



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

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Sydney Catchment Authority - CSIRO Land & Water Collaborative Research Project

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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

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1 Introduction

1.1 Preamble

Much of the Sydney Catchment Authority (SCA) water supply catchments in the Blue Mountains, New South Wales (NSW), are forested and prone to wildfire. Replacement of forest litter with ash and charcoal, and enhanced washoff of these materials along with soil particles, clay and dissolved or adsorbed nutrients and organic matter, have the potential to negatively affect water quality in streams and reservoirs.

Preliminary observations after the recent Sydney 2001 fires in the Nattai River catchment (Figure 1) showed that bushfires can have a significant impact on downstream water quality in Lake Burragorang/Warragamba Dam. The magnitude of fire impacts are determined by the intensity of the fire and its size, and the co-occurrence with subsequent rainfall events. The Sydney fires over Christmas 2001 were the largest in 40 years and were followed by six rainfall events of which one was at least 100 mm in volume. This special set of circumstances provides an excellent opportunity to investigate the highly episodic, but perhaps very significant, role of fires on the transfer of sediments and nutrients from hillslopes and their impact on the water quality of SCA reservoirs. This role may have been previously overlooked. However in times of drought, such as have prevailed during the past several years, the potential for such impacts is considerably increased.

This collaborative three-year project between CSIRO and the SCA on the impacts on water quality of extreme bushfires aims to investigate the rates and amounts of transfers of sediments and nutrients between different components of the Nattai catchment slope to reservoir continuum. The quantification of the material fluxes will use state of the art tracer techniques. The major outcome of this research will be an understanding of impacts from fire induced erosion on the water quality of SCA reservoirs.

1.2 Project approach and work plan

The overall project has been designed to provide four main deliverables each of which have been directed towards quantifying a component of the transfer of material from catchment slopes to Lake Burragorang:

- Quantification of the redistribution of soil/sediment and attached nutrients that occurs within, and from, small scale slopes in a severely burnt Sydney catchment;
- An understanding of the immediate post fire impacts on downstream water quality arising from the redistribution of soils, sediments and attached nutrients from hillslopes;
- Assessment of the downstream impacts of sediment/nutrient losses over the lifespan of waterbodies arising from the episodic release of wildfire induced slope erosion;
- An assessment of the long term contribution of sediment/nutrients to reservoir sediment archives from fires compared to non-fire related causes of catchment erosion.

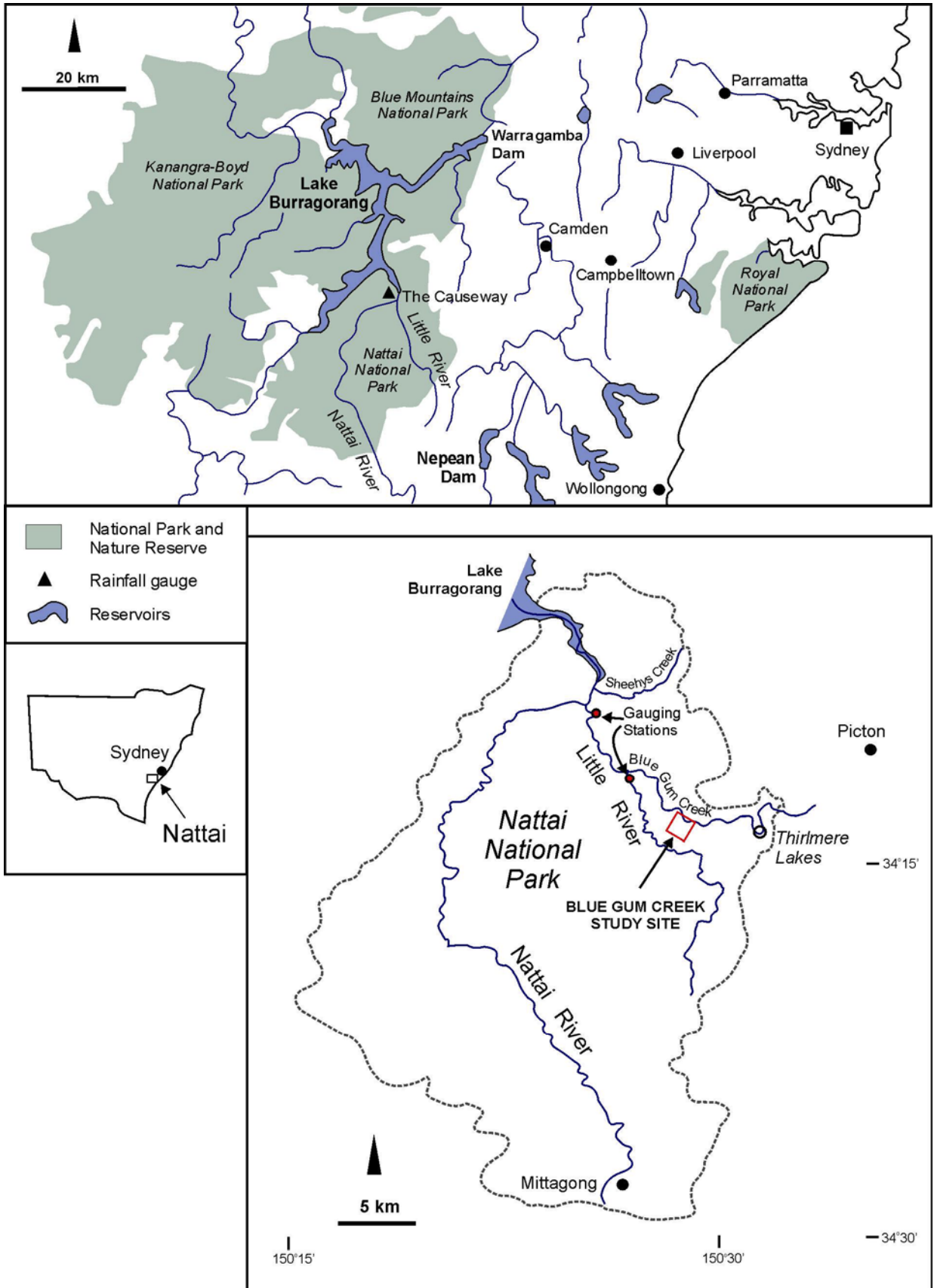


Figure 1. Lake Burragorang catchment and Nattai study area.

The project work plan is divided into the following four steps:

1. Literature review of available information and relevant data;
2. Construction of slope based sediment/nutrient budgets;
3. Post fire impacts;
4. Assessment of downstream impact on water quality.

1.3 This report

This report provides an overview of relevant literature on the erosional consequences and downstream effects of severe bushfires in forested catchments, particularly with respect to the context of the steep, eucalypt-forested sandstone catchments of NSW. We present information on:

- (i) the background to the present study;
- (ii) the occurrence and intensity of wildfires;
- (iii) the effect of fires on vegetation and soil cover;
- (iv) physical changes to soil properties after fire and their effect on soil erosion;
- (v) the effect of fire on soil wettability;
- (vi) the distribution and intensity of post fire rainfall/runoff;
- (vii) the effect of fire on erosion rates;
- (viii) initial observations of post-fire processes in the Nattai catchment.

2 Background

In 2001 a combination of drought and hostile prevailing weather led to a series of 'conflagration scale' wildfires that burnt significant areas of forested regions in NSW. The fires were responsible for burning a substantial fraction of the forests within Nattai River catchment, which with other catchments, form the watershed for Lake Burragorang/Warragamba Dam, the principal water supply catchment for Sydney (Shakesby et al., 2003). The fires of late 2001 were ignited by lightening strikes and were followed by high intensity rainfall events in early 2002. This combination of circumstances resulted in enhanced soil erosion rates, the significant redistribution of sediment from slopes and the deposition and storage of sediment/ash in rivers. There is the potential for this redistribution to result in severe degradation of downstream water quality (Good, 1973; Atkinson, 1984; Greene et al., 1990). Elevated nitrogen, phosphorus, calcium, magnesium and potassium concentrations have been observed after wildfire (Ice et al., 2004). Nitrogen and phosphorus movement after fire may be associated with eroded sediments and runoff water. In particular, export of phosphorus accompanying quantities of newly eroded sediment to the waterways is a potential problem because of its influence on the occurrence of commonly toxic algal blooms (Kuhn, 1993; Verhoeven, 1993). This review examines the impact of fire on soil erosion with particular emphasis on erosion rates and the influential factors. We also present some initial results from the impacts of the severe wildfire on erosion in the Nattai catchment.

3 The Occurrence and Intensity of Wildfires

Fire is a phenomenon that occurs naturally in almost all continents, although most frequently in Mediterranean regions (di Castri and Mooney, 1973; Zierholtz, 1997). Mediterranean ecosystems are generally characterized by distinct vegetation, hydrology and weathering regimes (di Castri and Mooney, 1973; Gill, 1975; van Wilgen et al., 1992; Moreno and Oechel, 1994; Zierholtz, 1997). Much of Australia is classified as having a Mediterranean climate and associated vegetation and is therefore also considerably prone to fire (Gill, 1975). Previous studies indicate that intense fire is capable of severely degrading soil cover and soil surfaces to the extent that major erosion can be promoted (Booker et al., 1993; Dragovich and Morris, 2002; Shakesby et al., 2003). DeBano et al., (1979) also argue that with increasing burn intensity, there are increasingly severe and long-lasting effects on soil and soil erosion.

The severity (the results of the burn, integrating burn intensity, duration and site conditions) and intensity (heat per area per time unit) of the Christmas 2001 wildfires in the relatively inaccessible Sydney catchments have been measured by Chafer et al. (2004) using pre- and post-fire satellite imagery from SPOT2. A Normalised Difference Vegetation Index (NDVI) was computed from satellite images captured before and after the fires and the latter subtracted from the former to produce a difference image (NDVI_{diff}) which was then classified into several fire severity classes from unburnt to extreme severity. The classification was tested in numerous sites within the 225 000 ha fire affected area and combined with detailed information on fuel loads and rates of fire spread to model fire intensity. Results of this analysis of the spatial distribution of fire impact are included below.

4 The Effect of Fires on Vegetation and Soil Cover

Fire can substantially reduce the amount of vegetation and surface cover on the soil (Shakesby et al., 2003). Loss of surface cover is critical to the detachment and entrainment of soil particles in particular and erosion rates are typically higher where surface cover is reduced (Lang and McCaffery, 1984; Singer and Walker, 1983). Loss of trees and other forms of soil cover also exposes the soil surface to degradation by erosive forces such as raindrop impact and flow (Moss, 1989). Soil cover also protects the soil from degradation such as surface sealing (Meyer and Mannering, 1971; Morgan, 1979; Hudson, 1986; Lang and McCaffrey, 1984). The presence of vegetation also enhances surface roughness and increases infiltration, which impedes overland flow (Croke et al., 1999a, b). The removal of this surface cover after burning has been shown to result in more rapid overland flow (Lavee et al., 1995). At the local scale this can increase rates of erosion and soil loss (DeBano et al., 1979; Atkinson, 1984; Scott and Van Wyk, 1992) while at the catchment scale it can result in increases to the duration, frequency and magnitude of channel hydrographs (Brown, 1972; Good, 1973; O'Loughlin et al., 1982; Cornish and Binns, 1987).

5 Physical Changes on Soil Properties after Fire and Their Effect on Soil Erosion

Changes to soil properties can occur following their heating by fires (DeBano et al., 1977; Humphreys and Craig, 1981; Valzano et al., 1997; Zierholz, C., 1997; Dekker et al., 2003; Doerr and Moody, 2004). Specifically, a fire heats the upper layer of the soil and creates deposits of ash (DeBano et al., 1979). This reduces infiltration capacity by clogging the soil pores. At higher temperatures, nutrients are lost as gases or converted (mineralized) into

forms more readily transported by surface runoff (Ice et al., 2004). Physiochemical changes occur with the aggregation of silt and clay into sand-sized entities at temperatures exceeding 220°C, organic matter is distilled at 300-315°C and nutrient volatilisation at 200-400°C (Neery et al., 1999). At these temperatures, volatilised organic matter is also involved in the generation of water repellence or *hydrophobicity* (discussed further below). Where rock is exposed to intense fire it may be subject to accelerated weathering through a process known as spalling (Christensen, 1994). As much as 6 kg of rock flakes per square metre have been recorded in the Blue Mountains (Adamson et al., 1983), representing some 50% of the surface area of severely heated outcrops. Humphreys et al. (2003) calculate this would provide long term denudation rates of up to 3 g m² y⁻¹. In addition to this flaking or exfoliation of sandstone, the passing of fire also releases charred algal coatings and weakens cement in the sandstone, making loosened sand grains and interstitial clay material mobile (Adamson et al., 1983).

It has also been demonstrated that reduced infiltration and increased runoff can occur after fire due to fire-induced water repellence and surface sealing by rain splash which, in turn, can promote increased erosion (DeBano et al., 1979; Shakesby et al., 2003). Imeson et al. (1992) however found substantial variability in water repellence and soil cover after burning which resulted in a heterogeneous distribution of areas where increases in erosion and runoff occurred.

It has been shown that fire can modify the particle size distribution of soil through formation of robust sand-sized aggregates from fine clays and silts in the topsoil subject to burning. Heating of topsoil by fires has been shown to promote new forms of cementation in which iron and aluminum are involved in a process very similar to soil lateritization (Giovanni et al., 1988). Importantly, newly-transported fire-induced aggregates of fine material demonstrate a potential for storage of nutrients within floodplains and river channels, with attendant implications for impact on downstream water quality.

The variation in magnetic enhancement of soil caused by fire and its use to trace the origins of eroded sediments has been investigated by Humphreys et al. (2003). Fire leads to formation of an overprint of secondary iron oxide minerals that can be distinguished from the primary magnetic signature of the host grain. At soil temperatures in excess of 400° C iron-rich substrates in the presence of reducing agents such as organic material, may generate substantial quantities of secondary magnetic minerals especially very fine-grained magnetite or maghemite (e.g., Rummery et al., 1979, Oldfield et al., 1981). These changes that can lead to increases in magnetic susceptibility and certain remanent magnetism values and are thereby useful as a means of tracing the provenance of eroded sediment.

Bioturbation of soils after fire can promote either runoff or infiltration and enhance or reduce overland flow and erosion. The following active agents in the soil bioturbation of the sandstone hillslopes of the Sydney basin have been described by Humphreys and Mitchell (1983): ants, termites, earthworms, cicadas, spiders, roots, lyrebirds, echidna and treefall. Under typical, unburnt conditions rates of surface mounding by animals and treefall in numerous sites exceeded the rates of erosion by rainwash by a factor of between 2 and 30. Faunal activity (ants' nests, mammal scrapes) is viewed as a significant factor in post-fire sediment transfer in sandstone terrain near Sydney (Humphreys and Mitchell, 1983, Dragovich and Morris, 2002). The role of lyrebird scrapings causing accelerated rates of erosion is emphasised by Adamson et al. (1983) who cite annual turnover of soil and litter of 63 t ha y⁻¹ in the Sydney Basin. At a population density of one lyrebird per ha, total turnover of the soil to 8 cm depth occurs in 13 years, the approximate lifespan of an individual bird. This activity is expected to be offset after intense wildfires in valley habitats if there is high mortality in populations. Rates of downslope movement of soil through biological activity typically exceed erosion rates by rainfall. Only in the case of burnt slopes (Blong et al., 1982) are the rates comparable (Humphreys and Mitchell, 1983).

A factor inhibiting net soil loss from burnt slopes is the widespread development of litter dams or microterraces parallel to contours which serve to trap surface sediment, particularly in low gradient positions (Mitchell and Humphreys, 1987). Charcoal, ash, charred leaves and bark and other post-fire residue is easily transported by flowing water. The slurries form dams transverse to slope on low-gradient areas wherever water velocity is reduced or irregularities are encountered. These litter dams serve to trap sand, charcoal and other debris which progressively accumulate after successive runoff events. Aggraded microterraces of soil subsequently promote vegetation colonization and mitigate further soil erosion (Adamson et al., 1983).

6 The Effects of Fires on Soil Wettability

The combination of a hydrophobic soil and reduction in the litter layer can lead to increased runoff and therefore to erosion (Zierholtz, 1997). A water repellent soil resists the uptake of water due to the coating of soil aggregates by hydrophobic substances (Bond, 1968; DeBano et al., 1979; Ma'shum and Farmer, 1985; Ma'shum et al., 1988; Shakesby et al., 2003). Fire induced water repellence has been well documented (e.g., DeBano and Krammes, 1966, DeBano et al., 1977; Humphreys and Mitchell, 1981; DeBano et al., 1979; Burch et al., 1989; Crockford et al., 1991; Scott and Van Wyk, 1990; Dekker and Ritsema, 1994; Doerr et al., 1998; Doerr et al 2000; Doerr et al., 2002; Dekker et al., 2003; Humphreys et al., 2003; Shakesby et al., 2003). Mechanisms causing water repellence include burning, leaching of organic compounds from litter, and growth of fungal hyphae (Savage, 1968; Savage, 1974). Giovannini et al. (1983) argue that the development of repellency during fire is attributed to the polymerisation of organic molecules into more hydrophobic ones, whilst Franco et al. (2000) describes the melting and redistribution of waxes from interstitial organic matter onto soil aggregates and mineral grains.

The water repellency status of soil can become more complex during burning since repellency can be eliminated at a critical temperature. This has been observed and confirmed experimentally at temperature ranges of between 280-400°C in US based laboratory studies (e.g. DeBano 2000), and at between 260-340°C for various Australian soils (Shakesby et al., 2003). The precise threshold of repellency elimination was found to depend on the temperature itself as well as the duration at which it was applied (Shakesby et al., 2003).

Most Australian soils naturally exhibit water repellency even when unburnt for long periods (Crockford et al., (1991). In these situations fire may lead to an increase or elimination of repellency. Shakesby et al. (2003) found that recent fires in the Sydney area had varying effects on repellency and on hydrogeomorphic changes. It is the presence of soil repellency combined with the loss of surface cover that creates considerable erosion potential (Zierholtz, 1997; Doerr et al., 2000). Using rainfall simulation experiments at the plot scale in Portugal, Doerr et al. (2003) demonstrated that soil water repellency reduced soil wetting by a factor of >700 and increased mean runoff enhanced runoff processes by up to 53%. In the Sydney area, Shakesby et al. (2003) found widespread erosion and colluvial and alluvial redeposition of topsoil in foot-slope positions and river systems but only localised redistribution of the repellent sandy subsurface layer. Additional findings from recent research on post-fire repellency in the Sydney area are included below. Comprehensive reviews of the role of fire and soil heating can be found in De Bano (2000) and Dekker et al (2003).

7 The Distribution and Intensity of Post Fire Rainfall and Runoff

Precipitation that reaches the ground surface may either infiltrate or flow over the surface. Infiltration is affected by soil conditions, as outlined above. When the infiltration capacity of the soil is exceeded and rainfall intensity is high, runoff and erosion are promoted. Severe fires have the potential of increasing the amount of rainfall reaching the ground. In pre-fire conditions raindrops intercepted by a forest canopy evaporate relatively readily, thereby decreasing the amount of rainfall reaching the ground. Humphreys and Craig (1981) report on various Australian studies that show forest canopy interception accounting for 7 to 20% of annual precipitation. In their study in the Sydney Basin, Dragovich and Morris (2002) emphasise accelerated rates of post-fire sediment erosion being promoted by the lack of raindrop interception by tree and shrub canopies and leaf litter layers. Destruction of vegetation by fire immediately upsets the water balance by curtailing transpiration and increasing available moisture for either transpiration or runoff.

The severity of erosion after fires is substantially dependent on the timing and characteristics of post fire rainfall (Hudson, 1986). In particular the coincidence of intense rainfall with fire affected hillslopes is seen as an important control on the rates of soil erosion (Good, 1973; Booker et al., 1993; Prosser and Williams, 1998). Even under average climatic conditions, erosion rates following fire are expected to increase when compared to the pre-fire levels (Zierholtz, 1997). Authors such as Brown (1972), Campbell et al. (1977), Burgess et al. (1981), Leitch et al. (1983), Atkinson, (1984), Scott and Van Wyk (1990), Scott (1993), and Shakesby et al. (2003) all reported significant erosion responses following rain. Catastrophic increases in erosion in burnt catchments following rainfall have also been reported (USDA, 1954, Wells et al., 1979; Booker et al., 1993; Ice et al., 2004). In these situations the combination of fire and high intensity rainfall may cause significant mud and debris flows.

In rainfall simulation experiments on water repellent soils in Portugal, Doerr et al. (2003) emphasised that at the catchment scale, compared to plot scale simulations (mentioned above), locally generated overland flow in response to storm runoff in repellent conditions was captured by bypass routeways or sinks that are under-represented at point and plot scales. The connectivity of transport pathways and water courses in catchment drainage systems may also influence the effective discharge, and hence sediment yields in catchments (Scott, 1993; Croke et al., 1999a, b; Hairsine et al., 2002). In particular any roads, tracks and skidpaths within managed forests can become extensions of the drainage system and enhance the efficiency of runoff routing and sediment transport to streams (Zierholtz, 1997). Zierholz et al. (1995) provide evidence for enhanced erosion from vehicle and pedestrian tracks where significant coalescence of overland flow could occur, and only minor soil redistribution from slope areas where runoff was mitigated by stable soil structure and dense rootmats. Croke et al (1999a, b) and Wallbrink and Croke (2002) argue that the ultimate fate and volumes of eroded material is dependent on the combination of sediment supply and effective connected transport pathways.

The role of rills and gully erosion that may arise following fires can also affect downstream sediment supply. For example in the Boise River, Idaho, Benda et al. (2003) found that intense rilling and gullying following fires greatly increased the sediment supply in stream orders 3 to 6. The same authors reported the expansion of alluvial fans following fires, this process in turn causing morphological changes including both increasing and decreasing channel gradients both upstream and downstream of the fans. This increased sediment storage in the fans was also associated with widening of floodplains and side-channels and the creation of terraces.

In addition to impacting on erosion, enhanced post-fire runoff is expected to increase streamflows. McArthur and Cheney (1965) report on 43 to 235% increases in streamflow following wildfires in the Australian Capital Territory. Mackay and Cornish (1982) found that peak flows, stormflow volume and annual flows increased appreciably in catchments burnt by high intensity wildfire. Rapid runoff responses and peak flows in burnt catchments exceeded expected levels by factors of between 2 and 10. These increases were attributed to lower levels of transpiration and infiltration in the burnt catchments. Where changes to hydrographs occur, second order effects can result in terms of increases in the severity and extent of channel bank and gully erosion (Wells et al., 1979; Booker et al., 1993).

8 The Effect of Fire on Erosion Rates

In addition to being dependent on the nature of post-fire rainfall, noted above, the severity of erosion relates to the velocity and depth of runoff, which are a function of slope, and to soil factors such as cohesion of particles, plant cover and amount and type of litter (Humphreys and Craig, 1981). The literature shows considerable variation in erosion rates following fires, and a good summary is given in Zierholtz (1997). For example Prosser, (1990) and Emmerich and Cox, (1994) observed large increases in erosion after fire. In contrast, Blong et al. (1982), Imeson et al., (1992), Scott and Van Wyk (1992), Prosser and Williams (1998) and Dragovich and Morris (2002) show relatively small increases. Interestingly in the case of two Australian studies (Blong et al. 1982, and Prosser and Williams, 1998) the fires were followed by droughts, presenting the argument that the low rates $2\text{-}8\text{ t ha}^{-1}\text{ yr}^{-1}$ are attributable to the lack of rainfall. The data are also given at both the plot and catchment scale and the values range from very small, i.e., zero - 102 gm^{-2} (Biswell and Schults, 1976; Gilmour and Cheney, 1968; Versfeld, 1981; Dragovich and Morris, 2002), up to very high values of $204\text{ t ha}^{-1}\text{ yr}^{-1}$ (Glendening et al., 1961), $40.7\text{ t ha}^{-1}\text{ day}^{-1}$ (Brown, 1972), $27\text{ t ha}^{-1}\text{ day}^{-1}$ (Good, 1973) and 306 t ha^{-1} for a single event (Colman, 1951). Erosion rate values for most of these systems in their non-fired state were found to be low, in the order of 0.013 to $1.4\text{ t ha}^{-1}\text{ yr}^{-1}$ (Adams et al., 1946; Smith and Stamey, 1965; Scott, 1993). Zierholtz (1997) argues accordingly that any enhanced erosion due to fires in these regions results in a large increase in erosion rate over the baseline measurement (e.g., Lavee et al., 1995 reported increases up to 320%).

It is also important to consider the different scales at which data are presented. For example, the differences between the (often high) loss rates given at the small plot scale, and the much lower rates given at the (broader) catchment scale, reveal much about the geomorphic processes of deposition and storage that occur on burnt hillslopes and within streamlines and watercourses (Zierholtz, 1997). This can be seen in Scott and van Wyk (1992) who provide sediment yield data from the plot ($0.2\text{-}7.3\text{ t ha}^{-1}\text{ yr}^{-1}$) and catchment scale ($0.42\text{ t ha}^{-1}\text{ yr}^{-1}$). The immediate effects of fire can readily be quantified at the plot scale and presumably represent the local redistribution of soil, although this is complicated by the heterogeneity of deposition and storage observed at the hillslope level (Burgess et al., 1981).

A similar phenomenon was quantified by Wallbrink et al. (2002) for a landscape disturbed by logging and fire in NSW. Those authors constructed a ^{137}Cs based sediment budget for a 13 ha hillslope that had been logged and burnt some 6 years previous. They demonstrated that losses of up to 25 and $101\text{ t ha}^{-1}\text{ yr}^{-1}$ had occurred from the skid trails and log landings but that the majority of this eroded material $97\pm 6\%$ had been retained within the catchment, either through storage or redeposition within the General Harvest Area or riparian buffer strips. Therefore, significant erosion had occurred at the local scale, although at the larger catchment (13 ha) scale, no net losses had occurred, presenting a case for redistribution of a given budget of sediment.

As noted above, however, catastrophic erosion rates following fires have been reported in the United States (Atkinson, 1984; Leitch et al., 1983; and USDA, 1954; Ice et al., 2004). In these situations intense burning by wildfires was followed by large rainfall events, in turn triggering mud and debris flows (Wells, 1987; Booker et al., 1993; Ice et al., 2004). These situations may have been unique to the particular landscape investigated although represent the higher end of values reported in the literature to date. Miller et al. (2003) additionally argue with data from west-central Idaho, U.S., that fires can also enhance catchment susceptibility to erosion and mass wasting processes, as well as the magnitude and timing of sediment mobilizing events. Ice et al. (2004) describe intense storms producing extreme stream sediment levels from accelerated runoff and erosion, citing how a moderate thunderstorm after a 1994 burn in Idaho resulted in a 1000 year flood event and an estimated 382 320 m³ of sediment deposited in the watershed's streams and reservoirs. In contrast, low-intensity burned or unburned areas in the watershed showed little response to the storm (Ice et al., 2004). Continuing at the catchment scale, Shakesby et al. (2003) note the impact and presence of large sediment/ash rafts in the Nattai River, NSW, after severe fires in late 2001, described further below. These were correlated with significant deposits of the same material on slopes and upstream riparian deposition areas.

Humphreys (1985) and Paton et al., (1995) provide data showing that a high erosion response occurs after the initial fire impact, after which a decrease in erosion rates occurs with time. Their data show that about an order of magnitude decrease in loss rates occurs from the initially high levels during the first year. They argue that losses thereafter will be strongly influenced by fire frequency and/or system recovery. In all cases, ground cover and resistance to erosion and re-establishment of pre-fire erosion rates were attained within 3-6 years after fire. A similar pattern of reduction in erosion rates from initially high values was demonstrated by Croke et al (1999a) and Wallbrink and Croke (2002) who provide sediment loss data from forest areas 0.5, 1, 3 and 5 years after they had been logged and burnt. Erosion rates decreased by factors of 5 to ten within the first 6 – 12 month period (from 0.03 kg m⁻² to 0.003 kg m⁻²). Such decreases are attributable to exhaustion of sediment supply and increases in surface cover at these sites with time.

9 Erosion in the Nattai Catchment: Initial Observations

Typical of the Sydney Basin, Nattai National Park (Figure 1) comprises horizontally bedded Permian and Triassic sandstones which are weathering to skeletal sandy soils (Lithosols and Earthy Sands, or Rudosols and Tenosols) of low water-retaining capacity. The terrain is subdivided into flat plateaux, steep upper hillslopes, gentle lower slopes and narrow, flat valley floors (Figure 2). The *Eucalyptus* vegetation of this deeply dissected sandstone landscape is highly flammable, dominated by oil-rich leaves, deciduous bark and abundant dry forest litter. Wildfire recurrence is typically at one to a few decades.

The Christmas 2001 bushfires in the Sydney area were extensive and, in places, highly destructive and had been preceded by hot and dry conditions. Nattai National Park was subject to a full range of fire severity, from extreme to unburnt. The fires afforded investigation of the relationship between destruction of *Eucalypt* forest, rainfall events, soil/sediment erosion, export of nutrients and the downstream impacts on water quality. Preliminary observations are reported in Shakesby et al. (2003) and Chafer et al. (2004). To date, collaborative research in the Nattai River catchment has mainly concentrated on processes in headwater sub-catchments, i.e., plateau/ridgetop, hillslope and upper valley floor land units, with particular emphasis on Blue Gum Creek sub-catchment, a tributary of the Little River (Figure 2). Current and future phases of the research are being directed towards down-catchment sites, particularly the impacts on water quality in the main waterways, Little River, Nattai River and Lake Burrangorang reservoir.

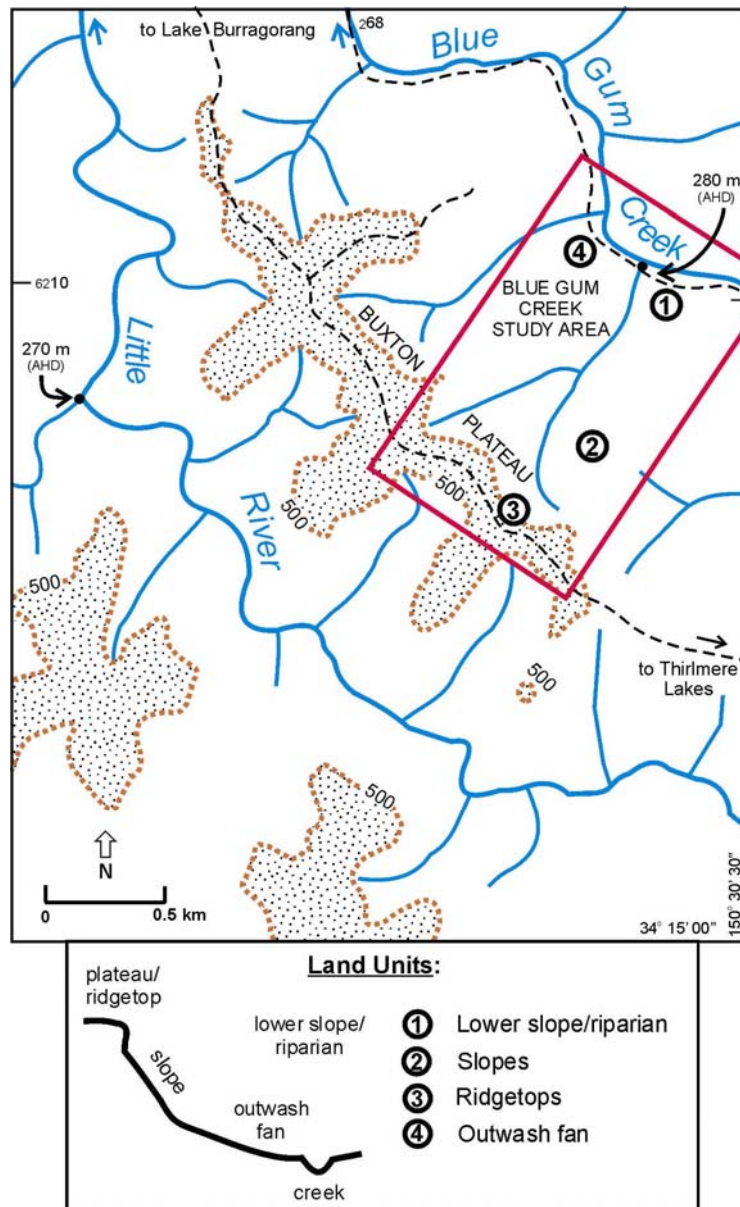


Figure 2. Blue Gum Creek study area, Nattai National Park.

Assessment of the spatial distribution of fire severity in the Christmas 2001 Sydney wildfires using pre- and post-fire satellite imagery and field observations produced an accuracy of over 88% within the 225 000 ha fire affected area (Chafer et al., 2004). The ground surveys indicate that image analysis accords well with the degree of vegetation consumption although is limited with respect to the magnitude of ground litter consumption and degree of heating. Modelling of fire intensity based on fuel load biomass indicate extreme heat energy levels exceeding $70\ 000\ \text{kW m}^{-1}$. This extreme fire intensity computed from the combination of satellite imagery and field assessment (Chafer et al., 2004) corresponds with soil temperatures exceeding 350°C at depths averaging 1.5-2 cm and extreme consumption of woody vegetation reported by Shakesby et al. (2003). Destruction of water repellency in surface soils, moreover, implies soil temperatures of at least $350\text{-}400^{\circ}\text{C}$. Exfoliation or spalling on sandstone outcrops also corroborates that substantial temperatures were attained. No strong positive affect of topography on fire severity was found, in fact an inverse relationship between slope and fire severity and no effect due to aspect is noted (Chafer et

al., 2004). Flat to moderate slopes (0-11°) suffered the greatest vegetal destruction. It is noted that flatter terrain, particularly plateau tops, within sandstone woodland environments typically support higher fuel loads (Chafer et al., 2004).

Geomorphological activity in the Nattai area was considerable following post-fire rainfall events. Conspicuous evidence of erosional activity included: the survival of ash and charcoal deposits; scorched and flaked rock surfaces and burn lines on plant stems elevated 1-2 cm above the ground surface; widespread soil pillars; drapes of white sand attributed to post-fire wind erosion and deposition; and colluvial deposition on hillslopes and fluvial deposition in stream channels. The latter deposits included dark-coloured rafts of tightly bound sediment and litter on valley floors.

Fire had varying effects on repellency in the Nattai area, based on determinations for burnt soils at 227 sites in both high and low intensity areas. In places, the soil was left unchanged, whilst elsewhere repellency was destroyed or enhanced, depending on the soil temperature attained (Shakesby et al., 2003). In spite of advanced repellency of sandy material, infiltration occurred and, in places, appears to be enhanced by pathways associated with ant tunnels systems, thereby mitigating erosive overland flow. It is clear that the combination of pre-fire fuel loads, fire intensity and fire residency time are important factors in understanding the spatial heterogeneity of post-fire hydrophobicity and the impacts on erosion.

Shakesby et al. (2003) note that by May 2002, large quantities of eroded burnt topsoil had been mobilised from the sub-catchments and transported to the stream. On steep slopes the ash layer and burnt soil, including the water repellent layer, had generally been eroded. Where fire severity was high, an average of 24% of rock was exposed in the footslope areas, compared to zero in corresponding areas that were subject to low fire severity. Similarly, more newly deposited sediment was measured in the high burn sub-catchments compared to corresponding landscape units in neighbouring low burn sub-catchments. Erosion of subsoil, additional to topsoil, is indicated by the widespread presence of pedestals that formed by rainsplash and by ground-level change measurements. In May 2002 the respective mean heights of soil pedestals and litter dams were in the ranges of 7-15 mm and 15-28 mm (Shakesby et al., 2003). Most of the burnt topsoil and sub-surface material eroded from the slopes was deposited on the footslopes. Further down-catchment transport of this eroded sediment appears to have been offset because infiltration was enhanced by both the spatial heterogeneity of repellency and widespread bioturbation in the footslope locations. Notwithstanding, preliminary observations of stream gauging data in the Nattai river system show high amplitude stream height/discharge peaks in the first five months following the Christmas 2001 fires, taken to correspond with local rainfall events and enhanced runoff from burnt hillslopes. Significantly, high turbidity measurements and high nutrient (nitrogen and phosphorus) concentrations are associated with these peaks in the hydrographs.

10 Conclusions

Fire can enhance soil redistribution and rates of erosion. This is achieved through removing vegetation and surface cover, and enhancing hydrophobicity of the underlying soil. The net effect is to increase: i) the likelihood of erosion and particle detachment by direct raindrop impact and a reduction in the thickness of the cover layer; ii) overland flow rates due to loss of surface cover; iii) the capacity to detach entrain and transport eroded material. The reduction in surface cover similarly tends to reduce the capacity of any downslope areas to trap and store materials and thus enhance sediment delivery to offsite areas. The magnitude of any erosion that occurs will also be strongly dependent on the duration and intensity of any post event rainfall. Where rainfall is lower than average, then rates of soil redistribution can be small in the order of 0-8 t ha⁻¹ yr⁻¹, however if fires have been widespread and

coincident with well above average rainfall, then catastrophic redistribution of $>40 \text{ t ha}^{-1} \text{ day}^{-1}$ can occur. Erosion rates tend to be reduced by about an order of magnitude in the first 6-12 months after the fire. Initial observations from investigation of the Nattai River catchment following the Christmas 2001 wildfires include the following:

- Fire severity has been successfully analysed using pre- and post-fire vegetation indices from satellite imagery and field observations. Burn intensity was assessed by combining this information with forest fuel loads. Extreme fire severities and intensities were attained within some sub-catchments.
- Flat to moderate slopes ($0-11^\circ$) suffered the greatest vegetal destruction.
- Post-fire rainfall events in the catchment were significant. The loss of canopy and forest litter through the fires decreased the amount of raindrop interception and evaporation and increased the amount of rainfall reaching the topsoil. Runoff and erosion tended to be increased, although ground responses were spatially variable.
- The fires had varying effects on hydrogeomorphic processes and the patterns of water repellency in the catchment, resulting in variable erosional potential.
- In places, the soil was left unchanged, whilst elsewhere 'natural' repellency was destroyed or enhanced, depending on the soil temperature attained.
- Widespread colluvial and alluvial redeposition of topsoil in foot-slope positions and river systems are noted; these deposits include large rafts of darkened sediment and burnt litter in the river channels.
- Sand-sized robust aggregates of minerogenic and organic material have been produced through heating of the topsoil; this distinctive material was prone to relocation in post-fire erosion events and is likely to be significant in terms of downstream impacts because of the propensity of the aggregates to sequester nutrients.
- Post-fire bioturbation has been considerable, particularly in the footslopes. In the case of ant tunnel networks erosive overland flow has been mitigated and infiltration has been enhanced in spite of advanced repellency of sandy material.
- Erosion of subsoil in addition to topsoil is indicated by the presence of soil pedestals that formed by rainsplash and by ground-level change measurements.
- Most of the burnt topsoil and sub-surface material eroded from the slopes was deposited on the footslopes.
- More newly deposited sediment was deposited in the high burn sub-catchments compared to corresponding landscape units in neighbouring low-burn sub-catchments.

11 References

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