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Reconstructing historical sediment yields from the infilling of farm reservoirs, Eastern Cape, South Africa

IAN D. L. FOSTER[1,2], JOHN BOARDMAN[3,4] & JOHN B. GATES[5]

1 *Department of Molecular and Applied Biosciences, School of Biosciences, University of Westminster, Cavendish Campus, 115 New Cavendish Street, London W1W 6UW, UK*
i.foster@westminster.ac.uk

2 *Department of Geography, Rhodes University, PO Box 94, Grahamstown 6140, Eastern Cape, South Africa*

3 *Environmental Change Institute, Oxford University Centre for the Environment, Dyson Perrins Building, South Parks Road, Oxford OX1 3QY, UK*

4 *Department of Environmental and Geographical Science, University of Cape Town, Rondebosch 7701, South Africa*

5 *Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, University Station, Box X, Austin, Texas 78713-8924, USA*

Abstract In order to calculate sediment yields, a chronology was established for sediments accumulating in two farm reservoirs at single coring locations in each reservoir. The chronology has been transferred to six adjacent cores in each reservoir using magnetic core correlation, particle size and visual stratigraphy. Reservoir sediment volumes corresponding to variable surface levels behind the two dams were estimated using GPS-based measurement of the contemporary reservoir in-fill, combined with coarse assumptions about underlying reservoir geometry derived from aerial photographs and topographic maps. Upper limits on volume were calculated for the hypothetical case of a reservoir with near-vertical sides, and lower limits for the case of linearly-sloping sides (i.e. a v-shaped cross-section). The arithmetic mean of these two boundary cases was taken as the best estimate. Reservoir sediment volumes, and volumes of sediment accumulating between dated horizons in the sediment cores, were obtained from the best estimate of changing sediment volumes derived from these assumptions. The volume of sediment accumulating between each time zone was adjusted by combining sedimentation rates with trap efficiency estimates. These data were subsequently converted to specific sediment yields using the average sediment density. Results from the two reservoirs to which this methodology has been applied show that the historical timing of increased sediment yields is different and that yields have not declined significantly over the last ~50 years, despite reductions in stocking density and the abandonment of rain-fed agriculture.

Key words sediment yields; reservoir sedimentation; Karoo; South Africa

INTRODUCTION

A key debate in fluvial geomorphology is the relative importance of climate and land use/management factors in influencing erosion. Land-use changes such as cereals to maize, or the move of cultivation onto steeper slopes, can have dramatic erosional impacts. Similarly, increases in stock numbers may also initiate erosion. Evidence from many parts of the world suggests that human impact in the form of clearance, cultivation and overgrazing significantly increases erosion rates and that this is both an historical and a contemporary phenomenon (e.g. Talbot, 1947; Trimble, 1983; Cooke *et al*., 2003; Boardman & Foster, 2008).

Semi-arid landscapes are particularly vulnerable to erosion due to seasonality of rainfall and its impact on vegetation, and due to the occurrence of drought. Many similar landscapes throughout the world have been affected by the introduction of European farming systems – generally grazing – and the lack of appreciation of vulnerability and carrying capacity of these “alien” landscapes. In the 18th and 19th centuries, parts of Australia, South Africa and the USA suffered this type of impact.

In South Africa, the progressive deterioration of vegetation quality (“desertification”) is much debated with competing climatic and overgrazing hypotheses (Hoffman & Cowling, 1990; Bond *et al*., 1994; Hoffman *et al*., 1995, 1999). Furthermore, the potential for alien invasive species to alter the hydrological behaviour of former grazing systems in the Eastern Cape has been implicated in regional land degradation, including gully and badland development (Kakembo & Rowntree, 2003; Boardman & Foster, 2008). However, less attention has been paid to physical changes to the landscape.

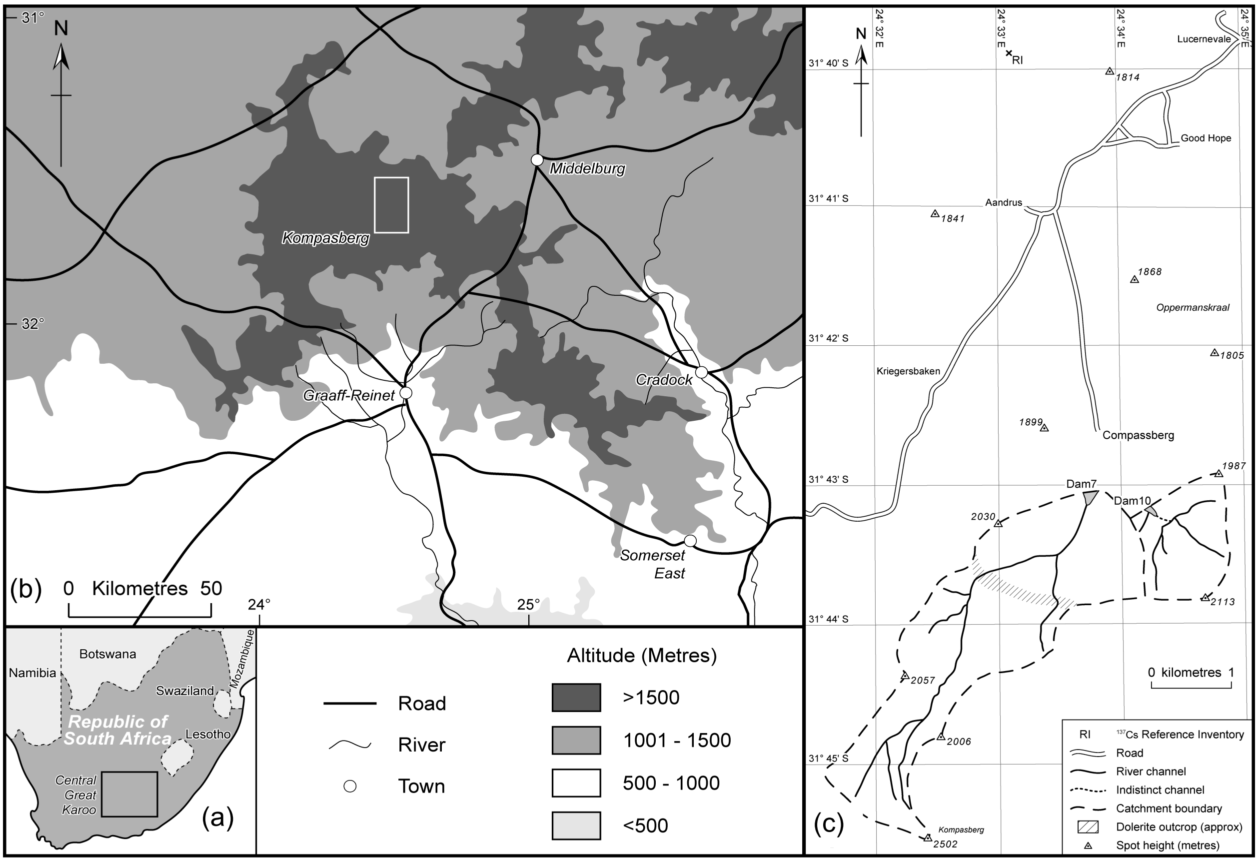

Fig. 1 Location of the research catchments in the Eastern Cape.

This paper is one of a series of studies of erosion, runoff and the development of gullies and badlands in the Klein Seekoei Valley in the Sneeuberg uplands (Fig. 1). The area is part of the South African Karoo, which is a dissected landscape of plains and flat-topped, east–west oriented mountains. The Sneeuberg is one such range rising to 2502 m. The region comprises horizontally-bedded Upper Permian to Triassic sandstones and mudstones of the Karoo Supergroup, capped by Jurassic dolerites (McCarthy & Rubidge, 2005). Holocene colluvium covers the footslopes and valley bottoms to a depth of several metres (Holmes *et al*., 2003), while the steeper slopes have an intermittent and thin soil cover. The study area is in the Upper Klein Seekoei Valley, which drains northward to the Orange River. The valley is wetter than the lowland Karoo, with average annual precipitation of ~498 mm, and a rainfall maximum in summer, with March the wettest month (Foster *et al*., 2007). The vegetation is karroid *Merxmuellera* mountain veldt (Acocks, 1988), a mixture of palatable and unpalatable shrubs with patches of grass. Non-native willows and poplars are found along water courses. European herders and farmers introduced cattle and sheep in the late 18th century. Valley bottoms and the lower footslopes were often used for cultivation of rain-fed wheat and fodder crops, but most cultivated land was abandoned by the 1980s; present-day farming concentrates on sheep production with some diversification into tourism and game farming (Keay-Bright & Boardman, 2007). Previous publications from this area (Foster *et al.* 2005, 2007) have detailed the methods used to establish a chronology for sediments accumulating in two farm reservoirs and have demonstrated that sediment sources have changed little since reservoir construction in the 1930s. Although extensive gully systems are present in both catchments, these do not appear to have been significant sediment sources over the lifespan of the reservoirs. Here we report methods used to calculate the sediment volume contained in each reservoir and use core correlation and the previously established ^{137}Cs chronologies to reconstruct sediment yield histories for the two catchments.

METHODS

The catchments were chosen in order to compare the impact of cultivation, as Dam 7 (Fig. 1) had historically been used for rain-fed cereal cultivation as well as for grazing, while Dam 10 (Fig. 1) had never been cultivated. Stocking data were available for the Middelburg magisterial district in which the study area lies and long-term daily rainfall data have been obtained from a rainfall station at Middelburg (Fig. 1). The Middelburg record has been supplemented by local data from farm raingauges.

Full details of the sampling and analytical methodologies are given by Foster *et al.* (2005, 2007). In brief, the two reservoirs were surveyed and cored at seven locations in December 2003 and the recovered sediment from one location in each reservoir (the master core) was analysed for ^{210}Pb and ^{137}Cs in order to establish a chronology (Foster *et al.*, 2007). Fine sediment signatures (radionuclides, environmental magnetism and sediment geochemistry) were also determined on the master cores in order to trace the origins of the accumulating sediments which appear to have changed little over the last ~70 years and which are dominated by inputs from surface soils rather than gully sidewalls. In order to reconstruct sediment yields from each reservoir, information was required on the depth of infill, the age of different levels within the sediment column, variability in sedimentation patterns within the reservoirs, the density of the accumulating sediments, the initial storage volumes and changing trap efficiencies through time.

Depth of infill and chronology

The depth of infill to the underlying soil/colluvium (approx. 2.4 m in both reservoirs) was obtained by coring and was confirmed by surveying the level of the original land surface (and its gradient) immediately downstream of the dam wall (Foster *et al.*, 2007). The methods used to obtain the chronology have been presented in detail elsewhere (Foster *et al.*, 2007). In both reservoirs a combination of the ^{137}Cs fallout record and the presence of coarse sedimentary layers that could be correlated with extreme events in the Middelburg rainfall records were used to date several levels within the sediment column. It was possible to subdivide the sedimentary sequence for the master core in each reservoir into five time zones for which sediment yields were estimated. Sedimentation ceased in the year 2000 in Dam 7 as a major flood breached the dam wall, which has not been repaired since that time.

Table 1 Depth of dated horizons in the sediments accumulating behind dams 7 and 10.

Dam 7 Year	Depth (cm)	Dam 10 Year	Depth (cm)
2000	0	2003	0
1974	67.5	1974	69.5
1965	97	1965	91
1958	200	1958	125
1941	230	1941	230
1935	240	1935	240

Core correlation

Only one core was dated in each reservoir and the chronology was transferred from the master core to the remaining cores using core correlation based on mineral magnetic measurements (see Foster *et al.*, 2008) and visible stratigraphy (Foster *et al.*, 2007). The most striking visual correlation was the presence of coarse gravel layers that were found at similar (±10 cm) depths at all coring locations in each of the two reservoirs. Both reservoirs showed fairly uniform rates of sedimentation between time zones across their basins as exemplified by the core correlation using magnetic susceptibility (χ_{lf}) and particle size in Fig. 2. In both cases it was assumed that sedimentation rates had remained relatively uniform across the two basins for each time period.

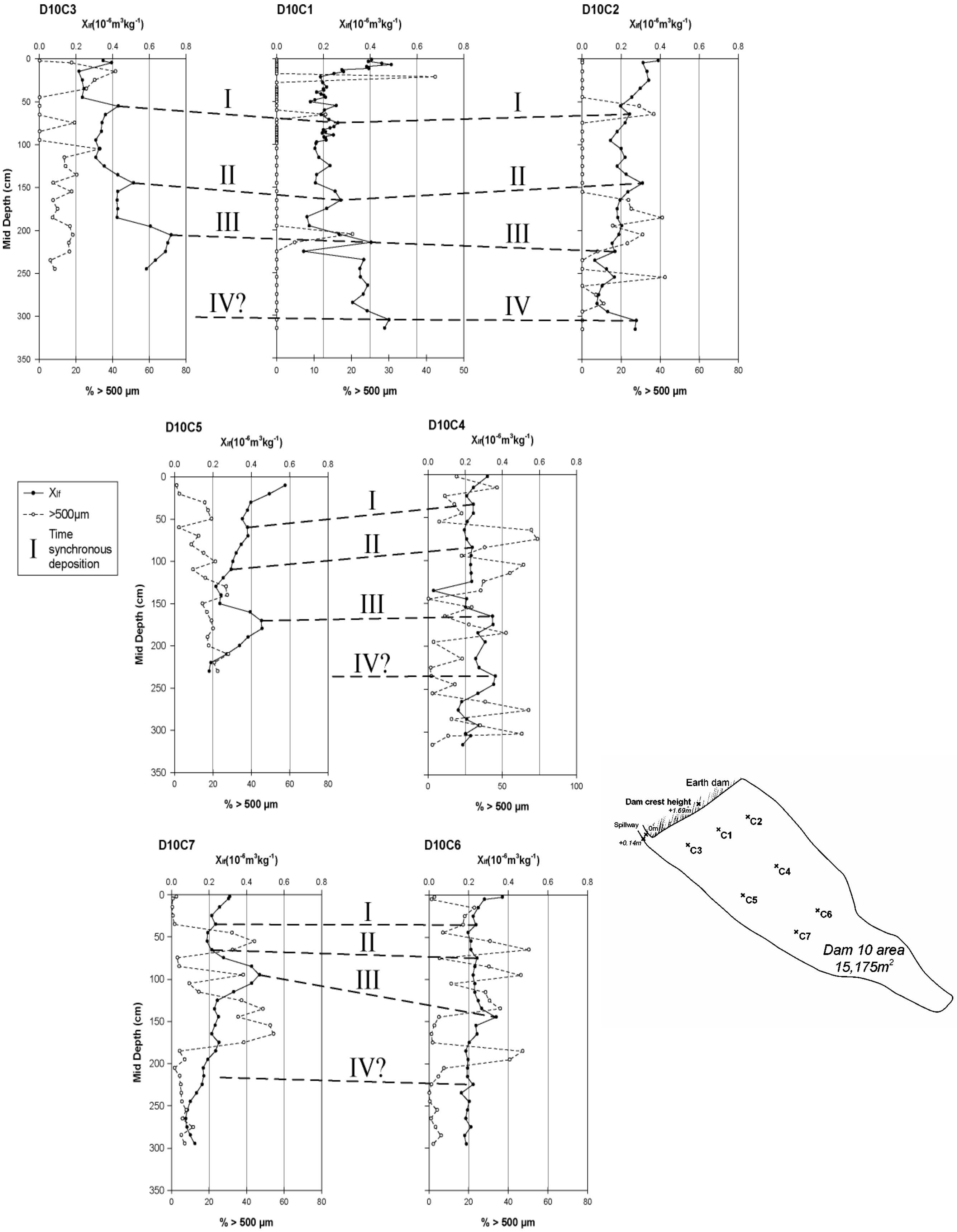

Fig. 2 Core correlation based on magnetic susceptibility (χ_{lf}) and particle size for the sediments accumulating behind Dam 10. (The inset shows coring locations in Dam 10; Fig. 1.).

Estimating sediment volume

Reservoir surface areas and sediment surface elevations relative to the spill weirs on each dam were determined during the field survey and were used to calculate: (1) initial storage volumes relative to the spill weirs, and (2) accumulated sediment volumes as a function of intermediate sediment surface elevations during reservoir infilling. (Storage relative to the elevation of the spill weirs was required in order to estimate the open water volumes for reservoir trap efficiency calculations; see below.) Volume functions $V(h)$ for each dam were based on two hypothetical basin shapes representing upper and lower bounds for the actual reservoir volume. The hypothetical upper bound was specified as the case of a reservoir with near-vertical sides, and the lower limit as a reservoir with linearly-sloping sides (i.e. a v-shaped cross section).

For a container with three vertical sides (two flanks and the dam wall) and one side of constant slope (the up-catchment side), the surface area at a given depth is linearly related to that depth:

$$A(h) = A^*(h/H) \tag{1}$$

where A is the contemporary reservoir surface area, h is sediment elevation relative to the spill weir and H is current total depth of sediment behind the dam.

To get an expression for the volume as a function of h, $A^*(h/H)$ is integrated with respect to h which is equivalent to summing $A^*(h/H)^*dh$ for an infinite number of infinitely thin dh intervals which yields:

$$V_{\max}(h) = 2V_{\min}(h) \approx Ah^2/2H \tag{2}$$

Both estimates make use of an assumption of constant slope of the underlying basin topography perpendicular to the dams.

This approach was taken in order to provide upper and lower bounding estimates with a high degree of confidence in the absence of detailed data on underlying topography. Percent errors will be the same for incremental changes between dated horizons (Table 1) as they are for the whole reservoir volumes; plus or minus 50%. Table 2 gives the resulting upper and lower limits and the arithmetic mean volume of the two, which is taken as the best estimate for dividing up the sedimentary record.

Table 2 Upper and lower limits to sediment volume estimates**.**

	Dam 7	Dam 10
Upper limit of volume (m^3)	43 200	36 960
Lower limit of volume (m^3)	21 600	18 480
Average volume (m^3)	32 400	27 720

Trap efficiency

Conventional trap efficiency (TE) models require estimates of both the capacity of the reservoir and of the annual inflow and use the capacity:inflow ratio to model the TE of the reservoir (Heinemann, 1981; Foster *et al*., 1990). Direct measurement of runoff has not been undertaken at the study sites but runoff ratios for South Africa are low by global standards (<10%) and, for the Klein Seekoei catchment, the estimate is <5% (Basson *et al*., 1997; Meadows & Hoffman, 2002). It is likely that the runoff ratio is higher in small catchments and we have therefore used the upper value (10%) in order to provide conservative estimates of TE for the two reservoirs. Annual rainfall data from the Middelburg meteorological station were used to provide average annual rainfall for the 70-year sedimentary histories at both sites.

Initial reservoir volumes and volumes of sediment accumulating between dated horizons in the sediment cores were calculated in the following way. The TE for the original storage capacity was estimated using the sediment volume calculations described above. Estimates of changing storage volume through time were obtained using the depth of infill to adjust the reservoir storage capacity, and at the time of survey were estimated from the equation of Heinemann (1981):

$$TE = -22 + (119.6C/I)/(0.012 + (1.02C/I)) \quad (3)$$

where C/I = capacity inflow ratio.

Calculated TEs ranged from >90% at the time of initial construction of the dams to <50% at the time of the 2003 survey.

Reconstructing sediment yield

The volumes of sediment accumulating in the reservoirs between each time zone were estimated by combining sedimentation rates with trap efficiency estimates. Average, maximum and minimum sediment yields are shown in Fig. 3, which use minimum and maximum (plotted as error bars) and average trap efficiency estimates (solid lines) for each time period. These data were

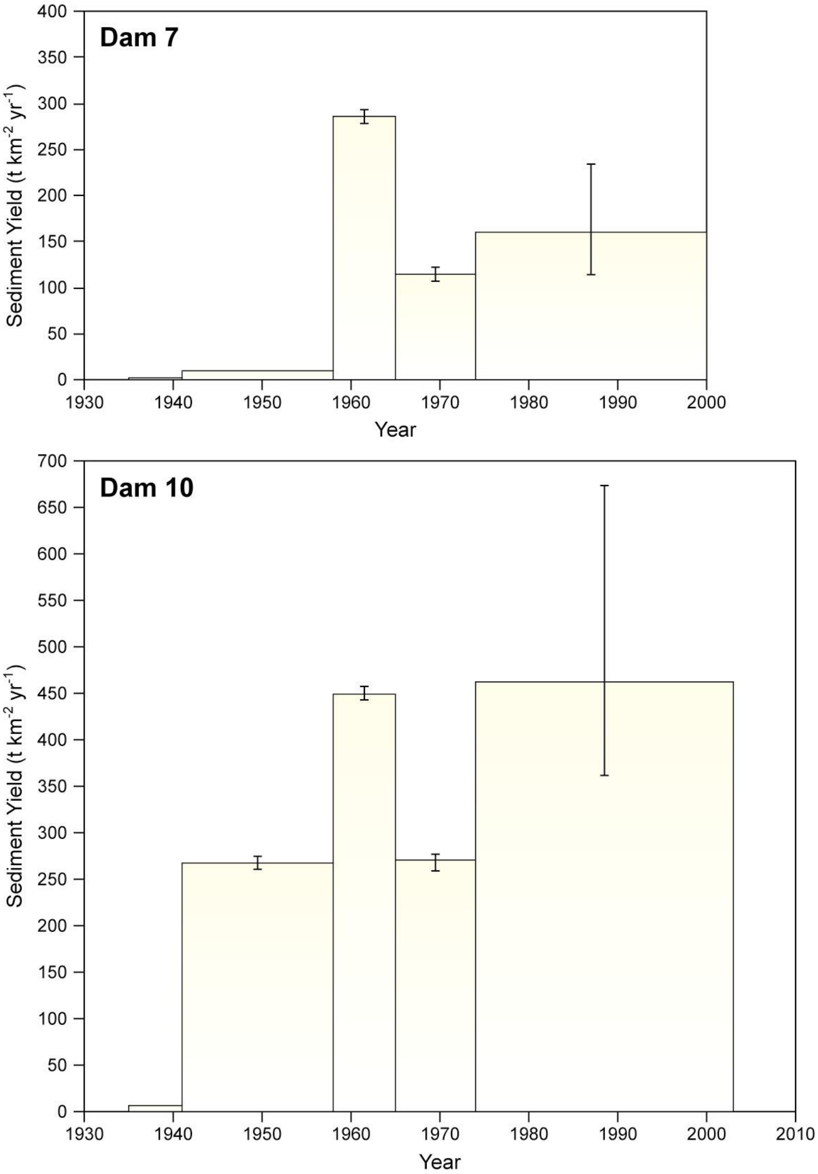

Fig. 3 Reconstructed sediment yields from the two farm reservoirs (error bars represent the range of sediment yield estimates derived from assuming maximum and minimum trap efficiencies between each dated sedimentary layer).

subsequently converted to sediment yields using the average density for each reservoir of approx. 1 t m^{-3} reported by Foster *et al.* (2007). The specific sediment yield was obtained by dividing the mass of sediment stored between each dated horizon by the number of years represented and the catchment areas of Dam 7 and 10, respectively.

DISCUSSION AND CONCLUSIONS

The estimates presented here show the first attempt in Southern Africa to reconstruct the recent history of sediment transport and, while the error bars of Fig. 3 are relatively wide and only encompass minimum and maximum estimates associated with variable trap efficiencies, it is likely that the trends are more reliable than the absolute estimates of yield. Given the close proximity of the two catchments to each other it seems unlikely (though not impossible) that they have experienced substantially different rainfall inputs historically, yet the timing of the major increase in sediment yield is dated to the early 1940s in Dam 10, but much later (late 1950s) in Dam 7. A period of valley bottom cultivation for rain-fed wheat coincides in time with the rapid increase in sedimentation rates behind Dam 7, with sediment originating from hillslope sources (Foster *et al.*, 2007). A complication in interpretation is that cultivation occurred in the larger catchment with the average lower sediment yields. This makes the high rates for 1958–1964 for the Dam 7 catchment all the more remarkable. However, Dam 10 has a much smaller catchment (1.5 km^2 compared to 6.3 km^2 of Dam 7) and the lack of substantial areas of valley bottom storage available in the Dam 10 catchment probably gives rise to a higher sediment delivery ratio, although the extensive gully networks in both catchments appear to have contributed to a high degree of connectivity in both catchments (see Foster *et al.*, 2007; Keay-Bright & Boardman, 2007).

Other work in South Africa suggests that erosion is often associated with cultivation and the abandonment of formerly cultivated land (Kakembo & Rowntree, 2003; Sonneveld *et al.*, 2005). Analysis of the patterns in stocking density reported by Boardman *et al.* (2003) suggest that stocking rates peaked in the late 1930s and have subsequently declined by a factor of ~5 to the present day. The rise in the sediment yields of Dam 10 appear to correlate in time with the peak in stocking rate yet the yields have subsequently remained high. The trends in sediment yield suggest that, despite the abandonment of cultivation and the significant reduction in stocking density, the landscape is showing little evidence of recovery from initial disturbance. There are many factors that might determine why the landscape has not returned to pre-baseline levels, one of which is that the once widespread Karoo grasses have yet to re-establish their presence to an extent that would be reflected in a decline in sediment yield. Recovery may take several more decades, even at significantly reduced stocking rates. An increase in the magnitude of daily rainfall since the late 1960s, as established from an analysis of the Middelburg rainfall record (Foster *et al.*, 2007), has probably also helped to maintain high sediment transport rates.

The absolute sediment yields to the two reservoirs is high by global standards for predominantly grazed catchments with post-disturbance estimates of approx. 150–300 t km^{-2} $year^{-1}$ for the Dam 7 reservoir and 250–450 t km^{-2} $year^{-1}$ for the Dam 10 reservoir. The estimates are of a similar order of magnitude to those of a temperate environment in Australia, with twice the annual rainfall, where Erskine *et al.* (2002) reported sediment yields for contrasting small basins of 710 (cultivated), 330 (grazed pasture) and 310 t km^{-2} $year^{-1}$ (woodland).

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