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River delta in the Wollondilly arm of Lake Burragorang, February 2003
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Scott Wilkinson[1], Peter Wallbrink[1], Rick Shakesby[2], William Blake[3] and Stefan Doerr[2]

[1]CSIRO Land and Water

[2]University of Wales at Swansea, UK

[3]University of Plymouth, UK

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Executive summary

This report summarises the findings of a four year project to investigate the impacts on water quality of sediments and nutrients released following the 2001 bushfires in the Lake Burragorang catchment. Much of the SCA water supply catchments are forested, prone to wildfire, and thus potentially susceptible to the negative impacts of forest fires on reservoir water quality. The magnitude of fire impacts are determined by the size and intensity of the fire, and the co-incidence of subsequent rainfall events. Preliminary findings and observations after the Sydney 2001 fires showed that bushfires can have a significant impact on downstream water quality in Lake Burragorang. The 2001 fires were the largest in over 30 years and were followed by several significant rainfall events. This special set of circumstances provided an excellent opportunity to investigate the highly episodic, but potentially very significant, role of fires on the transfer of sediments and nutrients from hillslopes and their impact on the water quality of SCA water supply reservoirs.

The research indicates that forest fire has the potential to cause large increases in the sediment and nutrient yield to Lake Burragorang, and other SCA water storages. The study found that significant amounts of mineral and organic sediment and attached nutrients were eroded from burnt hillslopes in the months following the fires. Some storage on flatter footslope areas indicates the capacity for these areas to act as hillslope sediment buffers. Given this capacity it may be important to avoid occurrence of fires of very high and extreme severity in these areas.

The fire had a large impact on the characteristics of sediment delivered to the river network and the reservoir. Large amounts of material from surface erosion of hillslopes were to the river network draining the burnt area. Consequently, a high proportion of the post-fire river sediment was derived from surface erosion, in contrast to the pre-fire sediment sources which were dominated by erosion of sub-surface material from rivers and gullies. The post-fire Phosphorus concentration of river sediment was many times that pre-fire as a result.

The sediment and nutrient yields to Lake Burragorang in post-fire runoff events were one to two orders of magnitude larger than in pre-fire conditions due to the vastly increased availability of sediment and nutrients. Given the importance of events in the delivery of post-fire sediment and nutrient delivery to the reservoir, monitoring the potential for an algae bloom following post-fire runoff events may be an important post-fire water quality management strategy.

The characteristics of post-fire river sediment returned towards pre-fire conditions over four years as the pulse of sediment was stored and evacuated from the river network. The below-average rainfall and runoff in the post-fire period of vegetation recovery limited the total post-fire sediment yield to Lake Burragorang well below the potential yield that could have occurred in wetter conditions. The actual sediment yield was in fact below the mean-annual average yield, but still one to two orders of magnitude above the yield that would have occurred without the fire.

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1. Introduction

This collaborative project with the Sydney Catchment Authority (SCA) has investigated the transfer of sediments and nutrients between different components of the Nattai River catchment slopes to Lake Burragorang reservoir continuum following the 2001 fire. The fire covered 225,000 ha and was the largest in the Lake Burragorang catchment in over 30 years. Separate to this project, a field investigation of the combustion of vegetation, coupled with analysis of remote sensing data, indicated that the fire was of high to extreme severity over much of the burnt area (Shakesby *et al.*, 2003; Chafer *et al.*, 2004). There were several significant rainfall events in the weeks following the fire that delivered a pulse of black post-fire sediment to the river network draining the burnt area (Shakesby *et al.*, 2003). The aim was to develop an understanding of the impacts of fire induced erosion on water quality in Lake Burragorang. In particular the research investigated:

- The redistribution of soil/sediment and attached nutrients that occurs within, and from, severely burnt hillslopes in the Sydney catchment
- The impacts of post-fire erosion and sediment movement on downstream water quality in the immediate post-fire period
- The impacts of post-fire sediment/nutrient losses compared to non-fire catchment erosion over the lifespan of Lake Burragorang

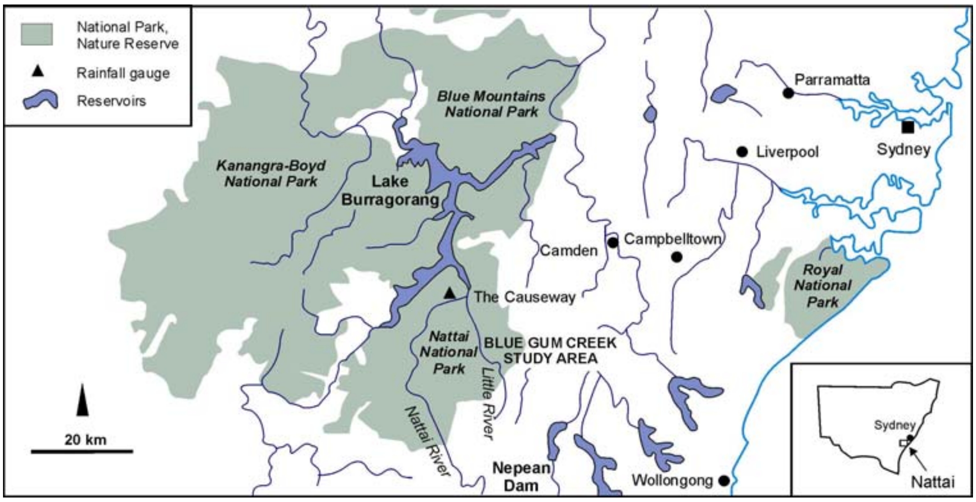

Figure 1: A map of Lake Burragorang catchment showing the location of the Blue Gum Creek study area in which the hillslope process and sediment redistribution studies were undertaken. The river network study encompassed the Little River and Nattai River and adjacent tributaries, and the impact on reservoir sedimentation focussed on the Nattai and adjacent Wollondilly arms of the reservoir (English *et al.*, 2005).

Figure 1 shows the study area. This report provides a summary and integration of the major findings of the research. All publications to date from this research are listed at the back of this report. In particular, this report is supported by four project reports that detail the methods and findings:

Wallbrink, P., English, P., Chafer, C., Humphreys, G., Shakesby, R., Blake, W. and Doerr, S. (2004). Impacts on water quality by sediments and nutrients released during extreme bushfires: Report 1: A review of the literature pertaining to the effect of fire on erosion and erosion rates, with emphasis on the Nattai catchment, NSW, following the 2001 bushfires. Client Report, CSIRO Land and Water, Canberra, http://www.clw.csiro.au/publications/consultancy/2004/nattai_catchment_fire_erosion.pdf.

English, P., Wallbrink, P., Humphreys, G., Shakesby, R., Doerr, S., Blake, W., Chafer, C. and Vigneswaran, B. (2005). Impacts on water quality by sediments and nutrients released during extreme bushfires: Report 2 Tracer assessment of post-fire sediment and nutrient redistribution on hillslopes: Nattai National Park, NSW. Client Report, CSIRO Land and Water, Canberra, http://www.clw.csiro.au/publications/consultancy/2005/SCA-Report2.pdf.

Wilkinson, S., Wallbrink, P., Blake, W., Doerr, S. and Shakesby, R. (2006a). Impacts on water quality by sediments and nutrients released during extreme bushfires: Report 3: Post-fire sediment and nutrient redistribution to downstream waterbodies, Nattai National Park, NSW. Science Report 64/06, CSIRO Land and Water, Canberra. 31 pp, http://www.clw.csiro.au/publications/science.

Wilkinson, S., Wallbrink, P., Hancock, G., Blake, W., Shakesby, R. and Farwig, V. (2007). Impacts on water quality by sediments and nutrients released during extreme bushfires: Report 4: Impacts on Lake Burragorang. Science Report 6/07, CSIRO Land and Water, Canberra. 22 pp, http://www.clw.csiro.au/publications/science.

2. Research Methods

The first phase (1) of the research comprised a review of the relevant literature. The post-fire material fluxes were then quantified at three scales in the remaining three phases of the project: (2) burnt hillslopes, (3) contributing streams in the river network and (4) the entire Nattai River catchment. At each of the three spatial scales studied, the research methods were:

- At the hillslope scale, hillslope budgets of sediment attached fallout radionuclides ^{137}Cs, $^{210}Pb_{ex}$ and ^{7}Be which label surface sediment and organic litter were used to construct budgets quantifying the losses and redistribution of material for the component units of the hillslope topography in the large rainfall events that occurred in the immediate months following the fires. Independent measurements of hillslope erosion and redistribution processes using erosion bridges and geomorphic investigations were also conducted to develop understanding of the post-fire behaviour.
- Within the river network downstream of the burnt area, radionuclide sediment tracers were used to track the spatial and temporal trends in sediment and nutrient fluxes over a four-year period following the fires. Using the sediment ^{137}Cs radionuclide activity, a mixing model was used to determine the mixture of surface and sub-surface sources making up post-fire river sediment, and how this changed over time. Sediment particle magnetic characteristics were used as an additional tracer of surface sediment from burnt areas. Sediment geochemistry was used to investigate the fire impact on Phosphorus movement. Water quality monitoring data was also used to understand the event-scale temporal dynamics of post-fire erosion on sediment and nutrient transport within the river network.
- The long-term contribution to reservoir sedimentation of fire relative to non-fire sources was investigated by reconstructing the chronology and source characteristics of sediment cores and samples collected from the Nattai and Wollondilly arms of Lake Burragorang. The signature of the deposited sediments was compared against the signatures of fire and non-fire source material. A combination of ^{137}Cs, $^{210}Pb_{ex}$ and ratios of fallout Plutonium isotopes was used in this analysis, as well as sediment geochemistry and physical characterisation of core strata.

The research involved five multi-day field expeditions and multiple analyses were conducted on over 700 sediment samples.

3. Summary of the project findings

3.1. Review of data available

The first phase of the project reviewed the available literature regarding the impact of fire erosion and sediment and nutrient movement (Wallbrink *et al.*, 2004; Shakesby and Doerr, 2006). The review found that fire has an impact on soil erosion by removing vegetation and surface litter cover, and to a lesser extent by affecting soil wettability; thereby increasing runoff. The literature showed considerable variation in the impacts on hillslope sediment yield following Australian forest fires; with both large and negligible increases on pre-fire sediment delivery rates being recorded depending on fire severity. The impact of fire on sediment yield was also found to be determined by the extent to which post-fire rainfall events exceeded the erosion resistance of catchments during the post-fire recovery of litter and ground vegetation cover, soil structure and soil wettability. Elevated Nitrogen, Phosphorus, Calcium, Magnesium and Potassium concentrations have been observed after wildfire, because of their release in combustion, and their affinity for fine sediment particles.

The 2001 Sydney fires burnt 225,000 ha of eucalypt forest surrounding Lake Burragorang. Modelling of fire intensity based on fuel load biomass indicate extreme heat energy levels exceeding 70,000 kWm^{-1}. This extreme fire intensity was computed from the combination of satellite imagery and field assessment, and corresponded to soil temperatures exceeding 350ºC at depths averaging 1.5-2 cm and estensive consumption of woody vegetation (Shakesby *et al.*, 2003).

By May 2002, large quantities of topsoil had been eroded from the burnt hillslopes and transported to the stream (Shakesby *et al.*, 2003; Shakesby *et al.*, 2006). Evidence of sediment movement was more prevalent in areas where the fire was of high severity than where the fire was of low severity. Some of the burnt topsoil and sub-surface material eroded from hillslopes was also deposited on lower gradient footslopes. The spatial heterogeneity of soil wettability and widespread bioturbation on footslopes enhanced infiltration and so prevented larger amounts of hillslope transport from occurring.

3.2. Hillslope erosion and sediment redistribution

Hillslope radionuclide budgets identified significant short term surface soil/sediment/ash redistribution on slopes in the Blue Gum Creek catchment (English *et al.*, 2005; Wallbrink *et al.*, 2005). Erosion rates were highest on steep side slopes, and some deposition occurred on lower gradient foot-slopes adjacent to Blue Gum Creek (English et al., 2005; Wallbrink et al., 2005). The estimated losses of the very surface layers of litter and topsoil were several times those of the deeper sandy sub-soil layers (Wallbrink et al., 2005; Shakesby et al., 2007).

Independent soil erosion measurements support these findings, with erosion of sandy sub-soil 6.8-14.9 mm deep in some locations but deposition of similar magnitude elsewhere indicating generally local redistribution of sand-sized material. Litter dams and ant faunal activity were important factors in limiting sediment transport on hillslopes (Shakesby et al., 2003; Shakesby et al., 2006). In places the fire also caused physico-chemical changes to sediment by fusing fine particles into sand-sized aggregates (Blake *et al.*, 2005). These other factors and also spatial variability in soil wettability limited the erosion impact of fire-induced changes to soil wettability which have been found to be important elsewhere (Doerr *et al.*, 2006). Comparisons between downstream sediment yields and hillslope erosion rates (Tomkins *et al.*, In press) also found that sediment storage on foot-slopes was an important buffer that constrained sediment delivery from the hillslope erosion to the river network. Importantly for the transport of nutrients, fine sediment and burnt organic material/ash were transported together (English et al., 2005).

3.3. Sediment and nutrient delivery to the river network

Sediment delivery to the river network in 2002 was approximately six times the pre-fire mean-annual rate in the fully burnt Little River catchment and 3 times the pre-fire amount in the partially burnt lower Nattai River (Wilkinson *et al.*, 2006a; Wilkinson *et al.*, 2006b). The results of mineral magnetics analysis (Blake *et al.*, 2004; Blake *et al.*, 2006a) closely supported the radionuclide analysis in this regard.

As well as increasing the amount of sediment delivered to the river network, the fire had a large impact on the characteristics of sediment delivered to the river network. The contribution of surface-derived material to river sediment in 2002 increased with the proportion of upstream catchment that was burnt, as illustrated in Figure 2. In the Little River, with a completely burnt catchment, 84% of post-fire sediment was derived from surface erosion; in contrast Gillans Creek, with a very small proportion of catchment burnt, had less than 10% of sediment derived from surface erosion (Wilkinson *et al.*, 2006a).

Field observations indicate that the predominant sources of subsurface material in the catchment are gully and riverbank erosion. The gullies in this environment can be considered as part of the fluvial incision of the landscape rather than as a response to historical landuse change as they are on the tablelands. The erosion rates of the forested sandstone area are relatively high by Australian standards, which can be attributed to long-term fluvial incision of the eastern Australian continental margin over the last 100 million years (van der Beek *et al.*, 2001).

As a consequence of surface erosion being the dominant post-fire sediment source, the Phosphorus concentration of river sediment in 2002 was 6 times that of pre-fire sources. Phosphorus was particularly associated with the organic fraction of sediment.

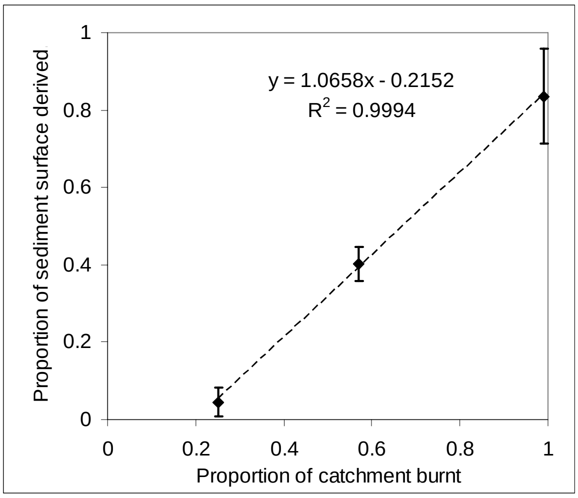

Figure 2: The contribution of surface-derived material to river sediment in 2002 was closely related to the proportion of catchment that was burnt (Wilkinson *et al*., 2006). The error bars show ±2 standard errors.

The post-fire concentrations of suspended sediment, Phosphorus and Nitrogen in the Little River were much more sensitive to increasing runoff than before the fire, as illustrated in Figure 3. This was attributed to the vastly increased availability of fine, surface derived sediment post-fire. Consequently, the post-fire transport of suspended sediment, Phosphorus and Nitrogen was much more event-driven. The yields from individual post-fire runoff events were 1–2 orders of magnitude higher than the yields for similar sized events before the fire.

Declines in the radionuclide activities of river sediment towards pre-fire levels over the 4 years to March 2006 indicate that the majority of the post-fire sediment was delivered to the reservoir during this time, as shown in Figure 4 (Wilkinson *et al.*, 2006a).

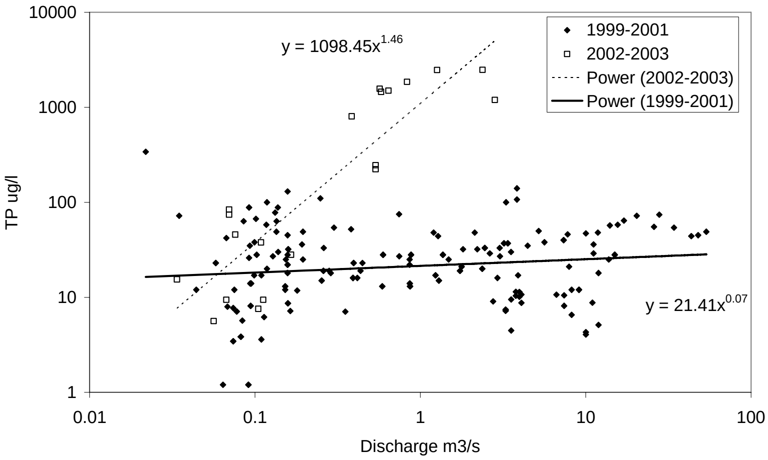

Figure 3: An example of the difference in the suspended sediment and nutrient concentrations between pre-fire runoff events 1999–2001 and post-fire runoff events 2002–2003. Total Phosphorus concentration is plotted against discharge on log scales. Separate power function trend lines are fitted to the pre-fire and post-fire data to illustrate the different responses to increasing discharge (Wilkinson *et al.*, 2006a).

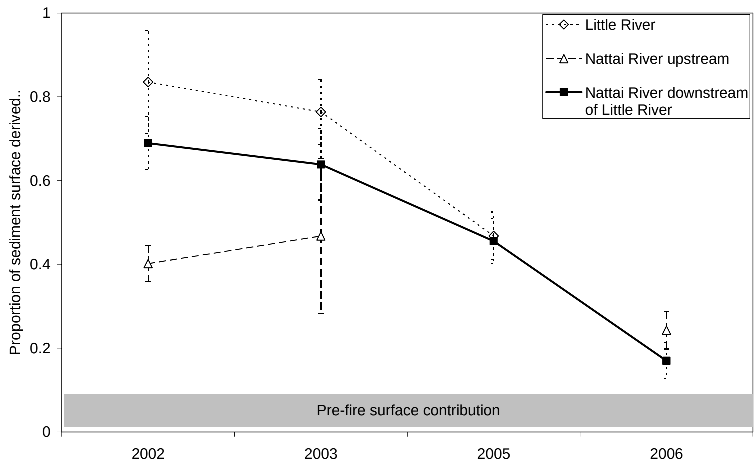

Figure 4: The proportion of river sediment derived from surface erosion declined back towards the pre-fire levels over the sampling period (Wilkinson *et al.*, 2006). The error bars show ±2 standard errors on the mean proportion.

3.4. Sediment yields to the reservoir

Although the 2001 fire was of high to extreme severity, the post-fire period remained much drier than average, which limited post-fire erosion and sediment delivery from hillslopes (Wilkinson *et al.*, 2006a), and also reduced the rate at which it was delivered to the reservoir. Independent of fire, the variability in runoff caused three orders of magnitude variation in annual sediment yield at the Nattai River gauge 212280; between one order of magnitude above and two orders of magnitude below the mean annual yield (Wilkinson *et al.*, 2007; Rustomji and Wilkinson, in review). Consequently, although sediment delivery to the river network from the burnt area was several times the mean annual delivery, deposition of post-fire sediment in the Nattai and Wollondilly arms of the reservoir in 2002 was minor relative to pre-fire deposition (Blake *et al.*, 2006b). The 2002 deposition was somewhat lower than the long-term mean-annual rate of deposition since dam completion in 1960, and comprised less than 1–1.6% of total reservoir deposition (Wilkinson *et al.*, 2007).

Thus the erosion pulse associated with the fire increased annual sediment yields from very low drought levels back towards the long-term average. A worst case combination of severe fire and above-average runoff in the post-fire period could, however, result in annual sediment yields two to three orders of magnitude above the mean yield.

Independent of the amount of sediment delivered from fires over the long term, the radically different characteristics of sediment released by post-fire erosion pose a risk to reservoir water quality. In particular the Phosphorus concentration of post-fire sediment and the dissolved Phosphorus concentration of post-fire runoff are both several times that of non-fire sources. Event yields of Phosphorus can be 1–2 orders of magnitude larger after fire (Wilkinson *et al.*, 2006a). Therefore the risk of algal bloom in the reservoir is elevated after post-fire runoff events. Modelling the risk of algal bloom after post-fire runoff events, and also regular algae monitoring by direct measurement or remote sensing, may be useful methods for managing the risk of algal bloom to water quality.

4. Overall conclusions

From this study we make the following conclusions:

- The 2001 fires and subsequent rainfall triggered widespread erosion of hillslopes. The combustion of ground vegetation and forest litter also increased the hydrologic connectivity of hillslopes to streams. Steep side slopes and also plateaux were the major areas contributing post-fire sediment in the Blue Mountains sandstone terrain.
- Lower gradient foot-slopes and riparian areas were the only hillslope units where net sediment deposition occurred. Therefore, preferential protection of riparian and foot slope areas from fire may be a useful strategy for buffering post-fire hillslope erosion from the river network.
- Post-fire sediment yields from the burnt area to the river network were approximately 6 times pre-fire levels.
- Post-fire sediment was sourced predominantly from surface erosion rather than the erosion of sub-surface material from gullies and riverbanks characteristic of unburnt catchments.
- Post-fire river sediment contained several times more Phosphorus than pre-fire sources.
- Sediment yields to the river network declined towards pre-fire levels over a four year period. The post-fire pulse in delivery of Phosphorus was somewhat shorter than four years.
- Drier than average conditions in the post-fire period of vegetation recovery limited annual sediment yields to the reservoir to less than the long-term average sediment yield in 2002, but greater than the yield that would have been experienced if the fire had not occurred.
- After fire, individual runoff events can transport one to two orders of magnitude more sediment and nutrients than during pre-fire events. Therefore the risk of algae blooms may be elevated following post-fire runoff events. Modelling the risk of algae blooms after post-fire runoff events, and regular algae monitoring by direct measurement or remote sensing, may help identify the risks of algae blooms.

5. Publications

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