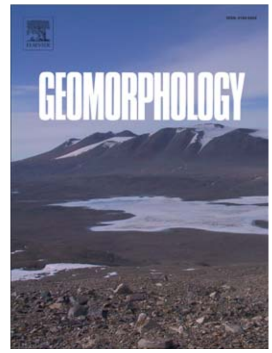
Title: Long-term studies of land degradation in the Sneeuberg uplands, eastern Karoo, South Africa: a synthesis

Creators: Boardman, J., Foster, I. D. L., Rowntree, K. M., Favis-Mortlock, D. T., Mol, L., Suich, H. and Gaynor, D.

DOI: 10.1016/j.geomorph.2017.01.024

Example citation: Boardman, J., Foster, I. D. L., Rowntree, K. M., Favis-Mortlock, D. T., Mol, L., Suich, H. and Gaynor, D. (2017) Long-term studies of land degradation in the Sneeuberg uplands, eastern Karoo, South Africa: a synthesis. *Geomorphology.* **285**, pp. 106-120. 0169-555X.

Accepted Manuscript



Long-term studies of land degradation in the Sneeuberg uplands, eastern Karoo, South Africa: A synthesis

J. Boardman, I.D.L. Foster, K.M. Rowntree, D.T. Favis-Mortlock, L. Mol, H. Suich, D. Gaynor

PII: S0169-555X(16)30993-X
DOI: doi: 10.1016/j.geomorph.2017.01.024
Reference: GEOMOR 5901

To appear in: *Geomorphology*

Received date: 17 October 2016
Revised date: 17 January 2017
Accepted date: 17 January 2017

Please cite this article as: Boardman, J., Foster, I.D.L., Rowntree, K.M., Favis-Mortlock, D.T., Mol, L., Suich, H., Gaynor, D., Long-term studies of land degradation in the Sneeuberg uplands, eastern Karoo, South Africa: A synthesis, *Geomorphology* (2017), doi: 10.1016/j.geomorph.2017.01.024

Long-term studies of land degradation in the Sneeuberg uplands, eastern Karoo, South Africa: a synthesis

J. Boardman [a,b] *, I.D.L. Foster [c,d], K.M. Rowntree[d], D.T. Favis-Mortlock[a] L. Mol[e], H. Suich[a,f], D. Gaynor[g]

[a]*Environmental Change Institute, Oxford Centre for the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK;* [b]*Department of Environmental and Geographical Science, University of Cape Town, Rondebosch 7700, South Africa;* [c]*Faculty of Arts, Science and Technology, University of Northampton, Newton Building, Northampton NN2 6JD, UK;* [d]*Department of Geography, Rhodes University, Grahamstown 6140, Eastern Cape, South Africa;* [e]*Department of Geography and Environmental Management, UWE Bristol, Coldharbour Lane, Bristol, UK, BS16 1QY, UK;* [f] *Crawford School of Public Policy, Australian National University, Canberra, ACT 2601, Australia;* [g]*Mammal Research Institute, Department of Zoology and Entomology, University of Pretoria, Private Bag x20, Hatfield, 0028, Pretoria, South Africa*

Abstract

For the past 15 yr, the Sneeuberg uplands in the eastern Karoo, South Africa, have been a focus for research on land degradation by the above authors and other colleagues. Earlier work in the Karoo emphasised vegetation change whereas we concentrate on physical changes to the landscape at the small catchment scale, e.g., bare, degraded areas (badlands) and gully (donga) systems. Analysis of sedimentation in farm dams allows for reconstruction of environmental histories using ^{210}Pb, ^{137}Cs, geochemical and mineral magnetic properties of the sediments. Erosion rates on badlands are monitored using arrays of erosion pins.

Sediment source tracing within small catchments points to the importance of hillslope sources and the relative erosional inactivity of gully systems.

Sediment supply from hillslope and colluvial sources is maintained by high rates of weathering on mudstones and sandstones. Current degradation should be viewed in the context of a c. 200 yr history of overgrazing by European-style stock farming and limited areas of former cultivation in the valleys. Grazing pressures are now much reduced but the loss of soils and vegetation suggests that landscape recovery will require several decades. Additional drivers of past degradation are likely to have been periods of drought and fire (natural and managed) and a gradual increase in both rainfall intensity and the frequency of extreme rainfall events. The future of the degraded Sneeuberg landscape will depend on future farming practices. Desirable options include more sustainable livestock practices, adoption of wildlife farming and other more benign regimes involving mixes of agriculture, tourism, and wildlife protection together with landscape rehabilitation measures.

Keywords: land degradation; Sneeuberg uplands; sediment sources, reservoir sedimentation; weathering; soil erosion; connectivity

*Corresponding author: John Boardman: email John.Boardman@eci.ox.ac.uk

1. Introduction

Land degradation, of which soil erosion is an important component, has been of global concern since the early years of the twentieth century. Bennett's (1939) book, which described both erosion and conservation methods, and the establishment of the US Soil Conservation Service in response to public and political pressure as a result of the Dust Bowl, marked major steps in awareness of a serious environmental problem. In recent years other important reviews have taken this work forward (e.g., Pimental, 1993; Morgan, 2003;

Montgomery, 2007). The causes of land degradation are recognised as a combination of physical and socio-economic factors (Boardman et al., 2003a). The use and management of the land is critical and is subject to economic, social and political pressures (Beinart, 1984). Much degradation is due to decisions regarding stocking rates and choice of crops resulting in bare ground vulnerable to rainfall, runoff or high winds. On-site consequences of land degradation include decline in crop yields as soils lose nutrients, become thinner and lose their moisture retention capacity. Off-farm impacts include reservoir sedimentation, ecological damage to freshwater systems and flooding of properties. Despite these adverse effects of erosion, soil conservation measures are rarely implemented unless encouraged by governmental policies and incentives.

Bennett (1945) drew global attention to the state of soil erosion in South Africa, where it had been recognised as an issue at least since the turn of the twentieth century (Rowntree, 2013). Despite this lengthy awareness of the problem, only limited research efforts have explored the extent and severity of degradation at the national scale, based on expert opinion (Hoffman and Ashwell, 2001) and modelling (Le Roux et al., 2007). Hoffman and Ashwell (2001) suggest a correlation between degradation and former communal land (as opposed to commercial farming areas) and with poverty, supporting Beinart's (1984) earlier contention. Dardis et al. (1988) provide a review of soil erosion forms in southern Africa, with a strong focus on gully erosion. More recently Laker (2004) has reviewed soil erosion research since the late 1970s. The national picture is reviewed in Boardman et al. (2012). Detailed case studies are rare, one exception being Talbot's (1947) perceptive analysis of serious erosion in the Swartland, with a more recent follow-up study by Meadows (2003). Other local studies include Watson's (2000) research from KwaZulu-Natal and Weaver's (1988) survey of soil erosion in the former homeland of the Ciskei. Off-site impacts have generally been neglected but are receiving increasing attention (cf., Gordon et al., 2013, 2014).

The aim of this article is to review work on land degradation in the Sneeuberg uplands in the Eastern Karoo of South Africa, undertaken by researchers from British and South African universities through a co-operative international project. Our research builds on earlier work by ecologists who sought explanations for the degraded nature of the Karoo vegetation cover (DEAN AND MACDONALD, 1994; DEAN ET AL., 1995). Although vegetation plays a key role in controlling erosion, much of this early work did not extend to investigating erosion processes themselves. This review aims to begin to fill that gap.

We pull together disparate studies conducted over the last ~15 yr, incorporating new material where appropriate. Causes of degradation are explored and possible solutions suggested. Interpretations focus on relatively new ideas in geomorphology; in particular we explore ideas of connectivity and complexity. We recognise that our geomorphological view of the world has moved away from simple ideas of cause and effect; instead we increasingly acknowledge that geomorphic systems are characterised by disorder, irregularity, instability, unpredictability and non-linearity (e.g., Church, 2010). Thus we now accept that several different processes can operate at the same place and time; that scale (temporal and spatial) affects our recognition of process operation; that sediment storage is important and, in consequence, so is recent history; that the existence of thresholds can lead to abrupt and rapid change, and that variable system forcing exists at all timescales. We explore these ideas here in relation to suggested causes of land degradation for which a plethora of postulated explanations exist.

2. The study area

The Sneeuberg uplands form a distinctive landscape in the eastern Karoo of South Africa and are described by Clark et al. (2009) as being surrounded by major river valleys and plains except in the northeast where the Suurberg provide a bridge to the Stormberg uplands (Fig.

1a). The highest point is Kompassberg (2502 m). Geologically they are composed of mudstones and sandstones of the Beaufort Group (late Permian and Triassic ~225 Ma) (Johnson et al., 1996; Adams et al., 2001). Igneous intrusions are likely to be a remnant of the continental-scale Karoo Igneous Event (~183 Ma) which led to formation of intrusive dykes and sills (Riley et al., 2006). The upper slopes tend to be fine sandstones (Katberg Formation) with mudstones and sandstones in the valleys (Balfour Formation). Dolerite dykes and sills outcrop on hilltops and form prominent steps in river long profiles (Johnson et al., 2006). Footslopes and valley-bottoms are mantled by alluvium, colluvium and debris-flow deposits up to 6 m thick. Oldknow et al. (2016) identify a series of cut and fill features in alluvial sediments in the upper Sundays Valley that accreted from the Late Glacial Maximum onwards. Former wetland (vleis) deposits overlie early Holocene colluvium and, in places, a pre-Holocene palaeosol and older weathered beds (Holmes et al., 2003). The valley-bottom sequence is often incised to bedrock by gullies (dongas) (Boardman, 2014).

The watershed between south-flowing tributaries of the Sundays River and the north-flowing tributaries of the Orange River runs through this area. The Klein Seekoi River is one such tributary which drains the area around Compassberg farm.

Soils are generally thin and often lack A and B horizons due to erosion. They are described as lithosols (shallow soils on hard or weathered rock (SANBI, 2012). This is particularly true of badlands and heavily degraded areas where surfaces are compact: bulk densities 1.6–1.9 g cm^3 with mean organic matter content of 2.4% (Keay-Bright and Boardman, 2009; Dickie and Parsons, 2012). Mean particle size for 10 badland sites (< 2mm) is reported as 7% clay, 66% silt and 27% sand using a Malvern laser-granulometer with Hydro-2000 dispersal unit (Boardman et al., 2015).

The current vegetation of the area is typically *Elytropappus rhinocerotis–Euryops annae* shrubland with *Merxmuellera* (now *Tenaxia*) *disticha* tussocks. Around the northern base of Kompassberg is a shrubby variant of Karoo Escarpment Grassland (Dr V.R. Clark, personal communication). The vegetation of the Sneeuberg in general is described in Clark et al. (2009). Detailed description of what is described as Albany Broken Veld is provided in SANBI (2012).

Rainfall across the region is temporally and spatially variable due to the mountainous topography. In the uplands annual rainfall approaches 500 mm with lower altitude sites c. 300 mm. Rainfall amount peaks in the summer months. Rainfall trends over the last century show a significant increase in mean wet day precipitation and shorter return periods for high magnitude events (Boardman and Foster, 2008; Foster et al., 2012). The temperature range in the Sneeuberg is considerable with a range of 41 to -19°C recorded at Kriegersbaaken in 2016 (Ms Shauna Westcott, personal communication).

For over 200 yr since settlement of the area by European farmers, stock farming (primarily sheep) has been the dominant activity. Stock numbers peaked 1850-1950 and have declined substantially since then. Stock numbers in the Middelberg magisterial district were around twice the Karoo average for nearly 100 yr (Hoffman et al., 1999) hinting at severe environmental stress. Stock numbers in the region had decreased by between 40-60% by 1980 (Esler et al., 2006). However, between 1950 and 1980 the average farm size was halved, putting more pressure on an already degraded landscape (Esler et al., 2006). In recent years many farms in the Sneeuberg have been amalgamated into bigger wildlife farms. Wheat and fodder crops have been grown on valley-bottom ‘lands’ with or without irrigation, although this practice has now sharply declined (Suich and Boardman, 2016).

Land degradation in the Karoo leads to changes in vegetation from mixed shrubs and grass to a shrub-dominated ecology; this change has been widely reported and has frequently been referred to as 'desertification' (Acocks, 1975). The extent, timing and causes of this vegetation change are contentious with both climatic shifts and overgrazing suggested (Hoffman et al., 1999). However, Beinart (2003) suggests that overgrazing by sheep in the Graaf-Reinet area as early as 1810-1850 resulted in loss of grass and shrub invasion. Present-day farmers report much higher stocking levels in the early and mid-twentieth century than now (Keay-Bright and Boardman, 2007). Physical degradation of soils is seen in the loss of A horizons and the formation of gully systems and badlands. Definitions of badlands vary (Boardman et al., 2015) but usually include, bare ground, a lack of soil, deep dissection, networks of gullies, little vegetation, and unsuitability for agriculture (Fig. 2). Gullies, or 'dongas' are permanent features of the landscape which, in semi-arid climates such as the study area, are generally hydrologically inactive for long periods. Their existence has important implications for sediment delivery to dams and major reservoirs, although not all valleys show evidence of gully formation.

3. Methodology

Land degradation and badland areas were mapped using air photography from 1945, 1959, 1966, 1980, 2002 and latterly using Google Earth images from 2010 (Keay-Bright and Boardman, 2006; Boardman et al., 2015). Remotely-sensed images and field mapping were used to delineate formerly cultivated land and identify the locations and state of small farm dams (Boardman and Foster, 2011). Agricultural management in the area and the history of wheat farming were investigated with farmer and farm advisor interviews plus archival sources (Keay-Bright and Boardman, 2007; Suich and Boardman, 2016). Archival sources from the nineteenth and early twentieth century were used by Rowntree (2013) to investigate the initiation of gully erosion.

Erosion rates on badland areas were monitored for 15 yr (2001–2016) using erosion pins repeatedly measured at roughly yearly intervals and correlated with rainfall amount and intensity (Boardman et al., 2015). However, it is problematic to obtain rain data which are relevant to the study sites, due to their remoteness. Official daily rain gauge records exist for Middelburg (Grootfontein college) (1878-present) and Graaf-Reinet (1878-1979). Records from farm gauges are also of value; those known to the authors are: Cranemere (1883-present), Gordonville (1905-2002), Compassberg-Lucernvale combined record (1975-present), Aandrus (1969-1999), Weltevreden (1901-2010), Kreigersbaaken ((1971-1993), Wellwood (1895-present), Nieu-Bethesda (1886-1999), Struishoek (1928-2007), Dalveen (1979 - present), Quaggasvlei (1945-present), The Rest (1969- present) and Doornberg (1904-present) (Fig. 1b). Additional short term erosion pin data has been obtained for the catchment of the Ganora Dam (Rowntree and Foster, 2012) and for a small catchment close to Ganora Farm (Rowntree, unpublished). Five-minute rainfall intensity data are available from 2009 for this site.

Rock weathering in the Compassbereg area was investigated by infield monitoring and strength testing and laboratory experiments.

A series of small farm dams have been cored and sediments have been dated using fallout radionuclides ^{210}Pb and ^{137}Cs. Sediment volumes have been estimated and several characteristics of the sediments have been measured including particle size (by laser granulometry), sediment geochemistry (ICP-OES) and colour (using a colour scanner), mineral magnetic properties and organic matter content (by loss on ignition and Carlo-Erba C:N analyser) (Foster et al., 2005, 2007, 2008, 2012; Pulley et al., 2015; Pulley and Rowntree, 2016a,b).

Characteristics of the main studied catchments are listed in Table 1. Ganora and the Compassberg catchments are in the Sneeuberg uplands typically at 1500–1600 m asl, whereas Cranemere is just south of the Sneeuberg on the plains of Camdeboo (Fig. 1b).

4. Degraded land and badlands

Here we distinguish between degraded land and badlands: the latter are considered to be a more degraded subset of the former. However, some surveys have not clearly distinguished the two, as discussed below. Degraded land forms a continuum from loss of some plant species to complete loss of all soil including nutrients, carbon and vegetative cover, at which stage the term 'badlands' is commonly applied.

Different surveys have produced different estimates of the area of degraded land due to contrasting methodologies, definitions and problems of the scale of remotely-sensed images. Acocks (1975) noted, "a conversion of 32,000 km^2 of grassveld into eroded Karoo" (Beinart 2003, p. 370). In the Compassberg area, Boardman et al. (2003b) classify 25% of the land as moderately to severely degraded in 1945 and give the same value in 1980. This is based on the SARRCUS (1981) system and analysis by Holland (2000). Keay-Bright and Boardman, (2006) using a sequence of air photographs from 1945-2002, estimated the degraded area to have declined over this time period from 17.8-14.5% of the research area (~35 km^2). These two surveys include badlands within 'degraded areas'.

It is clear that most of the area has experienced a severe loss of grass from a former mixed shrub-grass cover: Boardman et al. (2003b) had difficulty finding any grassed areas on which to carry out simulated rainfall experiments. This loss has led to a substantial increase in bare areas vulnerable to runoff generation and sediment production. Still, farmers now report that the condition of the veld (natural vegetation cover) is improved compared to former times, although they point to continued variation between farms related to stocking regimes. Fig. 3

shows severely degraded areas (badlands) and adjacent less degraded areas draining northwards to the Good Hope Dam.

Badlands have not been much reported in South Africa: there is probably a tendency to overlook them as a 'normal' part of the landscape. In the Eastern Cape, apart from those reviewed in this paper, only Kakembo and Rowntree (2003) and Kakembo et al. (2009) investigated badlands (in the Peddie area of the former Ciskei).

Boardman et al. (2015) estimate badlands to cover 4% of the study area based on field survey, the topographic map and Google Earth data. However, for some small catchments studied in detail up to 15% of the catchment area has been defined as badland e.g., Ganora catchment (Rowntree and Foster, 2012). Badlands in the Sneeuberg occur on valley-side footslopes and on formerly cultivated land, generally in valley-bottom locations. Some feed directly into valley-bottom gullies, others are less well connected (Grenfell et al., 2012), providing a complex mosaic of strong and weak functional connectivity (sensu Fryirs et al., 2007). Badland connectivity also varies temporally depending on the magnitude of rainfall and runoff events. Where connectivity is imperfect sediment is frequently stored in large fans in footslope positions.

Badland surfaces in the Sneeuberg are compact with high bulk densities. This results in rapid runoff response to rainfall events. Runoff and sediment production has been observed during rainfall events of only 10 mm. Although these badlands occupy a relatively small area of the landscape, they have erosion rates far higher than the degraded areas around them. Rates of erosion have been estimated at 10 badland sites in the Compassberg area for the past 15 yr using arrays of 25 erosion pins at each site (Fig. 4). This approach is discussed in Boardman and Favis-Mortlock (2016) and results have been presented in Keay-Bright and Boardman (2009) and Boardman et al. (2015). Table 2 updates these results to 2016.

Erosion pins were placed in distinctive topographic positions within the badlands (Fig. 5). Average rates of net erosion were highest on interfluves and footslopes with channel floor rates being inhibited by proximity to bedrock at three sites (Table 3).

Net rates of erosion vary between 2.4 and 8.1 mm yr^{-1} (~41 – 138 t ha^{-1} yr^{-1} assuming a bulk density of 1.7 g cm^{-3}). A similar rate (3 mm yr^{-1}) was measured at Ganora in 2007-08, on the southern slopes of the Sneeuberg (Rowntree and Foster, 2012). Differences between sites are difficult to explain but most likely result from contrasts in local slopes. When all site data are combined, a correlation exists (at 99% significance) between erosion amounts and rainfall during measurement periods, and between erosion amounts and numbers of rainfall events >10 mm. Correlations are not perfect because amounts of erosion are related not only to rainfall: erosion is also related to amounts of weathering (break-up and loosening) of the surface in the measurement period. This suggests temporal switches from energy-limited to supply-limited system states.

Rates of erosion on the Sneeuberg badlands are similar to those reported on other badlands worldwide although great ranges exist, and values are sensitive to measurement methods as well as factors such as parent materials, slope and rainfall (Boardman et al., 2015, Table 1).

We assume that the principal process of degradation on the Sneeuberg badlands is, in addition to runoff, the rate of weathering largely driven by wetting and drying. Some fine grained material is probably removed by wind but no studies of wind erosion have been undertaken in the region. In the past, drought and fires have damaged vegetation and must have affected runoff and erosion. The regular occurrence of fires in the area in the last 15 yr is a matter of observation and they appear to be both naturally caused and out-of-control fires originally started for management purposes. Fire frequency has not been quantified directly, although charcoal layers indicative of veld burning have been recorded in farm dam sediments. The record, however, is only since the 1930s and there appears to be no change in fire frequency (Mighall et al., 2012). Rainfall simulation experiments show that on small plots runoff is ~10 times greater on bare (badland) surfaces compared to well vegetated (grassed) surfaces. Similarly, erosion rates are increased by a factor of ~6 (Boardman et al., 2003b).

As well as being of limited spatial extent, the depth of incision on the Sneeuberg badlands rarely exceeds 2 m. This is related to the thickness of colluvium over bedrock on footslopes. It suggests a relatively recent age for the inception of badlands. Backcasting of current rates of erosion suggests an age of about 200 yr but many assumptions are involved in this exercise (Boardman et al., 2015, Table 4). The extensive badland near Lucernvale, on formerly cultivated land, has developed since the termination of wheat farming there in the 1920s (Keay-Bright and Boardman, 2009). At Ganora, badlands existed prior to 1945 and were probably initiated in the late 1930s to early 1940s (Rowntree and Foster, 2012) but a major badland became connected to the local gully system in the 1960s, contributing to high rates of dam sedimentation thereafter (Rowntree and Foster, 2012). Overgrazing appears to be the main driver of badland formation in this area both on valley-side footslopes and on formerly cultivated valley-bottom land.

5. Weathering

Rates of weathering on sandstones and mudstones of the Katberg Formation appear to be very high. A small alluvial fan formed in January 2010 as a result of a flood in an infilled dam at Compassberg farm. Within a month many mudstone clasts had disintegrated, presumably due to wetting and drying. Four years later, 36% of mudstone clasts were weathered with nearly half ‘completely weathered’. Low numbers of sandstone clasts suggest that most do not survive transport from hillslope and local colluvium exposures (Boardman, 2015).

Work carried out on the sandstone and mudstone outcrops around the infilled dam showed a complex lithology resulting in differentiated weathering patterns, and thus clast production. Field observations indicated that sedimentary layers in direct contact with igneous intrusions weather slower than sedimentary rock in unaffected parts of the sequence. This was particularly noticeable in the sandstone exposures, where overhangs are clearly pronounced within 0.5 m of overlying dolerite intrusions.

These observations were supported by infield microscopy, which showed that the non-altered sandstone layers were prone to crumbling and flaking, whereas altered layers exhibited a far greater degree of cohesion on the surface. Sediment traps placed beneath sandstone overhangs showed that sediment produced underneath these overhangs consists largely of fine sands with few larger lithic fragments.

Furthermore, field observations indicated that more friable surfaces were likely to sustain lichen colonies, which can accelerate deterioration (Paradise, 1997; Chen et al., 2000), thereby exacerbating differential weathering rates. Thus, lithic materials in the area produce both cohesive clasts, as observed on the alluvial fan, which are likely to have been strengthened through contact with igneous intrusions, and very fine material that directly contributes to the colluvium on the slopes of the valleys. Clasts from sections that have not been altered deteriorate as they are moved down slope and are returned to a loose sediment state before they reach the valley floor. The exception to this are rapid transport events, such as the January 2010 high-magnitude rain event (Boardman, 2015) which deposited clasts of both altered and unaltered material on the infilled dam. The unaltered material deteriorated rapidly after this rapid wetting and drying event, whereas reduced permeability in altered material ensured clasts from the igneous/sedimentary boundary survived for at least six subsequent years.

6. Gully systems

Gully systems are frequently, but not always, found in major and tributary valleys of the Sneeuberg. In some valleys discontinuous gullies and floodouts are typical (Grenfell et al., 2012, 2014). Characteristically gully systems are dry for much of the year and incised to several metres below the former flood plain level or slope surface. They may follow the line of former river systems as in the case of the Klein Seekoei.

Gully erosion is likely to have been the result of a number of different factors as is discussed by Rowntree (1988) who points to the dynamic nature of Karoo landscapes. Oldknow et al. (2016) identify a sequence of cut and fill cycles that formed four distinct terraces in the upper Sundays Valley through the Late Glacial and Holocene. Grenfell et al. (2012) present evidence that gullying and depositional floodout formation is a long-term landscape process. Changes to sediment supply and connectivity are thus a natural feature. There is strong evidence, however, that the present gullies are a response to environmental changes brought about by European settlement in the mid nineteenth century (Rowntree, 2013). She places the date of gully formation in the Karoo at between 1820 and 1850. Boardman (2014) argues that the extensive late-Holocene valley-bottom wetland deposits cannot have formed in the presence of gullies that incise, in many cases to bedrock, and effectively drain them. When the wetlands formed, non-incised streams with hippopotami (thus the Klein Seekoei name) existed (Neville, 1996; Holmes, 2001; Skead, 2007). A seasonal, semi-arid rainfall regime would have produced long periods of low flow with the pools (‘zeekoegaten’ - hippopotamus wallows) described by early travellers (Grenfell et al., 2014).

Changes in vegetation related to an overgrazed landscape is likely to have been a significant factor in causing gully erosion. One trigger for the incision of gullies may well have been the development of road networks in the Sneeuberg following the incursion of Trekboers in the 1770s and movement through the area in the 1870s associated with the Kimberly diamond rush. Outspanning of oxen and horses and transhumance of animals were other possible causative factors (Neville et al., 1994). Evidence of tracks becoming incised and leading to the development of gullies is not unusual in the Sneeuberg (Boardman 2014, Fig. 4).

Gully erosion does not appear to be a widespread process at the present day and gullies are reaching a more stable state. Major gully systems certainly pre-date the 1945 air photographs but evidence from aerial photographs suggests that they have not extended significantly in length since 1945. There has been some increase in density of the gully networks and rills which connect to them (Fig. 5 in Keay-Bright and Boardman, 2006). The gullies appear to operate as efficient transport routes for large quantities of hillslope sediment in extreme rainstorm events. The sedimentary records in the dams attests to this: the events of 1-4 March 1974 (329 mm), for example, resulted in gravel layers in Dams 7 and 10 and the breaching of Dam 53; the event of the 24 March 2000 (118 mm day^{-1}) resulted in the breaching of Dam 7 (Foster et al., 2007). The alluvial fan in Dam 7 resulted from a storm of ~50 mm on 22 January 2010 (Boardman, 2015).

The role of gully incision in valley planation is controversial. Grenfell et al. (2014) identify palaeo-floodouts and suggest repeated phases of gully incision. However, most current gullies incise minimally into bedrock. In both the Klein Seekoei and the Gordonville valleys pre-Holocene palaeosols overlie bedrock (Holmes et al., 2003; Grenfell et al., 2012) and therefore Holocene planation of the palaeo-valley surface seems unlikely.

7. Farm dams and small catchments

Since the first dam corings in 2003, seven small catchments with farm dams have been investigated (Foster et al., 2005 and Table 1). Four of these are located within the larger Good Hope (Dam 37) catchment. The dams were selected in order to isolate the effects of a range of land use, farming activities and the presence or absence of differing landscape elements (Foster et al., 2012). Dams 7 and 10, for example, have no badlands but Dam 7 has a large area of former cultivation. Ganora has extensive badland sytems and grazing but no history of cultivation back to 1910. Cranemere, on the plains of Camdeboo, has cultivation and badlands but is located on an extensive plain and has a record spanning over 150 yr as it was probably constructed in the 1840s (Foster and Rowntree, 2012). Dam 53 and Hartebeestefontein (Dam 94) have no cultivation and minimal badlands but Dam 53 has little dolerite in the catchment whereas Dam 94 contains extensive outcrops of dolerite. Good Hope (Dam 37) represents the integration of processes in the Dam 7, 10 and 53 subcatchments.

To date we have reconstructed sediment yield histories from only four sites, based on the methods of fallout radionuclide dating and multiple dam coring described by Foster et al. (2007, 2008), Foster and Rowntree (2012), Rowntree and Foster (2012), Foster et al. (2012), and Walling and Foster (2016). The final sediment yields from these dams show a complex temporal history with all four sites having twentieth century increases in yield. The sediment yield maxima are recorded in the 1950s (Cranemere and Dam 7) and the 1960s (Ganora and Dam 10).

By way of comparison, Midgley et al. (1994) provide modelled estimates of sediment yield for five quaternary catchments close to the catchments we have studied in the Compassberg region. On average they are of larger area than the catchments in which we have undertaken sediment yield reconstruction (see Table 6 for five small catchments referred to in South

African nomenclature as ‘quaternary catchments’). These modelled yields, however, are generally lower than estimates produced from palaeoenvironmental reconstruction suggesting that the models are poor representations of actual sediment yields in these degraded areas and more closely mirror those yields seen in the earliest period of reconstruction before significant mid to late twentieth century increases in sediment yield occurred.

Foster et al. (2012) explored four key drivers (extrinsic / intrinsic thresholds) likely to lead to significant increases in sediment yield:

1. High sediment yield is related to overstocking, but the temporal pattern of sediment yield reflects a lag effect as proposed by Archer (2000);

2. Increased sediment yields in the mid-twentieth century are due to the expansion of cultivation;

3. Increased sediment yields from the mid-twentieth century are due to changes in weather patterns that have resulted in increased rainfall energy, greater erosivity and flooding in the last 50 yr;

4. Increased sediment yields from the mid-twentieth century are due to changes in connectivity between sediment sources, sediment stores and the farm dams.

It is well documented that stocking rates peaked in the late 1930s, at a time when the Karoo was experiencing a significant number of drought years in succession and much lower than average temperatures (du Toit and O’Connor, 2016). This combination may well have triggered a reduction in veld density and quality subsequently leading to high erosion rates. However, some of the highest rainfalls in the Karoo were recorded in 1941 (4 and 5 Feb ~79 mm; Feb 13 ~83 mm) yet do not appear to have triggered extensive and widespread erosion. Until the last decade, fire has also been used as an important management tool perceived to increase veld productivity and frequently leaves records as charcoal layers in sedimentary deposits in farm dams (Mighall et al., 2012). Wild fires continue to cause widespread burning of the veld.

The area of cultivation peaked in the Karoo in the 1950s at a time when sediment yields increased to a maximum in Dam 7. High rates of accumulation in a core from Dam 37 probably reflect extensive cultivation in the Good Hope Valley adjacent to the dam (Fig. 6). The rise in sediment yield happened much earlier at Cranemere and appears to correlate with a significant change to the structure of the R63 road that links Somerset East to Graaf-Reinet. Here, the road was elevated above a former wetland and new drainage lines beneath the road re-connected the upper catchment to the dam.

Foster et al. (2012) demonstrated that there had been a significant increase in rainfall intensity at both lowland plain and mountainous catchments in the Karoo, most notably the exceptional rainfall in early March 1974. However, the non time-synchronous increase in yield at all sites suggests that catchment response was more complex than a simple erosional response to a single event in time and that simple single thresholds in rainfall intensity cannot be isolated as the direct cause of increased erosion rates across the region.

Trends in sediment yield therefore exhibit complex responses in these Karoo catchments to a range of potentially controlling variables and to a combination of factors that might trigger increases in erosion rates (drought, low temperature, fire, reduced vegetation density, high rainfall intensity, changing connectivity). What is also clear from the trends identified is that, despite several decades of lower stocking rates and not using fire as a veld management tool, sediment yields have remained stubbornly high and orders of magnitude above those rates estimated for the early history of all four dams (Table 4). Esler et al. (2006) stress that severely degraded Karoo veld is unlikely to recover by simply reducing livestock densities and point to the unpredictable response of veld to the combined factors of rainfall and grazing.

8. Sediment source tracing

In addition to dating and reconstructing sediment yields, many of the sedimentary deposits accumulating in farm dams have been analysed for a range of properties including particle size, loss on ignition, sediment geochemistry, mineral magnetism and geogenic radionuclides in order to determine whether changes in sediment yield are accompanied by changes in sediment source. Pulley and Rowntree (2016a) suggested that colour could also be used effectively for discriminating sediment sources in the Karoo. Environmental magnetism has proved to be especially useful in discriminating sediment sources in the region (e.g., Foster et al., 2007, 2012; Foster and Rowntree, 2012; Rowntree and Foster, 2012; Pulley and Rowntree, 2016b) as the records in almost all dams show good preservation of fine grained magnetites that appear to be unaffected by post-depositional dissolution (Pulley et al., 2015). The record in Ganora, for example, shows that the initial rise in sediment yield in the late 1930s / early 1940s is accompanied by a temporary switch in source from dolerite dominance to badland (sandstone / shale) dominance. From the 1960s onwards this switch in source dominance became permanent until the date of sampling (Table 1) and was associated with a channel avulsion connecting the badlands to the channel network (Rowntree and Foster, 2012). Sediment source changes appear to have significantly impacted the sedimentary records at Cranemere, Ganora and Dam 37 (Good Hope) whereas the other sites show little evidence for major or sustained changes in sediment sources over time.

An example of downprofile changes in magnetic susceptibility and the diameter of the 50th percentile of the particle size distribution, measured by laser granulometry, are shown for Dam 37 (Good Hope) in Fig. 7. The entire sequence spans the period from the late 1950s to the date of coring and the peaks in low frequency magnetic susceptibility are interpreted to be associated with contributions from relatively remote dolerite sources that are only connected to the dam during periods of extreme rainfall and runoff. The sustained increase in the D50 between 190 and 150 cm depth is tentatively linked to the 1974 flood and the breaching of Dam 53 upstream.

While changes in sediment source can be interpreted from mineral magnetic signatures, additional clues as to the dominance of surface sources come from the use of fallout radionuclides like ^{137}Cs (Walling and Foster, 2016). Table 5 provides the ^{137}Cs inventories for the master cores taken from each farm dam and also provides measured reference inventories for the Compassberg region and plains of Camdeboo.

Reference inventories are low (less than 50 mBq cm^{-2}) as would be expected in the Southern Hemisphere and it now seems likely that the first occurrence of ^{137}Cs in a sedimentary record is around 1958 (Foster et al., 2012). However, inventories in the farm dams are significantly higher and, in the case of the Good Hope Dam, exceed 1300 mBq cm^{-2}. Dam 53 has a low inventory, but sediment stopped accumulating there after 1974 when the dam wall was breached by a major flood. Examination of current potential sediment sources shows that undisturbed and cultivated topsoil contains measurable quantities of ^{137}Cs whereas it is generally undetectable in heavily eroded badlands (except in small pillars of undisturbed soil protected by bushes) or in gully sidewalls (except in topsoil to ~ 15 cm depth in the profile of uncultivated sites). This suggests that much of the sediment deposited in dams after the 1970s came from sources that were labelled with ^{137}Cs, i.e., topsoil or shallow rilling rather than badlands and gully sidewalls. Moreover, the observed stability of modern gully systems

(Keay-Bright and Boardman, 2006) casts doubt on the idea that the filling of small farm dams is a result of erosion of the gullies. Analysis of other source properties prior to the 1970s (Foster et al., 2007) supports the contention that for the entire history of dam sedimentation in the Compassberg area (approximately the last century) gullies acted as conduits and not sediment sources.

The large body of work emerging from an analysis of farm dam and other sedimentary deposits in the Karoo suggests that most sediment properties are likely to be well preserved and that a number of techniques could be used to identify sediment sources and to help design targeted catchment rehabilitation programmes. The early to mid-twentieth century erosion rates estimated from sediment yield reconstructions in farm dams could also provide a target rate for any catchment rehabilitation to achieve and emphasise that yields will naturally vary spatially, depending on local environmental conditions (see Foster et al. (2012) and Foster and Greenwood (2016) for a discussion of the value of dam sediments for establishing environmental targets).

9. Formerly cultivated land

On some farms in the Sneeuberg and adjacent plains, land degradation is clearly associated with former cultivated areas. In the mountains these are largely in valley bottoms and often on former wetland areas. There is some evidence that terracing and contour bunds were constructed, although it is not known whether these were built as water retention or erosion control features or a combination of the two. Most of these areas grew wheat either for home consumption, for sale off the farm, or as fodder with sheep frequently grazed on the growing crop. Latterly, lucerne has proved more popular. Both crops were irrigated from small dams and springs in some areas but in others were rainfed. Since the 1980s wheat has virtually ceased to be grown in the Sneeuberg. Suich and Boardman (2016) investigated the rise and fall of wheat and its association with land degradation. There was little evidence that land degradation *caused* the demise of wheat. Drivers of this decline were changes in farm economies, technological developments, government policy, a growing preference for lucerne as a fodder crop, and probable ecological factors. Many farmers mentioned the decline in soil quality as a result of wheat farming, and over a long period of time, overgrazing. These declines would have affected the productivity of the veld soils. These comments are supported by loss on ignition (LOI) data from the very long term record at Cranemere reservoir showing declining values of carbon incorporated into the sediments over the last ~170 yr as soils were stripped from the catchment (Fig. 8). The S ratio (a mineral magnetic index relating to the balance between hematite-type and magnetite-type minerals; see Walling and Foster, 2016) also reduces over time in the same sediment core (Fig. 8) suggesting that fine grained magnetites, that are often present as secondary minerals in topsoil, are reducing over time at the expense of coarser grained hematite-type minerals associated with less well weathered material. The trends are less clear in other shorter sedimentary records (possibly often due to significant changes in sediment sources), except for a strong and consistent decline in LOI from the base of the sequence at ca 5 m depth to the surface in Dam 53 (corresponding to the breach date in 1974). Changes in rainfall patterns and in the consistency of summer rainfall were also mentioned by interviewees and are backed up by rainfall analysis. There is no doubt that serious degradation occurred during the phase of wheat cultivation and this impacted on dam sedimentation (see above). Wheat cultivation peaked in the 1950s in the Good Hope Valley (Fig. 6).

Land degradation continued on formerly cultivated land after cultivation ceased. A good example of this is described in Keay-Bright and Boardman (2006, Fig. 11) where an early twentieth century threshing floor is now surrounded by severely eroded former cultivated fields.

10. Discussion

The Sneeuberg habitat has fundamentally changed from what it was before the introduction of livestock and cultivation, giving rise to increased rates of erosion and runoff. Rates of erosion and sedimentation vary predictably with scale of measurement, typically ~8500 t km^{-2} yr^{-1} on badlands and ~500 t km^{-2} yr^{-1} in small catchments. In contrast, the nearest large water-supply reservoir of Nqweba at Graaf-Reinet, has sedimentation rates of ~200 t km^{-2} yr^{-1} from a catchment area of 2197 km^2 (Msadala et al., 2010; Boardman and Foster, 2011). Rates also vary temporally with higher rates of both erosion and sedimentation in the second half of the twentieth century.

Erosion has led to the loss of the A horizon and what remains are shallow, nutrient poor soils. Valleys are incised by gullies that have changed the connectivity of the system and prevent the ancient process of vlei formation and the accumulation of moisture and fertile soils in the valley floors. There has thus been a state change in the system. In the Karoo, the drivers of this state change were the introduction of livestock at numbers above the natural carrying capacity of the land, and the introduction of cultivation of the valley bottom. Additional historic triggers include wagon and livestock tracks and periodic heavy rainfall. In addition, global climate change, and the resultant shifts in the rainfall regime to favour increased erosion, is now a further external driver of the system. Our research demonstrates that the response to these drivers is unpredictable and spatially and temporally variable. We are thus dealing with a complex, non-linear system that is best described using non-equilibrium conceptual frameworks. Esler et al. (2006) describes the non-linear response of the veld to rainfall; the same must apply to erosion which is highly dependent on vegetation condition.

An important change of state can be attributed to changes in connectivity that affect the movement of sediment between stores, representing a significant component of this non-linear response. The generic conceptual model of Fig. 9 shows the major elements and connections between landscape sources and stores in a typical small Karoo catchment at a snapshot in time. Important natural stores include colluvium on footslopes, fans, floodouts and valley floor sediments, the latter often associated with former wetlands. Channel systems have played a dynamic and changing role in connecting hillslopes to the valley floor throughout the Quaternary as evidenced by research by Grenfell et al. (2012) and Oldknow et al. (2016). Our research shows that a significant increase in connectivity in the recent past has played a major role in accelerating downstream sediment delivery rates. Both badland erosion and gully systems contribute to increased connectivity. Badlands promote rapid runoff while gullies (incised channels) form effective conduits for sediment transport. Increased connectivity has to some extent been offset by the buffering effect of farm dams built for water storage and erosion control walls constructed across channels. Many farm reservoirs are now filled with sediment and erosion control walls have reached their trapping capacity. A present concern is the reactivation of sediment stores due to the breaching of dam walls and the release of large volumes of sediment (Boardman and Foster, 2011).

A defining feature of a state change is that it cannot simply be reversed by removal of the pressures that drove the system to that state (Dickie and Parsons, 2012). The situation is well summarised by McAuliffe et al. (2014, p. 2):

“Sparsely vegetated, semiarid landscapes are especially prone to change because small alterations of vegetation caused by either climate or land use can have large effects on the hydrological responses and soils.”

In this case, relative aridity related to slope aspect, led to damage to vegetation and enhanced rates of erosion which has proved over hundreds of years to be an irreversible process. In the

Sneeuberg, we suggest, it was primarily land use pressures on the vegetation that led to hydrological change.

Rates of erosion remain high despite the reduction of livestock numbers and the cessation of cultivation at higher altitudes over the past 30 yr. Shallow soils with their low moisture holding potential and low nutrient content mean that simply reducing grazing will not result in the recruitment of vegetation as the vegetation cannot establish itself in the new regime (Esler et al., 2006). Vleis will not re-establish themselves until gullies are filled and the valley bottoms can become the traps for soil moisture and nutrients that they were in former times.

The challenge for land management in the Karoo is to recognise this state change and realise that we need to find creative interventions that go beyond simply decreasing stocking levels and stopping upland cultivation. Our research has shown that the abandonment of cultivation and fire as management tools and major declines in stocking density have not resulted in a dramatic or rapid decrease in erosion rates, probably because it may take decades to centuries for a full recovery of nutrient status and vegetation density to take place (Foster et al., 2012). The rate of runoff on slopes first needs to be slowed to allow soils to build up faster than they are eroded. Esler et al. (2006) point to the need for physical interventions to promote water retention and sediment trapping. This is in line with measures taken in the Mgwalana catchment in the Eastern Cape Province (Kakembo et al., 2012). The lack of repair of breached dams adds to the problem. More effective management methods should target landscape connectivity as a means of disconnecting those landscape elements from the fluvial system that lead to the rapid conveyance of sediment from hillslope to channel and thence to downstream dams and water-supply reservoirs (Fig. 9).

The studies reviewed here demonstrate that methods which have been tried and tested in other environments (e.g., Walling and Foster, 2016) work effectively in the Karoo and suggest that combinations of field mapping and measurement, process rate measurement and environmental reconstruction can contribute to an understanding of the history and magnitude of erosion rates and to the identification of sediment sources, stores and pathways. Such information could clearly enable targeted catchment rehabilitation in many ways.

11. Conclusion

It is clear from national surveys that the Sneeuberg is not one of the most degraded parts of South Africa although when perceptions of soil and veld degradation are combined, the Eastern Cape in general, ranks high as a 'problem area' (Hoffman and Ashwell, 2001, p. 152). The term 'degradation' is preferred to 'desertification' with the latter's emotive and misleading connotations.

The Sneeuberg is noteworthy in that there is a considerable body of evidence to assess the scale and development of the problem. We can summarise this as follows. Most degradation is a result of around 200 yr of sheep farming with stock numbers for much of that period at unsustainably high levels: this damaged the vegetation. Land degradation has not only affected the vegetation composition but has resulted in the development of degraded areas, badlands and gully systems. There is considerable evidence that these are relatively recent forms associated with human impact: such landscape changes have resulted in increases in runoff and sediment production. Degradation of former cultivated areas is also a clear, but local, impact on the landscape. Land degradation has had an obvious impact on soil quality and therefore the productivity of the veld but it has also had a largely unacknowledged impact on water resources. Many of the thousands of small farm dams in the Sneeuberg are sedimented and/or breached. Impacts on downstream reservoirs and public water supplies remain insufficiently investigated (Boardman and Foster, 2011).

The Sneeuberg has been shown to be a complex non-equilibrium system that has been subject to cycles of erosion and aggradation in response to environmental change through the Quaternary. The most recent driver of change has been European settlement and livestock farming (now shifting to game farming) that has had significant consequences for sediment processes, which have been variable in space and time. Erosion is a response to the interrelated effects of rainfall, vegetation cover, grazing pressure, cultivation and changing connectivity, but that response is unpredictable. This dynamic non-equilibrium state must be taken into account when advising rehabilitation measures, which need continued research and government support. Identifying key sediment source types and pathways is a useful starting point in targeting areas where rehabilitation can be most effective.

Acknowledgements

JB acknowledges funding from the Trapnell and Oppenheimer Funds (Oxford); HS and JB from a Leverhulme/British Academy grant; LM from a British Society for Geomorphology grant. Reservoir sedimentation studies (IDLF) were funded by the UK Natural Environment Research Council, the British Academy the South African National Research Foundation and Rhodes University. We thank hospitable and supportive landowners in the Sneeuberg, in particular Brenda and Alf James (Compassberg) and Hester and JP Steynberg (Ganora).

References

Acocks, J.P.H., 1975. Veld types of South Africa. 2nd edition, *Memoirs of the Botanical Survey of South Africa* 40, Botanical Survey, Pretoria.

Adams, S., Titus, R., Pietersen, K., Tredoux, G., Harris, C., 2001. Hydrochemical characteristics of aquifers near Sutherland in the Western Karoo, South Africa. Journal of Hydrology 241, 91–103.

Archer, S., 2000. Technology and ecology in the Karoo: a century of windmills, wire and changing farming practice. Journal of Southern African Studies 26 (4), 675-696.

Beinart, W., 1984. Soil erosion, conservationism and ideas about development: a southern African exploration, 1900–1960. Journal of Southern African Studies 11(1), 52-83.

Beinart, W., 2003. The Rise of Conservation in South Africa. Oxford: Oxford.

Bennett, H.H., 1939. Soil Conservation. Magraw-Hill, New York.

Bennett, H.H., 1945. Soil erosion and land use in the Union of South Africa. Department of Agriculture and Forestry, Pretoria.

Boardman, J., 2014. How old are the gullies (dongas) of the Sneeuberg uplands, eastern Karoo, South Africa? Catena 113, 79-85.

Boardman, J., 2015. Rapid and selective clast weathering on an alluvial fan, eastern Karoo, South Africa. Catena 126, 37-42.

Boardman, J., Favis-Mortlock, D., 2016. The use of erosion pins in geomorphology. In Cook, S.J., Clarke, L.E., Nield, J.M. (Eds.) *Geomorphological Techniques (Online Edition),* Chap. 3, Sec. 5.1, British Society for Geomorphology; London, UK. ISN: 2047-0371

Boardman, J., Hoffman, T., Holmes, P., Wiggs, G., 2012. Soil erosion and land degradation. In Holmes, P., Meadows, M. (Eds.), *Southern African Geomorphology: Recent Trends and New Directions,* (pp. 307-32), Sun Press: Bloemfontein.

Boardman, J., Favis-Mortlock, D.T., Foster I.D.L., 2015. A 13-year record of erosion on badland sites in the Karoo, South Africa. Earth Surface Processes and Landforms 40, 1964-1981. DOI: 10.1002/esp.3775

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

Boardman, J., Foster, I.D.L., 2011. The potential significance of the breaching of small farm dams in the Sneeuberg, South Africa. Journal of Soils and Sediments 8, 1456-1465.

Boardman, J., Poesen, J., Evans, R., 2003a. Socio-economic factors in soil erosion and conservation. Environmental Science and Policy 6(1), 1-6.

Boardman, J., Parsons, A. J., Holmes, P. J., Holland, R., Washington, R., 2003b. Development of badlands and gullies in the Sneeuberg, Great Karoo, South Africa. Catena 50(2–4), 165–184.

Chen, J., Blume, H.-P., Beyer, L., 2000. Weathering of rocks induced by lichen colonization – a review. Catena 39 (2), 121 – 146.

Church, M., 2010. The trajectory of Geomorphology. Progress in Physical Geography 34, 265-286.

Clark, V.R., Barker, N.P., Mucina, L., 2009. The Sneeuberg: a new centre of floristic endemism on the Great Escarpment, South Africa. South African Journal of Botany 75, 196–238.

Dardis, G., 1988. Soil erosion forms in southern Africa. In *Geomorphological Studies in Southern Africa*, Dardis, F.G., Moon, B.P. (eds.). Rotterdam: A A Balkema, pp 187-214.

Dean, W.R.J., Hoffman, M.T., Meadows, M.E., Milton, S.J., 1995. Desertification in the semi- arid Karoo, South Africa: review and reassessment. Journal of Arid Environments 30, 247–264.

Dean, W.R.J., Macdonald, I.A.W., 1994. Historical changes in stocking rates as a measure of semi-arid and arid rangeland degradation in the Cape Province, South Africa. Journal of Arid Environments 26, 281–298.

Dickie, J.A., Parsons, A.J., 2012. Eco-geomorphological processes within grasslands, shrublands and badlands in the semi-arid Karoo, South Africa. Land Degradation and Development 23, 534–547.

du Toit, J.C.O., O'Connor, 2016. Minimum temperatures and frost at Grootfontein in the eastern Karoo, South Africa, over 98 years. Transactions of the Royal Society of South Africa. doi.org/10.1080/0035919X.2016.1218373

Esler, K.J., Milton, S.J., Dean, W.R., 2006. Karoo Veld, Ecology and Management. – Briza Publications: 214 pp., Pretoria.

Foster, I.D.L., Boardman, J., Keay-Bright, J., Meadows, M.E., 2005. Land degradation and sediment dynamics in the South African Karoo. In Walling, D.E., Horowitz, A. (Eds.), *Sediment Budgets*. Proceedings IAHS, Foz do Iguacu, IAHS Pub. 295, 207-213.

Foster I.D.L., Boardman, J., Gates, J., 2008. Reconstructing historical sediment yields from the infilling of farm reservoirs, Eastern Cape, South Africa. International Symposium *Sediment dynamics in changing environments*, 1-5 December 2008: Christchurch, New Zealand, IAHS Publ. 325, 440-447.

Foster, I.D.L., Boardman, J., Keay-Bright, J., 2007. Sediment tracing and environmental history for two small catchments, Karoo uplands, South Africa. Geomorphology 90, 126-143.

Foster, I.D.L., Greenwood, M.T., 2016. Linking the past to the present: the use of palaeoenvironmental data for establishing reference conditions for the Water Framework Directive. In Gilvear, D.J., Greenwood, M.T., Thoms, M.C., Wood, P.J., (Eds.), *River Systems: Research and Management for the 21st Century*. (pp. 61-83), Chichester, Wiley.

Foster, I.D.L., Rowntree, K.M., 2012. Sediment yield changes in the semi-arid Karoo: a palaeoenvironmental reconstruction of sediments accumulating in Cranemere Reservoir, Eastern Cape, South Africa. Zeitschrift fur Geomorphologie 56, Suppl. 3,131-146.

Foster, I.D.L., Rowntree, K., Boardman, J., Mighall, T., 2012. Changing sediment yield and sediment dynamics in the Karoo uplands, South Africa: post –European impacts. Land Degradation and Development 23, 508-522.

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M., 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. Catena, 49–67.

Gordon, A.K., Niedballa, J., Palmer, G., 2013. Sediment as a Physical Water Quality Stressor on Macro-invertebrates: A Contribution to the Development of a Water Quality Guideline for Suspended Solids. Water Research Commission Report no. 2040/1/13, Pretoria.

Gordon, A.K., Griffin, N.J., Palmer, C.G., 2014. The relationship between concurrently measured SASS (South African Scoring System) and turbidity data archived in the South African River Health Programme's Rivers Database. Water SA 41(1): 21-25.

Grenfell, S.E., Rowntree, K.M., Grenfell, M.C., 2012. Morphodynamics of a gully and floodout system in the Sneeuberg Mountains of the semi-arid Karoo, South Africa: Implications for local landscape connectivity. Catena 89, 8–21.

Grenfell, S.E., Grenfell, M.C., Rowntree, K.M., Ellery,W.N., 2014. Fluvial connectivity and climate: a comparison of channel pattern and process in two climatically contrasting fluvial sedimentary systems in South Africa. Geomorphology 205, 142–154.

Hoffman, M.T., Ashwell A., 2001. *Nature Divided: Land Degradation in South Africa*. UCT Press: Cape Town.

Hoffman, M.T., Cousins, B., Meyer, T., Petersen, A., Hendricks, H., 1999. Historical and contemporary land use and the desertification of the Karoo. In Dean, W. R.J., Milton, S.J. (Eds.), *The Karoo: Ecological Patterns and Processes.* (pp. 257-273). Cambridge University Press: Cambridge.

Holland, R.M., 2000. An assessment of land degradation on the headwater catchment of the Klein Zeekoei River, Great Karoo, South Africa. Unpublished Master's dissertation, Department of Environmental and Geographical Science, University of Cape Town.

Holmes, P.J., 2001. Central Great Karoo headwater catchments and valley fills: an overview of short term change. South African Geographical Journal 83 (3), 274-282.

Holmes, P., Boardman, J., Parsons, A.J., Marker M.E., 2003. Geomorphic palaeoenvironments of the Sneeuberg Range, Great Karoo, South Africa. Journal Quaternary Science 18, 801-813.

Johnson, M.R., van Vuuren, C.J., Hegenberger, W.F., Key, R., Shoko, U., 1996. Stratigraphy of the Karoo Supergroup in southern Africa: an overview. Journal of African Earth Sciences 23 (1), 3 -15.

Johnson, M.R., van Vuuren, C.J., Visser, J.N.J., Cole, D.I., Wickens, H., de, V., Christie, A.D.M., Roberts, D.L., Brandl, G., 2006. Sedimentary rocks of the Karoo Supergroup. In Johnson, M.R., Anhaeusser, C.R., Thomas, R.J. (Eds.), *The Geology of South Africa*. (pp. 461–499). Geological Society of South Africa, Johannesburg. Council for Geoscience: Pretoria.

Kakembo, V., Ndlela, S., Cammeraat, E., 2012. Trends in vegetation patchiness: loss and implications for landscape function: the case of *Pteronia Incana* invasion in the Eastern Cape Province, South Africa. Land Degradation & Development 23 (6), 548-556.

Kakembo, V., Rowntree, K.M., 2003. The relationship between land use and soil erosion in the communal lands near Peddie town, Eastern Cape, South Africa. Geomorphology 110, 188-194.

Kakembo, V., Xanga. W.W., Rowntree, K.M., 2009. Topographic thresholds in gully development on the hillslopes of communal areas in Ngquhwa local municipality, Eastern Cape, South Africa. Geomorphology 110, 188-194.

Keay-Bright, J., Boardman, J., 2006. Changes in the distribution of degraded land over time in the central Karoo, South Africa. Catena 67, 1-14.

Keay-Bright, J., Boardman, J., 2007. The influence of land management on soil erosion in the Sneeuberg mountains, central Karoo, South Africa. Land Degradation and Development 18, 423-439.

Keay-Bright, J., Boardman, J., 2009. Evidence from field based studies of rates of erosion on degraded land in the central Karoo, South Africa. Geomorphology 103, 455-465.

Laker, M.C., 2004 Advances in soil erosion, soil conservation, land suitability evaluation and land use planning research in South Africa, 1978–2003. South African Journal of Plant and Soil 21(5), 345-368.

Le Roux, J.J., Newby, T.S., Sumner, P.D., 2007. Monitoring soil erosion in South Africa at a regional scale: review and recommendations. South African Journal of Science 103, 329-335.

Meadows, M.E., 2003. Soil erosion in the Swartland, Western Cape Province, South Africa: implications of past and present policy and practice. Environmental Science & Policy 6, 17–28.

McAuliffe, J.R., McFadden, L.D., Roberts, L.M., Wawrzyniec, T.F., Scuderi, L.A., Meyer, G.A., King, M.P., 2014. Non-equilibrium hillslope dynamics and irreversible landscape changes at a shifting pinyon-juniper woodland ecotone. Global and Planetary Change 122, 1-13.

Midgley, D.C., Pitman, W.V., Middleton, B.J., 1994. Surface Water Resources of South Africa 1990. Book of Maps Volume V. WRC Report 298/5.2/94 First Edition 1994.

Mighall, T.M., Foster, I.D.L., Rowntree, K.M., Boardman, J., 2012. Reconstructing recent land degradation in the Semi-Arid Karoo of South Africa: a Palaeoecological study at Compassberg, Eastern Cape. Land Degradation & Development 23 (6), 523-533.

Montgomery, D.R., 2007. *Dirt: the Erosion of Civilizations*. University of California Press, Berkeley.

Morgan, R.P.C., 2003. *Soil Erosion and Conservation*, Third Edition, Blackwell, Oxford.

Msadala, V., Gibson, L., Le Roux, J., Rooseboom, A., Basson, G.R., 2010. Sediment Yield Prediction for South Africa: 2010 Edition, Water Research Commission Report No. 1765/1/10 250 pp.

Neville, D., 1996. European impacts on the Seacow River Valley and its Hunter-Gatherer Inhabitants, AD 1770-1990. Unpublished MA dissertation, University of Cape Town. Part 1: 281 pp. Part 2: 63 pp.

Neville, D., Sampson, B.E., Sampson C.G., 1994. The frontier wagon track system in the Seacow River valley, north-eastern Cape. South African Archaeological Bulletin 49, 65-72.

Oldknow, C., Hooke, J., Lang, A., 2016. Late Quaternary landscape evolution in the Great Karoo, South Africa: processes and drivers. Geophysical Research Abstracts Vol. 18, EGU2016-990-1, 2016 EGU General Assembly 2016.

Paradise, T.R., 1997. Disparate sandstone weathering beneath lichens, Red Mountain, Arizona. Geografiska Annaler Series A 79 (3), 177 – 184.

Pimentel, D., (Ed.) 1993. *World Soil Erosion and Conservation*. Cambridge University Press, Cambridge.

Pulley, S., Rowntree, K.M., 2016a. The use of an ordinary colour scanner to fingerprint sediment sources in the South African Karoo. Journal of Environmental Management 165, 253-262.

Pulley, S., Rowntree, K.M., 2016b. Stages in the life of a magnetic grain: sediment source discrimination, particle size effects and spatial variability in the South African Karoo. Geoderma 271, 134-143.

Pulley, S., Rowntree, K.M., Foster, I.D.L., 2015. Conservation of mineral magnetic signatures in farm dams sediments in the South African Karoo: the potential effects of particle size and post-depositional diagenesis. Journal Soils and Sediments 15, 2387-2397.

Riley, T.R., Curtis, M.L., Leat, P.T., Watkeys, M.K., Duncan, R.A., Millar, I.L., Owens, W.H., 2006. Overlap of Karoo and Ferrar magma types in KwaZulu-Natal, South Africa. Journal of Petrology 47 (3), 541 – 566.

Rowntree, K.M., 1988. Equilibrium concepts, vegetation change and soil erosion in semi-arid areas: some considerations for the Karoo. In *Geomorphological Studies in Southern Africa*, Dardis, F.G., Moon, B.P. (Eds.). Rotterdam: A A Balkema, pp. 175-185.

Rowntree, K.M., 2013. The evil of sluits: a re-assessment of soil erosion in the Karoo of South Africa as portrayed in century-old sources. Journal of Environmental Management 130, 98-105.

Rowntree, K, M., Foster, I.D.L., 2012. A reconstruction of historical changes in sediment sources, sediment transfer and sediment yield in a small, semi-arid Karoo catchment, South Africa. Zeitschrift fur Geomorphologie 56, Suppl. 1, 87-100.

SANBI, 2012. South African National Biodiversity Institute national soils and vegetation map. http://bgis.snabi.org/SpatialDataset/Detail/18 accessed 08/12/2106.

SARCCUS, 1981. A system for classification of soil erosion in the SARCCUS region. South African Department of Agriculture and Fisheries: Pretoria.

Skead, C.J., 2007. Historical incidence of the larger land mammals in the broader Eastern Cape. In: Boshoff, A., Kerley, G., Lloyd, P. (Eds.), Second Edition, Centre for African Conservation Ecology, Nelson Mandala Metropolitan University: Port Elizabeth.

Suich, H., Boardman, J., 2016. Wheat growing and changing farming systems in South African dryland margins: the case of the Sneeuberg, South Africa. Land Degradation and Development DOI: 10.1002/ldr.2543

Talbot, W.J., 1947. *Swartland and Sandveld*. Oxford University Press, Cape Town.

Walling, D.E. Foster, I.D.L., 2016. Using environmental radionuclides and sediment geochemistry for tracing and dating fine fluvial sediment. In Kondolf, M., Piegay, H. (Eds.), *Tools in Fluvial Geomorphology* 2nd edition, (pp. 183-209), Chichester: Wiley. 183-209.

Watson, H., 2000. Land Reform implications of the distribution of badlands in the Mfolozi Catchment KwaZulu-Natal. South African Geographical Journal 82, 143-148.

Weaver, A., 1988. Factors affecting the spatial variation in soil erosion in Ciskei: an initial assessment at the macroscale. In *Geomorphological Studies in Southern Africa*, Dardis, F.G., Moon, B.P. (eds.). 8-11 April 1988. Rotterdam: A A Balkema, pp 215-228.

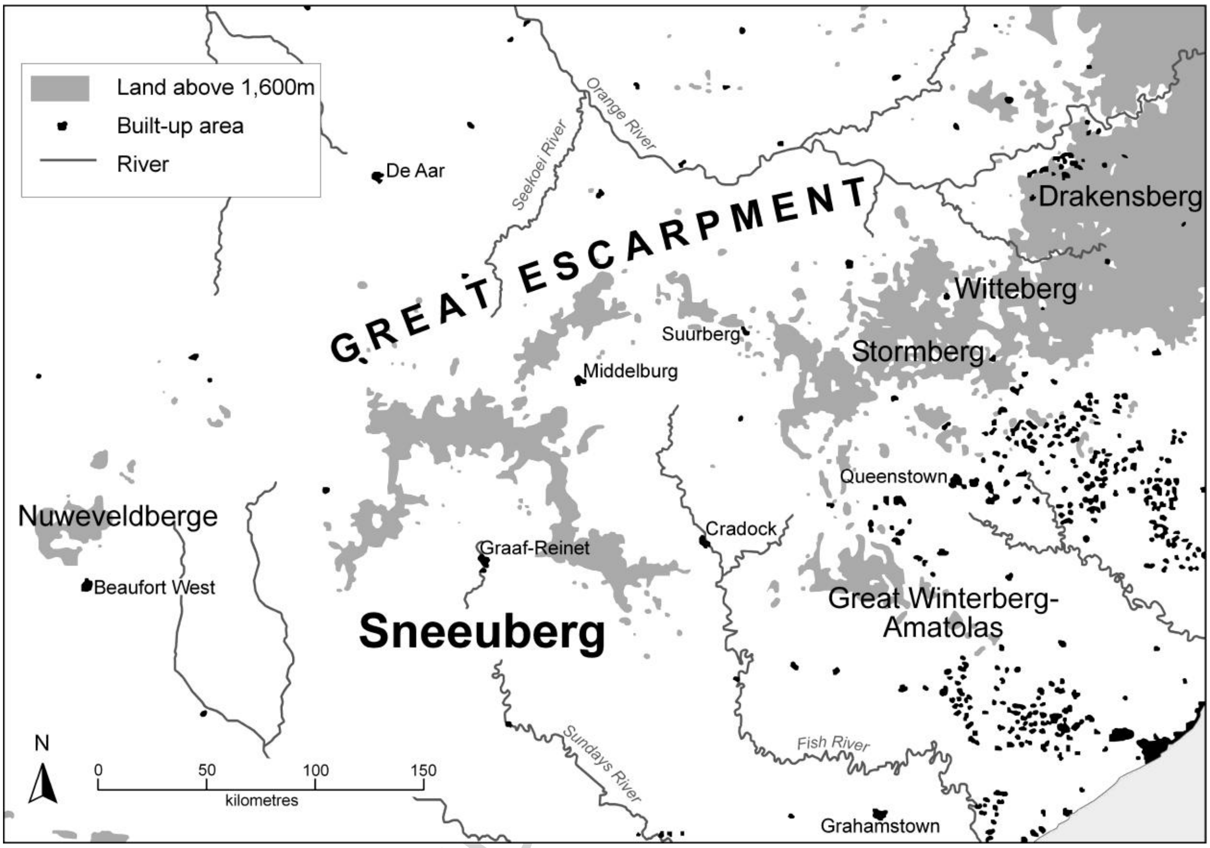
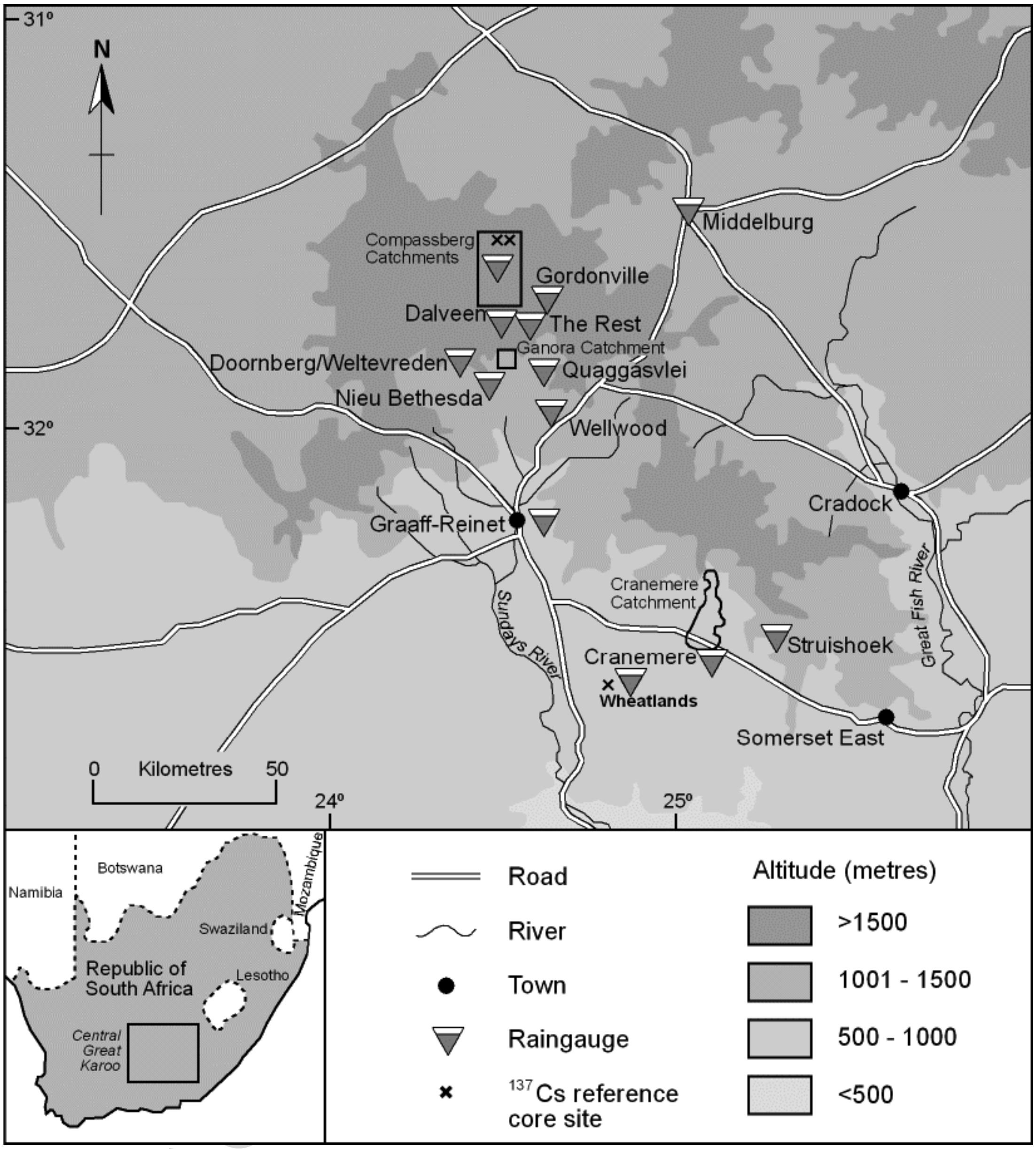

Land above 1,600m
Built-up area
River
De Aar
Seekoei River
Orange River
GREAT ESCARPMENT
Drakensberg
Witteberg
Suurberg
Stormberg
Middelburg
Queenstown
Nuweveldberge
Cradock
Graaf-Reinet
Beaufort West
Great Winterberg-
Amatolas
Sneeuberg
N
0
50
100
150
kilometres
Sundays River
Fish River
Grahamstown

Fig. 1a



31°
32°
N
Compassberg
Catchments
Gordonville
Dalveen
The Rest
Ganora Catchment
Doornberg/Weltevreden
Quaggasvlei
Nieu Bethesda
Wellwood
Middelburg
Cradock
Graaff-Reinet
Cranemere
Catchment
Struishoek
Cranemere
Wheatlands
Sundays River
Great Fish River
Somerset East
0 Kilometres 50
24°
25°
Namibia
Botswana
Mozambique
Swaziland
Lesotho
Republic of
South Africa
Central
Great
Karoo
Road
River
Town
Raingauge
137Cs reference
core site
Altitude (metres)
>1500
1001 - 1500
500 - 1000
<500

Fig. 1b

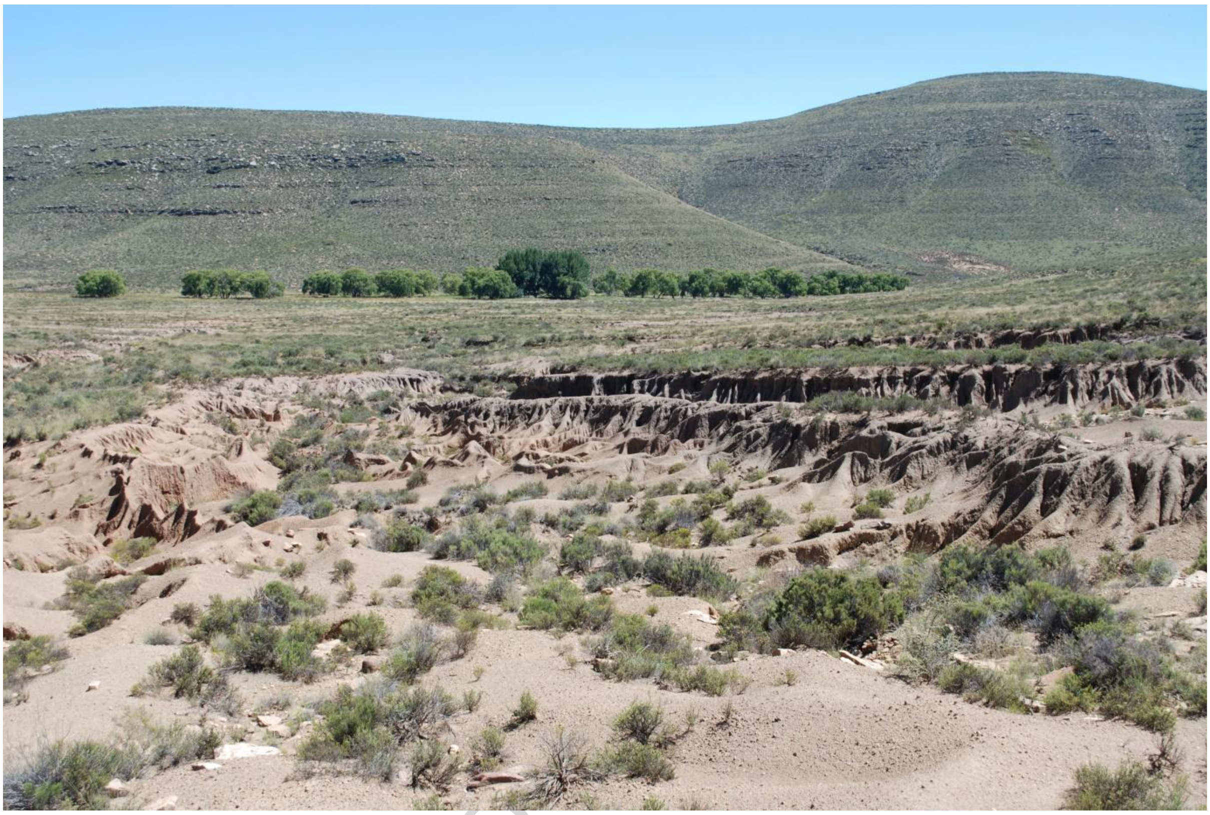


Fig. 2

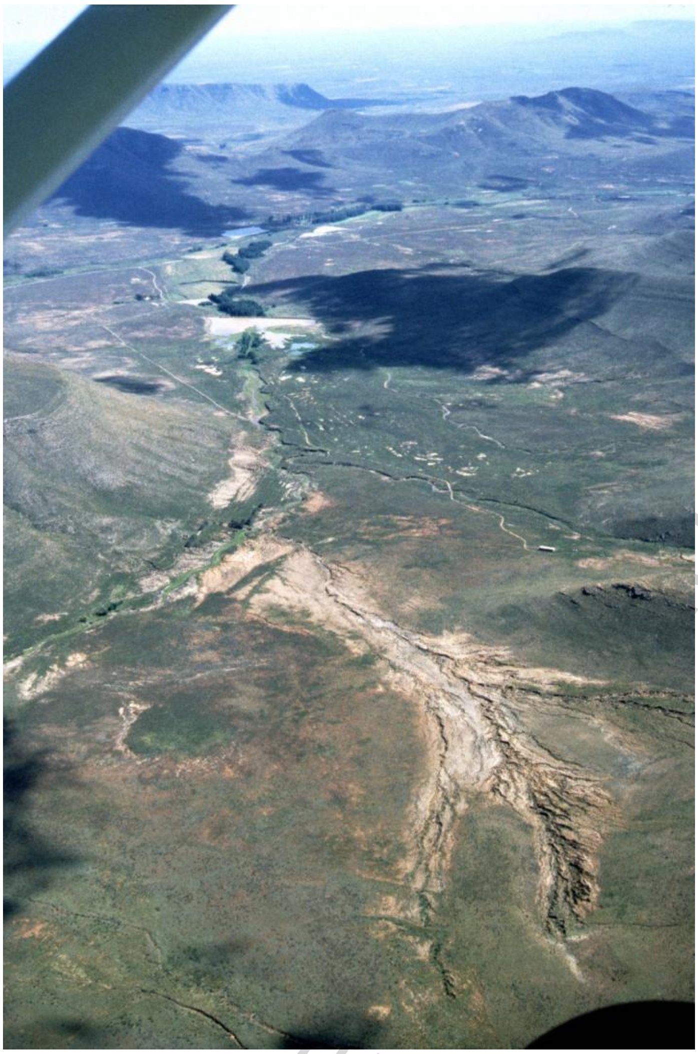
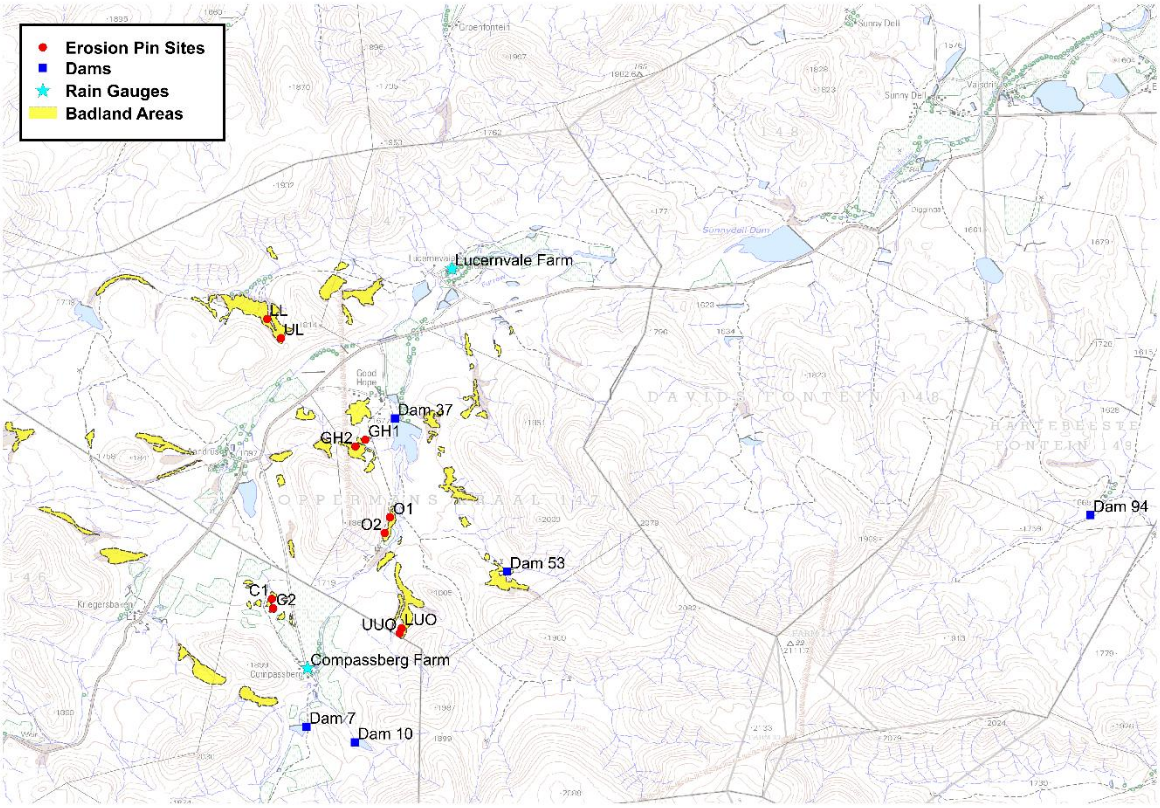


Fig. 3



Erosion Pin Sites
Dams
Rain Gauges
Badland Areas
Lucernvale Farm
LL
UL
Dam 37
GH2
GH1
O1
O2
Dam 53
Dam 94
C1
C2
UUO
LUO
Compassberg Farm
Dam 7
Dam 10

Fig. 4

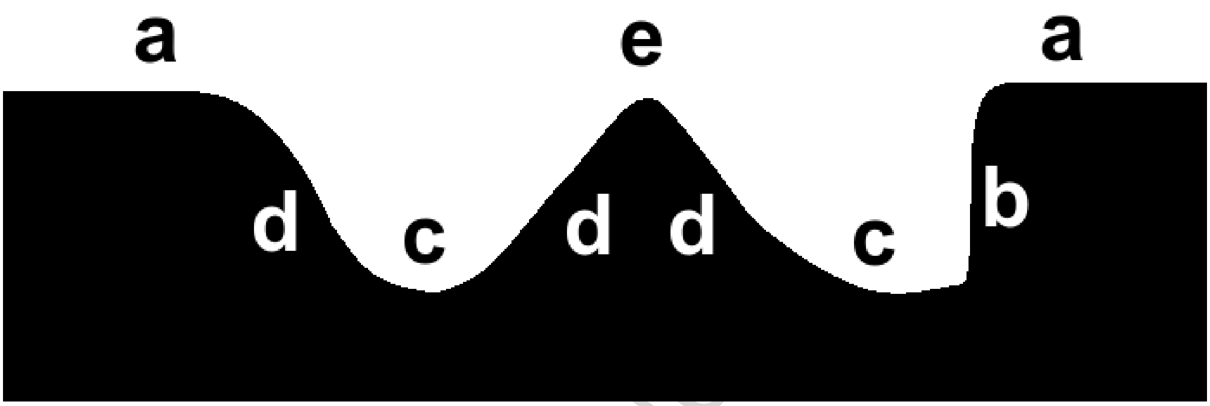


Fig. 5

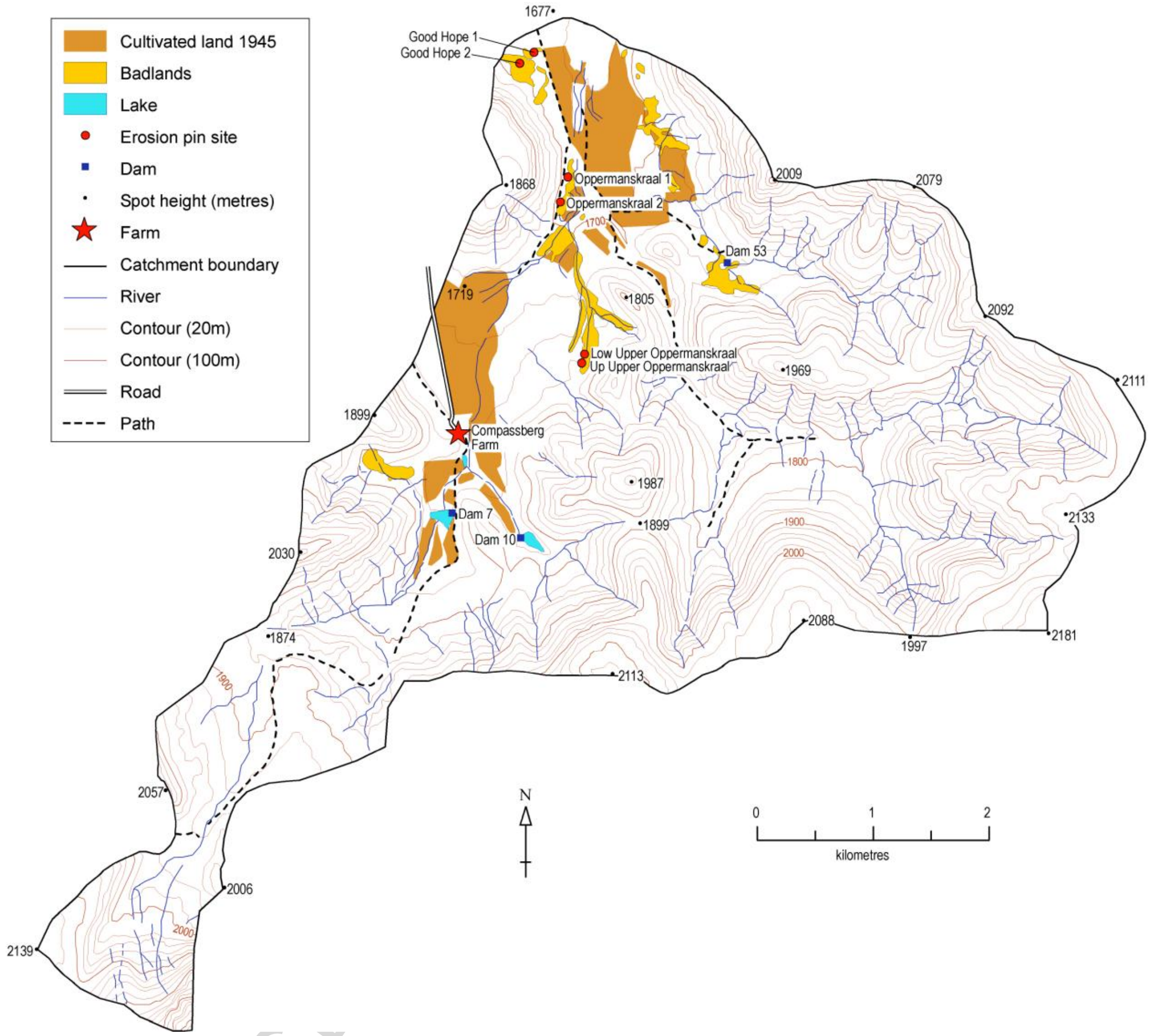
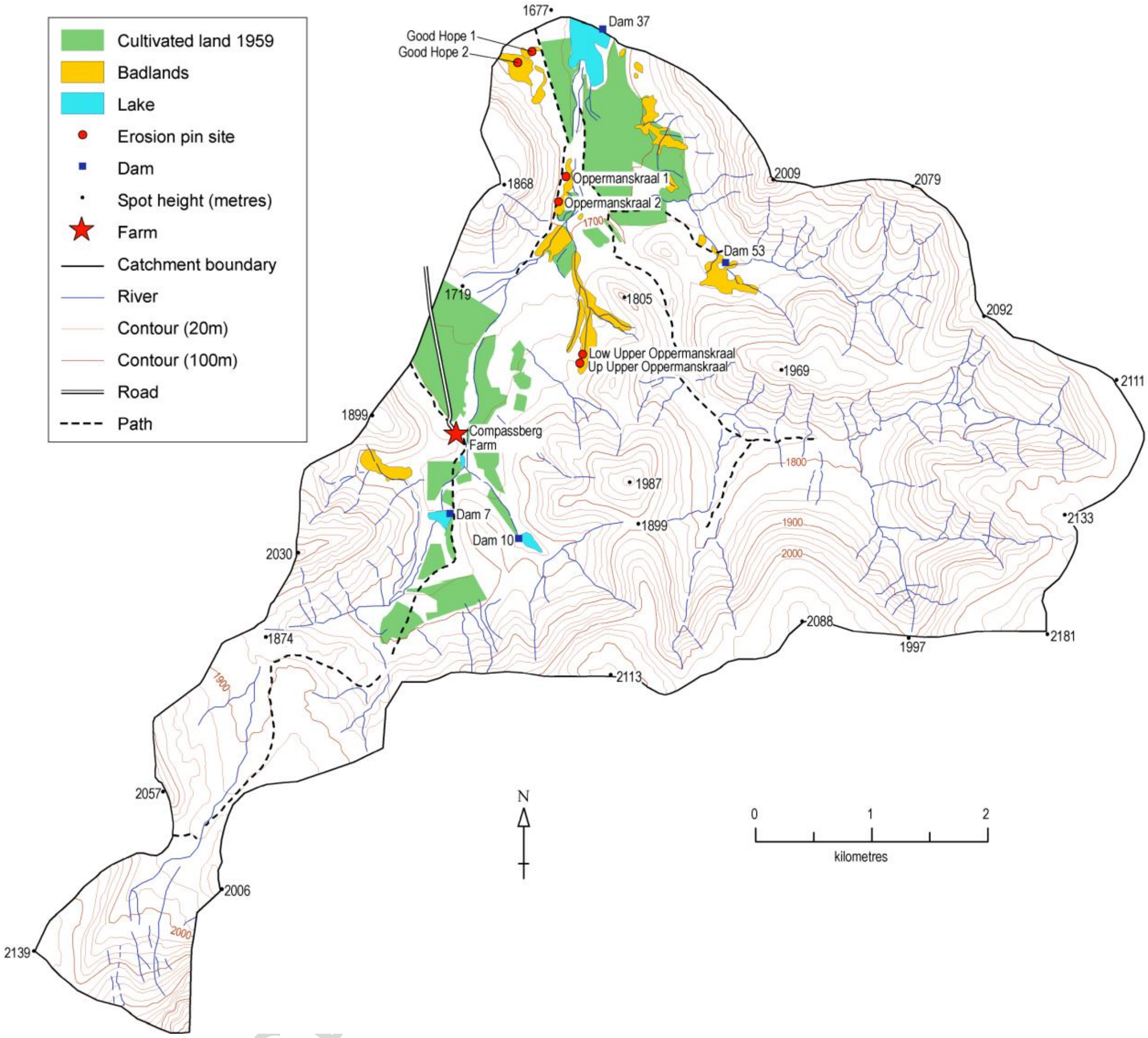

Cultivated land 1945
Badlands
Lake
Erosion pin site
Dam
Spot height (metres)
Farm
Catchment boundary
River
Contour (20m)
Contour (100m)
Road
Path
Good Hope 1
Good Hope 2
Oppermanskraal 1
Oppermanskraal 2
Dam 53
Low Upper Oppermanskraal
Up Upper Oppermanskraal
Compassberg Farm
Dam 7
Dam 10
1677
1868
2009
2079
1719
1805
2092
1969
2111
1899
1987
1899
2030
2133
1874
2088
1997
2181
2113
2057
2006
2139
1700
1800
1900
2000
N
0
1
2
kilometres

Fig. 6a



Cultivated land 1959
Badlands
Lake
Erosion pin site
Dam
Spot height (metres)
Farm
Catchment boundary
River
Contour (20m)
Contour (100m)
Road
Path
1677
Dam 37
Good Hope 1
Good Hope 2
1868
Oppermanskraal 1
Oppermanskraal 2
1700
2009
2079
Dam 53
1719
1805
2092
Low Upper Oppermanskraal
Up Upper Oppermanskraal
1969
2111
1899
Compassberg Farm
1800
1987
Dam 7
Dam 10
1899
1900
2133
2030
2000
2088
2181
1874
1997
2113
1900
2057
N
0
1
2
kilometres
2006
2000
2139

Fig. 6b

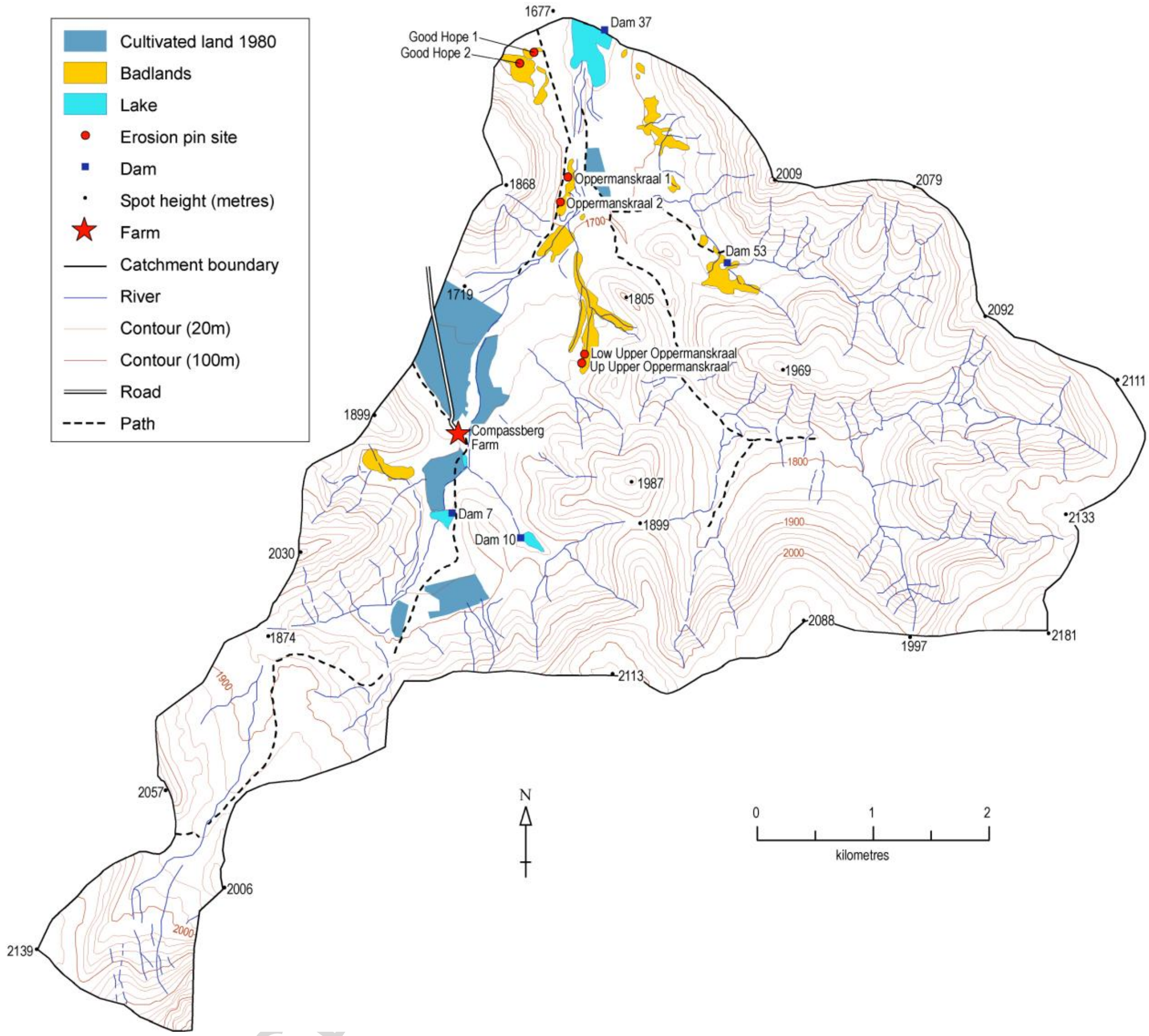
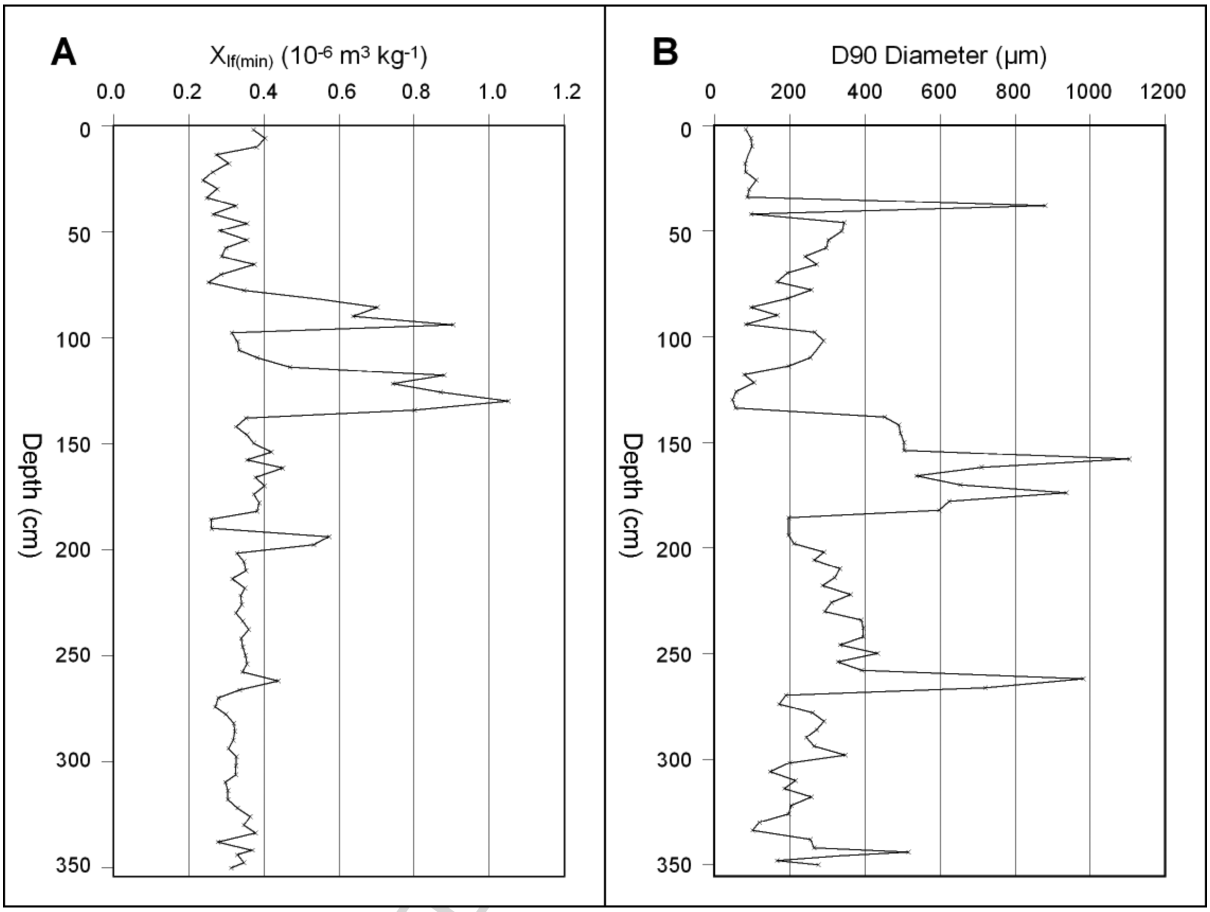
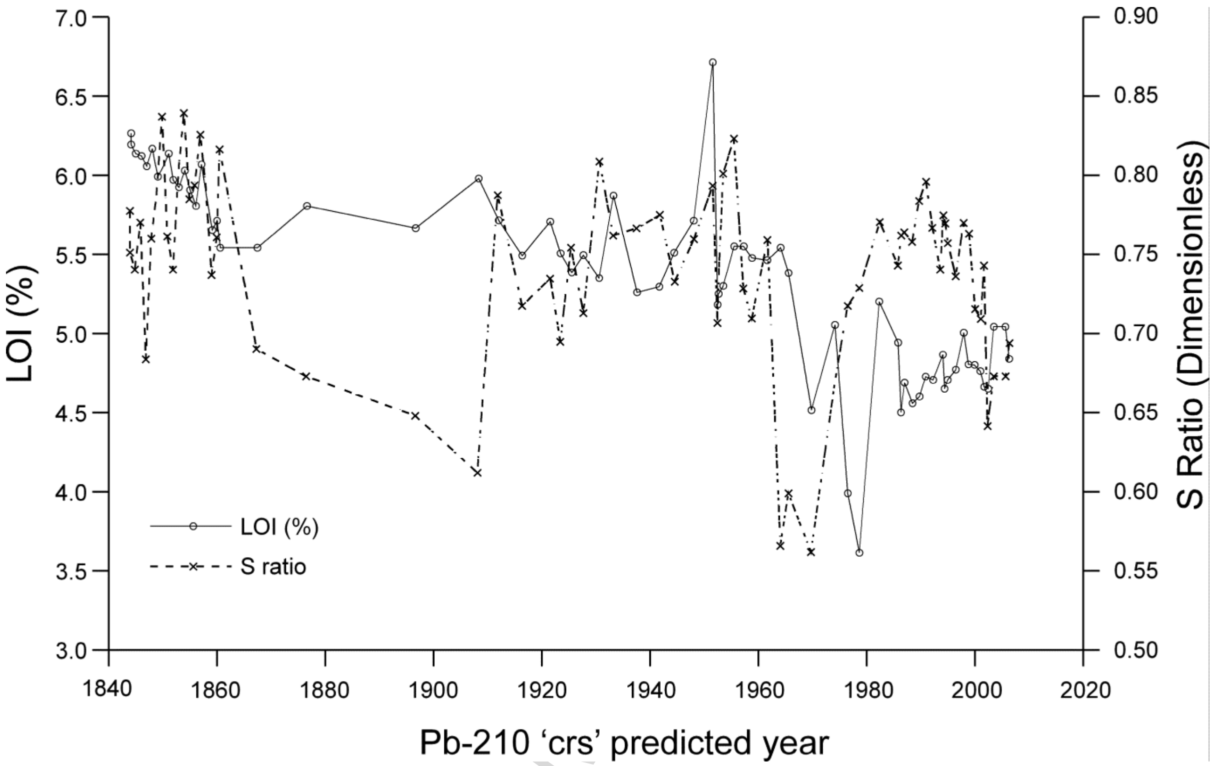

Cultivated land 1980
Badlands
Lake
Erosion pin site
Dam
Spot height (metres)
Farm
Catchment boundary
River
Contour (20m)
Contour (100m)
Road
Path
1677
Dam 37
Good Hope 1
Good Hope 2
Oppermanskraal 1
Oppermanskraal 2
1868
2009
2079
Dam 53
1700
1719
1805
2092
Low Upper Oppermanskraal
Up Upper Oppermanskraal
1969
2111
1899
Compassberg Farm
1800
1987
Dam 7
Dam 10
1899
1900
2133
2030
2000
2088
2181
1997
1874
2113
1900
2057
N
0
1
2
kilometres
2006
2000
2139

Fig. 6c



A
Xlf(min) (10-6 m3 kg-1)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Depth (cm)
0
50
100
150
200
250
300
350
B
D90 Diameter (µm)
0
200
400
600
800
1000
1200
Depth (cm)
0
50
100
150
200
250
300
350

Fig. 7a & b



7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
LOI (%)
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
S Ratio (Dimensionless)
LOI (%)
S ratio
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
Pb-210 'crs' predicted year

Fig. 8

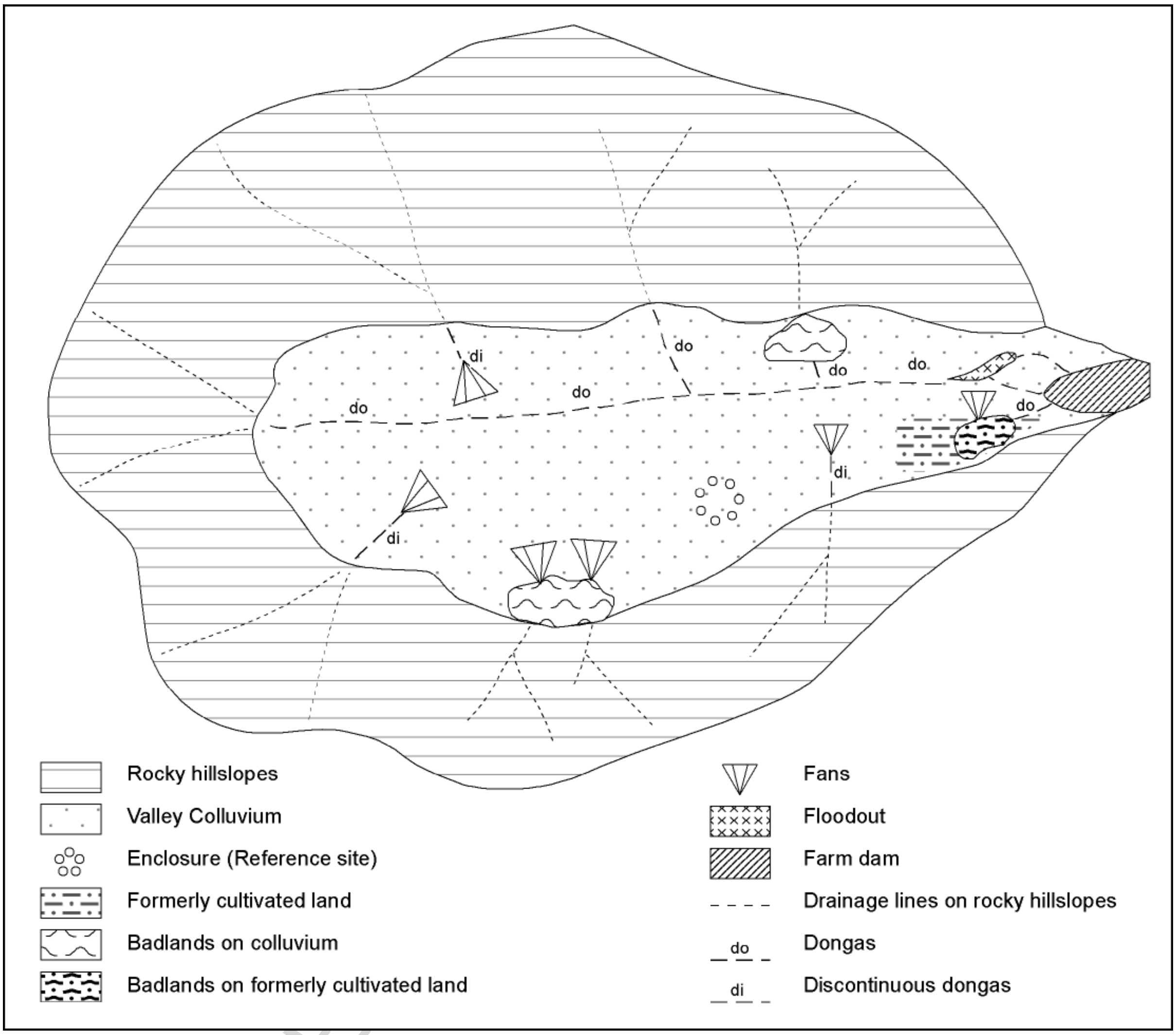

di
do
do
do
do
do.
do
di
di
Rocky hillslopes
Valley Colluvium
Enclosure (Reference site)
Formerly cultivated land
Badlands on colluvium
Badlands on formerly cultivated land
Fans
Floodout
Farm dam
Drainage lines on rocky hillslopes
Dongas
Discontinuous dongas

Fig. 9

Captions for figures and tables

Figure 1a. The location of the Sneeuberg uplands (adapted from Clark et al., 2009)

Figure 1b. Studied catchments and rain gauges in the Sneeuberg region (note Kreigersbaaken, Lucernevale, Compassberg and Aandrus gauges lie within the Compassberg Catchments Square)

Figure 2. Badland near Lucernvale farm

Figure 3. Severely degraded and less-degraded areas looking northwards to the Good Hope Dam (Dam 37)

Figure 4. Location of badlands and erosion pin sites in the Compassberg farm area

Figure 5. A schematic cross-section illustrating the topographic categories of Table 3

Figure 6a. Cultivated land in the Good Hope catchment 1945

Figure 6b. Cultivated land in the Good Hope catchment 1959

Figure 6c. Cultivated land in the Good Hope catchment 1980

Figure 7a. Changes in a low frequency magnetic susceptibility (X_{lf})

Figure 7b. The diameter of the 90th percentile particle size (D50; µm) in the sediments of Good Hope dam (see Foster et al., 2012)

Figure 8. Long term trends in the S ratio and loss on ignition (LOI) in the sediments of Cranemere dam plotted against the Pb-210 ‘crs’ model chronology extrapolated to the date of dam construction (see Foster et al., 2012)

Figure 9. Conceptual model of sediment stores and connectivity in a typical Karoo catchment

Table 1: Characteristics of the small catchments

Table 2. Erosion pin measurement details for ten sites (2001-2015) (updated from Table III in Boardman et al., 2015)

Table 3. Average net erosion (i.e. the difference between erosion and accumulation) in mm year-1 in five topographic categories at ten erosion pin sites. (See Table 2 for the period of measurement at each site. The topographic categories (see Figure 6) are a: interfluve, b: very steep or vertical channel side wall, c: channel floor, d: footslope, e: interfluve between channels)

Table 4. Minimum and post-1970 average sediment yields in the four Compassberg catchments

Table 5. Reference and dam sediment core ^{137}Cs inventories decay corrected to 2016 (Units are mBq cm^{-2})

Compassberg Dam Number	Dam 7	Dam 10	Dam 37	Dam 53	Dam 94		
Dam Name			Good Hope		Hartebeestefontein	Ganora	Cranemere
Catchment topography							
Catchment area (ha)	630	148	3058	244	852/813*	258	5751
Maximum altitude	2502	2113	2502	2092	2121	1741	1507
Maximum basin relief (m)	662	253	825	332	496	313	754
Percentage dolerite*	51	9	19	3	85	4	5
Percentage sedimentary	49	91	81	97	15	96	95
Reservoir metrics							
Reservoir dam construction date	~1935	~1935~1935	~1958	~1930's	~1914	1910	1843
Breach Date	2000	No	2010	1974	Probably 1974	No	No
Repair Date	No	No	2013	No	1976/7	No	No
Reservoir area (ha)	3.37	1.52	10.63	1.02	5.36/4.04**	5.23	30.22
Catchment to reservoir area ratio	187:1	98:1	288:1	239:1	159:1 / 196:1**	53:1	190:1
Erosion features							
Badlands	No	No	Yes	Yes	No	Yes	Limited
Gullies	Yes	Yes	Yes	Yes	Yes	Yes	Discontinuous
Fans and hillslope storage areas	Minor	Minor	Yes	No	No	Yes	Yes
Land use							
Grazing	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cultivation	Yes	No	Yes	No	No	No	Limited
Sampling year	2003	2003	2013	2013	2008	2006	2007

* Excludes Areas of Mapped Dolerite Dykes

** Dam and catchment area reduced after breach repaired as new dam wall was built over the existing dam sediments and excluded a small northern tributary.

Pre and post- new dam catchment areas are given as (pre/post) in Catchment Area, Reservoir Area and Catchment to reservoir area ratio

Site name	Measure-ment period (years)	N measure-ment intervals	Erosion pin measurements				
			N total	% missing	% showing erosion	% showing accumulation	% n chang
Good Hope 1	15.05	21	525	3	53	32	11
Good Hope 2	15.05	21	525	6	56	33	6
Compassberg 1	15.04	19	475	9	58	26	7
Compassberg 2	15.04	19	475	13	58	25	5
Oppermanskraal 1	14.31	18	450	8	60	23	9
Oppermanskraal 2	14.11	17	425	9	61	20	10
Low Upper Oppermanskraal	14.11	17	425	5	56	30	9
Up Upper Oppermanskraal	14.11	17	425	1	60	33	6
Lower Lucernvale	14.11	17	425	7	66	20	7
Upper Lucernvale	14.11	17	425	5	71	19	5
AVERAGES							

Table 2. Measurement details for the ten erosion pin sites, and average rates of erosion, accumulation, and net erosion

Site	Topographic category (see caption)				
	a	b	c	d	e
Good Hope 1	1.3	0.0	1.0	1.3	0.0
Good Hope 2	0.7	1.2	-0.2	2.2	0.1
Compassberg 1	2.5	0.6	0.2	0.3	0.5
Compassberg 2	3.0	1.1	1.3	1.4	1.3
Oppermanskraal 1	1.7	3.6	-0.3	0.8	0.9
Oppermanskraal 2	2.3	0.5	0.2	1.6	0.4
Low Upper Oppermanskraal	1.8	0.3	-0.4	1.3	0.0
Up Upper Oppermanskraal	1.4	0.2	-1.0	1.5	0.3
Lower Lucernvale	1.3	0.5	1.6	3.5	0.0
Upper Lucernvale	2.6	2.6	0.1	2.9	0.0
AVERAGE	**1.9**	**1.0**	**0.2**	**1.7**	**0.3**

Table 4 **Minimum and post-1970 average sediment yields in the four Compassberg catchments**

Location	**Period**	**Minimum Sediment Yield(t km^{-2} yr^{-1})**	**Period**	**Sediment yield (t km^{-2} yr^{-1})**
Ganora	1910-1922	1.7	1970–2007	1096
Dam 10	1935-1941	5.8	1970–2003	445
Dam 7	1935-1941	1.7	1970–2000	153
Cranemere	1843-1888	4.2	1970–2007	175

Table 5 **Reference and dam sediment core ^{137}Cs inventories {decay corrected to 2016 (mBq cm^{-2})}**

Compassberg Area	
Reference Inventory (2 sites)	41 +/- 8
Dam 7	732 +/- 122 (Breached 2000)
Dam 10	384 +/- 70
Dam 53	190 +/- 44 (Breached 1974)
Dam 37	1348 +/- 184
Ganora	184 +/- 37
Dam 94	522 +/- 73
Plains of Camdeboo	
Reference Inventory (2 sites)	35 +/- 6
Cranemere	212 +/-28

Table 6. Modelled sediment yields for nearby quaternary catchments (Midgely et al.,1994)

quaternary Catchment	Yield ($x\ 10^3$ t yr^{-1})	Area (km^2)	Specific Yield (t km^{-2} yr^{-1})
N12A	136	739	184
N12B	148	801	185
N12C	121	657	184
N11A	120	701	171
N11B	143	775	185