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2019-20 Bushfire impacts on sediment and contaminant transport following rainfall in the Upper Murray River catchment

2019-20 Bushfire impacts on sediment and contaminant transport following rainfall in the Upper Murray River catchment

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EDITOR'S NOTE: This article is part of the special series “Ecological consequences of wildfires.” The series documents the impacts of large-scale wildfires in many areas of the globe on biodiversity and ecosystem condition in both terrestrial and aquatic ecosystems, the capacity for systems to recover, and management practices needed to prevent such destruction in the future.

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Data Accessibility Statement

Data used in this study can be made available upon request to corresponding author: Tapas Biswas (Tapas.Biswas@csiro.au)

ABSTRACT

During the 2019–2020 Australian bushfire season, large expanses (~ 47%) of agricultural and forested land in the upper Murray River catchment of south-east Australia were burnt. Storm activity and rainfall following the fires generated increased sediment loads within rivers, resulting in localised fish kills and widespread water quality deterioration. We collected water samples from the headwaters of the Murray River for sediment and contaminant analysis as well as assessed changes in water quality using long-term monitoring data. A robust runoff routing model was used to estimate the effect of fire on sediment loads in the Murray River. Peak turbidity in the Murray River reached values up to 4,200 NTU shown as pitch black water coming down the river. The increase in suspended solids was accompanied by elevated nutrient concentrations during post-bushfire runoff events. The model simulations showed that sediment load could be 5 times higher in the first year after bushfire compared to pre-fire condition. It was estimated that Lake Hume, a large

reservoir downstream from fire affected areas, would receive a maximum of 600,000 tonnes of sediment per month, in the period immediately following the bushfire, depending on rainfall. Total zinc, arsenic, chromium, nickel, copper and lead concentrations were above the 99% toxicant default guideline values for freshwater ecosystems. It is also likely that increased nutrient loads within Lake Hume will have ongoing implications for algal dynamics, both within the Lake, and in the Murray River downstream. Information from this study provides a valuable basis for future research direction to support bushfire-related policy development in fire-prone catchments and the mitigation of post fire water quality and aquatic ecosystem impacts.

Keywords: Bushfire, Murray River, sediment transport, water quality, ecotoxicity

INTRODUCTION

In 2019–2020, around 5.8 million hectares of forest in eastern Australia were burned during an event widely referred to as the ‘Black Summer’ fires. These bushfires represent an extraordinary disturbance event (Boer et al. 2020), affecting catchment processes at an unprecedented scale, in terms of the spatial extent and severity of the fire footprint. The devastating bushfires, both by severity and extent, have been attributed to extremely low fuel moisture content, with vast areas of forest having fuel moistures below flammability thresholds for long periods during the fire season (Boer et al. 2020; Deb et al. 2020; Nolan et al. 2020). The severity of bushfires was variable (Bradstock et al. 2020), with fire weather (wind and temperature) during the passage of the fire fronts typically being the key determinant of fire severity within the fire footprint (Collins et al. 2014).

Across large parts of the burned areas, the bushfires were subject to intense rainfall in early January 2020 and the region shifted from El Nino (dry) to La Nina (wet) dominated weather patterns. The monthly rainfall in January to February 2020 was very much above average (8th-9th decile) across the entire burned areas, and in many locations, rainfall was highest on record (10th decile) (BOM 2020). The intense rainfall on recently burned catchments triggered widespread increases in erosion and sediment transport in waterways. This catchment response resulted in immediate impacts on biota (e.g. fish kills), changes to habitat, and impact on water quality that may persist for several years (DELWP 2020a; Silva et al. 2020). Fish kills (100–1000s of individuals) were documented in estuaries and in inland waterways in the fire affected north coast of New South Wales through to headwater of the Murray River in Victoria (Silva et al. 2020).

Bushfires are a regular feature of Australian summers, and their negative impacts on freshwater ecosystems are well documented. Some early work by Brown (1972) measured the effect of bushfires on suspended sediment concentration and detected increases of up to two orders of magnitude relative to unburned areas. More recently, White et al. (2006) recorded up to a 30-fold increase in turbidity, iron and manganese in reservoir water following bushfire. In their review of water quality impact from bushfire, Smith et al. (2011a) found evidence of consistent increases in suspended sediment and nutrient loads after bushfire, but that impacts can be highly variable across burned areas.

Hydrological and geomorphic processes that give rise to large erosion events and water quality impacts are complex and difficult to predict (Moody et al. 2013; Nyman et al. 2013). Complexity stems from multiple aspects related to the post-fire generation and transport of sediment and contaminants. First, post-fire erosion of ash

and soil in upland catchments are highly variable in space and time because of inherent variation in catchment properties (e.g. soil erodibility, soil infiltration capacity, vegetation attributes, terrain) and fire severity (Bodí et al. 2014; Noske et al. 2016; der Sant et al. 2018; Inbar et al. 2020). Second, contrasting sequences of post-fire rainstorms can give rise to a wide range of catchment response for any given bushfire (Moody and Martin 2009; Nyman et al. 2013; Murphy et al. 2015). Finally, once sediment, ash and contaminants are eroded from hillslopes in upland catchments, the rate of transport of these through waterways is subject to large uncertainty due to patterns of sediment deposition, reworking and the dependency of these on post-fire catchment discharge (Murphy et al. 2015; Moody 2017; Nyman et al. 2019).

This paper seeks to address limitations in our understanding of bushfire impacts on water quality and sediment transport in the upper Murray catchment in SE Australia. There are two themes to the paper: 1) the development and implementation of a method for modelling post-fire sediment transport through river reaches downstream of burned headwater catchments, and 2) detecting change in water quality in response to the first period of intense rainfall following bushfires. In interpreting our results, we link the measurement of catchment-scale water quality responses with the modelling of erosion and sediment transport to evaluate the impacts of bushfire on waterways and the processes that are driving this impact. This study is not a full-scale analysis, rather a case study of the upper Murray catchment bushfire impacts on downstream water quality directly after the end of bushfires and first rainfall event. It provides a first-hand quantitative estimate of sediment and nutrient loads generated by rainfall run-off from the burnt areas. Parallel analysis of heavy metals in water samples collected during the first weeks after the bushfires ended are briefly listed and is indicative of necessary future monitoring.

METHODS

Study area and fire severity

The study area comprises the catchments of the Upper Murray and Mitta Mitta rivers, including lakes Dartmouth and Hume (Figure 1). These catchments cover a total area of 15,350 km². Lake Dartmouth in the headwater catchment of the Mitta Mitta River intercepts much of the sediment in run-off from this upstream part of the catchment, hence these do not reach Lake Hume. Detailed hydrological modelling was configured and calibrated for the Cudgewa Creek, a headwater catchment of the Upper Murray River.

About 4,280 km² (47%) of the Upper Murray catchment was burned, while the Mitta Mitta catchment had about 1,008 km² burned area (16%) with fires burning largely un-controlled throughout the catchment. Burn severity (shown in Figure 2) was estimated from the difference Normalised Burn Ratio (dNBR) using Landsat 8 satellite imagery (Key and Benson 2005) The resulting maps with a spatial resolution of 30 meters were then aggregated to 1 km resolution to match erosion modelling. Burn severity maps are based solely on satellite observations and could not be verified on the ground due to fire zone access restrictions.

Estimation of hillslope erosion and sediment delivery

A model of post-fire sediment transport was developed for the Cudgewa Creek sub-catchment (797 km²), a tributary of the Upper Murray River. Our modelling approach combines a hillslope sediment delivery model with a hydrological model, which routes water and sediment through a river network as described subsequently. We then generalised the simulation study including the entire catchment area for the Upper Murray. This allowed us to estimate the sediment load in the River Murray flowing into the Lake Hume reservoir. As the entire Upper Murray catchment

includes multiple sub-catchments with high burn intensity like the Cudgewa catchment, the sediment load is expected to increase manyfold.

This study adopts the Revised Universal Soil Loss Equation (RUSLE) for predicting hillslope erosion rate for pre- and post-bushfire condition. The RUSLE is widely used for estimating rates of soil erosion in various landscape settings, including burned landscapes (Renard et al. 1991; Terranova et al. 2009; Fernández et al. 2010; Yang et al. 2018; Blake et al. 2020). The RUSLE calculates the mean annual hillslope erosion ($\text{t ha}^{-1} \text{ year}^{-1}$) rate based on a linear equation that is the product of six local environmental factors: (i) rainfall-runoff erosivity factor, (ii) soil erodibility factor (K), (iii) slope length factor, (iv) slope steepness parameter, (v) land cover factor (C), and (vi) support practice factor. The above factors were obtained for unburned condition at a 1 km resolution grid from prior modelling of the Australian continent (Teng et al. 2016). Both the erodibility factor (K) and cover factor (C) were adjusted to represent fire-effects and given parameters that allow for recovery back to pre-disturbance values as a function of time. The modified K and C values (and their decay parameters) were determined to generate erosion increases and recovery rates consistent with observations from recent bushfires in Victoria (Noske et al. 2016; der Sant et al. 2018). The drivers of spatial and temporal variability in post-fire erosion, represented by the model, are fire severity (dNBR) and aridity index, mapped using rainfall and potential evaporation grid from the Bureau of Meteorology (Nyman et al. 2014).

The RUSLE cover factor C is increased temporarily from the background value (C_{base}) after fire to a maximum value (C_{peak}), decaying exponentially back to C_{base} as a function of time since fire (t , years), at a decay rate proportional to the aridity index (AI), using the following function:

$$C = (C_{dNBR} - C_{base}) \left(\exp \left(-\frac{t}{\xi_{CAI}} \right) \right) + (C_{base}) \quad (t \geq 0) \quad \text{Eq. 1}$$

where C_{DNBR} is a fire-severity related factor to adjust the magnitude of change in C resulting from different severities of fire, represented here as a linear step-function of fire severity (dNBR) given by:

$$C_{DNBR} = \begin{cases} C_{base} + \left((C_{peak} - C_{base}) \frac{dNBR}{400} \right) & 0 < dNBR \leq 400 \\ C_{peak} & dNBR > 400 \end{cases} \quad \text{Eq. 2}$$

where C_{peak} is the maximum magnitude of the C factor due to fire, which is assumed to be a linear function of dNBR. A similar approach is used to temporarily increase the RUSLE erodibility factor K after fire:

$$K = (K_{fire} - K_{base}) \left(\exp \left(-\frac{t}{\xi_{KAI}} \right) \right) + (K_{base}) \quad (t \geq 0) \quad \text{Eq. 3}$$

The values of the parameters in Eq. 1 - Eq. 3 are given in Table 1. With these parameters, there is a maximum of about a 100-fold increase in erosion from the burned area relative to background conditions. This is consistent with the observed changes in erosion rates following high severity bushfire and intense rainfall (Nyman et.al. 2015, 2020) and includes the erosion in upland drainage networks caused by debris flows. In future refinement of this modelling approach, the debris flow processes, which is patchy and episodic should be considered separately, and the parameters “ C_{peak} ” and “ K_{fire} ” should be reduced so that the total combined post fire erosion (debris flow and hillslope) has a reasonable upper bound. For this study, an explicit model of sediment delivery by debris flows would require detailed information on rainfall fields (e.g. from radar) which was not available at sufficient accuracy at the study site. Our approach to modelling sediment delivery to the river network assumes that erosion in steep upland headwaters is the dominant sediment

source contributed to post-fire increases in sediment transport in the river network.

The approach does not explicitly consider debris flow processes.

The catchment was divided into a number of sub-catchments to construct a node-link network in the modelling domain. Sub-catchments were generated from the Shuttle Radar Topography Mission (SRTM) 30 m Digital Elevation Model (DEM) (Gallant et al. 2011). Selection of catchment outlets was guided by published stream gauge locations. Thirteen sub-catchments were delineated for the Cudgewa Creek catchment with areas ranging from 31.5 km² to 94.0 km² (Figure 1). The catchment delineation focused on providing a relatively even spread of the sub-areas while at the same time providing outlets at the various gauging station sites for potential calibration and validation of modelling results. The fine sediment supplied from hillslopes to the stream network is the product of gross erosion rate (E_i , t ha⁻¹day⁻¹), area of the i^{th} sub-catchment (A_i , ha) and a hillslope sediment delivery ratio (SDR_i). The annual hillslope sediment supply (H_s) to the stream was calculated as the sum of contributions from all sub-catchments at a point of interest in the stream network, $H_s = \sum_i E_i * A_i * SDR_i$.

Estimation of sediment loads in rivers

Flow and sediment routing were simulated using XP-RAFTS, a robust runoff routing model that is used extensively throughout Australia for rainfall-runoff modelling (Innovyze 2016). The main inputs to the model include catchment area, slope, degree of urbanisation, loss rates and observed or design rainfall. The main output is a time series of flows at each catchment outlet and any additional nodes, as well as along the river network. The XP-RAFTS model separates overland flow

routing from channel routing. Factors affecting overland flow calculations include roughness, impervious ratios, and catchment slope.

The model was run at an hourly timestep and the simulation was carried out over periods ranging from a single storm event to multiple storms. The model was calibrated using Manning's roughness coefficient (n) and two loss parameters (initial and continuing losses). Initial roughness and loss parameters were estimated based on published literature (LWA, 2009; Innovyze, 2016). Parameters were calibrated by constraining model simulations against observed flow data using an iterative process. Model results were evaluated using observed discharge data at two gauging stations (Berringama and Cudgewa north, refer to Figure 1 for location). The calibrated roughness coefficient varied between 0.04 and 0.06. Detailed calibration results can be found in Joehnk et al (2020).

Annual sediment loads were disaggregated to daily/monthly time steps using a disaggregation function which distributes the mean annual sediment supply across the daily runoff using a runoff factor (f_{RO}), which was estimated at monthly timesteps for each sub-catchment using XP-RAFTS. The runoff factor is estimated based on an exponential relationship between daily runoff and historical mean runoff. The mean value of f_{RO} over the long-term historical record is 1, being 0 during dry period and >1 during runoff events. Detail of disaggregation is given by Wilkinson et al. (2014).

Water quality measurements

Replicate grab water samples were collected from following three locations (Figure 1) from the Murray River on three occasions from 24th January to 7th February 2020 just after the main fires had ceased:

- i. A long-term monitoring site near Jingellic (35.928712S, 147.673476E)

- ii. Gadds Reserve (35.943860S, 147.705235E) and
- iii. Jingellic Hotel (35.928712S, 147.673476E)

Due to travel restrictions caused by active fires and then Covid pandemic, we were not allowed to collect further samples. Spot measurements of water pH, EC, dissolved oxygen (DO), temperature and turbidity were made using Horiba multi-parameter water quality meter (www.horiba.com). This probe was calibrated as per the manufacturer's instructions.

In the laboratory, water samples were measured for total and/or dissolved (0.45 μm filtered) metals and metalloids. Samples for dissolved metals analysis were filtered through acid-washed 0.45- μm syringe filters (Sartorius, Australia) with the first ~ 3 mL of sample pre-conditioning the filter and discarded to waste, before collecting the filtrate in an acid-washed polycarbonate vial. All samples were acidified with concentrated nitric acid to 0.2 % (v/v) prior to analysis.

Concentrations of metals and major ions were determined using an inductively coupled plasma-atomic emission spectrometer (ICP-AES, Agilent 5100) and inductively coupled plasma-mass spectrometer (ICP-MS, Agilent 8900 QQQ).

Continuous records of weekly water quality parameters (total phosphorus, total nitrogen, dissolved organic carbon) along with daily physical parameters (flow rate, water temperature, electrical conductivity, turbidity, dissolved oxygen) at two water quality stations on the two main tributaries flowing into Lake Hume were used in this study. Because of their proximity to Lake Hume, we have used data from these stations, Jingellic (NSW) on the Murray and Tallandoon (Victoria) on the Mitta Mitta Rivers, to calculate loads of sediments and pollutants entering the Lake Hume during the study period.

RESULTS

Changes in streamflow

Figure 3 shows a typical example of model simulated pre- and post-fire streamflow at Berringama on Cudgewa Creek. Results using the same precipitation input indicate that there is an increase in stream flow after bushfire, when compared to pre-fire (Figure 3). In terms of flow volume, the increase is in the range of 10-20% between the storm events following the bushfire. However, peak flow could increase by as much as 30% based on the magnitude of storm event and antecedent catchment condition.

Changes in sediment loads

Figure 4 shows an example of model-simulated monthly sediment load at a headwater catchment (Cudgewa Creek) in the Upper Murray catchment. Both pre- and post-fire sediment loads vary between months (Figure 4a). Assuming the same rainfall pattern for the post-fire year 1 and year 2, we can estimate a sediment load increase of as much as 200% in the first year compared to pre-fire condition and 27% higher in the second year. The total sediment load at Cudgewa North in the period Jan-May 2020 was 19,220 tonnes, about 1280 tonnes higher than the unburned scenario. When applied to the Upper Murray River our simulations indicate a sediment load in the first year after bushfires of up to 600,000 t month⁻¹, a 5-fold increase in potential sediment load compared to previous years (Figure 4b). The absolute magnitudes of sediment loads were not validated and are subject to model assumptions about sediment delivery and transport.

Water quality changes

Noticeable changes to water quality were huge loads of sediment and ash. Grab water samples were up to 30 times more turbid than normal, with total suspended solids peaking at 765 mg L^{-1} . Water pH was between 6 and 7, conductivity (EC) varied between 0.002 to 0.4 dS m^{-1} whereas dissolved oxygen (DO) was between 6.14 and 8.74 mg L^{-1} .

Long-term water quality monitoring data from the two main tributaries of Lake Hume were used to calculate contaminants loads for the lake, which lacked regular monitoring of nutrient concentrations. Large volumes of sediment and ash movement from burnt area, Jingellic site (NSW) on the Murray River recorded a peak turbidity of 4200 NTU (Nephelometric Turbidity Unit) during a run-off event seen as dark, pitch black water (data source: DELWP, 2020b for site 401201 MURRAY RIVER @ Jingellic). In comparison, Biswas and Mosley (2019) while analysing 40 years of water quality data from the Murray River reported a baseline median value of about 4 NTU at the Jingellic site.

Concentrations of total nitrogen (TN), total phosphorus (TP) and dissolved organic carbon (DOC) were much higher in the first year after runoff events. (Figure 5). In association with the first rainfall event after the bushfires in February to April 2020 concentrations of TP and TN were very high, but loads were relatively low due to relatively low flow rates generated by the first rainfall after fires. Turbidity readings remained high throughout 2020 with intensifying rainfall events, here seen in increased peak flows in Figure 5. In contrast, the Mitta Mitta River at Tallandoon downstream of Dartmouth Dam recorded low turbidity during the same periods due to the fact that the catchment area downstream of Dartmouth Dam was little affected by fires.

In general, loads (Figure 5) after bushfire were of the same size or larger compared to those in pre-bushfire years, although flow rates in 2020 were generally smaller compared to, e.g., the flood event in 2016. The post-fire flow events are small compared to larger flow events in non-bushfire years. Importantly, even after six months after the fires, runoff from the burnt catchment is still carrying huge amount of sediments, nutrients, and carbon. From 1990–2020 maximum peak loads of DOC, TP and TN) for the Murray River were 668 t day^{-1} , 14 t day^{-1} , and 83 t day^{-1} (major rainfall events following a multiyear drought), respectively, compared to 145 t day^{-1} , 6.5 t day^{-1} , and 33 t day^{-1} for peak loads in the 9 months after bushfires and increasing further with rainfalls). In general, nutrient (TN and TP) loads were very high compared to average TN and TP loads to the Murray which varies from about 0.1 to 1 t day^{-1} and 0.01 to 0.1 t day^{-1} respectively (Biswas and Mosley, 2019). The contribution of the Mitta Mitta River in terms of loads after bushfires is in the same range as in previous years with low flow.

Our analysis of soluble zinc and arsenic, total zinc, arsenic, chromium, nickel, copper and lead showed concentrations recorded above the 99% species protection default guidelines values (DGVs) and for total metals the values were often higher than the 95% DGVs for the respective metals for freshwater ecosystems (www.waterquality.gov.au/anz-guidelines). As an example, total and soluble copper in the Upper Murray catchment are presented in Figure 6. We had no pre-fire data to compare with, and can only assume that these high values are a result of increased loads.

DISCUSSION

Sediment transport

By linking hillslope sediment delivery with a hydrological model, our study provides estimates of changes in sediment transport from large fire-affected catchments in the Upper Murray. In the Cudgewa sub-catchment, where the model was calibrated, the modelling indicated increases of 200% and 27% in sediment loads in year 1 and year 2 following bushfire. These simulated increases in sediment loads fall within the range of post-fire sediment transport response (typically 10 to 100 fold increase) measured in tributaries of the Murray River following previous bushfires (Noske et al. 2016, Smith et al. 2011b, Lane et al. 2006, De Rose et al. 2003). Such large increases in sediment transport mean increased nutrient and carbon loading into receiving water bodies such as Lake Hume in the years to come. While such increased loadings have been documented previously (e.g., Smith et al. 2011b, White et al. 2006), this study is the first in Australia to use a large-scale hydrologic model to link erosion in headwaters with loadings into waterways and reservoirs. The implication of these modelled increases in nutrient loads is accumulation of nutrients in deposited sediments on the lake bed and thus future potential of increased internal nutrient loading which in turn can increase the likelihood of potentially harmful cyanobacterial blooms. Our estimates of sediment load should be taken as a qualitative outcome. A more quantitative estimation is only possible with intensive and large-scale monitoring, which we were unable to pursue due to limited access to the fire grounds (initially) and travel restrictions imposed by the coronavirus pandemic (subsequently).

The month-to-month variation in simulated sediment transport was determined by the method that we adopted for linking the hillslope erosion estimates from RUSLE with catchment runoff in XP-RAFTS. The majority of sediment is simulated to occur during periods when the discharge is high (autumn and winter), because sediment

delivery from hillslopes is disaggregated assuming a proportional relation between sediment transport and the runoff factor (fRO), which was estimated at monthly timesteps. This method for disaggregating the annual erosion estimates from RUSLE, provided a pragmatic solution for coupling RUSLE and XP-RAFTS. However, the approach gives little weighting to discrete sediment pulses (sediment slugs) which are caused by threshold-driven erosion processes such as debris flows which can account for a large proportion of the annual sediment delivered to streams (Nyman et al. 2019, Lyon et al. 2008). In future work, there are opportunities to develop linkages between hillslope and the river network that are more representative of the episodic and patchy distribution of erosion events and sediment transport (e.g., recent work by Nyman et al (2021). Modelling of rainfall as spatial temporal fields (Peleg et al, 2017) is critical to further refine the treatment of space and time in the disaggregation of annual erosion estimated from RUSLE.

Our modelling indicated large spatial variability in sediment transport, with changes in sub-catchment loads ranging from no increase to a ten-fold increase. Changes in streamflow following the burn are relatively modest (increase mean streamflow of 10-20% in the first year; 30% increase in peak flow), so the large spatial variability, and the overall increase in sediment loads across the burned area, can therefore be largely attributed to the erosion potential as represented by RUSLE. This variability is due to an interaction of topography, soil properties, burn severity and vegetation recovery, all of which affect the factors that are used to model erosion rates in RUSLE. The magnitude of variation in post-fire hillslope erosion rates are reasonable and consistent with what has measured previously on hillslope erosion studies (Yan et al. 2018, Nyman et al. 2015, Blong 1982). For streamflow, the interception and surface cover are key variables that would generate variation over

time and in space from one sub catchment to another (Ebel and Moody 2020, Brookhouse et al. 2013; Mannik et al. 2013, Moody et al. 2013). In sub-catchments with Mountain or Alpine Ash forest, there is a possibility of net loss in water yield in a longer time span as juvenile forest regrows (Brookhouse et al. 2013).

Water quality indicators

Immediately following the first pulse of sediment, dead fish (European carp and Murray cod) were observed on the bank of Murray at Gadds Reserve (Figure 1). Ash and nutrients combined with high summer water temperatures can trigger increased microbial activity, which in turn can deplete the dissolved oxygen concentration in the water (also known as hypoxia). Wide-spread hypoxia can lead to large scale fish kills as happened after the bushfires. However, low levels of dissolved oxygen were not observed. A DO logger installed in March 2020 at Jingellic with hourly recording of data showed above 6 mg L⁻¹ dissolved oxygen at the time during runoff events. The dead fish were observed with large quantities of sediment and ash trapped in their gills causing localised fish kills. These findings are not unusual; following the 2003 bushfires (Lyon and O'Connor 2008) and after the 2019-20 bushfires (Baumgartner et al. 2020) fish kills were attributed to a combination of low DO and high turbidity.

Sediment loads and major nutrients were estimated in the two major tributaries (Murray and Mitta Mitta) and then compared with monitored data. High ash content and pitch-black water colour were observed following the first flush after bushfires. Using satellite imagery, the river discharge into Lake Hume and sediment distribution could be visualised by the distinguished coloured plumes. Suspended sediments were dispersed within the entire lake via wind driven currents, however it can be assumed that sedimentation of suspended materials mainly took place near the inflow

depending on the lake water levels. The increased nutrients load in the lake is expected to augment the risk of algal blooms due to internal loading in the coming years.

High nutrient loading from the upper Murray into Lake Hume can also lead to increased internal loading (release of nutrients from the lake sediments) over following years contributing to potential toxic algal (cyanobacteria) blooms in summer months. In recent years we have witnessed an increased incidence of toxic algal bloom events within the Murray-Darling Basin (Biswas and Mosley 2019).

Heavy metals such as zinc, arsenic, chromium, nickel, copper and lead were recorded in concentrations well above guideline values for healthy waterways. In a separate study, McInerney et al. (2020) reported severe impacts of growth, reproduction and ultimately death rates of some aquatic biota primarily due to combined effects of the ash and contaminants.

How to minimise the effects of bushfires on streams?

Prevention of sediment transport to waterways following fire is difficult because of the vast spatial scale of bushfires. Sediment management through check dams and sediment barriers is often not an option because of the large number of catchments affected and contributing to water quality issues in receiving waterways. But if we are protecting high values assets (e.g. water supply reservoir) one can assume a fire will occur at some point in time and the investment in barriers and check dams to reduce sediment transport (Fox 2011) may be warranted.

Restoration of riparian zones adjacent to waterways can be an effective measure to reduce sediment transport into rivers in those settings where sediment delivery from

hillslopes adjacent to rivers makes up a large fraction of the load (Carline et al. 2007). Vegetation growing on streambanks can help trap sediment and reduce nutrient loads entering waterways. Other benefits of riparian restoration include increased shading that can reduce the impacts of extreme high temperatures to aquatic biota and supplying carbon to rivers from leaves and litter that fuel instream food webs (Rees et al. 2020). The emphasis in riparian restoration should be in those reaches where the vegetation was degraded prior to the fire and the post-fire restoration effort aimed to enhance ecological condition beyond that which existed prior to the fire.

Improving longitudinal connectivity within waterways is another mechanism that can help reduce the severity of impacts of fire to stream inhabitants. Man-made structures such as dams and weirs can limit the ability of biota to escape localised areas of poor water quality. For example, in regulated waterways the installation of fish-ways may be necessary to enable highly mobile taxa, such as fish, to move away from areas of poor water quality (Stuart et al. 2008). However, dams and impoundments can also be used to help mediate bushfire effects on streams. Release of high-quality water from dams can be used to dilute poor quality water washed in from fire affected tributaries.

Regardless of what mitigation strategy is pursued, there is a large demand for tools to help focus efforts to those areas where risk ecological, social or economic values is high. Simulations like those undertaken in this study provide the underpinnings for assessing water quality risks across catchments post-bushfires to prioritise actions.

CONCLUSION

The upper Murray River study area (15,000 km²) is a critical catchment for water supply. The 2019-20 bushfires were severely intense which burnt about 5,000 km² of

forested and rural lands. Localised heavy rainfall events immediately after fires generated large loads of sediment and contaminants (ash, nutrients, organics and metals) from the burnt catchment and moved them into the receiving Murray River. This cocktail of contaminants threatened water quality and the ecosystem in the upper Murray River and Lake Hume.

In this study, we estimated sediment transport from burnt areas and assessed short and long-term impacts on the receiving water quality, a vital element for aquatic functioning of the Murray-Darling basin. Streamflow increased by 10-20% in the first year. Assuming similar rainfall patterns in year 1 and year 2 after the bushfire, sediment load from Cudgewa sub-catchment is likely to increase by 200% in the first year followed by another 27% in the second year compared to pre-fire condition. For Lake Hume the load was even higher, up to 5 fold. As a result, high ash content and pitch-black watercolour were observed following the first flush after bushfires. Despite near normal dissolved oxygen in water, localised fish kills were observed due to extremely high sediment and ash that physically clogged their gills. The increased nutrient load in the lake is expected to augment the risk of algal blooms due to internal loading in the coming years. Combined effects of ash, sediment and contaminants has the potential to negatively impact growth, reproduction and survival of many aquatic biota.

The functional modelling framework developed in this project can be used to investigate the spatial scales of bushfire impact on suspended sediment loads under varying bushfire extent and severity. However, further work is warranted to improve the robustness of predictions by addressing knowledge gaps such as magnitudes and timing of predicted post-bushfires increases in sediment loads against real observations. For example, delivery will be especially impaired following post-fire

erosion events, which can mobilise large amounts of sediment on hillslopes and transport them to the first-order drainage network.

In our study, we could not do fire severity ground truthing and enough water sampling due to the Covid-19 pandemic and fire related travel restrictions and access issues. Despite its limitations, this study provides useful information to our understanding of bushfires impacts on water quality and will form an integrated approach to minimise the impact of future mega-fire events in many fire prone catchments across the world. The new modelling method we used can be applied elsewhere for preparing adverse effects of rain following a bushfire by minimising sediment flow offs.

LIST OF FIGURES

Figure 1. Study area map showing the catchment boundary, river network, stream gauge and lakes in the Upper Murray catchment in south eastern Australia. Numbers in the pink shaded area represent 13 sub-catchments of Cudgewa Creek catchment which were selected for detailed sediment modelling.

Figure 2. Burn severity map for the Upper Murray catchment using the difference Normalised Burn Ratio (dNBR). Green triangles represent the location of stream gauges. Landsat-8 imagery used in the calculation (courtesy of the U.S. Geological Survey).

Figure 3. Comparison between model-simulated pre- and post-fire streamflow at Berringama on Cudgewa Creek.

Figure 4. Model-simulated monthly post-fire sediment load at (a) the Cudgewa North sub-catchment in the Upper Murray catchment, and (b) at Jingellic upstream to the inflow into Lake Hume reservoir.

Figure 5. Nitrogen, phosphorus, dissolved organic carbon concentrations and flow rate during and after the 2019/20 bushfire (left panel) and loads for the period 2016-2020 (right panel). (Red line represents the Murray River at Jingellic, NSW and the blue line represents the Mitta Mitta River at Tallandoon, Victoria).

Figure 6. Total and soluble copper concentrations in the grab water samples collected from the Upper Murray at different time intervals. DGV: default guideline value, representing the 95% and 99% species protection guideline values (95% and 99% DGVs) for freshwater.

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Table 1. Modified RUSLE C and K parameter values to account for effects of fire.

Disturbance Type	C factor			K factor		
	C_{base}	C_{peak}	ξ_C	K_{base}	K_{fire}	ξ_K
Bushfire	0.01	0.35	0.4	0.027	0.081	1











