, but complex erosive systems that require further field-based investigations to develop an understanding of the dynamics involved.

**Resumo:** A região de Swartland, localizada no Cabo Ocidental na África do Sul, situa-se numa zona de clima mediterrâneo, afectada por grandes ravinas que ocorrem com frequência em quintas comerciais. Apesar da erosão das ravinas ser reconhecida como um processo significativo de degradação do solo, em especial nos climas mediterrâneos, acredita-se que estas grandes cicatrizes em Swartland são vestígios inactivos do passado. Devido a esta crença, a pesquisa sobre a erosão das ravinas de Swartland é um tema há muito ignorado. De modo a abordar esta carência de investigação, foi realizado um caso-de-estudo de um sistema clássico e descontínuo de ravinas em Swartland. O movimento dos sedimentos foi medido na escala de vertente e discutido no contexto de dados de precipitação e observações de campo da actividade das ravinas. Os resultados mostraram que o sistema de ravinas é uma fonte activa de sedimentos, como também um veículo para os sedimentos das vertentes. Notavelmente, os bancos de contorno arados, medida introduzida para controlar a erosão das ravinas, estão a causar a expansão desta rede, além de adicionarem sedimentos das vertentes aos sistemas de ravinas. A cobertura vegetal reduziu a erosão temporariamente até 91,6% durante o período do caso-de-estudo. Este demonstrou que as grandes ravinas não são apenas relíquias do passado, mas sim sistemas complexos de erosão que necessitam de mais investigação de campo para se desenvolver uma compreensão das dinâmicas envolvidas.

## Introduction

Gully erosion is regarded as a severe land degradation process worldwide (Valentin *et al.*, 2005). Gully formation occurs when concentrated surface water or subsurface water flow removes soil, causing incised channels to form (Kirkby and Bracken, 2009). These channels rapidly evolve into an interconnected network of gully channels, resulting in severe soil loss with various deleterious consequences (Sidorchuk, 1999). These negative consequences associated with gully erosion have an impact both at the source of a gully, on-site, and further in the catchment, off-site. On-site consequences mostly affect land resources that include the removal of fertile topsoil and biomass, which results in loss in soil quality and productivity. Simultaneously, gully erosion causes large landscape scars resulting in mosaic plots that increase farming costs (Valentin *et al.*, 2005). Off-site impacts mostly affect water resources. Sediment causes a reduction in downstream water quality that adversely affects eco-system health (Chaplot *et al.*, 2005; Hancock and Evans, 2006). Furthermore, increased amount of sediment can cause a loss of storage capacity of rivers and dams that leads to decrease in water availability, in addition to increasing the likelihood of flooding (Boardman, 2006; Le Roux and Sumner, 2012). Given the severity and extent of these negative consequences, it is imperative to further our understanding of gully erosion.

With recent technological advancements, there has been a shift from field-based work to remote, desktop modelling of gully erosion to assess gully density and dynamics. Remote work provides a platform to investigate gully erosion on a large spatial resolution at low cost. As a result of the aforementioned benefits, remote investigation is deemed an appropriate solution to assess the degree of gully erosion to help formulate regional strategies for land managers for sustainable land practises (Mararakanye and Le Roux 2012). Caution should be exercised so as not to conduct remote investigations prematurely. Gully erosion is a highly complex, systematic threshold phenomenon with numerous factors driving gully evolution at any given time (Nordstrom, 1988). Only with an understanding of gully erosion dynamics, insight can be gained into gully evolution that will aid the formulation of appropriate strategies for land managers. Classical fieldwork is a prerequisite to gain an understanding of gully erosion dynamics before remote modelling can successfully be applied. Castillo and Gómez (2016) emphasised this need for classical fieldwork to fill knowledge gaps in gully erosion and specifically indicated the need to address the scarcity of research on whole gully networks on hillslope scale under actual rainfall conditions.

The Swartland region in the Western Cape in South Africa (SA) was selected as a case study to investigate a whole gully network on hillslope scale, utilizing actual rainfall data through a combination of empirical field observations and in-field experiments. Gully erosion research in the Swartland is limited to an extensive survey that included classical fieldwork by Talbot (1947) and remote investigations by Morrel (1998), Meadows (2003) and more recently Olivier *et al.* (2016). Land-use change to extensive wheat cultivation in the 1930's caused severe gully erosion, but the landscape recovered due to soil conservation methods recommended by Talbot (1947). Follow-up studies by Morel (1998) and Meadows (2003) confirmed a marked reduction in gully erosion. The only signs still indicative of the historical gully problems in Swartland are numerous large gully scars found on main drainage lines and man-made contour banks throughout the Sandspruit catchment (Steudel *et al.* 2015). Meadows (2003) indicates that the large gully channels still found in the Swartland are inactive relics of past gullies, formed during the 1930's, with the only reason for its existence *in situ*, due to difficulty in removing it as the gullies were eroded to the bedrock. Farmers in the Swartland share this sentiment and believe these large gully systems to be inactive. Olivier *et al.* (2016) created a remote classification system to collect baseline information as a first step to conduct gully erosion research by using GeoEye-1 stereo imagery obtained in 2011. During this investigation bare gully channels were identified. Available data is, however, inadequate to verify whether the bare gully channels are indicative of active gully processes or whether it is merely a sign of a lack of vegetation. Since the Swartland is extensively used for agriculture and vital to the region's food security, it is imperative to investigate these large gully scars to identify

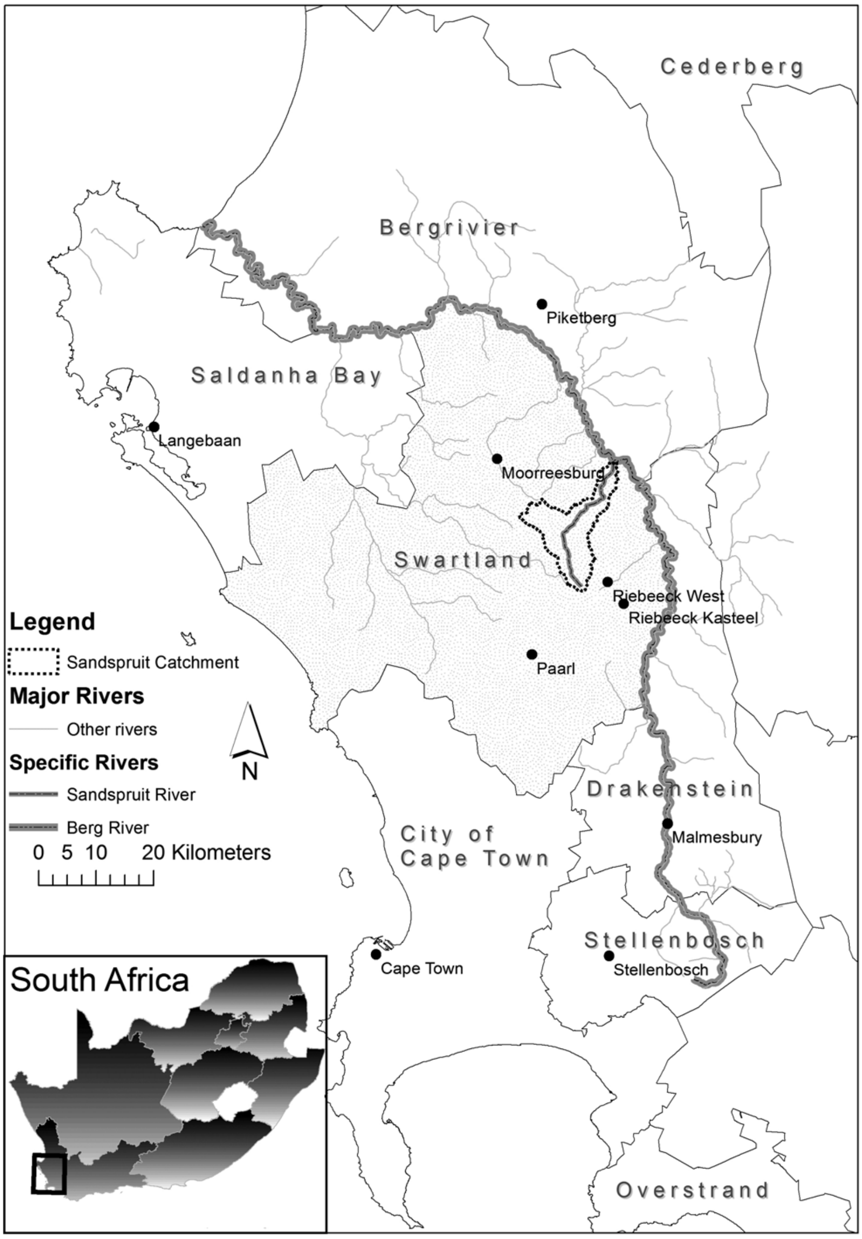


Figure 1: Sandspruit catchment

whether it is still active. Additionally, the Swartland has a unique Mediterranean climate; one of only two such climatic zones in Africa. Mediterranean environments have been strongly associated with gully erosion by numerous authors (e.g. Poesen and Hooke, 1997; Poesen *et al*., 2003; Valentin *et al*., 2005; De Baets *et al*., 2009). Poesen *et al.,* (2002) found that gully erosion contributes between 50– 80% of sediment yield in semi-arid Mediterranean environments.

The goal of this study is to investigate gully activity within one of these remnant, inactive gully scars in the Swartland region. The focus will be on identifying active processes thus indicating sediment source areas that will provide insight into gully evolution. This type of data could not only prove insightful, but also actionable, providing land managers with a means to implement appropriate mitigating strategies to limit gully erosion or rehabilitate gully prone areas.

Figure 2: Gully network at Malansdam and initial observations**:** *1) Boundary fence could have led to initial gully formation, 2) Gullies are currently expanding behind contour banks, 3) Tillage method used can cause increase amount of runoff leading to the gully expansion behind contour banks, 4) numerous gully channels at steep slope (4b) when compared to gentle slope (4a).*

## Methods

### Study site

The study site is the Sandspruit catchment, a tributary of the Berg River basin, which is located in the Swartland and approximately 152 km2 in extent (Figure 1). The Swartland region has a Mediterranean type climate with dry summers and wet winters. Annual rainfall varies between 400 and 750 mm, of which 80% occurs during winter, mostly due to cyclonic cold fronts (Meadows, 2003). The landform consists of gentle undulating hills with the only prominent mountain being Kasteelberg at the southerly tip of the Sandspruit catchment, with height above mean sea level ranging between 30 and 950 m (Steudel et al., 2015). The underlying geology is quite monotonous, consisting mostly of Malmesbury shale that was deposited during the pre-Cambrian period (Bugan et al., 2012). Lithic Glenrosa soil derived from Malmesbury shale dominates the Sandspruit catchment, accounting for 70% of soils (Steudel et al., 2015). These soils are characteristically course to medium textured with a low organic carbon content (usually less than 0.4%), resulting in a soil with low stability that is highly erodible. Furthermore, de Clercq et al. (2010) found the soils to be highly saline increasing its vulnerability to erosion.

### Observations from the case study site

A discontinuous, split channel gully network on Malansdam farm (Figure 2) was selected as the case study site. The gully network is located on a commercial wheat farm, within a thin sliver of Renosterveld. From initial observations, the gully shows signs that its origins are of anthropogenic nature. The main gully channel is found along the main drainage line where a fence was installed (Figure 2, along line drawn at position 1) – most likely during the 1930's during the land-use change to wheat cultivation. The fence line is hypothesized as the origin of the gully network, which contributed to gully erosion in two ways: 1) Livestock and vehicles moving along the fence; 2) Contour construction. Cattle and vehicles moving along the fence line would have compacted soil increasing vulnerability to soil erosion by limiting infiltration resulting in a higher volume of overland flow. Ploughed contours were introduced as a measure to curb soil erosion by reducing slope length on cultivated fields, but resulted in the generation of channelized overland flow towards the main drainage line. A higher volume of water would therefore have accumulated and flowed along the main drainage line at the fence, where soil was compacted. Ploughed contours, a measure implemented to prevent soil erosion by farmers, influenced gully evolution and appear to have played a key role in initiating this gully network. Observational evidence suggest that ploughed contours are continuing to influence gully evolution, discernible by bank gullies extending behind contours into the cultivated field (Figure 2, various positions labelled 2). The effect of slope on gully erosion is also evident in Figure 2, with numerous gully channels at the forefront of the picture (Position 3a), with the gully network fading into one channel where slope is gentle (Figure 2, position 3b).

### Methodology

A time-series of aerial photographs and satellite imagery from 2000 to 2017 was created as an initial assessment of temporal changes in gully activity. A georeferenced aerial photograph from 2000 was used in conjunction with GeoEye-1 stereo imagery from 2011 and georeferenced satellite imagery from the Google Earth

Pro platform for 2005 and 2017. These images were overlaid with ArcGIS 10.4.1 to allow a visual inspection by switching layers on and off. This provided a rapid assessment of any extensive geomorphic changes of the gully network. In addition to this, a topographical map from 1944 was used to determine the erosion base level and origin of the gully network.

Fieldwork consisted of installing perforated sediment traps in nine different gully channels, before the start of the winter, on 13 April 2012. The sediment traps, with a diameter of 110 mm and depth of 300 mm, were inserted into the gully channel floor in the flow path with the uppermost part of the sediment trap being level with the gully floor (Figure 3). After installation, sediment was collected at four points in time.

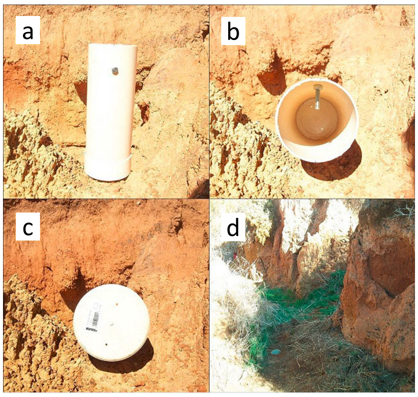


Figure 3: Perforated sediment traps installed in the gully channels at Malansdam: (a) Depicts a side view with the depth being 300mm; (b) top view with a diameter of 110mm; (c) indicates the perforated bottom to allow water drainage; (d) installed sediment trap installed level with surface and in line with the water flow path.

During installation, various attributes were noted:

- GPS position was recorded for each installation point. The GPS positions were loaded into ArcGIS 10.4.1 to calculate the total gully length in meters upstream of the sediment trap by making use of the digitised gully system from Olivier et al. (2016).
- Observations regarding activity were made based on criteria set by Oostwoud Wijdenes et al. (2000) that linked gully activity with gully geomorphological observations (Table 1). For a gully channel to qualify as active it had to display any combination of two or more of the active criteria, as each criterion given, except for piping, is interlinked. Similarly, a gully channel was classified as being inactive when it had a combination of any two (or more) of the non- active criteria, as these factors are evidence of stabilisation.

Hourly rainfall data for the winter of 2012 was obtained from a field weather station situated in the Sandspruit catchment at Langewens farm. The hourly measurements allowed both rainfall quantity and rainfall intensity to be related to sediment movement in the gully network.

Table 1: Observational criteria to assess gully activity

| Active | Not Active |
|---|---|
| Sharp edges | Rounded edges |
| Plunge pool | No plunge pool |
| Undercut | Inclined gully head wall |
| Tension cracks | Vegetation on gully walls and bed |
| Recently deposited sediment | Extremely small contributing catchment area |
| Flow marks | |
| Piping | |

## Results

During rapid assessment of the remotely sensed imagery time-series from 2000–2017, no geomorphic changes of the gully network was visualised. When comparing the 1944 topographical map and the time series, no change in base level was evident, as the discontinuous gully fades into a depositional zone near farm dwellings that had to be erected prior 1944. In-field observations indicated that gully processes were active. Figure 4 shows a bank gully extending away from the primary gully on a dirt farm road. Recent activity is noticeable from both gully channels, looking at the collapsed soil found in the gully along the walls and the head. The bank gully has a channel extending towards the vehicle most likely fed by increased overland flow, due to the compaction of the soil on the dirt road.

Numerous bank gullies with active gully heads behind ploughed contours were found throughout the extent of the gully network. These bank gullies had a variety of sizes and occurred in a systematic manner, behind ploughed contour banks.

Figure 4: Bank gully expansion along farm dirt road

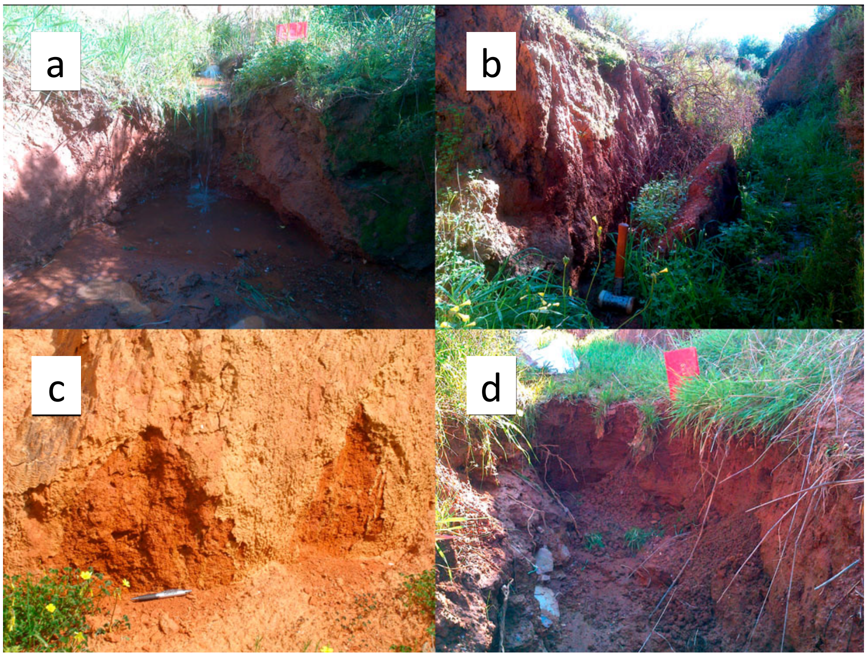


Figure 5: Active gully processes*: a – gully sidewall collapse as the gully wall became undercut due to waterflow within the gully; b – gully sidewall collapse due to tension cracks; c – gully headward retreat in action; d – newly established gully within a large established gully channel leading to gully deepening.*

Table 2: Observational and measured data for sampled gully channels

| Gully number - | Gully activity* | Gully channel length (in m) | Sediment yield (in g) | | | |
|---|---|---|---|---|---|---|
| | | | Period 1: 13 April-16 June | Period 2: 17 June-16 July | Period 3: 17 July-16 August | Period 4: 17 August-24 September |
| 1 | Not active | 10 | 91.2 | 8.6 | 0 | 0 |
| 2 | Active | 9 | 119.2 | 69.6 | 161 | 105.6 |
| 3 | Active | 30 | 887.2 | 712.2 | 512.4 | 349.2 |
| 4 | Active | 23 | 1883.8 | 514.5 | 752.1 | 96.3 |
| 5 | Active | 34 | 1423.7 | 0 | 177.9 | 145.3 |
| 6 | Active | 131 | 1624.7 | 2045.7 | 1493.9 | 125.3 |
| 7 | Active | 171 | 252.4 | 29.6 | 196.6 | 53 |
| 8 | Active | 721 | 563 | 588.2 | 0** | 138.7 |
| 9 | Active | 1468 | 5272.9 | 4283.4 | 2512.9 | 0*** |
| | TOTAL SY | | 12118.1 | 8251.8 | 5806.8 | 1013.4 |

**Activity determined from observations in field as per criteria in Table 2*
*** Sample contaminated with decomposing mouse.*
**** Sediment trap was damaged irreparably.*

Table 3: Rainfall characteristics for each collection period

| | Rain days | Total rainfall (mm) | Hourly high (mm) | 24 hour maximum (mm) | 2-day high (mm) | 2-day rainfall events* | 3-day high (mm) | 3-day rainfall events** |
|---|---|---|---|---|---|---|---|---|
| Period 1 | 21 | 92.2 | 5.8 | 18.0 | 27.6 | 6 | 28.0 | 1 |
| Period 2 | 15 | 54.8 | 8.4 | 10.8 | 12.6 | 3 | 15.8 | 2 |
| Period 3 | 16 | 77.8 | 7.0 | 19.6 | 20.8 | 5 | 25.6 | 1 |
| Period 4 | 17 | 48.0 | 4.8 | 12.2 | 13.0 | 3 | 13.6 | 2 |

** amount of times 2 continuous days of rainfall occurred*

*** amount of time 3 days of consecutive rainfall was observed*

Figure 5a shows one such a bank gully after a rainfall event. The active plunge pool causes the gully head to become undercut in addition to sharp edges are indicative of an active gully. After prolonged activity, the bank gully would extend laterally along the ploughed contour via headward retreat. In addition to bank gullying, other active widening processes were observed. Gully wall collapse occurred in numerous magnitudes. Figure 5b and c indicate the opposite ends of the scale with Figure 5b showing a collapsed wall visible on the gully floor, whilst Figure 5c shows a small-scale gully wall collapse episode due to tension cracks. Both of these collapsing events were deduced as recent activity due to the darker colourisation of the freshly exposed soil on the gully wall.

Whilst Figures 5a-c offer evidence of active gully widening, evidence was also found that indicated gully deepening. Figure 5d shows a recent, active smaller gully channel found within a larger established gully channel. This phenomenon occurred numerous times throughout the gully network.

Eight of the nine gully channels where sediment traps were installed were deemed active upon application of the criteria in Table 2. Sediment trap 9 was installed in close proximity, downstream of a newly developed, smaller, active gully headcut found in the main gully channel (in Figure 5d). Data about activity, sediment yield and gully length is given in Table 2.

A variety of gully channel lengths were sampled with the shortest channel measured at 9 m and the longest as 1468 m. Sediment was trapped during the first 2 periods for the non-active gully channel, where after it became dormant. The largest amount of sediment was trapped in sediment trap 9 that was installed downstream of the active gully head for the first 3 periods. As winter progressed, sediment total sediment collected decreased from 1211.1 g to 1013.4g.

A dry winter was experienced in the Swartland during the case study, with 272.8mm of rainfall measured from period 1 to 4, compared to the average winter rainfall of 400 and 750 mm (Meadows, 2003). Since short, high intensity, rainfall and long, low intensity rainfall both promote gully erosion, intensity in addition to longer durational rainfall events (2-day and 3-day rainfall events) were investigated. Rainfall characteristics for each collection period are summarised in Table 3.

The highest 24-hour rainfall period was 19.6 mm on 11 August during period 3. The most rain days, 21 days, and the highest total rainfall, 92.2 mm, occurred during period 1. Six 2-day rainfall events were observed during period 1, with the highest 2-day rainfall event accumulating 27.6 mm from 7–8 June. The highest intensity rainfall event occurred on 30 June during period 2 with a rainfall depth of 8.4 mm h-1 recorded. Two 3-day rainfall events occurred during period 2 and 4, whilst only one occurred during periods 1 and 3. The highest accumulating 3-day rainfall event accumulated a rainfall depth of 28.0 mm during period 1.

## Discussion

### Active gullying or inactive remnants of the past

This case study sought to determine whether seemingly historical remnant gully scars found in the Swartland are only remnants of historically unsustainable cultivating practises or still actively eroding systems. These pervasive gully scars were instigated when Renosterveld was extensively removed to make way for intensified wheat cultivation in the Swartland prior 1930's (Meadows, 2003) Gully channel formation is a rapid process after gully initiation Sidorchuk, 1999). It is hypothesised that gullies, including the gully network investigated in this case study, developed rapidly due to land-use change in the 1930's. The process of gully initiation and development at Malansdam is described in the Methods section. This is supported by hand drawn maps from Talbot (1947) that indicate severe gullying in the Kasteelberg area in close proximity to Malansdam. Since Talbot's (1947) survey, the Swartland landscape has recovered markedly (Morrel, 1998; Meadows, 2003), which can be attributed to soil conservation recommendations made by Talbot (1947). One such recommendation that was used to mitigate gully erosion was ploughing contours; it was used widely and in the Swartland there is estimated to be 25 000 km of ploughed contours (Meadows, 2003). The initial time-series that was created by imagery from 2000 to 2017 no significant geomorphic changes were observed, supporting the findings of Morrel (1998) and Meadows (2003). Sediment was however trapped during the study period confirming sediment movement through the gully network, suggesting sediment yield from a source elsewhere, as oppose to active gully processes (Rowntree, 2014).A similar sequence of events occurred, in the Sneeuberg region of the Karoo in SA. Gullying was initiated due to land-use change in conjunction of the occupation of the European settlers (Rowntree, 2014; Boardman et al., 2017). According to Boardman et al. (2017), gullies have not extended significantly since 1945, thus reaching a stable state. Instead, these large gully scars are acting as conduits for sediment from badlands and hillslopes. The role of these gullies have thus changed from being a sediment source due to active gully processes to providing effective transport channels for sediment from hillslopes to valley bottoms. Evidence from the time-series imagery and sediment yield indicates that the gully network at Malansdam is, as Rowntree (2014) described, an evil sluit / gully acting as a conduit, rapidly transporting sediment from hillslope sources.

Classical fieldwork conducted during this case study contradicts the above findings that the gully network is stable and acts as a conduit for sediment from hillslope sources only. Active gully processes causing widening and deepening of the gully network were observed. Tension cracks were found, but it is a small-scale process unable to account for the quantity of sediment trapped. Three major sediment sources were identified that could account for the sediment yield: 1) gully wall collapse, 2) bank gullies and 3) smaller gully systems within the larger confines of the gully network. Recent gully wall collapse episodes were observed, which is a large-scale event that causes sediment to be deposited on the gully floor and thereafter to be transported during flow periods. . Gully wall collapse was mostly observed in the upper reaches of the gully network, where near vertical gully walls are exhibited. During the study period 17 2-day rainfall events and 6 3-day rainfall events occurred. These sustained periods of rainfall would cause the near vertical gully walls to become unstable and collapse. Martínez-Casasnovas et al. (2004), similarly, found gully wall collapse to be a major sediment source in large established gully networks. Within existing gully networks, numerous newly propagating smaller gullies, were observed. These smaller gullies exhibit the same gully dynamics as a typical, individual gully. Sediment trap 9 was placed downstream of the headcut of one of these smaller gullies, trapping a large amount of sediment. This makes sediment yield estimations difficult as these smaller gully systems would actively erode large quantities of sediment at the gully head, only to be deposited elsewhere in confines of the gully network. Sediment yield from sediment trap 9 did indicate that these smaller gully systems are an important sediment source. Numerous bank gullies that extend behind ploughed contours were found to have active headcuts. Currently, contour banks are being counter intuitive and instead of curbing soil erosion, seems to be channelling overland flow towards the main gully network, driving gully evolution via headward retreat. These earthen structures are acting like embankments that Cooke and Reeves (1976) emphasized in playing a role in gully erosion due to concentrating overland flow and increasing hydraulic power. At this gully network, it is especially problematic as higher volumes of water are being diverted higher up in the gully network. This enables an increase in erosive power, since a larger volumes of water is diverted towards the gully network where a steeper gradient is exhibited. In addition to sediment yield, the bank gullies extending behind the ploughed contours creates mosaic field units, thereby increasing cost to farmers. Classical fieldwork found, contradictory to the remote work, that the gully network is still producing sediment via numerous active gully processes

With the remote work indicating stability and classical fieldwork identifying active gully erosion processes, the question remains: Is the gully network active or an old remnant of the past? The active gully processes is not a form of renewed gullying as no base level changes were observed nor did any anthropogenic or environmental changes occur from 2000–2017. The active gully processes observed during fieldwork would thus have been active during the period of the time-series from 2000–2017. Yet no detectable levels of soil loss on the time-series imagery can be identified. This case study finds that current gully erosion levels can be deemed negligible and potential remedial costs by the farmer would outweigh soil loss incurred through gully erosion.

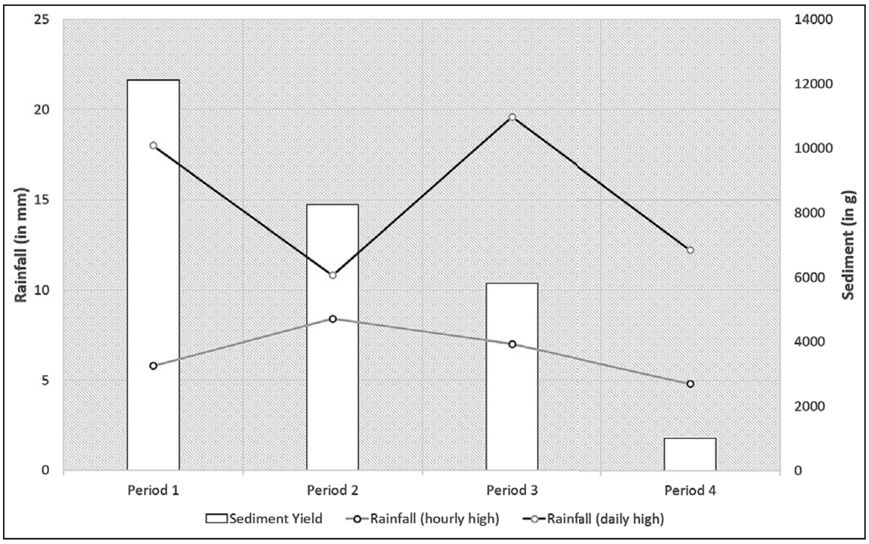


Figure 6: Sediment yield *versus* daily rainfall trends for each collection period

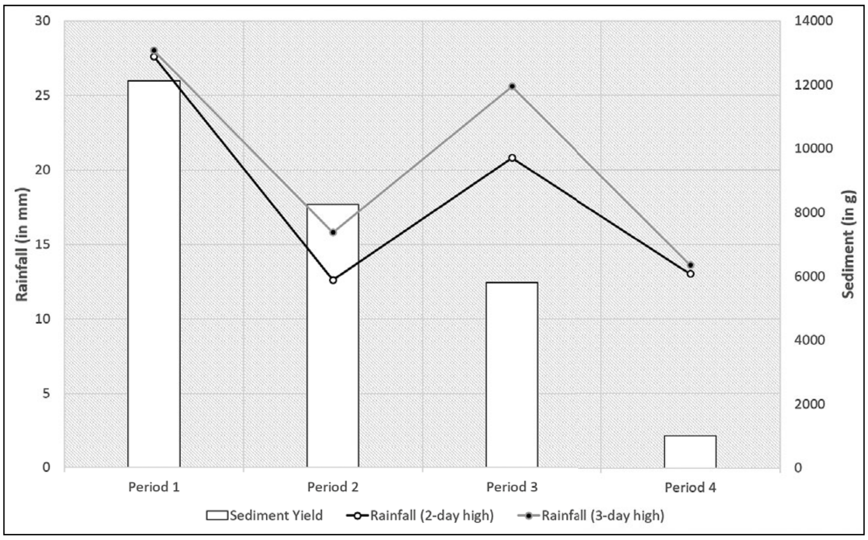


Figure 7: Sediment yield *versus* highest continuous rainfall depth for 2 and 3 consecutive days per period

## Sediment yield-Rainfall relationship

Although a drier winter was experienced during the case study, normal frontal rainfall events did occur. Similar rainfall characteristics were recorded for periods 1 and 3, and periods 2 and 4. Due to the rainfall characteristics being comparable, sediment yield should correspond with rainfall, producing similar sediment yield for periods 1 and 3, and 2 and 4. There is, however, no correlation between rainfall and sediment yield, with sediment yield decreasing by 91.6% during the case study. A reduction of 52.1% in sediment yield was calculated for periods 1 and 3, and a reduction of 87.7% between periods 2 and 4 (Figure 5 and 6 shows the decreasing trend of sediment yield versus some of the rainfall trends during the case study period).

Vegetation growth can potentially explain the disparity between sediment yield and rainfall trends. Numerous authors have demonstrated that vegetation plays a key role in reducing gully erosion (Francis and Thornes, 1990; Rey, 2003; Chen and Cai, 2006). More specifically Beuselinck et al. (2000), in addition to Gyssels and Poesen (2003) found that grass and wheat, the same vegetation found in the gully network at Malansdam, resulted in an exponential decrease in erosion rates in a Mediterranean environment. In the Swartland, soil will be at most risk to gully erosion during late autumn and early winter when soil is bare prior the start of the winter rainfall season. Natural vegetation and wheat follow a similar growth profile since wheat is a rainfed crop in SA. Gully channels will be bare due to summer aridity, in addition to the hillslopes as wheat is generally planted between May and mid-June (DAFF, 2017). Short, intense rainfall or longer durational, low intensity rainfall would therefore have a higher erosion potential during period 1, which is why the largest amount of sediment was produced during this stage. Sediment yield in period 1 would therefore be sediment from hillslopes transported via overland flow along the ploughed contours, and active gully erosion processes found in the gully network. After initial rainfall, vegetation in the gully channel would emerge and tillering phase of wheat growth will be reached. Minimum vegetation cover can thus be expected during period 2. During periods 3 to 4 vegetation cover reached 100% cover in the gully channels, with wheat reaching maturity. Vegetative trapping ability of sediment thus incrementally increased as the case study period progressed, explaining the sharp decrease in sediment yield found in the gully network at Malansdam. Figure 8 shows the bare channels observed at the beginning of the study period versus vegetated channels and fields at the end of the case study.

Even though vegetation was strongly linked to reduced gully erosion in this case study, Figure 8 indicates the temporary nature of the protection it offers. Vegetative growth only acts as a temporary store for newly generated sediment from hillslopes and active gully processes. As the vegetation in the gully network dies back during the summer, its trapping ability diminishes, resulting in stored sediments to be susceptible to erode due to water flow through the gully network. Betts et al. (2003) found that small rainfall events are required for these dormant, temporary sediment stores to be "flushed" down a gully system.

While the vegetative growth explains the reduction in sediment yield during the case study period, the temporary nature of the trapping ability of vegetation could also explain large sediment yields in period 1. Since vegetation buffers sediment yield, sediment from dormant stores can still be cycled through the gully network in addition to sediment yield from bare gully channels and hillslopes. The sediment stores could also explain the presence of smaller gully systems found in the established gully network, as gully heads can form at sediment stores where significant sediment eroded after vegetation has died off, resulting in the formation of a gully head, within the larger gully channel. From evidence in this case study, planting perennial grass in gully channels and along ploughed contours can promote stability, as it will inhibit gully erosion and impede on its ability to act as a conduit.

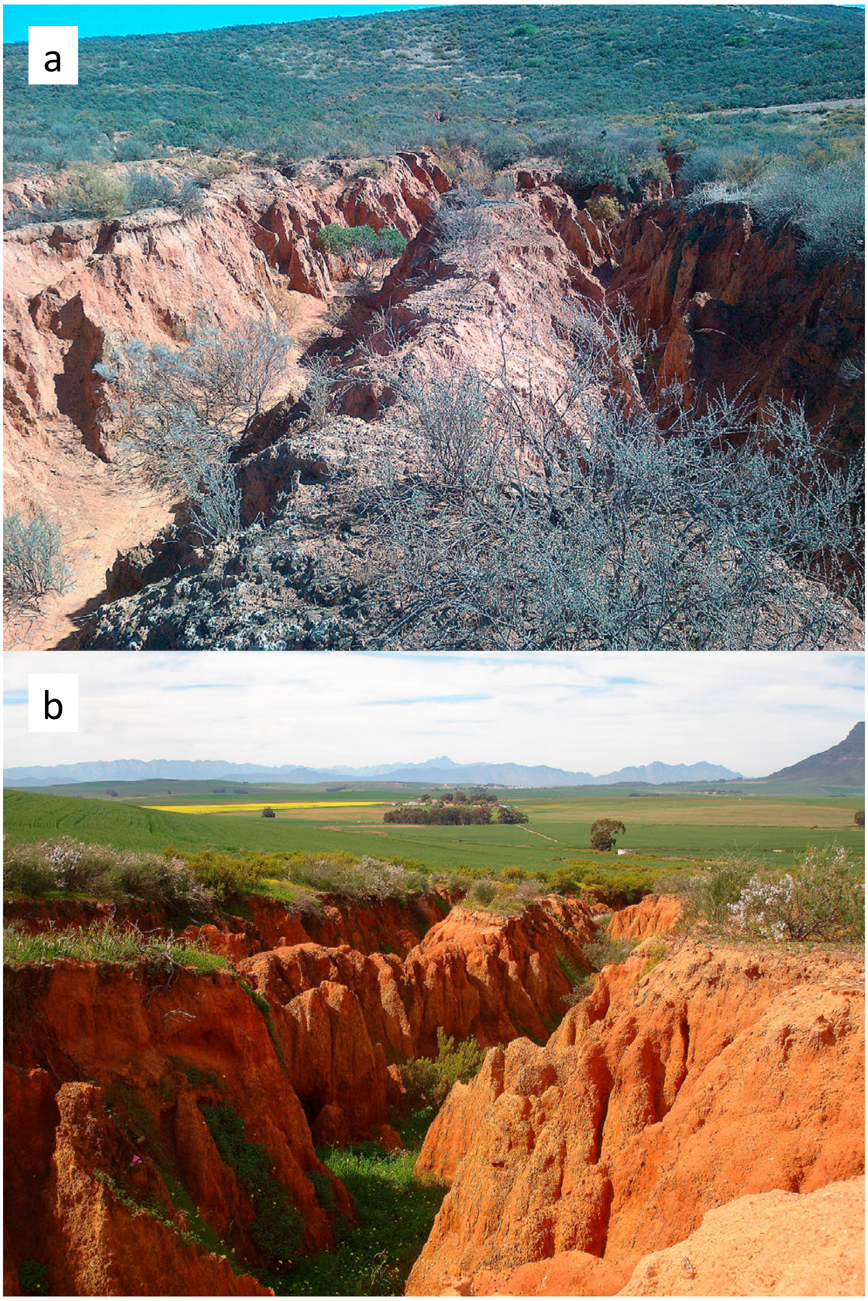


Figure 8: Temporal vegetation cover in the MGS: a) bare gully channels observed during sediment trap installation prior winter; b) gully channels fully covered by grass and wheat, in addition to wheat cover on the hillslope at the end of the case study

## Conclusion

Notably, this case study found that ploughed contours played a contributory role in the initiation and evolution of the gully network at Malansdam. This is worrying, especially since 25 000km of ploughed contours are found in the Swartland. Numerous bank gully channels with active headcuts were found extending behind these earthen structures established by farmers to reduce soil erosion. This is problematic for two reasons: 1) the active gully channel extending behind the ploughed contour shows that overland flow is directed towards the gully channel. This will promote sediment delivery from hillslopes to the gully network, which will be transported to the valley floor; 2) Active gully channels can retreat headward, as it will have a continuous supply of overland flow during rainfall events causing the gully channels to extend further into the cultivated field units. The gully extension will induce larger soil losses and increase farming costs as it will create mosaic field units.

During this investigation active gully processes incurring soil losses were observed, but a time series of imagery from 2000–2017 indicated no observable gully extension. Unfortunately, headward retreat was not measured during this case study and are not able to compare headward retreat rates with the remote observations. Such an experiment could yield interesting results. Currently, the large gully scars were found to be in a state of stability, despite active gully processes being observed in the field. Any costs incurred by remedial work will currently outweigh cost of soil loss.

According to climate data from (Meadows, 2003), larger amounts of rainfall in the period prior planting wheat will occur. Rainfall will thus come at a time when soils are bare, and at most risk to soil erosion. This could push the negligible amounts of sediment produced by active gully processes in the current stable gullies to relevant levels requiring remedial work. Vegetation was shown to reduce sediment movement significantly, as sediment yield dropped by 91.6% during the study period. The trapping ability of vegetation is however temporary. Sediment is stored when vegetation growth increases with winter rains, but the aggradational ability diminishes once vegetation dies out during summer aridity. These dormant stores can be easily activated and transported downstream by water flow through the gully channels. Remedial work can take the form of planting perennial grass in gully channels, in addition to along ploughed contours. This would ensure a trapping of sediment to be more permanent in nature restabilizing the gully network and reducing the effect that ploughed contours have at delivering sediment to the gully channel by overland flow. Lastly, it is worth mentioning that this was a short-term case study and longer monitoring times should be allocated to these large gully systems in the Swartland to establish the extent of activity and possibly fingerprinting sediment sources. This would lead to a better understanding as it could identify a ratio of sediment yield from different sediment sources. This study also focussed on one gully network and should be expanded to other large gully networks in the region to establish how active these gullies are. Further studies could also investigate sediment yield versus rainfall occurrence to monitor gully erosion on a rainfall event basis instead of monthly such as this study.

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