Hillslope erosion and post-fire sediment trapping at Mount Bold, South Australia

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Abstract Successful placement of sediment traps requires an understanding of how hillslope morphology influences erosion. Following the 2007 Mount Bold wildfire, in South Australia, a 1 in 5 year rainfall event resulted in the failure of many sediment traps due to substantial sediment movement within the reservoir reserve. This study assesses how hillslope morphology can influence post-fire surface erosion and the subsequent appropriate placement of sediment traps. Erosion pins and sediment traps were used at five different sites to measure hillslope surface change and trapped sediment volumes. Terrestrial laser scanning was used to model surface change where slope gradients are 1:2 or greater. Surface change was assessed in relation to slope gradient, slope length, cross-slope curvature, hillslope position and fire severity. The results suggested a threshold for substantial increased sediment yield at slope gradients of 1:2. The findings also suggested that concave cross-slope curvatures were associated with significantly larger amounts of sediment movement.

Key words water reservoir; sediment trap; erosion pins; terrestrial laser scanning; slope gradient; cross-slope plan curvature, South Australia

INTRODUCTION

Wildfires influence soil surface processes resulting in the potential for increased sedimentation of reservoirs and impacts on water quality (Smith *et al*., 2011). In order to reduce potential post-fire sedimentation, reservoir managers have used, amongst various mitigation measures, erosion barrier sediment traps (Hobson *et al*., 2004; Robichaud, 2005; deWolfe *et al*., 2008) with varying levels of success. Considerable research has been conducted into the design and construction of sediment traps (Robichaud & Brown, 2002) and, to a lesser degree, the success of sediment traps (Robichaud *et al*., 2000; Morris *et al*., 2008; Robichaud, 2009; Fox, 2011). Reservoir managers are often limited in material resources and staff time, resulting in the need for sediment trap placement to be effective and efficient. Effective trap placement in a catchment requires an understanding of hillslope morphology and associated erosion processes in order to anticipate the key potential sediment sources and risks for mobilisation and delivery towards receiving water bodies.

Substantial research has been conducted on post-fire erosion processes (Shakesby & Doerr, 2006; Shakesby *et al*., 2007; Shakesby, 2010). Predicting post-fire erosion hazards often involves applying erosion models (Fernandez *et al*., 2005; Fox *et al*., 2006; Miller *et al*., 2011). Many of these models are not applicable to steep gradients above the angle of repose (Lamb *et al*., 2011). Although the influence of slope gradient is well established in the theory of erosion (Sheridan *et al*., 2003), the actual application of theory to the installation of post-fire sediment traps in relation to slope gradients needs further investigation. When applying post-fire erosion models, hillslope morphology is often simplified to incorporate the slope length and slope gradient (Merritt *et al*., 2003; Fernandez *et al*., 2005; Fox *et al*., 2006). Rieke-Zapp & Nearing (2005) found that slope shape had a significant impact on rill patterns, sediment yield, and runoff production when modelling under controlled laboratory conditions. The irregular surface of the slope, such as the profile or the cross-slope (plan) curvature, is often overlooked (Rieke-Zapp & Nearing, 2005) or incorporated into modelling by dividing the topography into smaller morphological units (Di Piazza *et al*., 2007).

There is a need to determine how hillslope morphology can influence post-fire surface erosion. Sediment trapping after the Mount Bold 2007 wildfire, in South Australia, provided a case study where hillslope erosion could be measured in relation to sediment trap success. The aim of this study was therefore to assess hillslope surface erosion in the context of post-wildfire sediment trapping in a catchment. The key components of the research involved: (a) quantifying hillslope surface change using erosion pins, terrestrial laser scanning and sediment traps after a 1 in 5 year rainfall event; (b) assessing the influence of slope gradient, slope length, cross-slope curvature, hillslope position and fire severity in relation to surface change; and (c) evaluating the success of sediment trap placement in relation to hillslope morphology.

STUDY AREA

The Mount Bold Reservoir reserve is located in the Southern Mount Lofty Ranges, on the Onkaparinga River, approximately 35 km southeast of Adelaide. The area lies in a temperate climatic zone with warm, dry summers and cool, wet winters. The mean annual rainfall at Mount Bold from 1939 to 2010 was 768 mm (Australian Bureau of Meteorology Mount Bold weather station, ID 023734; 35.07°S, 138.41°E; elevation 251 m). The geology of the area is comprised of the Bungarider subgroup containing the Stoneyfells quartzite and Woolshed Flat shale members, the Mundalio subgroup (Skillogalee dolomite), and the Emeroo subgroup, which contains quartzite, sandstone, dolomite and conglomerate (GSAA, 1962). The majority of the catchment has either a high or very high water erosion potential with soils being shallow to moderately deep acidic soils on rock (Soil & Land Program, 2007). Vegetation is typically *Eucalyptus* forest and woodlands, pine plantations or grasslands. The reservoir reserve contains large areas of remnant vegetation formations of Messmate Stringybark (*Eucalyptus obliqua*) associations including open forest, low open forest, woodland and low woodland (Pound, 2005).

A wildfire ignited by a suspected arsonist commenced on land adjoining the Mount Bold Reservoir on 10 January 2007 and burnt over 1500 hectares. Fire severities ranged from extreme (complete canopy and shrub defoliation with no leaves remaining) to low (leaf litter was partially consumed but the understorey was unburnt). The area had no recent fire activity with the last recorded fire being in the 1970s (EarthTech, 2004). Following the wildfire, the South Australian Water Corporation initiated emergency erosion mitigation works involving the installation of 53 sediment traps. Rain was observed nine days after the fire with a total of 46 mm falling over three days. Total annual rainfall at Mount Bold in 2007 was 760 mm (Australian Bureau of Meteorology Mount Bold weather station). Rainfall during the study period, from 10 January to 17 May 2007, totalled 225 mm, falling over 32 separate rain days. The most substantial rainfall event during this time occurred during the 82 hours to 30 April 2007. On the basis of rainfall intensity–frequency–duration analysis, data from the Houlgraves weather station (Australian Bureau of Meteorology Houlgraves weather station ID 023913; 35.05°S 138.44°E; elevation 250 m) located on the boundary of Mount Bold Reservoir, suggested that the 30 April rainfall event had a 1 in 5 year average recurrence interval.

Five hillslopes, sites A to E (Fig. 1), were selected for study, on the basis of all being located in the water reservoir catchment, within a distance of 5 km, and having similar elevation, geology and soil. Site A was distinctively different to the other sites due to the steep slopes ranging from 27° to 50°. Site B differed due to the convex/linear slope profile and linear cross-slope curvature, and the presence of occasional pine trees. Sites C and D had similar vegetation structural types and slope properties to each other, but site D was unburnt. All sites had been burnt during the 2007 wildfire, except for site D. Unlike the moderate to high severity fires affecting sites A to C, Site E was located within a sub-catchment that had been subjected to a very high severity fire. A sediment trap designed to mitigate sediment delivery to the water reservoir was located below each of the experimental hillslopes.

METHODS

Hillslope surface movement was assessed using erosion pins, terrestrial laser scanning and sediment traps. Erosion pins were used to monitor surface level changes following the wildfire at

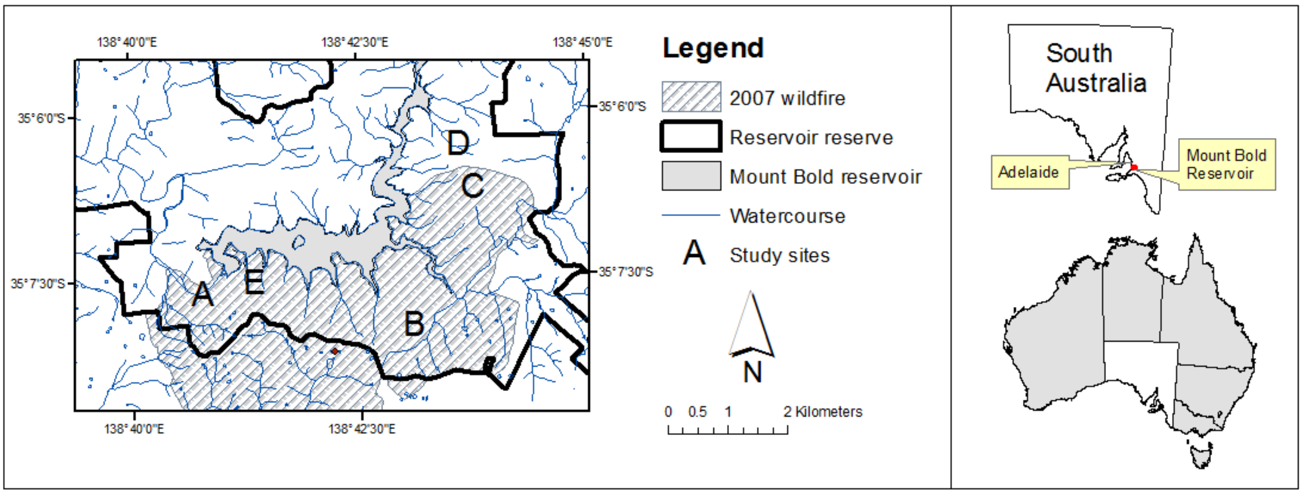


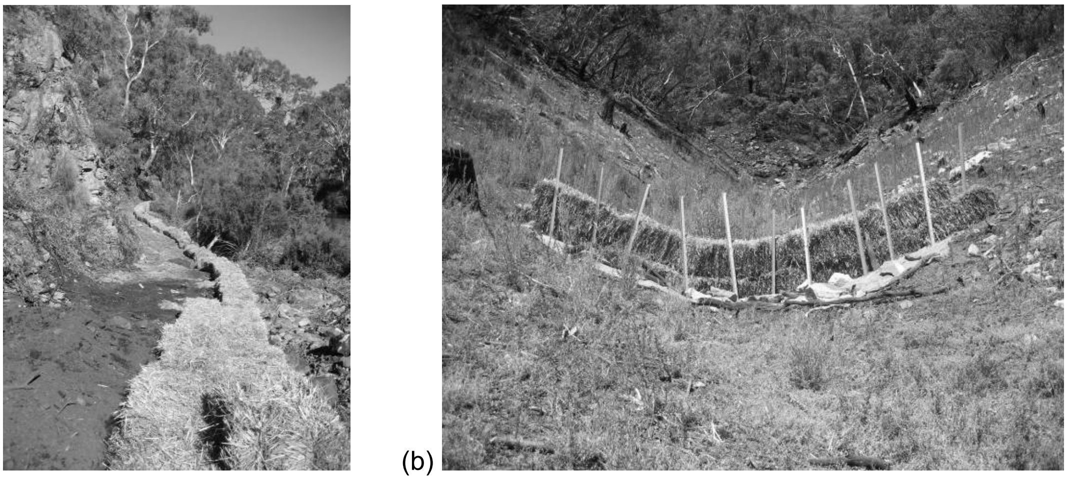
Fig. 1 Location map of the five study sites (A–E) at the Mount Bold reservoir in South Australia.

the five experimental hillslope locations. Targeting of erosion pin transects was based on the presence of an installed sediment trap, accessibility, permission from the water authority and sites of differing attributes including slope gradient, slope curvature, fire severity and vegetation type. In order to monitor differing hillslope positions the entire hillslope length was assessed, where possible, at 10-m intervals with replication by having two transects at each slope. Along four of the experimental hillslope profiles, sites B–E, two transect lines of pins were installed 10 m apart. To reduce operator bias when installing the pin, a tape measure was used to locate the pin entry point. At site A, one transect line was installed along the foot of the slope due to the steep slope gradient making the terrain inaccessible.

Installation of the erosion pins occurred between January and April 2007, and all pins were measured in May 2007. Pins were measured from the top to the ground surface using either callipers or metal rulers. A total of 126 marine grade stainless steel pins were installed. The pins were 4.7 mm in diameter and 500 mm long, except for 5 pins at site A that were 8 mm by 1500 mm. Erosion pins have previously been used to monitor hillslope erosion in temperate forests (Mackay *et al.*, 1984) and alpine areas in New South Wales, Australia (Smith & Dragovich, 2008), monsoonal savannah woodlands in Northern Territory, Australia (Russell-Smith *et al.*, 2006), moorlands in Yorkshire, UK (Imeson, 1971) and pine forest in Mexico (White & Wells, 1979). Haigh (1977) described numerous sources of data contamination when using erosion pins that included factors such as disturbance during establishment, influences on the pattern of soil erosion caused by the pin presence, trampling, vandalism, environmental variation, operator error and operator disturbance. The four erosion pins that had been disturbed during the study were not included in the analysed data set.

Terrestrial laser scanning (TLS) was used to model the surface level change at site A because slope steepness made the terrain inaccessible for erosion pins. Scans were conducted using a Maptek I-Site 4400LR in February and again in May 2007. The scanner is a time-of-flight pulsed rangefinder. Surface elevation models were created using Maptek I-Site studio software. Surface elevation change was modelled between February and May 2007.

Fifty-three sediment traps were constructed by the South Australian Water Corporation for emergency erosion mitigation. The vast majority of these traps were made from hay bales, star pickets and jute matting (Morris *et al.*, 2008). This study focuses on eight of the traps (Table 1) which were installed below the five experimental hillslope sites A to E. At site A, the sediment trap consisted of a 373-m long line of hay bales adjoining a recently installed road at the hillslope bottom (Fig. 2(a)). All other traps (Fig. 2(b)) were installed in dry channel positions using either hay bales or coir logs reinforced with star pickets and tensioned wire. Sediment volumes were determined using shovels, metal rulers and tape measures.



(a) (b)

Fig. 2 Hay bale sediment traps at: (a) site A, trap 17, and (b) site C, trap 14a (images courtesy of Shayne Callis).

Table 1 Sediment trap description.

Site	Trap	Length (m)	Height (m)	Position	Material
A	17	373	0.5*	Foothill	490 hay bales, star pickets
B	21a	12	1.5	Channel	Jute matting, 14 hay bales, star pickets
C	14a	6	1	Channel	Jute matting, 12 hay bales, star pickets
C	15a	5	1	Channel	Jute matting, 12 hay bales, star pickets
D	Control	2.5	0.5	Channel	Jute matting, 2.5 coir logs, star pickets
E	1a	4	1	Channel	Jute matting, 8 hay bales, star pickets
E	1b	4	1	Channel	Jute matting, 8 hay bales, star pickets
E	1c	2	0.5	Channel	Jute matting, 2 hay bales, star pickets

*In a minority of sections the height was doubled to 1 m.

Statistical analyses of the results involved using both the net surface-level change and the absolute surface change. Absolute surface change gives a better indication of which sites were experiencing the most active sediment movement regime (Smith & Dragovich, 2008). A Kolmogorov-Smirnov statistic with a Lilliefors significance level was used to test for normality (n = 122, p < 0.05). The test confirmed that data for both the net surface-level change (statistic of 0.397) and the absolute surface change (statistic of 0.394) were not normally distributed. Non-parametric tests, including the Mann Whitney U and Kruskal-Wallis tests, were applied to the surface change data due to the non-normal data distribution. Correlations were assessed using the non-parametric Spearman rank correlation.

HILLSLOPE EROSION AND SEDIMENT TRAPPING

Hillslope surface movement

A comparison of mean net surface change between the burnt (A,B,C,E) and unburnt (D) hillslope sites yielded a net loss of –20.2 mm (SE ±12.1 mm) at the burnt sites and a net loss of –0.7 mm (SE ±0.4 mm) at the unburnt sites, a difference which is significant (Mann Whitney U test, Z = –3.171, p < 0.05). The sediment movement regime was more active across the burnt sites over the study period, with the absolute mean total surface change of 34.9 mm at the burnt sites exceeding the 1.3 mm at the unburnt site. The amount of sediment movement was higher at the burnt sites, with a third of the pin measurements exceeding ±10 mm of change compared to the unburnt site where no pins exceeded this surface change.

The mean net surface change was significantly different between the five study sites (Kruskal-Wallis test, X^2 (4, n = 122) = 13.175, p < 0.05). Burnt site A was noticeably different with change at 67% of the pins exceeding ±10 mm, and at 37% exceeding ±50 mm of change. Although to a lesser extent than site A, burnt site E also experienced substantial surface change with measurements exceeding both ±50 and ±10 mm change. Erosion pins were lost at both sites A and E. A 1500 mm erosion pin at Site A was entirely removed and lost due to a steep colluvial debris flow (pyrocolluviation). At site E, one of the 500 mm erosion pins was destabilized then washed 3 m downstream. Another pin at site E was bent by the force of material being transported during the April 2007 rain event. There was a trend for high burn severity sites to yield more sediment than moderate or very high severity sites.

Sediment yield reached a threshold when slope gradients were more than 1:2, equivalent to a slope angle of >26.6 degrees (Fig. 3(a)). There was a significant correlation between slope angle and absolute sediment movement (Spearman rank correlation, $R = 0.462$, $n = 122$, $p < 0.01$). When slopes exceeded 18 degrees, there was a nine-fold increase in mean absolute sediment movement. There was also significant correlation between slope length and absolute sediment movement (Spearman rank correlation, $R = 0.285$, $n = 122$, $p < 0.01$). Comparison of mean absolute sediment movement (Fig. 3(b)) between concave, (136.9 mm, SE ±64.0), convex (41.9 mm, SE ±12.4) and linear (5.4 mm, SE ±0.7) cross-slope curvatures were significantly different (Kruskal-Wallis test, X^2 (2, $n = 122$) = 20.554, $p < 0.05$). The greatest mean surface change occurred at foothill slope positions (–45.1 mm, SE ±25.3) or within drainage lines (–15.8, SE ±10.2). When the steepest location, site A, was not included in the statistical analysis, the foothill position mean surface change altered to 2.3 mm (SE ±2.3).

A direct comparison of burnt Site A with the other experimental sites is limited by differing erosion pin configuration. To account for this difference, surface elevation models were created using the terrestrial laser scanning. The surface elevation modelling highlighted that the greatest surface change (>1 m) generally occurred in the concave cross-slope area of the hillslope (Fig. 4). Immediately following the fire, initial sediment movement occurred as dry ravel then subsequent rainfall events resulted in colluvial debris flows. The 1 in 5 year rainfall event caused an entire 1.5 m erosion pin to be dislodged and subsequently lost within the debris flow. The terrestrial laser scanning also modelled the surface change at this erosion pin location to be >1 m.

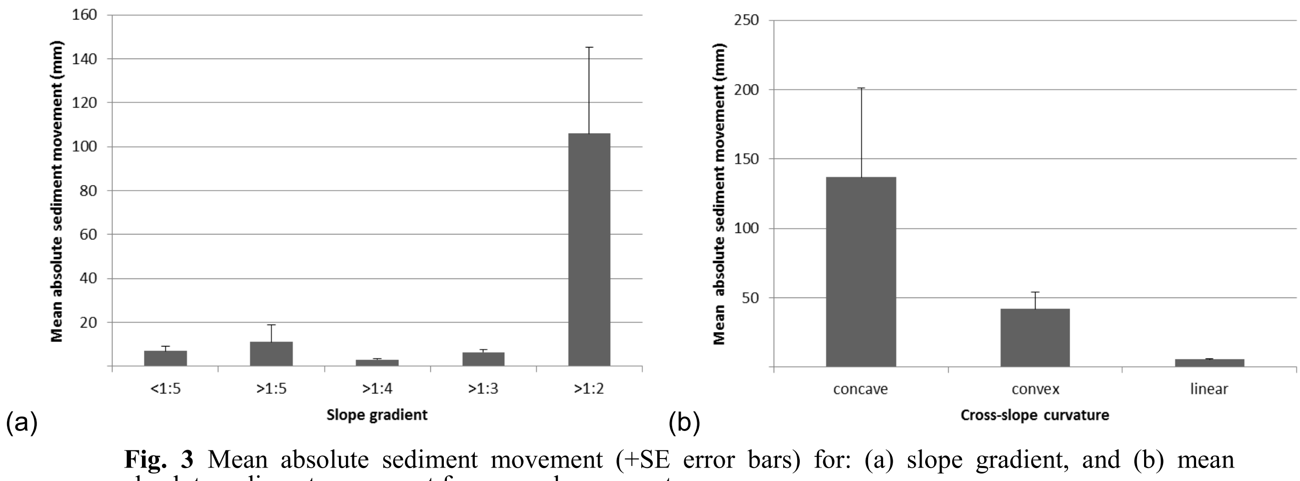


Fig. 3 Mean absolute sediment movement (+SE error bars) for: (a) slope gradient, and (b) mean absolute sediment movement for cross-slope curvature.

Sediment traps

Seventeen of the 53 sediment traps installed at Mount Bold partially failed to capture the moving sediment and debris following the April 2007 rainfall event (Morris *et al.*, 2008). Three of the five study sites (Table 2) captured sediment; however, the trap size was still not sufficient to capture all of the sediment moved. At site A, the 370-m long hay bale trap was often destroyed or breached below concave cross-slope curvatures where water flow converged. At site E, the hay bale traps were completely destroyed by the velocity of the water and the force of the transported sediment

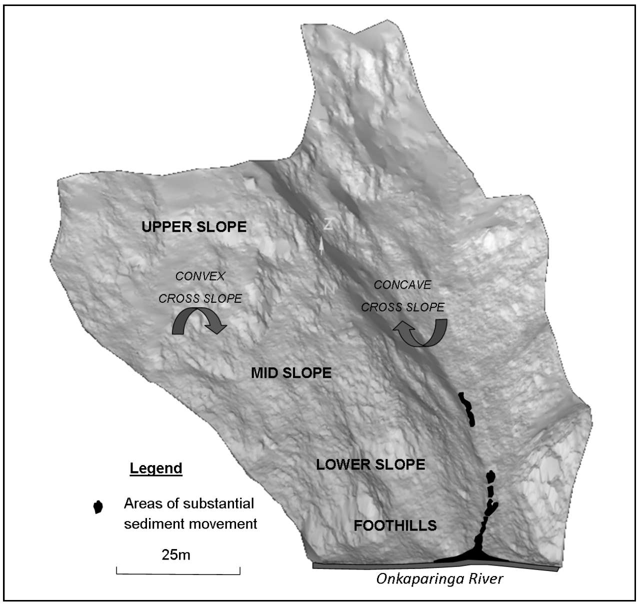


Fig. 4 Hillslope digital elevation surface model of sediment movement at site A between February and May 2007, using terrestrial laser scanning.

Table 2 Summary of trap success and the hillslope surface level change for each study site.

Study site	Trap failure	SV (m^3)	MAS (mm) (SE)	S (mm) (SE)	Fire severity	Slope degree	Slope gradient
A	Yes	>103	105.9 (39.2)	–76.7 (41.5)	M–H	27–50	1:2–1:1
E	Yes	>2.3	9.6 (3.4)	–2.5 (3.9)	VH	3–24	1:19–1:2
C	Yes	>8	7.9 (1.8)	2.6 (2.6)	M–H	0–22	1:57–1:2
B	No	0	4.9 (0.9)	4.4 (1.0)	H	0–25	1:57–1:2
D	No	0	1.3 (0.2)	–0.7 (0.4)	U	2–18	1:29–1:3

SV: Trapped sediment volume (minimum due to trap failures); MAS: Mean absolute surface level change; S: Mean surface level change; VH: very high; H: high; M: moderate; U: unburnt; (SE) Standard error.

and debris. The remaining two study sites (Table 2) contained traps that did not capture any quantifiable amounts of sediment.

The absolute mean surface change measured at site A was 10 times greater than at all other sites (Table 2). The sediment volume captured at site A was 12 times larger than the volume of sediment captured at the other sites. Sites A, D and E all had negative surface changes implying that surface erosion was the dominant sediment mobilisation process. It was only at Site A that negative values exceeded –75 mm. The sediment traps overflowed at sites A, C and E, whereas site B and the control site D did not sequester any quantifiable volumes of sediment.

DISCUSSION

Knowledge and appreciation of hillslope morphology and associated erosion processes can assist land managers in the targeting of mitigation measures for trapping mobilised sediment post-fire. In the case of Mount Bold, the capture of sediment following a 1 in 5 year rainfall event varied depending on slope properties. Similar to most post-fire studies (e.g. Shakesby & Doerr, 2006; Sheridan *et al*., 2007; Moody & Martin, 2009) surface movement increased substantially in areas that had been subjected to fire. The expected influence of fire severity on sediment movement was not detected from the data assembled, possibly due to the influence of slope properties at sites A and B.

Slope gradient and the cross-slope curvature may have influenced the differences in surface change between sites A and B. Site A was extremely steep, with the slope ranging from 27 to 50 degrees. The approximate angle of repose, where material may slide down the surface, is 34 degrees for dry sandy soil. Post-fire dry ravel gravitational movement, as observed by Lamb *et al*. (2011), was also noted at site A. In contrast, other sites such as site B had gentler slopes (0–25 degrees) and a linear cross-slope curvature that reduced the converging nature of surface water flow. Site A had concave cross-slope curvature that resulted in converging water flows. Our erosion pin results and TLS models indicated that surface change was greater at concave rather than linear cross-slope curvatures. This result contrasts with those of Rieke-Zapp & Nearing (2005) who reported that laboratory linear slopes generated the highest mean sediment yield. Along site A, the sediment traps below linear slopes remained intact, whereas below concave cross-slope curvatures the traps were generally breached.

Hay bale traps were sufficient to capture moving sediment during regular rainfall events at Mount Bold. When the average rainfall intensity–frequency–duration increased to a 1 in 5 year event, many of the traps were breached. Hobson *et al.* (2004) at Little Para Reservoir in Adelaide, South Australia, and Robichaud *et al*. (2008) in western Montana, USA, also found that natural rainfall events caused the sediment-laden runoff to overtop hay bales. At Mount Bold site A, sediment overtopped the trap at numerous locations resulting in substantial material reaching the Onkaparinga Creek within the water reservoir. At the foothill of steep slopes with gradients of ≥1:2 or within concave drainage lines, hay bale traps are unlikely to survive. Land managers need either to implement alternative trap designs such as rock gabions or to accept the likely outcome of increased reservoir sedimentation below steep slopes that require alternative management options. Alternative mitigation strategies such as mulches, seeding, geotextile bags and silt fencing can be combined with hay bales to improve the trapping efficiency (Robichauld, 2009). Mulching has been shown to be effective at reducing post-fire erosion; however, it is relatively expensive (Bautista *et al*., 2009). As the Mount Bold study is limited to areas with specific soil types and *Eucalyptus* vegetation, further research is needed into sediment trapping on hillslopes with slope gradients ≥1:2 and with differing soils and vegetation. Incorporating slope profile and cross-slope curvature into post-fire mitigation assessment and erosion modelling also requires further investigation.

CONCLUSION

Substantial sediment movement resulting in surface changes of greater than 1 m occurred after a 1 in 5 year rainfall event at Mount Bold Reservoir reserve, and this resulted in the failure of numerous sediment traps implemented as part of the mitigation strategy. In this rainfall event, fire severity (between moderate to very high), as a factor influencing trap effectiveness, was over-shadowed by the importance of slope properties, even though the presence of fire was necessary to trigger the considerable sediment mobilization and delivery observed. Higher slope gradients and longer slopes contributed to greater sediment transfer, with the largest surface change occurring in footslope positions. On the basis of the data assembled by this study, a threshold for substantial increase in sediment yield was identified at slope gradients of 1:2. Concave cross-slope curvature was also associated with significantly larger amounts of sediment movement. Incorporating the influence of hillslope morphology may be useful when using sediment traps in tandem with other measures, such as mulching and seeding. Concentrated mitigation efforts could focus on the concave cross-slope curvature of the slope. The successful placement of sediment traps and other mitigation strategies to protect water reservoirs requires an understanding of hillslope morphology and the ways in which it influences and controls erosion and delivery processes.

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