CHANGING SEDIMENT YIELD AND SEDIMENT DYNAMICS IN THE KAROO UPLANDS, SOUTH AFRICA; POST-EUROPEAN IMPACTS.

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ABSTRACT
We provide an overview of published results and a significant body of new data from an ongoing research programme designed to reconstruct sediment yields and sources in small (<60 km\textsuperscript{2}) catchments in the Eastern Cape, South Africa over the last 150 years. Our analysis of four catchments has determined that sediment yield increased significantly in the latter half of the 20\textsuperscript{th} Century but that the exact timing of these increases was different in each of the four catchments. In two high altitude locations, sediment yield increases were not associated with a significant change in sediment source, although in one case areas of former cultivation appear to have made a slightly greater contribution since the 1960s. In a third catchment, increases in sediment yield appear to have been driven by the development of badlands and by an increase in connectivity between the badlands and the main channel network in the 1960s. In the fourth catchment, increased connectivity between the main catchment and dam occurred as a result of the construction of a causeway to carry a main road and by the construction of culverts beneath the road. Occasional changes in sediment source have also been identified in the sedimentary record but these were not linked directly to road construction. Research to date shows the complexity of sediment delivery in these semi-arid catchment systems and emphasises the need to combine sediment yield with source ascription in order to better understand the dynamics of these systems.

KEYWORDS: Sediment yield, sediment sources, Karoo, weather and climate, land use change, catchment connectivity.
INTRODUCTION

Semi-arid landscapes are particularly vulnerable to water erosion due to the seasonality of rainfall and the occurrence of drought which, in combination, alter the type and density of the protective vegetation canopy. Globally these landscapes have been affected by the introduction of European farming systems, usually grazing, with some rain-fed cereal cultivation. In the eighteenth and nineteenth centuries parts of Australia, South Africa and the USA suffered this type of impact as European farming systems were introduced with little appreciation of how these new environments functioned (Australia - Wasson, 1994; Olley and Wasson, 2003; S. Africa - Fox, 2000; Hoffman and Ashwell, 2001; Foster et al., 2007; USA - Steiner, 1990; Follett, 2010). The semi-arid South African Karoo typifies this situation. Landscape degradation in this region (Figure 1) is characterized by the widespread presence of intensely dissected colluvial footslopes (badlands) and by incised channels locally termed dongas, located in valley bottoms (Boardman et al., 2003; Keay-Bright and Boardman, 2006). Their presence is widely blamed on European settlement and land use practices that degraded the vegetation cover of grassland and woody shrubs. Both badlands and dongas have undoubtedly reduced the agricultural productivity of these marginal areas, altered hydrological response and increased sediment yield to downstream areas, including storage reservoirs.

The progressive deterioration of vegetation quality (‘desertification’) in the Karoo of South Africa is much debated, with competing climatic and overgrazing hypotheses (Hoffman and Cowling, 1990; Bond et al., 1994; Hoffman et al., 1995; 1999; Hoffman and Ashwell, 2001). Although herding of domestic livestock has probably been a significant management component in parts of the Karoo landscape for at least 2000 years (Elphick, 1985; Bollong and Sampson, 1999), it is unlikely that pre-colonial herders caused widespread irreversible damage to the landscape. Lovegrove (1993) suggested that these early communities could have been responsible for some localized overgrazing, but Fox (2000) suggested that European colonisation, which began in the second half of the eighteenth century, was responsible for the most dramatic increases in degradation over the last 200 years.

The authors of this paper have completed a number of studies on erosion and sedimentation in the Sneeuwberg area of the eastern or Nama Karoo with the aim of contributing to the debate on land degradation during the period of European settlement. These have included local and regional studies of gully erosion (Boardman et al., 2003; Keay-Bright and Boardman, 2006, 2009; Boardman and Foster 2008) and assessment of changing catchment sediment yield and sediment sources through the study of sediment trapped in small farm dams (Foster et al. 2005; 2007; 2008; Boardman et al. 2010; Rowntree and Foster, 2012; Foster and Rowntree, in press). The four dams investigated provide the
opportunity to reconstruct regional processes of soil erosion and sediment yield and to use these to contribute to the debate on land degradation.

The amount of sediment transported by rivers (sediment yield) is often used as an indicator of catchment disturbance as driven by extrinsic (e.g. climate or land use change) or intrinsic (e.g. vegetation or soil erodibility change) factors. Long term erosion and sediment yield data are not available for the Karoo, although surveys of major reservoirs have provided information about erosion rates for large catchments (Rooseboom and Lotriet, 1992; Msadala et al., 2011). In the absence of long term data for small catchments we have undertaken sediment yield reconstructions for four catchments with dams at their downstream ends. The overall aim of the research programme was to: (1) reconstruct sediment yield through time by estimating rates of sediment accumulation in the reservoirs, (2) qualitatively model changes in sediment sources over time by using geochemical, radionuclide and mineral magnetic signatures of accumulating sediments compared to the signatures of potential sources and (3) use other available secondary data (maps, aerial photographs, satellite imagery, documentary records, weather records) in order to correlate changes in sediment yield with known periods of catchment disturbance or modification.

SITE SELECTION AND SITE DETAILS

Site selection
To date we have undertaken research in four catchments (Figure 1) that were chosen to represent a range of factors frequently deemed responsible for changing rates of erosion and land degradation. These are summarized in Table 1. The catchments were chosen to represent differences in altitude, land use and types of erosion feature in this area of the Karoo and represent the range of erosional and landscape conditions we have observed in the region. The dominant land use in all catchments has been grazing by sheep and cattle. Grazing intensity has changed through time as illustrated in Figure 2. Two catchments (Compassberg Dams 7 and 10; Table 1, Figure 3) have well developed donga systems but no badlands. Lying at similar altitudes north of the highest peak in the Sneeuwberg range (Compassberg; 2502 m asl), the catchment of dam 7 had rain-fed cereal cultivation that peaked in extent in the late 1950s (N Sheard pers. com.) while that of Dam 10 has no evidence of former cultivation. The Ganora catchment (Table 1, Figure 4) is in a similar physiographic setting to that of Compassberg Dam 7, but has clearly defined dongas and extensive badlands occupying ~ 15% of the total catchment area; it has not been cultivated (JP Steynberg pers.com). By contrast, Cranemere (Table 1, Figure 5) is a much larger catchment with only a small area occupied by mountains in the north (part of the Coetzesberg). The catchment has a complex drainage system with clearly defined dongas in some areas that are poorly connected to the main channel. The main channel itself frequently becomes indistinct and there are several alluvial fans that appear to be operating as
temporary sediment stores within the catchment, either on tributaries or on the main channel feeding the reservoir. A small areas of badland exists upstream of one fan but these badlands are disconnected from the main channel by a large fan. There are two sub-catchments feeding Cranemere dam, but only the largest sub-catchment in the west extends to the Coetzeesberg in the north. Much of the lower parts of the catchment lie on the plains of Camdeboo where there are limited areas of cultivation. The main road from Somerset East to Graaff Reinet (R63) runs close to the northern edge of the reservoir and was elevated on a causeway and culverted in 1950.

Table 1. Characteristics of the study catchments

<table>
<thead>
<tr>
<th></th>
<th>Compassberg Dam 7</th>
<th>Compassberg Dam 10</th>
<th>Ganora</th>
<th>Cranemere</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Catchment topography</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catchment area (ha)</td>
<td>630</td>
<td>148</td>
<td>258</td>
<td>5751</td>
</tr>
<tr>
<td>Relief ratio</td>
<td>0.13</td>
<td>0.23</td>
<td>0.15</td>
<td>0.08</td>
</tr>
<tr>
<td>Maximum altitude</td>
<td>2502</td>
<td>2113</td>
<td>1741</td>
<td>1507</td>
</tr>
<tr>
<td>Maximum basin relief (m)</td>
<td>662</td>
<td>253</td>
<td>313</td>
<td>754</td>
</tr>
<tr>
<td><strong>Reservoir metrics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir: dam construction date</td>
<td>~1935</td>
<td>~1935</td>
<td>1910</td>
<td>1843</td>
</tr>
<tr>
<td>Reservoir area (ha)</td>
<td>3.37</td>
<td>1.52</td>
<td>5.23</td>
<td>30.22</td>
</tr>
<tr>
<td>Catchment to reservoir area ratio</td>
<td>187:1</td>
<td>98:1</td>
<td>53:1</td>
<td>190:1</td>
</tr>
<tr>
<td><strong>Erosion features</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Badlands</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>limited</td>
</tr>
<tr>
<td>Dongas</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>Discontinuous</td>
</tr>
<tr>
<td>Fans and storage areas</td>
<td>no</td>
<td>no</td>
<td>limited</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Land use</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grazing</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Cultivation</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>limited</td>
</tr>
<tr>
<td><strong>Sampling date</strong></td>
<td>2003</td>
<td>2003</td>
<td>2006</td>
<td>2007</td>
</tr>
</tbody>
</table>

*Relief ratio = H/L where H = Maximum basin relief; L = longest dimension of basin parallel to principal drainage line (Schumm, 1956).

**Geology**

The solid geology of the research area comprises rocks of the Karoo Supergroup that date from the Permian, through the Triassic to the Jurassic periods and predate the breakup of Gondwanaland (McCarthy and Rubidge, 2005). The sedimentary sequence belongs to two major geological units, the
sandstones, siltstones and mudstones of the Permean Adelaide subgroup and the sandstones of the Triassic Katberg formation. Dolerite dikes and sills of Jurassic age intersect the landscape forming distinct ridges and capping many of the mountains (Johnson et al., 2010). More recent Quaternary scree, fans, colluvium and alluvium blanket lower slopes and plains. Steep hillslopes are generally devoid of a continuous soil cover, but valley fill reaches up to 5 m deep in places and is heavily dissected by dongas, usually to bedrock (Holmes et al., 2003).

The Katberg sandstones of Triassic age are found in the high altitude catchments of Dams 7 and 10. The lower altitude Ganora and Cranemere catchments comprise mainly Adelaide subgroup sediments. Dolerite outcrops are extensive in the catchment of Compassberg Dam 10 where they cover 50% of the total catchment area (Figure 3). Dolerite is absent from the Dam 7 catchment and only a small area (<5%) of the Ganora catchment contains dolerite outcrops (Figure 4). A narrow dolerite outcrop runs the length of the Cranemere catchment, forming a prominent ridge that separates the eastern and western subcatchments and caps the Coetzeesberg to the north (Figure 5).

Weather and Climate
Around 100 years of daily rainfall data have been obtained from a number of raingauges in the area (Figure 1), but analysis of these records shows no significant long term trends in annual amount (Hoffman et al., 2009; Figure 6), irrespective of altitude. There is much inter-annual variability, but the trends are similar for the different stations. Several significant features can be identified in these records, especially the drought years of the early 20th Century and the increased annual rainfall in the 1970s that gave rise to widespread floods. Although no trend can be discerned in the annual records, a magnitude and frequency analysis of daily rainfall for one of the upland stations (Middelburg) and a station on the Plains of Camdeboo (Cranemere), indicates that there has been a significant change in the magnitude of extreme daily rainfall (Figure 7), a finding also reported by Mason (1999) for South Africa. Changes in the Middleburg record are most extreme. For example, the daily rainfall that previously had an 80 year return period (1900-1950 data) now has a greatly increased frequency with a return period of only 6 years (1951-2000 data).

RECONSTRUCTION OF THE HISTORY OF EROSION AND SEDIMENT YIELD
Temporal changes in sediment yield from each catchment and tracing of sediment sources were determined by a palaeo-reconstruction using sediment cores taken from the dams. Methods for reconstructing sediment yields and discriminating sediment sources on the basis of fine sediment fingerprint properties (mineral magnetism, gamma-emitting radionuclides and sediment geochemistry) in the four catchments has been described in detail elsewhere (see Foster et al., 2005; 2007; 2008; Rowntree and Foster, 2012; Foster and Rowntree, In Press) and will not be repeated here. This paper will focus on a comparison of the sediment yield response over the lifetime of each
reservoir and a comparison of factors that appear to have influenced changes in sediment sources through time.

**SEDIMENT YIELD**

Changes in sediment yield derived from analysis of sediment cores are shown in Figure 8. The long term average yields post 1930 are given in Table 2. Ganora, a small steep catchment with extensive badland erosion, has the highest yield, followed by Dam 10 with a similar physiography but no badlands. Cranemere, the largest catchment with significant storage potential, has the lowest long term yield but is of the same order of magnitude as Dam 7 for the post 1970 average (Table 2). Sediment yield to the dams in the Karoo is high by global standards for predominantly grazed catchments. In a temperate environment with twice the annual rainfall, Erskine *et al.* (2002) report sediment yield contrasts for small basins of 710 (cultivated), 330 (grazed pasture) and 310 t km$^{-2}$ yr$^{-1}$ (woodland). In Tigray, Ethiopia, an area of tropical semi-arid climate with rainfall ~450 mm yr$^{-1}$, 10 small reservoirs in catchments with high population densities and serious land degradation give sediment yields ranging from 237 to 1817 t km$^{-2}$ yr$^{-1}$ (Haregeweyn *et al*., 2006).

### Table 2 Post-1970s average sediment yields in the four Karoo catchments.

<table>
<thead>
<tr>
<th>Location</th>
<th>Catchment Area km$^2$</th>
<th>Period</th>
<th>Sediment Yield t km$^{-2}$ yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ganora</td>
<td>2.58</td>
<td>1970-2007</td>
<td>1096</td>
</tr>
<tr>
<td>Dam 10 Compassberg</td>
<td>1.48</td>
<td>1970-2003</td>
<td>445</td>
</tr>
<tr>
<td>Dam 7 Compassberg</td>
<td>6.3</td>
<td>1970-2000</td>
<td>153</td>
</tr>
<tr>
<td>Cranemere</td>
<td>57.5</td>
<td>1970-2007</td>
<td>175</td>
</tr>
</tbody>
</table>

Cranemere had a low yield during the 19th century and all catchments had low yields in the early decades of 20th century. All yields increased significantly in the latter part of the 20th century. The timing of major increases and the peak sediment yields, however, are different. A significant increase in sediment yield occurred around 1930 for Cranemere, 1940 for Dam 10 and 1960 for Dam 7 and Ganora. Four hypotheses are proposed to explain the pattern of sediment yield illustrated in Figure 8. The first two are related to anthropogenic land use change, the last two to natural factors of climatic change and intrinsic geomorphological change.

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 yield in the mid 20th Century was due to the introduction of cultivation.
3. Increased sediment yield from the mid 20th Century is due to changes in weather patterns that have resulted in increased rainfall energy, greater erosivity and flooding.
4. Increased sediment yield from the mid 20th Century is due to changes in connectivity between sediment sources and the dam. Each of these will be considered in turn.

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

Overgrazing is commonly invoked as the cause of land degradation in the Karoo. Evidence points to a major transformation in land management at the end of the 19th Century, with the introduction of fencing to control stock movements and wind pumps to increase the number of watering stations (Archer, 2000). Livestock numbers increased dramatically (Figure 2). There was early concern about signs of land degradation even in the 19th Century. Archer (2000) reports that as early as 1875 Civil Commissioners were commenting on the loss of vegetation cover and a reduction in grazing capacity. Gordon, Director of Irrigation for the Cape of Good Hope, was one of a number of others who spoke passionately about the evils of soil erosion in the first decade of the twentieth Century (Gordon 1904). By the middle of the 20th Century a conservation movement was in place and farmers started to change their stocking practices to promote better veld condition (veld is the colloquial term for the vegetation community that makes up the local plant cover). The decline in stock numbers after 1940 is apparent in Figure 2.

This history of landscape transformation, overstocking and conservation is not coincident with the changes in sediment yield shown in Figure 8. Sediment yield in all cases was low prior to 1940, when livestock numbers and, presumably, damage to vegetation, was highest. These measures had no observable impact on sediment yield, as the calculated yields levelled out or continued to rise, peaking in the early 1970s for all dams except Dam 7 on Compassberg, which had a peak between 1958-1964.

It is reasonable to assume a time lag within a process-response system as implied by Archer (2000). The question is how long a lag is reasonable? An increased sediment yield from the early 1940s is consistent with the hypothesis that high stocking densities up to and including the 1930s would have led first to degradation of the vegetation cover, with a loss of grass species, an increase in bush cover and, second, to an increase in erosion. Although the overall pattern of sediment yield increase is similar for all catchments, the trigger for veld degradation to manifest itself as an increase in sediment yield may have been different in each catchment. Possible triggers are considered below. We are left with the question of why was there a lag of over 20 years before sediment yields drop following improved stock management? A number of authors question whether there can be a full recovery within the near future (Dean and MacDonald 1994; Dean et al., 1995; Archer 2000), a position supported by the sustained high yields from these catchments.
Hypothesis 2. Increased sediment yields in the mid 20th Century are due to the introduction of cultivation.

The only catchment with a significant area of cultivated land is that of Dam 7. There is evidence of limited cultivation on the 1945 aerial photographs that had increased significantly by 1959, after which the area of cultivation was reduced. Some cultivation continued until 1974 (Neil Sheard: Pers Com.). Linear gullies crossing the cultivated land to the dam can be clearly seen on the 1959 and 1966 photographs. The dramatic increase in sedimentation rates in Dam 7 between 1958-1964 can be attributed to the coincident peak in cereal cultivation. The cereal lands were close to the dam so the sediment delivery would have been efficient and rapid.

Further evidence for the impact of cereal cultivation on sediment yields for Dam 7 comes from an analysis of the downcore changes in the magnetic parameters HIRM and the S ratio, plotted in Figure 9. HIRM values are elevated (and S ratios depleted) in soils developed on dolerite and are especially high in freshly weathered dolerite. Both signatures are indicative of a greater proportion of hematite-type minerals in sediment (Walden et al., 1999). The magnetic signatures of the Dam 7 sediments suggest that a sustained change in sediment source occurred up-core of ~100 cm depth (Figure 9). This level was dated by Foster et al. (2007) to ~1963. Although particle size variations are often invoked to explain changes in mineral magnetic signatures (Foster et al., 1998), correlation between particle size characteristics of the deposited sediment (SPAN, SSA, D10, D50, D90) and the mineral magnetic signatures are not statistically significant in the Dam 7 sediments, thereby eliminating the likely effects of particle size on the magnetic signatures.

The peak in rain fed cereal production in the Dam 7 catchment was in 1959 and was established on contour terraces constructed in close proximity to the dam itself. These terraces extended into the dolerite outcrops on the southern fringes of the catchment. These terraces are now degraded and small gully systems extend upslope to areas of former cultivation on the dolerite, potentially linking these areas directly to the dam. Although badlands have not yet developed on these areas, unlike many formerly cultivated areas in the local region described by Boardman and Foster (2008), the sustained high sediment yield in Dam 7 could be associated with the slow recovery of a natural vegetation cover after cereal cultivation was stopped.

Hypothesis 3. Increased sediment yields from the mid 20th Century are due to changes in weather patterns that have resulted in increased rainfall energy, greater erosivity and flooding.
The analysis of annual rainfall shows significant synchronicity between stations that may be over 75 km apart (Figure 6). Three of the four catchments (Compassberg dams 7, 10 and Ganora) lie within ~25 km of each other. All the study catchments are therefore likely to respond in a similar way to climatic variability. Similarities in the pattern of sediment yield throughout the region could therefore be attributed to changes in rainfall characteristics.

All reservoirs show relatively low sedimentation rates for the first two decades of the record, which was a period dominated by drought and was the climatically least extreme period in terms of the number of daily rainfalls >25mm. The increasing rainfall intensity after 1950, as illustrated by the magnitude frequency relationships in Figure 7, may well have contributed to the increased sediment yield from the catchments and the low veld recovery rates, despite the reduction in stock numbers.

There is clear evidence from Figure 7 that daily rainfall has become more extreme since 1950, thus increasing both the potential for soil erosion and for floods that would be able to deliver sediment to the dams. The floods of the 1970s are more or less coincident with the peak sediment yield at Cranemere and Ganora. The most notable flood occurred on March 3rd 1974, coincident with widespread flooding over the Eastern and Northern Cape. It is assumed that lenses of coarse sediment evident in cores taken from Dams 7 and 10 are related to this flood (Foster et al., 2007). At Cranemere 70 mm fell over a two-day period, 106 mm at Mount Cambedoo in the nearby mountains. Although not especially intense (a daily maximum of 98 mm at Cranemere was recorded in 1977), the storm fell on a wet landscape that had already received 115 mm in January and 113 mm in February. Water a metre deep flowed over the dam overspill at Cranemere. Although this storm resulted in intense runoff, family correspondence indicates that soil erosion was not severe due to the good vegetation cover resulting from the rain over the previous two months. This raises the question – did these floods cause widespread soil erosion, or was the increase in sediment deposition in the reservoir due to floodwaters mobilizing stores of sediment that had been accumulating over a longer time period? We will return to this point later.

Hypothesis 4. Increased sediment yields from the mid 20th Century are due to changes in connectivity between sediment sources, sediment stores and the reservoir.

The degree of connectivity within the sediment cascade has been recognized as an important driver of geomorphic systems at various scales including the catchment scale (Fryirs et al., 2007; Trimble, 2010) and the channel scale (Hooke, 2003). It is commonly accepted that connectivity can change through time, often as a result of human activity, leading to non-linearity in sediment delivery from source areas (Turnbull et al., 2008).
Sediment delivery is significantly increased by the presence of a well-connected drainage network, whereas sediment delivery is decreased when there are extensive areas for sediment storage. Connectivity for sediment movement is provided firstly by the main channel network and secondly, at a more local scale, by channel networks in badlands. Both of these networks can also contribute sediment directly and can therefore be considered sediment sources. Sediment stores take the form of alluvial fans, floodouts and floodplains that act to disconnect an otherwise continuous channel network.

The Compassberg catchments
Deeply incised channels are common throughout the area. In the Compassberg catchments they provide good connectivity between the hillslopes and reservoirs. There is good evidence from aerial photographs that these incised channels were present prior to 1940 (Keaybright and Boardman, 2007). The presence of $^{137}$Cs in the sediments of Dam 7 and Dam 10, and geochemical and mineral magnetic characteristics, strongly negates the dongas being the source of dam sediments (Foster et al., 2007). Therefore since the 1940s at least they have acted as efficient conduits for sediment from the hillslopes, but have not contributed sediment themselves. Localized gullies in the formerly cultivated areas have been described above as a factor promoting continued delivery of sediment to Dam 7.

The Ganora catchment
Ganora is the only catchment with extensive badlands, which were anticipated to be a major sediment source. Measurements of erosion rates in Karoo badlands (Boardman et al., 2003; Keay-Bright and Boardman, 2009) produced estimates at least an order of magnitude higher than average erosion rates for the catchments in which they were located.

The analysis of sediment properties from the Ganora dam suggests significant source changes through time that can be related to changes in connectivity (Rowntree and Foster, 2012). The downcore plot of magnetic susceptibility is given in Figure 10. The magnetic measurements of the sediment core samples were matched with those from 31 samples taken from locations in the catchment representing different source types (Figure 4). These included badlands, un-dissected footslopes, channel banks, and fans. The fan at the head of the eastern main channel was dominated by doleritic material, that in the western catchment by sandstones and shales (Figure 4).

The values of $\chi_{lf}$ in Figure 10 change significantly through time. Period 0-1 (Figure 10) has high $\chi_{lf}$ values, similar to those of samples taken from the dolerite fan at the head of the eastern catchment. Period 1-2 has much lower values, similar to those of the badlands, but recover to pre-existing levels during Period 2-3. Period 3-4 again shows a decline in $\chi_{lf}$ that is sustained until the most recent period.
Sediment yield was generally low up to period 3 but increased significantly from the mid 1960s onwards, declining towards the end of the 20th and beginning of the 21st Centuries. By comparing the γIf values of the core and the source samples, it appears that the main source from 1910 to the mid 1950s was the doleritic fan at the head of the eastern channel. Sediment yield was low throughout this period because headward erosion and incision of one main channel was probably the primary source. After 1950 it appears that the badlands in the west of the catchment started to contribute, and soon dominated the magnetic signature in the reservoir sediment. Coincident with this shift in source was a rapid increase in sediment yield. The higher yield is also associated with a peak in the 137Cs activities of the reservoir sediment, suggesting a significant influx of topsoil (Rowntree and Foster, 2012).

The badlands at Ganora are clearly evident on the 1945 aerial photograph, but it was only after 1960 that there was a rise in the sediment yield and a change in the γIf and other magnetic signatures in the reservoir sediment. There was a drop in γIf values in the 1930s, but no concomitant rise in sediment yields. To explain this pattern it is necessary to look at the channel network itself. Evidence from aerial photographs indicates that the western channel connected with the main badland area sometime between 1945 and 1966. In 1945 the badlands were poorly connected to the reservoir but by 1966 they were well connected (Rowntree and Foster, 2012). The pattern of γIf values suggests that badland erosion was initiated in the early 1930s, with sediment reaching the reservoir from sources close to the main channels, but only in the early 1960s did the main badland area started to contribute significant amounts of sediment that also produced the significant increase in sediment yield (Figure 10). A date of 1930 for badland initiation is reasonable given the findings of Boardman et al. (2003) and Keay-Bright and Boardman (2009). Current rates of badland erosion measured by Boardman (pers. comm.) are an order of magnitude higher than the post 1970 sediment yield at Ganora reported in Table 2, suggesting that it is unlikely that badland erosion at this rate could be sustained for more than a few decades.

The change in sediment yields at Ganora can therefore be explained by a two-stage process. First was the initiation of badland erosion on the footslope areas of the western catchment, possibly during the 1930s in response to overstocking, veld degradation and a series of high energy storms after the drought of the 1920s. Badlands have a high internal connectivity, but their downstream impact will depend on their structural connectivity to catchment scale conveyance systems. The second process was therefore the transport of this material to the reservoir after 1960 when channel extension connected the badlands to the main drainage system. Thus changes to connectivity in both time and space can be invoked as a major contributor to changes in dam sedimentation rates.

The Cranemere catchment
A continuous network of incised channels is absent from the Cranemere catchment. The low relief of the middle and lower catchment provides much space to accommodate storage (Figure 5) of eroded material. Sediment is stored in fans and valley floor floodouts, causing discontinuities in the channel network. Soils eroded from hillslopes (the sources) can be stored for considerable periods in valley floor storage zones where they undergo sorting, weathering and possible further soil formation processes. Field observations indicate that sand sized material is widely distributed in these intermediate storage locations, yet the extremely fine sediments deposited in the reservoir suggest that there has been insufficient energy to transfer even fine sand sized material to the dam.

Valley floor storage thus tends to disconnect the channel system, but headward erosion of channels into these areas can also reactivate sediment transport and possibly enhance the catchment yield. A small fan has been identified immediately upstream of the main road (Figure 5). Family documents of the farm owners describe this as a wetland prior to the 1950s. A change in connectivity occurred in the 1950s. The road was upgraded and culverts built under the road, thus connecting the fan to the reservoir. This could have contributed to the increase in yields experienced at around this time (Figure 8).

Downcore trends in two magnetic properties for the dam sediments in Cranemere are plotted in Figure 11. The data suggest relatively constant sediment sources between periods 0-1, 2-3 and 4-5 and two periods when major sediment sources changed, dating from the late 1930s (period 1-2) and the early 1970s respectively (period 3-4). Analysis of the possible effect of a particle size control on these signatures, in common with Ganora, show no statistically significant relationship between particle size and any of the mineral magnetic signatures. The periods over which sources changed are not necessarily associated with periods of maximum sediment yield in the historical record (Figure 11).

Analysis of the mineral magnetic characteristics of potential catchment sources was based on a subdivision of the contributing catchment into five distinct sub-catchments, four within the larger western catchment and the much smaller eastern sub-catchment (Figure 5). Differences between the low frequency magnetic susceptibility, expressed on a minerogenic basis, for the 5 catchment units, shows that the eastern catchment and the upper western sub-catchment are characterised by sediment sources that have low magnetic susceptibility and remanence values. It seems unlikely that the upper western catchment makes a major contribution of sediment to Cranemere dam because of the presence of intermediate stores. Analysis of sediment accumulating in the small fan upstream of the R63 (labelled AF2 on Figure 5) confirms this interpretation. A ~50 cm sediment core retrieved in 2010 was analysed for $^{137}$Cs and a number of mineral magnetic properties (Figure 12). Rowntree and Foster (2012) have demonstrated that $^{137}$Cs is not likely to be measurable in South African environments before 1958 and we therefore ascribe a date of 1958 to a depth of ~38 cm in this core. Extrapolating
this date to the former soil surface suggests that the fan began to accumulate sediment at this coring location in the early 1940s. The major decrease in mineral magnetic signatures recorded in the dam sediments in the 1970s are not matched by similar changes in the fan sediments suggesting that the western catchment is unlikely to be the source of the sediment deposited in the late 1930s and 1970s and that the smaller eastern sub-catchment contributed significant amounts of sediment for two short periods over the lifetime of the dam. This catchment comprises only one fifth of the total catchment area, it lacks a clearly defined drainage network except where it meets the reservoir and lacks badlands or any other form of intense erosion. The main road crosses this catchment and, although culverts connect the two sides of the road, they do not feed into well-defined channels. Yet this catchment appears to be responsible for the peak sediment yields in the 1970s.

A possible explanation is that, being close to the dam the sediment delivery is relatively high, despite the lack of a channel network. Moreover soils are relatively shallow and there are no obvious sink areas. Thus severe storms can result in widespread overland flow that is effective in mobilizing surface soil across the catchment and delivering it to the reservoir. It is interesting to note that, according to the owner of Cranemere (Alex Palmer pers. Comm.), the dam is most likely to fill up when the eastern catchment is flowing, as it did during the flood of 1974. The two decades of the 40s and 70s both experienced five daily rainfall events of 50 mm or greater against an average for the 129 year period of record of only 2.5.

DISCUSSION AND CONCLUSION

Reconstruction of sediment yield and sediment sources for four reservoirs in the Sneeuwberg of the South African Karoo has shown that the response to land use change is complex and individual factors can be difficult to identify. All reservoirs showed a lag in the timing of peak sediment yields relative to peak stocking rates and a slow and incomplete recovery in response to veld conservation measures. Trimble (1999) noted that the geomorphological effects caused ultimately by changes of land management and vegetation cover are not always linked directly in space and time. Trimble & Lund (1982) proposed a hysteresis model to describe the lag effect between land use and upland erosion at Coon Creek, Wisconsin. This model was only directly applicable to farmed hillslopes and did not include the channel conveyance system, but demonstrated that soil deterioration lagged behind agricultural expansion while recovery lagged behind soil conservation measures. This model appears to be directly applicable to reconstructed changes in sediment yield in the Karoo. It is thus evident that overstocking has reduced the resilience of the Karoo landscape to erosive forces, and it can be deduced from the graphs of sediment yield in Figure 8 that each catchment has crossed a threshold from low erosion to high erosion. The trigger that has caused the shift may be different for each catchment, or the manifestation of erosion rate as sediment yield may be delayed for different reasons.
In the case of Dam 7 the trigger for increased erosion appears to have been cereal cultivation close to the reservoir. Gullies across abandoned fields continue to transport sediment to the reservoir. In the case of Ganora, badland erosion may have begun as early as the 1930s, but sediment was only delivered to the reservoir when catchment-scale connectivity increased. In Cranemere anthropogenic changes to connectivity may explain part of the story, but it is also likely that increased rainfall amounts are reworking sediment stores on the valley floor. Dam 10 is more of an enigma as there is no obvious reason for the sudden change in sediment yield in 1940s. This could have been due to some local factor for which evidence is lacking, such as an extreme rainfall event or fire. The early response of this catchment (~1940) might be due to the better coupling between hillslope and reservoir, reducing the potential for temporary storage of sediment (note the high relief ratio for Dam 10 in Table 1).

An increase since 1950 in the frequency of high magnitude rainfall events has been identified for two Karoo rainfall stations, confirming findings of Mason et al. (1999) for South Africa. The coincidence of this increase with increases in sediment yield across all study catchments points to storm rainfall as a key driver of sediment transport in an already degraded landscape. Where increased rainfall intensity is coupled with increased connectivity, the impact on sediment yield is likely to be dramatic, as was the case for Ganora and, possibly, Cranemere.

Sediment storage is an important factor that must be considered in any model of catchment sediment dynamics. Storage of sediment in alluvial fans, floodouts and floodplains can buffer the impact of hillslope erosion on downstream sediment yield for significant time periods. Reworking of sediment stores delivers sediment to the downstream point many years after it was first eroded from the hillslopes. Meade (1982), for example, attributed the continued high sediment load of east coast rivers in the United States following successful soil conservation measures in the upper catchment to reworking of floodplain sediments by rivers deprived of sediment eroded from hillslopes. We believe that sediment storage and subsequent reworking has contributed to the delayed response to overgrazing observed for Cranemere.

This paper is a response to the call by ecologists for further investigation into landscape processes in the Karoo, citing the dynamic nature of the vegetation-rainfall response as one factor that makes it hard to decipher the direction of long term trends (Hoffmann and Todd, 2000). We have extended this to a vegetation-rainfall-landscape structure response. Our findings point to a regional trend of increased sediment yield from small to moderate sized catchments postdating, but probably responding to, widespread overgrazing and veld degradation up to the 1940s. A regional increase in rainfall intensity has probably contributed to sustained high yields, but some measure of recovery has
been evident since the 1970s. Land degradation and sediment dynamics at the catchment scale are controlled by lags in space and time in which connectivity and storage play key roles. These are intrinsic geomorphic determinants related to the structure of the landscape and are particular to each catchment. Future strategies for soil and water conservation need to take account of the place specific dynamic that determines the vegetation-rainfall-landscape structure response.

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REFERENCES


Figure 1  Location of the main research catchments and rain gauges.
Figure 2  Grazing Intensity in the Karoo and in the Middelburg District (after Boardman et al., 2010)
Figure 3  The Compassberg Catchments

A  Topography and source sampling sites

B  Geology
Figure 5  The Cranemere Catchment

A  Topography, morphology and sampling sites*

B  Geology

*Note that sampling site codes in the western catchment are recorded as follows:
WU – western upper catchment
WF – western fan catchment
WC – western central catchment
WL – western lower catchment
Figure 6  Variations in Annual Rainfall in lowland (A), middle altitude (B) and high altitude (C) rainfall stations.
Figure 7  Changing magnitudes and frequency of daily rainfall at Middelburg and Cranemere post 1950.

The plot in C shows how the return periods of specific rainfall amounts for the stations shown in plots A and B have changed between the first and second halves of the twentieth century. Using the regression lines in plots A and B, return period for a given rainfall amount was determined from the pre 1951 data set. The new return period for this same rainfall amount was then determined from the regression line for the post 1950 data set. The plot in C was constructed by calculating the pre and post 1951 return periods for specified rainfall amounts, up to a return period of 80 years. Note that the biggest difference is recorded in the Middelburg data set across all return periods as the return period has decreased more than at Cranemere.
Figure 8  Reconstructed sediment yields for Compassberg Dams 7 (A) and 10 (B), Ganora (C) and Cranemere (D).

Figure 9  Downcore variations in mineral magnetic properties the Compassberg Dam 7 sediment core.
Figure 10  Downcore variations in magnetic susceptibility in the Dam sediments of Ganora linked to changes in sediment yield (see text for explanation).
Figure 11  Downcore variations in magnetic susceptibility in the Dam sediments of Cranemere linked to changes in sediment yield.
Figure 12  Downcore variation in Cs-137 activity, Low frequency magnetic susceptibility and HIRM at core location AF2 (Figure 5).