# The issue below the surface: wildfire, riverbed sediments and flow regulation

**MARTIN C. THOMS**
*Riverine Landscapes Research Laboratory, University of New England, Armidale, NSW 2351, Australia*
martin.thoms@une.edu.au

**Abstract** The composition and structure of upland riverbed substrates subjected to variable but multiple stressors of wildfire and flow regulation were investigated. A range of coarse–fine riverbed sediment mixtures were recorded in the upland channels draining the Brindabella Ranges, in southeast Australia and these mixtures reflected the combination of stressors studied. Significant post-wildfire increases in the accumulation of fine sediment within the riverbed substrate occurred only in association with the individual stressor of wildfire. In contrast, no change in the accumulation of matrix sediment occurred in the regulated river that was also subjected to wildfire. The presence of a well-developed surface armour layer – a feature of gravel-bed regulated rivers – prevented the infilling of these riverbed substrates post-wildfire. Further study of the combined impacts of different stressors on the composition and structure of upland gravel-bed rivers will contribute to an improved understanding of their recovery from wildfire.

**Key words** sub-surface riverbed sediment; wildfire; fine sediment; flow regulation

## INTRODUCTION

The composition and structure of riverbed substrates is important for numerous ecological, engineering and geomorphological concerns. Their evolution, sedimentation and the influences of direct and indirect drivers were reported as one of nine major scientific hydrological challenges that require further study (UNESCO, 1984). The natural character of gravel-bed substrates is complex, consisting of a wide range of sediment textures and an array of coarse-fine sediment mixtures in natural river channels. Riverbed substrates can acquire quasi-uniform characteristics that reflect prevailing hydrological and sedimentological regimes operating at a range of scales. Because of the inherent heterogeneity and spatial variability of riverbed substrates, many previous studies have tended to focus on the character and behaviour of surface layer sediments only, ignoring perhaps the relatively more important sub-surface sediment. Studies examining the character of sub-surface riverbed sediments have demonstrated their spatial and temporal complexity often in association with a range of catchment conditions (Thoms, 1992).

Riverine ecosystems are frequently subjected to multiple stressors and interactions between individual stressors. Either through positive or negative feedback loops, these stressors can enhance or diminish expected individual impacts. Despite the ubiquitous nature of multiple stressors, their impact on riverine ecosystems has received limited attention (Thoms, 2007). Recently Ormerod (2010) hypothesised that antagonistic and synergistic responses to multiple stressors may range from simple additive impacts to those that are increasingly complex. Catchment wildfires and the regulation of flows through dam construction are amongst the most significant stressors on riverine ecosystems (Stanley *et al*., 2010), especially in headwater systems. The impact of wildfires on catchment runoff, sediment yields and resultant changes in channel morphologies, water and sediment quality, biological communities and instream ecological productivity are well documented (Minshall, 2003). In particular, large quantities of fine sediment can accumulate within those river channels whose catchments have been extensively burnt (Beschta *et al*., 2004). Recoveries of riverine ecosystems following wildfires can be slow in river systems that are also subject to additional stressors such as the grazing of livestock and water resource development (Beschta *et al*., 2004). Flow regulation directly affects sediment and water regimes, which are key drivers of the structure and composition of riverbed sediments and riverine ecosystems, and have the potential to influence recovery following wildfire disturbance. Sediment movement is a function of the river capacity and competence, as well as sediment availability in the catchment. Either factor can limit sediment transport rates and therefore influence the character of riverbed sediments. Despite increasing evidence of the compound nature and negative effects of multiple stressors influencing rates of recovery in riverine ecosystems, relatively few studies have examined the impact of wildfire in riverine ecosystems regulated by dams.

In January 2003, wildfires burned over 500 000 ha of the Southeast Highlands of Australia, including large sections of the Brindabella Ranges within the Australian Capital Territory. Some of the impacted areas are key source water catchments for Canberra, the nation's capital. Riverine ecosystems that drain these catchments also support several endangered native fish species that rely on riverbed substrates for various stages of their life-cycles. In an effort to reduce the impact of the 2003 wildfires, the local water authority implemented a series of flow releases to remove excess fine sediments that accumulated in the river channel of the main regulated system of the region. This provided an opportunity to investigate the multiple impacts of wildfire and flow regulation on the sedimentological character of the riverbed substrates. The research questions addressed in this study are: (1) what is the effect of multiple stressors (wildfire and flow regulation) on the composition and structure of riverbed substrates; and, (2) do reservoir releases enhance the recovery of riverbed substrates subjected to these multiple stressors.

## STUDY AREA

This study was undertaken in three adjacent upland forested catchments within the Brindabella Range of SE Australia: the Cotter, Goodradigbee and Goobarragandra rivers (Fig. 1). All three catchments have a temperate climate with a long-term average regional rainfall (1954–2008) of 930 mm, most of which occurs during August–October. Granites are prevalent on the ridges with Ordovician sediments (shales, sandstones and clays) on the slopes. Land use over most of the three catchments is National Park or Nature Reserve, with limited commercial forestry in the lower Cotter catchment (<8% of total catchment) and some rural grazing/cultivation along the mid to lower sections of the Goodradigbee and Goobarragandra rivers. The study catchments are typical mountain rivers (Wohl, 2010) flowing across highly constrained valleys with characteristic cobble/gravel bed riverbed sediments. The Cotter River has a catchment area of 482 km$^2$ and is regulated by three dams (Corin, Bendora and Cotter), whereas the unregulated Goodradigbee and Goobarragandra rivers have catchment areas of 890 km$^2$ and 673 km$^2$, respectively. Environmental flow releases designed to minimize the impact of the dams and mimic the natural flow regime occur in the Cotter River.

In January 2003, lightning started wildfires that burned the majority (>95%) of the Cotter and Goodradigbee. The Goobarragandra catchment was not burned. In an attempt to manage significant increases in the accumulation of fine sediment within the main channel of the Cotter River post wildfire (Southwell & Thoms, 2012), the local water authority conducted a series of "flushing flows" to remove "excess" sediment from the channel and maintain river habitats considered to be important for two endangered native fish species, the Macquarie Perch and Two-Spined Blackfish, (Broadhurst *et al.*, 2011). Both species utilize the riverbed during parts of their life cycle and the nature of the substrate is important for their recruitment. The release of flushing flow includes a pre-release of 0.12–0.35 m$^3$ s$^{-1}$ that increased to 1.7 m$^3$ s$^{-1}$; the latter release is designed for riffle maintenance.

## STUDY DESIGN

A modified BACI study design was employed in this study. Riverbed sediments were collected pre-wildfire during December 2001, and then on two occasions post-wildfire. The first post-wildfire sampling period was several weeks after significant regional rainfall (June 2002) and the second, several weeks after the first flushing flow in the Cotter River. This sampling period occurred after several floods in the Goodradigbee and Goobarragandra rivers (May 2004). Bed material samples were collected by the freeze coring method (Thoms, 1992). This technique efficiently collects fine sediment, enables undisturbed volumetric samples to be obtained and

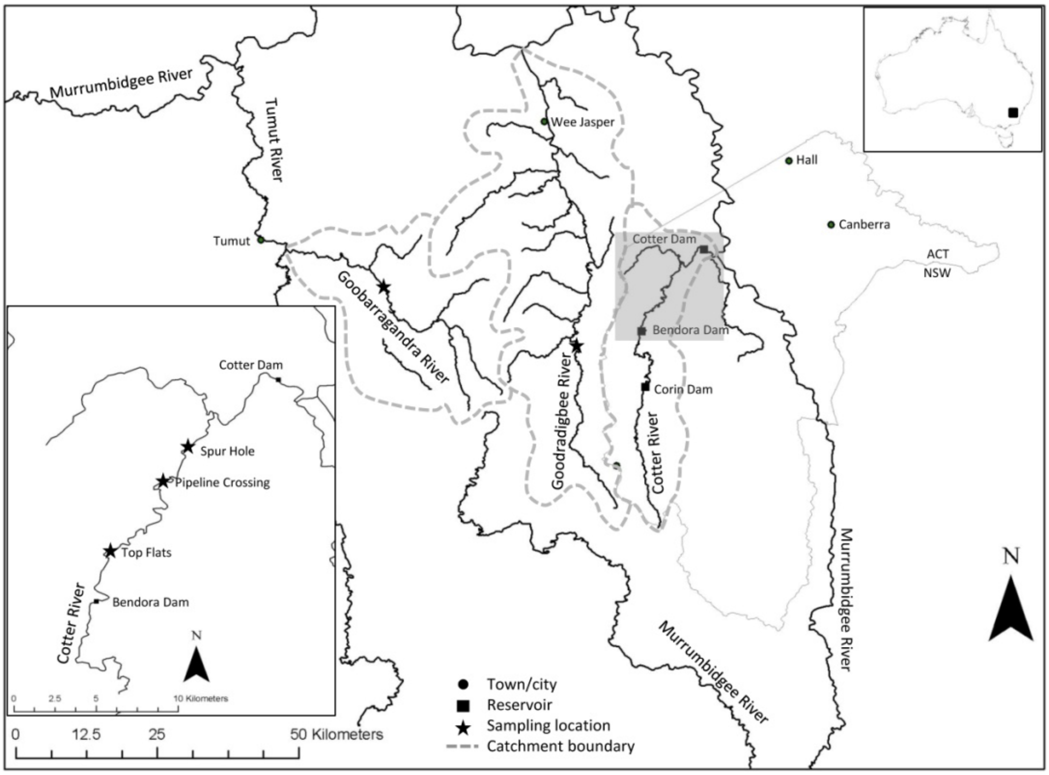

**Fig. 1** Study catchments and sample locations.

allows the composition and depositional history of riverbed substrates to be examined. The surface/armour layer was removed first, before the freeze core samples were collected, because this study was primarily concerned with the accumulation of fine sediment within the riverbed. Five freeze-core samples, weighing approximately 10 kg each, were removed from three riffle sites in the Cotter River and two riffle sites in the Goodradigbee and Goobarragandra rivers on each sampling occasion (*n* = 105). This sampling effort ensured the percent weight of the largest particle was less than five percent of the total sample weight (Mosley & Tinsdale, 1985) and to further reduce the influence of the largest particle, samples were combined to produce a composite sample for each site. Samples were dried at room temperature and then sieved to obtain graphic statistical measures, with results expressed in phi (Ø) units.

The resultant grain-size data were analysed using the multivariate statistical procedure (Forrest & Clark, 1989). Entropy analysis is a nonparametric clustering technique where individual sediment samples are represented by the entire grain-size distribution and the analysis classifies samples into groups sharing common grain-size distribution characteristics. The optimum number of groups, or classes, is obtained when the between-class entropy similarity increases at a significantly decreasing rate with the addition of more classes (Forrest & Clark, 1989). Grouping of samples with similar sediment character based on the entire grain-size distribution offers advantages over methods that use only summary statistics of individual samples. In addition, a series of standard textural statistical measures were calculated, with between site and sampling period differences tested via an Analysis of Variance (ANOVA).

Surface sediment sampling was also undertaken at each site during December 2001. The Wolman random walk method was employed with the intermediate "b" axis of 250 surface sediment particles counted at each site. Statistical differences between the grain-size distributions of each site were determined via the Kolomogorov-Smirnov test. The initiation of motion of surface sediments at each site was calculated using the Schoklitsch bed load transport equation (Bathurst *et al*., 1987). In addition, an Armouring Index (AI) and the Relative Bed Stability Index (RBS) for all sites were calculated via equations given by Kaufmann (1999).

## RESULTS

Surface sediments at all sites are comprised of particles ranging from 0 to –8 ϕ: very coarse sand to cobble material on the Wentworth size scale. Overall, surface sediments are dominated by cobble-sized particles (–6 to –8 ϕ) comprising 63 to 77% by weight of the total sample mass. There was no statistical difference in the surface sediment grain-size distributions between sites at the 0.05% level. Armour index values range from 1.97 for the Goobarragandra River to 3.27 at Spur Hole in the Cotter River; typical values of 1.2 to 2.8 are reported in the literature (e.g. Bathurst *et al.*, 1987).

Discharges required for the initiation of motion of the surface sediment (critical discharge) varied between sites; ranging from 85.38–381.80 $m^3 s^{-1}$ for the Cotter River sites to 62.83 $m^3 s^{-1}$ for the Goodradigbee River sites and 75.42 $m^3 s^{-1}$ for the Goobarragandra River sites. Presumably these differences are associated with differences in stream power in each of the rivers.

Combining the initiation of motion data with flow data for each of the rivers, the frequency of surface sediment movement was calculated for 1987–2002 (pre-wildfire) and 2003–mid 2004 (post-wildfire) periods (Table 1). Flows in the regulated Cotter River were not of a sufficient magnitude to initiate movement of the coarser surface sediment during either the pre- or post-wildfire period. In contrast, the initiation of motion in the unregulated Goodradigbee and Goobarragandra rivers was exceeded 1.54 and 1.93% of the time in the post-wildfire period, respectively. During the pre-wildfire period, the initiation of motion was exceeded 3.2% of the time at sites in the Goodradigbee River and 2.81% of the time at sites in the Goobarragandra River (Table 1). This variation in the relative stability of the surface riverbed sediment is confirmed by the RBS values. RBS values are an order of magnitude higher for the Cotter River sites compared to those in the Goodradigbee and Goobarragandra rivers. RBS values >1 indicate a stable riverbed, while those <1 indicate an unstable riverbed (Jowett, 1989). By comparison, flows were of a sufficient magnitude to move finer surface sediments at all sites and the frequency of occurrence ranged from 14.67% of the time (75 days) at Pipeline to 55.55% of the time (287 days) at Site 2 in the Goobarragandra River during the post-wildfire period.

Composite grain-size histograms for the three rivers show the sub-surface sediment to be bimodal (Fig. 2). There is a coarser mode (the "framework") with particles between –10 and –4ϕ and a secondary mode of finer sediments (the matrix) with particles between –2 and +4ϕ. These two modes can be considered separate populations. The resolution of the two individual modes is commonly based on the presence of a saddle frequency, in this case located at –3ϕ. This bimodal grain-size distribution is a feature of all sites in the study area and is indicative of high-energy upland gravel-bed rivers. As a first approximation the coarser framework deposit, i.e. sediment larger than –4ϕ, represents the traction load of the channel while the finer matrix sediment, i.e. that finer than –2 ϕ, is characteristic of a saltating suspended load. Commonly grain-size analyses are based on the assumption of a Gaussian distribution, therefore Carling & Reader (1982) suggest that with bimodal sediment populations, each mode should be analysed separately.

**Table 1** Frequency of coarse surface sediment movement and riverbed stability.

| Site | No. of days of sediment movement | | % occurrence | | RBS |
|---|---|---|---|---|---|
| | Pre-wildfire | Post-wildfire | Pre-wildfire | Post-wildfire | |
| *Cotter River – multiple stressors of wildfire and flow regulation* | | | | | |
| Burkes Creek | 0 | 0 | 0 | 0 | 12.5 |
| Pipeline | 0 | 0 | 0 | 0 | 10.2 |
| Spur Hole | 0 | 0 | 0 | 0 | 7.3 |
| *Goodradigbee River – singe stressor of wildfire* | | | | | |
| Site 1 | 187 | 10 | 3.2 | 1.93 | 0.98 |
| Site 2 | 187 | 10 | 3.2 | 1.93 | 1.02 |
| *Goobarragandra Riv*er *– no stressor* | | | | | |
| Site 1 | 164 | 8 | 2.81 | 1.54 | 1.01 |
| Site 2 | 164 | 8 | 2.81 | 1.54 | 0.99 |

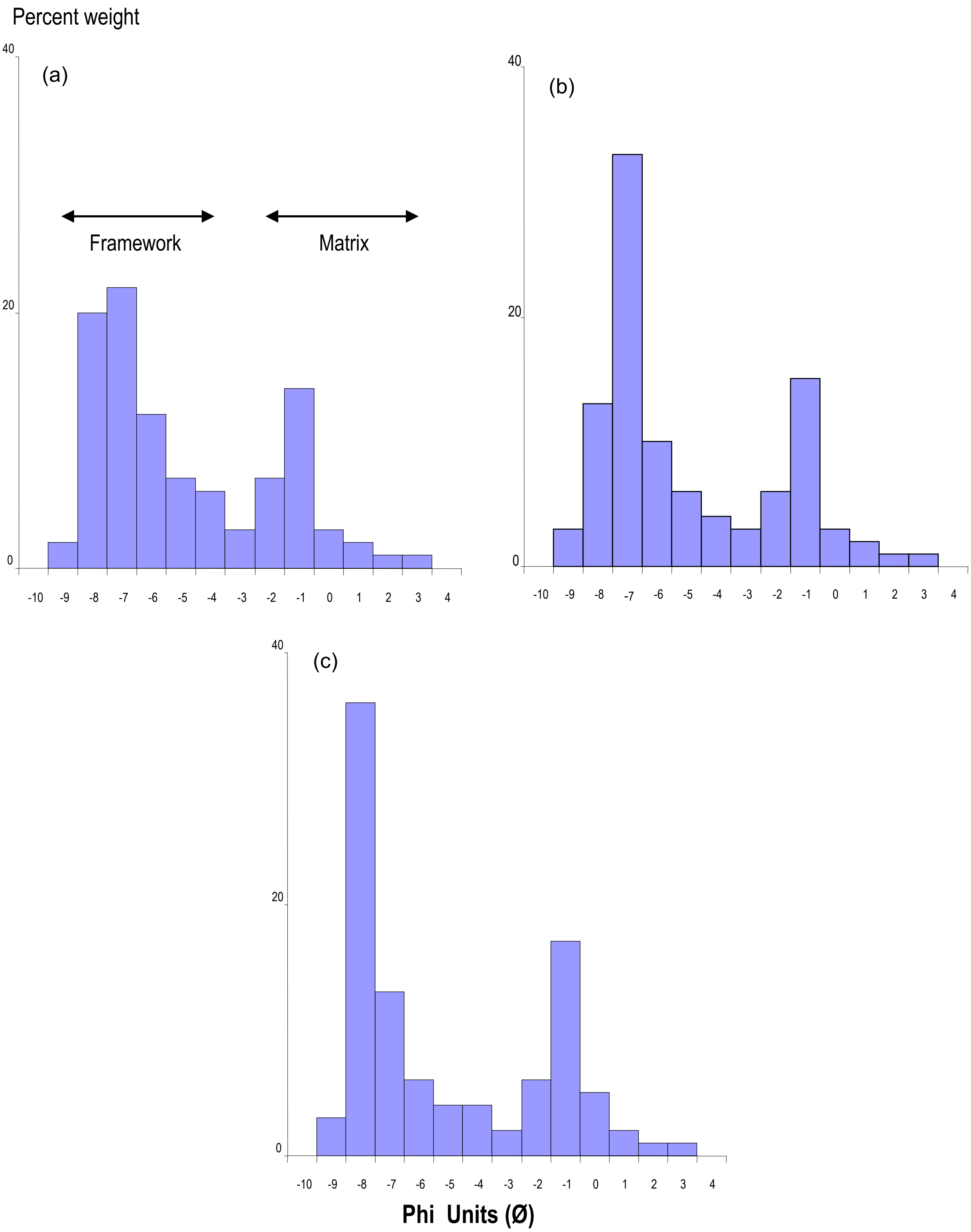

**Fig. 2** Composite grain-size histograms for sub-surface riverbed sediments for: (a) Cotter River; (b) Goodradigbee River; and (c) Goobarragandra River.

**Table 2** The contribution of matrix sediments to the sub-surface sediment in the study area. The average and range of the percentage weight of matrix are given for the three sampling periods are provided with the ratio of average pre- to post-wildfire matrix contribution, are given.

| River | Pre-wildfire | Post-wildfire I | Post-wildfire II |
|---|---|---|---|
| *Cotter* | | | |
| Average | 25.97% | 26.12% | 25.23% |
| Range | 22.88–31.87% | 23.11–31.90% | 23.51–30.75% |
| Ratio | | 1 | 0.91 |
| *Goodradigbee* | | | |
| Average | 18.23% | 51.23% | 36.21% |
| Range | 15.99–21.21% | 42.52–59.68% | 34.15–39.51% |
| Ratio | | 2.81 | 1.97 |
| *Goobarragandra* | | | |
| Average | 16.87% | 17.23% | 17.01% |
| Range | 15.37–17.93% | 16.21–19.18% | 16.88–19.17% |
| Ratio | | 1.02 | 1 |

There was no statistical difference in the mean grain size of the coarser framework mode of the sub-surface sediments between sites or sampling periods (ANOVA: $F_{(0.05),3,21} = 5.3$). Framework mean grain sizes for the Cotter, Goodradigbee and Goobarragandra rivers ranged from –6.89 to –7.21 $\phi$, –6.90 to –7.31 $\phi$ and –6.85 to –7.19 $\phi$, respectively.

The range in the contribution of the matrix component to riverbed sub-surface sediment between different sites and sampling periods was a dominant feature of the individual grain-size histograms (Table 2). The contribution of matrix sediment varied most in the Goodradigbee River over the three sampling occasions (15.99 to 59.68% by weight) compared to the Cotter (22.88 to 31.90 % by weight) and Goobarragandra Rivers (15.37 to 19.18% by weight). There was a significant difference in the percent weight of the matrix sediment between the three rivers (ANOVA: $F_{(0.05),3,21} = 25.6$). However, there was no significant difference in the percentage weight of the matrix sediment between sites or sampling period in the Cotter River (ANOVA: $F_{(0.05),7,21} = 34.2$). Thus, wildfire had no effect on the accumulation of finer matrix sediments within the riverbed substratum of the Cotter River. Similarly, there was no significant difference (ANOVA: $F_{(0.05),2,6} = 2.6$) between sites or sampling period in the Goobarragandra River. In contrast, there was a significant difference (ANOVA: $F_{(0.05),2,6} = 14.1$) between sampling events in the Goodradigbee River. Although the percentage weight of matrix sediment for the Goodradigbee sites was comparable to that recorded at the Goobarrangandra sites for the pre-wildfire sampling period (an average of 18.23 and 16.87% by weight for the Goodradigbee and Goobarrangandra, respectively), there were marked differences between the two rivers in the two post-wildfire sampling periods. Immediately following the wildfires, the contribution of the matrix component increased on average by 181% (18.23 to 51.23% by weight) in the Goodradigbee, while the difference between the pre-wildfire and sampling period 2 post-wildfire the difference was only 98.63% (18.23 to 33.21% by weight).

Results of the entropy analysis confirm differences in the overall grain-size composition of the sub-surface sediment between some rivers and sampling periods. Entropy analysis identified three distinct sub-surface sediment texture groups accounting for 83.2% of the total variation between individual samples. Group 1 contained all the Cotter River samples, while Group 2 contained all the Goobarragandra samples plus the pre-wildfire Goodradigbee samples, and Group 3 was comprised of post-wildfire samples from the Goodradigbee. These differences in the overall grain-size composition were a result of variations in the contribution of the finer matrix sediment.

## DISCUSSION

The purpose of this paper was to detail the sub-surface sedimentological character of three upland rivers subjected to varying multiple stressors and to assess the recovery of riverbed substrates whose catchment have been subjected to wildfire. The substrate of gravel-bed rivers can be separated into four broad categories: open-work gravels, matrix-filled contact or framework dominated gravels, framework dilated gravels, and matrix dominated, on the basis of framework packing and matrix contribution. Where the matrix forms less than 25% of the total sediment weight the substrate is termed open-work gravels; when the matrix is 25–32% of the sediment weight, the substrate is "framework dominated" in which the clasts are in tangential contact with one another (Carling & Reader, 1982) forming a stable self-supporting structure but interstitial spaces between framework clasts are occupied by the finer matrix sediment. Further contributions of matrix sediment theoretically reduce the stability and inter-clast contact of the coarser framework sediments. A range of riverbed substrates was recorded in the three rivers. Framework dominated sub-surface sediments were present in the Cotter River, while open-work gravels characterise the Goobarragandra and the pre-wildfire Goodradigbee sediments. By contrast the post-wildfire sub-surface sediments of the Goodradigbee River are framework dilated and matrix dominated.

Large quantities of fine matrix sediments can be stored within coarse riverbed substrates. In this study, up to 59% by weight of fine matrix sediment was recorded within the substrate of the Goodradigbee River, in comparison with a maximum of 31.91% in the Cotter River and 19.17% in the Goobarragandra River. The supply of finer sediment to the riverbed surface is the primary factor governing the accumulation of matrix sediment within coarser riverbed substrates. The ingress of matrix sediment into a framework substrate can be rapid, even at low concentrations (Carling, 1984). In this study, rates of fine sediment deposition increased by three orders of magnitude within those river channels whose catchments were subjected to wildfire (Southwell & Thoms, 2012). This was prevalent following the first major rainfall event post-wildfire and for over 18 months following this catchment disturbance. Increased accumulations of fine matrix sediments within coarse riverbed substrates have also been reported to occur in association with a range of catchment stressors such as urban development (Thoms, 1987), dam construction (Davey *et al.*, 1987) and forestry activities (Eibse, 1983).

The results of this study demonstrate variations exist in the response of riverbed substrate composition to different individual stressors and stressor combinations. Goodradigbee River sites, subjected to the single stressor of wildfire, experienced the greatest change in the composition of the riverbed substrate. Average change ratios of 2.81 and 1.97 for the percentage weight of matrix sediment were recorded for the two post-wildfire sampling periods in the Goodradigbee River compared to those in the Cotter River – sites subjected to the multiple stressors of wildfire and flow regulation (1 and 1.01), and those in the Goobarragandra River which experienced no stressor (1.01 and 1) (cf. Table 2). It appears there was no additive response from the combined stressors of flow regulation and wildfire on the composition of the riverbed substrate in the Cotter River. Rather, the single wildfire stressor had a greater impact on the changing the textural composition of the riverbed substrate (Table 2). However, the marked reduction in the percentage weight of matrix sediment between the two post-wildfire sampling periods in the Goodradigbee River (average percent reduced from 51.23 to 36.21%) suggests the impact may be transient. Competent river flows, as experienced during floods that result in movement of coarser framework sediments and turnover of the riverbed substrate, will flush finer sediment from the sub-surface substrate (Gomez, 1987). In contrast, the pre-wildfire conditions show a higher matrix component within the riverbed substrate of the regulated Cotter River compared to the other two rivers, and this did not change significantly post-wildfire (Table 2). This suggests a more synergistic response to the combined stressors of wildfire and flow regulation.

The presence of fine sediments within coarse-bed river deposits has been inferred to result from the processes of: simultaneous deposition (Frazer, 1935), particle overpassing (Allen, 1983), or secondary infiltration or ingress (Einstein, 1968). Regardless of the actual mechanism of accumulation, the vertical structure of riverbed substrates influences the residence of matrix sediments within the substrate overtime. The vertical structure of gravel-bed substrates is rarely uniform, with the presence of a coarse surface layer being a feature of heterogeneous gravel-bed sediments. Generically termed the armour layer, it has also been referred to as a pavement or censored layer, depending on its relative mobility. Once formed, the armour layer protects riverbed turnover and disturbance of the sub-surface deposit during floods. During sediment transport where the riverbed is mobilised, finer sediment is flushed out of the substrate effectively, increasing its sub-surface porosity. A well-developed armour layer is a feature of the regulated Cotter River, resulting in highly stable riverbed and framework dominated sub-surface gravels where all interstitial spaces are occupied by matrix sediment. Since dam construction in the Cotter River there has been no bed load movement and therefore no disturbance of the sub-surface sediments. In the unregulated Goodradigbee and Goobarragandra rivers by comparison, there is no well-developed armour layer and as a consequence riverbed sediments are more frequently disturbed. This not only cleanses the sub-surface gravels, but also allows excess matrix accumulation to occur during periods of elevated fine sediment supply, as happens post-wildfire.

Programmes of predetermined flow releases, downstream of dams, for a given duration are frequently employed to meet a variety of management goals in regulated rivers. The maintenance of some “desired” channel characteristic is a common goal and these flow releases are termed “channel maintenance flows” or, more commonly, “flushing flows” for the effect of removing (flushing) fine sediments from riverbed gravels. Following wildfires in the study region, a programme of flushing flows was implemented in the Cotter River to remove ‘excess’ fine sediments, that had accumulated as a result of the wildfires and improve habitat conditions for two endangered native fish species. The results of this study have demonstrated that this programme of flushing flows had no measureable effect on the sediment composition of the sub-surface riverbed. This presumably was because of the presence of a well-developed surface armour layer that prevented sediment movement bed turnover and the flushing of fine sediments from within the substrate.

**Acknowledgements** Many undergraduate students from the University of Canberra’s Catchment Science Unit assisted with the collection of field data – to them a debt of gratitude is owed. The majority of the research undertaken in the Cotter Catchment was undertaken in collaboration with Prof. Richard Norris; I enjoyed the journey Richard and may you rest in peace. Comments on an earlier draft of this manuscript by Dr Melissa Parsons were appreciated.

## REFERENCES

Allen, J. R. L. (1983) Gravel overpassing on humpback bars supplied with mixed sediment: Examples from the Old Red Sandstone, southern Britain. *Sedimentology* 30, 285–294.

Bathurst, J. C., Thorne, C. R. & Hey, R. D. (eds) (1987) *Gravel Bed Rivers: Fluvial Processes, Engineering and Management.* Wiley, Chichester, UK.

Beschta, R. L., Rhodes, J. J., Kauffman, J. B., Griesswell, R. E., Minshall, G. W., Karr, J. R., Perry, D. A., Hauer, E. R. & Frissell, C. A. (2004) Postfire management on forested public lands of the western United States. *Conservation Biology* 18(4), 957–967.

Broadhurst, B. T., Dyer, J. G., Ebner, B. C., Thiem, J. D. & Pridmore, P. A. (2011). Response of two-spined blackfish *Gadopsis bispinosus* to short-term flow fluctuations in an upland Australian stream. *Hydrobiologia* 673, 63–77.

Carling, P. A. (1984) Deposition of fine and coarse sand in an open-work gravel bed. *Can. J. Fisheries and Aquatic Sciences* 41, 263–270.

Carling, P. A. & Reader, N. A. (1982) Structure, composition and bulk properties of upland stream gravels. *Earth Surface Processes and Landforms* 7, 349–365.

Davey. G. W, Doegm T. J & Blyth, J. D. (1987) Changes in benthic sediment in the Thomson River, Victoria, during construction of the Thomson Dam. *Regulated Rivers: Research and Management, Research and Managemen*t 1.

Ebise, S., Aizaki, M., Otsubo, K. & Muraoka, K. (1983) Estimation of river sediments as pollutants loadings. *National Institute for Environmental Studies, Japan* 6, 93–103.

Einstein, H. A. (1968) Deposition of suspended particles in a gravel bed. *J. Hydraulics Div. ASCE* 94, 1197–1205.

Frazer, H. J. (1935) Experimental study of the porosity and permeability of clastic sediments. *J. Geology* 43, 910–1010.

Forrest, J. & Clark, N. (1989) Characterising grain-size distributions: evaluation of a new approach using multivariate extension of entropy analysis. *Sedimentology* 36, 711–722.

Gomez, B. (1983) Temporal variations in bedload transport rates: the effect of progressive armouring. *Earth Surface Processes and Landforms* 8, 41–54.

Kaufmann, P. R., Faustini, J. M., Larsen, D. P. & Shirazi, M. A. (1999) A roughness corrected index of relative bed stability for regional stream surveys. *Geomorphology* 99, 150–170.

Minshall, G. W. (2003) Responses of stream benthic macroinvertebrates to fire. *Forest Ecology and Management* 178(1-2), 155–161.

Mosley, M. P. & Tindale. R. S. (1992) Sediment variability and bed material sampling in gravel bed rivers. *Earth Surface Processes and Landforms* 10, 465–482.

Ormerod, S. J., Dobson, M., Hildrew, A. G. & Townsend, C. R. (2010) Multiple stressors in freswhater ecosystems. *Freshwater Biology* 55, 1–4.

Reid, M. A., Thoms, M. C. & Southwell, M. (2012) Changes in benthic community structure and function in an Australian regulated upland stream following wildfire. In: *Wildfire and Water Quality: Processes, Impacts and Challenges* (Proc. conference held in Banff, Canada, June 2012). IAHS Publ. 354, IAHS Press. Wallingford, UK (this volume).

Southwell, M. & Thoms, M. C. (2012) Double trouble: the influence of wildfire and flow regulation on fine sediment accumulation in the Cotter River, Australia. In: *Wildfire and Water Quality: Processes, Impacts and Challenges* (Proc. conference held in Banff, Canada, June 2012). IAHS Publ. 354, IAHS Press. Wallingford, UK (this volume).

Stanley, E. H., Powers, S. M. & Lottig, N. R. (2010) The evolving legacy of disturnace in stream ecology; concepts, contributions and coming challenges. *J. North American Benthological Society* 29, 67–83.

Thoms, M. C. (1987) Channel sedimentation in the urbanised River Tame, UK. *Regulated Rivers: Research and Management* 1, 229–246.

Thoms, M. C. (1992) A comparison of grab- and freeze-sampling techniques in the collection of gravel-bed sediment. *Sedimentary Geology* 78, 191–200.

Thoms, M. C (2007) The distribution of heavy metals in a highly regulated river: the River Murray, Australia. In: Water Quality and Sediment Behaviour of the Future (ed. by B. W. Webb & D. de Boer), 145–153. IAHS Publ. 314. IAHS Press, Wallingford, UK.

UNESCO (1984) International Hydrological Challenges. Ref. NS/188, Annex II, Paris.

Wohl, E. E. (2010) *Mountain Rivers Revisited*. Water Resources Monograph 19, American Geophyiscal Union.