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# Double trouble: the influence of wildfire and flow regulation on fine sediment accumulation in the Cotter River, Australia

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**Abstract** In January 2003, the Australian Capital Territory and surrounding areas of New South Wales experienced one of the most severe wildfires in living memory. The majority of the Cotter River catchment (266 000 ha), which is a water supply region for the ACT was burnt. This study monitored the accumulation and movement of fine surficial sediment in the regulated Cotter catchment and several free flowing streams for 15 months after the fire. Significant quantities of fine surficial sediment were deposited within the channel of the Cotter River immediately following the fire. Seven months after the fire, a major rainfall event increased quantities of fine sediment by several orders of magnitude. The organic matter was significantly higher after the wildfire. Flushing flows released from the Bendora Dam removed sediment from downstream reaches causing fine surficial sediment to be preferentially eroded from riffle sections and deposited in adjacent pools. Quantities of fine surficial sediment delivered to the two unregulated streams; the Goodradigbee and Goobarragandra rivers, were much lower compared to the regulated Cotter catchment. Flows in the unregulated rivers had a greater capacity to flushing the fine material through downstream reaches because of longer duration of high flows. The results have implications for flow management and aquatic habitat in the Cotter catchment.

**Key words** wildfire; river regulation; fine sediment; flow management

## INTRODUCTION

Wildfires have significant impacts on terrestrial and aquatic environments (Rhoades *et al.*, 2011). During severe wildfires, the majority of the ground cover is removed from catchment surfaces, leaving bare soils that are easily eroded during subsequent rainfall events. While leaf litter that falls from the burnt vegetation can help to stabilize catchment soils (Shakesby *et al.*, 2007), in most cases the extreme temperatures experienced during the wildfire reduce soil aggregate stability, increasing its susceptibility to erosion (Shakesby *et al.*, 2007). Rainfall events following wildfires can accelerate erosion from the catchment surface and increase sediment deposition in streams. This process can have significant impacts on the geomorphology, ecology and water quality of the receiving streams by increasing nutrient loads, smothering existing habitats and creating sediment slugs (Flosheim *et al.*, 1991; Lane *et al.*, 2006; Rhoades *et al.*, 2011).

Fine in-channel sediments (sand to silt sized particles) are often removed over time, following wildfires, with competent high flows flushing the excess material downstream (Flosheim *et al.*, 1991). However, in regulated rivers wildfire related sediment may not be as readily transported through the system, exacerbating the negative impacts of increased sediment loads on riverine ecosystems for longer periods of time. To promote the removal of excess fine in-channel sediments in regulated rivers, controlled dam releases, or “flushing flows” are commonly employed. The magnitude, frequency and duration of flushing flows have received much attention in the literature (see reviews by Reiser *et al.*, 1985, 1990; Kondolf & Wilcock, 1996). They are typically calculated on the basis of pre-regulation flow regime or on the requirements of stream morphology or ecology, such as flushing of fines to promote pool depth or habitat maintenance for fish species (Reiser *et al.*, 1985; Kondolf & Wilcock, 1996).

One of the most severe and destructive wildfires in the Australian Capital Territory (ACT), Australia resulted from a series of lightning strikes on 8 January 2003. The fire began after an extended drought when conditions were favourable for a catastrophic wildfire (high fuel loads, low-humidity, extremely dry soils, prevailing winds and high temperatures). The wildfires swept across native forest, farmland and into the outer suburbs of Canberra, resulting in the largest footprint in the ACT of any wildfire during the past 88 years (McLeod, 2003). The wildfire burnt 95% of the Cotter River catchment (47 000 ha), a near pristine water supply catchment, that supplies the majority of the ACT's drinking water. Although the intensity of the wildfires was patchy, the majority of this catchment experienced high to very high intensity burns with up to 15 m high flames (White *et al.*, 2006). Accordingly, the wildfire removed most of the ground cover vegetation, litter, soil organic matter, and large tracts of riparian vegetation (White *et al.* 2006) which increased the rates of hill slope runoff and soil erosion. Turbidity levels in the impoundments of the Cotter River increased due to the 2003 wildfires (White *et al.*, 2006) but little is known about post-fire sediment accumulation within the river channel. This paper documents the influence of the wildfires on the accumulation of fine sediments in the channel of the Cotter River. Sediment accumulation in the Cotter River catchment is compared to two similar river catchments to the west that were less affected by wildfires. The utility of flushing flows employed to move fine sediment through the system during the post-wildfire period is discussed.

## STUDY AREA

This study was undertaken in three adjacent catchments located west of the ACT in southeastern Australia; the Cotter, Goodradigbee and Goobarragandra river catchments (Fig. 1). All three catchments have a temperate climate, with average winter and summer temperatures of approximately 6°C and 21°C, respectively. Average annual rainfall ranges from 927 mm in the east of the study area to 790 mm in the west. Rainfall event data over the study period for stations in close proximity to the three catchments are presented in Fig. 2. The Cotter River catchment has native forest covering in its headwater regions and pine plantations are located in the lower catchment. The Cotter River is regulated by three large dams: Corin Dam upstream, Bendora Dam in the mid reaches and Cotter Dam in the lower section of the river. Water is pumped out of Bendora Dam to supply drinking water to the ACT. The Goodradigbee and Goobarragandra rivers

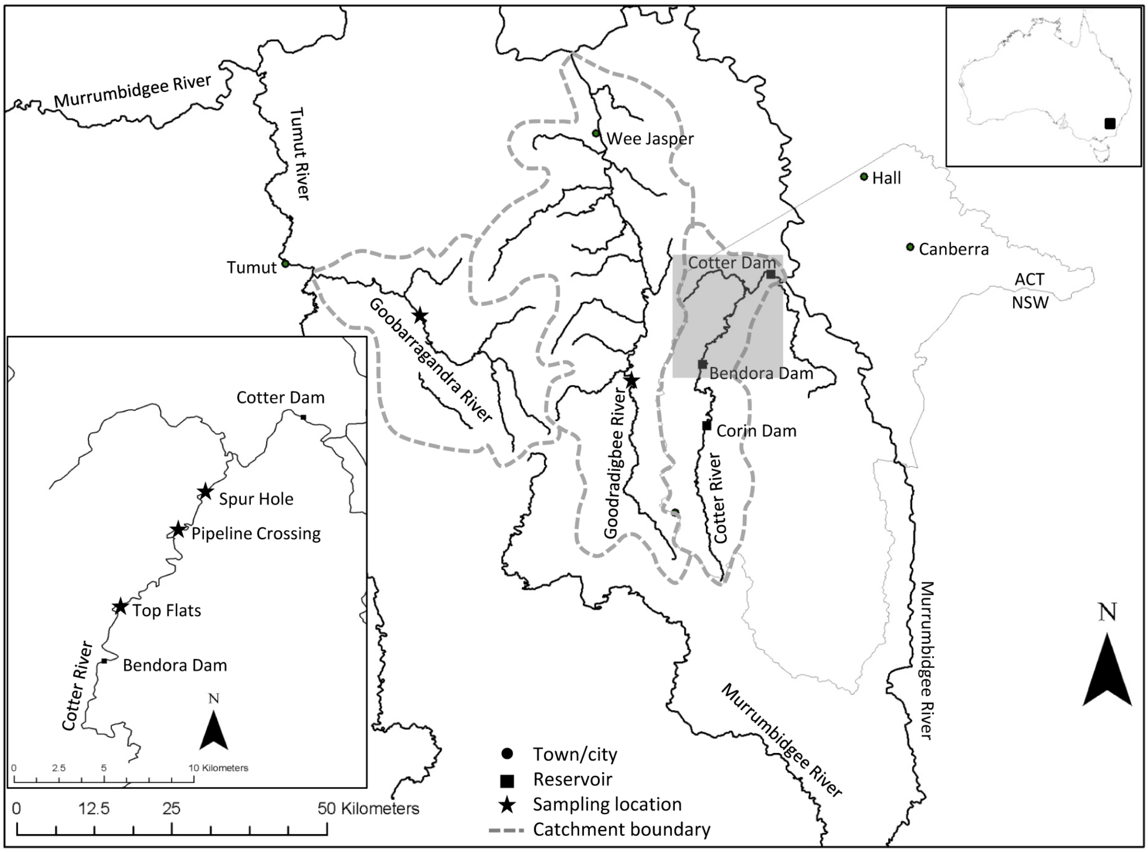


**Fig. 1** Study area in southeastern Australia.

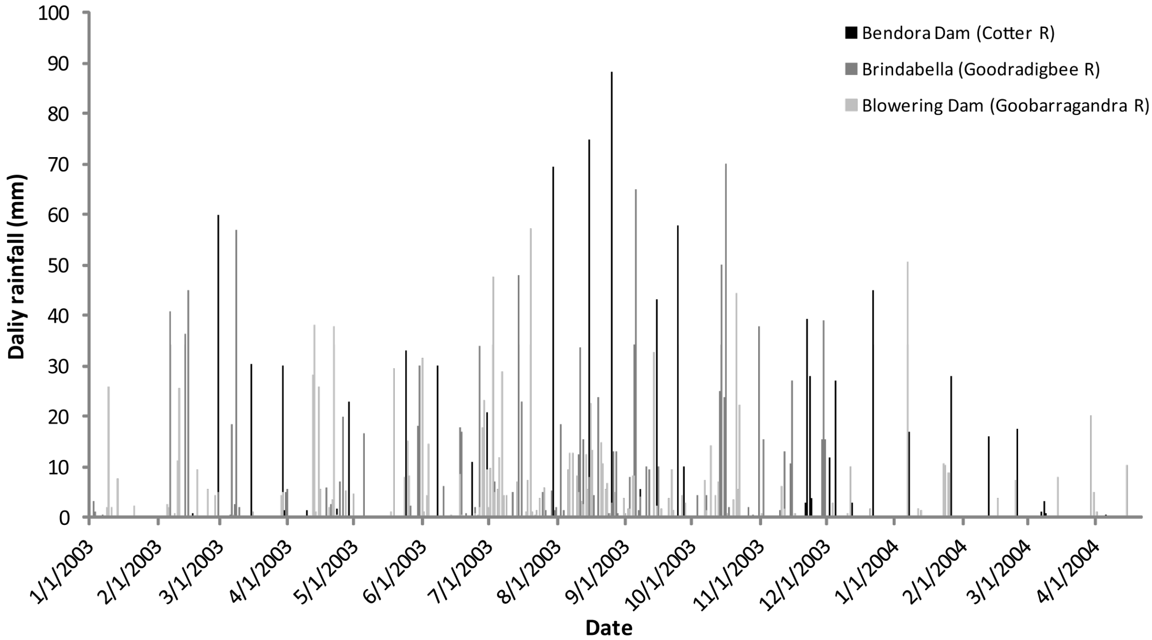


**Fig. 2** Daily rainfall records for the study catchments.

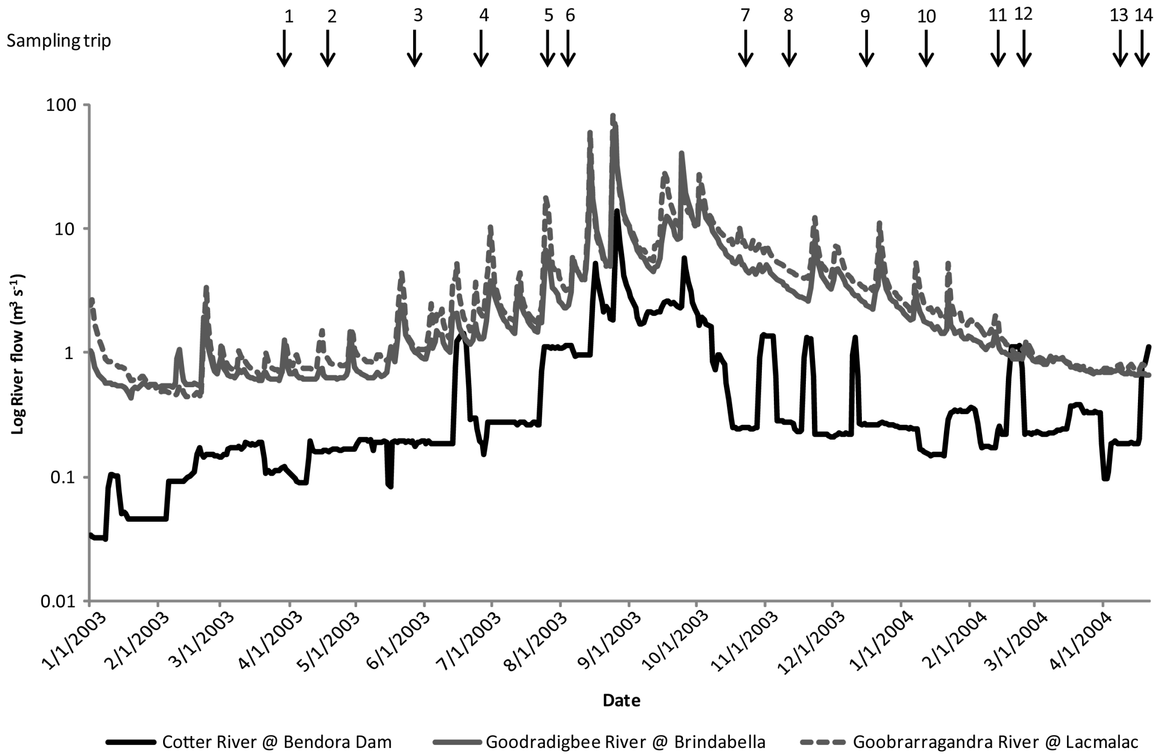


**Fig. 3** Flow data. Arrows indicate the timing of monitoring trips.

are both free-flowing streams draining catchments of predominantly native forest with some pine plantation and cleared farming land. Flows in the three rivers during the study period are presented in Fig. 3.

The 2003 wildfires burned more than 95% of the Cotter and Goodradigbee river catchments, while the Goobarragandra River catchment remained un-burnt. In response to perceived increases in fine sediment accumulation within the main channel of the Cotter River, a controlled environmental flow program was conducted to maintain river habitats considered important for Macquarie Perch and Two-Spined Blackfish, which are endangered native species (Broadhurst *et al.*, 2011). The flow program included a low flow release (0.12–0.35 $m^3\ s^{-1}$) followed by a riffle maintenance flow (approx 1.7 $m^3\ s^{-1}$) to create flow variability and maintain spawning habitats and threatened populations of endangered fish species (Broadhurst *et al.*, 2011).

## METHODS

Fine surficial sediment (Fss) samples (2 mm–32 μm) were collected at three riffle sites downstream of Bendora Dam on 18 occasions. Pre-wildfire samples were collected during 2001 and 2002 (November and December 2001, and then May and June 2002) and 14 post wildfire samples were collected from April 2003 and May 2004. Pre- and post-wildfire sampling was conducted at three individual riffle sites in both the Goodradigbee and Goobarragandra rivers. At all sites, Fss samples were collected using a modified Surber sampler with a base area of 0.09 $m^2$ and mesh size of 32 μm. The sampler was placed on the bed of the stream with the net and collection bottle extended in the direction of flow. The area of stream bottom within the base was disturbed by hand to entrain the fine sediment and trap it in the net and collection bottle. Five replicate samples were collected at each site on all sampling dates. Samples were dried at 40°C to a constant weight. Fine surficial sediments were not collected in pools because increased water depths meant more time consuming sampling methods would have had to been employed. The proportion of inorganic material present in each sample was determined by the procedure outlined in APHA (1997) for ash free dry mass (AFDM). A weighed sub-sample of each fine sediment sample was heated at 550°C for 2.5 hours and the loss on ignition recorded.

The downstream movement of fine sediments in the Cotter River and its impact on channel morphology was monitored by surveying paired riffle and pool cross-sections before (July 2002) and after the wildfire (September 2004). Standard channel dimensions were calculated from the survey data using the Channel program (Thoms & Ranson 2000).

## RESULTS

Flows were quite different for the three rivers (Fig. 3). There were fewer pulses on the regulated Cotter River and they were considerably smaller in magnitude compared to the unregulated Goodradigbee or Goobarragandra rivers (Table 1). Mean pulse discharges were 13.33 $m^3\ s^{-1}$ in the Goodradigbee River, 7.04 $m^3\ s^{-1}$ in the Goobarragandra River and 4.35 $m^3\ s^{-1}$ in the Cotter River. Pulses down the Goodradigbee River (defined as a flow that increased more than 1 $m^3\ s^{-1}$ in consecutive days) were the longest in duration (average: 9.59 days) compared to the Cotter River (average: 8.7 days) and Goobrarragandra River (average: 7.27 days). By comparison, the four regulated flushing flows in the Cotter River had a mean pulse discharge of 0.83 $m^3\ s^{-1}$ and an average duration of 8.5 days (Table 1). Base flows were smaller (average: 0.4 $m^3\ s^{-1}$) and occurred for longer (87% of the time) in the Cotter River, than in the Goodradigbee River (average: 1.44 $m^3\ s^{-1}$; 66% of the time) and the Goobarragandra River (average: 1.76 $m^3\ s^{-1}$; 66% of the time).

Mean pre-wildfire Fss reach accumulations for the Cotter River (reach means: 8.9–15.3 g $m^2$) were markedly lower compared to the post period (reach means: 98.76–1392.79 g $m^2$). Post-wildfire, fine sediment accumulations in the Cotter River varied by over two orders of magnitude (range: 77.55–15 317 mg $m^2$) and this pattern was relatively consistent between sites. During relatively large rain storms that produced an extended period of flow, there was a notable increase in Fss accumulation between sampling times 6 and 7 (Fig. 4). Prior to the October–November 2003 flow event, the mean Fss for the reach was 478.90 g $m^{-2}$. Immediately after the flow event, mean Fss increased to 15 317.16 g $m^{-2}$ and then decreased to a reach mean of 186.93 g $m^{-2}$ (Fig. 4(a)).

**Table 1** Flow pulse and base flow data in three rivers.

| | Cotter R at Bendora Dam | Cotter River flushing flows | Goodradigbee R at Brindabella | Goobragandra R at Lacmalac |
|---|---|---|---|---|
| *Flow pulses* | | | | |
| Number | 7 | 4 | 17 | 22 |
| Mean pulse discharge ($m^3 s^{-1}$) | 4.35 | 0.83 | 13.33 | 7.04 |
| Max pulse discharge ($m^3 s^{-1}$) | 13.85 | 1.45 | 66.54 | 81.88 |
| Min duration (days) | 5 | 5 | 3 | 3 |
| Max duration (days) | 12 | 12 | 15 | 14 |
| Mean duration (days) | 8.71 | 8.50 | 9.59 | 7.27 |
| *Base flows* | | | | |
| Duration in days (%) | 417 (87%) | | 314 (66%) | 317 (66%) |
| Mean discharge ($m^3 s^{-1}$) | 0.40 | | 1.44 | 1.76 |

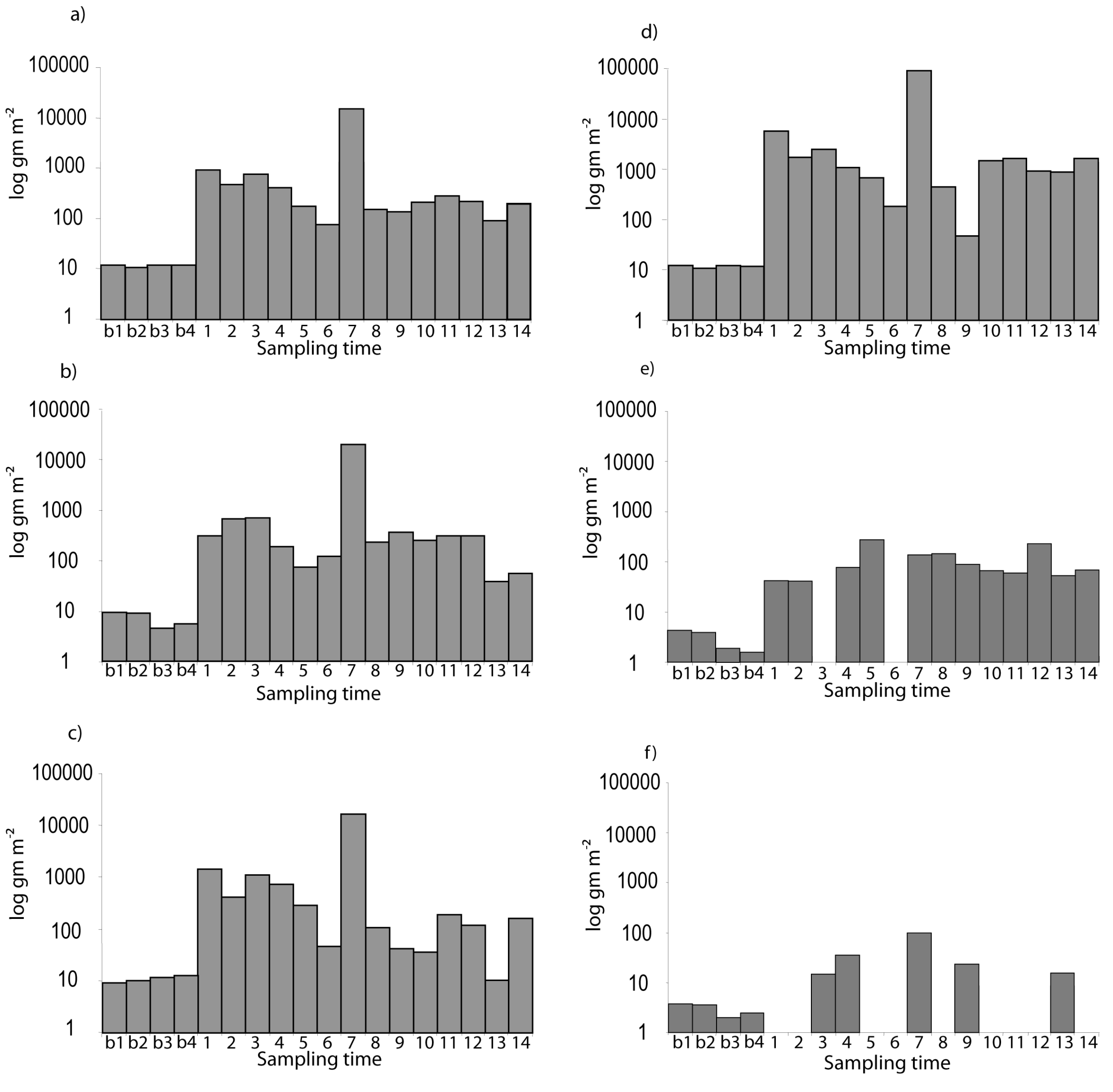


**Fig. 4** Quantities of fine surficial sediment recorded during the study: (a) combined Cotter River sites (b) Top Flats site, (c) Pipeline Crossing site, (d) Spur Hole site, (e) Goodradigbee River site, and (f) Goobarragandra River site. Sampling time b1 = November 2001, b2 = December 2001, b3 = May 2002 and b4 = June 2002 and represent before fire samples. For sampling times 1–14 refer to Fig. 3.

There was considerable inter site variation in the quantity of Fss accumulation. Site means in the regulated Cotter River, ranged from 965.30 g $m^{-2}$ at Spur Hole to 1653.66 g $m^{-2}$ at Top Flats, while individual values ranged between 10.67 g $m^{-2}$ at Pipeline Crossing to 19 550.78 g $m^{-2}$ at Top Flats (Fig. 4(b)–(d)). By comparison, quantities of Fss in the Goodradigbee and Goobarragandra rivers were much lower than the Cotter River (Fig. 4(e),(f)). Means for each reach were: 1392.78 g $m^{-2}$ for the Cotter, 107.46 g $m^{-2}$ for the Goodradigbee and 37.40 g $m^{-2}$ for Goodradigbee.

The majority of the Fss at the Cotter sites was organic matter. The loss on ignition ranged from 30.30 to 85.93% (Fig. 5). Overall, there was very little variation between sites (site means ranged from 66.82% at Pipeline Crossing to 67.57% at Spur Hole). There was a marked increase in LOI following the 2003 flow event at all sites; LOI increased by 32.09% at Top Flats and 45.24% at Spur Hole. The increase in Fss organic matter is presumably associated with the input of material from the catchment, much of which would have resulted from the wildfires. However, since the 2003 flow event, the proportion of organic matter in Fss has decreased at Top Flats by 8.15% and at Pipeline Crossing by 7.02%. However, it increased at Spur Hole by 14.40%. Presumably organic matter is being flushed from upstream reaches and accumulating in downstream reaches below Spur Hole.

Four flushing flows were released from Bendora Dam over the study period. The flows were short sharp releases approximately a week in duration and of magnitude ~1.4 $m^3 s^{-1}$. One flushing flow occurred between sampling times 7 and 8, two between sampling times 8 and 9, and one between sampling times 11 and 12 (Fig. 3). After the first flushing flow, there were marked reductions in Fss accumulation at all sites. This high flow appeared to remove the majority of sediment that was deposited after the large flow event in 2003. Successive flushing flows had much less of an influence on Fss deposits at all sites, although Spur hole did show a decline in

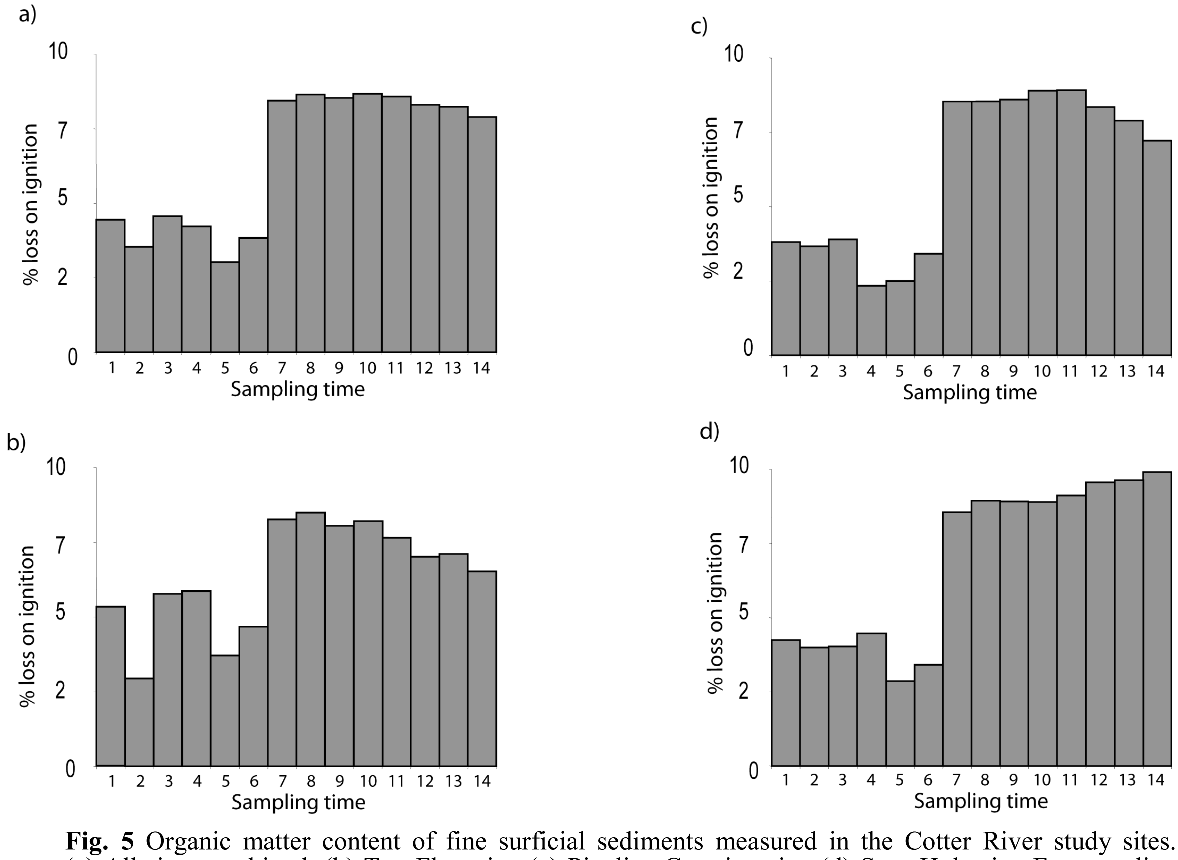


**Fig. 5** Organic matter content of fine surficial sediments measured in the Cotter River study sites. (a) All sites combined, (b) Top Flats site, (c) Pipeline Crossing site, (d) Spur Hole site. For sampling times refer to Fig. 3.

sediment accumulation of around 700 g $m^{-2}$. The amount of sediment removed as a result of the flushing flows did not appear to be influenced by the character of the flushing event, we suggest due to the short durations of these events.

Notable changes in the channel cross-section morphology were measured after the 2003 wildfires at the Cotter River pool sites (Fig. 6). Minor change occurred at the riffle cross sections. Large changes were seen to pool cross-sectional depth and channel cross-sectional area. Channel depth decreased by 2.22 m at Top Flats, 0.88 m at Pipeline Crossing and 2.80 m at Spur Hole. Accordingly, cross-sectional areas were reduced by 57%, 36% and 55% at Top Flats, Pipeline Crossing and Spur Hole, respectively.

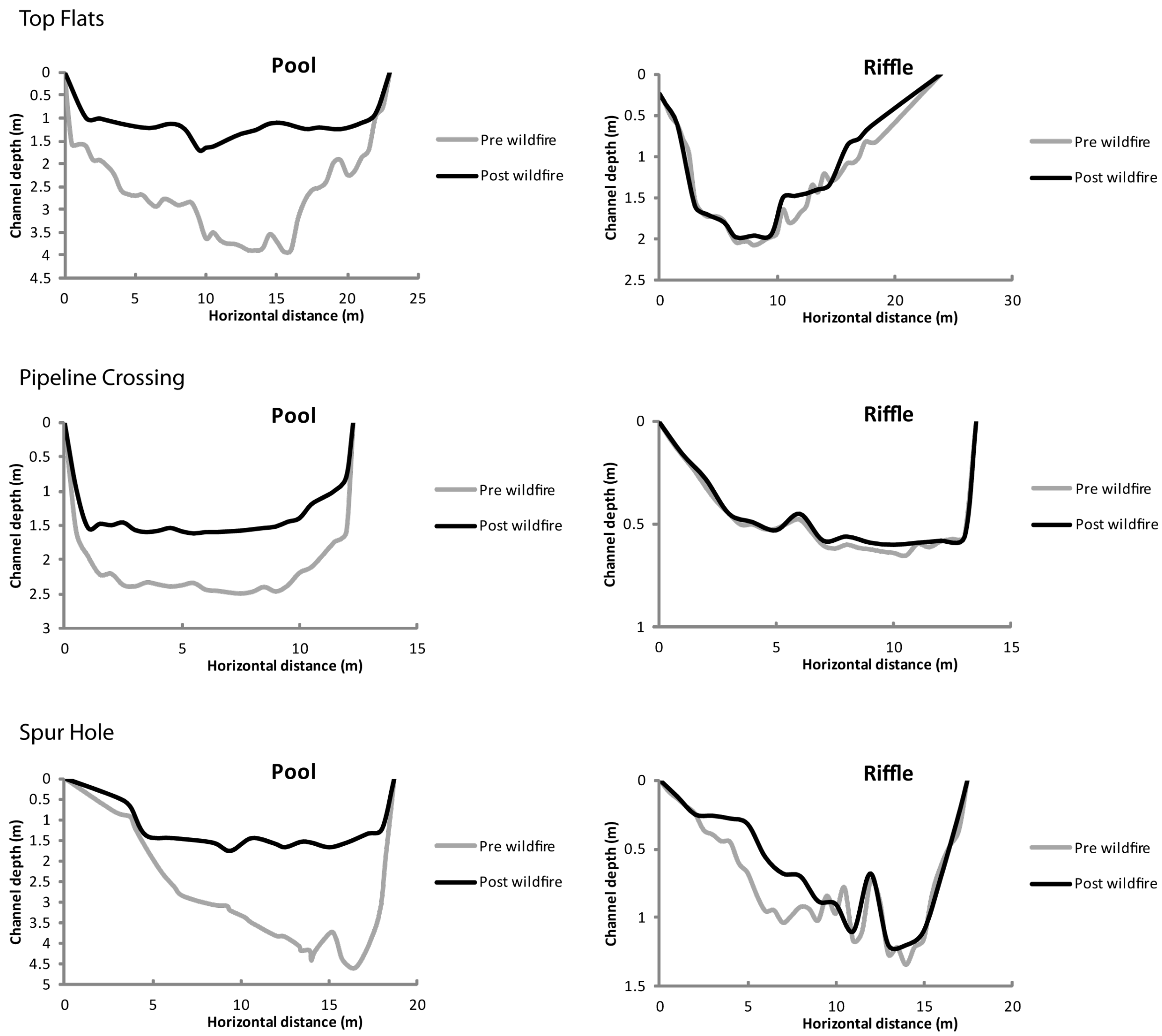


**Fig. 6** Cross–sections of pools and riffles at the Cotter River sites before and after the wildfire.

## DISCUSSION

Increases in the quantity of in-channel fine surficial sediment of three upland streams affected by severe wildfire highlight the combined influence of direct catchment (wildfire) and river channel (flow regulation) disturbances on riverine ecosystem processes. Increases in fine sediment accumulation in this study are comparable with other studies in the literature (Flosheim *et al.*, 1991; Minshall *et al.*, 2001; Peat *et al.*, 2005; Lane *et al.*, 2006; Rhoades *et al.*, 2011). The organic matter content of accumulated in-channel sediment increased following significant sediment inputs during the October–November 2003 high flow event. White *et al*. (2006) also noted significant increases in turbidity levels within Bendora Dam on the Cotter after several storms in early 2003 following the wildfire. These authors noted that 75% of the material transported into the dam was topsoil from the surrounding catchment rather than reworked aquatic sediments. Lane *et al.* (2006) showed that 60% of the fine sediment delivered to the East Keiwa River in southeastern Australia occurred as a result of two post-wildfire storm events.

Accumulations of fine surficial sediments in the regulated Cotter River were much larger than those recorded in either of the two unregulated catchments; even though the Goodradigbee River experienced a very similar level of burn intensity. Rainfall records for this period show that the Cotter and Goodradigbee catchments experienced rainfall events of >40mm/day throughout the sampling period (Fig. 2) that were capable of eroding the relatively bare hill slopes and transporting material to the river channels. However, the resultant river flows were quite different, highlighting the influence of flow regulation in the Cotter downstream of the dams. We suggest that the typically higher magnitude flashy flows in the unregulated Goodradigbee catchment were more capable of moving fine sediment through the system, hence the observed lower Fss accumulation. Similarly, Flosheim *et al.* (1991) observed that although the first post-wildfire storm flow deposited gravels into the channels of several unregulated streams in southern California, successive flows effectively moved sediment through the channel system. The lower Fss accumulations recorded in the Goobarragandra catchment were most likely supply-related as this catchment was not affected by the 2003 wildfires.

This study indicates the limited success of flushing flows in terms of fine surficial sediment removal. While the first flushing flow appeared to be successful in removing excess Fss accumulations from riffles deposited during several storm events in October–November 2003, successive flushing flows did not appear as effective in removing fine sediments from the sampling areas. The cross-sectional data collected in this study suggests that material may have simply been flushed from riffle sites and deposited into adjacent pools rather than being transported through the system. Flushing flows, such as the ones utilized in this study, have been advocated as a means of managing fine sediment in regulated rivers around the world (Reiser *et al.*, 1985; Reiser *et al.*, 1990; Kondolf & Wilcock, 1996; Batalla & Vericat, 2009). The magnitude and duration of these flows is very dependent on the specific objectives to be achieved (Kondolf & Wilcock, 1996). The flushing flows released downstream of Bendora Dam in the Cotter River during the study period were targeted for fine sediment removal from riffle sites, and initiation of motion calculations suggest that the flows should have been large enough to remove fine sediment from the riffle areas investigated. The apparently small influence of several of the flushing flows in removing sediment may suggest that the duration of these flows was not long enough to successfully remove significant quantities of sediment, or perhaps the extensive armoured layer on the river bed (Thoms, 2012, this volume) aided in trapping this fine sediment, restricting its removal.

Fine sediment deposited into river channels following wildfires has been shown to influence biotic communities in those systems, through changes in aspects such as water quality, temperature and habitat availability due to fine sediment accumulation (Reiser *et al.*, 1990; Minshall *et al.*, 2001; Osmundson *et al.*, 2002; Rhoades *et al.*, 2011). Indeed several studies have shown an effect of the 2003 wildfires on the macroinvertebrate and algae communities (Peat *et al.*, 2005) and benthic primary productivity (Reid *et al.*, 2012, this volume), that may be quite long lasting (Peat *et al.*, 2005). The increase in fine sediment in riffles and in particular pools of the Cotter River post-wildfire may have implications for several endangered and threatened native fish species in the river. The Cotter catchment constitutes the last remaining viable populations of both the Macquarie Perch and the Two-Spined Blackfish (Lintermans *et al.*, 2008). While both these species commonly spawn in gravel and cobble habitat within riffles (McDowall, 1996; Lintermans *et al.*, 2008), telemetry studies suggest that both species spend the majority of their time in pool habitats during a range of flow conditions (Broadhurst *et al.*, 2011). Increased sedimentation in the pools demonstrated in this study may therefore negatively impact the habitat of these endangered and threatened species.

## CONCLUSION

This study demonstrates the influence of a severe wildfire on fine sediment transport and accumulation in the Cotter River in southeastern Australia. While increases in sediment were observed over a year-long period following the wildfires, the majority of it was transported during several large rainfall events in October and November of 2003. Much of the resultant sediment was removed from riffle habitats by regulated flushing flows. However, it appears to have been re-deposited in adjacent pools rather than being flushed through the system. This may have implications for the future success of several endangered and threatened fish species that frequently use pools as refuge habitats in this system.

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