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Development of badlands and gullies in the Sneeuberg, Great Karoo, South Africa

J. Boardman[a,*], A.J. Parsons[b], R. Holland[c], P.J. Holmes[c], R. Washington[d]

[a] Environmental Change Institute, University of Oxford, 5 South Parks Road, Oxford 0X1 3UB, UK
[b] Department of Geography, University of Leicester, University Road, Leicester LE1 7RH, UK
[c] Department of Environmental and Geographical Science, University of Cape Town, Rondebosch 7701, South Africa
[d] School of Geography and the Environment, University of Oxford, Mansfield Road, Oxford OX1 3TB, UK

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Abstract

The study aims to examine the origin and development of land degradation with particular emphasis on badland and gully systems in the Sneeuberg uplands of the Great Karoo. This is an area of semiarid extensive stock farming where land degradation in the form of rill and gully erosion has accompanied the replacement of grassland by shrub vegetation. Species diversity has declined and ground cover has been reduced, leading to a positive feedback loop which exacerbates the degradation. Many foot slopes developed in shales, clays and colluvium have extensive, incipient badland development with closely spaced gullying up to 1.5 m deep. In valley-bottom and valley-side depression locations gullies up to 8 m deep have developed, usually cut to bedrock through valley fills of mainly Holocene colluvium. Both badlands and gullies appear to have developed since European settlement and to be part of the same hydrological system with extensive areas of bare ground (badlands) feeding water to incising gullies. Experiments using simulated rainfall throw some light on current processes. Badland areas are active under high-frequency, low-magnitude rainfall events. Major gullies are likely to be the result of occasional, high-magnitude events, but these have not been observed. Overgrazing in the past is the most likely cause of the degradation.

Keywords: Land degradation; Badlands; Gullies; Karoo; Soil erosion; Rainfall simulation

* Corresponding author.
E-mail address: John.Boardman@eci.oxford.ac.uk (J. Boardman).

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1. Introduction

1.1. Aims and methodology

Several studies have examined the impact of climate change and/or overgrazing on semiarid landscapes in South Africa. These have largely been confined to the issue of vegetation change or 'desertification' (Bond et al., 1994; Hoffman, 1995; Hoffman and Cowling, 1990; Hoffman et al., 1995, 1999a); the effects on the physical landscape have been of less interest. A recent general survey of degradation notes the need to redress this balance by giving more attention to soil and water issues (Hoffman et al., 1999b).

This study aims to examine the origin and development of a degraded landscape in the eastern Karoo. It focuses on extensively rilled and gullied areas. Current processes are examined by means of rainfall simulation experiments on experimental plots; this is a new approach in this region. Some insight into the development of the landscape is provided by accounts of early travellers; the relations of walls, fences and dams to geomorphological features; and maps based on aerial photographs.

1.2. Physical setting

The Karoo comprises a vast, semiarid region covering some 30% of the land surface of South Africa. It is situated approximately between latitudes 28° and 33° south, and to the west of the 500-mm isohyet. The Karoo is a dissected landscape of plains and flat topped hills, dominated by east–west orientated mountain ranges. The Sneeuberg Mountain Range is one such range, forming one of the most prominent ranges of the Great Escarpment. Kompasberg (2502 m) is, with the exception of the summit of the Cape Drakensberg, the highest peak in the Eastern Cape Escarpment. The study locality is situated to the north of Kompasberg. It comprises the upper catchment and headwaters of the Klein Seekoei River, a tributary of the Seekoei River, which in turn feeds the Orange River (Fig. 1). First- and second-order headwater valleys have been largely infilled with colluvially and fluvially derived sediments to maximum depths of ~ 8 m. Incision of these sediments has resulted in the formation of a number of badlands and gullies which are the focus of research reported here.

1.3. Geology, geomorphology and soils

The high-lying relief in the study locality comprises Triassic Katberg Formation sandstone and mudstone of the upper Permian to Triassic Karoo Supergroup, capped by Jurassic dolerites. Numerous dolerite intrusions occur, with corresponding localised metamorphosis of the adjacent sediments. The prominent Kompasberg Peak is a dolerite pluton, while dolerite tors are common in the headwater valley of the Klein Seekoei River. They comprise deeply weathered corestones in a matrix of red ferruginous sand. Hillslopes display horizontally bedded sandstone and shale. The resistant sandstone bands stand out prominently, resulting in structurally controlled slopes dominating the landscape within the study locality. The valley floors comprise less resistant Balfour Formation mudstones, shales and sandstones covered by a veneer of unconsolidated Quaternary sediment. A

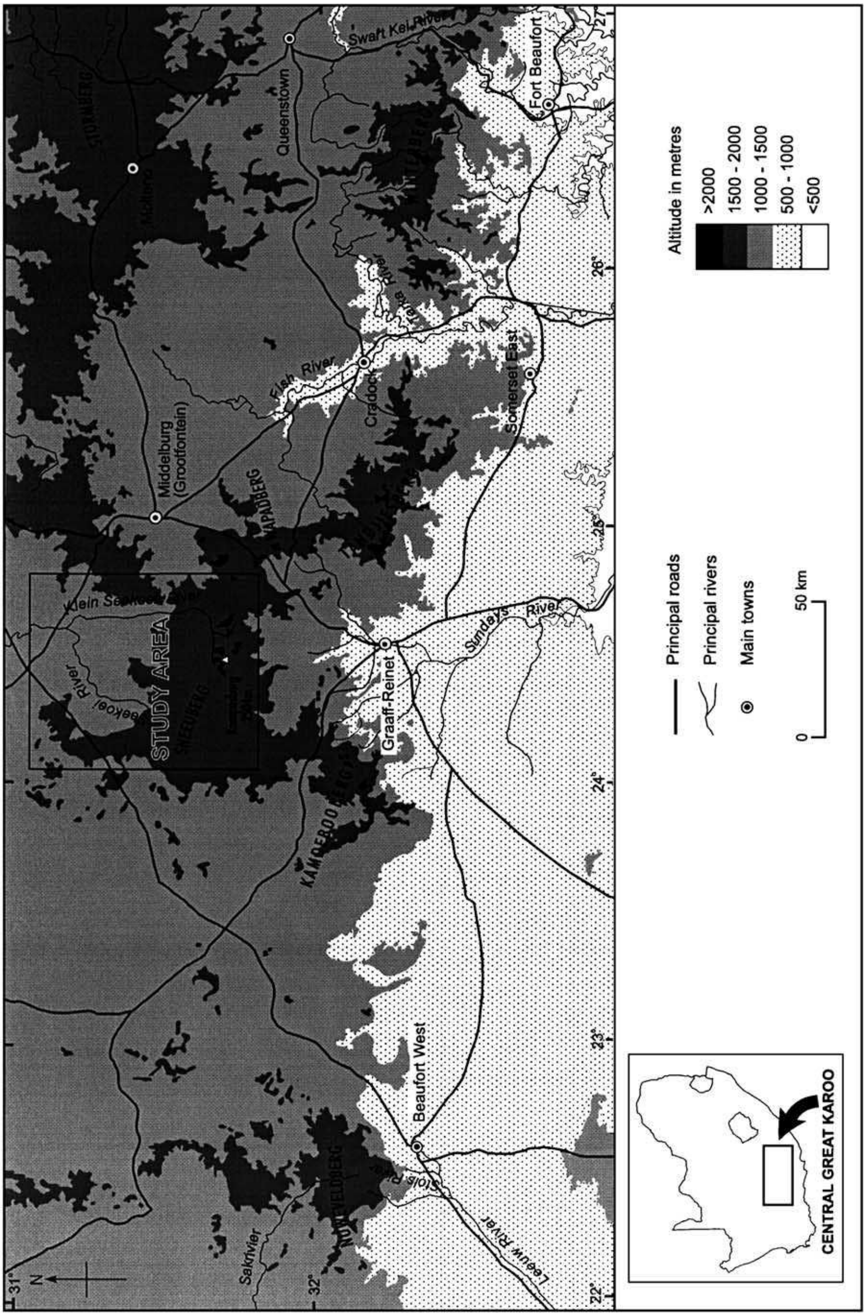

Fig. 1. Location of the study area.

notable feature of the soils within the upper catchment of the Klein Seekoei River valley is the large-scale absence of a modern A horizon (Holmes, 1998). Near valley-side slopes, there is often a surface lag of sandstone or dolerite stones overlying fine-grained colluvium.

1.4. Climate

The Sneeuberg Mountains fall within the eastern region of the Warm Temperate Zone (Sugden, 1989). According to Schultz (1980), the area receives on average 346 mm of rain annually. Rainfall follows an annual cycle with a distinct peak in late summer (March) (Sugden, 1989). Convectional thunderstorms are common in summer, although an average of less than two days report rainfall of greater than 10 mm in the peak rainfall month. Snowfalls, associated with the west to east passage of cold fronts, occur in the upper mountainous areas and valley headwaters during winter. A long-term rainfall record exists for Graaff Reinet 50 km from the study area. Fig. 2 shows the number of daily rainfall totals greater than 10 mm, this being an approximate threshold at which runoff commenced on badland areas (see below). Rainfall records are available for Compassberg farm (Fig. 3, altitude 1720 m) for 1988–1999. They show a higher mean annual rainfall (517 mm) for this high-altitude station. This data set includes the exceptionally wet year of 1988 (Table 1). Rainfall records from 1959 to 1993 for Aandrus (Fig. 3, altitude 1660 m) show a mean of 433 mm and a coefficient of variation of 39.4%.

There is no evidence that rainfall in the study region has either increased or decreased during the late 19th and 20th centuries. Instead, the most striking characteristic of the long-term rainfall record is the marked degree of multidecadal variability with highly significant

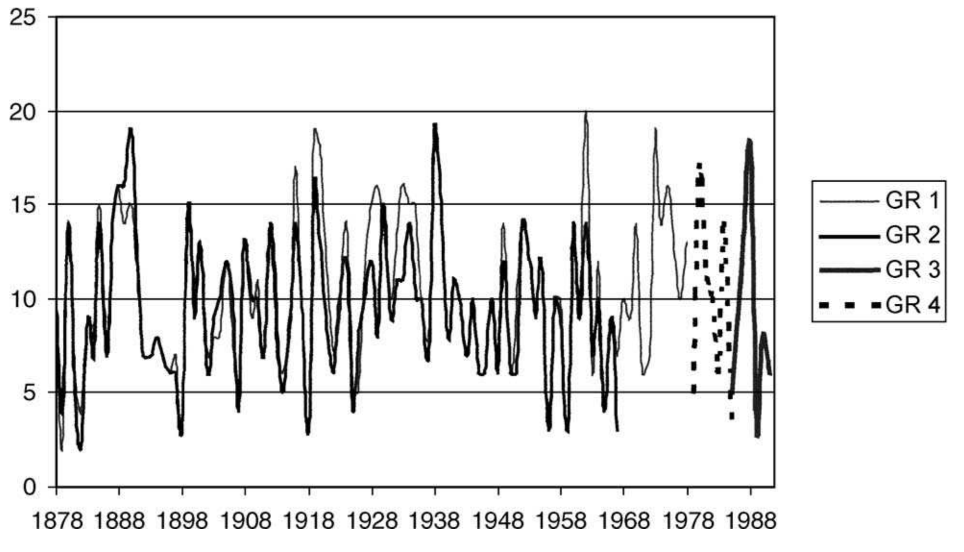

Fig. 2. Annual number of rainy days with rainfall >10 mm at Graaff Reinet. Four partly overlapping rainfall stations from Graaff Reinet are shown. All rainfall stations are located at 24°15′S, 24°32′E. The altitudes are shown below: GR 1, 741 m; GR 2, 751 m; GR 3, 753 m; GR 4, 752 m.

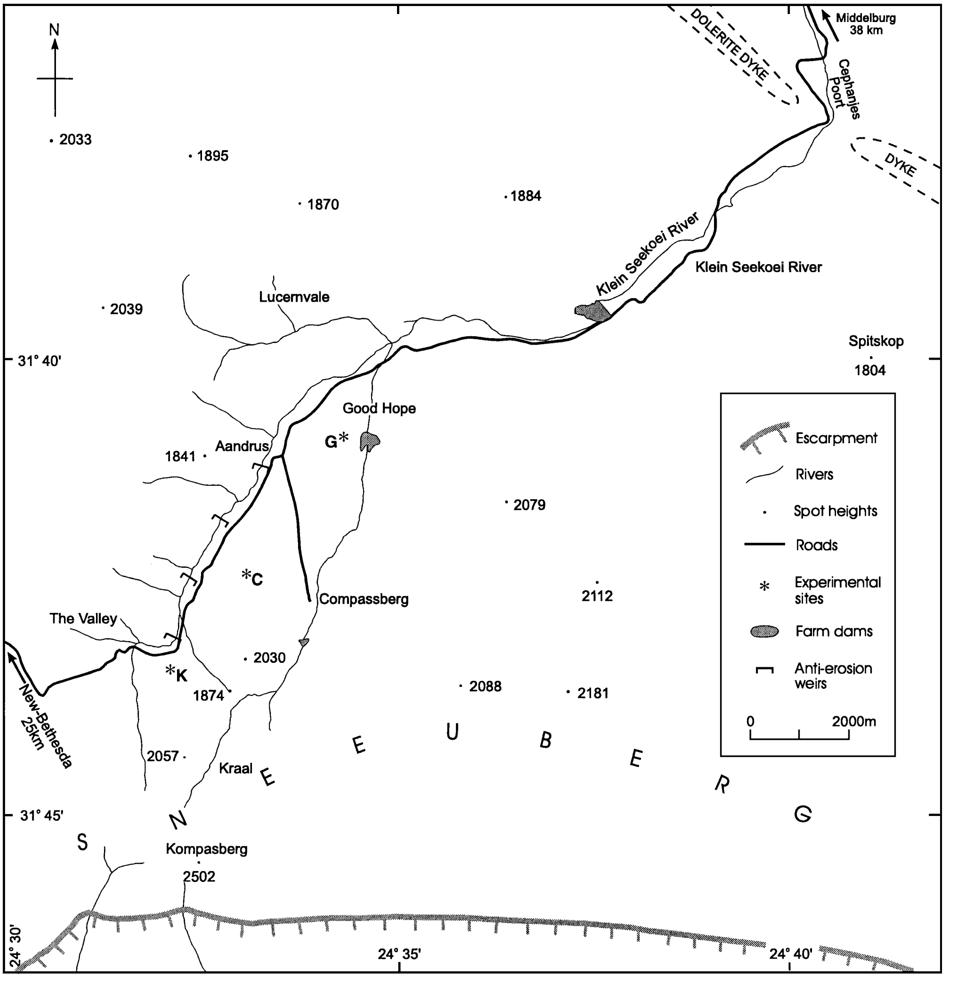

Fig. 3. The study area. Experimental sites: G, Good Hope; C, Compassberg; K, Klipkoppie.

periodicities between 16 and 20 years so that near decadal alternating wet and dry spells have occurred. This is a well-known feature of southern African rainfall (Tyson, 1986; Folland et al., 1998).

Both the diurnal and seasonal temperatures show large fluctuations, with summer maxima of ~ 30 °C and winter minima of below − 10 °C being recorded (Schultz, 1980).

1.5. Vegetation

The vegetation of the Sneeuberg Range comprises Karroid scrub on the plains and sourveld in mountain reaches (Sugden, 1989). Low and Rebelo (1996) classified this as

Table 1
Rainfall at Compassberg, Klein Seekoei River valley, Great Karoo (1988–1999)

Year	Total (mm)	Raindays (no.)	>10 mm/day (no.)	>50 mm/day (no.)
1988	1249	60	37	7
1989	668	50	23	2
1990	359	30	12	0
1991	592	41	20	2
1992	281	20	12	0
1993	384	39	13	0
1994	365	44	16	0
1995	518	53	19	0
1996	587	47	24	1
1997	442	46	22	0
1998	456	37	17	1
1999	308	27	16	0
Mean	517			

Southeastern Mountain Grassveld of the Grassland Biome, and Eastern Mixed Nama Karoo of the Nama Karoo Biome, respectively. This classification is synonymous with Acocks' (1988) classification of Karroid *Merxmuellera* Mountain veld in the higher lying areas, and False Upper Karoo in the valleys. The extensive sheetwash on the foot slopes in the study locality has stripped much of the topsoil, resulting in the absence of a modern A horizon, with the vegetation taking root in the B horizon. Where extensive sheetwash has occurred, *Lycium cinereum* and *Eriocephalus spinescens* frequently dominate. Opportunistic *Asteraceae* such as *Pentzia incana*, as well as short-lived grasses such as *Aristida congesta*, are also typical pioneers on degraded surfaces.

1.6. Land use

The primary land use is large and small stock grazing. The sourveld grass of the upper slopes is utilised for grazing cattle, while the Karroid vegetation of the footslopes is more suited to small stock. In such places, the valley floors have been cultivated to produce fodder crops, as well as cash crops such as wheat and potatoes, on a small scale. Fig. 4 is a composite of formerly cultivated areas. Inspection of aerial photographs for 1945, 1959, 1966 and 1980 show that approximately 10.4% of the land within the mapped area has been cultivated. At the present time, there is little cultivated land. A veld management strategy of intensive, nonrotational grazing has been implemented on Compassberg farm over the past few decades. The strategy aims for ecological rehabilitation in terms of a climax vegetation which includes grass species which have been severely impacted as a result of past veld management practices (Hoffman et al., 1999a).

Stock figures in the Karoo which peak in the 1920s and early 1930s show a wide variation across the region (Fig. 5 from Hoffman et al., 1999a). In the Middelburg Magisterial District, of which the study area forms a part, stock densities again peak around 1930 but the period 1865–1961 is characterized by densities two to three times

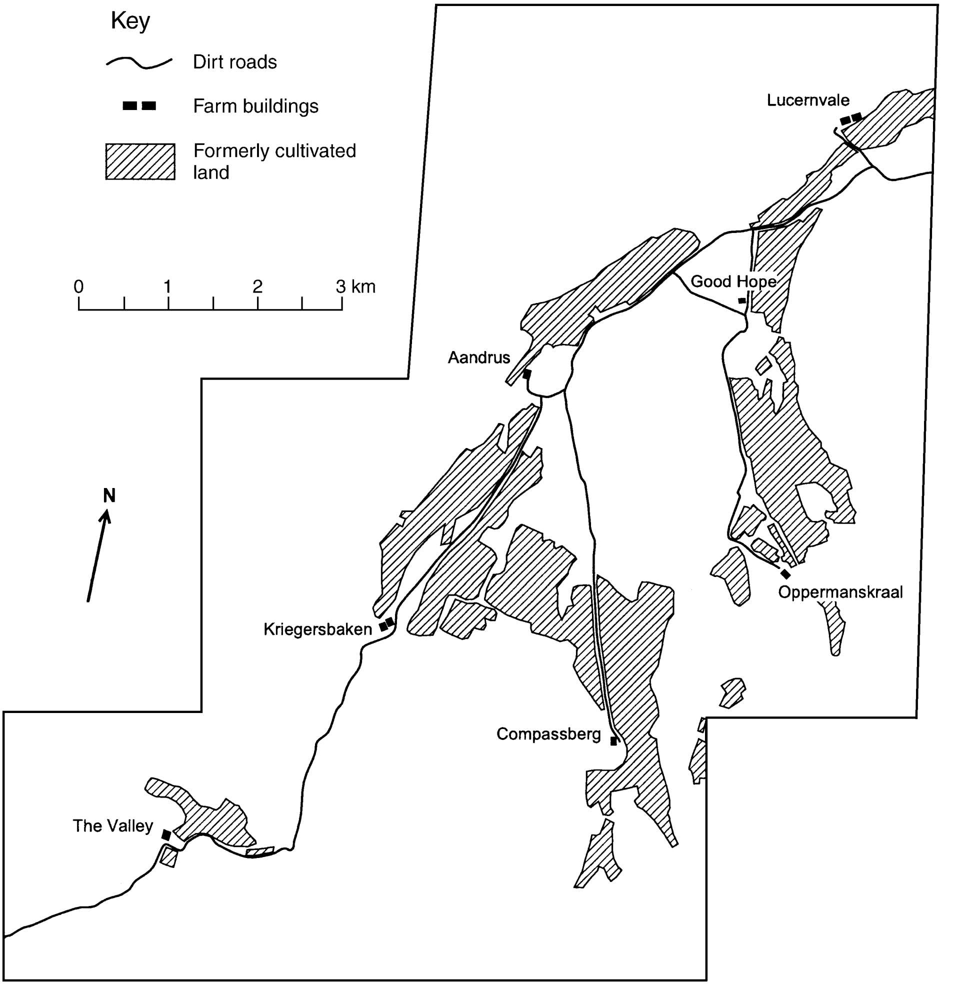

Fig. 4. Formerly cultivated land: composite map based on aerial photographs for 1945, 1959, 1966 and 1980.

1995 levels (Table 2), and also persistently higher than average figures for the Karoo (Fig. 5).

2. Land degradation

We do not attempt to assess vegetation degradation but have confined our study to physical degradation. Where relevant, we refer to vegetation cover and type at the present time. However, the assumption is made that vegetation degradation is widespread in the study area. The vegetation is dominated by karroid shrubs and grasses are rare. A site for experiments on grass was difficult to locate.

Table 2
Stock densities for Middelburg Magisterial District (Dr. T. Hoffman, unpublished)

Year	Density LSU[a]/km^2
1865	10.5
1875	10.4
1889	9.7
1904	10.6
1911	12.8
1918	13.6
1923	13.7
1928	11.9
1930	14.5
1934	10.6
1939	10.5
1946	10.7
1951	12.5
1956	10.5
1961	10.9
1967	8.6
1971	6.8
1976	8.4
1981	8.9
1983	9.4
1995	4.6

[a] LSU (large stock units) comprise mainly sheep.

2.1. Badlands and gullies: typology, extent and changes

Badlands occur extensively on valley-side footslopes with gradients of generally less than 10°. They consist of areas of very-high-density gully systems often separated by short steep unvegetated slopes. Interfluves may be flat and relatively nondegraded but in many areas, they are sloping and have lost all vegetation cover. The scale of incision in the badlands is 1–2 m and they are more appropriately referred to as ‘incipient badlands’; for conciseness, the term ‘badland’ is used hereafter. Incision is into colluvial sediments and weathered shale bedrock. Badland gullies frequently erode down to bedrock.

Landscape degradation within the area was examined on aerial photographs from 1945, 1959, 1966 and 1980. Unfortunately, different scales, quality and season of photography makes comparison difficult. More recent photography is at a small scale. Most reliable comparisons were between 1945 and 1980 photographs. Classification of degradation uses the SARCCUS (1981) system. Most badland areas are recorded as having combinations of sheet erosion, rilling and gullying (Table 3). The situation in 1945 is shown in Fig. 6 and that of 1980 in Fig. 7.

Analysis of change in the extent of degradation shows marked contrasts between areas:

- At Lucernvale, there is a 36% decrease in the degraded area from 1945 to 1980; this may be related to the construction of an antierosion bank.

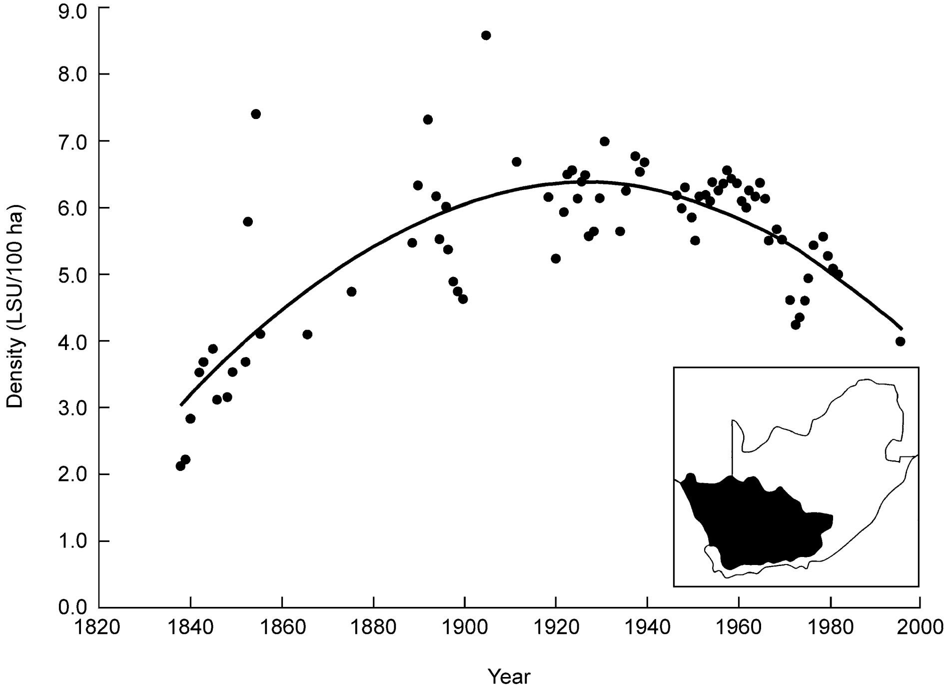

Fig. 5. The density (large stock units per 100 ha) of cattle, sheep and goats from 1838 to 1995 for the core region of the Karoo (see inset) (from Hoffman et al., 1999a).

- At Good Hope, there is a 10% increase.
- At Kriegersbaken, there is a 9% decrease.

With reference to the whole area of Fig. 6, 25% is classified as moderately to severely degraded in 1945, and the figure is the same in 1980.

At Compassberg, the area of land cultivated is similar in 1945 and 1980 (19% and 23%) but these figures disguise high intermediate values: 57% in 1959 and 52% in 1966. Of land classified as previously cultivated (Fig. 4), 22% was degraded in 1945. Some areas that were degraded by rilling and sheetwash in 1945 were being cultivated in 1959 and 1966 (e.g. at Kriegersbaken). However, some areas of degradation on cultivated land appear to be the result of runoff from upslope badlands. Some former cultivated land shows no sign of degradation.

2.2. Historical evidence for land degradation

It is not possible to provide a precise date for the commencement of gully erosion within the study area. The historical evidence for land degradation in the Karoo is discussed elsewhere (Holmes, in preparation; Holmes et al., in preparation), and is briefly reviewed here. Prior to European colonisation, there was no written account of the area.

Table 3
Types and classes of erosion caused by water (SARCCUS, 1981)

Type of erosion	Class of erosion	Symbol	Description and remarks
Sheet (surface)—uniform removal of surface soil	none apparent	S1	No visible signs of erosion on air photo. Level of management appears to be high.
	slight	S2	Areas of light tone observed on air photos. Erosion deduced from poor cover, sediment deposits and plant pedestals.
	moderate	S3	Eroded areas obvious on air photos. Plant cover very poor and sediment deposits extensive. Associated with small rills.
	severe	S4	Sheet erosion of such severity always associated with rills and gullies. Much or all of the A-horizon has been removed.
	very severe	S5	
Rill—removal of soil in small channels or rivulets, mainly on arable land	none apparent	R1	As for sheet erosion.
	slight	R2	Small, shallow (mainly < 0.1 m) rills present but not readily observed on air photos.
	moderate	R3	Rills of considerable depth (mainly 0.1–0.3 m) and intensity usually observed on air photos.
	severe	R4	An abundance of deep rills (less than 0.5 m) easily observed on air photos. Subsoil may be exposed.
	very severe	R5	Large well-defined rills but may be crossed by farm machinery. Associated with gully erosion.
Gully (donga)—removal of soil in large channels or gullies by concentrated runoff from large catchment areas	none apparent	G1	As for sheet erosion.
	slight	G2	Clearly observed on air photos and usually up to 1 m deep. Cannot be crossed by farm machinery.
	moderate	G3	Intricate pattern of deep gullies (mainly 1–3 m) exposing entire soil profile in places. Many "islands" of topsoil remain.
	severe	G4	Landscape dissected and truncated by large (3–5 m deep) gullies; 25–50% of area unproductive.
	very severe	G5	Large and deep (often >5 m) gullies have totally denuded over 50% of the area.

The lack of communication between the original Bushman inhabitants and the European settlers also precludes any verbal record. Europeans began to move into the semiarid central portion of South Africa during the late 18th century (Neville, 1996). The upper reaches of the Seekoei River formed a strategically important part of the Cape colonial frontier by the end of the 18th century (Sampson, 1995). Following the total subjugation of the local Bushmen inhabitants, European settlement and the number of farms in the Seekoei River valley increased rapidly during the first two decades of the 19th century (Neville et al., 1994).

Prior to 1892, some 25 documented accounts of travellers through the valley exist (Neville et al., 1994; Neville, 1996). Although there are numerous references to the Seekoei River, as well as to "vleis", pools and what is presumably riverine vegetation, no specific mention is made of gullies or any channel form which might be interpreted as alluding to valley floor erosion. Neville (1996) observes that the river and its tributaries

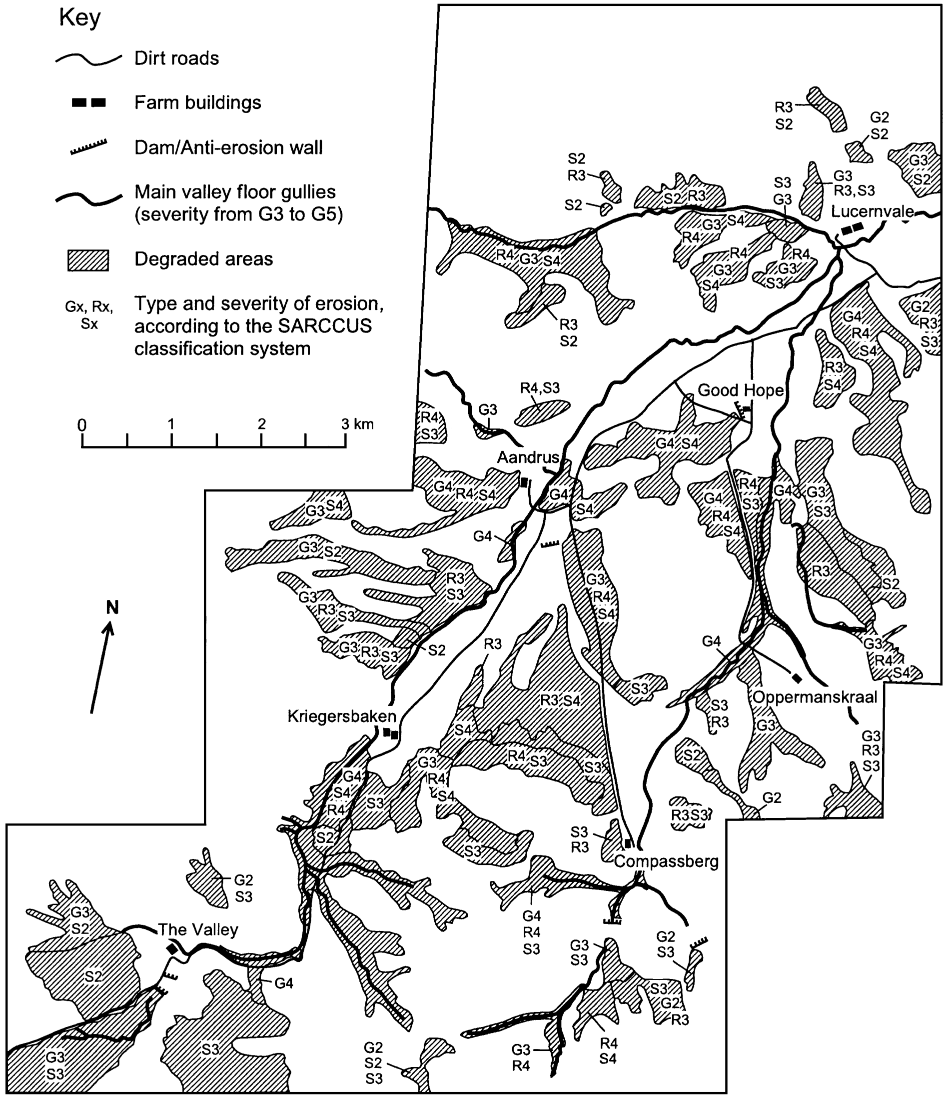

Fig. 6. Degraded areas in 1945.

were seasonal. During dry periods, the main channel was restricted to a "long chain of pools, commonly referred to as *zeekoegaten* (or hippopotamus wallows)" (Neville, 1996, p. 31). Neville et al. (1994) have reconstructed the 19th century wagon track system along the Seekoei River. This route to the interior became heavily utilised after the opening up of the Kimberley diamond fields in the 1870s. They point out that the growth of this traffic network was dictated by the occurrence of water and grazing. It can be speculated that the main wagon thoroughfares, which closely followed the north–south drainage lines, served

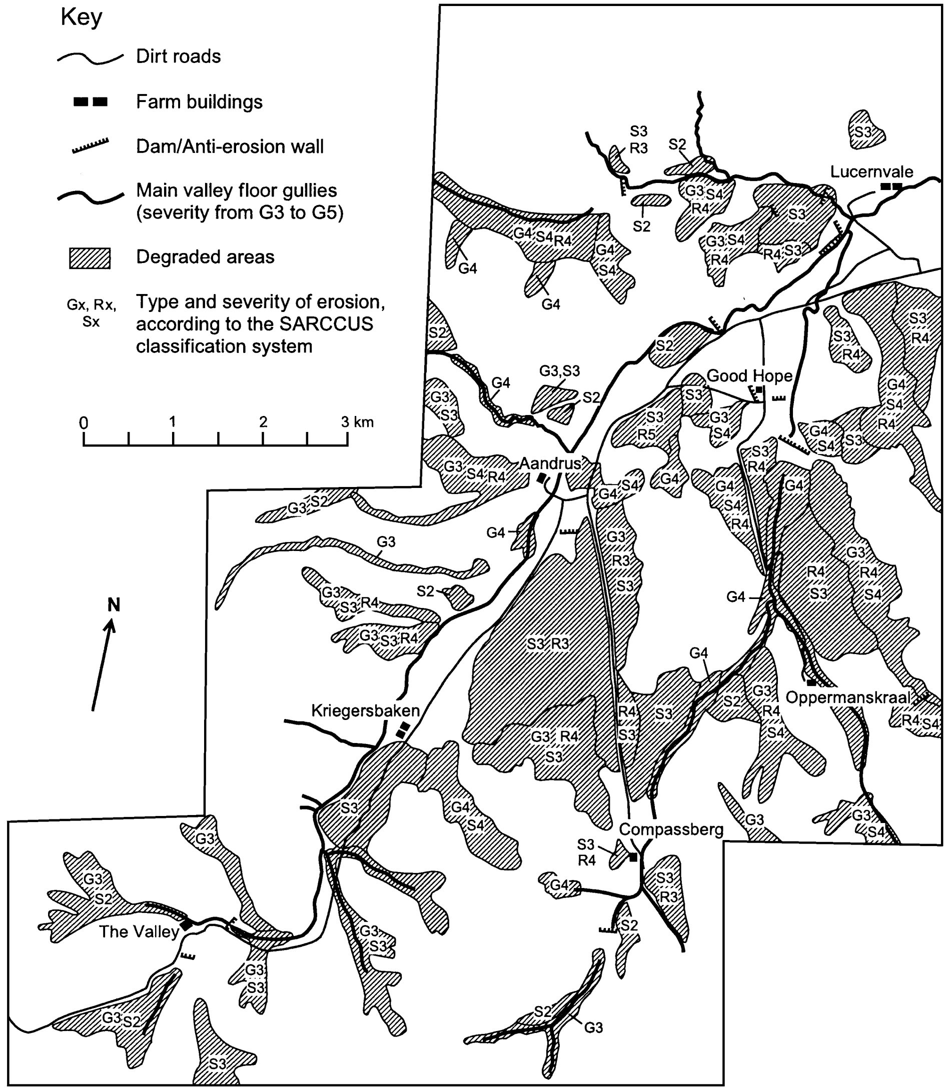

Fig. 7. Degraded areas in 1980.

as a trigger to gully erosion. Large numbers of stock were grazed alongside pools to drink. The comparative lushness of vegetation in the proximity of such drainage lines might also have resulted in overgrazing, trampling and soil compaction with a corresponding decrease in infiltration. The increased runoff on vulnerable surfaces would have exacerbated such erosion. Neville et al. (1994) conclude that the impact of a developing road network was instrumental in causing large-scale degradation of the natural vegetation which, in turn, facilitated the development of gullies. However, no dates are available for the onset of this erosion.

2.3. Evidence for recent degradation

Stock control walls, probably built by Trekboers in the early 19th century, show evidence of build-up of colluvial sediments behind them (e.g. at Kraal: Fig. 3). At other sites in the Good Hope valley, remnants of walls traverse badland areas; it seems unlikely that walls to contain grazing stock were constructed across existing badland areas.

At a gully site 2 km west of Lucernvale (Fig. 3), a fence with hanging posts traverses the gully. It seems unlikely that posts would have been attached to the fence in the absence of a ground surface and no fences existed prior to 1937 (Neil Sheard, personal communication). The gully is not visible as an incised feature on the 1945 aerial photograph. Incision starts to be apparent on the 1966 aerial photograph and by 1980, a well-developed gully can be seen. Field measurements estimate a volume of sediment lost in the last 40 years of approximately 11,500 m^3 from a catchment that is about 1 km^2.

Four stone-built dams were constructed in the 1950s on the Klein Seekoei River between Aandrus and The Valley (Fig. 3) as erosion control dams. These are now completely full of sediment to a depth of about 6 m at the dam wall. There are also many earth dams built by farmers at different dates, which have retained eroded sediment.

3. Hydrology and sediment yield of the badlands

3.1. Rainfall simulation experiments

To investigate the effects of the vegetation change on runoff and erosion, we conducted rainfall simulation experiments on twenty-two 0.5×1.0-m runoff plots at three locations within the study area, hereafter referred to as Klipkoppie, Good Hope and Compassberg. The simulator used was an Amsterdam drip-type simulator (Bowyer-Bower and Burt, 1989). The average intensity of the simulated rainfall in the experiments was 25.2 mm/h, the median drop size was 0.67 mm and the fall height was 140 cm, giving a kinetic energy of the simulated rainfall of 0.089 J m^{-2} s^{-1}. Rainfall intensities for individual experiments ranged from 15.6 to 35.5 mm/h. With the exceptions of plots 10, 11 and 20, which had durations of 40, 45 and 60 min, respectively, all simulations ran for 30 min. As soon as runoff began, it was collected in 1-min contiguous samples from the outlet of the plot. After each experiment, the volume of water in each sample was determined by transferring it to a measuring cylinder. The total runoff from each plot was subsequently collected into a large bottle, allowed to settle, decanted and oven dried at 105 °C. The weight of the remaining sediment was then recorded. Prior to each experiment, a soil sample was taken from a depth of 5 cm adjacent to the plot for subsequent determination of antecedent soil moisture. After each experiment, the percentages of the plot covered by vegetation, stones equal to or larger than 5 mm diameter, stones $2 \leq 5$ mm diameter and particles smaller than 2 mm were determined by grid sampling of 100 points over the plot. In addition, the gradient of the plot was measured.

The three locations of the simulation experiments were selected as representative of the land cover types within the study area (Fig. 3 and Table 4). The Klipkoppie site is typical

Table 4
Surface cover characteristics of runoff plots

	Vegetation (%)	Stones ≥ 5 mm	Stones 2 to < 5 mm	Particles < 2 mm
Klipkoppie	65.3	23.5	0.0	11.2
Good Hope: shrubland	30.6	39.8	8.1	21.4
Good Hope: degraded area	7.5	25.8	14.0	52.7

of the grass-covered hillslopes that are believed to have been formerly more extensive over the Karoo. The Good Hope site is representative of the shrubland vegetation that is thought to have replaced the grassland over many hillslopes and footslopes and of the bare surfaces that have developed on footslopes in many locations within the study area. Finally, the Compassberg site is in a valley floor flatland that has previously been cultivated, but is now abandoned.

3.2. Hydrology

Table 5 shows the correlations of the infiltration rate at the end of each experiment and the total infiltration with rainfall rate and the measured properties of the plots. As might be expected, there is a good deal of similarity in the two patterns of correlations. However, with the single exception of percentage cover of stones >5 mm, significant correlations with the final infiltration rate is always stronger. Therefore, further analysis will focus on the controls of the final infiltration rate.

Vegetation and large stones are positively correlated with the final infiltration rate. Poesen et al. (1990) demonstrated that rock fragments may either promote or inhibit infiltration depending on whether they are embedded within the soil surface or lying loose on top of it. At our field sites, they lie loose on the surface and, as Poesen et al. (1990) found, promote infiltration. Vegetation, likewise, has been observed to promote infiltration (e.g. Abrahams et al., in press), both because of the tendency for fine material to be present around the bases of plants, and for these sites to be preferential locations for burrowing animals and because vegetation reduces raindrop impact and, thereby, inhibits sealing of the soil surface. Greater percentage cover of fine materials denotes the absence of these

Table 5
Correlation of the final infiltration rate and total infiltration with measured properties of the runoff plots

	Final max observed infiltration (mm/h)	Total infiltration (mm)
Antecedent soil moisture	**0.54**	*0.43*
Percent fines	− **0.72**	− *0.48*
Percent vegetation	**0.60**	0.18
Percent stones >5 mm	0.22	*0.41*
2 to ≤ 5 mm	− **0.57**	− 0.19
Fines + < 5 mm	− **0.78**	− *0.46*
Vegetation + stones	**0.77**	*0.46*
Slope	0.08	0.13
Rainfall (mm/h)	**0.67**	*0.48*
	0.43	Correlation significant at 5% level
	0.54	Correlation significant at 1% level

influences, as well as the greater likelihood of soil sealing which inhibits infiltration. Of the correlations observed between the final infiltration rate and plot surface characteristics, that with the total percentage of the plot covered by material <5 mm is the strongest. Consequently, it is used in further analysis.

Despite a design intensity for the simulated rainfall of 25 mm h^{-1}, actual rainfall on individual plots varied substantially. As is to be expected from the analysis of Hawkins (1982), there is a positive relationship between the final infiltration rate and the rainfall rate.

Finally, we observe a positive relationship between the final infiltration rate and antecedent moisture. This result may appear surprising and contrary to what may be expected. However, it can be explained as an artefact of the sequence in which the experiments were undertaken. Prior to the experiments, there had been no rain for a week, but after experiments had been undertaken on the first five plots, 26 mm of rain fell over 2 days. The average antecedent moisture for these five plots was 5.7%, whereas that for plots undertaken subsequent to the rainfall was 9.45%. As it happened, the plots with the lowest infiltration were those studied prior to the rainfall event and at the end of the sequence. This order of working explains the positive relationship between antecedent moisture and infiltration. Inasmuch as we argue below that the vegetation change from grassland to shrubland leads to increased runoff, the sequence of our experiments is fortunate. If the sequence of our experiments introduces any bias in our results, it is contrary to the argument we seek to advance.

Using the three independent variables of percentage ground cover of fine particles, antecedent moisture and the rainfall rate, we performed a multiple regression with final infiltration rate as the dependent variable. Antecedent moisture failed to enter the equation at $p=0.95$, and the final equation is

$$I = 8.67 + 0.69R - 0.18F5 \qquad (1)$$

in which I is final infiltration rate (mm h^{-1}), $F5$ is percentage of plot surface covered by particles <5 mm and R is rainfall (mm h^{-1}), and which has an r^2 of 0.83. Of the independent variables, $F5$ enters the equation first and a simple regression of I on $F5$ has the form

$$I = 27.48 - 0.21F5 \qquad (2)$$

and has an r^2 of 0.58.

Using Eq. (1), a nominal value for rainfall of 25 mm h^{-1} and measures of the percentage of ground covered by particles <5 mm, it is possible to estimate the infiltration (and runoff) from the grassland and shrubland areas. We obtained the percentage of ground covered by vegetation, stones >5 mm, stones 2 to <5 mm and particles <2 mm in the grassland and shrubland communities by sampling every 0.5 m along 50-m transects. The Compassberg site was omitted from this survey (Table 4), as it does not represent a transition phase between natural vegetation and bare ground, but rather land which was intentionally ploughed for agriculture. Under rainfall at 25 mm h^{-1}, after 30-min rainfall, the infiltration rate on the grassland would be 23.9 mm h^{-1}, whereas in the shrubland it would be 20.6 mm h^{-1}. Conversely, runoff would be 1.1 and 4.4 mm h^{-1}, respectively. The importance of rainfall intensity as a factor influencing infiltration needs to be mentioned here. This result does not imply that rainfall would need to be in excess of 20 mm h^{-1} before runoff would occur on the shrubland. In fact, we observed runoff on the shrubland area during the rainfall event that occurred after the experiment on plot five, when our measure of peak intensity over a 30-min period was 10 mm h^{-1}.

Using the same equation and similar transect data from the degraded footslopes at the Good Hope site yields an estimated infiltration rate of 13.9 mm h^{-1} (runoff of 11.1 mm h^{-1}).

3.3. Sediment yield

Table 6 shows the correlations of the total amount of sediment contained in the runoff from each plot (expressed as grams m^{-2} min^{-1}) and the sediment concentration with rainfall rate and the measured properties of the plots. With the exception of rainfall rate, the stronger correlations are with total sediment production. A similar pattern in the influences of the surface properties of the plot to that observed for the runoff is evident. Fine particles lead to greater sediment production, whereas stones and vegetation are associated with lower sediment production. In addition to the correlations presented in Table 6, total sediment production is also correlated strongly ($r = 0.83$) with total runoff. Inasmuch as runoff itself is inversely related to infiltration (and, hence, positively related to runoff), this correlation is to be expected. Given the latter relationship, it is inappropriate to include both runoff and percentage of surface fines in a multiple regression to predict sediment loss. Accordingly, a simple regression of sediment load on percentage of the plot surface covered by particles smaller than 2 mm has been obtained, as follows

$$S = 0.003\%F2$$

in which S is sediment yield (g m^{-2} min^{-1}) and $F2$ is the percentage of the plot surface covered by particles finer than 2 mm. This equation has an r^2 of 0.54.

Table 6
Correlation of the total sediment yield from plots and sediment concentration, with rainfall rate and measured properties of the runoff plots

	Sediment yield (g/m^2/min)	Sediment concentration (g/l)
Antecedent soil moisture	− 0.38	0.06
Percent fines	**0.83**	0.32
Percent vegetation	− **0.56**	− **0.42**
Percent stones >5 mm	− 0.34	0.26
2 to ≤ 5 mm	0.38	0.02
Fines + <5 mm	**0.81**	0.27
Vegetation + stones	− **0.81**	− 0.27
Slope	− 0.18	0.04
Rainfall (mm/h)	− 0.14	− **0.41**
	0.83	Correlation significant at 1% level

Using the same transect data as before, estimates of sediment production from grassland, shrubland and the degraded sites are 0.034, 0.085 and 0.203 g m^{-2} min^{-1}, respectively.

3.4. Observational evidence

During the field visit in January 2000, one rainfall event occurred. On 15–16 of January, 26 mm fell at Compassberg. Maximum intensity was about 10 mm for 30 min. Depth of infiltration into the soil was of the order of 5–10 cm. There was a significant ponding on flat interfluves with some vegetation cover. Interrill and rill flow was occurring after as little as 10 mm of rainfall on bare interfluves with runoff flowing directly into badland gullies. There was little flow on higher, stone-covered and better-vegetated slopes, upslope of badland areas. Bedrock areas in channels generated initial flows. Major channels in and from badland areas carried shallow (< 10 cm) sediment-laden flows. These flows did not travel far along channel systems beyond badland areas: losses were by seepage into channel floors and, at least in the Good Hope area, neither sediment nor runoff from the badlands reached major valley floor gullies. Inspection of other major gully systems next day failed to find evidence of flow.

4. Discussion

The results of the experiments allow us to hypothesise on the geomorphic effects of vegetation change in the Sneeuberg area of the Karoo. On hillslopes with stony soils, a change of vegetation from grassland to shrubland leads to a reduction in the proportion of the surface area covered by vegetation and an increase in both areas covered by stones and fine particles. In consequence, there is an increase in runoff and erosion rate. However, whereas runoff increases four times, the erosion rate increases only 2.5 times. On the finer-textured footslope soils, runoff increases dramatically (tenfold) and the erosion rate increases sixfold. The results imply that the footslope areas which have less stony soils are more susceptible to degradation as a result of vegetation change and it is in these locations that increases in runoff and erosion rates are most significant. These areas coincide with the areas of badland development.

Badland systems are not connected to major gullies. Deposition of eroded sediments appears to occur in areas between the two geomorphic elements, i.e. downslope of the badlands. Little runoff reaches the major gullies by overland flow routes as a result of storms of < 26 mm/2 days. We surmise that this is not the case during more extreme events. The recent rainfall record includes 13 events of >50 mm/day in 12 years (Table 1).

The origin of the gullies is likely to relate to vegetation disturbance by the first European trekers and settlers who used the valley bottom as a routeway. However, the badlands and gullies appear to have been erosionally active since the construction of fences and dams in the area. Thus, active erosion of major gully systems postdates, in part at least, 1937 and continued into the 1960s. There is no evidence of present day erosion of major gullies but we cannot rule it out. Erosion of badlands continues at the present time.

For erosion to occur, disturbance of the vegetation is necessary. Rainfall simulation experiments indicate that a shift to a more shrubby vegetation increases runoff and erosion. Other authors have noted that there is little evidence of significant changes in rainfall in the Karoo during the last 100 years, but certainly there have been periods of drought which would affect vegetation. Hoffman et al. (1995) noted extended droughts in the years 1919–1931, 1944–1949 and 1962–1973. Of these periods, the drought years of the 1940s and 1960s show most clearly in the time series of raindays greater than 10 mm (Fig. 2). Since 1974, 'the region has experienced one of the highest rainfall periods on record with a number of very high rainfall years' (Hoffman et al., 1995, p.160), particularly in the 1970s.

Vegetation disturbance and assumed loss of grass species in the area are most likely the result of overgrazing exacerbated by periodic drought. Stock numbers peaked in the first half of the 20th century but remained at comparatively high levels for 100 years (Table 2; Fig. 5) and it seems reasonable to associate this with the observed phase of landscape degradation. This, however, must remain tentative until conclusive evidence is available. This hypothesis is similar to that of Patton and Schumm (1975), who describe the impact of introduction of cattle to a Colorado watershed in the 1880s: this instigated an increase in runoff from the slopes and incision of Douglas Creek into its flood plain.

Both badlands and major gully systems are frequently eroded through colluvial fills to bedrock. In the case of the badlands, incision is therefore, limited to 1–2 m, and in the case of valley-bottom gullies this control limits incision to about 8 m. The shale bedrock is not resistant and there are instances of local incision into the shale.

Anti-erosion measures seem to have been relatively effective. Dams are full of sediments and have at least inhibited further incision of major gullies in valley bottoms. Local decreases in badland area may be due to anti-erosion banks which have trapped sediments (e.g. at Lucernvale). Over the period 1945–1980, there appear to have been areas of badland expansion and areas of successful control and revegetation. The situation is clearly complex and there are dangers in comparing two years and thus, ignoring seasonal and annual patterns of change. However, rainfall events of moderate to high frequency give rise to considerable erosion on existing badlands.

It is tempting to try to relate areas of degradation to former cultivated land. At several valley bottom and footslope sites, there is probably a causal link with degradation beginning with the cessation of cultivation. But at other degraded sites, there is no evidence for former cultivation.

From a catchment-management perspective, an understanding of the mechanisms which control erosion in the Sneeuberg is important for two reasons. Firstly, there is the question of land degradation and reduced stock carrying capacity per se. Secondly, there is the important issue of downstream siltation of some of South Africa's main storage dams within the Orange River drainage basin, of which this region forms part.

5. Conclusion

It is unlikely that in this area, badlands and gullies are long-term features of the landscape. Both appear to have formed relatively recently and the badlands are actively eroding during low-magnitude, high-frequency rainfall events. There is no evidence for cut and fill sequences that would suggest a previous history of gullying. The details of the current evolution of the badlands, the change in areal extent, slope form, spatial patterns of sediment production and the fate of eroded sediment, require further study. Similarly, we can only speculate about conditions under which the major gullies were eroded. Hypotheses concerning the connection of runoff-producing badland areas and gully incision in the valley bottoms remain attractive, though tentative. There is, however, significant evidence for active gully development in the period 1937 to the 1960s. It seems likely that this is related to high stock numbers and disturbance of the vegetation in the first half of the 20th century.

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