Received: 8 April 2022 | Revised: 19 August 2022 | Accepted: 12 September 2022

DOI: 10.1111/ddi.13640

RESEARCH ARTICLE

Diversity and Distributions WILEY

Modelling the spatial extent of post-fire sedimentation threat to estimate the impacts of fire on waterways and aquatic species

Michelle Ward[1,2,3] | Darren Southwell[4] | Rachael V. Gallagher[5] | Tarmo A. Raadik[6] | Nick S. Whiterod[7] | Mark Lintermans[8] | Gary Sheridan[9] | Petter Nyman[10] | Andrés F. Suárez-Castro[1,11] | Jessica Marsh[12] | John Woinarski[13] | Sarah Legge[1,13,14]

[1]Centre for Biodiversity and Conservation Science, The University of Queensland, St Lucia, Queensland, Australia

[2]School of Earth and Environmental Sciences, The University of Queensland, Brisbane, Queensland, Australia

[3]WWF-Aus, Brisbane, Queensland, Australia

[4]Conservation Biology Research Group, School of Environmental and Life Sciences, The University of Newcastle, Callaghan, NSW, Australia

[5]Hawkesbury Institute for the Environment, Western Sydney University, Penrith, New South Wales, Australia

[6]Department of Environment, Land, Water and Planning, Arthur Rylah Institute for Environmental Research, Heidelberg, Victoria, Australia

[7]Aquasave–Nature Glenelg Trust, Victor Harbor, South Australia, Australia

[8]Centre for Applied Water Science, University of Canberra, Canberra, Australian Capital Territory, Australia

[9]School of Ecosystem and Forest Sciences, University of Melbourne, Parkville, Victoria, Australia

[10]Alluvium Consulting Australia, Cremorne, Victoria, Australia

[11]Australian Rivers Institute, Griffith University, Nathan, Queensland, Australia

[12]Harry Butler Research Institute, Murdoch University, Murdoch, Western Australia, Australia

[13]Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, Northern Territory, Australia

[14]Fenner School of Environment & Society, The Australian National University, Canberra, Australian Capital Territory, Australia

Correspondence
Michelle Ward, Centre for Biodiversity and Conservation Science, The University of Queensland, St Lucia, Qld, Australia.
Email: michellesarahward1@gmail.com

Funding information
Australian Government National Environmental Science Program

Editor: Alan Andersen

Abstract

Aim: Fires can severely impact aquatic fauna, especially when attributes of soil, topography, fire severity and post-fire rainfall interact to cause substantial sedimentation. Such events can cause immediate mortality and longer-term changes in food resources and habitat structure. Approaches for estimating fire impacts on terrestrial species (e.g. intersecting fire extent with species distributions) are inappropriate for aquatic species as sedimentation can carry well downstream of the fire extent, and occur long after fire. Here, we develop an approach for estimating the spatial extent of fire impacts for aquatic systems, across multiple catchments.

Location: Southern Australian bioregions affected by the fires in 2019–2020 that burned >10 million ha of temperate and subtropical forests.

Methods: We integrated an existing soil erosion model with fire severity mapping and rainfall data to estimate the spatial extent of post-fire sedimentation threat in waterways and in basins and the potential exposure of aquatic species to this threat. We validated the model against field observations of sedimentation events after the 2019–20 fires.

Results: While fires overlapped with ~27,643 km of waterways, post-fire sedimentation events potentially occurred across ~40,449 km. In total, 55% (n = 85) of 154 basins in the study region may have experienced substantial post-fire sedimentation. Ten species—including six Critically Endangered—were threatened by post-fire sedimentation events across 100% of their range. The model increased the estimates for potential impact, compared to considering fire extent alone, for >80% of aquatic species. Some species had distributions that did not overlap with the fire extent, but that were entirely exposed to post-fire sedimentation threat.

Conclusions: Compared with estimating the overlap of fire extent with species' ranges, our model improves estimates of fire-related threats to aquatic fauna by capturing the complexities of fire impacts on hydrological systems. The model provides a method for quickly estimating post-fire sedimentation threat after future fires in any fire-prone region, thus potentially improving conservation assessments and informing emergency management interventions.

KEYWORDS
Australia, erosion, fires, megafires, model validation

1 | INTRODUCTION

Freshwater species represent some of the most imperilled of ecological groupings globally (Johnson et al., 2017), and their conservation is becoming increasingly challenging given the complex and interacting ecological and social challenges inherent to their protection (Dudgeon et al., 2006; Lintermans, 2013). An emerging threat to aquatic species and habitats is changing fire regimes. Many parts of the world are experiencing larger, more frequent and more intense fires, often outside of the traditional fire season (Bowman et al., 2020). Whereas the impacts of changing fire regimes on terrestrial ecosystems and species are well recognized (Enright et al., 2015; Legge, Rumpff, et al., 2022), less attention has been directed towards understanding the consequences of fire regime change for aquatic ecosystems (Bixby et al., 2015; Gomez Isaza et al., 2022). This omission is problematic because approaches to assessing impacts developed for terrestrial systems may not adequately capture impacts in freshwater systems, decreasing the potential for effective post-fire conservation actions.

In freshwater ecosystems, fires can cause immediate impacts from the radiant heating of the water and the loss of vegetative cover (Cooper et al., 2015). However, the largest impacts on freshwater ecosystems often occur post-fire, when rainfall causes surface run-off and influxes of ash, soil and timber debris into waterways (Gomez Isaza et al., 2022). Such sediment influxes increase markedly after fire due to the loss of the vegetation filter and because of changes in soil structure and increased hydrophobicity (i.e. water repellence) increase erosion (Nyman et al., 2014; Sheridan et al., 2007). The sediment influxes may contain a complex milieu of nutrients (e.g. phosphorus and nitrate), ions (e.g. sodium and chloride), metals (e.g. magnesium, iron and copper) and polycyclic aromatic hydrocarbons (PAHs), all of which can be toxic to aquatic fauna (Gomez Isaza et al., 2022). Water quality is often reduced, typically through the rapid reduction in dissolved oxygen concentrations, along with excessive growth of cyanobacteria caused by the mobilization of nutrients (Lyon & O'Connor, 2008). As well as causing mortality in freshwater species, post-fire sedimentation can cause sublethal impacts through infilling of thermal refugia (pools), increased predation and disease, reduced fecundity and impaired physiological performance and behaviour (Cramp et al., 2021). Importantly, fire-related sedimentation and adverse water quality events can occur tens of kilometres downstream of the nearest fire (Lyon & O'Connor, 2008; Silva et al., 2020) and habitat changes may persist for decades (Leonard et al., 2017).

In Australia, a three-year drought and high temperatures combined to create an extreme fire season over the austral summer of 2019–2020 (Nolan, Blackman, et al., 2020). More than 10 million hectares of temperate and subtropical forested environments burned (Legge, Woinarski, et al., 2022). Ecosystems were impacted over a much greater spatial extent than previously recorded. For example, over 20% of Australia's eucalypt forests burned, a much higher proportion than the annual average of 2% (Boer et al., 2020). For terrestrial species, the overlap between the fire extent and their geographic range has been used as the starting point for estimating ecological impact (Gallagher et al., 2021; Gallagher et al., 2022; Legge, Rumpff, et al., 2022;

Legge, Woinarski, et al., 2022; Ward et al., 2020). This approach is inadequate for aquatic species, as the downstream passage of post-fire sediment means that even species with distributions that do not overlap at all with the fire footprint can be affected. To achieve a better representation of fire impact on aquatic systems, approaches are needed that consider fire effects on soil and vegetation, the landscape context and the potential for sediment transport downstream. The approach should bring together the factors that affect the threat of elevated sedimentation after fire, which include how fire extent and severity, and post-fire rainfall, increase the usual erosion rates in a given area.

Here, we produce a spatial modelling approach for estimating the short-term post-fire sedimentation threat and apply it to Australian waterways within, or downstream of, the footprint of the 2019–2020 fires. We adapt an existing soil erosion model based on erodibility of soil, rainfall erosivity, slope and land cover (Renard et al., 1997; Teng et al., 2016), by adding consideration of fire extent and severity in the upstream catchment, and the occurrence of upstream rainfall likely to lead to surface run-off. We then intersect our post-fire sedimentation threat model with the distributions of 46 aquatic animal species (many of which are recognized as threatened) to explore the possible exposure to post-fire sedimentation for a range of freshwater species. As well as providing insight into the impacts of the 2019–2020 Australian fires on freshwater species, this modelling approach is broadly applicable to assessing short-term post-fire impacts on aquatic systems in other regions globally.

2 | MATERIALS AND METHODS

The study region for this analysis comprises 43 temperate, Mediterranean and subtropical bioregions (area = 2.2 million km^2), as defined in the Interim Biogeographic Regionalisation for Australia dataset (Commonwealth of Australia, 2018). These bioregions were previously identified as the most heavily fire-impacted areas (DAWE, 2020).

We aimed to estimate the spatial extent of substantial post-fire sedimentation events, or so-called "sediment slugs" (Lyon & O'Connor, 2008). These highly visible soil, debris and ash sludges in waterways can cause high rates of immediate mortality and/or long-term changes in waterway habitat. Sediment slugs arise because fires followed by rain can cause sediment influxes to waterways that are many times greater than pre-fire (Biswas et al., 2021; Smith et al., 2011). To create a spatial model for post-fire sedimentation threat for all rivers, streams and lakes (hereafter, waterways) within the study region, we built on the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997; Renard & Freimund, 1994) by also considering fire extent and severity, and rainfall events likely to cause surface run-off (and thus transport of sediment into waterways). Below we describe each component of the post-fire sedimentation threat model (rainfall, fire severity, RUSLE) and then outline how these components were combined in that model (Figure 1).

2.1 | Rainfall

Sedimentation into waterways is more likely after heavy rain as it increases the chance of surface run-off (Wilson et al., 2018). Surface run-off can be triggered by short periods of heavy rain or longer periods of less intense rain that accumulate to a high running total. A spatial layer of rainfall conditions in the 2-month period (15 January to 15 March 2020) immediately after the majority of fires was created using daily and fortnightly rainfall data from the 5 km resolution Australian Water. Availability Project via http://www.bom.gov.au/jsp/awap/. This period was characterized by anomalously high rainfall relative to long-term averages for these months, most of which dissipated by mid-March 2020. The mean and standard deviation for daily and fortnightly rainfall was calculated using rainfall data for the same period for the years 2000 to 2019. Locations with daily or fortnightly rainfall that were 1 standard deviation above the average rainfall over the previous 20-year period were classified as areas of "high rainfall."

2.2 | Fire severity

Sedimentation into waterways tends to increase with fire severity—the most dramatic impacts occur after high severity fires which entirely remove vegetation and large amounts of decaying organic material on the forest floor such as twigs, branches, logs and leaves, which would otherwise filter sediment from entering the water (Nyman et al., 2015, 2019; Reneau et al., 2007). Vegetation and organic material can also intercept rainfall, therefore reducing the erosion potential of the fire-impacted soils. To map fire severity, we used the Australian Government's Remote Sensing and Landscape Science Branch's Australian Google Earth Engine Burnt Area Map (AUS GEEBAM) (Commonwealth of Australia, 2020). The dataset uses Sentinel-2 satellite imagery from before and after the 2019–2020 fire season to assess burn area and severity. AUS GEEBAM presents four fire severity classes for the areas represented in the National Indicative Aggregated Fire Extent Dataset. These classes include the following: unburnt (little–no change in vegetation); burnt at low and moderate severity (some–moderate change in vegetation); burnt at high severity (vegetation scorched); and burnt at very high severity (vegetation consumed); and with relatively small areas (<1%) categorized as no data (outside fire footprint, or not vegetated) (Roff, 2020).

2.3 | Combining rainfall with fire severity

We merged the fire and rainfall raster layers to calculate a combined score (F) for each raster cell, where F represents relative rankings of fire and rainfall combinations in terms of how they might amplify sediment mobilization in a given area (Table 1). We used ranked values for fire because the raw data on fire severity is also ranked (e.g. low–moderate, high and very high). While the raw rainfall data are numerical, we converted them to ranked values because we cannot

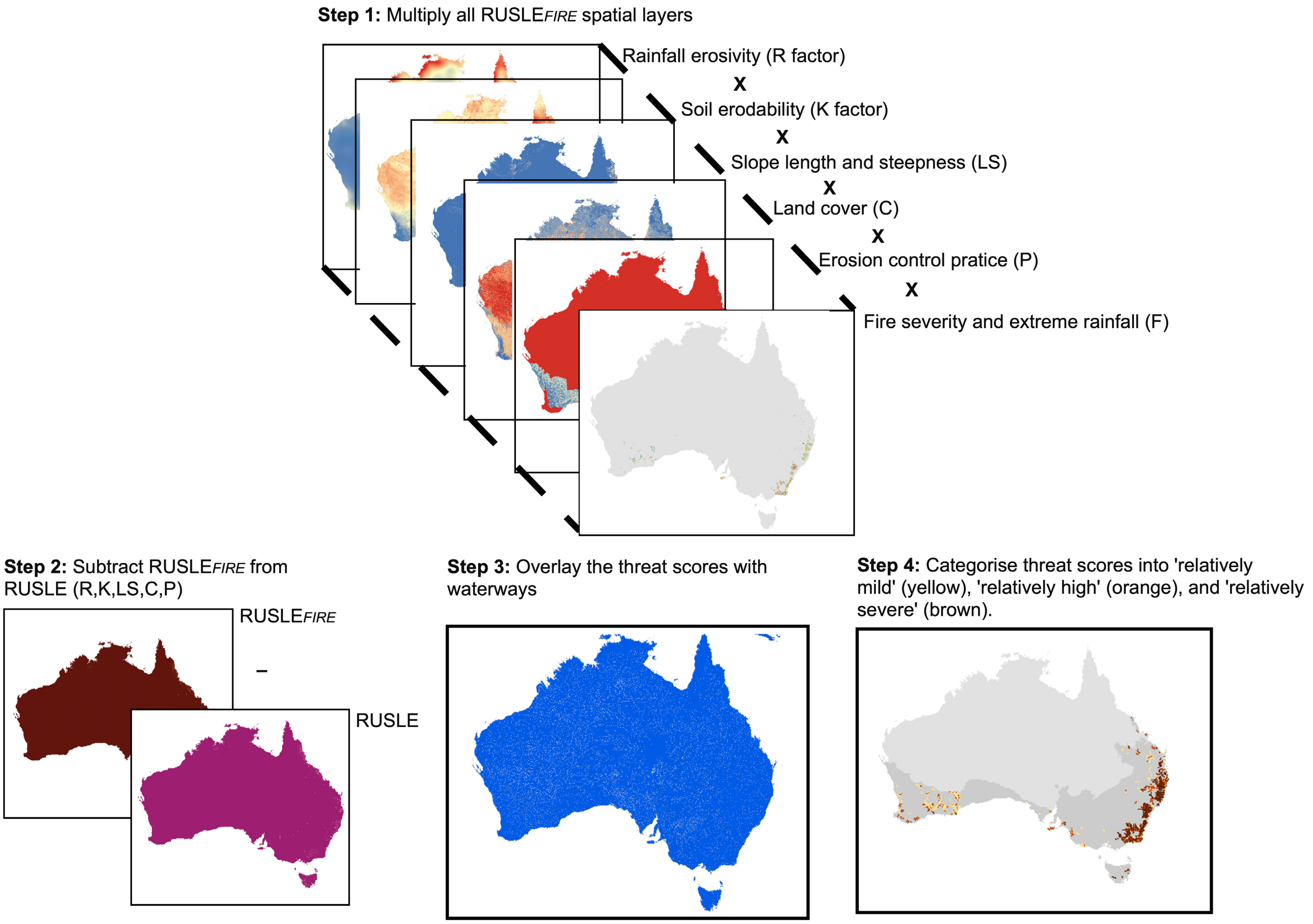

FIGURE 1 Conceptual figure of the post-fire sedimentation threat model. The darker grey shading in the map at Step 4 is the 43 Australian subregions that were most heavily affected by the 2019–2020 fires.

TABLE 1 Rank scores of changes in risk of sediment (soil/ash) mobilization from combinations of fire severity and rainfall (*F*)

F: rank scores for changes in risk of soil/ash mobilization	No fire	Low and moderate fire	High and very high severity fire
Normal rainfall	1	1	2
High rainfall	1	2	4

presume a linear relationship between increases in rainfall and sediment mobilization, given the scale of our study area and the diversity of soil types, slopes and land uses across that area. Ranked values are also appropriate because the base RUSLE model incorporates dimensionless attributes (e.g. LS, C and P).

We then assume that above-average rainfall in combination with fire would likely result in higher risk of sediment mobilization. Without fire, and with normal rainfall, the erosion into a waterway is predicted by RUSLE alone, so the *F* score is 1. If normal rain follows low–moderate severity fire, or high rainfall occurs in the absence of fire, the rank score for sediment mobilization remains 1 (i.e. no change). The risk of sediment mobilization increases to an intermediate level when severe fire is followed by normal rain, or when low–moderate fire is followed by high rainfall, so these combinations receive a score of 2. The greatest increase in sediment mobilization is when high severity fire and high rainfall co-occur, so this combination receives the highest score of 4 (Table 1). These ranked values are arbitrary; the relative order of the ranks is important, but changing the scores (e.g. using 6 instead of 4 for high severity fire plus heavy rainfall) is unlikely to affect our assessments of the exposure of each species to sedimentation threat. This is because of the multiplicative nature of our formula, which implies that the areas with high rainfall and high fire severity will always rank first compared with the other categories.

The *F* scores were calculated at a 1 km resolution, to match the resolution of the RUSLE layer (see below; Teng et al., 2016).

2.4 | Revised Universal Soil Loss Equation

The RUSLE model can be applied on any land use, including areas of modified vegetation. It was first introduced in the USDA Soil and

Water Conservation Service in 1993 and has been used extensively to explore soil loss in many countries (Renard et al., 1997; Suárez-Castro et al., 2021; Teng et al., 2016). The RUSLE calculates the annual soil loss by water on a hillslope using a linear equation that is the product of six environmental factors:

$$\text{RUSLE} = R \times K \times L \times S \times C \times P \tag{1}$$

where RUSLE is the average annual soil erosion at each cell ($\text{t ha}^{-1}\ \text{year}^{-1}$); R is the rainfall-run-off erosivity factor ($\text{MJ mm ha}^{-1}\ \text{h}^{-1}\ \text{year}^{-1}$); K is soil erodibility factor ($\text{t ha h ha}^{-1}\ \text{MJ}^{-1}\ \text{mm}^{-1}$); L is the slope length factor; S is the slope steepness parameter; C is the cover management factor (representing the ratio of soil loss from land cropped under specific conditions to the corresponding loss from a tilled, continuous fallow condition); and P is the erosion control support practice factor (which provides a ratio between the soil loss expected for a certain soil conservation practice to that with increasing and decreasing surface slope) (Table 2) Teng et al. (2016) have calculated the RUSLE values for all of Australia at a scale of 1 km.

2.5 | Revised Universal Soil Loss Equation with fire and rainfall ($\text{RUSLE}_{\text{Fire}}$)

We expanded upon the RUSLE variables (Table 2) by incorporating fire severity and rainfall score (F) within the linear equation and then subtracted the standard RUSLE from the expanded formula to find the relative amounts of annual erosion expected, on average, as a result of the fire and rainfall combinations (Table 1; Figure 1). The new $\text{RUSLE}_{\text{Fire}}$ is calculated using:

$$\text{RUSLE}_{\text{Fire}} = (R \times K \times L \times S \times C \times P \times F) - \text{RUSLE} \tag{2}$$

Since the fire and rainfall score is a rank, the $\text{RUSLE}_{\text{Fire}}$ indicates relative differences in erosion among waterways as a result of fire and rainfall, over the background erosion rates. If background RUSLE values are low, then the multiplier of high severity fire × high rainfall could have a smaller effect on post-fire sedimentation threat than if the background RUSLE values are high, but the catchment experienced low severity fire and high rainfall, or high severity fire and normal rainfall. Note that these rankings do not predict the actual post-fire sediment load in waterways and how sediment changes over time, nor do they consider the potential interactions between fire severity and the key soil and topographical variables. More complex modelling that considers these issues has been carried out at the sub-catchment scale (Biswas et al., 2021), but is not yet possible at the scale of our study region. Our aim instead was to create a tool that could be used to quickly estimate the spatial extent of the threat of post-fire sedimentation and use these data to inform rapid conservation interventions, such as fish rescues (Shelley et al., 2021), and conservation status assessments (Legge, Rumpff, et al., 2022).

The post-fire sedimentation threat scores ($\text{RUSLE}_{\text{Fire}}$) were intersected with waterways using HydroRivers (Version 10) (Linke et al., 2019; WWF, 2019). We recognize that areas of the drainage that do not intersect with the waterway can also contribute to post-fire sedimentation, but consider the waterway intersect to be a reasonable sample of the modelled values in that drainage area. When there were multiple risk scores intersecting with waterway segments (where a segment is the waterway between two network nodes), the mean value was assigned to the entire segment (mean segment length = 5 km). To account for downstream cumulative impacts, sediment scores were cumulatively summed from the most upstream segment affected by fire down to segments within 50 km of the fire extent perimeter. The 50 km threshold was selected based on in situ sedimentation observations from previous fires, but we also examined the sensitivity of the model by varying this threshold to 30 km and 70 km past the fire extent boundary (Lyon & O'Connor, 2008; Silva et al., 2020).

To explore the patterning of sedimentation threat scores across waterway systems, catchments and aquatic species, we divided

TABLE 2 Variables, value ranges, and description for our new model, $\text{RUSLE}_{\text{Fire}}$

Variable	Value range	Description
R	157–18,727	Rainfall erosivity is used to indicate the ability of water to detach and move soil.
K	0.02–0.03	Soil erodibility indicates the susceptibility of soil to erode using soil particle size.
LS	0.03–61	The slope length is defined as the horizontal distance from the original point of overland flow to the point where the slope decreases to the extent that deposition begins, or where run-off flows into a waterway. The slope steepness is the influence of slope gradient on erosion.
C	0.01–0.35	The cover management represents the ratio of soil loss from land cropped under specific conditions to the corresponding loss from a tilled, continuous fallow condition.
P	0.5–1	The erosion control practice gives the ratio between the soil loss expected for a certain soil conservation practice to that with increasing and decreasing surface slope.
F	1–4	Rank scores from the combination of fire severity during 2019–2020 Australian fires and rainfall (as per Table 1).

positive scores into "relatively mild," "relatively high" and "relatively severe" threat classes using the interquartile range of logged sedimentation scores, where the classes of threat are defined relative to each other:

- No risk (score of 0, outside the study region, or too far downstream)
- Relatively mild threat score (≤25%)
- Relatively high threat score (25%–50%)
- Relatively severe threat score (>50%)

We then calculated the proportion of waterways inside and outside the fire extent, and in each basin, that was exposed to mild, high and severe sedimentation threat.

2.6 | Validating the model predictions with field data

The $RUSLE_{fire}$ model was validated by overlaying the model predictions of post-fire sedimentation threat with field observations of sedimentation slug events, where ash and soil sediment was clearly visible in the water. The proportion of observed sedimentation slug events that corresponded with the spatial model was calculated. Sixteen observations were made by co-authors of this report (T. Raadik and M. Lintermans); another 10 observations are collated in Shelley et al. (2021). In addition, Silva et al. (2020) reported sedimentation events at 15 sites. Five of the 41 observations did not geographically align with waterway segments mapped in this study and, therefore, were removed from comparison.

2.7 | Potential impacts on freshwater fauna

We intersected the post-fire sedimentation threat model with the distributions of 25 aquatic vertebrate species (21 fish, 3 turtles and 1 mammal) that had been identified as fire-impacted in earlier assessments (Legge, Rumpff, et al., 2022; Legge, Woinarski, et al., 2022). Sub-catchment distributions were available for fish species from data compiled during the 2019 IUCN Red List assessment for Australian freshwater fish (https://www.iucnredlist.org/). Species distribution polygons for two species were enhanced by additional data supplied by experts (Legge, Rumpff, et al., 2022; Legge, Woinarski, et al., 2022; Southwell et al., 2020). Species distribution polygons for three turtles, the Manning River snapping turtle (*Myuchelys purvisi*), Georges' snapping turtle (*Wollumbinia georgesi*) and Bell's turtle (*Wollumbinia belli*), were compiled during the 2017 reptile assessment carried out by IUCN (Tingley et al., 2019). A distribution polygon for platypus (*Ornithorhynchus anatinus*) was based on distribution modelling (including areas where the platypus was known to occur or likely to occur) developed by DAWE. The distribution polygons for the fish, turtles and platypus were clipped to waterways.

We also intersected the post-fire sedimentation threat model with the distributions of 22 species from one representative invertebrate group, the spiny crayfish, *Euastacus* spp. This invertebrate group has relatively consistent and reliable information on ecology and distribution (Austin et al., 2022; Furse & Coughran, 2011; McCormack, 2012) and a high proportion of threatened species (Richman et al., 2015). We focussed our analyses on fire-impacted species previously identified as priorities for remedial management intervention (Legge, Rumpff, et al., 2022; Legge, Woinarski, et al., 2022) but modified this set by excluding one species with uncertain taxonomic status (Austin et al., 2022) and included two additional species where new knowledge indicated that they were fire-impacted: Cudgegong giant spiny crayfish (*Euastacus vesper*) (Hyman et al., 2020), and including a new candidate species *E.* cf. *rieki* (Austin et al., 2022). Species distribution polygons were compiled from previous distribution data and new observations collected in 2021 during a national conservation status assessment (Whiterod et al., 2022). Note that all the range maps encompass occurrence records for each species, but ignore habitat availability within the polygon, and therefore may overestimate the occupied range. We clipped each species' distribution polygons to waterways.

We considered the additional insight into potential fire impacts gained by using our post-fire sedimentation threat model over a simpler fire extent spatial dataset, by comparing estimates of the overlaps with species' distributions generated from both approaches.

3 | RESULTS

The fires overlapped with 24,713 km of waterways, yet considering the downstream impacts of post-fire sedimentation, the fires potentially affected more than 40,449 km of waterways across southern Australia (Figure 2). We found that of the 24,713 km inside the fire extent, 25.3% (6250 km) was exposed to relatively mild sedimentation threat, 21.9% (5410 km) to relatively high and 52.8% (13,053 km) to relatively severe threat; of the 15,736 km of waterway outside the fire extent, 24.6% (3870 km) was exposed to relatively mild sedimentation threat, 33.0% (5191 km) to relatively high, and 42.4% (6675 km) to relatively severe threat. The model predicted high-to-severe post-fire sedimentation threat at 86% of the 36 sites with field observations of sedimentation slug events (Figure 2).

We found that the total waterway length impacted when assuming sediment was carried up to 50 km downstream (40,449 km) did not change dramatically if that distance was changed to 30 km (37,137 km) or to 70 km downstream (42,412 km). This is due to the large fire extent that covered the majority of the mid and upper parts of waterway networks; if the fire extent were smaller, the relative proportions of waterways inside/outside the fire-affected areas would shift, and altering the downstream distance would make a larger difference to the change in total waterway length. The field observations of sedimentation events matched the modelled extent of sedimentation threat well (86%) regardless of whether the 30 km,

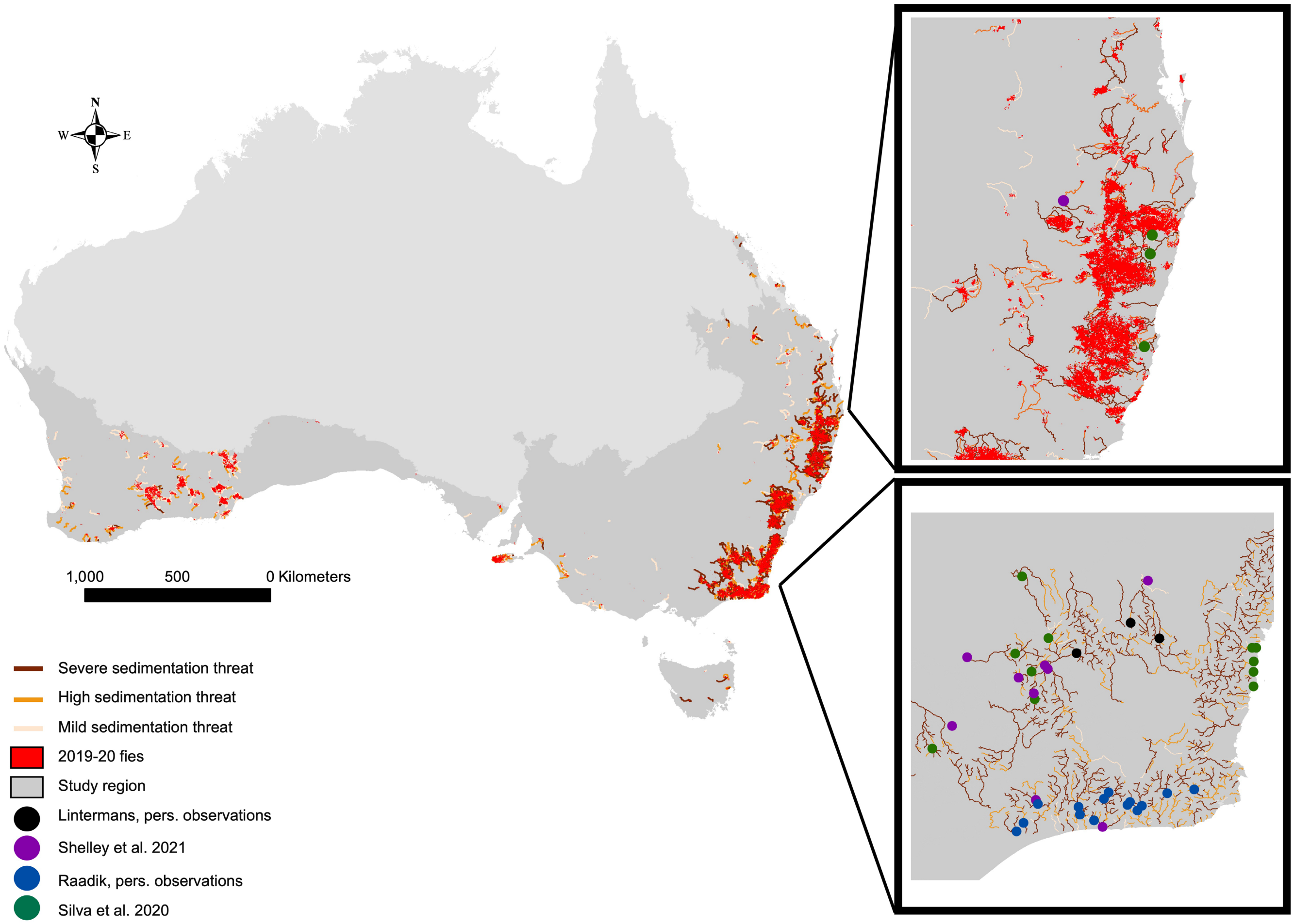

FIGURE 2 Overview of 2019–2020 fire extent (red) and waterway network representing relatively mild post-fire sedimentation threat (cream), relatively high threat (orange) and relatively severe threat (brown). The two panels on the right are zoomed-in to show the overlap of observed post-fire sedimentation events over the modelled post-fire sedimentation threat; the top panel shows the fire extent, but fire extent is omitted from the bottom panel for clarity. Four different datasets were used to validate the model. M. Lintermans, personal observations (black dots); Shelley et al. (2021) (purple dots); Silva et al. (2020) (green dots); and T. Raadik, personal observations (blue dots). The study region (of 43 subregions) is represented as darker grey on the main map.

50 km or 70 km threshold for downstream sediment transport was used.

In total, 55% of 154 basins in the study region were exposed to the threat of post-fire sedimentation after the 2019–20 fires (Appendix S1). The basin with the longest total waterway length exposed to post-fire sedimentation threat was the Salt Lake basin in Western Australia, of which >5000 km was exposed to post-fire sedimentation threat (5% of waterway length, at mostly relatively mild threat, Figure 3), closely followed by the Clarence River basin (3400 km; 64% of waterway length) and the Hawkesbury River basin in the Sydney region (3000 km; 60% of waterway length). The Clarence River, Hawkesbury River and Murrumbidgee River basins were all predicted to have >1000 km of waterways exposed to relatively severe post-fire sedimentation threat, while the Salt Lake, Clarence River and East Gippsland basins were predicted to have >500 km of waterways exposed to relatively high post-fire sedimentation threat. The East Gippsland, Clyde River-Jervis Bay, Tuross River and Moruya River basins had the largest proportions of affected waterways, all with >80% of their lengths exposed to post-fire sedimentation threat. The basins with the highest proportions (>50%) of waterway length exposed to relatively severe post-fire sedimentation threat included Tuross River, Moruya River, Clyde River-Jervis Bay and Hawkesbury River basins (Figure 3).

Of the 25 aquatic vertebrate species included in this analysis, all had distributions that overlapped with the spatial model's predicted extent of post-fire sedimentation threat. Five fish species had their entire range exposed to the threat of post-fire sedimentation. Four of these are listed as Critically Endangered by the IUCN Red List (East Gippsland galaxias (*Galaxias aequipinnis*), McDowall's galaxias (*Galaxias mcdowalli*), stocky galaxias (*Galaxias tantangara*) and Yalmy galaxias (*Galaxias* sp. nov "Yalmy")), with the fifth yet to be assessed by the IUCN (Cann galaxias [*Galaxias* sp. 17 "Cann"]) (Figure 4). Four species had distributions that overlapped substantially (50–99%) with the predicted extent of post-fire sedimentation threat. This included the Vulnerable eastern freshwater cod (*Maccullochella ikei*), the Endangered nonparasitic lamprey (*Mordacia*

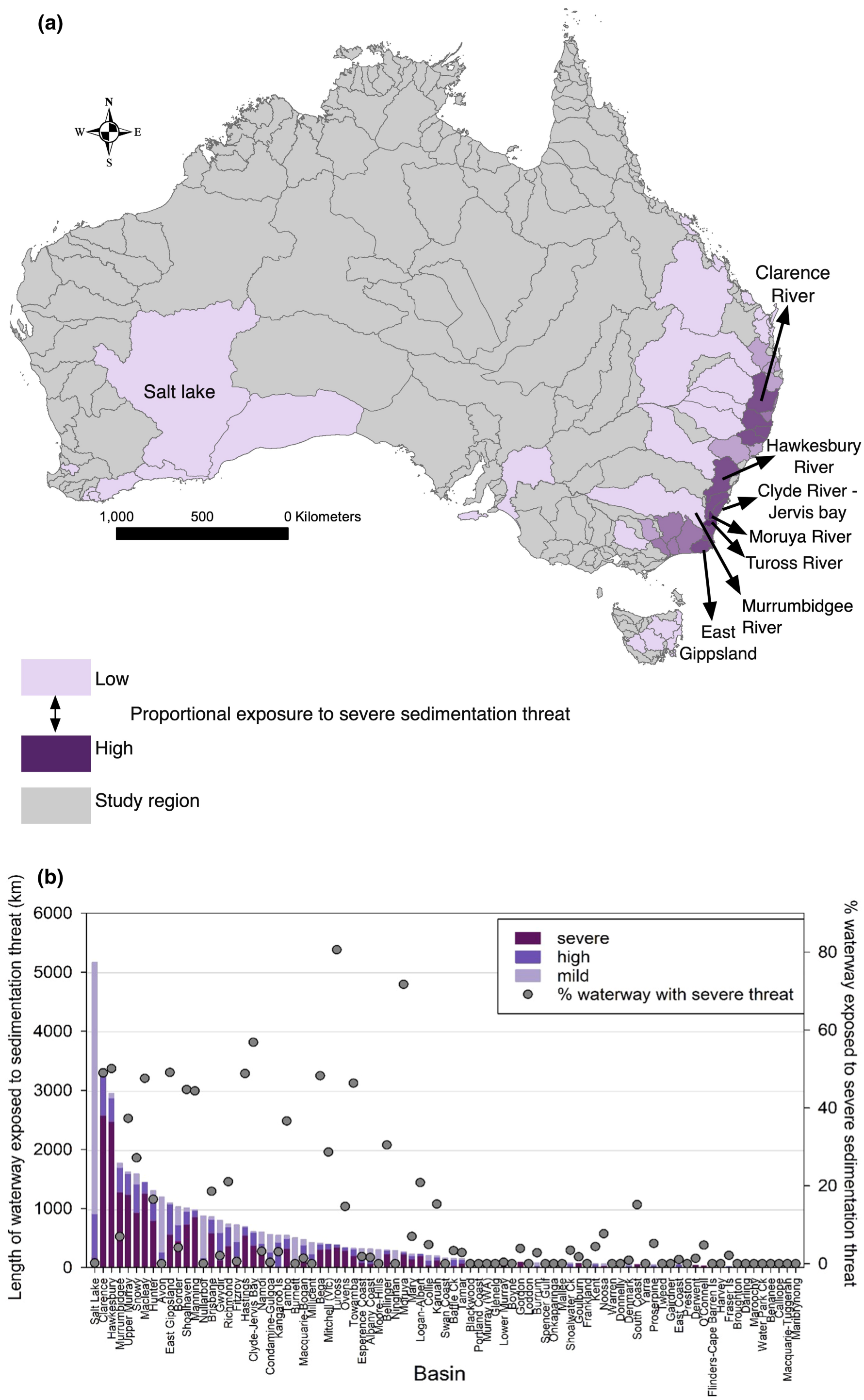

FIGURE 3 Overview of post-fire sedimentation threat to the Australian basin network following the 2019–2020 fires. (a) Low proportional exposure (minimum was 0.32% of waterway length) to relatively severe post-fire sedimentation threat is illustrated using light purple, while high proportional exposure (maximum was 73% of waterway length) to relatively severe post-fire sedimentation threat is illustrated using dark purple. (b) Graph illustrating the threat in kilometres (left *Y* axis) on basins (*X* axis) with values for each catchment shown as a stacked bar (where relatively mild is represented in light purple, relatively high in dark purple, and relatively severe is maroon), and proportion of river length exposed to severe sedimentation threat as grey dots (right *Y* axis). Note that one basin extends substantially outside the study region (Salt Lake); the sedimentation threat is depicted for the whole basin but would only apply to the portion of the basin that intersects the study region.

praecox) and the Vulnerable Blue Mountains perch (*Macquaria* sp. nov. "Hawkesbury"). Four species had between 30 and 49% of their range overlapping with the predicted post-fire sedimentation threat, including SE Victorian blackfish (*Gadopsis* sp. nov. SE Victoria) which has not been assessed, Manning River snapping turtle (*Wollumbinia purvisi*) which is Data Deficient and Dargo galaxias (*Galaxias mungadhan*) and short-tail galaxias (*Galaxias brevissimus*), both of which are Critically Endangered.

Of the 22 invertebrate species, we estimated that 83% ($n = 19$) were exposed to post-fire sedimentation threat. Five species, the Critically Endangered smooth crayfish (*Euastacus girurmulayn*), the Critically Endangered Tianjara crayfish (*Euastacus guwinus*), and three species yet to be assessed by IUCN, *Euastacus* sp. 1, *Euastacus* sp. 3 and Cudgegong giant spiny crayfish (*Euastacus vesper*), had ranges that overlapped entirely with the predicted extent of post-fire sedimentation threat. Ten species, including the Endangered East Gippsland spiny crayfish (*Euastacus bidawalus*), the Endangered Orbost spiny crayfish (*Euastacus diversus*) and the Endangered Clark's crayfish (*Euastacus clarkae*), had ranges that overlapped substantially (50%–99%) with the predicted extent of

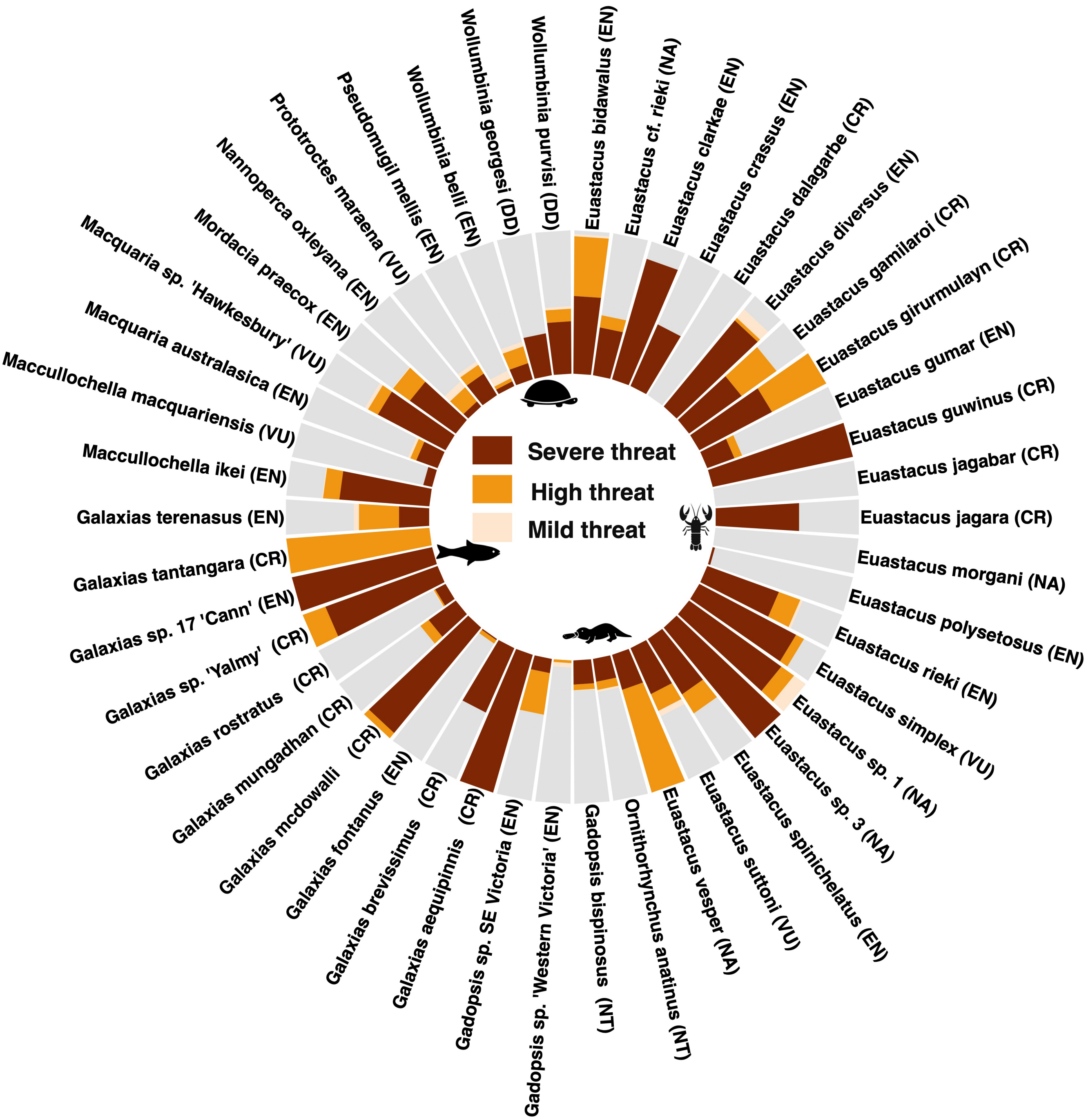

FIGURE 4 Proportion of species distribution threatened by post-fire sedimentation for each taxon assessed. Relative levels of threat are colour-coded as relatively mild (cream), relatively high (orange) and relatively severe (brown). Each taxon name includes their current IUCN conservation status, which can either be Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Data Deficient (DD), Least Concern (LC) or not assessed (NA).

post-fire sedimentation threat. Two species had between 30% and 49% of their range with the predicted extent of post-fire sedimentation threat (Figure 4).

The value of using the spatial model for post-fire sedimentation threat relative to fire extent alone can partly be seen by comparing the proportion of a species distribution that is considered as fire-affected using the two approaches (Figure 5). We found that 81% (n = 38) of species assessed had larger proportional overlaps when using the post-fire sedimentation threat spatial model, compared to using the fire extent overlap. For example, species such as stocky galaxias and smooth crayfish have 0% of their range affected when using fire extent, but this increases to 100% of their range affected using the post-fire sedimentation threat model.

4 | DISCUSSION

The impact of fires on aquatic systems extends well beyond the fire footprint, because fires can cause substantial sedimentation influx that can be transported downstream, and such influxes can occur long after the fire event itself. In this study, we developed an approach to predicting the spatial extent of post-fire sedimentation threat by considering the background erosion rates (which depend on attributes of the soil and topography), the extent and severity of fire, the occurrence of rainfall likely to cause surface run-off and the likely sediment transport distances in affected waterways. When overlapped with the distributions of representative aquatic fauna species, this spatial model increased estimates of potential impact from fire increase for most species, sometimes markedly so.

We predicted that the waterway length exposed to impacts from the Australian 2019–2020 fires was 46% greater than the length of waterways that directly overlapped with the fire extent. Post-fire sedimentation threat affected 85 basins, including the East Gippsland, Clyde River-Jervis Bay, Tuross River and Moruya River basins, which all had >70% of their waterways exposed to the threat of post-fire sedimentation. Our mapping of post-fire sedimentation threat, complemented by anecdotal observations (Gillanders & Reis-Santos, 2020), indicates that sedimentation may also affect some estuarine systems and near-shore marine environments due to their connectivity with fire-affected waterways. We found that 39% of the modelled sedimentation threat was outside the fire extent, although relatively severe sedimentation threat affected a slightly higher proportion of waterways within the fire extent (53%) rather than downstream of it (42%).

Using the post-fire sedimentation threat model, we identified species whose distributions minimally overlapped with fire, but which were likely impacted by fire-caused sedimentation events.

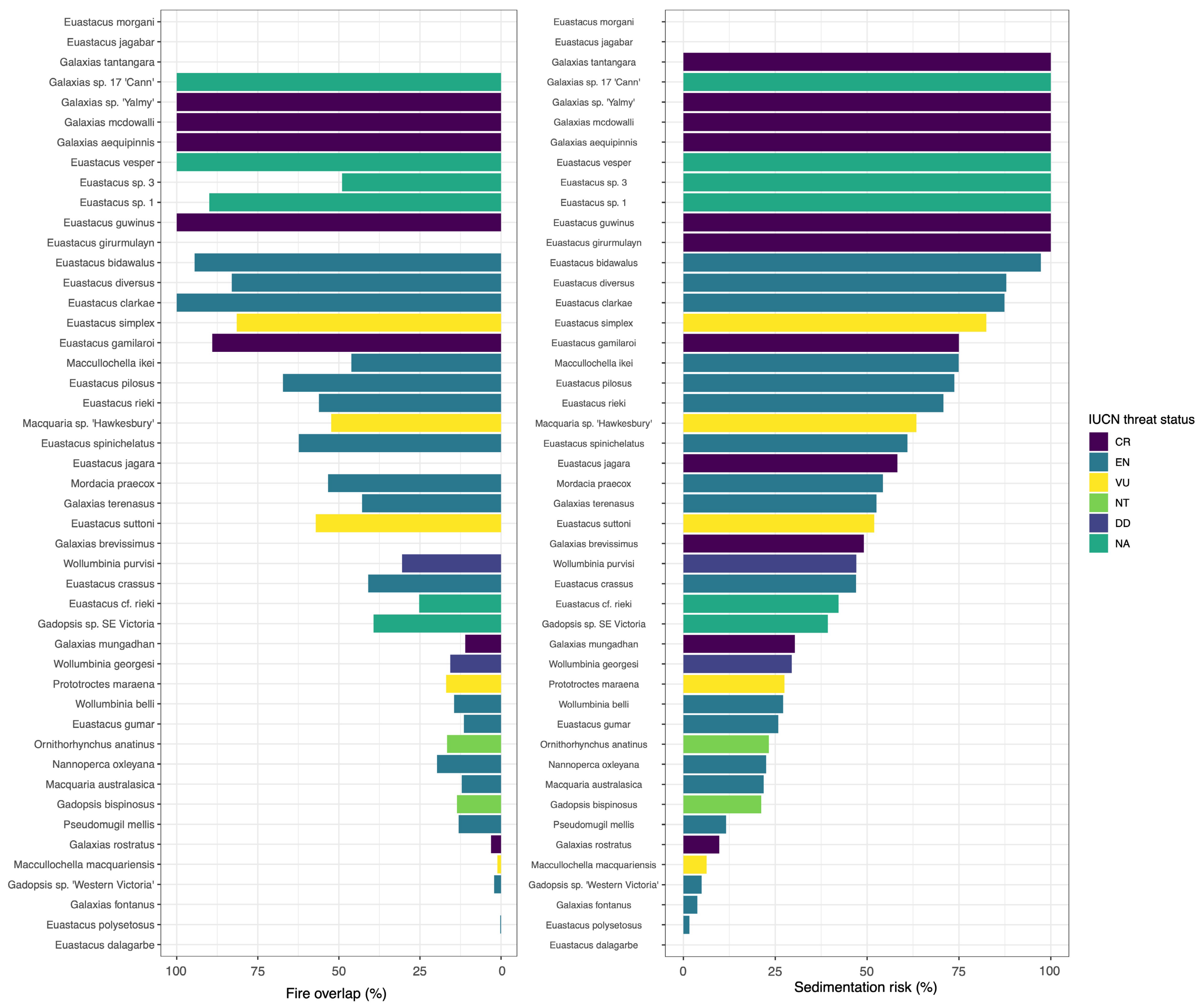

FIGURE 5 Comparison of the assessed threat to aquatic species distributions when intersected with fire extent overlap (left) and post-fire sedimentation threat mode (right). Each taxon is colour-coded by their current IUCN conservation status, which can either be Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Data Deficient (DD), Least Concern (LC), or not assessed (NA).

For example, smooth crayfish had 0% of its range overlapping with fire extent, yet once we considered the downstream sedimentation threat, this potential impact increased to 100% of its range. Similarly, *Euastacus* cf. *rieki* had 25% of its range overlapping the fire extent; however, this increased to 42% when we considered the downstream sedimentation threat. Without the application of the post-fire sedimentation threat model, species such as these may be overlooked and not receive the required post-fire management attention, illustrating how terrestrial approaches for estimating fire-related threats may fail in aquatic systems.

Our analysis indicated that parts of the ranges of at least 25 vertebrate species and 19 spiny crayfish species overlapped with the predicted extent of post-fire sedimentation threat. Of the species we considered, ten species (East Gippsland galaxias, McDowall's galaxias, stocky galaxias, Yalmy galaxias, Cann galaxias, smooth crayfish, Tianjara crayfish, *Euastacus* sp. 1, *Euastacus* sp. 3 and Cudgegong giant spiny crayfish) had 100% of their range overlapping with predicted post-fire sedimentation threat. Some of the species in our analysis were already considered at high risk (probability of extinction >50%) of becoming extinct within the next 20 years before the 2019–2020 fires (Lintermans et al., 2020; Richman et al., 2015). These include species such as short-tail galaxias and Dargo galaxias—both of which were predicted to have between 30% and 50% of their range overlapping with post-fire sedimentation threat. It is possible that the Yalmy galaxias is now functionally extinct as a result of post-fire sedimentation, with recent surveys recording only two males present (T. Raadik, unpublished data).

Aquatic species are not all equally vulnerable to sedimentation impacts. For example, unlike fish and other freshwater species, platypus could survive a sedimentation event, including a short-term drop in dissolved oxygen. However, platypus may be affected in the long-term if the riverbed shape or substrate is transformed and food resources are removed or scant for an extended period (Bino et al., 2021). Spiny crayfish shelter in burrows, with some species relying on burrows that connect directly to the waterway, while other species use burrows that are not connected to the waterway (Horwitz & Richardson, 1986). Spiny crayfish also have the capacity to temporarily exit water to avoid adverse water quality (McKinnon, 1995). The impacts of sedimentation events on spiny crayfish will therefore vary depending on aspects of the species' ecology and of the sedimentation event. Although specific animal behaviours may reduce the impact of sedimentation events, projected increases in fire frequency in coming decades may contribute to cumulative stress on individuals and populations, which increase the likelihood of local or global extinctions.

For vertebrates, we applied the model to distributions of fish, turtles and platypus. It is possible that some stream-dependent frog species were also affected by post-fire sedimentation events, but which species, and where, could be idiosyncratic depending on the reliance of different life stages (i.e. egg, tadpole and adult) on water, and the timing of those life stages relative to the post-fire sedimentation event. For invertebrates, we applied the post-fire sedimentation threat model to spiny crayfish, but there are many hundreds of freshwater invertebrate species, and applying the sedimentation threat model to these species is challenging, mainly because distributional data are so limited: in a complementary analysis of ca. 45,000 invertebrate species (terrestrial and aquatic) in the fire-affected regions, Marsh et al. (2021) found that 31% had only one record and 14% had only two records. Furthermore, there is no existing trait database for Australian invertebrates that categorizes species as aquatic or semi-aquatic, and the susceptibility of most species to sedimentation is not known. Marsh et al. (2021) recently undertook an assessment of fire impacts for 381 aquatic or semi-aquatic invertebrates (i.e. with part of the life cycle occurring in water) in the study region. Using the post-fire sedimentation threat model presented here, they estimated some sedimentation threat for 237 aquatic and semi-aquatic invertebrates, with 64 of these species having at least 50% of their known distribution being exposed to sedimentation threat. These comprised species from very diverse taxonomic groups including spiders (Arachnida: Trombidiformes), beetles (Coleoptera: Dytiscidae), mayflies (Ephemeroptera), flies (Diptera: Dolichopodidae), caddisflies (Trichoptera), stoneflies (Plecoptera), scorpionflies (Mecoptera), flatworms (Rhabditophora), freshwater snails (Gastropoda: Hypsogastropoda), copepods (Maxillopoda: Harpacticoida) and dragonflies (Odonata), suggesting that the Australian 2019–2020 fires may have had wide-ranging impacts on aquatic assemblages.

The impacts of the 2019–2020 fires on aquatic species are in addition to a legacy of other threatening processes such as land clearing resulting in polluted and degraded habitats, incursion of invasive species, water extraction and flow alteration, and anthropogenic climate change exacerbating drought, fire and flooding events (Dudgeon et al., 2006; Lintermans, 2013). For example, we estimated that 27% of the distribution of Bell's turtle was exposed to post-fire sedimentation threat, but the species also is already facing significant nest predation rates (>96%) by invasive foxes (*Vulpes vulpes*) (Thompson, 1983). This example highlights that for a conservation assessment our estimates of fire-related sedimentation threat need to be considered in the context of other information on past and future population trajectories and threats for each taxon. Ideally, post-fire surveys should be undertaken urgently to provide field data on population status across the range of each taxon, in both fire-affected areas and locations not affected by the 2019–2020 fires. Those surveys should also seek to identify any important populations surviving in fire-affected areas and provide an evidence base for better resolving species' fire susceptibility and a baseline for monitoring future trends and responses to post-fire recovery management actions.

Our model of post-fire sedimentation threat was founded upon a well-established soil loss model (Renard et al., 1997; Renard & Freimund, 1994; Teng et al., 2016) and refined to incorporate the extra erosion threat caused by high severity fires and above-normal rainfall. While it corresponded well with observed sedimentation events, it is not without limitations. We used modelled estimates of fire extent and severity and rainfall. However, fire and rainfall may not be detected across all waterways due to averaging techniques used across 40 m^2 grid cells in the fire models and 5 km^2 grid cells in the rainfall models. We therefore may have missed sedimentation events from severe fire or heavy, localized downpours that occurred during our study period. Ideally, many more observations of sedimentation events would be available to further fine-tune the model, especially to improve the relative scores for the fire–rainfall combinations to make them more closely match relative differences in sediment loads. We ranked severe fire and above-normal rainfall as the combination most likely to cause sedimentation. However, heavy sedimentation can occur when rain falls after drought but without fire as both phenomena led to the loss of vegetation cover (Nolan, Boer, et al., 2020). Similarly, we selected rainfall events that were one standard deviation above the average daily or fortnightly rainfall over the previous 20-year period; it is possible that other rainfall patterns also lead to surface run-off. In addition, we considered a relatively short-term post-fire rainfall pattern (January–March 2020) based on observations of when heavy rain occurred across the region in 2020. It is possible that later rainfall contributed to sedimentation threat as post-fire erosion can alter sediment influx for prolonged periods (Leonard et al., 2017). Rates of vegetation recovery in burnt areas will also affect the likelihood of sedimentation, and recovery is likely to vary spatially across the fire extent. Finally, there could also be unseen and unmappable gully erosion in some waterways or missing riparian vegetation that can exacerbate sedimentation events that may have been missed.

We aimed to develop a modelling approach that could be used quickly to identify aquatic species most at risk from fire impacts, in order to inform management interventions and conservation assessments (e.g. Legge, Rumpff, et al., 2022; Shelley et al., 2021). However, our spatial model predicts exposure to the threat of sediment slugs without considering variation in the impacts of sedimentation on specific species. We currently have very little data on physiological tolerance (lethal and sublethal) thresholds for freshwater species, and therefore, more research is required in this area (Cramp et al., 2021). In addition, our model addresses how sediment threat in waterways is affected by interactions between time since fire, fire severity and soil and topographical properties (Cawson et al., 2016). More complex modelling approaches that focus on modifying the parameters of the RUSLE model to reflect the changing conditions of the post-fire environment may be more powerful if current case studies can be extrapolated to larger scales (Biswas et al., 2021).

Despite the caveats outlined above, we consider our spatial model for post-fire sedimentation threat to be an advance on relying on fire extent mapping to estimate fire impacts on aquatic ecosystems. This model could be rapidly applied after any future comparable fire event in any fire-prone region, for example, to predict where heavy rain may cause the largest sedimentation events, thereby informing urgent post-fire management responses, including emergency rescue after fire, but before sedimentation occurs (Shelley et al., 2021). Used in combination with future fire (Dowdy et al., 2019) and flood risk projections (Hirabayashi et al., 2013) under anthropogenic climate change, our model could also be adapted to coarsely predict where waterways may experience the greatest sedimentation threats in the future, after extreme fire or flood events. While we apply the spatial modelling approach to Australian waterways, this model could be adapted for use in other waterways.

ACKNOWLEDGEMENT

This project was supported by the Australian Government's National Environmental Science Program through the Threatened Species Recovery Hub.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are included in Appendix S1.

ORCID

Michelle Ward https://orcid.org/0000-0002-0658-855X
Darren Southwell https://orcid.org/0000-0002-8767-9014
Rachael V. Gallagher https://orcid.org/0000-0002-4680-8115
Nick S. Whiterod https://orcid.org/0000-0002-7356-9834
Andrés F. Suárez-Castro https://orcid.org/0000-0002-6621-3821
Jessica Marsh https://orcid.org/0000-0002-4062-4155
Sarah Legge https://orcid.org/0000-0001-6968-2781

REFERENCES

Austin, C. M., Whiterod, N. S., McCormack, R., Raadik, T. A., Ahyong, S. T., Lintermans, M., Furse, J. M., & Grandjean, F. (2022). *Molecular taxonomy of Australia's endemic freshwater crayfish genus Euastacus (Parastacidae), with reference to priority 2019–20 bushfire-impacted species – 2022 update*. Deakin University and Aquasave-NGT.

Bino, G., Hawke, T., & Kingsford, R. T. (2021). Synergistic effects of a severe drought and fire on platypuses. *Science of the Total Environment*, *777*, 146137.

Biswas, T. K., Karim, F., Kumar, A., Wilkinson, S., Guerschman, J., Rees, G., McInerney, P., Zampatti, B., Sullivan, A., Nyman, P., Sheridan, G. J., & Nyman, P. (2021). 2019–2020 Bushfire impacts on sediment and contaminant transport following rainfall in the Upper Murray River catchment. *Integrated Environmental Assessment and Management*, *17*, 1203–1214.

Bixby, R. J., Cooper, S. D., Gresswell, R. E., Brown, L. E., Dahm, C. N., & Dwire, K. A. (2015). Fire effects on aquatic ecosystems: An assessment of the current state of the science. *Freshwater Science*, *34*, 1340–1350.

Boer, M. M., Resco de Dios, V., & Bradstock, R. A. (2020). Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, *10*, 171–172.

Bowman, D. M. J. S., Kolden, C. A., Abatzoglou, J. T., Johnston, F. H., van der Werf, G. R., & Flannigan, M. (2020). Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment*, *1*, 500–515.

Cawson, J. G., Nyman, P., Smith, H. G., Lane, P. N., & Sheridan, G. J. (2016). How soil temperatures during prescribed burning affect soil water repellency, infiltration and erosion. *Geoderma*, *278*, 12–22.

Commonwealth of Australia. (2018). *Interim Biogeographic Regionalisation for Australia (IBRA), version 7 (subregions)*. Dep. Environ. Energy. https://data.gov.au/dataset/ds-nsw-188ae132-d7b4-4a1a-8785-21786bcbe0bf/details

Commonwealth of Australia. (2020). *AUS GEEBAM fire severity NIAFED20200224*. Remote Sens. Landsc. Sci. Branch, Sci. Econ. Insights Div. New South Wales Dep. Planning, Ind. Environ. http://

www.environment.gov.au/fed/catalog/search/resource/details.page?uuid=%7B8CE7D6BE-4A82-40D7-80BC-647CB1FE5C08%7D

Cooper, S. D., Page, H. M., Wiseman, S. W., Klose, K., Bennett, D., Even, T., Sadro, S., Nelson, C. E., & Dudley, T. L. (2015). Physicochemical and biological responses of streams to wildfire severity in riparian zones. *Freshwater Biology*, *60*, 2600–2619.

Cramp, R., Mulvey, C., Cameron, J., Wintour, M., Isaza, D., & Franklin, C. (2021). *Impacts of post-fire ash and runoff sediment on the physiological tolerances of Australian freshwater aqautic fauna*. Project 8.3.7 report. NESP Threatened Species Recovery Hub, Brisbane, Australia.

DAWE. (2020). *Preliminary area for environmental analysis – 2019/20 fires*. https://www.environment.gov.au/system/files/pages/a8d10ce5-6a49-4fc2-b94d-575d6d11c547/files/preliminary-analysis-area-19-jan-2020.pdf

Dowdy, A. J., Ye, H., Pepler, A., Thatcher, M., Osbrough, S. L., Evans, J. P., Virgilio, G. D., & McCarthy, N. (2019). Future changes in extreme weather and pyroconvection risk factors for Australian wildfires. *Science Reports*, *9*, 1–11.

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z.-I., Knowler, D., Leveque, C., Naiman, R. J., Prieur-Richard, A. H., Soto, D., Stiassny, M. L. J., & Sullivan, C. A. (2006). Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biological Reviews*, *81*, 163–182.

Enright, N. J., Fontaine, J. B., Bowman, D. M., Bradstock, R. A., & Williams, R. J. (2015). Interval squeeze: Altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment*, *13*, 265–272.

Furse, J. M., & Coughran, J. (2011). An assessment of the distribution, biology, threatening processes and conservation status of the freshwater crayfish, genus Euastacus (Decapoda, Parastacidae), in continental Australia. I. Biological background and current status. In *New Frontiers in Crustacean biology* (pp. 241–252). Brill.

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.

Gallagher, R. V., Allen, S. P., Mackenzie, B. D. E., Keith, D. A., Nolan, R. H., Rumpff, L., Gosper, C. R., Pegg, G., van Leeuwen, S., Ooi, M. K. J., Yates, C. J., Merow, C., Williams, R. J., Nikolopoulos, E. I., Beaumont, L. J., & Auld, T. D. (2022). An integrated approach to assessing abiotic and biotic threats to post-fire plant species recovery: Lessons from the 2019–2020 Australian fire season. *Global Ecology and Biogeography*, *31*, 2056–2069. https://doi.org/10.1111/geb.13478

Gillanders, B., & Reis-Santos, P. (2020). *Effects of the January 2020 bushfires on estuarine systems of Kangaroo Island – Post event data collection*. Bushfire and Natural Hazards CRC.

Gomez Isaza, D. F., Cramp, R. L., & Franklin, C. E. (2022). Fire and rain: A systematic review of the impacts of wildfire and associated runoff on aquatic fauna. *Global Change Biology*, *28*, 2578–2595. https://doi.org/10.1111/gcb.16088

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., & Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, *3*, 816–821.

Horwitz, P., & Richardson, A. (1986). An ecological classification of the burrows of Australian freshwater crayfish. *Australian Journal of Marine and Freshwater Research*, *37*, 237–242.

Hyman, I. T., Ahyong, S. T., Köhler, F., McEvey, S. F., Milledge, G. A., Reid, C. A. M., & Rowley, J. J. L. (2020). Impacts of the 2019–2020 bushfires on New South Wales biodiversity: A rapid assessment of distribution data for selected invertebrate taxa. *Technical Reports Australian Museum Online*, *32*, 1–17.

Johnson, C. N., Balmford, A., Brook, B. W., Buettel, J. C., Galetti, M., Guangchun, L., & Wilmshurst, J. M. (2017). Biodiversity losses and conservation responses in the Anthropocene. *Science*, *356*, 270–275.

Legge, S., Rumpff, L., Woinarski, J. C. Z., Whiterod, N. S., Ward, M., Southwell, D. G., Scheele, B. C., Nimmo, D. G., Lintermans, M., Geyle, H. M., Garnett, S. T., Hayward-Brown, B., Ensbey, M., Ehmke, G., Ahyong, S. T., Blackmore, C. J., Bower, D. S., Brizuela-Torres, D., Burbidge, A. H., … Zukowski, S. (2022). The conservation impacts of ecological disturbance: Time-bound estimates of population loss and recovery for fauna affected by the 2019-20 Australian megafires. *Global Ecology Biogeography*, *31*, 2085–2104. https://doi.org/10.1111/geb.13473

Legge, S., Woinarski, J. C. Z., Scheele, B. C., Garnett, S. T., Lintermans, M., Nimmo, D. G., Whiterod, N. S., Southwell, D. M., Ehmke, G., Buchan, A., Gray, J., Metcalfe, D. J., Page, M., Rumpff, L., van Leeuwen, S., Williams, D., Ahyong, S. T., Chapple, D. G., Cowan, M., … Tingley, R. (2022). Rapid assessment of the biodiversity impacts of the 2019-20 Australian megafires to guide urgent management intervention and recovery, and lessons for other regions. *Diversity and Distributions*, *28*, 571–591.

Leonard, J. M., Magaña, H. A., Bangert, R. K., Neary, D. G., & Montgomery, W. L. (2017). Fire and floods: The recovery of headwater stream systems following high-severity wildfire. *Fire Ecology*, *13*, 62–84.

Linke, S., Lehner, B., Ouellet Dallaire, C., Ariwi, J., Grill, G., Anand, M., Beames, P., Burchard-Levine, V., Maxwell, S., Moidu, H., Tan, F., & Thieme, M. (2019). Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. *Science Data*, *6*, 283.

Lintermans, M. (2013). A review of on-ground recovery actions for threatened freshwater fish in Australia. *Marine & Freshwater Research*, *64*, 775–791.

Lintermans, M., Geyle, H., Beatty, S., Brown, C., Ebner, B., Freeman, R., Hammer, M. P., Humphreys, W. F., Kennard, M. J., Kern, P., Martin, K., Morgan, D. L., Raadik, T. A., Unmack, P. J., Wager, R., Woinarski, J. C. Z., & Garnett, S. (2020). Big trouble for little fish: Identifying Australian freshwater fishes in imminent risk of extinction. *Pacific Conservation Biology*, *25*, 365–377.

Lyon, J. P., & 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.

Marsh, J., Bal, P., Fraser, H., Umbers, K., Greenville, A., Rumpff, L., & Woinarski, J. (2021). *Assessment of the impacts of the 2019–20 wildfires of southern and eastern Australia on invertebrate species*. Project 8.3.1 Final report. NESP Threatened Species Recovery Hub, Brisbane, Australia.

McCormack, R. B. (2012). *A guide to Australia's spiny freshwater crayfish*. CSIRO.

McKinnon, L. J. (1995). Emersion of Murray crayfish, *Euastacus armatus* (Decapoda:Parastacidae), from the Murray River due to post-flood water quality. *Proceedings of the Royal Society of Victoria*, *107*, 31–38.

Nolan, R., Blackman, C. J., de Dios, V. R., Choat, B., Medlyn, B. E., Li, X., Bradstock, R. A., & Boer, M. M. (2020). Linking Forest flammability and plant vulnerability to drought. *Forests*, *11*, 779.

Nolan, R. H., Boer, M. M., Collins, L., Resco de Dios, V., Clarke, H., Jenkins, M., Kenny, B., & Bradstock, R. A. (2020). Causes and consequences of eastern Australia's 2019–20 season of mega-fires. *Global Change Biology*, *26*, 1039–1041.

Nyman, P., Rutherfurd, I. D., Lane, P. N., & Sheridan, G. J. (2019). Debris flows in Southeast Australia linked to drought, wildfire, and the El Niño–Southern oscillation. *Geology*, *47*, 491–494.

Nyman, P., Sheridan, G. J., Smith, H. G., & Lane, P. N. (2014). Modelling the effects of surface storage, macropore flow and water repellency on infiltration after wildfire. *Journal of Hydrology*, *513*, 301–313.

Nyman, P., Smith, H. G., Sherwin, C. B., Langhans, C., Lane, P. N., & Sheridan, G. J. (2015). Predicting sediment delivery from debris flows after wildfire. *Geomorphology*, *250*, 173–186.

Renard, K., Foster, G., Weesies, G., McCool, D., & Yoder, D. (1997). *Predicting soil erosion by water: A guide to conservation planning with* *the Revised Universal Soil Loss Equation (RUSLE)*. U.S. Department of Agriculture.

Renard, K. G., & Freimund, J. R. (1994). Using monthly precipitation data to estimate the R-factor in the revised USLE. *Journal of Hydrology*, *157*, 287–306.

Reneau, S. L., Katzman, D., Kuyumjian, G. A., Lavine, A., & Malmon, D. V. (2007). Sediment delivery after a wildfire. *Geology*, *35*, 151–154.

Richman, N. I., Böhm, M., Adams, S. B., Alvarez, F., Bergey, E. A., Bunn, J. J. S., Burnham, Q., Cordeiro, J., Coughran, J., Crandall, K. A., Dawkins, K. L., DiStefano, R. J., Doran, N. E., Edsman, L., Eversole, A. G., Füreder, L., Furse, J. M., Gherardi, F., Hamr, P., … Collen, B. (2015). Multiple drivers of decline in the global status of freshwater crayfish (Decapoda: Astacidea). *Philosophical Transactions of the Royal Society B Biological Sciences*, *370*, 1–11.

Roff, A. (2020). *Australian Google Earth engine burnt area map: A rapid, national approach to fire severity*. https://doi.org/10.13140/RG.2.2.13434.52167

Shelley, J. J., Raadik, T. A., & Lintermans, M. (2021). *Summary of the 2019/20 bushfire impacts on freshwater fish and the emergency conservation responses in south-eastern Australia*. NESP TSR Hub Project 8.3.6. Arthur Rylah Institute for Environmental Research Technical Report Series No. 2021/330. Department of Environment, Land, Water and Planning, Heidelberg, Australia.

Sheridan, G. J., Lane, P. N., & Noske, P. J. (2007). Quantification of hillslope runoff and erosion processes before and after wildfire in a wet Eucalyptus forest. *Journal of Hydrology*, *343*, 12–28.

Silva, L. G. M., Doyle, K. E., Duffy, D., Humphries, P., Horta, A., & Baumgartner, L. J. (2020). Mortality events resulting from Australia's catastrophic fires threaten aquatic biota. *Global Change Biology*, *26*, 5345–5350.

Smith, H. G., Sheridan, G. J., Lane, P. N., & Bren, L. J. (2011). Wildfire and salvage harvesting effects on runoff generation and sediment exports from radiata pine and eucalypt forest catchments, south-eastern Australia. *Forest Ecology and Management*, *261*, 570–581.

Southwell, D., Hao, A., Smart, A., Valavi, R., Wilkinson, D., & Wintle, B. (2020). *Design considerations for post natural disaster (fire) on-ground assessment of status of species, ecological communities, habitats and threats*. The University of Melbourne. https://www.awe.gov.au/sites/default/files/env/pages/a8d10ce5-6a49-4fc2-b94d-575d6d11c547/files/final-post-fire-rapid-assessment-guidelines.pdf

Suárez-Castro, A. F., Beyer, H. L., Kuempel, C. D., Linke, S., Borrelli, P., & Hoegh-Guldberg, O. (2021). Global forest restoration opportunities to foster coral reef conservation. *Global Change Biology*, *27*, 5238–5252.

Teng, H., Viscarra, R. A., Shi, Z., Behrens, T., Chappell, A., & Bui, E. (2016). Environmental modelling & software assimilating satellite imagery and visible e near infrared spectroscopy to model and map soil loss by water erosion in Australia. *Environmental Modelling & Software*, *77*, 156–167.

Thompson, M. B. (1983). Populations of the Murray River tortoise, *Emydura* (Chelodina): The effect of egg predation by the red fox, *Vulpes vulpes*. *Wildlife Research*, *10*, 363–371.

Tingley, R., Macdonald, S. L., Mitchell, N. J., Woinarski, J. C., Meiri, S., Bowles, P., Cox, N. A., Shea, G. M., Böhm, M., Chanson, J., Tognelli, M. F., Harris, J., Walke, C., Harrison, N., Victor, S., Woods, C., Amey, A. P., Bamford, M., Catt, G., … Chapple, D. G. (2019). Geographic and taxonomic patterns of extinction risk in Australian squamates. *Biological Conservation*, *238*, 108203.

Ward, M., Tulloch, A. I. T., Radford, J. Q., Williams, B. A., Reside, A. E., Macdonald, S. L., Mayfield, H. J., Maron, M., Possingham, H. P., Vine, S. J., O'Connor, J. L., Massingham, E. J., Greenville, A. C., Woinarski, J. C. Z., Garnett, S. T., Lintermans, M., Scheele, B. C., Carwardine, J., Nimmo, D. G., … Watson, J. E. M. (2020). Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nature Ecology & Evolution*, *4*, 1321–1326.

Whiterod, N. S., Furse, J., Lutz, M., Lintermans, M., McCormack, R., Zukowski, S., Thompson, R., Raadik, T. A., Marshall, J., Miller, A. D., & Austin, C. Ahyong, S. T. (2022). *The 2022 action plan for priority 2019–20 bushfire-impacted species from Australia's endemic freshwater crayfish genus Euastacus (Parastacidae). A report to the Department of Agriculture, Water and the Environment*. Aquasave–Nature Glenelg Trust.

Wilson, C., Kampf, S. K., Wagenbrenner, J. W., & MacDonald, L. H. (2018). Rainfall thresholds for post-fire runoff and sediment delivery from plot to watershed scales. *Forest Ecology Management*, *430*, 346–356.

WWF. (2019). *HydroRivers*. https://www.hydrosheds.org/page/hydrorivers

BIOSKETCH

The 2019–20 Australian megafires had extensive effects on aquatic fauna, and prioritizing management attention was critical for mounting an effective response. The co-authors collaborated to model the spatial extent of post-fire sedimentation threat to estimate the impacts of the 2019–20 fires on waterways and aquatic species described in this paper. We have varying backgrounds including spatial analysts, aquatic ecologists, soil scientists, general ecologists, aquatic conservation management and sedimentologists.

Author contributions: M.W. and S.L. conceived the study, M.W., D.S., R.G., S.L., P.N., A.S., G.S., T.R., N.S.W., M.L., developed the idea and methods, D.S., T.R., N.S.W., M.L., J.M. and J.W. developed ecological data and models, M.W. conducted the analysis of results, and M.W. and S.L. led the writing of the manuscript with input from all authors.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Ward, M., Southwell, D., Gallagher, R. V., Raadik, T. A., Whiterod, N. S., Lintermans, M., Sheridan, G., Nyman, P., Suárez-Castro, A. F., 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*, *00*, 1–14. https://doi.org/10.1111/ddi.13640