Land degradation and sediment dynamics in the South African Karoo

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Abstract Land degradation has led to sedimentation in farm dams in the headwaters of the Seekoei River. Two small catchments (<10 km^2) with farm dams were selected for investigation, but detailed results are only presented for one of them. Caesium-137 and unsupported ^{210}Pb are present in the dam sediments; event-driven layers are apparent from fine gravels contained within layers deposited over the last ~50 years. The ^{137}Cs reference inventories are low by northern hemispheric standards (~53 mBq cm^{-2}). Activities in dam sediments frequently exceed 4 mBq g^{-1}, and the total inventory for the dam master core exceeds 470 mBq cm^{-2}. While extensive gully systems exist in both catchments, the high ^{137}Cs activities in the sediments suggest that sediment delivered to the dam over the last five decades is dominated by topsoil erosion. This conclusion is generally supported by the mineral magnetic data.

Key words caesium-137; environmental magnetism; Karoo; land degradation; radionuclides; South Africa

INTRODUCTION

This contribution is part of a long-term study of erosion and land degradation in the Seekoi valley in the Sneeuberg uplands, ~70 km north of Graaf Reinet, South Africa (Fig. 1). Degradation is characterized by the development of badlands on footslopes of upland areas and by the presence of gully systems in the lowlands (Boardman *et al*., 2003; Keay-Bright & Boardman, 2004). Within the region, over 70 farm dams have been identified, many of which have been in existence since a systematic aerial photographic survey in 1945, and thus, pre-date the onset of southern hemispheric ^{137}Cs fallout in the mid 1950s. In contrast to the northern hemisphere, the onset of significant ^{137}Cs fallout occurred about two years later (1956), with a major increase observed in 1958, and a weapons fallout peak in 1964, again later than that of the northern hemispheric fallout peak (Longmore, 1982). Some early evaluations of the ^{137}Cs technique were made in Lesotho (Kulander & Strömquist, 1989; Lundén *et al*., 1991), but few attempts have been made to use the method for evaluating erosion and sediment dynamics in southern Africa (Quine *et al*., 1993, 1999; Owens *et al*., 1996; Walling *et al*., 2000), despite widespread applications in other southern hemispheric locations (e.g. Loughran & Campbell, 1995). This is the first attempt to apply this technique in South Africa, and the main objective of this paper is, therefore, to

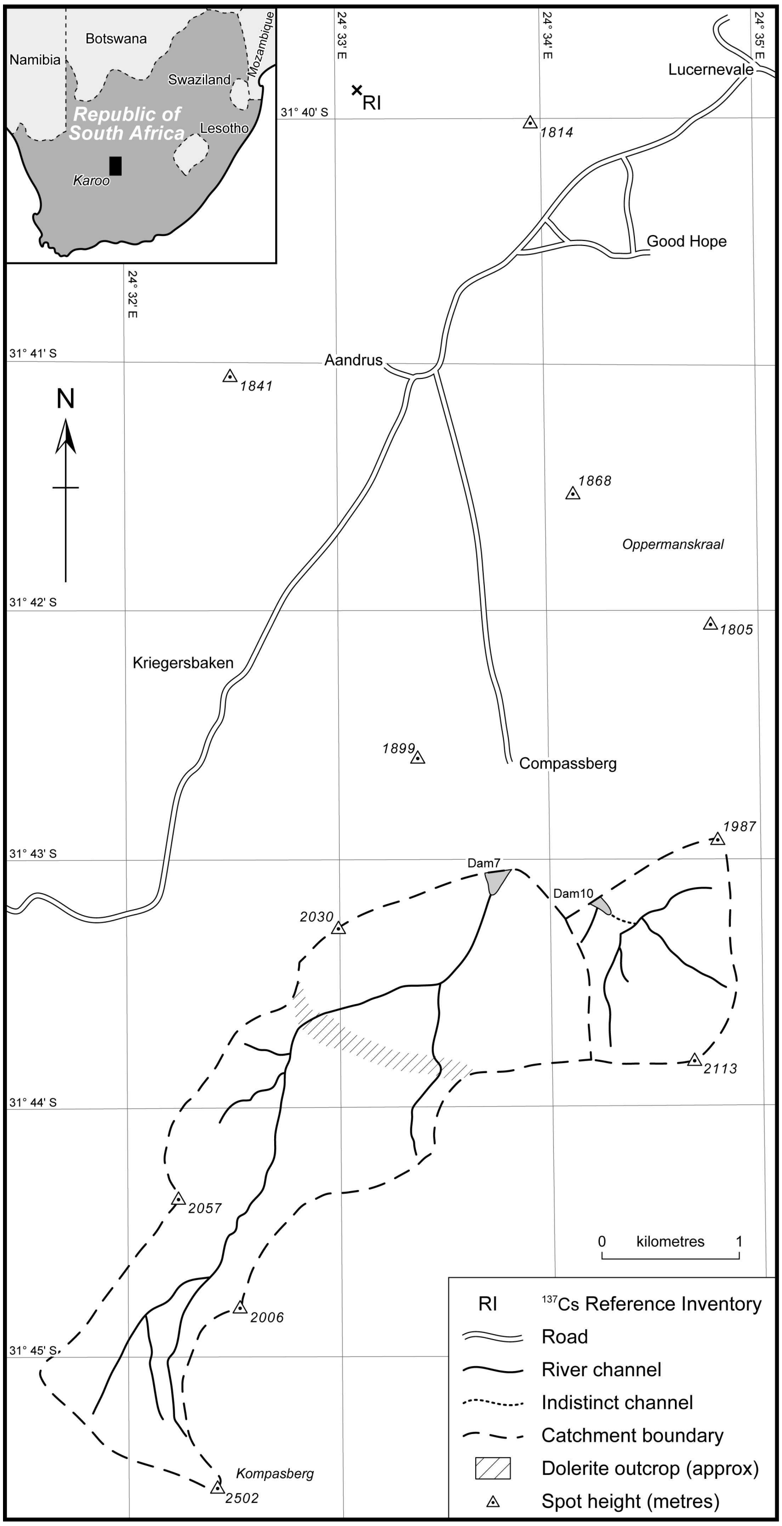

Fig. 1 Location and details of the research catchments and sampling sites.

evaluate the potential for using ^{137}Cs and other gamma emitting radionuclides, in understanding the sediment dynamics of the region. The second objective is to evaluate the potential use of environmental magnetism for similar purposes.

THE FIELD AREA AND FIELD AND LABORATORY METHODS

The research area lies between 31°39′–46′ south and 24°31′–35′ east in the Seekoei River catchment which drains north towards the Orange River. It is in the Sneeuberg uplands and lies above 1500 m altitude (Fig. 1). The area is dominated by summer rain and 71.8% of annual rainfall (~428 mm) falls between October and March (Keay-Bright & Boardman, 2004). Hillslope soils develop on shales and sandstones, or on occasional dolerite outcrops and, in the valley bottoms, on alluvial and colluvial infill. There is a marked difference between the shallow, poorly developed soils of the rocky hillslopes and those that have developed on the valley fill. Vegetation is largely Karoo shrubs, interspersed with palatable grasses that support extensive sheep grazing. Cultivation of rainfed wheat has occurred in one catchment that was studied in detail, in the recent past.

Two catchments with farm dams at their downstream end were selected for detailed analysis (Fig. 1, Table 1). The main criteria for selection were that the dams had been in existence since the 1945 aerial photographic survey, and that both catchments had extensive gully systems. One catchment (7) contained some formerly cultivated land. The second catchment (10) had no record or evidence of cultivation. This paper will focus on results obtained from the Dam 10 catchment only.

Sampling was undertaken in December 2003. A profile of ~1 m depth was manually excavated at the mid point, and ~30 m upstream of the Dam 10 wall; sampling was undertaken from the profile using bulk density tins of either 2 or 5 cm diameter. Where present, sampling was based on stratigraphic units, or at 2 cm intervals where no major stratigraphic units were visible. Coring to ~3 m depth was continued from the base of the excavated profile at 10 cm intervals using a "Dutch Auger" from which material was subsampled for analysis. This provided 58 samples. An additional six cores were retrieved using the same coring method, and mineral magnetic and particle size analyses were undertaken on these cores for core correlation purposes only.

Six gully sections were sub-sampled at intervals based on stratigraphy and magnetostratigraphy (field Kappa measurements) to depths of up to 4.4 m, giving an additional 28 samples. An undisturbed soil profile in a nearby catchment, with similar lithology, was sampled using bulk density tins at 5 cm intervals (six samples) in order to provide a provisional ^{137}Cs reference inventory (Fig. 1). Fourteen surface samples representative of the main lithological units, areas that had been recently burned, and areas of grazing, were also sampled from the Dam 10 catchment.

Table 1 Characteristics of Dam 7 and Dam 10 and their respective catchments.

Characteristic	Dam 7	Dam 10
Catchment area (including reservoir) (ha)	633.09	149.76
Catchment area (excluding reservoir) (ha)	629.72	148.24
Reservoir area (ha)	3.37	1.52
Catchment to reservoir area ratio	187:1	98:1
Maximum altitude (m)	2502	2113
Minimum altitude (m) (approx.)	1840	1860
Relative relief (m)	662	253

All samples were oven-dried at 40°C for the determination of moisture content and dry bulk density. Weight loss on ignition was measured on the master core, and source samples, after heating for 12 h at 450°C in a muffle furnace following oven drying at 105°C. Caesium-137 and a range of other gamma emitting radionuclides were analysed using Eurisys or EG&G hyper-pure germanium "well" detectors (Foster *et al*., 2002). Count times were typically 1.5–2 days. A range of magnetic susceptibility and remanence properties were also measured and, where necessary, corrected for loss on ignition following the methods of Foster *et al*. (1998).

Particle size analysis was determined with a Malvern Instruments Laser Mastersizer following destruction of organic matter. With the exception of the fine gravel layers within the dam sediments, the 90th percentile (D_{90}) particle size of the dam sediments had an upper limit of ~250 µm. In consequence, all coarser dam sediments, and potential sources, were screened to this upper limit before analysis. ^{137}Cs analysis was undertaken on two fractions on samples taken at the reference inventory site (<2 mm and <250 µm) in order to first estimate the fallout inventory, and secondly, to establish ^{137}Cs activities associated with the particle size fractions that were likely to reach the dam.

RESULTS AND DISCUSSION

Selected summary statistics for the Dam 10 sediments, gully, and potential soil sources are given in Table 2. While not in the Dam10 catchment, the ^{137}Cs reference profile is included since it is at a similar altitude and has the same underlying lithology as the hillslopes of the Dam 10 catchment.

The reference inventory soil profile has a negative exponential decline in ^{137}Cs activity with depth (Fig. 2(a)); there are no significant differences in activity, relative to the counting errors, between samples screened to <2 mm and <250 µm. Although only a single profile was analysed as part of this preliminary study, results suggest that atmospheric fallout for the region is low (~53 mBq cm^{-2} to December 2003). However, activities in the upper 5 cm exceed 4 mBq g^{-1}, which suggests that ^{137}Cs would be suitable for tracing topsoil sources in the dam sediments.

Table 2 Selected characteristics of the Dam 10 sediments and potential sources.

Dam 10 sediments (n = 58)	D_{10} (µm)	D_{50} (µm)	D_{90} (µm)	SSA (m^2 g^{-1})	LOI (%)
Mean	3.13	42.9	139.9	0.89	3.22
Standard deviation	2.54	26.6	56.4	0.41	1.41
Loss on ignition (%):					
	Mean		Standard deviation		
^{137}Cs Reference profile (n = 6)	2.63		1.90		
Gullies (n = 28)	2.36		0.79		
Surface samples (n = 14)	4.32		1.51		

D_{10}, D_{50}, D_{90}: 10th, 50th and 90th percentile particle diameter; SSA: specific surface area; LOI: loss on ignition.

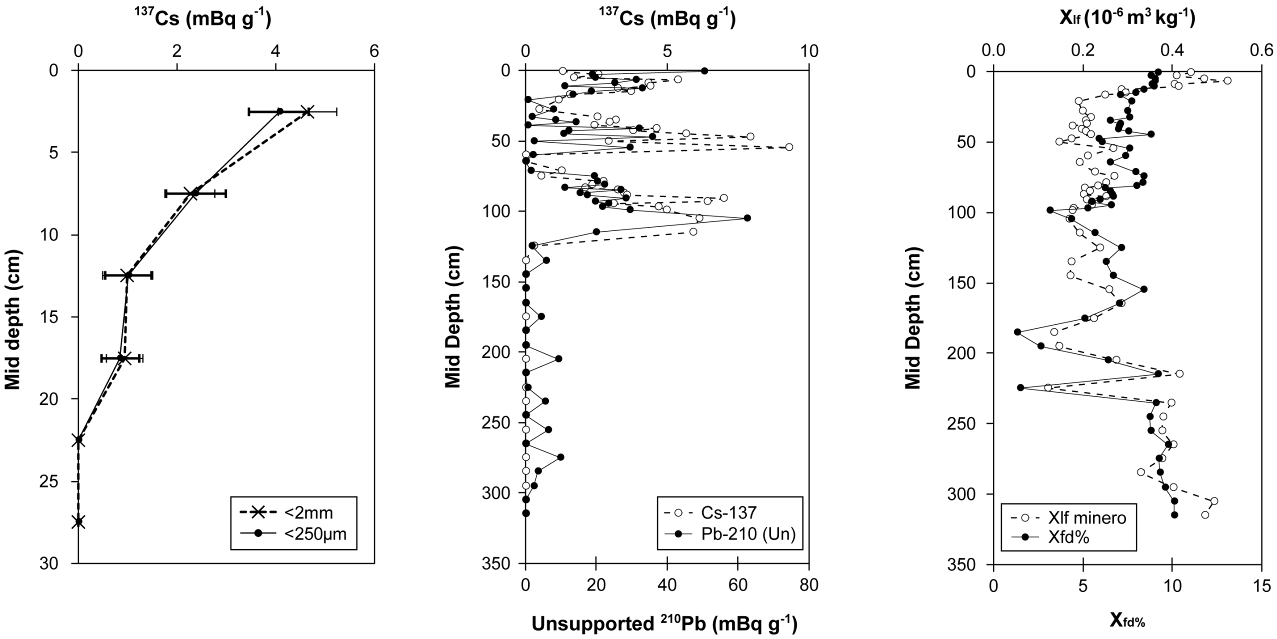

Fig. 2 Caesium-137 activities in the <2-mm and <250-µm fraction of the reference inventory profile. (a) Error bars show counting errors to ±1 SE, (b) ^{137}Cs and ^{210}Pb activities in the Dam 10 sediment core, (c) X_{lf} (organic matter corrected) and $X_{fd\%}$ in the Dam 10 sediment core.

Of the six gully sections sampled, only the upper 0–5 cm of two gullies had ^{137}Cs activities above the detection limit (~0.3 mBq g^{-1}). Activities were 1.4 and 9.3 mBq g^{-1} in these two samples; no ^{137}Cs was detected in gully sidewalls. Assuming that the almost flat surfaces of these alluvial/colluvial deposits adjacent to the gully systems had accumulated ^{137}Cs over the entire fallout history, and that the depth of penetration was similar to that of the reference inventory profile, these data would suggest that in four out of six cases, as much as 15–20 cm of topsoil could have been removed since the 1950s. This is not unreasonable since surface lowering of badland interfluves in the same region, recently monitored by Keay-Bright (unpublished data) using erosion pins, was estimated to be ~5.5 mm year^{-1} over the last three years. Extrapolation of these rates over the last 50 years would be sufficient to remove all of the ^{137}Cs labelled topsoil adjacent to the gullies.

Fourteen additional samples were collected from the Dam 10 catchment. These included four streambed samples, seven samples from soils developed on sandstones/ shales, and three from recently burned areas (natural fires) on colluvial soils in the valley bottom. Activities ranged from below the limits of detection in five samples, to a maximum of 5.45 mBq g^{-1} (mean: 2.3; SD: 1.9 mBq g^{-1}). Of the streambed samples, only one contained ^{137}Cs above the limit of detection, and the three recently burned soils all had ^{137}Cs activities above 3.5 mBq g^{-1}. Of the seven hillslope samples, two were collected at depths greater than 5 cm in the profile, and neither recorded ^{137}Cs above the limit of detection while the remaining five samples collected from the upper 2–3 cm of the profile had activities ranging from 1.56 to 5.45 mBq g^{-1} (mean: 3.4; SD: 1.5 mBq g^{-1}).

The^{137}Cs profile for the Dam 10 master core is given in Fig. 2(b), where unsupported ^{210}Pb activities also are plotted. The total ^{137}Cs inventory of 471.8 mBq cm^{-2} is

~10 times higher than that of the soil reference inventory. Caesium-137 is first detected at 120–130 cm depth in the profile. However, it is unlikely that the initial fallout in the southern hemisphere would be detectable in southern hemispheric sediments today (Loughran, 2002, personal communication), and it is suggested that this initial rise is probably associated with the 1958 peak in fallout described by Longmore (1982). If this interpretation is correct, Dam 10 contains between 1.2 and 1.3 m of sediment deposited since 1958, a period of 46 years. Within this time scale are two major periods of extremely low ^{137}Cs activity at ~18–24 and 62.5–70 cm depth in the profile. These correlate with two layers containing fine gravels in excess of 4 mm diameter; hence, the decrease in ^{137}Cs activity appears to be controlled by particle size since ^{137}Cs enrichment is strongly correlated with an increase in specific surface area (SSA) in these sediments ($R = 0.536$, $P < 0.001$, $n = 48$). The remaining periods of deposition are associated with ^{137}Cs activities that approach a maximum of 10 mBq g^{-1}, and are largely indicative of activities measured in surface soils.

The likelihood of a topsoil origin for the majority of the sediments deposited behind the dam generally is supported by the magnetic susceptibility profile (Fig. 2(c)). Sediments deposited behind the dam appear to contain a high proportion of superparamagnetic grains that are generally characterized by a high, low frequency susceptibility (X_{lf}), and by a high frequency dependent ($X_{fd\%}$) susceptibility that is commonly associated with pedogenesis (Dearing, 1999). However, high susceptibilities also have been recorded in some of the gully sections that suggest that much of the valley alluvial/colluvial infill also has topsoil as a primary source. The sustained rise in X_{lf} and $X_{fd\%}$ below 235 cm depth in the core may be indicative of a buried soil (the pre-dam flood plain surface). This seems to be supported by a rise in organic matter content at the same depth (LOI 5.75%).

Boardman & Keay-Bright (2004) have calculated sediment yields in this catchment from dam sedimentation (uncorrected for trap efficiency) of ~440 m^3 km^{-2} $year^{-1}$ (~510 t km^{-2} $year^{-1}$). Assuming that the dam is ~70 years old, ~1 m of sediment was deposited at the master core site in Dam 10 in the 24 years prior to 1958, and ~1.35 m in the 46 years after 1958. While it would be tempting to suggest that these data indicate that sediment yields have declined significantly over the last ~50 years in comparison with the previous ~25, this interpretation does not account for a declining trap efficiency, as the dam is now totally full of sediment. Conventional trap efficiency corrections are inappropriate in these environments since the dams are dry for most of the year. New methods will have to be developed, in future work, to correct dam sedimentation rates for trap efficiency.

CONCLUSIONS

This preliminary investigation has demonstrated that ^{137}Cs activities are sufficiently high in the South African Karoo to be used for tracing the origins of sediment deposited in farm dams, and for dating sedimentary sequences. Of particular importance to the present study is that sediments deposited behind Dam 10 appear to be dominated by ^{137}Cs enriched-material whose origin is primarily topsoil, suggesting that over the time period of deposition since ^{137}Cs fallout first occurred, gully sidewall erosion has probably not made a significant contribution to the sediment transported in this catchment. While the mineral magnetic signatures are suggestive of a primary topsoil origin for the dam sediments, the gully sidewalls also have similar characteristics and only the ^{137}Cs data provide unequivocal discrimination to suggest that the origins of much of the sediment deposited in the dam has come directly from topsoil erosion rather than re-eroded gully sediments.

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