Desktop review – Impact of bushfires on water quality

For the Australian Government Department of Sustainability, Environment, Water, Population and Communities

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The Ovens River after the 2003 fires in Victoria.
Photo: Rex Humphreys, North East Water.

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Executive summary

Landscape scale fires in forested south-eastern Australia have critically impacted a range of catchment values, including water quality, and heightened community concern about fire management (Ellis et al., 2004; Parliament of Victoria, 2008; Victorian Bushfires Royal Commission, 2009). While extended drought has increased the frequency and scale of fire, severe follow-up storms have resulted in large quantities of sediment, nutrients, organic matter, ash and metal contaminants entering streams and reservoirs. This change in water quality may result in water supplies that are unfit for use (White et al., 2006; Smith et al., 2011). The objective of this report is to review literature on the impact of bushfires on water quality, including recommendations for management actions immediately before, during and after a bushfire. A major focus of the report is on how various uses and values of water may be impacted by fire-related changes to water quality.

Several factors may contribute to water quality impacts following fire. Rates of runoff and erosion often increase as a result of landscape disturbance, particularly on the soil surface – i.e. increased soil water repellence, loss of surface vegetation and canopy cover, and ash sealing of soil pores (Shakesby and Doerr, 2006; Sheridan et al., 2007b). Combustion of organic matter, soil heating and the production of ash and charcoal contribute to the release of numerous nutrients, metals and toxins that might otherwise be unavailable for transport into waterways. For example, ash contains particulate carbon, various nutrients, trace metals and other contaminants (Amiro et al., 1996; Goforth et al., 2005; Johansen et al., 2003). The loss of riparian vegetation reduces the buffer effect that traps sediment before it enters streams and means that there is less shade to prevent increases in stream temperatures (BAER, 2009). Fire suppression activities may also contribute to water quality impacts, particularly the construction of control lines with bulldozers and possibly the use of fire retardants and fire suppressant foams (Boulton et al., 2003; BAER, 2009).

The impact of bushfires on water quality can be highly variable for many of the individual water quality constituents (Smith et al., 2011). This variability is caused by a number of landscape influences and climatic factors, most notably rainfall. High magnitude and intensity rainfall events soon after fire generate the largest impacts on water quality and sometimes trigger extreme erosion events (e.g. localised flash floods, large floods and debris flows). For example:

- two large storm events eroded most of the annual sediment yield in two small headwater catchments of the East Kiewa River in the first year after fire in north-eastern Victoria (Lane et al., 2006)
- a very high intensity, short duration storm event in the burnt Upper Buckland River catchment (north-east Victoria) generated debris flows resulting in very high sediment concentrations (59,000 mg L^{-1} or 129,000 NTU – Nephelometric Turbidity Units) (Leak et al., 2003) and dissolved oxygen concentrations near zero levels (EPA 2003)
- a large rainfall event in the burnt catchment area of the Gippsland Lakes in eastern Victoria caused flooding which resulted in elevated nutrient concentrations and a prolonged blue-green algae (cyanobacteria) bloom (Cook et al., 2008), and
- an intense summer storm in the catchment area for the Ovens River in north-eastern Victoria resulted in concentrations of iron, copper, zinc, chromium, arsenic and lead that were 47, 32, >50, 40, 4 and 33 times the pre-event concentrations, respectively (North East Water, 2003).

Debris flows in burnt forest environments are an emerging area of research in Australia and have only recently been recognised as a major contributor to water quality impacts following fire (Nyman et al., 2011). Occurring in steep, upland terrain they are a fast moving mass of unconsolidated saturated debris, which cause large amounts of channel scour and deliver large quantities of sediment downstream.

For some of the water quality parameters there is very little information available, which makes it difficult to draw conclusions about bushfire impacts. For example, there is little Australian literature on the effects of fire on bulk water chemistry, such as for levels of chloride and sulfate. Limited research from North America on these anions suggests that only small impacts from fire may occur (Gallaher et al., 2002; Malmer, 2004; Mast and Clow, 2008). However, it is difficult to extrapolate these findings to the Australian context given the differences between North American and Australian forest environments. Similarly, there is very little information on stream temperatures or concentrations of fire pyrolysis products such as cyanides, polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-*ρ*-dioxins and dibenzofurans (PCDD/Fs), and polychlorinated biphenyls (PCBs).

In relation to water quality impacts within reservoirs, the extent of post-fire water quality changes will reflect the magnitude of pollutant loads entering the reservoir relative to its capacity to attenuate impacts (reflecting the reservoir size, storage levels after the fire, and the extent of stratification). Additionally, benthic sediments within storages receiving large amounts of organic matter can release much larger than normal amounts of methane, ammonia, phosphorus, sulfide, arsenic, iron and manganese. Numerous reservoirs have experienced substantial water quality impacts as a result of fire. Examples include the Bendora Reservoir in the ACT (White et al., 2006), Lake Glenmaggie in eastern Victoria (Goulburn Murray Water, 2008) and Lake Buffalo in north-eastern Victoria (Goulburn Murray Water, 2008). Yet other reservoirs have shown little to no water quality changes despite high constituent loads in tributary streams (e.g. Dartmouth reservoir in north-eastern Victoria (Alexander et al., 2004) and Mount Bold reservoir in South Australia (Morris and Calliss, 2009)).

The constituents of most concern following fire from a drinking water perspective are elevated levels of suspended sediment, nutrients and metals, while possible blooms of cyanobacteria after fire also present a threat. For example, in the Bendora Reservoir (supplying Canberra) after the 2003 ACT fires, turbidity was 3000 NTU at the bottom and iron and manganese concentration levels exceeded all previous peaks by factors of three and four, respectively. This necessitated the introduction of water restrictions in Canberra (White et al., 2006). For other constituents (e.g. sulfate and chloride, organic carbon, cyanide, PAHs, PCDDs/Fs and PCBs), post-fire levels generally do not exceed guideline values. However, with such a limited number of studies available for these constituents, it is difficult to draw conclusions about their impacts on drinking water quality following fire.

Extremely high turbidities and low dissolved oxygen concentrations resulting from large post-fire inputs of sediment and ash to streams pose the greatest threat to aquatic ecosystems following fire. For example, there was a large decline in the abundance of fish populations following a post-fire debris flow in north-eastern Victoria (Lyon and O'Connor, 2008). Other threats may result from increased water temperatures and increased inputs of nutrients. Despite the immediate impacts, aquatic ecosystems in Australia are quite resilient to major disturbance events such as fire, and often populations of aquatic fauna recover quickly provided there is connectivity between affected and unaffected habitats (Lyon and O'Connor, 2008). Those species that are more vulnerable tend to have smaller, more isolated populations or are not as well-adapted to survive periods with elevated suspended sediment concentrations.

For recreation and aesthetic values of water, elevated levels of suspended sediment and blooms of cyanobacteria are of most concern after fire. Suspended sediment affects the visual clarity of the water and although this constituent has no guideline value, acceptability thresholds would have been crossed during some events described in this review. Cyanobacteria are a potential health risk and therefore if a bloom is triggered following a fire, recreational use of the water may be affected.

The major water quality concerns for agriculture following fire relate to high loads of suspended sediment and, to a lesser extent, nutrients, metals, cyanobacteria, chloride and sulfate. The primary concern with suspended sediment is the potential for increased sedimentation of dams. Guideline values for agriculture in relation to phosphorus, nitrogen and various metals were not exceeded except following an extreme erosion event after fire in the Upper Buckland River (north-eastern Victoria). Similarly, in the few studies that showed some elevation of chloride and sulfate levels, ions that can affect some crops such as spray irrigated citrus, levels remained well below the guideline values.

There are numerous management actions that can be taken prior to, during and after a fire to minimise the impacts on water quality. Before the fire there can be preparations to reduce the risk of fire in water supply catchments (such as fuel reduction burning, the construction of fuel breaks and a greater preparedness for early fire suppression), as well as risk assessments to identify townships whose water supply is most vulnerable were a bushfire to occur. Operations during a fire should adhere to the best practices and local standards in relation to the construction of mineral earth breaks and the application of fire retardants. Following fire, managers need to act quickly to prepare an area before it rains and particularly before intense rain, although in many landscapes this may not be feasible or may conflict with other values ascribed to the catchment. The first task is to undertake a rapid assessment of the burnt area to identify priorities. Then various works such as rehabilitating control lines, sediment control measures, erosion mitigation works and water quality monitoring may commence. Development of integrated fire and water quality risk management plans would enable better coordination of all management actions designed to mitigate post-fire water quality impacts.

There are substantial knowledge gaps in our understanding of water quality impacts following bushfires in Australia. Greater understanding of these impacts from regions outside south-eastern Australia is required, while further research in south-eastern Australia is also needed, given that the steep, forested highland areas in central Victoria and NSW are particularly prone to large, severe bushfires. Expanded stream and reservoir monitoring before and after fires would provide important information on concentrations of constituents (particularly metals, organic carbon and nutrients) that are less frequently measured. Furthermore, greater knowledge of post-fire erosion processes and catchment sources of key constituents would contribute to development of models to quantify post-fire risks to water quality, as well as guiding post-fire management actions aimed at reducing water quality impacts.

Contents

1 Introduction

1.1 Preamble

Bushfires pose a significant threat to life, property, infrastructure, and natural resources in fire-prone forest areas in Australia. Fires in Victoria alone burned a combined area of over three million hectares across largely forested upland regions in 2003, 2006-07 and 2009 (Department of Sustainability and Environment, 2009). In response to recent fires, there has been an increased focus on all aspects of Australian fire management (Ellis et al., 2004; ACT Coroner's Bushfire Inquiry, 2006; Parliament of Victoria, 2008; Victoria Bushfires Royal Commission, 2009). One area of concern that has emerged is the potential impact of bushfires on the quality of water supplies.

Forested catchments are an important source of water to many communities in Australia. The water is supplied for a number of uses including domestic water supply, agriculture and recreation as well as providing aquatic habitat. Climatic conditions and the vegetation type make many of Australia's forested catchments particularly susceptible to fires. In recent years, bushfires burnt part or all of the forested reservoir catchments which supply potable water to Sydney (2001), Canberra (2003), Adelaide (2007) and Melbourne (2009). Fire has also affected supplies to various regional towns. Advantages of using largely undisturbed forest catchments for water supply are the generally high quality of water and their often otherwise unexploited status (Neary et al., 2009). However, following a bushfire, increased erosion rates, runoff generation and changes to the major sources of pollutants can greatly increase influxes of sediment, nutrients and other constituents (e.g. ash or metals) that may be transported by streams and delivered to reservoirs (e.g. Lane et al., 2008; Sheridan et al., 2007a; Wilkinson et al., 2009; White et al., 2006).

1.2 Report objectives

The objective of this report is to review literature on the impact of bushfires on water quality, including recommendations for management actions immediately before, during and after fire. Using mostly Australian literature, the report considers:

- the processes that may cause changes to water quality following bushfire
- the potential post-fire changes to water quality that may occur
- how these changes may affect the major uses and values of water, and
- management actions that could be taken before, during and after bushfires to mitigate the risks to water quality.

1.3 Scope and limitations

This report considers mostly Australian literature on the impacts of bushfires on water quality. Literature from overseas is included where there is very little relevant Australian material available. This is especially the case for some of the lesser researched water quality constituents (e.g. trace metals, chloride, sulfate and cyanide).

Research into bushfire impacts on stream constituent fluxes and water quality has tended to focus on suspended sediment and, to a lesser extent, on nutrients with other contaminants receiving little attention. As a result, post-fire data is limited (Table 1). The level of focus in this review on particular water quality constituents reflects the extent of available information on these constituents after fire.

Although the behaviour of fires and the nature of the fire regime vary widely across Australia, the review takes a particular focus on burnt forest environments in south-eastern Australia. This reflects the relatively large amount of publically available literature for this part of Australia, especially data and published information for recent bushfires in various water supply catchments.

1.4 Uses and values of water and associated guidelines for water quality

This report focuses on the major uses and values of water, as identified by the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality 2000* (ANZECC). These uses and values are:

- drinking water
- aquatic ecosystems
- agriculture – including water for irrigation and stock drinking water
- recreation and aesthetics

- industrial water – no guidelines are provided for this use
- cultural and spiritual values – no guidelines are provided for this use, and
- water resource infrastructure.

This report considers a range of materials that may be derived from forested catchments and be supplied to streams and reservoirs. Table 1 summarises the recommended limiting water quality requirements for the key uses listed above, and focuses on the constituents likely to be affected by fire.

Table 1: Guidelines for selected characteristics of water quality in relation to various uses or values of water

Guideline values for aquatic ecosystems, recreation and aesthetics, and agriculture are from the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality 2000* (ANZECC). Guideline values for drinking water and water resource infrastructure are from the *Australian Drinking Water Guidelines 2004* (NHMRC). No guideline values exist for industrial or cultural uses of water.

Characteristic of water quality		Use of water / environmental value					
		Aquatic ecosystems	Recreation and aesthetics[a]	Drinking water	Agriculture: irrigation[b]	Agriculture: stock drinking water	Water resource infrastructure
Suspended sediment measured as turbidity (NTU)		Upland: 2-25 Lowland: 6-50 Lake or reservoir: 1-20 (for SE Aust.)	Visual clarity and colour not reduced by > 20%	5 (aesthetic)	ID	ID	>1 may shield some microorganisms from disinfection
Nutrients (mg/L) (for SE Aust)	Nitrogen (total)	Upland: 0.25 Lowland: 0.5 Lake / reservoir: 0.35	0.01	ID	25 – 125	ID	ID
	Nitrate and Nitrite	Upland: 0.015 Lowland: 0.040 Lake/reservoir: 0.010	10 & 1	50	ID	Nitrate = 400 Nitrite = 30	ID
	Phosphorus (total)	Upland: 0.02 Lowland: 0.05 Lake / reservoir: 0.01	ID	ID	0.8 – 12	ID	ID
Metals (mg/L)	Aluminium	0.055 (for pH >6.5)	0.2	0.5	20	5	0.0002 – based on post-flocculation problems
	Arsenic	0.024	0.05	0.007	2	0.5	ID
	Barium		1	0.7	ID	ID	ID
	Copper	0.0014	1	2	5	0.4 – 5 (depends on species)	>1 may stain fittings
	Chromium	0.001	0.05	0.05	1	ID	ID
	Iron	Insufficient data	0.3	0.3 (aesthetic)	10	NN	0.3 =taste threshold
	Lead	0.0034	0.05	0.01	5	0.1	ID
	Manganese	1.9	0.1	0.5	10	NN	>0.1 causes staining
	Mercury	0.00006	0.0001	0.001	0.002	0.002	
	Zinc	0.008	5	3 (aesthetic)	5	20	>3 causes taste problems
Other constituents (mg/L)	Chloride	ID	400	250 (aesthetic)	175 – 700	ID	250
	Sulfate	ID	400	250 (aesthetic)	ID	1000	ID
	TDS (mg/L or µS/cm)[c]	Upland: 30-350 Lowland: 125-2200 Lake / reservoir: 20-30 µS/cm	1000 mg/L	500 mg/L	950 – 12200 µS/cm	3000 – 13000 mg/L	500 mg/L
	Organic carbon	ID	ID	ID	ID	ID	ID
	Cyanide	0.007	0.1	0.08	ID	ID	ID
	PAHs	ID	ID	0.00001	ID	ID	ID
	PCDD/Fs	ID	ID	ID	ID	ID	ID
	PCBs	ID	0.1	ID	ID	ID	ID
Dissolved oxygen (% saturation)		Upland: 90-110 Lowland: 85-110 Lake or reservoir: 90-110	>80 (>0.0065 mg/L)	>85 (aesthetic)	ID	ID	ID
Cyanobacteria (cells/mL)		ID	15,000 – 20,000	6500 for microcystins	ID	11,500 for microcystins	ID
Temperature (°C)		ID	15-35 for prolonged exposure	NN	ID	ID	ID

[a] Values are for primary contact with the water e.g. swimming; [b] Values based on short-term use (up to 20 years); ID = Insufficient data to derive guideline values; NN = Guideline value not necessary for water use; [c]Total Dissolved Solids (TDS) measured in mg/L or approximated using electrical conductivity (EC) in µS/cm.

2 Processes that may cause changes to water quality following fire

A number of processes can cause water quality impacts following fire. In this section, we briefly review these processes and the key factors influencing them (Figure 1).

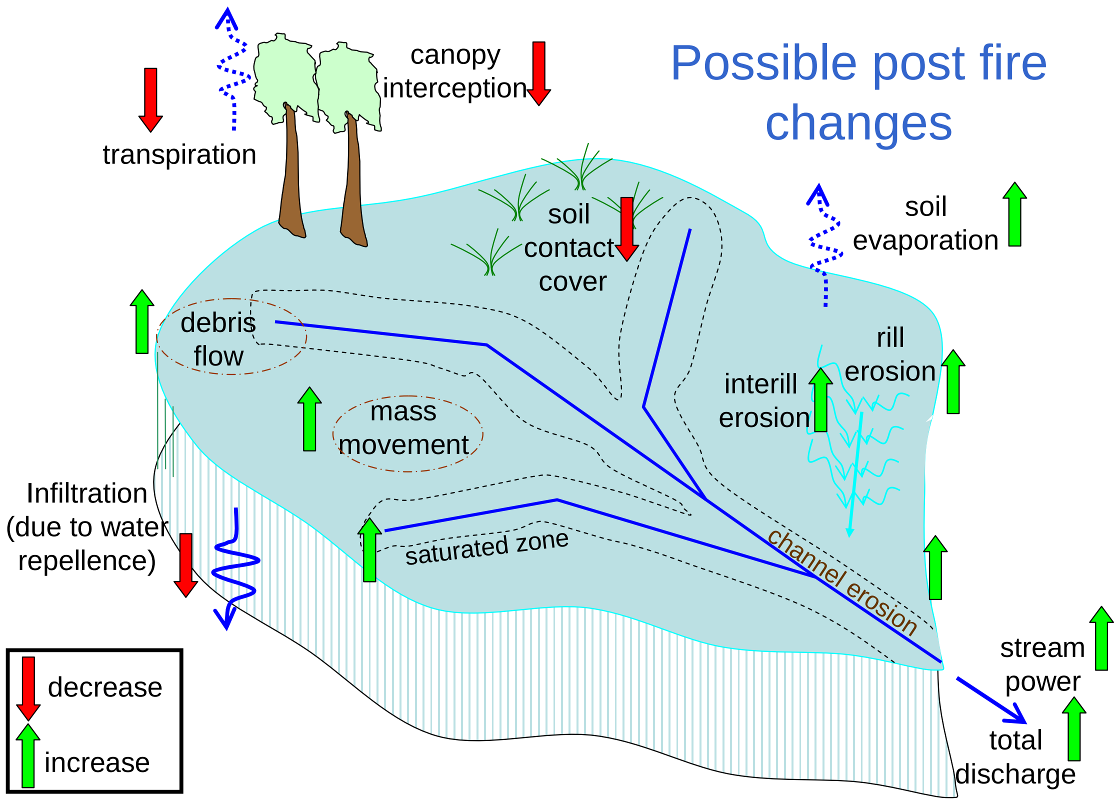

Figure 1: Schematic diagram showing possible post-fire changes in hydrologic and erosion processes.

2.1 Runoff and erosion

Runoff and erosion are responsible for supplying and delivering sediment to streams. Widespread hillslope erosion by both concentrated and unconcentrated overland flow is commonly documented following fire (e.g. Shakesby and Doerr, 2006; Sheridan et al., 2007b; Dunkerley et al., 2009). These erosion processes are called rill and interrill erosion respectively (Knighton, 1998). Rill erosion involves the formation of small channels across the soil surface where water flows preferentially. Soil particles are detached by the flowing water in the rills and transported within the network of rills. Interrill erosion generally involves detachment of soil particles by raindrop impact and transport via sheetwash, which is a more spatially uniform flow. In both instances, runoff is initiated when the rate of water input to the soil surface (from rainfall or flow above that point in the landscape) exceeds the hydraulic conductivity of the soil (infiltration-excess overland flow) or when the soil is saturated (saturated overland flow).

The largest water quality impacts result from high magnitude erosion events such as localised flash floods, large floods and debris flows (Smith et al., 2011). Debris flows are an extreme type of erosion event that sometimes occurs after fire, involving a fast moving mass of unconsolidated, saturated debris. This form of erosion is a newly emerging area of research in Australia, in contrast to the USA where their impacts are well documented (Nyman et al., 2011). In Victoria, post-fire debris flows have occurred in severely burnt, steep upland catchments in response to high intensity rainfall events

(Nyman et al., 2011). Such flows are highly erosive and generally associated with extensive channel scouring, which may deliver large quantities of sediment downstream.

The rate of runoff and erosion is influenced by many factors (e.g. rainfall intensity and duration, vegetation cover, soil hydrologic properties and slope). The magnitude and distribution of rainfall soon after fire, and before vegetation cover is re-established, is a key driver of post-fire erosion and water quality impacts. Fire increases the landscape susceptibility to runoff and erosion by altering several factors controlling the infiltration capacity of soil, raindrop impact, the scour potential of runoff, and the erodibility of the soil surface (Table 2).

Table 2: How fire can affect runoff and erosion

1. How fire affects **runoff**	Runoff ↑ Increase ↓ Decrease	2. How fire affects **erosion**	Erosion ↑ Increase ↓ Decrease
1a) Alters soil water repellency which changes the infiltration capacity of the soil. For example, fire often enhances water repellency, which reduces soil infiltration capacity and results in more runoff (DeBano, 2000; Shakesby and Doerr, 2006).	mostly ↑	2a) Reduces vegetative cover on the soil surface, which increases overland flow energy and erosion (Zierholz et al., 1995; Wondzell and King, 2003; Smith and Dragovich, 2008).	↑
1b) Creates burnt-out root channels, which provide easier flow paths for infiltrating water, thus increasing the infiltration capacity of the soil (Ferreira, 1996 in Shakesby et al., 2000).	↓	2b) Reduces vegetation cover overall, which leads to increased rainfall energy at the soil surface and makes raindrop impact and interrill erosion more severe (Benavides-Solorio and MacDonald, 2001).	↑
1c) Creates ash, which may seal soil pores, thus reducing the infiltration capacity of the soil (Shakesby and Doerr, 2006).	↑	2c) Increases the total volume of water available for runoff (1d) leading to increased overland flow energy and scour erosion.	↑
1d) Reduces or completely removes vegetation, leading to reduced rainfall interception and storage. This increases the volume of water available for runoff (Crockford and Richardson, 2000).	↑	2d) Produces large amounts of ash and charcoal that may be easily detached from the soil surface (Cerdà and Doerr, 2008).	↑
		2e) Changes soil erodibility (Giovannini and Lucchesi, 1983; Scott et al., 1998).	↓ or ↑
1e) Changes levels of bioturbation, which may increase soil infiltration capacity (Dragovich and Morris, 2002; Garkaklis et al., 1998).	↓	2f) Changes levels of bioturbation, which may aid the movement of soil downslope (Dragovich and Morris, 2002; Shakesby et al., 2007).	↑

2.2 Release of nutrients, metals and toxins

Fire can change the levels of chemical constituents in soils and may make some constituents more readily available for transport into waterways. For example:

- ash beds deposited after fire may form a large store of particulate carbon as well as considerable quantities of salts (notably calcium, magnesium, chloride, sulfate, bicarbonate), nutrients (nitrogen and phosphorous), trace metals, and other contaminants (Amiro et al., 1996; Gorforth et al., 2005; Johansen et al., 2003). The low density of ash means that it may be readily entrained by overland flow and result in water quality impacts soon after initial post-fire rainfall events (Reneau et al., 2007)
- manganese stores are reported to increase in soils following fire through ash from burnt vegetation and the physiochemical breakdown of the manganese combined with organic matter (Chambers and Attiwill, 1994; Parra et al., 1996; Raison et al., 1995). A similar pattern may be expected for iron, copper, and zinc (Certini, 2005)
- sulfate concentrations are reported to increase in surface soils through oxidation of sulfur in soil organic matter, while both sulfate and chloride may be leached from burnt plant litter (Khanna and Raison, 1986; Murphy et al., 2006b), and
- total nitrogen and phosphorus in the surface organic matter may decrease substantially following fire (in some cases, nitrogen can decrease by 92% and phosphorous by 76%) (Murphy et al.,

2.3 Riparian disturbance

In some cases, fire does not burn the riparian vegetation (that is, the vegetation in the immediate vicinity of the stream) due to moisture differentials (Pettit and Naiman, 2007). However, where the riparian zone is burnt, this can have a number of implications for water quality. Streamside vegetation often acts as a buffer, reducing the amount of runoff, sediment and associated contaminants reaching a stream (Croke et al., 1999a; Croke et al., 1999b). If fire removes this vegetation, then the eroding parts of the catchment are more interconnected with the stream network and result in more sediment being delivered to streams. Riparian vegetation is also important for stabilising channel banks and thus its removal promotes scour erosion within the channel. Since vegetation provides stream shading, increased light penetration following removal of this cover may cause stream temperatures to rise and the balance of primary producers within the stream to change (BAER, 2009; Ryan, 1991). Notably, the lack of canopy cover and increased light penetration have been reported to increase algae growth in streams after fire (Petticrew et al., 2006) and reduce the amount of direct leaf and insect fall to streams.

2.4 Fire suppression and post-fire salvage harvesting

Activities associated with fire suppression and post-fire salvage harvesting operations can exacerbate water quality problems. Mineral earth fuel breaks are often constructed during fire-fighting efforts using bulldozers and hand crews. During the 2003 alpine fires in Victoria, approximately 9000 km of control lines were constructed, some of them more than 60 metres wide (Dunkerley et al., 2009). These breaks leave the soil exposed and more susceptible to erosion, which can have water quality consequences, especially in steep terrain or when the breaks are near watercourses. Temporary stream crossing and helipads may also have a localised effect on water quality (Department of Sustainability and Environment, 2003).

Fire retardants and fire suppressant foams may cause water quality impacts when applications unintentionally occur over streams, riparian zones or reservoirs. Fire retardants contain chemicals generally found in a broad range of fertilisers - 85% water, 10% fertiliser and 5% other constituents such as colour additives, thickeners, corrosion inhibitors and bactericides (Boulton et al., 2003; Department of Natural Resources and Environment, 1999b). The fertilisers are mostly ammonium phosphate and ammonium sulfate. In relation to water quality, the main concerns with fire retardants are the addition of nutrients to streams and sensitive wetlands and ammonium toxicity for aquatic fauna (Boulton et al., 2003). Fire suppressant foams contain surfactants (wetting agents), foaming agents, corrosion inhibitors and dispersants (Boulton et al., 2003; Department of Natural Resources and Environment, 1999a). These foams may impact on aquatic biodiversity by altering the permeability of biological membranes and reducing the surface tension of water (Boulton et al., 2003).

Post-fire salvage harvesting may impact on water quality in excess of the effect of burning alone. Substantial increases in sediment and nutrient exports were recorded following salvage harvesting of a burnt pine plantation when compared to burnt and unharvested eucalypt catchments and pre-fire data in north-east Victoria (Smith et al., in press). Likewise, water quality issues resulted from salvaging of burnt softwood plantations in the lower Cotter River catchment in the ACT (Wade et al., 2008). This culminated in the abandonment of softwood plantations in the Cotter after the 2003 fire.

3 Potential changes to water quality following fires

This section reviews literature on the impact of fire on water quality (Table 1). The most frequently reported impacts from fire relate to suspended sediment and nutrients. In Australia, much of the research has focused on the south-east, which reflects the impact of multiple large fires in this region over the last decade and, more specifically, the fire-prone nature of high country temperate eucalypt forests.

3.1 Suspended sediment

An increased amount of suspended sediment is the most commonly reported impact on water quality following fire (Smith et al., 2011). The magnitude of impacts is highly variable, reflecting the complex interaction of a range of factors that influence post-fire erosion and sediment delivery (see Section 2). In this section, we summarise the results of numerous Australian studies that examine post-fire suspended sediment load (t) and yield (t ha^{-1} yr^{-1}) data as well as suspended sediment concentration and turbidity data.

3.1.1 Post-fire suspended sediment loads/yields

Table 3 summarises annual suspended sediment yields from catchment-scale studies in Australian forested environments burnt by bushfire. Yields in the first year following fire vary substantially, from 0.017 to 3.3 t ha^{-1}. These yields are 1.3 to 1459 times unburnt annual averages (i.e. pre-fire or unburnt control catchment averages).

The range in yields reflects various factors, including:

- post-fire rainfall patterns
- catchment burn area extent and severity
- erosion processes
- suspended sediment sources (location and connectivity to major tributary streams), and
- scale effects (such as increased opportunities for sediment storage with catchment size).

Suspended sediment yields in subsequent years after fire generally decline as vegetation cover is re-established and fire impacts on soil and hillslope hydrological properties decline to pre-fire levels (Lane et al., 2006; Prosser and Williams, 1998; Sheridan et al., 2007b).

Post-fire rainfall plays an important role in explaining the large variation in suspended sediment yields. For example, in south-eastern Australia, a single summer storm (>2 h; 43 mm; peak 15-min intensity of 80 mm h^{-1}) accounted for 45% (127 t) and 47% (101 t) of the total suspended sediment yield in the first year after fire from two small mountain catchments (Lane et al., 2006). In contrast, Tomkins et al. (2007) observed a first year suspended sediment yield of only 0.017 t ha^{-1} from the Nattai River catchment (446 km^2; >50% burnt) during a period of well below average rainfall following bushfire in 2001-02.

Table 3: Summary of post-fire annual suspended sediment yields from catchment-scale studies in forested environments burnt by bushfire

Authors	Location	Catchment area (km^2)	Percent burnt	Method[b]	Annual suspended sediment yield in t ha^{-1} yr^{-1} (and total load in t)[a]			Multiple increase relative to pre-fire yields (1st year after fire)
					1st year after fire	Subsequent years after fire		
Blake et al. (2009a)	Blue Mountains, NSW	0.89	100	TB	0.58 (51.6)[c]	n/a		Not available
Lane et al. (2006)	East Kiewa River, NE Victoria	a) 1.36 b) 2.44	a) 99[d] b) 100[d]	CM	a) 2.05 (280) b) 0.88 (216)	2nd year: a) 0.39 (56) b) 0.35 (84)		8-9
Wasson et al. (2004)	Bendora Reservoir, ACT	91.5	Not available	VS	2.3 (21200)	n/a		Not available
Lane et al. (2006)	West Kiewa River, NE Victoria	100.5	98[d]	CM	0.29 (2890)	n/a		Not available
Wilkinson et al. (2009)	Little River, Blue Mountains, NSW	183	99	RC	0.21 (3843)	2nd year: 1.02 (18666)		109-250
Tomkins et al. (2007)	Nattai River, Blue Mountains, NSW	446	57	RC	1st year: 1968 bushfire: 0.74 (33,004) 2001-02 bushfire: 0.017 (763)	2nd year: 1968 bushfire: 0.011 (508) 2001-02 bushfire: 0.011 (486)	3rd year: 1968 bushfire: 0.106 (4741) 2001-02 bushfire: 0.003 (120)	Not available
Sheridan et al. (2007a)	Rivers in Victoria: a) Ovens River b) Tambo River-1 c) Dargo River d) Tambo River-2 e) Mitta Mitta River f) Kiewa River	 a) 495 b) 523 c) 676 d) 895 e) 1533 f) 1655	 a) 55 b) 90 c) 62 d) 70 e) 80 f) 24	OLE	1st year: a) 0.83 (41260) b) 0.46 (24147)[e] c) 0.22 (14854) d) 0.37 (32967) e) 3.3 (511559) f) 0.11 (17880)	2nd year: a) 0.26 (12678) b) n/a c) 0.30 (20131) d) 0.35 (31386) e) 0.54 (83374) f) n/a	3rd year: a) 0.05 (2588) b) n/a c) 0.40 (27188) d) 0.07 (6101) e) 0.68 (104170) f) n/a	 a) 24 b) 1459 c) 21 d) 171 e) 168 f) 1.3

[a] For the purpose of comparison, suspended sediment yields are presented in t ha^{-1} yr^{-1}. However, it should be noted that such a measure can be misleading, given that the supply of sediment is generally not uniform across a catchment (Smith, 2008).

[b] Method of sediment yield estimation: Continuous monitoring of discharge and turbidity/SSC (CM); rating curve derived from measurements of discharge and SSC (RC); other load estimation techniques based on flow and SSC data (OLE); volumetric surveys of reservoirs converted to mass of sediment (VS); and sediment tracer budgeting (TB). Note: Measurement of sediment yields using different estimation techniques may hinder comparability. To address this, we limited comparison to catchment-scale studies that report suspended sediment (using flow-based estimation techniques) or fine sediment (generally <63 µm for studies using volumetric surveys or tracer techniques) yields for the first year after fire.

[c] Sediment yield estimate is based on Be-7 sediment budget (<63µm fraction) for first 3-months after bushfire (Blake et al., 2009a).

[d] Lane et al. (2006) reported areas burnt according to fire severity classes, with 71% (a) and 95% (b) of the two East Kiewa catchments experiencing crown burn or scorch, while only 43% of the West Kiewa catchment experienced crown burn or scorch.

[e] Suspended sediment yield data for the Tambo River (site 1) is for a six month period only.

3.1.2 Post-fire suspended sediment concentrations and turbidity

Table 4 summarises maximum suspended solid concentrations (SSC) and turbidities and compares these values to unburnt/pre-fire maximums[1]. Maximum concentrations measured during stormflow in the first year after fire range from 11 to 143,000 mg L^{-1} for streams with catchments varying in size

[1] In assessing the suspended sediment concentration and turbidity response to fire, we focus on maximum values. However, in streams these maximum values may only occur over a brief period, particularly during a storm event. Routine weekly to monthly sampling may not capture these peaks and, therefore, we need to carefully consider the sampling regime used when drawing conclusions from the data.

from 1.36 to 1655 km^2. For all studies in Table 4, the SSC in burnt areas exceed the unburnt/pre-fire maximums. Periods of maximum SSC or heightened turbidity may occur briefly (minutes to hours) during stormflow events, whereas elevated levels may persist beyond initial event timescales (days to weeks), particularly when there are large post-fire inputs of sediment to streams leading to in-channel storage and remobilisation by subsequent flow events (e.g. Lyon and O'Connor, 2008). The extent and duration of subsequent water quality impacts will depend upon the amount of sediment in storage, the magnitude and frequency of post-fire flow events required to re-suspend and transport this material, as well as new sediment inputs from erosion during storm events.

The highest post-fire suspended sediment concentrations in streams generally occurred in response to erosion events triggered by intense summer storms (Lane et al., 2006; Leak et al., 2003; Sheridan et al., 2007a; Smith et al., 2011). For example, after the large 2003 and 2006/07 fires in Victoria, debris flows were generated by very high intensity, short duration storm events in several upland catchments (e.g. in the Upper Buckland River in north-eastern Victoria and the upper Macalister River in eastern Victoria) (Lyon and O'Connor, 2008; Tryhorn et al., 2008; Nyman et al., 2011). In the Upper Buckland River, a pulse of highly turbid water with a peak SSC of 59,000 mg L^{-1} (129,000 NTU) travelled down the Buckland River and into the Ovens River (Figure 2; Leak et al., 2003). Subsequent turbidity levels in the Ovens River remained high. The peak turbidity recorded at Wangaratta (150 km downstream from the source) occurred twelve days after the event and was 2370 NTU (Figure 4; Leak et al., 2003; Lyon and O'Connor, 2008). Similarly, the impacts on downstream water quality of high magnitude erosion events in the upper Macalister River catchment (Figure 3) were long lasting with turbidities remaining high for at least four months after the event (>650 NTU during peak flows and >25 NTU during low flows compared to the pre-fire monthly mean turbidity of 3.5 NTU for the period 1977-2006; Victorian Water Resources Data Warehouse, 2008).

Figure 2: Channel scoured by a post-fire debris flow in a tributary of the Upper Buckland River, Victoria, which was burned in 2003. (Photo: Gary Sheridan).

Figure 3: Flow downstream of a post-fire debris flow in the Wellington River (above the junction with the Macalister River). (Photo: Adrian Murphy, Melbourne Water).

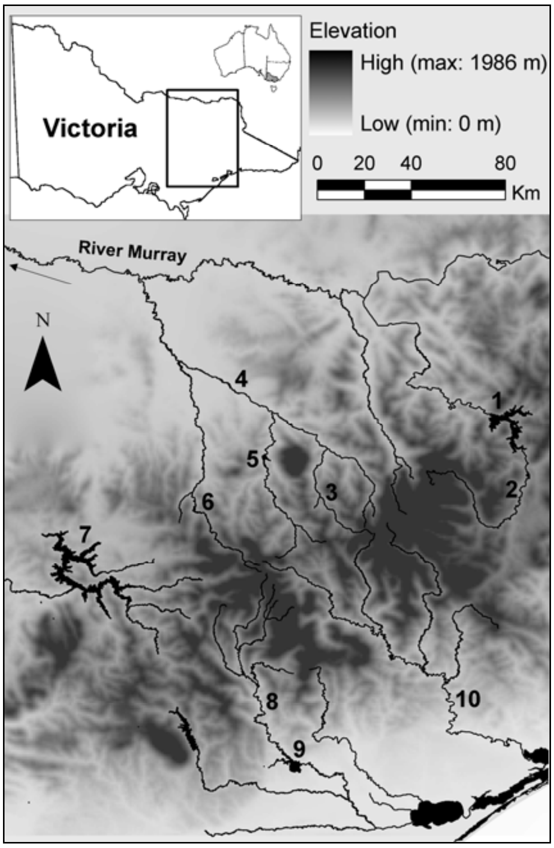

Figure 4: Map of eastern Victoria showing rivers and reservoirs impacted by bushfires in 2003 and 2006/07. Number labels refer to: 1) Dartmouth Reservoir; 2) Mitta Mitta Reservoir; 3) Buckland River; 4) Ovens River; 5) Lake Buffalo; 6) Lake William Hovell; 7) Lake Eildon; 8) Macalister River; 9) Lake Glenmaggie; 10) Mitchell River.

Table 4: Maximum total suspended sediment concentration and turbidity data from streams and reservoirs in forested environments burnt by bushfire

Authors	Location	Catchment area (km^2)	Post-fire sampling regimes and duration of sampling	Pre-fire maximum sediment concentration (mg L^{-1})	First year after bushfire: Maximum sediment concentration (mg L^{-1})	First year after bushfire: Maximum turbidity (NTU)
Streams						
Lane et al. (2006)	East Kiewa River, Victoria	a) 1.36 b) 2.44	Weekly to fortnightly and event sampling; 3 years	Not available	47,152	Not available
Brown (1972)	Snowy Mountains, NSW	a) 27 b) 141	Manual sampling; 5 years	a) 7052 b) 334	a) 143,000 b) 112,000	Not available
Wilkinson et al. (2007)	Little River, Blue Mountains, NSW	183	Manual flow and storm flow sampling; 12 months	82	2646	Not available
Chessman (1986)	Victoria, SE Australia	40-750 (11 sites)	Manual flow and storm flow sampling; 3 months	Not available	Burnt: 11-2300 Unburnt: 163 (110 km^2)	130 (>100; n=3)
Leak et al. (2003)	Buckland River, Victoria	322	Grab samples; single event	Not available	59,000	129,000
Sheridan et al. (2007a)	Victoria a) Ovens River b) Tambo River-1 c) Dargo River d) Tambo River-2 e) Mitta Mitta River f) Kiewa River	 a) 495 b) 523 c) 676 d) 895 e) 1533 f) 1655	Event sampling; 3 years	Event flow: a) 280 b) 9 c) 34 d) 90 e) 260 f) 63	1st year: a) 1700; b) 59,000; c) 1600; d) 15,000; e) 43,000; f) 140 2nd year: a) 330; b) n/a; c) 990; d) 9100; e) 2200; f) n/a 3rd year: a) 83; b) n/a; c) 930; d) 2000; e) 2000; f) n/a	Not available

Authors	Location	Catchment area (km^2) / reservoir capacity (GL)	Post-fire sampling regimes and duration of sampling	Pre-fire maximum turbidity (NTU)	First year after bushfire: Maximum sediment concentration (mg L^{-1})	First year after bushfire: Maximum turbidity (NTU)
Reservoirs						
White et al. (2006)	Bendora Reservoir, ACT	91.5/11.5	Not reported; 3 years	Previous maximums: - 118 at bottom after 1983 bushfire - 18 at 15 m after 190mm/d event (Jan 1995)	Not available	3000 at bottom
Goulburn-Murray Water (2008)[a]	Victoria: Lakes a) William Hovel b) Buffalo c) Glenmaggie[b] d) Eildon	a) 332/13.7 b) 1150/23.9 c)1891/178 d)3885/3334	Fortnightly to monthly; 2 years	a) 4 b) 18 c) 130 d) 7	Not available	a) 5.7 b) 20 c) 1398 d) 16
Alexander et al. (2004)	Dartmouth Reservoir, Victoria	3611/3900	5 sampling intervals; 7 months	1 (surface)	<4 (all depths to 100 m)[c]	5 (surface)

[a] Reservoir sampling at take-off points.
[b] Data for Lake Glenmaggie from the Victorian Water Resources Data warehouse: http://www.vicwaterdata.net/vicwaterdata/home.aspx
[c] Data from depth-stratified sampling location near the dam wall.

There are also instances of increased sediment concentrations and turbidity levels in reservoirs following the 2003 and 2006-07 bushfires in south-eastern Australia (Table 4). For example:

- for the Bendora Reservoir (supplying drinking water for Canberra), White et al. (2006) reported an increase in turbidity following the 2003 bushfire which was some thirty times the previously recorded maximum turbidity. This affected all depths in the reservoir, which made the water unfit for supply and forced water restrictions in Canberra. Water quality in the reservoir returned to near pre-fire conditions within two years of the fire, and
- for Lake Glenmaggie (60 km downstream of debris flow in the upper Macalister catchment, eastern Victoria), there were large increases in sediment concentrations and turbidity after fire in 2003 and 2006/07 (maximums recorded were 280 mg L^{-1} and 1398 NTU, respectively). As a result, the water stored in Lake Glenmaggie was unfit for domestic consumption, necessitating increased water restrictions and water carting for communities dependent on this supply.

However, large water quality impacts in reservoirs do not always result from inflows with high concentrations of suspended sediment. For example, the Dartmouth Reservoir in north-eastern Victoria showed only a small change in turbidity and the sediment concentration remained <4 mg L^{-1} at all depths despite the 2003 fires burning 95% of the catchment area and high sediment concentrations in tributary rivers (Mitta Mitta River = 43,000 mg L^{-1}; Sheridan et al., 2007a). Another example comes from the Mount Bold Reservoir in South Australia (with a catchment dominated by dry eucalypt forest and some pine plantation), where no water quality impacts were recorded following fire in 2007, despite the failure of numerous sediment traps (Morris and Calliss, 2009). This contrast between inflows and the reservoir water quality probably reflects the attenuating capacity of the reservoir, which may depend on the size of the reservoir, storage levels after the fire and the extent of stratification within the reservoir which may change seasonally.

3.2 Ash

Water quality is impacted by ash washed into streams and reservoirs when storms occur soon after fire. Ash is readily transported by runoff and contains high concentrations of soluble inorganic material. The composition of ash is highly variable and depends on the type of vegetation burnt, the part of the plant burnt (bark, wood or leaves), soil type, climate, and combustion conditions (Someshwar, 1996; Demever et al., 2001). Examples of constituent levels in ash include:

- calcium carbonate ($CaCO_3$) in wood ash (Demever et al., 2001)
- phosphorus in bark ash (15700 mg kg $^{-1}$) (Someswhar, 1996)
- phosphorus (160-12,000 mg kg^{-1}) and nitrogen (300-14,000 mg kg^{-1}) in burnt eucalypt leaf litter (Khanna et al., 1994)
- organic carbon and nitrogen, concentrations depending on the extent of combustion (Demever et al., 2001; Goforth et al., 2005)
- iron is the most abundantly present microelement and probably part of the structural framework of ash (Someshwar, 1996; Demeyer et al., 2001)
- iron (1466 mg kg^{-1}), manganese (2570 mg kg^{-1}), zinc (201 mg kg^{-1}) and copper (57 mg kg^{-1}) in pine ash (Ferreira et al., 2005)
- iron (600-10000 mg kg^{-1}), manganese (60-100,000 mg kg^{-1}), zinc (20-370 mg kg^{-1}), copper (12-340 mg kg^{-1}), aluminium (1000-18000 mg kg^{-1}), lead (4-152 mg kg^{-1}) and sulfur (410-9000 mg kg^{-1}) in eucalypt litter ash (Khanna et al., 1994)
- mercury (<0.5 mg kg^{-1}), cadmium (<10 mg kg^{-1}) and arsenic (23 mg kg^{-1}) in wood ash (Someshwar, 1996), and
- Cl^- (162-1331 mg kg^{-1} based on solution extracts) in different ash types from low intensity fire in *Eucalyptus pauciflora* forest, south-east Australia (Khanna and Raison, 1986).

The increased concentration of constituents in ash relative to unburnt fuels, together with the mobility of ash (i.e. low density ash is readily transported by water and wind erosion), presents a risk to water quality in the immediate post-fire period. Ash can form a significant component of suspended material flux in the first year after fire, with the rate of removal of ash from hillslopes dependent upon the erosivity of post-fire rainfall and wind events. For example, Cerdà and Doer (2008) reported 153 mm of rainfall over a six day period removed most of a 3.6 cm ash layer only three weeks after a high severity fire in eastern Spain.

3.3 Nitrogen and phosphorus

The effect of bushfires on exports of nitrogen and phosphorus varies markedly between catchments, from no change or minor increases to substantial increases (multiple change from pre-fire exports of 1-94 times for nitrogen and 1-431 times for phosphorous). Table 5 summarises first year post-fire exports of total nitrogen (TN) (ranging from 1.2 to 15.3 kg ha^{-1} yr^{-1}) and total phosphorus (TP) (ranging from 0.03 to 3.2 kg ha^{-1} yr^{-1}) for catchments of varying size (0.12 to 1533 km^2).

Several studies also report levels of nitrogen and phosphorus in streams following fire:

- in eucalypt forest catchments (40-750 km^2; eastern Victoria), Chessman (1986) reported maximum values during storm events for nitrate (5.3 mg L^{-1}), nitrite (0.36 mg L^{-1}), ammonia/ammonium (4.0 mg L^{-1}) and TP (0.82 mg L^{-1}) during a 3 month period after fire
- in wet eucalypt forest catchments (136 and 244 ha; north-east Victoria), Lane et al. (2008) reported that the highest mean and median concentrations of nitrogen and phosphorous occurred during the first 3-6 months after bushfire but the peak concentrations occurred during a high intensity storm 12 months after the fire
- in the Buckland River catchment (north-east Victoria), Leak et al. (2003) recorded maximum TN concentrations (410 mg L^{-1}) and TP concentrations (110 mg L^{-1}) at a water supply off-take point 30 km downstream of the post-fire debris flows. In contrast, in the Ovens River (upstream of the junction with the Buckland River) post-fire maximum TN (14 mg L^{-1}) and TP (2.9 mg L^{-1}) were much lower
- in sandstone terrain and dry eucalypt forest (183 km^2; near Sydney), Wilkinson et al. (2006) observed maximum post-fire TN and TP concentrations of 24.7 mg L^{-1} and 2.5 mg L^{-1} (1.6 and 7 times the pre-fire maximum, respectively) during a storm event, and
- in a very different setting of open eucalypt forest streams in the tropics of northern Australia, Townsend and Douglas (2004) reported no significant difference between pre- and post-fire concentrations of TN and TP. The absence of an effect was attributed to the low severity of the burn and the low relief of the catchment.

The examples listed above illustrate some of the key factors contributing to the variability in values for TN and TP often observed after fire, such as: differences in burn area and severity, erosion processes, the extent of delivery to streams, soil and forest vegetation types, storage and retention of nutrients and rates of pre-fire atmospheric deposition. Notably, fire may increase soil aggregate size and density, potentially increasing the duration of sediment storage and delay release of nutrients after fire from degrading aggregates (Blake et al., 2007; Blake et al., 2009b).

In relation to lakes and reservoirs, data on post-fire changes to nutrient concentrations are available for several reservoirs in south-eastern Australia (Table 6). For example, Figure 5 compares pre-fire and post-fire samples (routine sampling every 2-4 weeks) from four reservoirs in Victoria following the 2006-07 bushfires. For these reservoirs, post-fire increases in mean NO_x (nitrate + nitrite), TN, and TP concentrations range from 1 to 11 times pre-fire levels for the first year after fire and the differences are statistically significant in all cases (Mann Whitney U test, 0.05 probability level), except for TP in two of the reservoirs. Furthermore, maximum post-fire values for NO_X, TN, and TP exceeded all maximum pre-fire values, with both pre and post-fire monitoring occurring during a period of generally below average rainfall in south-eastern Australia (except for the longer pre-fire record at Lake Glenmaggie).

Table 5: Summary of post-fire exports of phosphorous (TP, particulate P) and nitrogen (TN, nitrate) from catchment-scale studies in Australian forests

Authors	Location	Vegetation	Sampling regime	Catchment area(s) (km^2)	P or N form	Post-fire export (kg ha^{-1} yr^{-1}) in first year (multiple increases over unburnt control)	
						P	N
Lane et al. (2008)	East Kiewa River, North East Victoria	Wet Eucalyptus forest	Weekly-fortnightly after event	1.36, 2.44	Nitrate		13
Blake et al. (2009a)	Blue Mountains, near Sydney	Dry Eucalyptus forest	n/a	0.89	Particulate P	0.49 [a]	
Lane et al. (2008)	East Kiewa River, North East Victoria	Wet Eucalyptus forest	Weekly-fortnightly after event	1.36, 2.44	TP, TN	1.67 (x4-5)	15.3 (x6)
Townsend and Douglas (2004)	Kakadu National Park, Northern Territory	Tropical savannah, open dry Eucalyptus forest	Every 3 days after event	6.6	TP, TN	0.03 (x1.8)	1.2 (x1.6)
Sheridan et al. (2007a)	Victoria, SE a) Ovens River b) Tambo River-1 c) Dargo River d) Tambo River-2 e) Mitta Mitta River f) Kiewa River	Dry and wet Eucalyptus forests, sub-alpine woodland	Pre-fire: monthly; Post-fire: event	a) 495 b) 523 c) 676 d) 895 e) 1533 f) 1655	TP, TN	a) 1.1 (x9) b) 0.6 (x431)[b] c) 0.41 (x10) d) 0.26 (x30) e) 3.2 (x37) f) 0.13 (x1)	a) 8.2 (x9) b) 2.7 (x94)[b] c) 2.8 (x7) d) 1.4 (x12) e) 14.1 (x20) f) 2.2 (x1)

[a] TPP export based on Be-7 sediment budget (<63 µm fraction) for the first 3 months after bushfire (Blake et al., 2009a).

[b] TP and TN data for the Tambo River (site 1) are for a six month period only (Sheridan et al., 2007).

Table 6: Comparison of pre and post-fire (first year) nutrient (NO_x, TN, TP) concentrations in four water supply reservoirs in south-eastern Australia[a]

Reservoir	Capacity (GL)	Catchment area (km^2)	Water quality parameter	Mean (and maximum) concentrations (mg L^{-1})[b]					
				Pre-fire	N	Post-fire	N	Multiple Increase	p-value
Lake William Hovell	13.7	332	NO_x	0.03 (0.27)	35	0.20 (0.74)	15	6.8	0.005
			TN	0.15 (0.40)	35	0.47 (1.4)	15	3.1	<0.001
			TP	0.01 (0.02)	35	0.03 (0.13)	15	3.1	0.011
Lake Buffalo	23.9	1150	NO_x	0.03 (0.17)	37	0.20 (0.76)	13	6.6	0.004
			TN	0.21 (0.39)	37	0.52 (1.2)	13	2.4	0.004
			TP	0.01 (0.029)	35	0.02 (0.034)	13	1.3	0.281
Lake Glenmaggie	178	1891	NOx	0.05 (0.43)	190	0.56 (0.98)	12	10.8	<0.001
			TN	0.29 (1.2)	190	1.43 (3.4)	12	5.0	<0.001
			TP	0.02 (0.18)	188	0.14 (0.61)	12	7.0	<0.001
Lake Eildon	3334	3885	NO_x	0.05 (0.17)	48	0.25 (0.69)	18	5.1	0.011
			TN	0.28 (0.89)	48	0.50 (1.3)	18	1.8	0.002
			TP	0.01 (0.05)	48	0.02 (0.11)	18	1.6	0.116

[a] Data supplied by the Goulburn-Murray Water Authority and the Victorian Water Resources Data Warehouse.
[b] Concentrations of NO_x are reported in mg N L^{-1}.

The largest recorded post-fire impact on reservoir water quality occurred in Lake Glenmaggie (catchment 90% burnt) following a debris flow (February 2007) and a subsequent high magnitude flood (June 2007), resulting in persistent poor water quality in the reservoir, with TN and TP concentrations in outflows only approaching pre-fire levels after three years (Figure 6).

In contrast, following the 2003 bushfires, Alexander et al. (2004) monitored nutrient levels in Dartmouth Reservoir (capacity: 3900 GL; catchment area: 3,611 km^2; 95% burnt) within the first year after the fire. These authors reported very high event concentrations of TN (maximum 21 mg L^{-1}) and TP (maximum 8 mg L^{-1}) in tributary streams; however, only a comparatively small change was recorded in the reservoir near the dam wall.

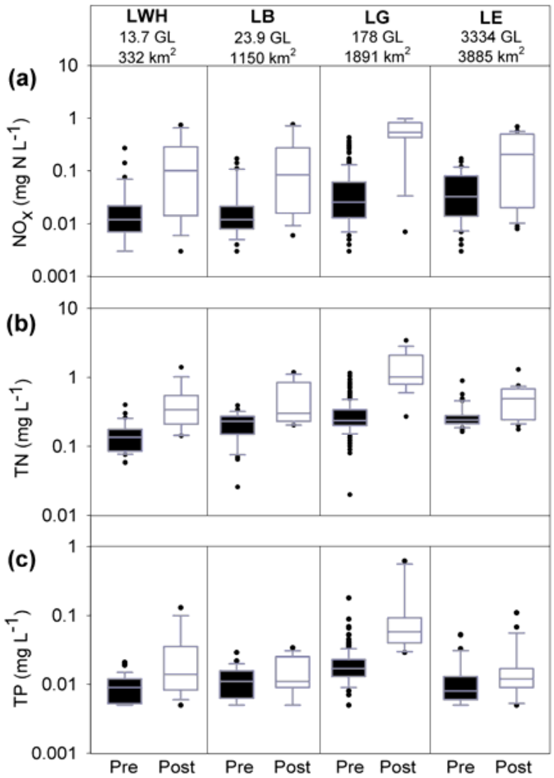

Figure 5: Box plots of pre and post-fire two-four weekly measurements of a) NO_x, b) TN and c) TP in four reservoirs (LWH: Lake William Hovell; LB: Lake Buffalo; LG: Lake Glenmaggie; LE: Lake Eildon) with catchments burnt by bushfire in 2006-07 in Victoria, south-eastern Australia. Box plots display the 10th, 25th, median, 75th, 90th percentiles and outliers. Data supplied by the Goulburn-Murray Water Authority and the Victoria Water Resources Data Warehouse.

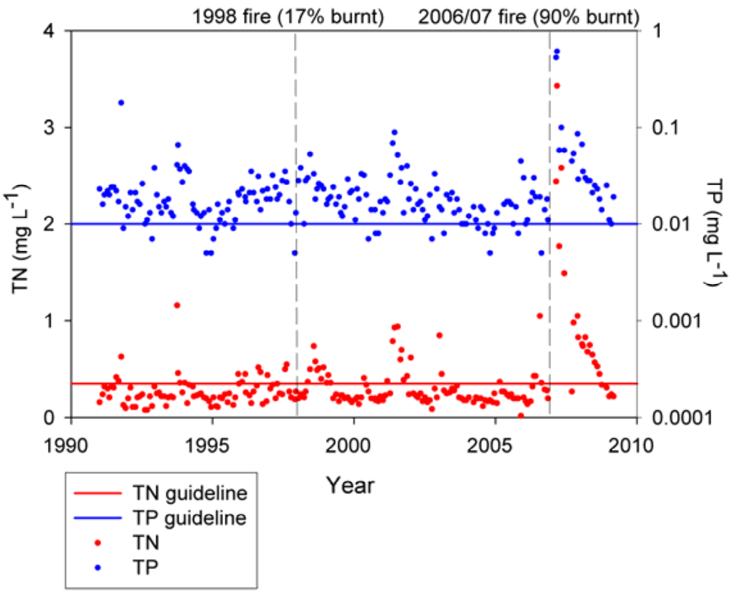

Figure 6: Monthly TN and TP concentrations measured at the Lake Glenmaggie outflow before and after bushfires in 1998 and 2006-07, Victoria, south-eastern Australia. Note the difference in axis scales between TN and TP. Data accessed through the Victoria Water Resources Data Warehouse.

3.4 Metals

Information on post-fire exports of metals is sparse but has been occasionally reported:

- Townsend and Douglas (2004) reported first year post-fire iron and manganese exports of 1.2 kg ha^{-1} and 0.022 kg ha^{-1}, respectively, from a tropical dry savannah forest catchment (6.6 km^2). This represented a negligible change from pre-fire exports, and
- Wasson et al. (2003) estimated individual event loads of iron and manganese entering Corin reservoir, which supplies Canberra (197 km^2; 98% burnt) following the 2003 bushfires in south-east Australia. Three storms within two months of the fire generated the following iron/manganese loads (kg ha^{-1}): 0.007/0.002 (59 mm/day; 25.8 ML inflow), 0.04/0.001 (72 mm/2 days; 280 ML), and 0.02/0.007 (rainfall data unavailable; 153 ML).

Reports of post-fire metal concentrations in streams and reservoirs are also limited. Table 7 summarises data from a small number of samples collected following intense summer storms within one month of the 2003 bushfires in north-eastern Victorian streams.

Table 7: Post-fire metal concentrations in streams in north-eastern Victoria after the 2003 bushfires and following intense summer storm events

Author	Location	Location description	Metal	Pre-event concentration ($mg\ L^{-1}$)	Storm event concentration ($mg\ L^{-1}$)
Leak et al. (2003)[a]	Buckland River, NE Victoria	30 km downstream of a cluster of debris flows	Iron	Not available	740
			Arsenic		0.28
			Chromium		0.92
			Lead		0.98
North East Water (2003)	Ovens River, NE Victoria	Upstream of water quality impacts from debris flow	Iron	0.64	30
			Copper	0.001	0.032
			Zinc	<0.002	0.1
			Chromium	0.001	0.04
			Arsenic	0.003	0.012
			Lead	0.001	0.033

[a] These concentrations should not be considered event maximums given that the sample was collected on the receding limb of the hydrograph at 1.5 $m^3\ s^{-1}$, compared to the peak flow of 68 $m^3\ s^{-1}$ that occurred less than 12 hours earlier.

Monitoring of iron and manganese concentrations in the Bendora Reservoir (supplying Canberra) on the Cotter River (482 km^2; 98% burnt) was undertaken following the 2003 bushfire (White et al., 2006). An estimated 21,200 t of sediment was deposited in the reservoir in the first year after the fire, although this estimate only included sediment exported from a small number of ephemeral streams discharging to the reservoir (Wasson et al., 2004). The main Cotter River inflow to Bendora Reservoir also transported large amounts of sediment but the quantities of this material could not be estimated effectively. Major water quality problems resulted, with post-fire iron and manganese concentration peaks exceeding all previous peaks by factors of three and five, respectively (White et al., 2006).

Further information on post-fire concentrations of metals in streams and reservoirs is not readily available but warrants investigation, particularly in fire-prone forest regions susceptible to high magnitude erosion events (such as debris flows) that may generate large suspended sediment loads (Smith et al., 2011). Information on the duration of elevated metal concentrations in streams and reservoirs is required to determine the longevity of post-fire water quality impacts (e.g. White et al., 2006).

3.5 Other constituents

3.5.1 Chloride and sulfate

Changes to the bulk water chemistry (major cations and anions) resulting from fire are not well documented. Likewise, measurements of total dissolved solids (TDS) are rarely reported by studies of post-fire water quality (Neary et al., 2005). However, some observations of changing levels of chloride and sulfate attendant to fire have been reported. There is no Australian literature on exports of chloride and sulfate following fire but there has been some limited reporting of changes to these ions in the international literature. For example, following fire in *Pinus pinaster* forests of central Portugal, Ferreira et al. (2005) found SO_4^{2-} exports of 18.1 kg ha^{-1} yr^{-1} (278 times unburnt) at the plot-scale (16 m^2) and 13.2 kg ha^{-1} yr^{-1} (4400 times unburnt) at the catchment-scale (burnt: 1.1 km^2; unburnt: 0.61 km^2).

Since there is no Australian literature on concentrations of chloride (Cl^-) and sulfate (SO_4^{2-}) following fire, conclusions are inferred from findings from other forest environments. Some examples from the international literature include:

- in north-western Montana (subalpine conifer forest), Mast and Clow (2008) reported a 4-fold increase in Cl^- levels and 2.7–fold increase in SO_4^{2-} levels in the first year following fire. Despite the post-fire increase, maximum sampled Cl^- concentrations remained <0.8 mg L^{-1}
- in a semi-arid environment in New Mexico, Gallaher et al. (2002) reported that the post-fire maximum Cl^- (53.2 mg L^{-1}) concentration only slightly exceeded the pre-fire maximum, while the maximum SO_4^{2-} (16.7 mg L^{-1}) concentration was below the pre-fire level
- in the humid tropics (Malaysian Borneo), Malmer (2004) reported small rises in Cl^- baseflow concentrations for two months after fire
- in boreal shield lakes (Québec, Canada), Garcia and Carignan (1999) reported a 6-fold increase in Cl^- and SO_4^{2-} over levels recorded in reference lakes. However, maximum sampled post-fire concentrations of both Cl^- (<0.53 mg L^{-1}) and SO_4^{2-} (<8 mg L^{-1}) were very low by drinking water standards (Carignan et al., 2000), and
- in Yellowstone National Park, Lathrop (1994) found negligible impact from bushfire on lake water quality.

3.5.2 Organic carbon

Bushfires may cause significant changes to the store of organic carbon on the forest floor and in surface soils, which, in conjunction with increases in post-fire erosion and leaching from the ash/soil, has implications for post-fire exports and concentrations of particulate and dissolved organic carbon. For example, in the initial six month period after the 2003 bushfires in south-eastern Australia, Wasson et al. (2003) estimated that approximately 137 t (6.7 kg ha^{-1}) of particulate organic carbon entered the Corin Reservoir (compared to the pre-fire average annual input of 1.2 kg ha^{-1} yr^{-1}). For dissolved organic carbon, studies overseas indicate that bushfire effects are generally minor:

- in subalpine conifer forests of North America, Mast and Clow (2008) reported that bushfire had a minimal effect on dissolved organic carbon concentrations (burnt mean: 1.1 mg L^{-1}; unburnt: 0.7 mg L^{-1}) in forest streams over a four year period

- in mixed conifer forests in the Rocky Mountains, Minshall et al. (2001) reported increased dissolved organic carbon levels in streams in burnt catchments in the first-year after fire during the peak spring flow period, although maximum sampled concentration remained <4 mg L^{-1}
- in boreal forests of northern Alberta, McEachern et al. (2000) observed a statistically significant 1.6-fold increase in dissolved organic carbon concentrations of burnt catchment lakes (mean: 25 mg L^{-1}) compared to levels recorded in reference lakes (mean: 16 mg L^{-1}), and
- in boreal forests in Québec, Canada, Lamontagne et al. (2000) and Carignan et al. (2000) reported that bushfire did not cause a statistically significant increase in dissolved organic carbon stream exports or dissolved organic carbon concentrations (sampled maximums <11 mg L^{-1}).

Overall, particulate organic carbon flux appears to depend on the magnitude and timing of storm events after fire, and may be most problematic in those burnt forest environments susceptible to large increases in overland flow and erosion. Dissolved organic carbon concentrations may reflect inputs from both storm runoff and sub-surface flows. However, fire effects on dissolved organic carbon were minor in the forest environments studied, with the high concentrations measured in Canadian boreal lakes largely reflecting background conditions.

3.5.3 Cyanide

Cyanide release into streams as a result of ash leaching or aerial deposition has been reported (Barber et al., 2003). However, any impacts are probably short-lived and confined to initial post-fire rainfall events, while impacts are more likely to occur in small catchments where dilution is limited (Barber et al., 2003). Two studies in the US measured cyanide concentrations following fire:

- in North Carolina, Barber et al. (2003) found that cyanide concentrations were an order of magnitude (mean 0.049 mg L^{-1}) higher than runoff from unburned areas. These authors also found that available cyanide concentrations in ash leachate greatly exceeded that of unburned fuel in laboratory test burns, and
- near Los Alamos (New Mexico) following the Cerro Grande fire, Gallaher et al. (2002) measured elevated post-fire concentrations of cyanide, with a maximum concentration for available cyanide (used as an approximation to the toxic fraction of cyanide) of 0.062 mg L^{-1} and a maximum concentration of total cyanide of 0.176 mg L^{-1}.

3.5.4 PAHS, PCDD/Fs and PCBs

Data on the release of polycyclic aromatic hydrocarbons (PAHs) after fire is limited:

- Kim et al. (2003) reported increased levels of PAHs in forest soils (15.5 times unburnt maximums) one month after bushfire in Korea
- Vila-Escalé et al. (2007) observed increased post-fire PAH inputs to streams associated with increased overland flow and soil erosion in Spain. PAH concentrations approached background levels 15 months after the fire and never reached levels of toxicological concern, and
- Olivella et al. (2006) reported an increase in PAH concentration in streams associated with atmospheric deposition of ash into streams (in the absence of rain) one month after fires in Spain.

Low rainfall after fire may contribute to increased PAH concentration, adsorption and bioaccumulation, while heavy rain may dilute PAH concentrations (Vila-Escalé et al. 2007; Olivella et al. 2006).

Polychlorinated dibenzo-*ρ*-dioxins and dibenzofurans (PCDD/Fs) and polychlorinated biphenyls (PCBs) concentrations in sediments were studied following forest fires in northern Alberta, Canada (Gabos et al., 2001). These authors observed very low concentrations of both PCDD/Fs and PCBs that were consistent with background levels at all sites investigated. However, Kim et al. (2003) reported increased PCDD/Fs (2.3 times unburnt maximums) in burnt forest soils in Korea one month after fire, with concentrations comparable to unburnt soils five months later. The short-term increase was attributed to inputs of PCDD/Fs from ash, which was subsequently removed by wind and runoff.

3.6 Dissolved oxygen

Data for dissolved oxygen concentrations in streams and reservoirs following fire are of limited availability. However, it would appear that dissolved oxygen concentrations decline following major post-fire rainfall events that deliver large quantities of sediment and organic material to streams.

Lyon and O'Connor (2008) measured dissolved oxygen in the Ovens River about 70 km downstream of post-fire debris flows in the Upper Buckland River in north-eastern Victoria (Figure 7). Concentrations as low as 0.2 mg L^{-1} that lasted for 12 hours were recorded during the initial pulse of sediment caused by the debris flow. Over subsequent days, the dissolved oxygen concentrations remained at levels lower than were recorded before the pulse of sediment entered the river.

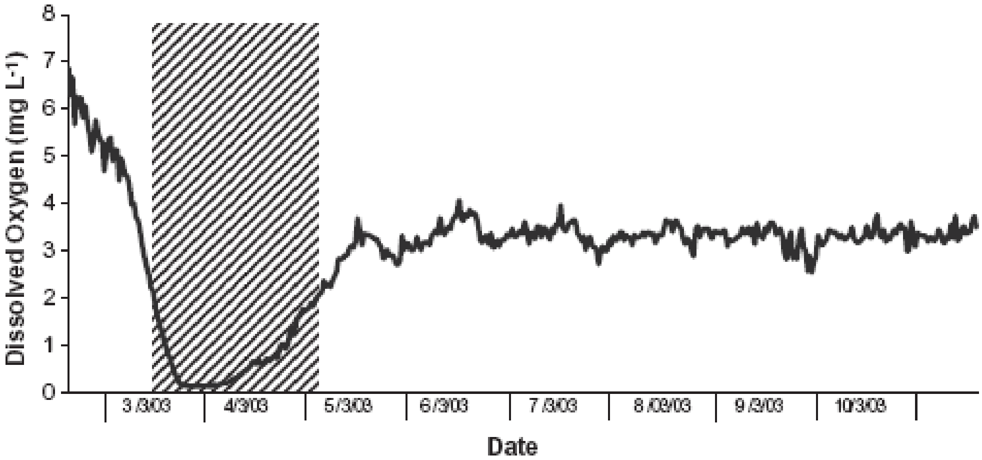

Figure 7: Dissolved oxygen concentration in the Ovens River at Tarrawingee (north-east Victoria) before, during and after a pulse of sediment passed down the river as a result of post-fire debris flows further upstream. The shaded area indicates the head of the sediment slug passing downstream through the Tarrawingee area. Source: Lyon and O'Connor (2008).

Frame et al. (2009) observed reduced dissolved oxygen concentrations in Diamond Creek (a tributary of the Yarra River that was burnt in February 2009) following a large rainfall event. Dissolved oxygen declined from 6-8 mg L^{-1} to 4.8 mg L^{-1} but soon returned to normal levels after the event. Direct comparison of these results (and the data from Lyon and O'Connor, 2008) with the dissolved oxygen guideline value for aquatic ecosystems (expressed as % saturation) is not possible in the absence of stream temperature and salinity data that were not reported.

3.7 Cyanobacteria

Cyanobacteria (blue-green algae) are present in almost all aquatic ecosystems and only become a concern when they increase rapidly and blooms or scums develop. Blooms are likely to form when the water is relatively still, nutrient levels are high and the temperatures remain warm (CRC for Water Quality and Treatment, 2008). High nutrient levels in the water can cause a bloom to persist for longer than usual.

Fires are likely to contribute to higher nutrient loads and subsequent cyanobacteria blooms in lakes and reservoirs. However, it is difficult to attribute a bloom to a fire because of the natural occurrence of cyanobacteria in waterways and the pre-existing propensity for lakes and reservoirs to experience blooms. For example, following the extensive 2006/07 fires in Victoria, which burnt 34% of the catchment area for the Gippsland Lakes, there was a large prolonged *Synechococcus* bloom in the Lakes afterwards. This bloom was most likely caused by high nutrient loads entering the Lakes following a large post-fire rainfall event (Cook et al., 2008). In particular, the nitrate load was four times the average load and twice that of the second highest recorded load. Although the intense rain and resultant floods were the most likely cause of this bloom, the fires contributed to the magnitude of the event by making the catchment area more susceptible to runoff and by aiding the release of nutrients (Cook et al., 2008).

3.8 Temperature

Water temperatures can be changed by fire either directly during the course of a fire or indirectly as a result of the removal of riparian vegetation and increased turbidity. There is very little literature on this topic. Hitt (2002) measured water temperatures bi-hourly during a bushfire in Montana, USA. The maximum temperature recorded was 17.2^{o}C, which was 7.8^{o}C above the maximum recorded in a nearby unburnt stream. During the Black Saturday bushfires in Victoria (February 2009), water temperatures in streams and ponds were reported to have reached 55^{o}C (BAER 2009).

Following a fire, loss of riparian vegetation cover will make water temperatures higher during the day (BAER 2009). Hitt (2002) found that daily maximum temperatures were consistently higher in the burnt stream compared to the unburnt stream (mean $\Delta_{max} \pm 1$ SD = 2.23 $\pm$ 0.59) but daily minimum temperatures were similar for both streams (mean $\Delta_{min} \pm 1$ SD = 0.063 $\pm$ 0.19).

3.9 Water availability and flow

Water quality impacts following fire are generally short-term (usually between 2-5 years), so the flow changes of most importance to water quality occur during this period. Studies in the Mountain Ash forests of Victoria predict increased water yields in the short-term following fire (Langford 1976; Kuczera 1985 and 1987). There are few studies in other forest types, but a similar short-term trend is expected due to the loss of vegetative cover. In relation to water quality, higher water yields could lead to lower contaminant concentrations due to dilution if constituents are supply limited and behave conservatively. Increased loads may occur when there is no limit on supply and constituent flux is dependent upon the capacity of post-fire flows to transport material. Transport limitation can be an important restriction on sediment delivery to streams and catchment outlets following fire, particularly during low rainfall periods (Moody and Martin, 2001; Petticrew et al., 2006). However, generally higher water yields in the first few years following fire are likely to contribute to larger loads of constituents being transported into streams and reservoirs. During the post-fire period as revegetation occurs and flows decline, transport limitation may become more important, resulting in stored sediment and increasing residence time (Moody and Martin 2001). If large quantities of sediment go into channel storage after fire, subsequent higher flow periods may re-suspend this material and contribute to adverse water quality impacts (Wilkinson et al., 2009). The length of time after fire that such impacts could occur will depend on the extent of in-channel sediment storage as well as the pattern of rainfall and associated flows capable of remobilising the stored material.

4 How changes to water quality may affect the major uses and values of water

The changes to water quality described in Section 3 may affect major uses and values of water (introduced in Section 1) and are reviewed here for the values identified in the ANZECC Guidelines.

4.1 Drinking water

There are several recent examples where water quality impacts in reservoirs following fire have necessitated emergency actions such as water carting or water restrictions. For example, high turbidities in the Bendora Reservoir following the 2003 ACT fires resulted in water restrictions in Canberra (White et al., 2006), while high nutrient levels in Lake Glenmaggie in eastern Victoria necessitated water restrictions and water carting to some communities reliant on supply from this storage.

From a drinking water perspective, the constituents of most concern following fire are elevated levels of suspended sediment, nutrients and metals. For other constituents (e.g. sulfate and chloride, organic carbon, cyanide, PAHs, PCDDs/Fs and PCBs), post-fire maximums are unlikely to exceed guideline values. However, with a limited number of contaminant studies, drawing conclusions about their potential impacts is difficult.

4.1.1 Suspended sediment in relation to drinking water

Suspended sediment inputs to streams and reservoirs impact on the colour and turbidity of water and may also transport particle-associated nutrients, metals, and other contaminants (Horowitz and Elrick, 1987; Horowitz, 1991; Ongley et al., 1992). From a drinking water quality and treatment perspective, elevated turbidity may hinder detection of bacteria and viruses, promote bacterial growth from elevated levels of adsorbed nutrients, and limit effective disinfection (NHMRC, 2004). The guideline value of 5 NTU for turbidity (which is largely dependent on levels of suspended sediment) is based on the visual amenity of tap water and hence its acceptability (NHMRC, 2004). There is insufficient information to provide a health-based guideline, but disinfection can become problematic when the turbidity exceeds 1 NTU.

This guideline value for turbidity is often exceeded in streams and reservoirs following fire. For example:

- in the Upper Buckland River in north-eastern Victoria and following post-fire debris flows, turbidity values (129,000 NTU) were 26000 times the drinking guideline value. Subsequent turbidity downstream in the Ovens River remained high, with the peak turbidity at Wangaratta (150 km downstream of the debris flows) occurring twelve days after the event and exceeding the guideline by 474 times (Leak et al., 2003)
- in the Bendora Reservoir (ACT) following the 2003 fire and several storm events, maximum turbidity values were 600 times the guideline value. Water quality returned to pre-fire levels within two years and is unlikely to be again exceeded in the absence of fire (White et al., 2006), and
- in Lake Glenmaggie (east Victoria) following post-fire debris flows in a tributary river, turbidity values were 280 times the guideline value (Goulburn Murray Water, 2008).

4.1.2 Nitrogen and phosphorus in relation to drinking water

Increased exports and concentrations of nitrogen and phosphorus following bushfire can be problematic for managers of water supply catchments. Elevated concentrations of nitrate (NO_3) and nitrite (NO_2) present a potential risk to human health primarily through reduction of NO_3 to NO_2, which may affect oxygen transport in red blood cells. High concentrations of ammonia/ammonium may corrode copper pipes and fittings. Nitrogen and phosphorus are limiting nutrients for growth of aquatic plants, algae and cyanobacteria (blue-green algae), of which cyanobacteria have implications for human health (NHMRC, 2004; Drewry et al., 2006). Post-fire increases in nutrient levels following fire is particularly an issue for water storage facilities and lakes (Chorus and Bartram, 1999; EPA Victoria, 2003; Spencer et al., 2003). In rivers, the nutrients tend to be more rapidly removed from the system. Conversely, in reservoirs and lakes the water detention times are longer, which means that nutrients tend to either accumulate or be stored in sediments and recycled.

There are no guideline values in the Australian Drinking Water Guidelines (NHMRC, 2004) for total nitrogen and total phosphorus since the nutrients themselves are of little, if any, health consequence. However, the guideline values for aquatic ecosystems may be used as a guide (see Section 4.2.2). The guideline value for nitrate is 50 mg L^{-1}, which is much higher than the maximum post-fire concentrations observed by Chessman (1986) in eastern Victoria. Similarly the post-fire concentrations of nitrate and nitrite observed in Victorian reservoirs following the 2006/07 fires (Goulburn-Murray Water Authority, 2008) are much lower than the guideline value.

4.1.3 Metals in relation to drinking water

Contamination of streams and water supply reservoirs by post-fire inputs of trace metals from catchment sources is problematic for mainly aesthetic reasons. Elevated concentrations of iron, manganese and zinc cause aesthetic problems (taste, colour, staining of pipes and fittings), whereas poisoning may occur from continued consumption of water containing high concentrations of barium and copper, with less severe gastrointestinal symptoms possible with copper concentrations of 3-5 mg L^{-1} (NHMRC, 2004; WHO, 2008). Arsenic and chromium, though rarely present in Australian waters other than mine drainage, may be carcinogenic, while aluminium, lead and mercury are toxic when consumed in sufficient quantities for prolonged periods.

Although reports of post-fire metal concentrations in streams and reservoirs are limited, where concentrations are reported, they often exceed the guideline values. For example:

- in the Upper Buckland River (north-eastern Victoria) following post-fire debris flows, Leak et al. (2003) recorded maximum iron, arsenic, chromium and lead concentrations of 2467, 40, 18 and 98 times the respective guideline values
- in the Ovens River (north-eastern Victoria) following fire, North East Water (2003) recorded maximum iron concentrations 100 times the guideline value, arsenic concentrations 1.7 times the guideline value and lead concentrations 3.3 times the guideline value. By contrast, concentrations of copper, zinc and chromium were below the guideline values, and
- in the Bendora Reservoir (supplying Canberra) major water quality problems resulted, with post-fire iron and manganese concentration peaks exceeding all previous levels by factors of three and five, respectively (White et al., 2006).

4.1.4 Other constituents in relation to drinking water

Elevated concentrations of Cl^- in water supplies present aesthetic concerns (corrosion of pipes and fittings), whereas SO_4^{2-} may be problematic for both aesthetic (taste at concentrations over 250 mg L^{-1}) and health reasons (purging effects possible with concentrations over 500 mg L^{-1}) (WHO, 2008). Based on the limited range of studies, it is difficult to characterise the Cl^- and SO_4^{2-} response to bushfires. It appears that exceedance of the guideline values in streams and lakes after fire is unlikely to occur in North American coniferous forest catchments, whereas for other fire-prone forest environments the level of risk remains unclear. It seems that the largest post-fire increases in Cl^- and SO_4^{2-} concentrations are short-lived.

There is no Australian drinking water guideline value for organic carbon since organic matter is benign. In Canada, a dissolved organic carbon guideline value of 5 mg L^{-1} has been set for aesthetic reasons and to reflect the growth of biological slimes in distribution systems and the difficulties these cause for maintenance of disinfection, as well as the need to minimise the formation of potential disinfection by-products (Ministry of Environment, 2003). Chlorination of water with elevated dissolved organic matter can be problematic due to formation of a wide range of chlorinated by-products (e.g. trihalomethanes and haloacetic acids) and their high chlorine demand that may cause problems in maintaining an adequate level of disinfection (NHMRC, 2004). Of the few studies available from North America, fire effects on organic carbon concentrations are minimal and the post-fire concentrations were less than 5 mg L^{-1} except for the Canadian boreal lakes, which had high background levels of organic carbon.

Cyanide is highly toxic, affecting the thyroid and nervous system. There is very little information on post-fire concentrations of cyanide. Barber et al. (2003) reported mean concentrations of 0.049 mg L^{-1} that is less than the guideline value of 0.07 mg L^{-1}, while Gallaher et al. (2002) reported a maximum for available cyanide slightly below the guideline but a maximum for total cyanide 2.5 times above the guideline value. Importantly, increases in cyanide concentrations in stream water are probably of short duration (Barber et al. 2003).

Concern about PAHs, PCDD/Fs, and PCBs relates to their toxicity, carcinogenicity, environmental persistence, and tendency to bioaccumulate (Gabos et al., 2001; Olivella et al., 2006; Vila-Escalé et al., 2007). Once released, PAHs are subject to various transformations and the different physiochemical properties of PAHs result in different interactions with suspended ash, sediment and biota in streams (Olivella et al., 2006). In a study of PAH concentrations in streams after fire in Spain, all measurements remained within the drinking water limit (Olivella et al., 2006).

4.1.5 Cyanobacteria in relation to drinking water

Cyanotoxins produced by cyanobacteria blooms present a major concern from a drinking water perspective. Toxic alkaloids such as *Cylindrospermopsin* and neurotoxins released into the water by cyanobacteria may pass through filtration systems (Chorus and Bartram, 1999). Cyanobacterial poisoning can occur directly through ingestion of cyanobacterial cells from the water or indirectly through consumption of other animals that have ingested water containing cyanobacteria. High cyanobacterial biomass may also affect the taste of treated drinking water (WHO, 2008). No human deaths have been recorded from ingesting cyanobacteria toxins but gastroenteritis may result from drinking water containing toxic species, while extended exposure, including skin irritations from contact during recreational activities, may result in more serious health effects.

4.2 Aquatic ecosystems

Extremely high turbidities and low dissolved oxygen concentrations resulting from large erosion events pose the greatest threat to aquatic ecosystems following fire. For example, there was a large decline in the abundance of fish populations following the post-fire debris flows in north-eastern Victoria (Lyon and O'Connor 2008).

Despite the immediate impacts of fire, aquatic ecosystems in Australia are quite resilient and populations of aquatic fauna often recover quickly provided there is connectivity between affected and unaffected habitats (Lyon and O'Connor 2008). Those species that are more vulnerable tend to have smaller, more isolated populations (e.g. the endangered barred galaxias, *Galaxias fuscus*), or are not as well-adapted to survive periods with elevated suspended sediment concentrations (e.g. introduced species like trout) (Lyon and O'Connor 2008).

The level of impact is also a function of the antecedent stream condition. For example, following the 2009 fires, Melbourne Water observed less resilience to the impacts of the bushfires in streams that were considered to be drought-stressed and in poor or moderate conditions before the fire, than in streams considered to be in better condition (Frame et al., 2009).

4.2.1 Suspended sediment in relation to aquatic ecosystems

Biologically, the most significant impact of increased suspended sediment is on the primary producers (i.e. periphyton and aquatic macrophytes) because these organisms form the basis of the food chain (Spencer et al., 2003). Turbidity and sediment deposition can have direct impacts on aquatic fauna (e.g. clogging fish gills and insect food-filtering apparatus, and smothering benthos) and their physical habitat, leading to reduced population densities, changed species composition, increased mortality, invertebrate drift and altered fish migration patterns (as summarised by Ryan, 1991; Wood and Armitage, 1997). However, the impact on biodiversity is highly variable. This variability is attributed to a number of factors including the duration of impact (Ryan, 1991; Wood and Armitage, 1997), the sediment particle size (Bond and Downes, 2003; Earl and Blinn, 2003; Ryan, 1991; Wood and Armitage, 1997), the dispersal ability of the affected species (Ryan, 1991; Vieira et al., 2004), and the background sediment levels (Ryan, 1991).

Guideline values for suspended sediment in streams and lakes (ANZECC, 2000) are often exceeded following fire. For example:

- in the Upper Buckland River in north-eastern Victoria, turbidity values (129,000 NTU) were 5160 times the maximum guideline values for upland rivers (Section 1, ANZECC, 2000) following post-fire debris flows. Subsequent turbidity downstream in the Ovens River remained high. The peak

- in the Bendora Reservoir (ACT), turbidity values (3000 NTU at bottom of reservoir) were 150 times the maximum guideline value (see Section 1) for lakes/reservoirs following the 2003 fire and several storm events (White et al., 2006), and
- in Lake Glenmaggie in eastern Victoria, turbidity values of 1398 NTU were 70 times the maximum guideline value for lakes/reservoirs following post-fire debris flows in a tributary river (Victorian Water Resources Data Warehouse).

4.2.2 Nitrogen and phosphorus in relation to aquatic ecosystems

Elevated nutrient concentrations, particularly nitrogen and phosphorus, are key contributors to eutrophication, resulting in the enhanced growth of aquatic plants and algae (Chorus and Bartram, 1999; EPA Victoria, 2003; Spencer et al. 2003). Phosphorus is the major nutrient controlling the occurrence of algal blooms while nitrogen may influence the type of species present, since nitrogen-fixing species tend to dominate in the absence of nitrogen (Chorus and Bartram, 1999). Eutrophication can affect the normal functioning of aquatic ecosystems by, for example, favouring particular plant and algae species or reducing the amount of dissolved oxygen in the water. The implications of elevated nutrient concentrations for aquatic biodiversity may be more apparent in slower-moving streams, particularly during the dry season, where there is less capacity to flush nutrients from the system.

Examples of phosphorus and nitrogen levels in streams and lakes exceeding guideline values (ANZECC, 2000) following fire include:

- in sandstone terrain and dry eucalypt forest (near Sydney, NSW), post-fire maximum concentrations for TN were 99 times the guideline value and for TP were 125 times the guideline value (Wilkinson et al. 2006)
- in the Upper Buckland River following post-fire debris flows, maximum TN concentrations were 1640 times the guideline value and maximum TP concentrations were 5500 times the guideline value (Leak et al. 2003)
- in the Ovens River at Bright, upstream of the impact of post-fire debris flows, post-2003 fire maximum TN concentrations were 56 times the guideline value and TP concentrations were 145 times the guideline value. During the subsequent 2.5 years, TN and TP concentrations in the Ovens River at Bright exceeded the guideline values during all automatically sampled flow events (Figure 8), and
- in several reservoirs downstream of the Victorian 2006/07 fires, maximum TN concentrations were 1.3-4 times the guideline value and maximum TP concentrations were 1-7 times the guideline value (Goulburn-Murray Water Authority, 2008).

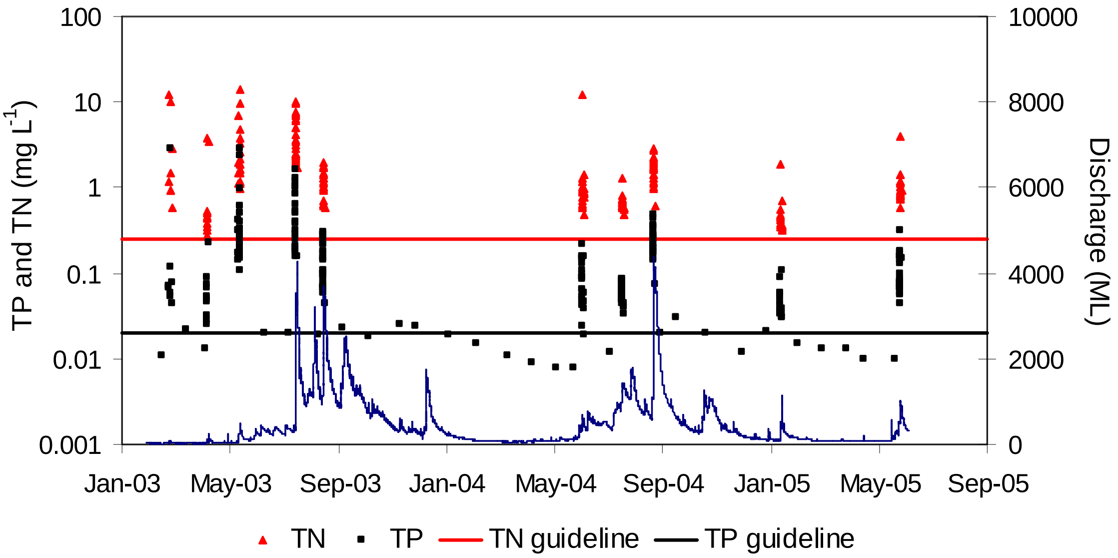

Figure 8: Comparing guideline values to total nitrogen and total phosphorus concentrations for the Ovens River at Bright (north-east Victoria) following the 2003 bushfires (data provided by North East Water).

4.2.3 Dissolved oxygen in relation to aquatic ecosystems

High levels of dissolved oxygen are important for maintenance of aquatic biodiversity. Very low levels of dissolved oxygen can cause fish death and macroinvertebrate drift, death or suppressed development. Macroinvertebrate drift and death were found to occur across most taxa under a naturally low dissolved oxygen (<10% saturation) regime (Connolly et al 2004). Sub-lethal effects such as suppressed emergence were also observed above this level (10-35% dissolved oxygen). From these observations, Connolly et al. (2004) concluded that macroinvertebrates can tolerate moderately low levels of dissolved oxygen for short periods but, in the long-term, it suppresses development and probably influences reproductive success, productivity and persistence at any given location.

Fish deaths were reported downstream of post-fire debris flows in the Ovens River in north-eastern Victoria where, as a result of the fire, extremely low dissolved oxygen levels were recorded (Lyon and O'Connor, 2008; EPA, 2004).

4.2.4 Cyanobacteria in relation to aquatic ecosystems

Aquatic organisms tend to be more tolerant to cyanotoxins than terrestrial organisms but toxic effects can still occur (WHO, 2008). Since blooms of cyanobacteria can also lead to the depletion of dissolved oxygen in the water (Chorus and Bartram, 1999), it is difficult to ascribe the deaths of aquatic fauna to cyanotoxins (WHO, 2008). Since cyanotoxins are known to bioaccumulate in aquatic vertebrates and invertebrates, there is considerable potential for toxic effects to be magnified in aquatic food chains. There is no specific guideline value for cyanobacteria for the protection of aquatic ecosystems.

4.2.5 Temperature in relation to aquatic ecosystems

Temperature affects the amount of oxygen dissolved in water, the rate of photosynthesis and the sensitivity of aquatic organisms to toxic wastes and disease. Unusually high or low temperatures can directly affect heat-sensitive species (Spencer et al., 2003). There are no guideline values for stream temperature and there is very little information on how fire affects stream temperatures. However, it is likely that some species are affected either during the passage of the fire or after the fire, especially if the riparian overstorey is burnt and results in reduced shading. For example, Spencer et al. (2003) found a number of dead fish in their study streams the day after a fire and suggested that higher water temperatures during the fire may have been the cause of death.

4.3 Recreation and aesthetics

From a post-fire recreational water use perspective, key concerns are suspended sediment, cyanobacteria and, to a lesser extent, contamination by metals.

4.3.1 Suspended sediment in relation to recreation and aesthetics

High concentrations of suspended sediment will affect the visual clarity of a water body. This is important for recreational use from both an aesthetic point of view and for safety reasons, since highly turbid waters may prevent swimmers from seeing obstructions beneath the surface. The ANZECC (2000) document provides no guidance on the tolerable amount of suspended sediment or upper limit of turbidity for acceptable recreational use or aesthetics. However, visual clarity for recreation would have been compromised in the examples cited above where the turbidity guidelines for aquatic biodiversity were greatly exceeded following fire (see Section 4.2.1).

4.3.2 Metals

Contamination of recreational water by trace metals can be an issue for both health and aesthetic reasons. There are less risks to health outcomes than for drinking water (section 4.1.3) because people tend to consume less water as part of their recreational activities (an estimated maximum of 100 mL being swallowed from recreational contact versus a daily intake of 2 L from beverages and cooking; ANZECC, 2000). In practice, for recreational use the guideline values are generally not exceeded. However, the guideline values signal potential concern in several recorded instances:

- in the Upper Buckland River in north-eastern Victoria following post-fire debris flows, maximum iron concentrations were 2467 times the guideline value, arsenic concentrations six times the guideline value, chromium concentrations were 18 times the guideline value, and lead 20 times the guideline value (Leak et al., 2003), and
- in the Ovens River in north-eastern Victoria following fire, North East Water (2003) recorded maximum iron concentrations 100 times the guideline value and lead concentrations 3.3 times the guideline value. In contrast, concentrations of arsenic, lead, copper, zinc and chromium were within guideline values for recreational use.

4.3.3 Cyanobacteria

Cyanobacteria blooms can impair the quality of water for recreation by reducing clarity, creating unpleasant odours and surface scum, and causing skin irritation, eye irritation and gastrointestinal problems (Chorus and Bartram 1999; ANZECC, 2000). As discussed previously, it is difficult to attribute a bloom to fire. However, the existence of blooms, where fire is likely to have been a contributing factor, certainly reduce the recreational use of these water bodies (e.g. Lake Glenmaggie, eastern Victoria).

4.4 Agriculture

Irrigation and livestock watering are the major agricultural uses of surface and groundwater in Australia. Key concerns for agricultural water quality after fire are suspended sediment, nutrients, metals, chloride, sulfate and cyanobacteria. Those constituents and their guideline values (ANZECC, 2000) are considered below in the context of fire-related impacts.

4.4.1 Suspended sediment in relation to agriculture

An important concern for agriculture following fire is the potential for dam sedimentation associated with increased sediment flux. In worst-case scenarios, farm dams may be completely filled by sediment washing down from burnt areas, resulting in lost productivity and costly excavation works. Suspended sediment may also damage water infrastructure (e.g. clog pipes and pumps) and floods, potentially exacerbated by fire, may wash away or damage irrigation infrastructure. Additionally, transport of particle-associated nutrients, metals and other contaminants into the water supply used for washing produce or for food processing are of potential concern. While there is no guideline for the acceptable amount of suspended sediment in water for agriculture, the requirements for aquatic ecosystems and drinking water may be used as a guide (see Sections 4.1.1 and 4.2.1).

4.4.2 Phosphorus and nitrogen in relation to agriculture

Excessive quantities of nitrogen in irrigation water can leach into groundwater and overstimulate plant growth, resulting in reduced yields (ANZECC, 2000). Nitrate and nitrite can be toxic to livestock, with nitrite being far more toxic than nitrate (ANZECC, 2000). The primary concern with phosphorus in irrigation water is that it may stimulate excessive algal growth, although it may be of value to cropping and pasture growth. For phosphorous and nitrogen, only one instance of guideline concentrations being exceeded has been reported and that was downstream of a post-fire debris flow in the Upper Buckland River in north-eastern Victoria (Leak et al., 2003). It therefore appears that nutrient guideline levels for agriculture are generally not exceeded following fire.

4.4.3 Metals in relation to agriculture

Many metals are essential for plant growth and animal health but elevated concentrations in water may be undesirable. Guideline values are provided for many metals in relation to both irrigation water and stock drinking water (Table 1). Based on the few studies available, these guideline values are rarely exceeded following fire. Some exceptions include the iron concentration in the Upper Buckland River in north eastern Victoria (Leak et al., 2003) following a post-fire debris flow, which was 74 times the guideline value for irrigation. In the same study, the lead concentration was found to be ten times the guideline value recommended for stock drinking water. In the Ovens River after fire, the iron concentration was three times the guideline value for stock drinking water (North East Water, 2003).

4.4.4 Cyanobacteria in relation to agriculture

The main problem with cyanobacteria or algal blooms in irrigation water is the blockage of pipes and pumps resulting in uneven flow throughout the irrigation system (ANZECC, 2000). Other concerns relate to the accumulation of toxin residues on irrigated lands and crops that may be an issue for human or animal health. There is no guideline value for cyanobacteria in relation to irrigation water since any health effects are secondary. In relation to stock drinking water, cyanotoxins may be toxic to stock.

4.4.5 Chloride and sulfate

Chloride can be an issue for irrigation water, resulting in foliar injury or increased uptake of cadmium from the soil (ANZECC, 2000). Sulfate can have adverse effects on stock water if the concentration exceeds 1000 mg L^{-1}, with chronic or acute health problems occurring above 2000 mg L^{-1}. Based on the few studies from overseas that examine chloride and sulfate concentrations, it seems that concentrations would not be expected to exceed guideline values as a result of fire (e.g. Mast and Clow, 2008; Gallaher et al., 2002; Carignan et al., 2000).

4.5 Industrial water

Water is used by a number of industries (e.g. mining, manufacturing, energy production and food processing) and each of these industries differs in their requirements for water quality. Probably as a consequence, ANZECC (2000) do not provide guideline values for industrial water. Industry users of water tend to be aware of the limitations and problems presented by raw water supplies and are generally knowledgeable about where they source their water and water quality requirements.

4.6 Cultural and spiritual values

The ANZECC Guidelines (2000) do not provide limits for water used for cultural and spiritual purposes, but the guideline values described in Section 4.3 for recreational and aesthetic uses of water in relation to bushfire impacts may be relevant.

4.7 Water resource infrastructure

Fire-related impacts on water quality could have implications for water resource infrastructure and for treatment processes. These impacts were outlined in the discussions about drinking water and agriculture, and can be summarised as:

- suspended sediment can reduce the storage capacity of dams and reservoirs and clog pipes and pumps. Thus, high sediment loads can affect the distribution of water and the amount of water available (ANZECC, 2000). Suspended sediment may also shield some micro-organisms from disinfection (NHMRC, 2004). High turbidity was the principle reason for shutting off the supply of water from the Bendora Reservoir following the 2003 fires given the absence of treatment facilities other than chlorination (White et al., 2006)
- metals at higher concentrations can cause blockages and corrosion (e.g. iron), staining (e.g. iron, manganese and copper) and post-flocculation problems (NHMRC, 2004). Although the guideline value for manganese is 0.1 mg/L, even concentrations as low as 0.03 mg/L can cause reticulation problems associated with build-up of manganese slimes (NHMRC, 2004)
- chloride and zinc may affect the taste of water (NHMRC, 2004)
- algal blooms can block pipes and pumps, and
- excessive debris build-up in streams following fire poses a risk to infrastructure such as bridges (Department of Sustainability and Environment, 2008).

Recent disruptions to the operation of water supply infrastructure as a result of bushfires have resulted in water restrictions and water carting for several communities in south-eastern Australia. For example, communities dependent on Lake Glenmaggie in Victoria for their water supply had to resort to water carting following the 2006/07 fires and ACT residents were required to adopt strict water restrictions when the Bendora Reservoir was contaminated following the Canberra fires in 2003.

5 Management actions

Management actions to mitigate the risks posed by bushfires to water quality require that consideration be given to actions before, during and after fire. The proposed measures focus on the protection of water resources and the many values they represent, and are intended to highlight the importance of minimising the disturbance impact from large unplanned fires.

5.1 Before the fire

Fire prevention and preparedness activities that aim to reduce the likelihood of bushfires and improve the success of suppression may also reduce the likelihood of adverse impacts on water quality. For example, effective fuel reduction burning in and around catchment areas lowers the amount of fuel available for bushfires. The resultant landscape mosaic may reduce the potential for bushfires to spread across large areas and improves the effectiveness of suppression tactics (Department of Sustainability and Environment, 2009). Measures such as fuel-reduction burning in water supply catchments present a management challenge with the need to reduce the impact of wildfire while maintaining some cover to protect the hydrological integrity of catchments. However, fuel-reduction burns generally have considerably less impact on water quality than large unplanned bushfires because they are mostly less severe and riparian vegetation is less likely to be burnt (Smith et al., 2010).

Another fire preparedness activity that may have a positive outcome for post-fire water quality impacts is the construction of fuel breaks. In Victoria, 600 km of fuel breaks are being constructed around Melbourne's water supply catchments (DSE, 2008). These breaks, while in part designed to limit the spread of a bushfire, have the primary purpose of providing a safe and effective area from which back-burning can be undertaken to protect the water supply catchments during a major bushfire (Department of Sustainability and Environment, 2008).

Water authorities also need to consider undertaking risk assessments based on catchment attributes and erosion potential to identify townships with water supplies that might be most vulnerable following a bushfire. This would enable the development of pre-fire contingency plans to allow for a more rapid response in managing adverse water quality outcomes following fire. This planning could be expanded to include actions taken before, during and after a bushfire event. Development of integrated fire and water quality risk management plans prior to the occurrence of fire would enable better coordination of management actions designed to mitigate post-fire water quality impacts. Such plans may also incorporate a communication strategy to inform stakeholders of actions after a fire as well as outlining a post-fire monitoring phase to determine the effectiveness of rehabilitation procedures.

5.2 During the fire

During bushfires, it is important that fire-fighters adhere to best practices and local standards for construction of mineral earth breaks and the application of fire retardants and fire suppressant foams (BAER, 2009). In Victoria, codes of practice (e.g. Department of Sustainability and Environment, 2006) already specify that control lines should not be constructed in stream beds and riparian zones and it is common practice to avoid using fire retardants and fire suppressant foams near waterways (Boulton et al., 2003). Other actions that may assist in achieving best practice include:

- minimising the use of bulldozers – use hand crews wherever viable, provide access to the fire via helipads rather than bulldozer trails to minimise land disturbance
- the use of a resource advisor to coordinate with bulldozer managers to minimise environmental impacts, in particular those that may impact on runoff water quality
- using GPS units in all bulldozers to track the location of bulldozer lines – this may facilitate more rapid land rehabilitation after fire
- rehabilitating temporary control lines as soon as possible
- minimising fire impacts in riparian zones during fuel-reduction and back-burning operations, and
- avoiding the use of fire retardants and foams near waterways and sensitive wetlands or in riparian zones.

5.3 After the fire

There are numerous actions that may be taken after a fire to reduce the risk of post-fire storms impacting on water quality. Most importantly, and where possible, managers need to act quickly to prepare an area before rain and particularly before intense rain. A critical starting-point is to assess the impacts of the fire and then prioritise rehabilitation works. Areas that might be most susceptible to erosion and areas that might afford most protection to drainage lines would sensibly be prioritised for remediation, where feasible. Agencies usually develop a rehabilitation plan (e.g. Department of Sustainability and Environment, 2003; Frame et al., 2009) which covers rehabilitation for a number of purposes, including protecting water quality. In the US, a special taskforce, comprised of multiple Burned Area Emergency Response (BAER) teams, is responsible for undertaking rapid post-fire assessments. The advantage of having teams already assembled and dedicated to this task is that the response is more rapid. The BAER team risk assessment involves (BAER, 2009):

- identifying post-fire changes to soil properties (water repellency, soil infiltration) that affect hydrologic function
- identifying risk areas for post-fire flash flooding or debris flows
- mapping soil burn severity[2] and bulldozer lines
- identifying sediment source areas and estimating erosion potential, and
- identifying potential threats to human life, property and critical natural and cultural resources.

The types of management actions taken after the initial risk assessment will depend on the risks identified and the feasibility of adopting these actions in a timely manner. The first management action is often to rehabilitate fire control lines (e.g. Department of Sustainability and Environment, 2003). This reduces the supply of sediment to waterways. Works include returning logs, branches and debris to the breaks, cross-draining and replanting. Following the 2003 alpine fires in Victoria there were about 9000 km of control lines to rehabilitate (Dunkerley et al., 2009). Other management actions that need to be considered include:

- erosion mitigation works (e.g. mulching, revegetation and bank stabilisation) and sediment control measures (e.g. straw bales, silt fences, rock walls, log barriers, de-silting of weirs, sediment curtains and booms, and coir logs in drainage lines) (Frame et al., 2009). Riparian buffer areas should be a focus for these management actions to reduce sediment delivery to streams
- water quality monitoring to ensure that mediation measures are effective in reducing water quality impacts (Frame et al., 2009; Department of Sustainability and Environment, 2003; BAER, 2009)
- establishing alternative water distribution plans to protect infrastructure and water supplies from ash and sediment flows (BAER, 2009)
- removal of debris from streams immediately adjacent to bridges to facilitate the passage of flood flows and minimise damage to infrastructure (BAER, 2009; Frame et al., 2009; Department of Sustainability and Environment, 2003)
- rehabilitation of road drainage to help minimise sediment laden runoff (Frame et al., 2009)
- construction of debris basins to capture sediment and debris flows (BAER, 2009). This was recommended by the BAER team in Marysville following 2009 Victorian bushfires to protect assets from such a potential threat
- public warnings of potential dangers from flash flooding and debris flows (e.g. installation of flood warning signs, door knocks and letter drops) (BAER, 2009), and
- provision of technical advice and support for farmers and rural residents whose water sources may be affected by sediment and ash transported in runoff from burnt areas (BAER, 2009).

Not all of these measures may be feasible and there are instances where the scale of geomorphic processes may simply overwhelm protective infrastructure that, in the absence of fire, is provided by landscape vegetation. However, all these measures require careful consideration in terms of their potential to mitigate the impact of post-fire storms on water quality, which may limit some of the consequences fires have for the various uses and values of water.

[2] Soil burn severity is not the same concept as fire intensity or fire severity. Soil burn severity relates specifically to effects of the fire on soil conditions (e.g. the amount of surface litter and duff, infiltration rate, erodibility and soil structure) (BAER, 2009).

6 Knowledge gaps

Knowledge gaps which further research could address include:

- *Poor knowledge of the impacts of fire on water quality outside south-eastern Australia*. Most research to-date has focussed on New South Wales, Victoria and Tasmania, with other regions, such as south-west Western Australia and northern Australia, receiving little attention. Research examining fire impacts on water quality should be made a priority in these other jurisdictions.
- *Limits to understanding fire effects on water quality in south-eastern Australia*. This region is where the impacts on water quality are likely to be greatest and where the largest number of communities may be affected. Since the steep, forested highland areas in central Victoria and NSW are particularly prone to large, severe bushfires, an expanded knowledge of the range in magnitude and duration of post-fire water quality effects in this region would greatly improve the ability to predict the likely impacts following future fires.
- *Little knowledge about specific water quality impacts beyond sediment and nutrient export from burnt catchments*. There is a lack of information on the impact of fire on concentrations of metals, organic carbon, salts and other constituents. An expanded stream and reservoir monitoring program that includes measurement of these constituents, as well as sediment and nutrients, would greatly improve our knowledge of post-fire water quality impacts. The role of reservoirs as sinks for contaminants released into streams after fire should also be investigated to determine the fate of these contaminants and their impact on longer-term reservoir water quality. In addition, further research into the potential effects of fire retardants and fire suppressant foams on water quality is required.
- *Limited understanding of post-fire erosion and hydrological processes across different forest environments and burn severities*. Research to identify areas most at risk of large post-fire erosion events and water quality impacts is required. The development of predictive models to quantify the risk to water quality in affected catchments is also urgently needed.
- *Poor identification of the sources of key constituents within burnt catchments*. Determining the primary locations for erosion after fire would offer considerable benefit to catchment managers when attempting to mitigate water quality effects, particularly where drinking water supplies are vulnerable to contamination. Techniques are available which enable the identification of relative contributions from different sources (such as hillslopes or channels) of sediment and sediment-associated contaminants. Application of these techniques to burnt catchments would enable a more targeted approach to post-fire rehabilitation.
- *The effectiveness of erosion mitigation measures in Australia has received limited attention*. Given the threat fires pose to high value water supply assets, greater investment in erosion mitigation and control measures should be the subject of active investigation. Research is needed to understand what treatments are most effective and to trial various techniques in burnt environments that differ to regions in the USA, where much of this type of work has previously been undertaken.

7 Key findings and conclusions

This review critically examines the Australian literature on the impact of bushfires on water quality. A core focus is on the uses or values of water and how fire-related changes to water quality may impact upon these values. Overall, it finds that water quality values are threatened especially in respect to suspended sediment, nutrients and metals. The key issues identified are:

- **Drinking water**: Elevated levels of suspended sediment, nutrients and metals, as well as possible cyanobacteria blooms are of most concern. For other constituents, notably sulfate, chloride, organic carbon, cyanide, PAHs, PCDDs/Fs and PCBs, post-fire maximums generally do not exceed guideline values. However, with a limited number of water quality studies available, there remains considerable uncertainty regarding post-fire levels.
- **Aquatic ecosystems**: Extremely high levels of turbidity and low dissolved oxygen concentrations resulting from export of fine sediment and organic matter present the greatest threat. Other adverse aquatic ecosystem impacts may be attributed to increased water temperatures and increased inputs of nutrients.
- **Recreation and aesthetics**: Suspended sediment and cyanobacteria are probably of most concern.
- **Agriculture**: High loads of suspended sediment and, to a lesser extent, nutrients, metals and cyanobacteria may have potential impacts on water quality values. Chloride and sulfate levels appear to remain well within the guideline value limits.
- **Cultural and spiritual values**: While there are no specified guideline values, the perceived concerns are likely to be similar to those for recreation and aesthetics.
- **Industrial water**: There are no guideline values for industrial water but sediment, nutrients and metals are of potential concern for food processing.
- **Water resource infrastructure**: High loads of suspended sediment, metals, chloride and algal blooms are a concern for water resource infrastructure, particularly for irrigation systems and water treatment infrastructure. A greater threat is probably that of increased flooding damage.

These findings highlight the importance of high magnitude and high intensity post-fire rainfall events. Numerous studies have shown that high intensity rainfall events may result in the largest water quality impacts after fire. Various factors following fire contribute to water quality impacts (such as the loss of vegetative cover, low infiltration rates, very intense rain and steep terrain). Suspended sediment, nutrients and metals are of particular concern to water quality. These impacts can occur large distances downstream of the source and last for weeks or up to several years.

Finally, the report considers management actions that can be taken before, during and after a fire to minimise the impacts on water quality, including:

- **Before the fire:** preparations to reduce the risk of fire in the water supply catchments (such as fuel-reduction burning and the construction of fuel breaks) as well as risk assessments to identify townships whose water supply is most vulnerable were a bushfire to occur.
- **During the fire:** adherence to best practice and local standards in relation to the construction of mineral earth breaks and the application of fire retardants.
- **After the fire:** immediate deployment of resources to make a rapid assessment of the burnt area to identify priorities such as the rehabilitation of control lines and establishment of sediment control measures, erosion mitigation works and water quality monitoring.

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