Sediment source tracing in the Thina catchment, Eastern Cape, South Africa

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Abstract The Mount Fletcher Dam on the Thina River, South Africa, was completed in 2008; 33% of its storage capacity has since been lost to sediment deposition. Highly erodible soils developed from mudstones and shales that dominate the lower catchment lithology are a likely source of sediment. Soils developed from basalt located higher in the catchment are less erodible, but steep slopes increase the erosion potential. As these two soil types have distinctive magnetic signatures, the reservoir sediment should provide a record of its main source area. Magnetic signatures from a sediment core revealed a cyclical pattern of sedimentation, with alternating high and low values that may be linked to the passage of floods. These magnetic signatures do not match those of mudstone/shale-derived soils, and point to a significant but variable input of basaltic sediment. A number of hypotheses are proposed to explain this anomaly. Implications for catchment restoration are discussed.

Key words land degradation; gully erosion; sediment tracing; magnetic signatures; watershed restoration

INTRODUCTION: THE RESEARCH CONTEXT

The Maluti-Drakensberg escarpment has strategic importance in South Africa, supplying 25% of the country's surface water (Maloti Drakensberg Transfrontier Project, 2007). It is also reputed to have high sediment loads resulting from a combination of high rainfall intensities, steep slopes, erodible soils and land-use practices conducive to erosion. The Mzimbuvu River, the subject of this paper, is one of the largest in the region (Fig. 1 insert), with a mean annual water yield of 2851 Mm^3 (Midgley *et al.*, 1994). Its entire basin of 19 840 km^2 is located in the former black homeland state of Transkei, still largely undeveloped in terms of modern commercial agriculture and water resource infrastructure. There is pressure to develop both the land and water resources in the catchment to improve local wellbeing and to augment the national water supply. A 600 Mm^3 dam on the Mzimvubu has recently been proposed as part of a regional development initiative.

Land degradation was identified as a serious problem in the Transkei state in the early 1950s by Tomlinson (1955) who estimated that 30% of the area was badly eroded and 44% moderately so. Combating erosion was one aim of the policy of Betterment Planning implemented from 1963 (de Wet, 1989; McAllister, 1989), but the imposition of practices antagonistic to local cultural norms resulted in resistance to the policy and erosion continuing unabated (McAllister, 1989; Khan, 1994). In 1997 Hoffman & Ashwell (1997) identified the Mt Fletcher Magisterial District in the upper Mzimvubu as one of the eight municipalities in the Eastern Cape that had severe land degradation levels and was therefore a priority area for restoration intervention.

The national and local importance of the upper Mzimvubu catchment as a water supply area, coupled with its degraded state, prompted a feasibility study of implementing a Payment for Ecosystem Services (PES) project (Maloti Drakensberg Transfrontier Project, 2007) in the upper Thina and Kinara catchments, tributaries of the Mzimvubu. In 2010, the Watershed Services Project (WSP) was initiated as a pilot project further evaluating the potential for implementing PES. The project aims to combat accelerated soil erosion in the catchment, reduce silt loads in the river and enhance baseflows through fire management, grassland rehabilitation, gully and wetland rehabilitation, livestock control and grazing management (WSP, 2010). The project is co-funded by the Department of Water Affairs' Working for Water Programme and the United Nations Environment Programme (UNEP).

The Maloti Drakensberg Transfrontier Project (2007) used hydrological models to predict changes in catchment runoff and sediment yield following modified land-use practice. Streamflow data for the area are limited and unreliable and flow-related sediment data are entirely absent so

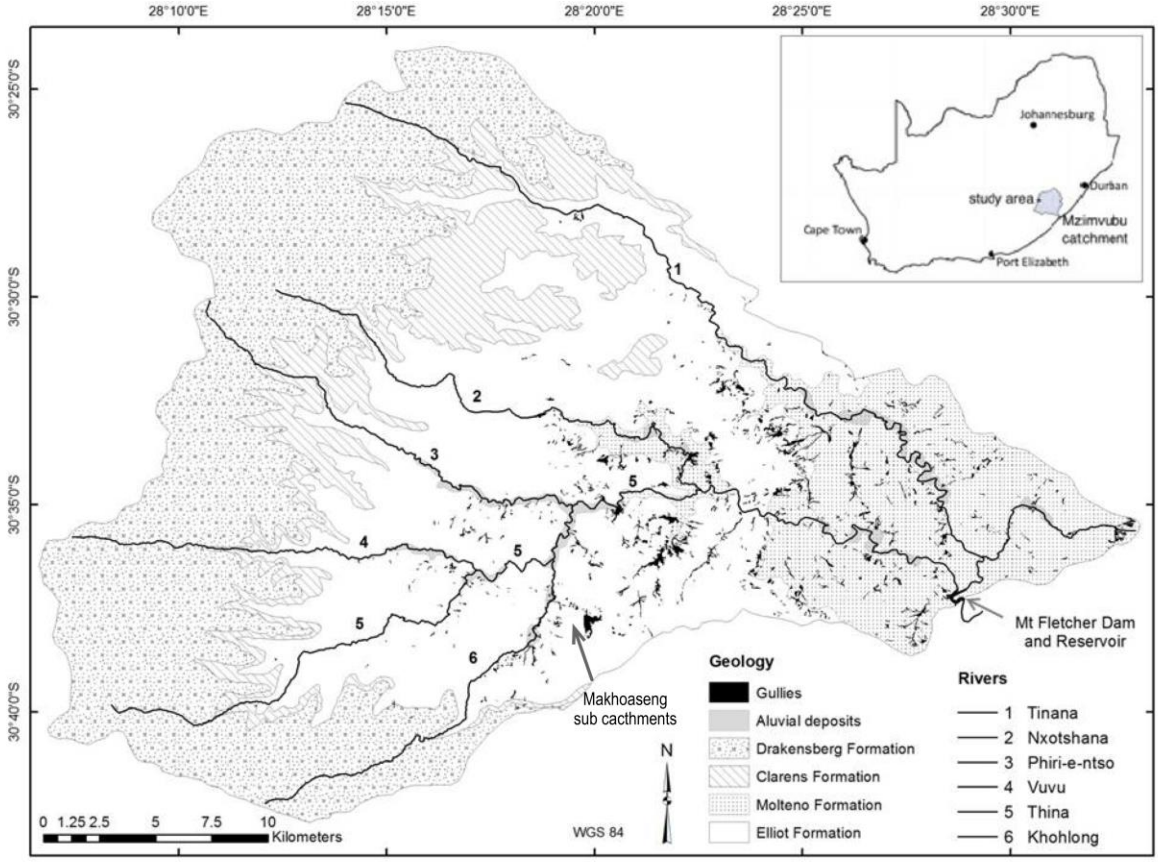

Fig. 1 Location of study area and geology of the Mt Fletcher Dam catchment. Dolerite dikes are widespread but not shown. (Gully data from Le Roux *et al*., 2010).

model results are unverified. An effective rehabilitation programme for this catchment needs to be based on good knowledge of sediment processes; rehabilitation needs to target the most significant present-day sediment sources. Sediment fingerprinting techniques are being used increasingly to identify sources of sediment deposited in sink areas such as wetlands and reservoirs (cf. Hatfield & Maher, 2009) and have been used successfully in the Karoo of South Africa (Foster *et al*., 2007, 2012; Rowntree & Foster 2012). Preliminary results on the use of environmental magnetism to fingerprint sediment in the Thina catchment are described in this paper.

THE THINA CATCHMENT: SEDIMENT SINKS AND SEDIMENT SOURCE AREAS

An important condition for successful sediment source tracing is the presence of a sink that is able to trap sediment from upstream. The Mount Fletcher Dam on the Thina River (latitude 31 01 54.5 ° S, longitude 28 53 04.2 ° E, altitude 1374 m a.s.l.) was completed in October 2008, since when 70% of its 500 000 m^3 storage capacity has been lost to sediment deposition. The dam therefore provides an active sink that enables investigation of recent sediment processes. The 771 km^2 catchment extends to the top of the Drakensberg Escarpment at an altitude of 2700 m a.s.l. Average annual rainfall over the catchment is estimated to be 800–1000 mm, concentrated in the summer season between December and February (Lynch, 2003). Slopes are steep, especially on the escarpment, and valley floors are narrow, limiting floodplain development. The main vegetation type over the catchment is acid grassland, known locally as *sourveld*. Burning is a common practice to improve palatability of spring grazing.

Geology is an important factor determining soil erodibility. Shale and mudstone of the Elliot and Molteno formations dominate the catchment lithology at low altitude, and basalts of the

Drakensberg Formation at high altitude (Fig. 1). Smaller areas of sandstones (Clarens Formation) separate these two lithologies. Soils are heavily leached. Those developed from Elliot Formation shales and mudstones are dispersive and highly erodible (Laker, 2000) and are often deeply dissected by gullies (Fig. 1); they are a likely source of sediment. Soils developed from basalt are less erodible, but steep slopes increase the erosion potential. As these two soil types have distinctive magnetic signatures, the sediment in the dam should provide a clear record of its main geological provenance.

Dardis *et al*. (1988) and Dardis & Beckerdahl (1988) describe gully erosion in the Transkei caused by piping under saturated soil conditions. Le Roux & Sumner (2011) found piping-dominated gully erosion to be associated with mudstones of the Tarkastad Formation in the Tsitsa catchment, a tributary of the Mzimvubu adjacent to the Thina. Colluvial soils developed from Elliot sediments are especially prone to piping. Mzobe (2012) identified similar gullies in the Taung catchment, a small subcatchment of the Makhoaseng tributary of the Thina, dominated by the Elliot Formation. Piping, and subsequent pipe collapse, has resulted in severe incision of colluvium by a dendritic gully network. Mzobe (2012) has shown that gully erosion in the Makhoaseng catchment was probably initiated as late as 1980 after the local people were moved from valley floor settlements onto ridges, closer to roads and other amenities. Valley bottomland was abandoned and was soon deeply gullied. Dissection of abandoned cultivated land has also been shown to be a widespread problem in other homeland areas of the Eastern Cape (Kakembo & Rowntree, 2003) and in the Mediterranean (Arnaez *et al.*, 2011). Volumes of sediment lost were estimated by Mzobe (2012) to be 284×10^3 t for the 2.14 km^2 Taung catchment, and 61×10^3 t for the 5.73 km^2 adjacent catchment where incision of a valley floor wetland by a single channel has taken place.

The rapid siltation of the Mount Fletcher Dam has given further justification to the PES project reported above. The question is, what is the source of this sediment, and where should erosion control measures target? The erosion in the Makhoaseng catchments observed by Mzobe (2012) is believed to be typical of the Elliot Formation within the Thina catchment. Large volumes of sediment have been lost since the 1980s, indicating high sediment yields from catchments underlain by the Elliot Formation. The intense gully networks of the Elliot Formation were therefore assumed to be the main source of sediment infilling the Mount Fletcher Dam since construction in 2008. A comparison of magnetic signatures from the Makhoaseng catchments with those from a sediment core taken from behind the dam wall would help to confirm or refute this hypothesis.

METHODS

An 84-cm core was extracted from behind the wall of the Mount Fletcher Dam in August 2011 using a Mackereth corer that had a maximum core tube of 1 m. Thus the top section of the sediment was sampled, probably representing sediment deposited during intense storms over the summer of 2010/2011. This was thought to be sufficient to give a representative sediment signature. Potential source samples were collected from gully sidewalls (31), surface soil from intact colluvium (11) and shallow soils on hillslopes (32) in the Makhoaseng catchments. The sampling depth for colluvium and shallow hillslope soils ranged from 7 to 15 cm. While the Taung catchment is dominated by the Elliot Formation, the watersheds of the two catchments adjacent to Taung extend into the Drakensberg Formation basalts, so that the soils may also have a local basalt component derived from down-slope or down-channel movement of sediment. These two catchments both contain former wetlands on the valley floor, now dissected by linear gully systems. They are collectively termed the wetland catchments in the analysis presented below.

Source sampling outside Makhoaseng tended to be opportunistic due to generally poor accessibility by road, steep slopes and the focus of Mzobe's research being the Makhoaseng catchments. Eleven samples were taken along the course of the main Thina River, from close to the basalt/shale boundary to immediately upstream of the dam. Four of these were from the channel bed, the rest from the surface of channel banks. Additional samples were taken from a gully wall in the Elliot Formation outside the Makhoaseng catchments and from high altitude basalt soils. Basalt samples were taken from a small upland floodplain at depths of 10 and 45 cm, and from a footslope consisting of basalt-derived colluvium, at depths ranging from the soil surface to 40 cm. An additional sample was taken from the soil surface close to the drainage divide.

The core was cut into 2 cm subsamples, giving a total of 35 samples. Soil colour and soil texture were determined using a Munsell Colour chart and hand texturing, respectively, before samples were dried at 40°C. The magnetic signature was determined on the less than 63 micron fraction using a combination of mass specific magnetic susceptibility (χlf), anhysteretic susceptibility (χARM), saturation remanence (SIRM), Hard Isothermal remanence (HIRM) and the S ratio, following procedures used by Rowntree & Foster (2012). Instruments used were the Bartington Instruments® MS2 susceptibility meter with an MS2 B dual core sensor, a Molspin® rotating magnetometer, a Molspin® a.f. demagnetiser and a Molspin® pulse magnetiser. Corrections were made for organic content measured by loss on ignition at 450°C. Further details of methods and an explanation of terms can be found in Walden *et al.* (1999), Foster *et al.* (2008) and Hatfield & Maher (2009). The source samples were similarly treated and the same procedure used to derive their magnetic signature.

RESULTS

The downcore variation in χlf, χARM, SIRM and HIRM all follow a similar pattern, but that for the S ratio differs (Fig. 2). The first four variables display a series of cycles between high and low values. It is tempting to speculate that these represent a series of flood waves, with a cyclical pattern of sediment from different sources being deposited through the wave.

The S ratio is more consistent throughout the core, but there is evidence of an increase at between 14 and 24 cm depth. A high S ratio is indicative of the mineral magnetite, whereas low values indicate haematite.

Figure 3 shows the relationship between and χARM and χlf and SIRM for all samples, while Fig. 4 expands the lower section of these graphs to show the relationship for samples with low signature values. The core samples all have χlf values either close to or less than 1. Samples with higher values (Fig. 3) include most of the river channel samples and those taken from basalt soils. This suggests that the river samples all contain significant proportions of basalt-derived sediment.

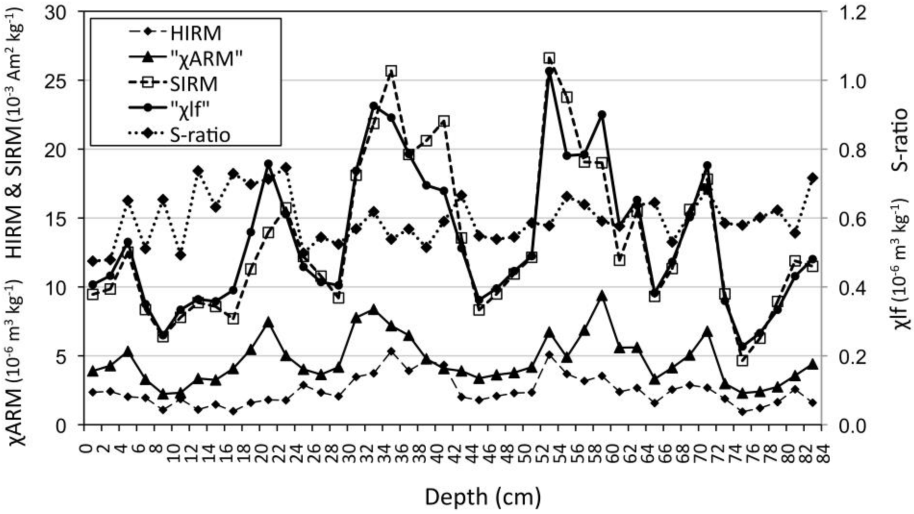

Fig. 2 Downcore variability of magnetic signatures, Mt Fletcher Dam core.

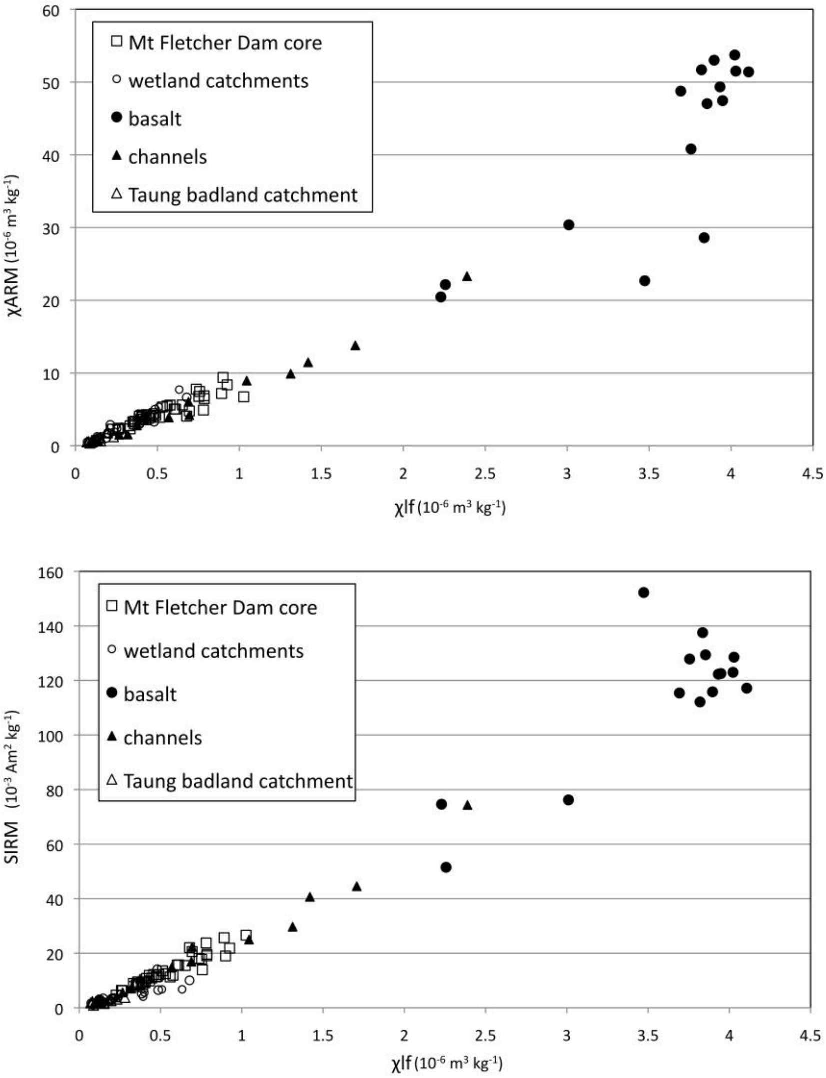

Fig. 3 Relationship between χARM and χlf and SIRM, for all samples. Core samples are all located in the tight cluster at the bottom left.

More detail can be seen in Fig. 4. In the case of both χARM and SIRM, the core samples have distinct signatures when compared to the Taung catchment, but overlap with the wetland catchments at Makhoaseng. This overlap is less apparent when relating SIRM and χlf as the wetland catchment samples diverge from the core samples, with relatively low SIRM values at higher χlf. These results, therefore, do not confirm the Taung type sediments as being the main source for Mount Fletcher Dam. Figure 5 presents a plot of χlf against the S ratio for all samples. Two groups can be distinguished. The first group includes basalt soils, core samples and most river samples; these have higher S ratio values, lying between 0.4 and 0.8, but with the majority close to 0.6. The second group consists of samples from the two Makhoaseng catchments. The S ratios for most samples in this group fall between 0.1 and 0.4; the Taung samples range from 0.08 to 0.4, while samples from the wetland catchments range from 0.14 to 0.64. These two groups represent magnetite-dominated and haematite-dominated signatures, respectively. Magnetite is likely to be associated with basalt-derived sediments, whereas haematite is associated with the sedimentary shales and mudstones. The outliers in the wetland catchments with higher S ratios can be explained by inferring inclusion of basalt material from higher up the catchment slopes.

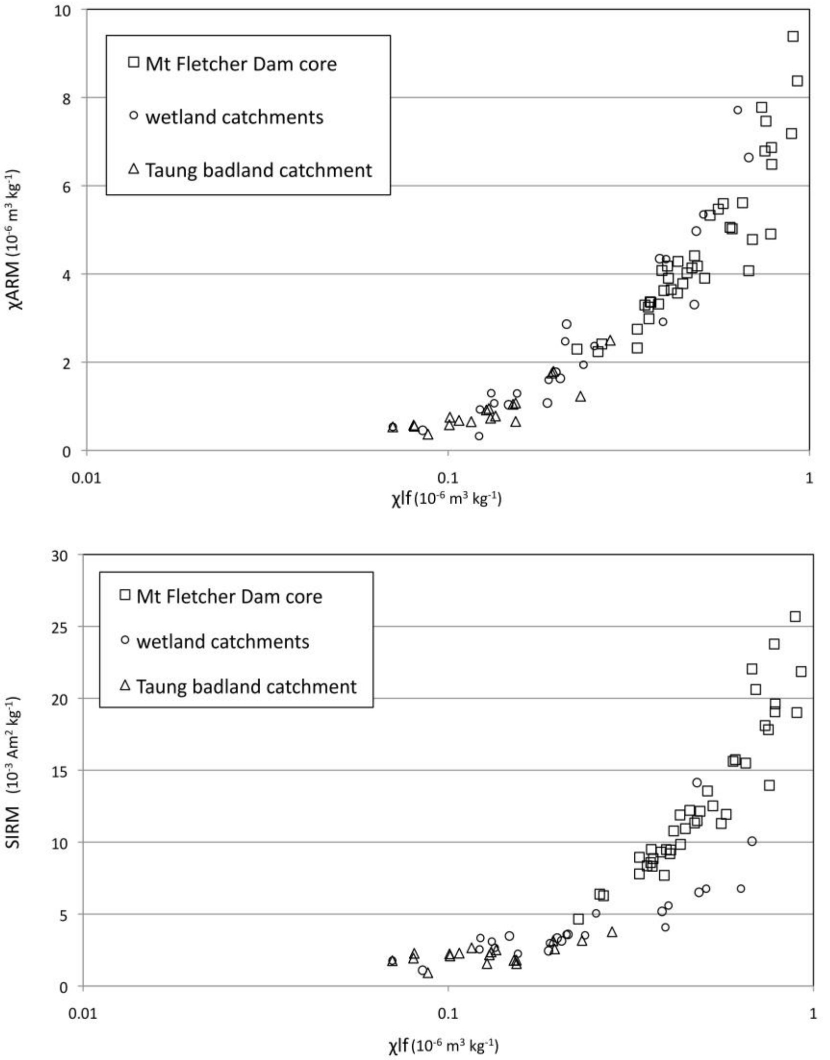

Fig. 4 Relationship between χlf and χARM and SIRM for Mt Fletcher Dam core and Makhoaseng catchments.

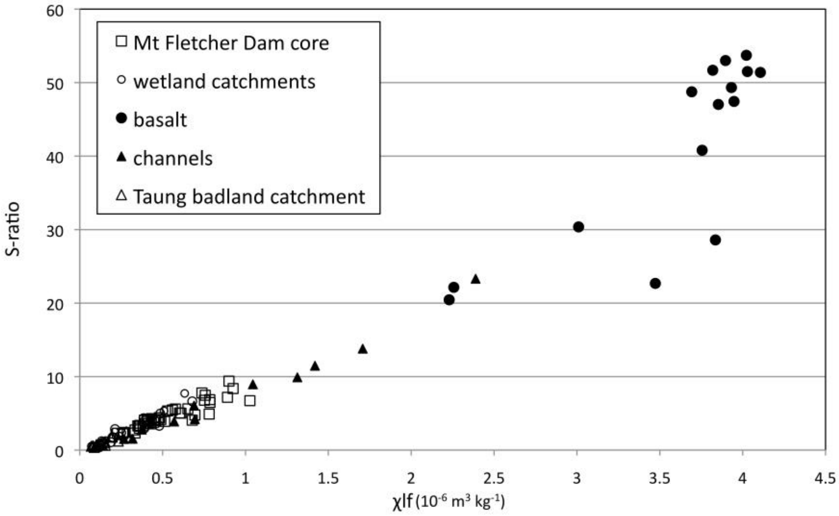

Fig. 5 Relationship between χlf and S ratio, all samples.

DISCUSSION

The results of the sediment tracing work do not confirm the shales and mudstones of the Elliot Formation as the primary source of sediment deposited in the Mount Fletcher Dam. There is a clear basalt signature evident in the core samples, which is also seen in most of the river samples. This does not mean that the samples are only derived from basalt, as a small amount of magnetite can dominate the signature. The core samples are therefore likely to be a mixture of shale/ mudstone-derived sediment and basalt-derived sediment. The relative amounts vary through a flood event, with basalt from the upper catchment dominating at times, and the shale/mudstone sediment contribution increasing at others.

Shales and mudstones are derived from fine sediments in the silt and clay range, which therefore dominate the derived soil. During high floods that wash over the dam wall, much of the suspended silt and clay will be lost downstream, only settling out during the flood recession. In contrast, basalt produces coarser textured sediment that can only be transported during high flows. The peak signatures in Fig. 3, therefore, may relate to flood peaks that are able to bring in coarser basaltic material, whereas the troughs may relate to the silts and clays of the shales and mudstones. Analysis of the particle size distribution of the sediment core samples will allow this hypothesis to be tested further.

A number of possibilities can be put forward to explain the limited contribution from the badly eroded Elliot derived colluvium to the Mount Fletcher Dam sediment. First, as indicated above, the low retention capacity of the dam allows much of the fine sediment carried in suspension to pass over the dam wall, rather than settling behind it. This means that settling only takes place at low flows when the sediment concentration is low. The overall contribution to the sediment in the Dam is therefore small. Second, although the gullies are dramatic landscape features and represent a significant soil loss since their initiation around the 1980s, they may be stabilizing and therefore their contribution to catchment sediment yield is reduced. Foster *et al.* (2007) have pointed to comparable processes operating in the Karoo of South Africa, where linear valley floor gullies, similar to those in the wetland catchments, no longer contribute significant amounts of sediment to downstream sinks. The basalt soils are associated with steep slopes in the upper catchment, providing suitable conditions for sheet wash and rill erosion. Heavy grazing and burning exacerbate the erosion potential.

The results presented in this paper are part of an ongoing research project and clearly do not yet point to firm conclusions as to the main sources of sediment entering the Mount Fletcher Dam, or threatening the life span of future dams further downstream. Source samples were collected mainly from the Makhoaseng catchment because this was the primary research focus. A better spread of samples from the entire catchment is needed. A mixing model as proposed by Collins *et al*. (1998) and Collins & Walling (2002) could be used to estimate the relative proportions of different sources, thus accounting for the tendency of magnetite to dominate the signature. It would also be useful to collect samples during floods to capture the suspended sediment portion. Fire is another factor that should be investigated as fire has a significant effect on magnetic signatures (Oldfield & Crowther, 2007). None-the-less, the results are significant in that they are a reminder that the most obvious manifestation of erosion is not necessarily the main source of sediment in a catchment, and restoration projects that are concerned with reducing sediment yield need to be cognizant of all possible sources. Targeting intensely gullied areas that are beginning to stabilize can be both costly and ineffective as a conservation measure.

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