Department of Climate Change, Energy, the Environment and Water

dcceew.nsw.gov.au

NSW GOVERNMENT

Impacts of bushfires on freshwater ecosystems and potential water management options

A literature review

January 2024

Acknowledgement of Country

The Department of Climate Change, Energy, the Environment and Water acknowledges that it stands on Aboriginal land. We acknowledge the Traditional Custodians of the land and we show our respect for Elders past, present and emerging through thoughtful and collaborative approaches to our work, seeking to demonstrate our ongoing commitment to providing places in which Aboriginal people are included socially, culturally and economically.

Published by NSW Department of Climate Change, Energy, the Environment and Water

dcceew.nsw.gov.au

Impacts of bushfires on freshwater ecosystems and potential water management options

First published: June 2024

Department reference number: DOC24/7396

Copyright and disclaimer

TMP-MC-R-DC-V1.2

Table of Contents

Executive summary

Purpose statement

The purpose of this document is to review the published literature on the effects of bushfires on aquatic ecosystems and to develop potential strategies to aid in the recovery and resilience of waterways to fires. Potential management strategies are explored in the form of possible Water Sharing Plan rules that may be able to provide increased bushfire protection or ecosystem resilience.

Key findings

Research shows that moderate and low intensity fires do not pose a significant threat to aquatic ecosystems unless during periods of extreme drought, when the water quality of river refuge pools may already be at critical levels. However, severe and extreme bushfires can pose a significant risk to aquatic ecosystems, particularly when followed by large rain events. In these events, effective management options could include cease-to-pump rules during fire periods to increase the resilience of riparian vegetation, ensure longitudinal connectivity to allow fish movement away from fire-affected areas and maximise flow velocities to reduce sedimentation and disperse sediment and debris downstream.

Introduction

Australian summers are becoming hotter and drier, and hence the fire season longer (Tran et al., 2020). Consequently, bushfires are predicted to become more frequent and more severe in many parts of Australia (Tran et al., 2020; IPCC, 2021). Whilst the palaeoecological record indicates extreme fire such as the 2019–2020 bushfires are rare, climate change is creating unprecedented conditions with areas that have never or very rarely burned experiencing significant bushfires (Black and Mooney, 2006; Mooney et al., 2011; Graves et al., 2019). The increasing occurrence of bushfires in Australia is threatening the integrity of freshwater ecosystems and the sustainability of the services they provide. Developing strategies to aid the resilience and recovery of aquatic ecosystems during and after fires is becoming increasingly important for effective river management.

As the intensity of a bushfire increases, so does the severity of its ecological impacts (Smith et al., 2011). Fires often occur during droughts when the water content of fuel loads and soils are already low, compounding the impacts on an already stressed aquatic system. Typically, high intensity fires followed by heavy rainfall events cause the most severe effects on aquatic ecosystems. These effects occur over a range of spatial (local habitat to entire catchments) and temporal (days to decades) scales. Often the most acute impacts of fires occur within the first few weeks post-fire. The effects of bushfires are many, and may alter the water quantity, riparian vegetation, geomorphology, water quality and biodiversity of waterways.

Bushfires modify the quantity of water entering rivers. Initially after fires, the amount of rainfall run-off entering rivers is greatly increased compared to pre-fire conditions. This increased run-off is caused by a combination of processes such as: the fires impact on soils, the loss of catchment vegetation and, reduced forest drawdown on the water table. This initial change in runoff after bushfire can exacerbate geomorphic and associated water quality impacts. In the long-term (years to decades), annual streamflow may decrease by up to 25% (or 50% in extreme cases) compared to pre-fire averages as forests simultaneously regrow, drastically increasing drawdown on river water (Cornish and Vertessy, 2001). However, the level of streamflow reduction is variable and highly dependent on the composition of species in the vegetation community, the amount of catchment burnt and severity of the burn (Benyon et al., 2023).

Bushfires affect the composition, structure, canopy cover and regenerative capacity of riparian vegetation (Douglas et al., 2015). High intensity fire can also lead to tree death and the collapse of the trees, effectively removing them from the riparian zone. These changes to the structure and function of riparian vegetation affects several processes in aquatic ecosystems including increasing erosion and sedimentation, decreasing water quality, and reduced habitat availability (Rice et al., 2012; Verkaik et al., 2013; Bixby et al., 2015). Steep declines in riparian canopy cover may increase rainfall run-off and in-stream light availability. Changes to light and water quality impact in-stream primary productivity and can increase macrophytes, benthic algae growth and the likelihood of cyanobacterial blooms. The impacts of bushfires on riparian vegetation typically occur immediately following fires however can last for several years to decades post-fire.

Burnt landscapes are highly sensitive to erosion, particularly during rainfall. Increased erosion and subsequent sediment deposition into waterways caused by bushfires is a major pathway for the degradation of aquatic ecosystems. Increases in post-fire erosion vary between 10 and 1000 times the pre-burnt state with rainfall and post-fire flow pulses playing a major role in increasing erosion levels. As erosion increases, the amount of sediment mobilised by eroded landscapes greatly increases, leading to changes in the morphology and heterogeneity of riverbeds with sedimentation a key cause in the degradation of in-stream habitat. These changes to river form may take years to recover. Sediment slugs caused by erosion may lead to fish kills and the smothering of riverbeds and habitat as they move downstream of burnt areas, expanding the effects of a bushfire kilometres downstream of the burn.

Bushfires can severely degrade river water quality (Robinne et al., 2020). Sediment, ash and debris from burnt areas affect both the physical and chemical make-up of riverine waters. In the days to weeks following high intensity bushfires, turbidity, suspended sediments, nutrients, organic carbon, metals and ions have all been found to increase drastically, with phosphorus and nitrogen recording respective increases of 450 and 100 times pre-fire levels (Sheridan et al., 2007; Smith et al., 2011;

Johnston and Maher, 2022). Dissolved oxygen, pH and salinity have all been found to exceed survivable thresholds for aquatic biota following fires, with in-stream anoxia being commonly reported for >12-hour periods. In the longer-term, concentration to discharge relationships for nutrients and organic carbon, in-stream phosphorus dynamics and nutrient and sediment loads have all been found to be significantly higher than long-term monthly averages and take several years to recover to pre-fire levels (Smith et al., 2011; Baldwin, 2022; Johnston and Maher, 2022). These changes to water quality may affect in-stream productivity, ecosystem processes, habitat availability and may surpass survival thresholds for aquatic biota.

Riverine biodiversity is underpinned by a healthy ecosystem. Bushfires affect riverine biodiversity through several different processes; by directly causing mortality due to heat, anoxia or turbidity; indirectly through loss of habitat, food resources and physiological stress; and by a failure to successfully breed and/or recruit due to changes in breeding habitat and flow regimes (Vieira et al., 2004; Rodríguez-Lozano et al., 2015; Dahm et al., 2015; Sherson et al., 2015). Adverse water quality caused by ash, sediment and contaminants from fires have been found to cause steep declines in benthic macroinvertebrate abundance (Vieira et al., 2004) and mass fish kills through anoxia and turbidity (Da Silva et al., 2020). Fish populations in burnt reaches have been found to decline by 90-100% with fish stocks taking up to 3 years to recover (Lyon and O'Connor, 2008; Serena et al., 2022). Severe impacts to the growth, reproduction and death rates of aquatic biota have also been attributed to the combined effects of sedimentation and poor water quality post-fire (McInerney et al., 2020).

Semi-terrestrial animals such as platypus and turtles may be more resilient to bushfires due to their ability to avoid anoxic conditions and potentially move to areas of better water quality. However, loss of food resources, such as macroinvertebrates, plus sediments smothering habitat, may still lead to significant negative impacts to platypus and turtle populations, including the mortality of individuals. The response of frog populations to bushfires is highly species dependent. However, abundance, metacommunity occupancy and species richness have all been found to decline following severe bushfires (Hossack and Pilliod, 2011; Beranek et al., 2023), with local extinction events also recorded (Lemckert, 2000). Changes to the availability of shelter, breeding habitat and the number of refuges in-stream or in riparian vegetation may also cause lagged declines in frog populations (Hossack et al., 2013).

Currently, there are no strategies or policy options (within the Regional Water Strategy, NSW-Water Strategy or extreme events policy) that directly address bushfires. However, several mention the impacts of climate change and drought. A risk assessment in Victoria has recently added the impacts of bushfires as risks to water availability. The Natural Resource Commission has made several recommendations to the Water Group in the NSW Department of Climate Change, Energy, the Environment and Water (the Water Group) around monitoring, evaluating and reporting, flow provisions and collaboration to address some of the most severe impacts of bushfires on waterways. The aim of this review is to collate information on the impacts of bush fires on riverine systems and identify potential adaptive management options to improve management of rivers post fire events in NSW.

Impacts of bushfires on aquatic ecosystems

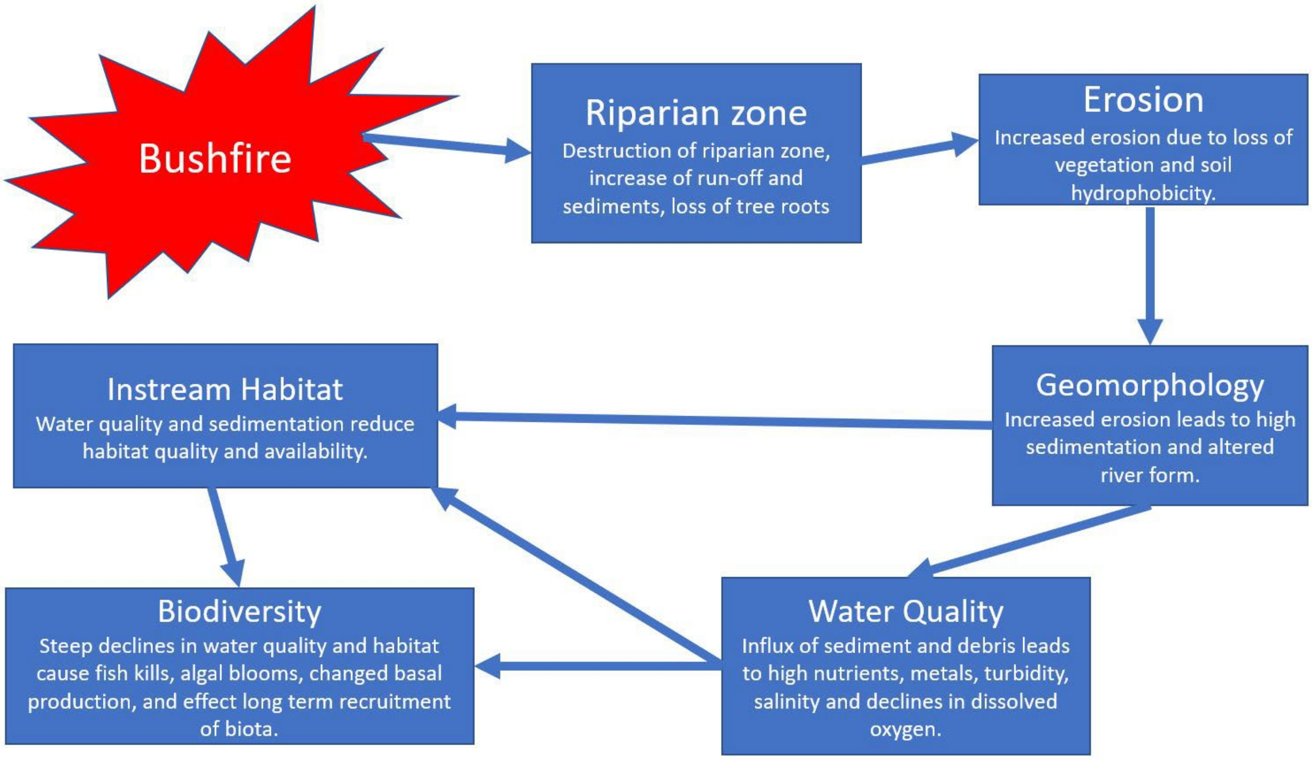
Under climate change, summers are becoming hotter and drier, resulting in longer fire seasons (Abram et al., 2012). Bushfires are predicted to become more frequent and more intense in many parts of Australia (Tran et al., 2020; IPCC, 2021). The increasing occurrence of bushfires in Australia is threatening the integrity of freshwater ecosystems and the sustainability of the services they provide. Drought and extreme temperatures contribute to the dryness of the landscape, which makes rainforest and riverine vegetation more prone to combustion (Abram et al., 2021). Bushfires have an extensive set of complex impacts on aquatic systems from changed nutrient dynamics to large scale fish kills and habitat loss. These impacts span across a range of temporal scales, from the immediate and temporary, to long-term disturbances that last years to decades (Bixby et al., 2015; Rhoades et al., 2011). Similarly, the impacts of bushfires occur over a range of spatial scales from local ecosystems and specific aquatic habitat to entire catchments. The variation and magnitude of the effects a bushfire may have on an aquatic ecosystem is often attributed to the severity of the fire which is related to catchment characteristics such as antecedent rainfall and vegetation density. The following shows how fire severity can be classified for terrestrial environments (Santin et al., 2015):

- Low fire severity: ground and understory (<0.5 m high) fuels burnt. Canopy unaffected.
- Moderate fire severity: ground and understory (<4 m high) fuels burnt. Canopy unaffected.
- High fire severity: ground and understory (<4 m high) fuels burnt. Canopy scorched.
- Very high severity: all available fuels consumed, including stems <0.5 cm thick.
- Extreme fire severity: all available fuels consumed, including stems <1 cm thick.

Several reviews and empirical research into the impacts of bushfires in Australia and internationally, show consistent patterns into the effects of fires on freshwater ecosystems (Smith et al., 2011, Dahm et al., 2015, Johnston and Maher, 2022,). Water quantity, geomorphology, water quality and biodiversity have been identified as highly affected areas of concern during and after bushfires. Rain events immediately following fires also play a large role on the influence of a bushfire on aquatic ecosystems. Large rainfall or flow events drastically increase erosion, sedimentation and mobilisation of nutrients and ash into the water column, resulting in immediate impacts on biota (for example, fish kills), changes to habitat and impacts on water quality that may persist for several years (DELWP, 2020; Silva et al., 2020).

The following sections review key findings in the scientific literature around each major factor affecting freshwater systems. Significantly, all these factors may interact following a bushfire (Figure 1), which may increase the severity of the associated impacts.

Figure 1: Example of interacting effects of bushfires on aquatic ecosystems

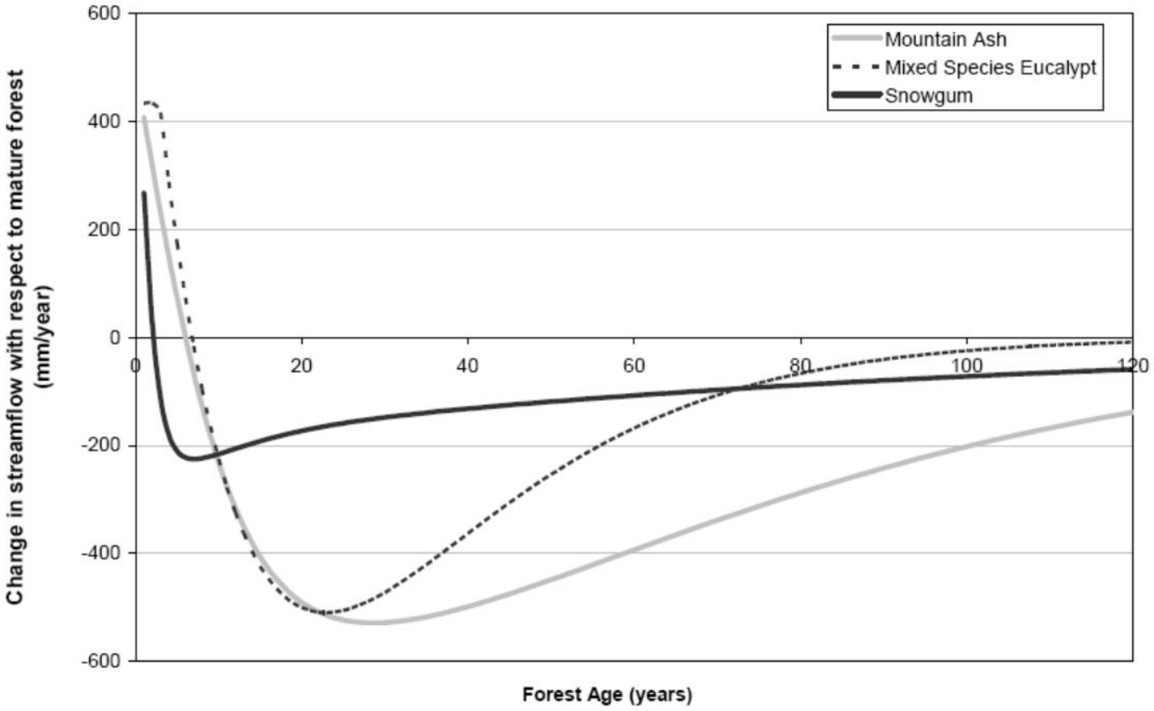


Water quantity

Bushfires modify the quantity of water in rivers through changes to vegetation growth, evapotranspiration, interception and soil moisture storage (Robichaud, 2000; Shakesby and Doerr, 2006). In the short-term post fire, water quantity may increase due to increased runoff caused by the loss of vegetation, soil hydrophobicity (when soil repels water rather than absorbs it) and reduction in plant transpiration (Lane et al., 2006; Murphy et al., 2018). Post-fire runoff has been found to increase by several orders of magnitude relative to pre-burn conditions (Shakesby and Doerr, 2006, Shakesby, 2011). A study in the Kiewa Valley, Victoria found moderate increases in runoff (40-95% increase) in eucalypt forests, and these increases in run-off persisted for up to 2 years post-fire (Lane et al., 2006). Temporarily altered hydrologic flow paths caused by erosion may also have a significant effect on the levels of run-off and water quantity following a large bushfire event (Murphy et al., 2018). Increased run-off and significantly larger flow peaks are likely to persist for months after bushfires until vegetation regrows and soil hydrophobicity reduces to levels similar to pre-burn. Significantly, while water quantity may increase following bushfires, the quality of this water may be extremely low (*see* Water quality *subsection*) and thus, water availability may decrease despite higher total flows.

In the longer-term, water quantity in bushfire-affected areas is likely to decrease as forested areas regrow. Young trees consume considerably more water than mature vegetation, coupled with the simultaneous regrowth of forested areas and soil nutrient loads greatly increasing total leaf area, the drawdown on available water in affected areas can be significant (Cornish and Vertessy, 2001). The effects of forest regrowth on water quantity can occur approximately 5 to 30 years after a fire with some models suggesting inflows will not return to pre-burn levels for up to 90 years post-fire (SKM, 2008; Figure 2). An extreme example of this reduction in streamflow is from the Black Friday fires in Victoria in 1939. In that fire, mature Mountain Ash (*Eucalyptus regnans*) forests were severely burned. Over the next 30 years, water yield from local areas of regrowth diminished by up to 600 mm/year. On a catchment-wide basis, where regrowth occupied some 50% of the area, this represented a reduction in annual streamflow of about 25% (Vertessy et al., 1998). Similarly, a bushfire in 2006/2007 in mixed species eucalypt forest around the Gippsland Lakes, Victoria, resulted in an estimated maximum reduction of inflows between 530 and 730 GL/year, constituting 18-24% of average yearly inflows (SKM, 2008). Such significant reduction in streamflow has implications for water availability for the environment and downstream water users.

Figure 2: Change in discharge as forested area recovers from fire (Sinclair Knight Merz, 2008)



The severity of post-fire declines in water availability is directly related to the percentage of total catchment burned, severity of the burn and tree species present within the burnt forest. Previous research shows Ash forests consume much more water during regrowth and greatly reduce water availability compared to more fire tolerant Eucalypt forests which may only have mild effects on streamflow (Gharun et al., 2013; Nolan et al., 2014). The Kuczera curve (Kuczera, 1987) was developed to model the impacts of forest disturbances such as bushfires and clearing on river streamflow. While the Kuczera curve applies to streamflow declines related to mountain ash bushfires, it may be highly inaccurate for other forest types (Benyon et al., 2023). Research into the long-term hydrological impacts of bushfires on different forest types is required to build more robust models for predicting these impacts. Burnt areas of low or zero forest cover are likely to have negligible impacts on the hydrology of a river, particularly in the long-term.

Aquatic ecosystems where bushfires are rare may be more impacted by the long-term alteration of flow regimes caused by fires than more fire prone environments. It is likely the long-term hydrological impacts of these fires will be more pronounced and potentially have long-term impacts on in-stream biotic communities less adapted to reduced or variable flow conditions. Similarly, downstream water users and local communities may be more impacted by long-term reduction in water availability in areas where bushfire occurrence is rare.

Riparian vegetation

Riparian vegetation forms the interface between terrestrial and aquatic ecosystems, influencing hydrology, geomorphology, sediments, light, temperature, organic matter, and biota (Naiman et al., 2005). Bushfires affect the composition, structure, and regenerative capacity of riparian vegetation. Previous research has found bushfires reduce the species richness, total abundance (particularly of small and medium sized trees) and total basal area of woody species as well as overall canopy cover in the riparian zone (Douglas et al., 2015). Fires also reduce seed production of some riparian eucalypts, increase grass cover in burnt areas and can reduce overall species richness by up to 50% compared to unburnt areas (Douglas et al., 2015). Previous research has found high intensity burns significantly reduced riparian vegetation cover for more than 5 years post-fire, whereas areas of low intensity burns were indistinguishable from unburnt areas (Jackson and Sullivan, 2009). The extent that bushfires impact riparian vegetation is dependent on factors such as the degree of fire resistance in the riparian flora, environmental conditions such as soil type, moisture and topography, and the frequency and intensity of bushfires (Pettit and Naiman, 2007, Verkaik et al., 2013). Antecedent weather also plays a significant role with drought and extreme temperatures affecting the dryness of the landscape and preventing certain fire-sensitive species from growing to maturity and reproducing, leading to irreversible changes in riparian ecosystem structure (Abram et al., 2021; Gallagher et al., 2021).

Changes to the structure and function of riparian vegetation caused by bushfires alter the hydrology, channel morphology, sediment delivery and habitat availability of aquatic ecosystems (Rice et al., 2012; Verkaik et al., 2013; Bixby et al., 2015). These changes typically occur within the first few weeks following a wildfire, however, can last for years to decades and have ongoing consequences for the bordering aquatic systems. Riparian vegetation plays a critical role in reducing bank erosion and intercepting sediments from run-off (Pettit and Naiman, 2007). Thus, erosion, sedimentation and their subsequent impacts on water quality may be closely linked to riparian vegetation degradation and recovery. Steep declines in riparian canopy cover due to fires result in decreased interception of rainfall and consequent increases in run-off (Lane, 2006; Smith et al., 2011). Further, loss of canopy cover results in increased in-stream light availability, promoting increased benthic algae, macrophyte production and cyanobacterial blooms, particularly when coupled with increased nutrient loads (Klose et al., 2015). Leaf litter is an important source of nutrients, organic matter and habitat for primary producers, macroinvertebrates and fish (Jardine et al., 2012, Douglas et al., 2015). Substantial losses in leaf litter may therefore affect riverine productivity and resource availability until the riparian zone has recovered. Fire intensity and the timing and magnitude of post-fire run-off define the extent to which fire-induced changes to riparian vegetation affect in-stream processes (Shakesby, 2011).

Geomorphology

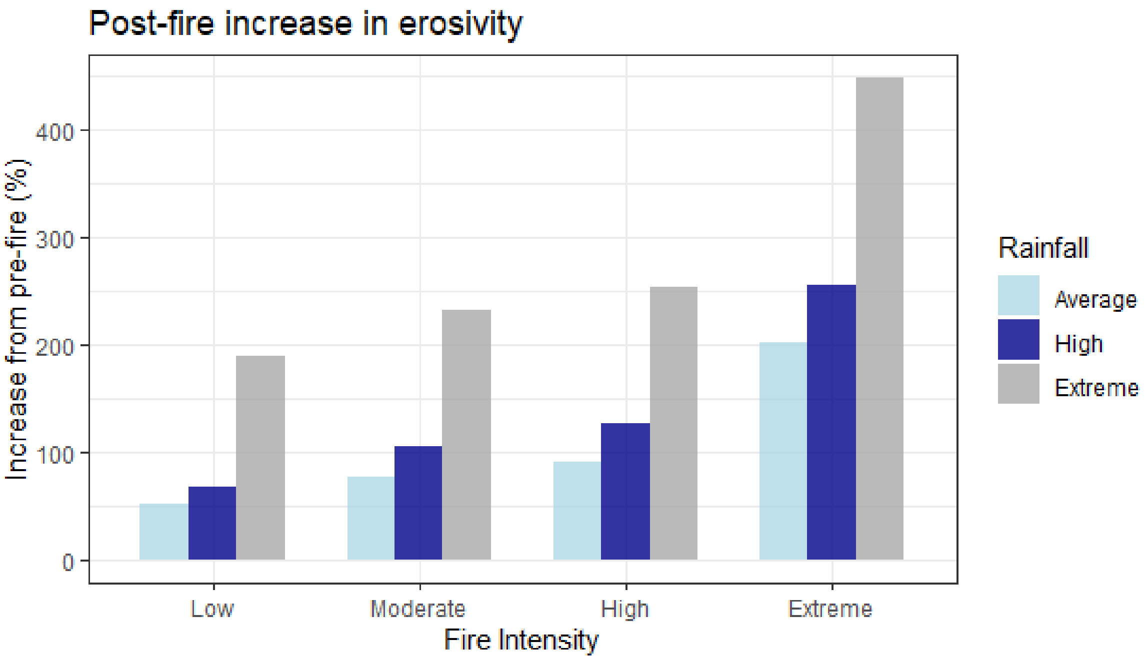
Sharp increases in run-off, clearing of vegetation and hydrophobicity of soils all lead to increased levels of erosion following bushfires. High-intensity bushfires expose soil surfaces and change soil structures, further increasing erosion around riverbanks and gullies (Blake et al., 2020). The magnitude of the increase in erosion relative to the unburned state is highly variable, ranging from 10 to 1000 times the background levels (Smith et al., 2011). Factors such as the nature of the terrain, geological basement and soil profiles, fire regimes and the frequency of intense rainstorms all contribute to high variability from region to region (Nyman and Sheridan, 2014). After fires, erosion, sedimentation and the consequent effects on river geomorphology, water quality and biodiversity remain elevated until catchment vegetation regenerates (Neris et al., 2021).

A combination of rainfall regime, slope, slope length and certain lithology/soil matrices increases the volume of hillslope sediment transported to rivers (Nyman et al., 2013). Catchment erodibility varies by slope and slope length initiated by moderate to high runoff (Prosser and Williams, 1998; Biswas et al., 2021). Local lithology may provide more readily transported sediment and increase sedimentation in river channels within and downstream of bushfire affected areas.

Intensive rainfall on recently burned catchments can trigger especially large increases in erosion and sediment transport into waterways (Yang et al., 2020; Neris et al., 2021), causing fish kills and extreme declines in water quality. Exposure of bars and inset floodplain strips resulting from bushfires greatly increases the risk of erosion when subsequent floods scour along bushfire affected channels. This erosion in turn causes river channels to enlarge, increasing the hydraulic conveyance of floods and increasing shear stress on riverbanks, benches and floodplain strips. Channel expansion and removal of channel roughness causes greater rates of erosion than along unburned rivers (Nyman and Sheridan, 2014).

Fire severity also affects the level of erosion following a fire, combined with an extreme rainfall event such as that following the 2019/2020 fire, erosion may increase by up to 450% compared to pre-fire conditions (Yang et al., 2020; Figure 3). Excluding extreme rain events, the highest sensitivity to erosion is typically during initial flow events following fires, particularly during/after drought conditions.

Figure 3: Percentage increase of mean erosion rates at different fire intensities and rainfall levels (adapted from Yang et al., 2020)



Previous studies have found specific river styles to be the most at risk of burning and high geomorphic degradation following fires. The most frequently affected rivers in Australia are in confined bedrock valleys (38% of stream length burnt; Fryirs et al., 2021) as these river types are most commonly found in highland forested areas that are prone to devastating bushfires. Unconfined rivers with discontinuous channels that normally contain wet or saturated ground have also been highly impacted by fires across Australia (18% of stream length). Approximately 17% of stream length burned along partly confined rivers with discontinuous floodplain pockets. Laterally unconfined rivers with continuous channels were the least affected, accounting for 7% of total stream length burned, as these rivers lie on coastal or inland plains with much smaller proportions of stream length lying in bushland (Fryirs et al., 2021; Fryirs et al., 2022).

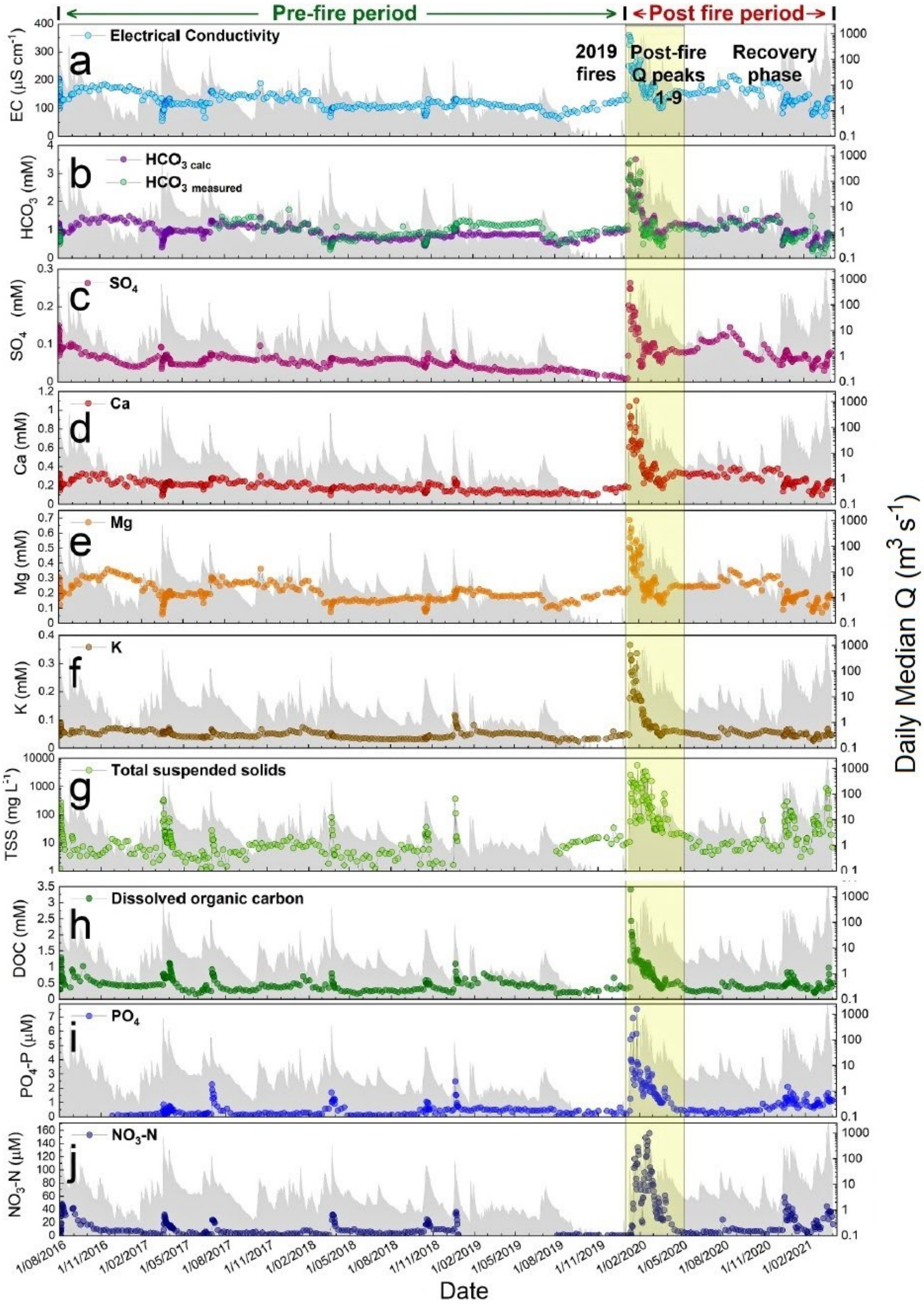
Fire and rainfall regimes determine how frequently the landscape is primed for an erosion response. Terrain attributes determine how this 'priming process' translates to an erosion response (Nyman and Sheridan, 2014). Recent research with the Bushfire Cooperative Research Centre indicates that in southeast Australia the aridity of the landscape can be an important predictor of post-fire erosion. The most sensitive catchments are those located in dry sclerophyll forests. Those river sections overlying granite or sandstone geology will generate larger volumes of sand that is more easily eroded and transported downslope into watercourses where it will then be transported downstream. A common result is large sand slugs that infill river pools and smother channel features.

Water quality

Bushfires can severely degrade river water quality (Robinne et al., 2020). Sediment, ash and debris from burnt areas affect both the physical and chemical make-up of riverine waters (Johnston and Maher, 2022; Figure 4). Sedimentation caused by erosion following fires can lead to large increases in turbidity with values up to 3000 NTU being recorded previously (Wasson et al., 2004; Dahm et al., 2015). Similarly, suspended sediment has been found to increase to 100 times pre-fire median levels (Johnston and Maher, 2022). The sediment and ash from fires contains high levels of nutrients such as nitrogen and phosphorus. Previous studies have found approximate increases in phosphorus up to 450 times and nitrogen 100 times pre-burnt levels (Sheridan et al., 2007; Smith et al., 2011) while others have found nutrients to increase by 7 to 15 times pre-burnt levels (Johnston and Maher, 2022). Similarly, organic carbon in both particulate and dissolved form is mobilised during/after bushfires, with dissolved organic carbon (DOC) concentrations 7 times higher than pre-fire medians immediately after burns on the Macleay River (Johnston and Maher, 2022). Metals and ions have also been shown to increase following bushfires with a greater than 30-fold increase in iron, copper, zinc, chromium, lead, and arsenic levels found in the Ovens River following a storm event after a fire on the Murray River in 2003 (Smith et al., 2011). These increases in sediment, nutrients, carbon and ions have often been closely linked to erosion and ash concentrations, which in turn may be closely linked to bushfire severity (Santin et al., 2015; Santin et al., 2018). In any case, previous research has consistently found large increases in the concentrations of these parameters in riverine ecosystems following bushfires (Smith et al., 2011).

Bushfires also affect the physico-chemical parameters of riverine water such as dissolved oxygen, pH and salinity. Sediment and ash mobilisation have been linked to significant declines in dissolved oxygen concentrations as the material moves through the catchment. These changes in dissolved oxygen concentration are comparable to those of a flow event after extended low flows leading to hypoxic or anoxic conditions (Dahm et al., 2015). Spikes in salinity caused by increased anion and cation concentrations and declines in pH have also been found to occur following bushfires (Reale et al., 2015; Dahm et al., 2015). These changes to pH, salinity and dissolved oxygen may exceed water quality thresholds for the survival of biota and/or affect in-stream biological and chemical processes such as carbon processing and ecosystem metabolism.

Figure 4: Water quality on the Macleay River before and after a large bushfire. Discharge is shown in grey (Johnston and Maher, 2022)



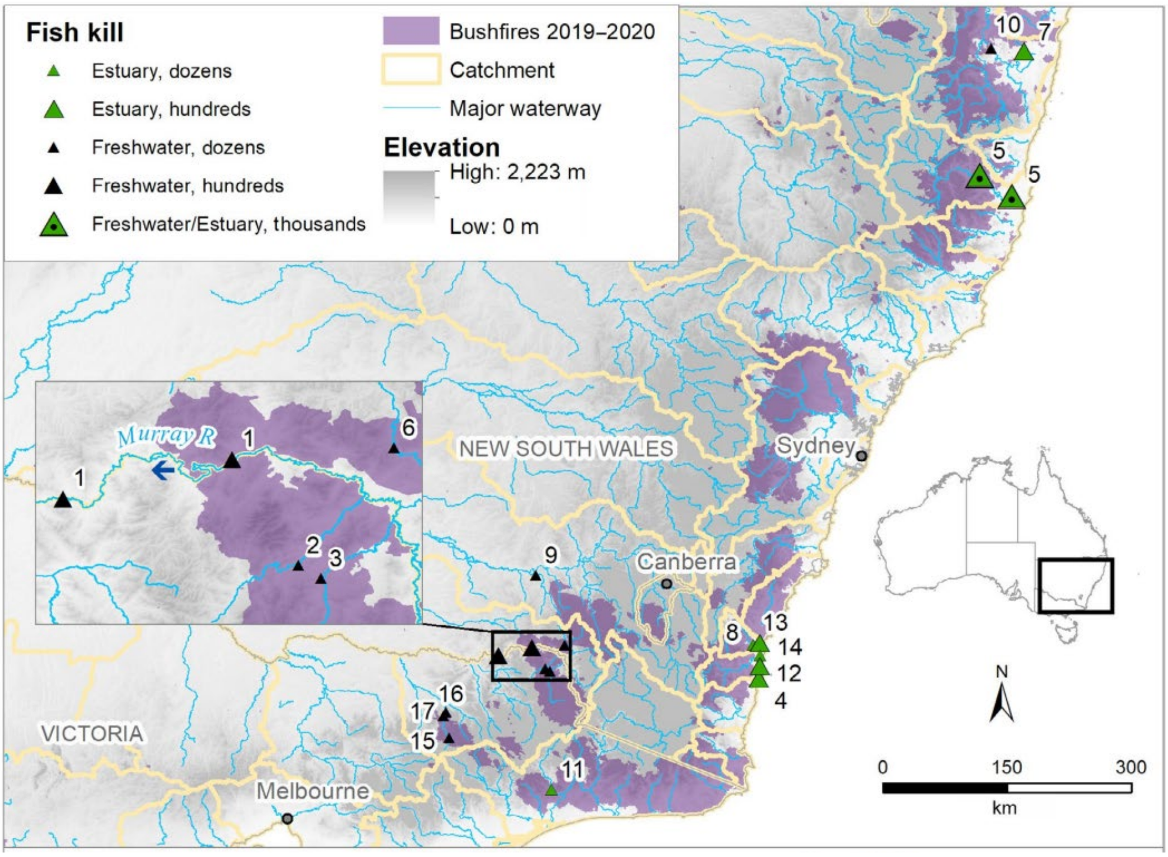
Bushfires also affect riverine water quality in the medium and long term (that is, months to years). A study on the Macleay River from 2016-2021 found concentration-discharge relationships of major ions, DOC and nutrients took 3-12 months to recover to pre-bushfire levels (Johnston and Maher, 2022). Another study found the impacts of bushfires on in-stream phosphorus dynamics could persist for up to seven years post-fire (Emelko et al., 2016). Sediment and nutrient loads mobilised from fire-affected areas have also been found to remain much higher than long-term averages for more than two years following fires (Baldwin, 2022). High nutrient loads being exported into dams can also lead to release of nutrients from lake sediments over the following years, potentially contributing to algal blooms (Santin et al., 2015). Changed nutrient and sediment dynamics in rivers may have significant implications for in-stream productivity, native biodiversity and ecological processes. Consequently, the resilience and recovery potential of aquatic ecosystems to bushfires may be greatly affected by the long-term effects of fires on these basal resources and processes.

Rain and flow events are major pathways for the delivery of sediments and ash into waterways following bushfires. Large rain events form a particularly significant hazard, causing spikes in runoff leading to immediate declines in water quality post-fire. A “rain bomb” following the 2019/2020 fires has been attributed to exacerbating the impacts of the fires on effected rivers and reservoirs due to greatly increased erosion and sedimentation (Neris et al., 2021). Similarly, large flow events following fires may drastically increase erosion of riverbeds and consequently sedimentation (Johnston and Maher, 2022). Increases in the delivery of both dissolved and suspended water-quality constituents often coincide with rainfall and flow events.

Biodiversity

Riverine biodiversity is underpinned by a healthy ecosystem. Bushfires affect riverine biodiversity in several ways; directly by causing mortality due to heat, anoxia or turbidity; indirectly through loss of habitat, food resources and physiological stress; and lagged effects caused by a failure to successfully breed and/or recruit due to changes in breeding habitat and flow regimes (Vieira et al., 2004; Rodríguez-Lozano et al., 2015; Dahm et al., 2015; Sherson et al., 2015). Ash, sediment and contaminants from fires have been found to cause steep declines in benthic macroinvertebrate abundance (Vieira et al., 2004) and mass fish kills through anoxia and extreme turbidity fluxes (Figure 5, Silva et al., 2020). Fish populations in affected reaches have been found to decline by 90-100% with fish stocks taking up to 3 years to recover (Lyon and O’Connor, 2008; Serena et al., 2022). Severe impacts to the growth, reproduction and death rates of aquatic biota have also been attributed to the combined effects of ash and sediment in rivers post-fire (McInerney et al., 2020).

Figure 5: Recorded fish kills on the NSW coast following the 2019-2020 bushfires (Silva et al., 2020)



Semi-terrestrial animals such as platypus and turtles may be more resilient to bushfires due to their ability to avoid the effects of anoxia and potentially move to areas of better water quality. However, loss of food resources such as macroinvertebrates and sediment smothering habitat may still lead to substantial negative impacts to platypus and turtle populations. The response of frog populations to bushfires is highly species dependent. However, abundance, metacommunity occupancy and species richness have been found to decline following severe bushfires (Hossack and Pilliod, 2011; Beranek et al., 2023), with local extinction events also recorded (Lemckert, 2000). Changes to the availability of shelter, breeding habitat and the number of refuges in-stream or in riparian vegetation may also cause lagged declines in frog populations (Hosack et al., 2013).

Ecosystem processes such as food web productivity are likely to be affected long-term by fires. Higher than average nutrient loads caused by sediment influx may result in algal blooms and changes in algal community composition often towards more competitive cyanobacterial species (Klose et al., 2015; Bladon et al., 2014; Baldwin, 2020). In contrast, benthic algae may be severely reduced by sedimentation in the short to medium term, resulting in extreme food limitation for the biota that feed on them. In the longer term, silt and sediment may result in increased macrophyte growth as macrophyte beds are able to form in rock beds smothered by sediment, further impacting food resources and key ecological processes within the river. Changes to flow regimes due to forest regrowth may impact flow events and their consequent mobilisation of organic matter and nutrients crucial for the productivity of rivers (see Flood pulse concept, Junk et al., 1989). These flow pulses play an important role in providing food for larval and juvenile fish, suggesting fire-affected flow regimes may result in lower recruitment in some fish species, particularly when combined with the impacts of poor water quality and habitat loss.

Increased erosion and sedimentation into rivers affect the physical form of riverbeds by smothering and infillings course substrates. Smothering rocky substrates and filling pools reduces both the quality and availability of habitat for the biota that live within them (Table 1, Lyon and O'Connor 2008; Verkaik et al., 2013). Reducing habitat availability increases competition for resources and important breeding locations. The loss of riverbed mesohabitat likely has both short-term and long-term implications as biota initially effected by severe degrading of water quality may also miss important breeding opportunities or experience reduced recruitment due to a lack of appropriate habitat (Verkaik et al., 2013; Bixby et al., 2015). Declines in available habitat for riffle dwelling biota such as macroinvertebrates can have bottom-up effects on the animals that feed on them with potentially large effects on the survival of fish and platypus communities. Drought may play a strong role in limiting the resilience and resistance of macroinvertebrate communities in streams in catchments that have experienced wildfire. This is believed to be driven by dispersal success and resilience of common opportunistic macroinvertebrate taxa after a disturbance such as wildfire leading to highly skewed or modified macroinvertebrate communities (Verkaik et al., 2015).

Table 1: Level of threat sedimentation presents to various fish and crustacean species (adapted from Ward et al., 2022)

		Proportion of species distribution threatened by post-fire sedimentation (%)			
Species (IUCN conservation status**)**	**Group**	**Severe Threat**	**High Threat**	**Mild threat**	**Total proportion at risk**
Euastacus bidawalus (EN)	Crayfish	54.19	41.66	1.47	97.32
Euastacus cf. rieki (NA)	Crayfish	33.64	8.59	-	42.23
Euastacus clarkae (EN)	Crayfish	87.38	-	-	87.38
Euastacus crassus (EN)	Crayfish	46.99	-	-	46.99
Euastacus diversus (EN)	Crayfish	77.79	2.29	7.81	87.88
Euastacus gamilaroi (CR)	Crayfish	45.02	29.95	-	74.98
Euastacus girurmulayn (CR)	Crayfish	57.22	42.78	-	100.00
Euastacus gumar (EN)	Crayfish	20.14	5.68	-	25.82
Euastacus guwinus (CR)	Crayfish	100.00	-	-	100.00
Euastacus jagara (CR)	Crayfish	58.25	-	-	58.25
Euastacus polysetosus (EN)	Crayfish	1.63	-	-	1.63
Euastacus rieki (EN)	Crayfish	53.09	15.91	1.77	70.77
Euastacus simplex (VU)	Crayfish	76.18	6.26	-	82.44
Euastacus sp. 1 (NA)	Crayfish	79.07	10.88	10.04	100.00
Euastacus sp. 3 (NA)	Crayfish	100.00	-	-	100.00
Euastacus spinichelatus (EN)	Crayfish	45.36	15.62	-	60.98
Euastacus suttoni (VU)	Crayfish	35.03	12.88	4.03	51.93
Euastacus vesper (NA)	Crayfish	25.42	74.58	-	100.00
Gadopsis bispinosus (NT)	Fish	16.85	3.96	0.37	21.18
Gadopsis sp. 'Western Victoria' (EN)	Fish	-	1.88	3.08	4.96
Gadopsis sp. SE Victoria (EN)	Fish	9.97	29.34	-	39.31
Galaxias aequipinnis (CR)	Fish	100.00	-	-	100.00
Galaxias brevissimus (CR)	Fish	49.11	-	-	49.11
Galaxias fontanus (EN)	Fish	0.89	2.90	-	3.79
Galaxias mcdowalli (CR)	Fish	95.26	4.74	-	100.00
Galaxias mungadhan (CR)	Fish	23.21	7.12	-	30.33
Galaxias rostratus (CR)	Fish	8.09	1.13	0.54	9.76

		Proportion of species distribution threatened by post-fire sedimentation (%)			
Species (IUCN conservation status**)**	**Group**	**Severe Threat**	**High Threat**	**Mild threat**	**Total proportion at risk**
Galaxias sp. 'Yalmy' (CR)	Fish	83.18	16.82	-	100.00
Galaxias sp. 17 'Cann' (EN)	Fish	100.00	-	-	100.00
Galaxias tantangara (CR)	Fish	-	100.00	-	100.00
Galaxias terenasus (EN)	Fish	21.04	27.98	3.53	52.55
Maccullochella ikei (EN)	Fish	62.87	11.45	0.60	74.92
Maccullochella macquariensis (VU)	Fish	6.32	-	-	6.32
Macquaria australasica (EN)	Fish	15.77	4.38	1.70	21.85
Macquaria sp. 'Hawkesbury' (VU)	Fish	53.25	7.76	2.41	63.42
Mordacia praecox (EN)	Fish	39.32	14.48	0.50	54.30
Nannoperca oxleyana (EN)	Fish	4.52	12.89	5.12	22.52
Ornithorhynchus anatinus (NT)	Platypus	16.07	5.78	1.40	23.26
Prototroctes maraena (VU)	Fish	17.61	7.23	2.66	27.50
Pseudomugil mellis (EN)	Fish	3.53	2.44	5.65	11.62
Wollumbinia belli (EN)	Reptile	11.71	12.19	3.24	27.14
Wollumbinia georgesi (DD)	Reptile	29.49	-	-	29.49
Wollumbinia purvisi (DD)	Reptile	36.58	8.77	1.72	47.06

Considerations for Recovery

Across Australia in 2019, rainfall was the lowest on record, with rainfall 62% below average (BoM, 2021). As large-scale fire events often occur during dry or drought conditions, they typically coincide with periods when water resources are already under stress. Understanding how wildfire may exacerbate the effect of drought on water availability is critical for planning and setting long-term strategies for river management. This section outlines the relevant processes that occur during ecosystem recovery after fire events. These processes may inform possible management actions that could improve ecosystem resilience during this critical period of time.

Vegetation

The effects of run-off and drawdown on in-stream water quantity are directly related to the regeneration of surrounding vegetation. Similarly, the severity and duration of erosion, sedimentation and adverse water quality are closely related to the recovery of the riparian zone. Understanding the size and intensity of the burnt area within the catchment and the expected time frame of recovery will give a strong indication of the expected impacts of the fire on the aquatic ecosystem and the duration of its rehabilitation.

Flow regime

The flow regime is a critical factor in the health of riverine ecosystems. Hence, restoring flows to pre-fire levels, particularly when drawdown from forest regrowth is at its peak, is critical for the long-term health of the river. Increased forest drawdown on river inflows may result in increased cease-to-flow and low flow conditions within the river.

The first flow event following a bushfire is the most sensitive to erosion, thus the sediment loads will be most extreme during the resumption of flow. Protecting the flow volume and velocity will aid in moving sediment and debris downstream and ensuring sediment remains suspended in the water column for as long as possible.

Biodiversity

It is important to identify risks to threatened taxa and critical habitat within the affected area and understand their ecological and biological requirements to effectively support their survival.

In the short-term, minimising the most acute impacts of adverse water quality and sediment slugs (such as anoxia) is critical for the survival of taxa with the river during and after a fire. Inflows that flush sediment loads or replenish rivers with water from unaffected areas to maintain dissolved oxygen may play an important role in reducing the most severe effects of a fire. In the longer-term, restoring water quality to a level that supports productivity and, using flows to flush excess sediment from important habitat may support survival, breeding and recruitment of instream biota.

Community needs

Ensuring water is of a quality and availability to allow for continued supply to towns and livestock is critical for the financial and physical recovery of towns post-fire. High suspended sediment loads and turbidity is likely to make filtering water for human consumption extremely difficult and expensive.

Management

Management background

Water Management Act and Water Sharing Plans

Under the Water Management Act NSW (2000), Water Sharing Plans are the primary statutory instrument for managing water resources in NSW. The rules and access restrictions within each plan help to provide for environmental protection, as well as equitable sharing among the different categories of users within a plan area.

The Natural Resources Commission conducts periodic Independent Audits of Water Sharing Plans, and in that process has made a number of formal recommendations to the New South Wales Department of Climate Change, Energy, the Environment and Water (the department) to investigate how the resilience and rehabilitation of NSW waterways can be improved post-fire using water management strategies.

In addition, there are a number of water management strategies, policies and statutory reviews that address the importance of managing rivers during extreme, episodic events including bushfires. Together, these reviews, reports, strategies and policies can guide the selection of potential management options and access rules within water sharing plans that may address bushfire risks.

Natural Resource Commission recommendations

Murray Unregulated River Water Sources:

- Recommendation 5: Consider how plan provisions can help to ameliorate water quality issues, including those arising from the 2019-20 bushfires.
- Recommendation 6: In remaking the plan, revise the provisions to improve management of the Mannus Creek water source by: ”…*review environmental flow requirements in light of*

recent studies (including the five-yearly assessment of environmental impacts), the impact from bushfires and the needs of water users".

Bega and Brogo Rivers Area, Murrah-Wallaga Area, and Towamba River water sources:

- Recommendation 11: By 1 July 2023, to assist the environment in recovering from bushfires and minimise future risks, the Water Group should:
    - a) collaborate with the department's Biodiversity, Conservation and Science Group (BCS Group) and the Department of Primary Industries – Fisheries (DPI – Fisheries) to better understand the impacts of bushfires on aquatic species and determine any specific flow requirements that may aid recovery (e.g. cues for fish spawning)
    - b) include a provision that can be triggered to support the protection of particular flow events to aid the post-fire recovery of aquatic ecosystems.

Additionally, NRC have made some generic recommendations across all of NSW:

- Water Group work with other agencies, including the BCS Group and DPI – Fisheries to implement Monitoring Evaluating and Reporting programs to examine bushfire impacts *and potential implications for plan rules to aid recovery of aquatic ecosystems.*
- Impacts of bushfires should be considered in remaking plans. However, recent pressures from drought and bushfire have highlighted several issues that should be addressed, particularly to ensure risks from climate change and variability can be managed.

NSW Water Strategy

The NSW Water Strategy has details on priorities or actions for water-related management. In relation to fire, the Strategy indicates that:

- Fire accompanies drought
- There is a need to better consider if we have the right organisational arrangements in place to improve resilience to extreme events such as *bushfire* (and drought and flooding)
- Drought, high temperatures and *bushfires* followed by heavy rainfall resulted in millions of native fish deaths between 2018 and 2020
- Recent impacts from extreme drought and *bushfires* are all pressure points stretching water management capability and preparedness.

The accompanying NSW Water Strategy, Implementation Plan – 2022 to 2024 contains no specific actions to better manage potential bushfire impacts. However, *Priority 4: Increase resilience to changes in water availability (variability and climate change)* has several actions (Actions 4.2 and 4.3) where water management and fire management could be considered as relevant areas of work. That may include bushfire impacts.

https://www.dpie.nsw.gov.au/water/our-work/plans-and-strategies/nsw-water-strategy/toward-2050/priority-4

Extreme Events Policy

The Extreme Events Policy (EEP) is to improve resilience and provide certainty to Murray-Darling Basin Plan communities *'in the event of a water quality event of an intensity, magnitude and duration that is sufficient to render water acutely toxic or unusable for established local uses and values'*. However, whilst 'fire' meets this definition it is not mentioned specifically in the policy, which is largely focused on human consumptive needs during drought. The Extreme Events Policy does not appear to have been designed to consider or address bushfire risk, nor post-fire management options, and has not historically been used for these purposes. No similar policy exists for coastal water sources in NSW.

Risk assessments as management mechanisms

Recently the Wimmera-Mallee Risk Assessment in Victoria incorporated bushfire risks and considered declines in volume, connectivity and habitat as well as increases in salinity, suspended sediment, nutrients and toxicants among several other factors for impacts on surface water in the area. Risk assessments for rivers in NSW do not currently consider long or short-term impacts of fires on hydrology, water quality or risk to flora and fauna.

Water for Bushfire Preparedness and Firefighting

NSW government is currently consulting with stakeholders and seeking feedback on a policy to allow water to be taken and used by landholders for specific purposes (bushfires) without the need to hold a water access licence or a water use approval. Consistent with the Water Management Act priority for critical human needs, this proposal enables water take for direct fire-fighting and preparing for imminent fires by wetting down of domestic households and outbuildings, and the land directly surrounding them. While such water access naturally has potential to exacerbate environmental stress during and preceding bushfire events, any water management options considered in bushfire response must consider this prioritisation of immediate fire risk to human need.

Management options

Many management actions to mitigate the risks to the riverine environment from bushfires lay outside the influence of the department. Actions such as fire prevention and preparedness activities to reduce the likelihood and/or intensity of a bushfire, minimising damage to the riverine environment during firefighting and the construction of on-ground works in burnt areas to minimise erosion are largely controlled by other NSW departments.

The potential management options available to the Water Group for consideration in managing post fire impacts on freshwater aquatic ecosystems may include:

- **Managing for long-term changes to flow regimes, affecting water availability for the environment and stakeholders**. Ensuring additional flows are allocated to the environment and/or Environmental Water Requirements are being met following fires are an important step in the recovery of the ecosystems and reducing post-fire stress on biota. Adjusting access for extraction to maintain flows above ecologically critical levels and ensure access for basic landholder rights may be required.
- **Reducing pre-existing ecological stress on waterways** during drought conditions leading to bushfires, for example, ensure water quality and productivity are appropriate for fish dispersal and growth during drought conditions.
- **Maintaining longitudinal connectivity to allow fish passage** away from impacted environments.
- **Enable flows that flush sediment** from affected areas and enhance the water quality of important refuges.

- **Identify habitats, water sources, reaches or parts of known or recorded range of distribution** for threatened or endangered species or communities that are at high risk of bushfire impacts.
- **protecting flows that dilute sediment loads** may be important for protecting water accessibility for biota and community consumption.

Improved consultation and collaboration by the department with other agencies and fire experts could also improve management of the impact of fire on freshwater aquatic ecosystems, including:

- consulting with fire experts from relevant state agencies to determine if proposed management actions are appropriate and if there are links to other Natural Resource Management legislation that need to be considered.
- participate in working groups forming policies on fire reduction and fire suppression to ensure the needs of the aquatic environment are considered in potential management actions.

Other things to consider may include:

- Improved communication and education of water users on the effects of fire on water quality and quantity, for example:
    - After fire, previously dry watercourses may commence to flow more often for a few years before they revert to their previous state. This may temporarily improve the reliability of the river under the access rules in the water sharing plan, that is, in the short term there may be less cease to pump days, but this should not prompt long term change in their business models.
    - Forest regeneration may reduce runoff, leading to an increase in cease to pump days as new growth uses more water in the catchment and that this may have a longer-term effect on their access.
    - Water quality impacts may linger for several years.
    - Access points may become smothered by liberated sediments and sand slugs.
- The temporary change in water quantity from fire effected catchments should not lead to a change in the water management framework that applies to the area in relation to issuing

additional entitlements from surface water or groundwater, water trading rule or rules around works approvals.

Interpreting management options into potential water sharing plan rules

Water sharing access rules can be used to build fire resilience and support the recovery of a river in the event of a bushfire. To manage fire related impacts more specifically, suggested management options (from above) need to be translated or interpreted as different types of rules in water sharing plans. These rules could be considered for enactment after catastrophic bushfire (ie following an extreme event) or for the life a plan. Examples could include:

Cease to pump rules

These types of rules could be considered as a post fire response for an appropriate period to enable suitable resilience and rehabilitation of the in-stream environment, biota and water quality. They could target specific tributaries to allow inflows from unburnt catchments into affected areas or apply across affected areas.

Possible benefits of cease to pump rules include:

- Increasing resilience of riparian corridors as a pre-emptive protection.
- Maintaining and protecting water quality of refuge pools.
- Minimise the potential for fish deaths caused by anoxia.
- Reducing sedimentation of ash and debris by protecting flow velocity.
- Maintaining movement of sediment slug downstream.
- Allowing for longitudinal connectivity for aquatic biota to migrate away from fire affected areas.
- Continued flushing of water quality, including maintaining dissolved oxygen.
- Reducing the possible stress of bushfire conditions from compounding with cease to flow conditions.

Resumption of flow rule

These types of rules could be considered as an emergency response after a period of no river flow during and after a bushfire. They could protect a specific flow for a specified duration based on research/knowledge of potential water quality impacts, and how best to move ash/sediment slugs through a river system.

Possible benefits of resumption of flow rules include:

- Flush pools and refugia to remove ash and additional sediments.
- Improve water quality, break down any algal blooms, dilute nutrient loads from fires.
- Protect flow velocities to scour substrates, clear interstitial spaces and increase habitat heterogeneity.
- Re-introduce flow-related habitat for fish and invertebrates.
- Increase longitudinal and lateral connectivity for biota and riparian vegetation.

Water storages – contingency allowances.

Using a contingency allowance to manage potential water quality impacts and ash slugs through a river system could be considered for dams owned by local government and WaterNSW. This would require clear evidence that if water is allocated to a contingency allowance, it would provide the benefits of improving water quality and flushing ash from a fire.

Possible benefit of the use of a contingency allowance in storages include:

- Similar to resumption of flow rules but could be controlled to have a low peak to reduce erosion and be timed to best suit ecosystem requirements and flush sediment slugs.
- Could be timed to match rainfall events and dilute the impacts of ash and sediment inputs.

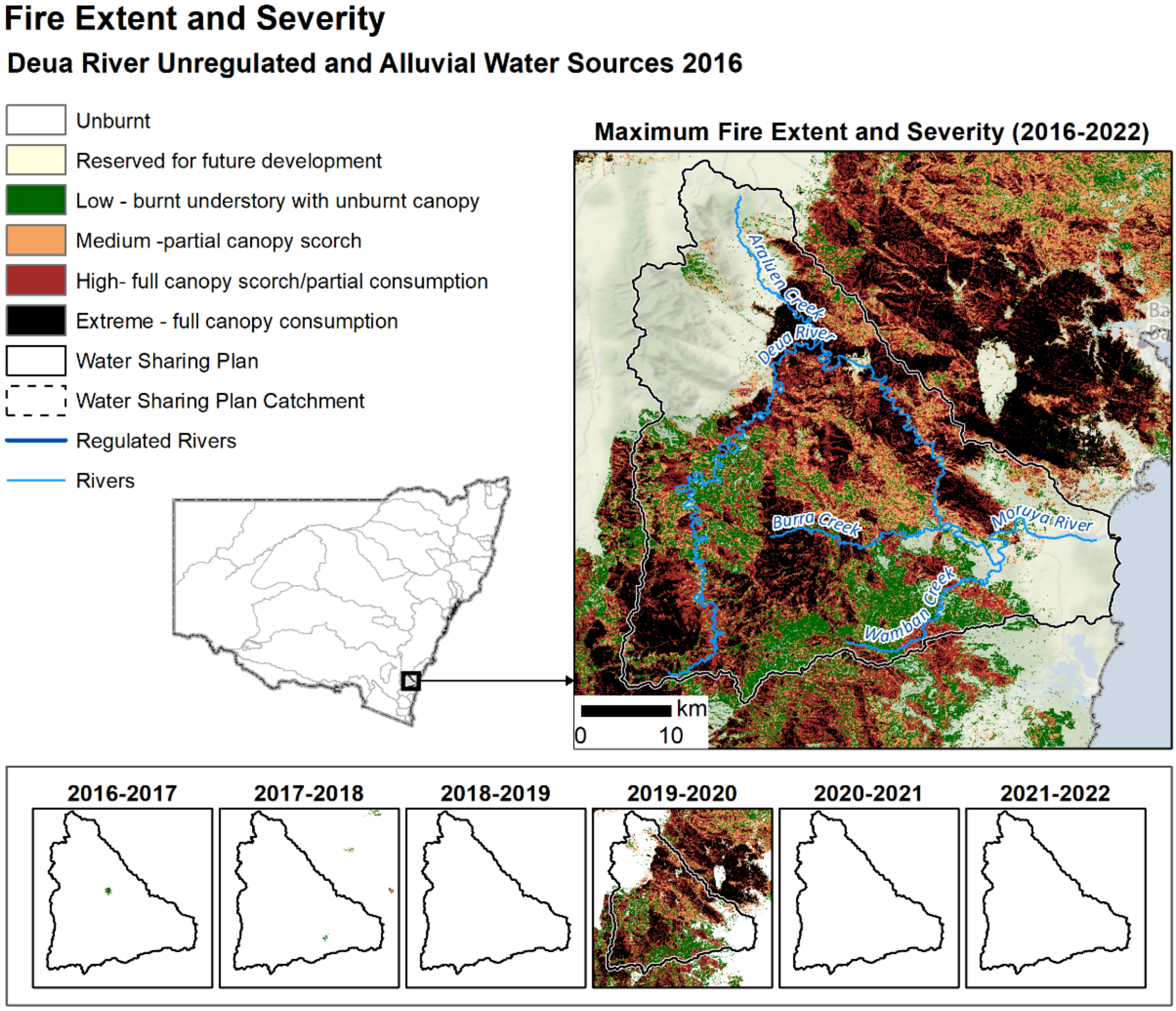
Case study of the 2019/2020 bushfires in the Deua River catchment

The bushfires in the summer of 2019/2020 were particularly severe on the south coast of NSW. The following information uses the Deua River catchment as an example.

During the 2019/2020 fires 61.8% (959 km^2) of the total Deua catchment was burnt with 18.1% extreme severity and 17.5% high severity (Figure 6). This fire covered the entire area immediately surrounding the Deua River as well as most of Burra Creek and Wombat Creek. Araluen Creek was the only major tributary with a large proportion of unburnt catchment.

Flow conditions leading up to and during the bushfire were extremely dry with discharge remaining under 2 ML/d from mid-August 2019 and reducing to cease to flow (less than 1 ML/d) from mid-October. On February 10, 2020, a significant flow event occurred, peaking at 33441 ML/d on the 11th of February.

Figure 6: Fire extent and severity in the Deua river catchment from 2016/17 until 2021/22



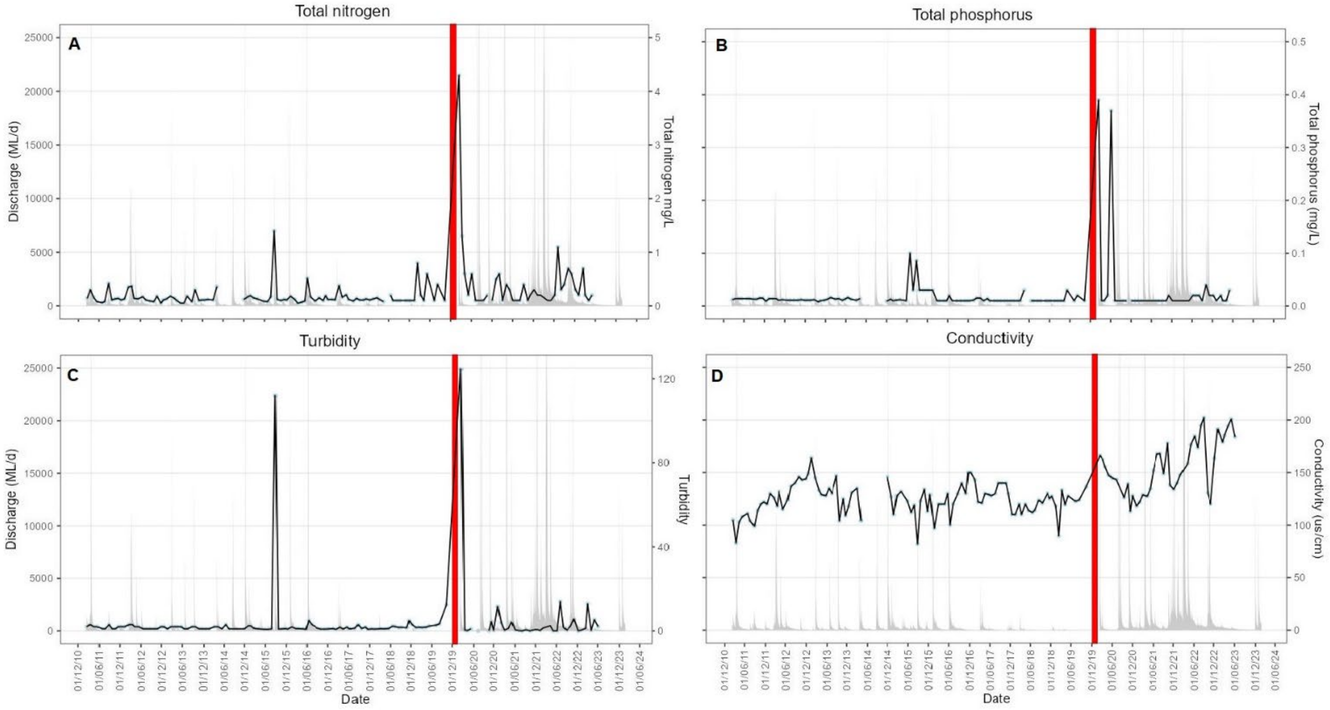
Fire data: Department of Planning and Environment 2020, https://datasets.seed.nsw.gov.au/dataset/f7eb3f73-5831-4cc9-8259-8d1f210214ac
Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under ODbL

Water quality samples were taken monthly from 2010 on the Deua River as part of the state wide water quality monitoring program. Figure 7 highlights some of the effects of the 2019/2020 bushfires on water quality and they are summarised below.

- Immediately after the fire event - total nitrogen (Figure 7A), total phosphorus (Figure 7B) and turbidity (Figure 7C) all show extreme increases in concentration. Conductivity showed a clear increase post-fire (Figure 7D).
- December 2019 – January 2020 - No samples were taken due to safety risks.

- February 2020, following a rain event, total nitrogen was 25 times above the long-term pre-fire average, total phosphorus 26 times higher and turbidity 43 times higher, conductivity consistently declined during the flow event.
- Long-term post-fire averages (not including the extreme spikes in February), were double the pre fire average for total nitrogen and 1.6 times higher for total phosphorus with no clear difference in turbidity long-term, conductivity returned to above pre-fire averages once flows had reduced and was still above pre-fire averages as of June 2023.

Figure 7: Water quality data sampled on the Deua River at Riverview from 2010 until 2023. Shaded grey area indicates discharge (ML/d), the red line indicated the period the bushfire occurred and black line indicates WQ parameter measured. A: total nitrogen, B: total phosphorus, C: turbidity, D: conductivity.



Discussion of management options

Water quantity

A significant amount of forested area was burnt within the Deua catchment and although there may be short-term increases in run-off immediately post-fire, there may also be more significant reductions in water availability over the next decade. More information on the vegetation composition and the species water requirements post fire is needed to quantify changes in instream water availability. Provisions to temporarily reduce extraction within this period of time to ensure there is sufficient water to protect ecologically critical flows and for basic landholder rights may be an effective measure for aiding the rehabilitation of the river post-fire. Further information is required to understand the economic, social and cultural impacts of such a measure on what is arguably a fragile and vulnerable community.

Water quality

The water quality results presented above show extreme increases in nutrients and turbidity immediately after the fires followed by heightened levels of nitrogen, phosphorus and conductivity in the longer term. Without data during December and January it is impossible to know the concentrations of these parameters before the large flow event in February 2020. However, this data suggests first flush rules may effectively clear some of the nutrient loads and debris from the river given the steep decline in nitrogen, phosphorus and turbidity concentrations after this initial flow event.

Cease to pump rules implemented on Araluen Creek were likely beneficial for maintaining water quality in the Deua downstream. Araluen Creek remained largely unburnt, and thus water quality of flows from Araluen Creek was not fire-impacted. Due to low flow protections via CTP rules, these flows of better water quality were able to enter the Deua River and dilute run-off from burnt areas. Inflows from Araluen into the Deua will have maintained dissolved oxygen at survivable thresholds following the fires for longer than would otherwise have been observed, and will also have diluted pulses in turbidity and salinity.

Biodiversity

Cease to pump rules implemented throughout the Deua catchment during and after the fire likely aided aquatic fauna by supporting connectivity through to unburnt river reaches (such as the upper Araluen). This connectivity allowed fish to escape areas of extreme habitat and water quality degradation to up- or downstream refuges. This is particularly significant in catchments such as the Deua where endangered Australian Grayling have been recorded. Due to low population numbers, any large-scale fish kills may massively reduce local populations. Figure 5 shows locations of recorded fish death events.

Catchment wide cease to pump rules post-fire are likely to increase the rate that debris and sediments are flushed from the system and minimise sedimentation of the river bed.

Extreme rain events following bushfires play a large role in increasing the severity of the fires impact on the aquatic ecosystem. Implementing appropriate management options according to weather forecasts ensuring the environment is protected during the first significant rainfall post-fire may be highly effective at supporting river rehabilitation.

Bushfires may continue to effect aquatic ecosystems until the surrounding riparian vegetation has completely regrown. The scale of burnt forested area in the Deua catchment suggests this may have long term effects on water availability and water quality within the river and should therefore be considered in subsequent water sharing plan remakes and risk assessments until forested areas around the Deua have re-established.

Recommendations for future research

How to manage water to best protect and rehabilitate ecosystems while still balancing water for human consumption requires further research and understanding. The following recommendations are made to progress the information needed to make adaptive water management decisions during and post severe bushfire events:

- A full results report analysing water quality data from all 14 water quality monitoring sites on the NSW South and North Coasts including analyses of catchment burn size and severity.
- A full High Ecological Values of Aquatic Systems analysis of impacts of fires using fire intensity mapping and Rural Fire Service fire risk maps to determine key environmental assets are at risk of burning.
- Create a list of species threatened by severe decline in water quality (similar to that of the Sedimentation risk table shown in this document (Table 1)), to further inform bushfire risks.
- Collaborate with the Water Group’s Groundwater team to establish if changes to Electric conductivity concentrations are driven by groundwater intrusion (including marine influenced groundwater) or changes in soil chemistry.

References

Abram, N.J., Henley, B.J., Sen Gupta, A. *et al.* Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Commun Earth Environ* **2**, 8 (2021). https://doi.org/10.1038/s43247-020-00065-8

Baldwin DS, (2022) *Third interim report on the impacts of bushfires on water and sediment quality in Lake Hume and its catchment: January 2020 to May 2022.* A report prepared for the Murray-Darling Basin Authority, 50 pp.

Benyon RG, Inbar A, Sheridan GJ, Lyell CS, Lane PNJ, 2023, Variable self-thinning explains hydrological responses to stand replacement in even-aged forests, Journal of Hydrology 618, 126157.

Beranek, Chad & Hamer, Andrew & Mahony, Stephen & Stauber, Andrew & Ryan, Shelby & Gould, John & Wallace, Samantha & Stock, Sarah & Kelly, Oliver & Parkin, Thomas & Weigner, Rudolf & Daly, Garry & Callen, Alex & Rowley, Jodi & Klop-Toker, Kaya & Mahony, Michael. (2023). Severe bushfires promoted by climate change negatively impact forest amphibian metacommunities. Diversity and Distributions. 29. 00:1–16.. 10.1111/ddi.13700.

Biswas TK, Fazlul Karim, Anu Kumar, Scott Wilkinson, Juan Guerschman, Gavin Rees, Paul McInerney, Brenton Zampatti, Andrew Sullivan, Petter Nyman, Gary J. Sheridan and Klaus Joehnk 2019–2020 Bushfire impacts on sediment and contaminant transport following rainfall in the Upper Murray River catchment. *Integrated Environmental Assessment and Management* — Volume 17, Number 6—pp. 1203–1214

Bixby, Rebecca & Cooper, Scott & Gresswell, Robert & Brown, Lee & Dahm, Clifford & Dwire, K.A.. (2015). Fire effects on aquatic ecosystems: An assessment of the current state of the science. Freshwater science. 34. 000-000. 10.1086/684073.

Black, M.P. & Mooney, S.D. (2006) Holocene fire history from the Greater Blue Mountains World Heritage Area, New South Wales, Australia: the climate, humans and fire nexus. Regional Environmental Change, 6, 41–51.

Blake, D., Nyman, P., Nice, H., D'Souza, F., Kavazos, C., & Horwitz, P. (2020). Assessment of post-wildfire erosion risk and effects on water quality in southwestern Australia. International Journal of Wildland Fire, 29, 240– 257. https://doi.org/10.1071/WF18123

Brookhouse MT, Farquhar GD, Roderick ML. (2013). The impact of bushfires on water yield from south-east Australia's ash forests. Water Resources Research 49: 4493-4505.

Cornish, PM; Vertessy, RA. (2001), Forest age induced changes in evapotranspiration and water yield in a eucalypt forest. Journal of Hydrology.; 242

Dahm CN., RI Candelaria-Ley, CS.Reale, JK Reale and DJ van Horn (2015). Extreme water quality degradation following a catastrophic forest fire. Freshwater Biology 60(12): 2584-2599.

DELWP. (2020). Victoria's bushfire emergency: Biodiversity response and recovery. Department of Environment, Land, Water and Planning (DELWP), State Government of Victoria, Melbourne, Australia. https://www.wildlife.vic.gov.au/__data/assets/pdf_file/0030/484743/Victoriasbushfire-emergency-Biodiversity-response-and-recovery-Version-2-1.pdf

Douglas MM, Setterfield SA, McGuinness K, Lake PS. (2015). The impact of fire on riparian vegetation in Australia's tropical savanna Freshwater Science 34(4):1351–1365

Emelko, M. B., M. Stone, U. Silins, D. Allin, A. L. Collins, C. H. S. Williams, A. M. Martens and K. D. Bladon (2016). Sediment-phosphorus dynamics can shift aquatic ecology and cause downstream legacy effects after wildfire in large river systems. Global Change Biology 22(3): 1168-1184.

Fryirs, Kirstie & Cowley, Kirsten & Hejl, Natalie & Chariton, Anthony & Christiansen, Nicole & Dudaniec, Rachael & Farebrother, William & Hardwick, Lorraine & Ralph, Timothy & Stow, Adam & Hose, Grant. (2021). Extent and effect of the 2019-20 Australian bushfires on upland peat swamps in the Blue Mountains, NSW. International Journal of Wildland Fire. 30. 10.1071/WF20081.

Fryirs K. A., Zhang N., Duxbury E., Ralph T. (2022) Rivers up in smoke: impacts of Australia's 2019–2020 megafires on riparian systems. *International Journal of Wildland Fire* 31, 720-727.

Gallagher, R. V., Allen, S., Mackenzie, B. D. E., Yates, C. J., Gosper, C. R., Keith, D. A., Merow, C., White, M. D., Wenk, E., Maitner, B. S., He, K., Adams, V. M., & Auld, T. D. (2021). High fire frequency and the impact of the 2019–2020 megafires on Australian plant diversity. *Diversity and Distributions*, *27*, 1166–1179.

Gharun, M., Turnbull, T.L. and Adams, M.A., 2013. Stand water use status in relation to fire in a mixed species eucalypt forest. *Forest Ecology and Management*, *304*, pp.162-170.

Graves BP, Ralph TJ, Hesse PP, Westaway KE, Kobayashi T, Gadd PS, Mazumder D (2019) Macro-charcoal accumulation in floodplain wetlands: Problems and prospects for reconstruction of fire regimes and environmental conditions. *PLOS ONE* 14, e0224011

Hossack, B. R., Lowe, W. H., & Corn, P. S. (2013). Rapid increases and time-lagged declines in amphibian occupancy after wildfire. *Conservation Biology*, *27*(1), 219–228.

Hossack, B. R., & Pilliod, D. S. (2011). Amphibian responses to wildfire in the western United States: Emerging patterns from short-term studies. *Fire Ecology*, *7*(2), 129–144.

IPCC (Intergovernmental Panel on Climate Change) (2021) Climate Change 2021. The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. (Eds V Masson-Delmotte, P Zhai, A Pirani, SL Connors, C Péan, S Berger, N Caud, Y Chen, L Goldfarb, MI Gomis, M Huang, K Leitzell, E Lonnoy, JBR Matthews, TK Maycock, T Waterfield, O Yelekçi, R Yu, B Zhou) (Cambridge University Press)

Jackson BK, Sullivan SMP. (2009). Influence of wildfire severity on riparian plant community heterogeneity in an Idaho, USA wilderness. Forest Ecology and Management 259: 24-32.

Jackson BK, Sullivan SMP. (2020). Influence of wildfire severity on geomorphic features and riparian vegetation of forested streams of the Sierra Nevada, California, USA. International Journal of Wildland Fire 29: 611-617.

Jardine, T.D., Pettit, N.E., Warfe, D.M., Pusey, B.J., Ward, D.P., Douglas, M.M., Davies, P.M. and Bunn, S.E. (2012), Consumer–resource coupling in wet–dry tropical rivers. Journal of Animal Ecology, 81: 310-322. https://doi.org/10.1111/j.1365-2656.2011.01925.x

Johnston SG, Maher DT. (2022). Drought, megafires and flood - climate extreme impacts on catchment-scale river water quality on australia's east coast. Water Research 218: 118510.

Junk, Wolfgang & Bayley, Peter & Sparks, Richard. (1989). The Flood Pulse Concept in River-Floodplain Systems. Can. Spec. Public Fish. Aquat. Sci.. 106.

Klose, K., Cooper, S.D., & Bennett, D.M. (2015). Effects of wildfire on stream algal abundance, community structure, and nutrient limitation. *Freshwater Science, 34*, 1494 - 1509.

Kuczera, G., 1987. Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. J. Hydrol. 94 (3–4), 215–236. https://doi.org/10.1016/ 0022-1694(87)90054-0.

Lane P.N.J, Sheriden G.J and Noske P. J. (2006) Changes in sediment loads and discharge from small mountain catchments following wildfire in south eastern Australia. Journal of Hydrology 331: 495-510.

Legge S, et al. (2022). Rapid assessment of the biodiversity impacts of the 2019–2020 Australian megafires to guide urgent management intervention and recovery and lessons for other regions. Diversity and Distributions 28: 571-591.

Lemckert, F. (2000). Observations on the effects of fire on the hip-pocket frog, *Assa darlingtoni*. *Herpetofauna*, *30*(2), 32–33.

Lyon J. P. and O'Connor J. P. (2008) Smoke on the water: can riverine fish populations recover following a catastrophic fire-related sediment slug? Austral Ecology 33: 794-806.

McInerney, P., Kumar, A., Rees, G., Joehnk, K., & Biswas, T. (2020). *How bushfires and rain turned our waterways into 'cake mix', and what we can do about it?* The Conversation.

Mooney, Scott & Harrison, Sandy & Bartlein, Patrick & Daniau, A.-L & Stevenson, Janelle & Brownlie, K. & Buckman, Solomon & Cupper, Matthew & Luly, Jon & Black, M. & Colhoun, Eric & D'Costa, Donna & Dodson, John & Haberle, Simon & Hope, Geoffrey & Kershaw, Peter & Kenyon, Christine & Mckenzie, Gwendolyne & Williams, N.. (2011). Late Quaternary fire regimes in Australia. Quaternary Science Reviews. 30. 28-46. 10.1016/j.quascirev.2010.10.010.

Murphy, S.F., McCleskey, R.B., Martin, D.A., Writer, J.H., Ebel, B.A., 2018. Fire, flood, and drought: extreme climate events alter flow paths and stream chemistry. J. Geophys. Res. 123, 2513–2526.

Naiman, R. J., Bechtold JS, Drake D, Latterell JJ, O'Keefe TC, Balian EV . (2005). Origins, patterns, and importance of heterogeneity in riparian systems. Pages 279– 309 *in* G. Lovett, C. G. Jones, M. G. Turner, and K. C. Weathers . *Ecosystem function in heterogeneous landscapes*. Springer-Verlag, New York, New York, USA.

Neris J, et al. (2021). Designing tools to predict and mitigate impacts on water quality following the Australian 2019/2020 bushfires: Insights from Sydney's largest water supply catchment. Integrated Environmental Assessment and Management 17: 1151-1161.

Nolan, R.H., Lane, P.N.J., Benyon, R.G., Bradstock, R.A., Mitchell, P.J., 2014. Changes in evapotranspiration following wildfire in resprouting eucalypt forests. Ecohydrology 7 (5), 1363–1377. https://doi.org/10.1002/eco.1463

Nyman P., Sheridan G.J., Moody J.A., Hugh G. Smith, Philip J. Noske,and Patrick N. J. Lane (2013) Sediment availability on burned hillslopes. Journal Of Geophysical Research: Earth Surface, Vol. 118, 2451–2467, doi:10.1002/jgrf.20152, 2013

Nyman, P and Sheridan, G. (2014) Erosion in burned catchments of Australia: Regional synthesis and guidelines for evaluating risk. AFAC/Bushfire CRC/University of Melbourne

Pettit, Neil & Naiman, Robert. (2007). Postfire response of flood-regenerating riparian vegetation in a semi-arid landscape. Ecology. 88. 2094-104. 10.1890/06-1270.1.

Prosser, I. P. & L. Williams, 1998. The effect of wildfire on runoff and erosion in native Eucalyptus forest. Hydrological Processes 12: 251–265.

Reale, J. K., D. J. Van Horn, K. E. Condon, and C. N. Dahm. 2015. The effects of catastrophic wildfire on water quality along a river continuum. Freshwater Science 34: 4, 1426-1442

Rhoades, Charles C.; Entwistle, Deborah; Butler, Dana. 2011. The influence of wildfire extent and severity on streamwater chemistry, sediment and temperature following the Hayman Fire, Colorado. International Journal of Wildfire Science. 20: 430-442

Rice S, Stoffel M, Turowski JM, Wolf A (2012) Disturbance regimes at the interface of geomorphology and ecology. *Earth Surface Processes and Landforms* 37, 1678–1682. doi:10.1002/ESP.3326

Robichaud, P.R., Beyers, J.L., Neary, D.G., 2000. Evaluating the effectiveness of postfire rehabilitation treatments. General Technical Report RMRS-GTR-63, September 2000

Robinne F-N, Hallema DW, Bladon KD, Buttle JM. 2020. Wildfire impacts on hydrologic ecosystem services in north American high-latitude forests: A scoping review. Journal of Hydrology 581: 124360.

Rodríguez-Lozano, Pablo & Rieradevall, Maria & Rău, Marius & Prat, Narcís. (2015). Long-term consequences of a wildfire for leaf-litter breakdown in a Mediterranean stream. Freshwater Science. 34. 1482-1493. 10.1086/683432.

Santín, C., Doerr, S. H., Otero, X. L., & Chafer, C. J. (2015). Quantity, composition and water contamination potential of ash produced under different wildfire severities. Environmental Research, 142, 297–308.

Santín, C., Otero, X. L., Doerr, S. H., & Chafer, C. J. (2018). Impact of a moderate/high-severity prescribed eucalypt forest fire on soil phosphorous stocks and partitioning. Science of the Total Environment, 621,1103–1114.

Serena, Melody & Lyon, Jarod & Tonkin, Zeb & Lieschke, Jason & Williams, G.. (2022). Differential impacts of a wildfire and post-fire sedimentation event on platypus and fish populations in a Victorian upland river. Marine and Freshwater Research. 74. 10.1071/MF22201.

Shakesby, R., 2011. Post-wildfire soil erosion in the Mediterranean: review and future research directions. Earth-Science Reviews 105(71): 100.

Shakesby, R. A., and S. H. Doerr. 2006. Wildfire as a hydrological and geomorphological agent. Earth-Science Reviews 74:269– 307.

Sheridan G.J., Lane P. N.J., Noske P Feikma P., Sherwin C. and Grayson R. (2007). Impact of the 2003 Alpine bushfire on streamflow: estimated changes in stream exports of sediment, phosphorus and nitrogen following the 2003 bushfires in eastern Victoria. A report to the Murray- Darling Basin Commission, Canberra.

Sherson, Lauren & Van Horn, David & Gomez-Velez, Jesus & Crossey, Laura & Dahm, Clifford. (2015). Nutrient dynamics in an alpine headwater stream: Use of continuous water quality sensors to examine responses to wildfire and precipitation events. Hydrological Processes. 29. n/a-n/a. 10.1002/hyp.10426.

Sinclair Knight Merz, 2008, Impacts of Bushfires on water quality in the Gippsland Lakes: exploring options for mitigation, Final Report. Prepared for the Gippsland Lakes and Catchment Taskforce, pp 14

Silva LGM, Doyle KE, Duffy D, Humphries P, Horta A, Baumgartner LJ. (2020). Mortality events resulting from Australia's catastrophic fires threaten aquatic biota. Global Change Biology 26: 5345-5350.

Smith, H. G., G. J. Sheridan, P. N. J. Lane, P. Nyman and S. Haydon (2011). Wildfire effects on water quality in forest catchments: A review with implications for water supply. Journal of Hydrology 396(1-2): 170-192.

Tang W, Llort J, Weis J, Perron MMG, Basart S, Li Z, Sathyendranath S, Jackson T, Sanz Rodriguez E, Proemse BC, Bowie AR (2021) Widespread phytoplankton blooms triggered by 2019–2020 Australian bushfires. Nature 597, 370–375. doi:10.1038/s41586-021-03805-8

Tran BN, Tanase MA, Bennett LT, Aponte C (2020) High-severity bushfires in temperate Australian forests have increased in extent and aggregation in recent decades. PLOS ONE 15(11), e0242484. doi:10.1371/journal.pone.0242484

Verkaik I, Rieradevall M, Cooper SD, Melack JM, Dudley TL, Prat N. (2013). Fire as a disturbance in mediterranean climate streams. Hydrobiologia 719: 353-382.

Verkaik I, Vila-Escale M, Rieradevall M, Baxter C, Minshall G, Reich P, Prat N. (2015). Stream macroinvertebrate community responses to fire: Are they the same in different fire-prone biogeographic regions? Freshwater Science 34: 1527-1541.

Vertessy R, Watson F, O'Sullivan S, Davis S, Campbell R, Benyon R, Haydon S, 1998, Predicting water yield from mountain ash forest catchments, Cooperative research centre for catchment hydrology, Industry report 98/4Vieira NK, Clements WH, Guevara LS, Jacobs BF (2004) Resistance and resilience of stream insect communities to repeated hydrologic disturbances after a wildfire, Freshw. Biol., 49, pp. 1243-1259

Ward M, Southwell D, Gallagher R, Raadik T, Whiterod N, Lintermans M, Sheridan G, Nyman P, Suárez Castro A, Marsh J, Woinarski J, Legge S. (2022). Modelling the spatial extent of post-fire sedimentation threat to estimate the impacts of fire on waterways and aquatic species. Diversity and Distributions. 28. n/a-n/a. 10.1111/ddi.13640.

Wasson R. J., Worthy M., Olley J., Wade A., and Mueller N. (2004) Source of turbidity in Bendora Reservoir. A report to ACTEW AGL. Centre for Resource and Environmental Studies, Australian National University

Yang X, Zhang M, Oliveira L, Ollivier Q, Faulkner S, Roff A, (2020). Rapid Assessment of Hillslope Erosion Risk after the 2019-2020 Bushfires and Storm Events in Sydney Drinking Water Catchment. Remote Sensing. 12. 3805. 10.3390/rs12223805.