ADDENDUM: COTTER CATCHMENT ACTION FOR CLEAN WATER (ACWA) PLAN

Bushfire and erosion risk assessment in the Cotter River Catchment: risk framework and options for management

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Summary

The Cotter Catchment Actions for Clean Water (ACWA) Plan 2020 was developed to guide efforts to stabilise and rectify erosion risk in the Cotter catchment. Recommended management interventions were prioritised based on the risks to water quality. Erosion risks were mapped for hillslope, gully, and channel sources. In an unburned setting, the erosion risk in the upper Cotter Catchment is generally low. Dense vegetation and relatively stable soils and floodplain sediments means that background erosion rates are low, and that high-quality water is delivered to the Corin, Bendora and Cotter Dams.

The Cotter ACWA plan was developed given the extant catchment conditions; however, bushfire is a major risk to water quality and yield in forested water supply catchments. The 2020 Orroral Valley Fire occurred after the Cotter Catchment ACWA Plan investigations and analyses were undertaken and findings and recommendations developed.

As an Addendum to the Cotter Catchment ACWA Plan, this report is concerned with the water quality risk associated with bushfire in the upper Cotter River catchment, and the impact of the 2020 Orroral Valley Fire in particular, which burned through the upper reaches of the Cotter River. The report provides:

- A review of the scientific literature, data, and reports from the 2003 Canberra bushfires to build an understanding of water quality risks in the Cotter catchments due to bushfire.
- An assessment of erosion and water quality risks using a framework underpinned by this review and aligned with the Cotter River ACWA plan and availability of data.
- Outlines of strategies for risk mitigation through a catchment management plan aimed at reducing the threats to water quality from bushfire.

The threats to water supply can be separated into short term and longer-term impacts on sediment contaminant transport. Short-term threats are those that are linked to surface runoff from hillslopes, which cause erosion of topsoil and headwater gullies. Longer-term threats are associated with changes to floodplain structure, sediment availability, and contaminant sources along waterways. Degradation of floodplain, riparian zones and bogs can lead to changes in the rates of channel incision and lateral migration. And increased abundance of vertebrate pests can exacerbate the degradation, whilst also increasing the concertation of Cryptosporidium in waterways. These threats can persist in the landscape for several decades. The report outlines and implements a set of geoprocessing steps aimed at identifying where these risks are likely to be concentrated following the Orroral Valley Fire.

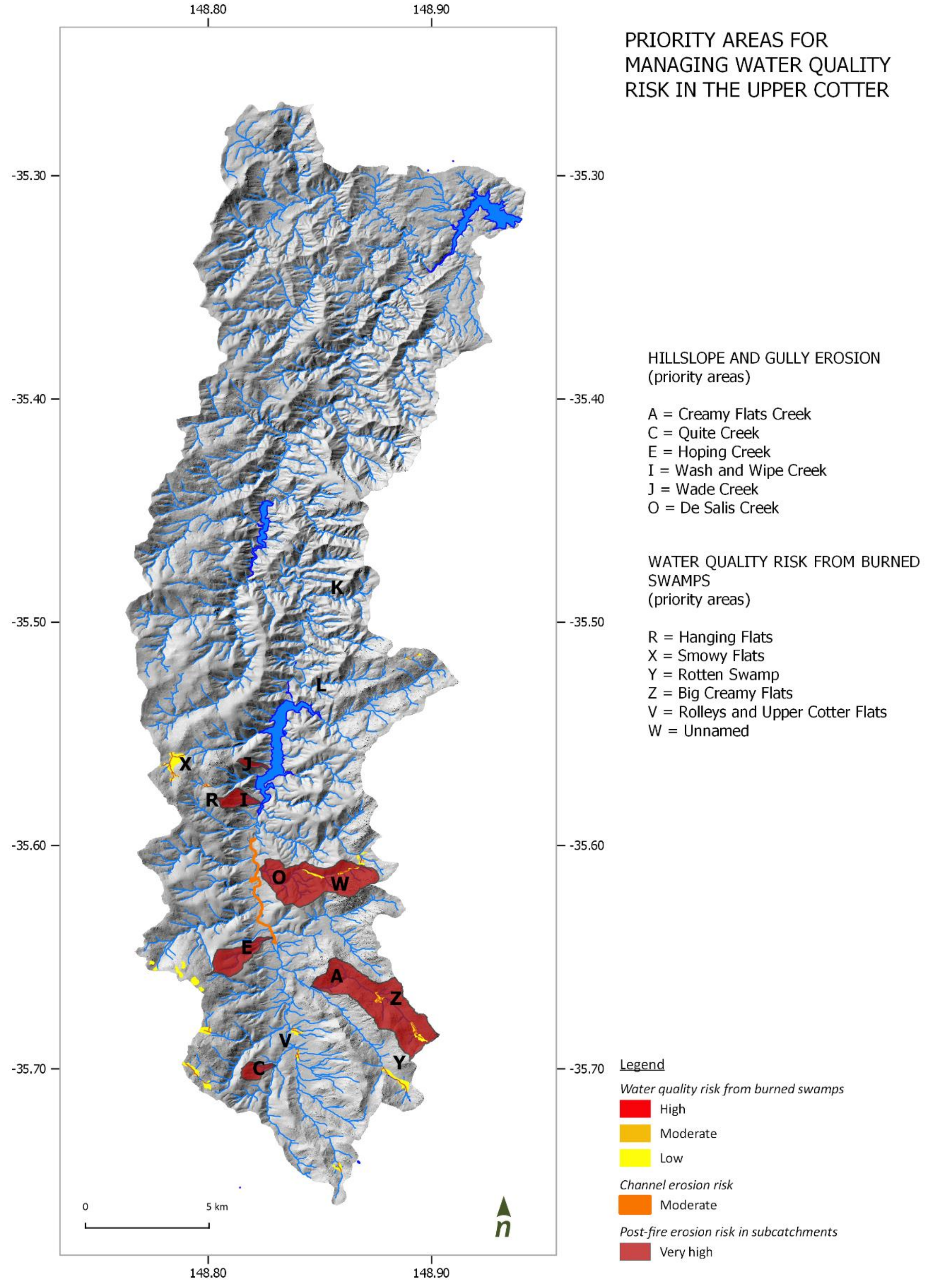
The report provides a comparison of fire severity in between the 2003 bushfire and the Orroral Valley Bushfire in 2020 (Appendix B). For context, this comparison is summarised in the table below for Corin and Bendora catchments, which were both impacted by the Orroral Valley Bushfire. In the Corin catchment the fire footprint is very similar for the two fires. In the Bendora catchment, the Orroral Valley Bushfire impacted on a much smaller fraction of the catchment area, when compared to the 2003 bushfires. The Lower Cotter catchment was unaffected by the Orroral Valley Bushfire.

Comparison of the fire severity of the 2003 and 2020 fires within Bendora and Corin catchments. Green numbers mean less impact in 2020 fires relative to 2003. Red numbers mean more impact.

Fire Severity Category	**Bendora catchment [%]**		**Corin catchment [%]**	
	2003	**2020**	**2003**	**2020**
Unaffected landscape	0	**71**	0	1
Unburnt to low intensity understory only scorch	6	7	19	22
Moderate Intensity Burn. Complete understorey burn and partial canopy scorch	16	12	35	35
High Intensity Burn. Complete canopy scorch	38	**6**	35	26
High Intensity Burn. Complete canopy destruction	39	**3**	10	**15**

The Upper Cotter, and Corin catchment in particular, contains considerable areas that represent high risk to water quality (shown below but also in maps in Section 5).

Priority areas for managing water quality risk in areas of the Upper Cotter affected by the Orroral Valley Fire



The key priority areas are listed in tables below and separated according to two main sources of risk that were identified in the review as having the potential to cause major impacts on water quality in the short- and long-term.

1. **Steep hillslopes and gullies** draining into the Cotter main stem or directly into reservoir. Large amounts of topsoils and colluvium are likely to erode during intense rainfall events and deliver fine sediment, organics and other pollutants into reservoirs. The table below lists the subcatchments to Corin where post-fire hillslope and gully erosion risk is very high. There are other subcatchments that are classified as high risk and these are mapped in Figure 6. Also, there are hillslope draining directly into the Corin Reservoir that were burned at very high severity and which are at high risk of erosion.

Subcatchment	Reservoir	Map reference in Figure 6	Area (ha)	Hillslope erosion risk	Gully erosion risk
Creamy Flats Creek	Corin	A	882	Very high	Very high
Quite Creek	Corin	C	77	Very high	Very high
Hoping Creek	Corin	E	208	Very high	Very high
Wash and Wipe Creek	Corin	I	95	Very high	Very high
Wade Creek	Corin	J	29	Very high	Very high
De Salis Creek	Corin	O	711	Very high	Very high

2. **Burned swamps in the upper reaches of Corin Catchment.** There are large areas of impacted bogs and swamps that are at risk of degradation. The water quality impacts from these degrading bogs is not clear but could be significant and possibly exacerbated by vertebrate pests such as pigs, deer, and horses.

Swamp/Flat	Reservoir	Map reference in Figure 8	High risk (ha)	Moderate risk (ha)	Low risk (ha)
Hanging Flats	Corin	R	1.5	2.2	0.6
Snowy Flats	Corin	X	6.1	11.0	32.1
Rotten Swamp	Corin	Y	4.2	6.8	20.4
Big and Little Creamy Flats	Corin	Z	5.8	9.9	11.7
Rolleys and Upper Cotter Flats	Corin	V	3.1	5.2	8.1
Unnamed	Corin	W	3.6	6.0	15.3

Strategies, principles, and techniques for mitigating risk to water quality are presented. These can be used alongside the risk mapping to develop a management plan for fast-tracking recovery and mitigating potential impacts on treatability of water in the Cotter water supply system.

The specifics around management interventions would need to be developed based on field assessments, availability of funding and feasibility studies. However, any management intervention should be guided by the following general principles:

- Mitigation should be *targeting hotspots* at the source and where most runoff and erosion are likely to be generated. Typically, 90% of the erosion is from 10% of the catchment area. This provides a basis for prioritising and focusing interventions.
- Mitigation through a *multipronged approach* that reduces pollutant delivery to the reservoir by interventions along the entire transport pathway between source (hillslopes) and asset (reservoir).
- The *reduction in risk is quantifiable* so the benefits can be evaluated against economic costs, safety, and environmental impacts.

- Mitigation forms part of an *adaptive management approach* with clear pathways for evaluating benefits and refining strategies and methods for erosion control as new information and data come available.

The Orroral Valley Fire presents an opportunity to produce knowledge that will improve the capacity within Icon Water to work in collaboration with ACT Parks and Conservation Service to respond to future bushfire. Ultimately the any investment should be embedded within the well-established four-phase disaster management approach of prevention (planning), preparedness, response and recovery. The report identifies the following priorities for monitoring and research:

- Collect data on water quality (turbidity, TSS, organics, nutrients, metals and pathogens) in reservoirs and downstream of high-risk areas, focusing on capturing response to significant rainfall events.
- Use satellite imagery (Landsat or Sentinel) to monitor vegetation change over time.
- Use repeat topographic surveys (photogrammetry, lidar, erosion pins) in strategic locations to construct sediment budgets and identify sediment sources and sinks. Bathymetric surveys of dams could be recommended as way to assess what sediment infill has occurred and how this may affect water availability.
- Monitor gully erosion through regular field surveys and identify the rainfall intensities when key events such as debris flows are triggered.
- Sample sediment to analyse geochemistry with the aim to identify the degree with which nutrients and metals are transported in association with ash and sediments.
- Carefully design a monitoring system for evaluating the effectiveness of any management intervention that is pursued.

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1 Introduction

1.1 Context

The Upper Cotter River catchment forms part of the Namadgi National Park and managed as Zone 1 – “Remote Area (Core Conservation and Catchment Area)’. The Namadgi National Park Plan of Management (2010) was prepared under the Planning and Development Act 2007 and policies in the Territory Plan (ACT) and the National Capital Plan (Commonwealth). Given the importance of the Cotter Catchment for Canberra’s water supply, the plan gives high priority to water resource management. This is in accordance with legislative requirements for catchment management in the ACT.

The primary management objectives for Zone 1 are delineated under three core values:

- *Water.* Maintain the ecological and hydrological condition of water catchments and, where desirable and feasible, improved, to ensure a continuing high quality and cost-effective water supply for the ACT.
- *Natural heritage. C*onserve the biodiversity and geodiversity and manage ecosystems so that they can continue to function and evolve naturally and protect the integrity of landscapes and scenery.
- *Cultural heritage*. Cultural heritage is identified, conserved, and where appropriate, interpreted and promoted to retain and foster community associations and an appreciation of the past.

The Cotter Catchment Actions for Clean Water (ACWA) Plan[1] was developed to guide efforts to stabilise and rectify erosion risk in the Cotter catchment. Recommended management interventions were prioritised based on the risks to water quality. Erosion risks were mapped for hillslope, gully and channel sources. In an unburned setting, the erosion risk in the Cotter Catchment is generally low, except for the Lower Cotter catchment where the legacy of intensive plantation forestry has destabilised hillslopes and headwater drainage networks. Elsewhere in the catchment, the dense vegetation and relatively stable soils and floodplain sediments, means that background erosion rates are low, and that high-quality water is delivered to the Corin, Bendora and Cotter Dams.

The Cotter ACWA plan was developed given the extant catchment conditions; however, bushfire is a major risk to water quality and yield forested water supply catchments (Hohner et al., 2019; Nyman et al., 2019; Smith et al., 2011). The 2020 Orroral Valley Fire occurred after the Cotter River catchment ACWA Plan investigations and analyses were undertaken and findings and recommendations developed.

As an Addendum to the Cotter Catchment ACWA Plan, this report is concerned with the water quality risk associated with bushfire in the Cotter River catchment, and the impact of the 2020 Orroral Valley Fire in particular, which burned through the upper reaches of the Cotter River, including the Corin Dam catchment, which was entirely within the fire ground.

The Rapid Risk Assessment Report for Orroral Valley Fire[2] identified several areas within the upper Cotter River catchment that are susceptible to high post-fire erosion rates and debris flows. Increased erosion susceptibility means that streams and the water supply reservoir are exposed to events that lead to poor water quality. The consequence of the 2003 Canberra Bushfires for water quality were significant, and there is a need to consolidate the lessons learned from that event to help guide current recovery efforts. More broadly, there is a need to develop planning frameworks to manage the risk associated with bushfire on ACT water supply catchments.

In this report, the emphasis is on threats to water quality. However, strategies to reduce bushfire-related impact on water quality in the Cotter should be developed to balance the management objectives associated

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[1] Alluvium Consulting (2020) Cotter Catchment Actions for Clean Water Plan. Report produced for Icon Water, Canberra.

[2] ACT/NSW Rapid Risk Assessment Team – February 2020. Orroral Valley Fire Rapid Risk Assessment Namadgi National Park. Unpublished report. Environment, Planning and Sustainable Development Directorate. ACT Government, Canberra.

with other values in Namadgi National Park, and where possible, seek to achieve outcomes across the three values that the catchment is being managed for.

1.2 Report objectives and contents

This report considers the impacts of bushfire on water quality as an additional risk factor and planning element that complements the Cotter Catchment ACWA Plan, completed in March 2020. It specifically addresses erosion risk stemming from the Orroral Valley Fire and recommends management strategies and techniques to mitigate threats, as part of a broader bushfire recovery program.

The report provides:

- A review of reports from the 2003 Canberra bushfires, guidelines and scientific literature more generally, to build understanding of water quality risks in the Cotter catchments due to bushfire
- An assessment of erosion and water quality risks using a framework underpinned by this review and aligned with the Cotter Catchment ACWA plan and availability of data.
- Outline of strategies for risk mitigation through a catchment management plan aimed at reducing the threats to water quality from bushfire.

The management options include commentary regarding the ‘holistic risk/impact’ to the catchment with a temporal scale. This includes rehabilitation of upper catchment bogs (no immediate impact on water quality but will assist over time) and also with respect to observations and conversations on vertebrate pests such as wild horses, deer, pigs and rabbits. The work will not only add value to the Cotter Catchment ACWA Plan and post Orroral Valley fire recovery strategies, but also uncover what other work may add value over time, such as new bathometric studies, photo points, repeat topographic surveys, etc.

2 Review of values at risk from bushfire in the Cotter River catchment

2.1 The Cotter Catchment and Bushfire in the Alps

The Cotter catchment comprises a wide range of ecosystems that are associated with different fire regimes and that have different hydrological response to fire. Bushfires occur regularly in the catchment, controlled largely by moisture, which dictates fuel availability. Ignition sources are also an important control. However, as evident from the recent 2019/20 bushfire season, when the landscape is dry, the ignition sources tend not to be a limitation on bushfire activity in SE Australia.

Major bushfires in the Cotter catchment of greater than 5000 ha have been recorded in the summers of 1920, 1926, 1939, 1983, 2003, and 2019/20 and generally have corresponded with droughts, often linked to regional hydroclimatic drivers such as El Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). Fire return intervals tend to be shorter in dry, low elevation forests compared to wet forest and montane and alpine vegetation communities. Climate change is likely to exacerbate the bushfire activity through the SE Australia region by promoting more extreme fire weather (i.e. hot, dry and windy days).

Based on charcoal records and reconstruction of past fire regimes the general trend for all vegetation types across South Eastern Australia is that fire frequency/intensity prior to European settlement was significantly less than it was during the early European period, but slightly greater than it is currently. The role of fire management in modulating fire regimes is a subject of intense debate. But there is increasing evidence that fuel management, through planned burning and other mechanisms, can be an effective tool for reducing the intensity and impact of bushfire.

2.2 Sources of risk and key processes at play

Bushfire results in increased erosion and transport of sediment, nutrient and metals to water supply reservoirs. The mobilisation of organic and inorganic sediment after a severe fire poses the greatest threat to water chemistry of water reservoirs, including increases in turbidity, manganese, iron, and biological oxygen demand (BOD) well above national water standard. In a review of water quality impacts from bushfire, Smith et al (2011) found that the most significant water quality impacts following large wildfire in SE Australia were attributed the sudden pulses of sediment delivered from extreme erosion processes that are triggered by short burst of rainfall on steep slopes with high severity bushfire. This type of response is what triggered the majority of impacts on the Cotter water supply systems following the bushfires in 2003 (White et al., 2006). After these inputs, the changes in water chemistry and microbial activity within the reservoir itself can also trigger a change in the processes that regulate the exchange between particulate and dissolved forms of metals.

Main sources sediment contaminants are hillslope and steep headwater gullies. However, the sediment that is available along the main trunk streams (in alluvial fans, along floodplains and wetland) can also be eroded and mobilized, providing an additional threat during periods of high discharge. Risk from increased abundance of vertebrate pests is another factor to be considered and is a concern for the effectiveness of long-term conservation land management objectives.

Hillslope erosion in response to thunderstorms

Surface runoff leading to widespread erosion of topsoil is a key triggering mechanism for water quality impacts. This process has been found to be strongly linked to fire severity and soil hydraulic properties (Moody et al., 2015; der Sant et al., 2018), which can vary significantly at relatively fine spatial scales. A large proportion of sediment delivered to the Upper Cotter catchment water supply reservoirs following 2003 bushfire stemmed from erosion of topsoils during short intense thunderstorms (Wasson et al., 2003). The most severely burnt dry (west and north facing) slopes are the most likely source of water quality deterioration. The timescale of recovery of hillslope processes is in the order of 5 years, but most of the erosion occurs within the first few years after bushfire (Noske et al., 2016), because readily available hillslope sediment becomes depleted (Nyman et al., 2013).

Debris flows and gully erosion
Debris flows, a threshold-driven process that causes widespread erosion (or scour) of headwater channels, has been identified as a dominant process of post-bushfire sediment generation and delivery (Nyman et al., 2015), and was one of the key processes contributing to water contamination in the Cotter following the 2003 bushfire (Wasson et al., 2003; White et al., 2006). Gully erosion by debris flows is triggered by surface runoff, whilst intense rainfall and steep terrain are key controlling factors. The magnitude of erosion is typically dictated by sediment availability in headwater channels, so if events occur at short return intervals, the sediment can become limited. Sediment fans deposited at the base of headwater gullies can act as major sediment sources for long periods of time after the initial bushfire disturbance.

Erosion of floodplain sediments
Increased river discharge and reduced resistance to erosion in riparian areas can trigger increased channel-bank erosion in the river networks. The magnitude of change in channel erosion following fire is poorly documented. The impacts are likely to be highly transient (and relatively short-lived) because vegetation recovery along streams tend to be relatively fast given that water availability is generally not a constraint, when compared to exposed hillslopes. However, vegetation composition can change, resulting in reduced channel stability. A shift towards sedge and grass dominance instead of woody vegetation, for example, may reduce erosion resistance over the long-term, and may increase stream incision and rates of lateral migration.

Degradation of wetland and bogs
Loss of peatlands and bogs due to bushfires can result in deteriorating water quality due to:

- increased availability of sediment and other contaminants. Extensive erosion of wetland and bogs were observed following bushfires in 2003. While the impact on water quality in reservoirs were less pronounced, the erosion of these systems leads to persistent increase in background loadings, and therefore increase in treatment effort and cost.
- reduced capacity to act as buffers for lateral input of water and sediment delivered from hillslopes. Peatlands or bogs moderate runoff, filtering mineral sediment and steadily releasing clean water for extended periods of time (months) following rainfall. When degraded, these systems no longer serve this important function, resulting in increased connectivity between headwater sediment sources (hillslopes and gullies) and streams.

Providing there is a total absence of fire and grazing, and subject to climate change, Sphagnum bogs that do recover from fire will take a minimum of 20 years.

Increased exposure to pathogens
Burned landscapes can see an increase in the abundance of vertebrate pests such as wild horses, deer, pigs, and rabbits. These vertebrate pests can result in increased abundance of Cryptosporidium in waterways. As described in (Cinque et al., 2008) Cryptosporidiosis represents a major water quality concern to water utilities in the developed world due to Cryptosporidium being difficult to treat. Not only are traditional methods of disinfection, such as chlorine and chloramine ineffective against Cryptosporidium but it is also excreted in large numbers by affected hosts, is persistent in the environment and has a very low infectious dose. It is due to these factors that it is listed by the World Health Organisation (WHO) as a “reference pathogen” for monitoring of water quality globally.

3 Bushfire recovery and risk framework

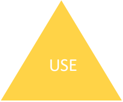
3.1 Recovery framework

A recovery framework provides a high-level input to the development of effective risk management strategies that is cognisant of the multiple threats, values, and timescales of impacts that a risk management plan seeks to address. For a catchment recovery plan to have appropriate response actions for a bushfire event, it is necessary to understand:

1. the intrinsic **uses** and **values** of the catchment
2. the potential **impact** of bushfire on catchment and waterway values
3. the **objectives** and **desired outcomes** for the catchment and waterway, post-bushfire.

The framework applied to the development of a bushfire recovery plan considers risks and impacts related to natural disasters or emergency events in terms of **Values**, **Threats** and **Causes**, and is summarised in Figure 1. Under this framework, the Values of the catchment (e.g. water for potable use, biodiversity) may be impacted by Threats (e.g. soil erosion, loss of habitat, etc.) because of bushfire. **Recovery Objectives** are critical to the framework and depend upon the relationship between the values of the catchment and the anticipated future values of the catchment, in the event of a bushfire. In this framework we assumed the values and management objectives remain unchanged in the event of a bushfire. **Recovery Actions** reflect Recovery Objectives and are directed towards managing and mitigating the Threats and, in the long-term, managing the processes that result in bushfire.

For the purposes of this framework, Values, Threats, Causes, Recovery Objectives and Recovery Actions are defined as follows:



Use (or value) – The *beneficiaries and beneficial uses of the catchment.* These essentially represent the components that are dependent on the catchment condition/processes and are valued by society. Examples include the provision of safe and secure residential housing, high quality water for potable use, thriving terrestrial ecosystems.

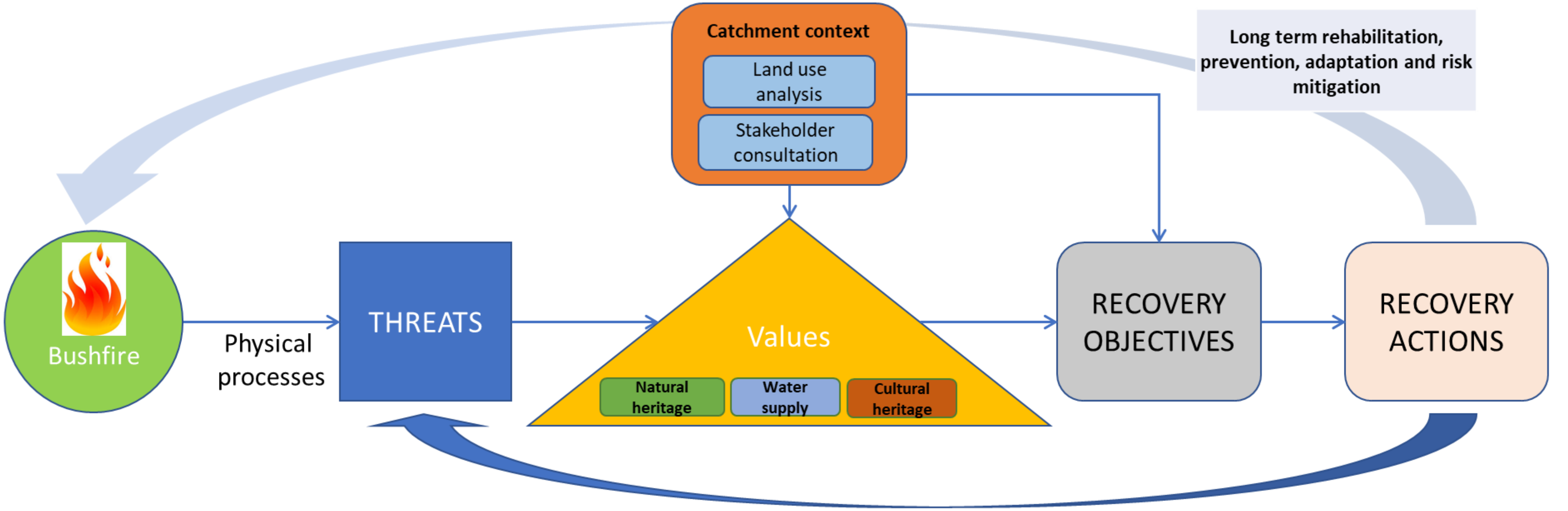
Threat – A threat is a *deviation from an agreed starting point that may affect beneficial uses*. These include 'loss of forest and wildlife habitat', 'loss of biodiversity', 'loss of ecosystem services', 'increased soil erosion', 'encroachment for settlement'.

Cause (Bushfire) – *This gives rise to or generates a threat*.

Recovery Objectives – *Management objectives for the catchment if a catastrophic emergency event occurs*. These objectives will generally be to intervene strategically to assist natural systems to restore the pre-existing Beneficial Uses / Values of the catchment, or to establish new uses and values.

Recovery Actions – *Activities directed towards managing and mitigating the Threats* (e.g. assist natural system recovery through erosion control, infrastructure repair, water quality monitoring) and, in the long-term, managing the processes that result in the Cause themselves (e.g. fuel reduction, land management plans).

Threats to water supply are the focus of this report. There are multiple threats, and these are described schematically in Figure 2.



Cause: Bushfire

Threat: Deviation from an agreed starting condition that affects values

Values: The values (or benefits) that the catchment is managed for

Recovery objectives: Restore or build resilience to maintain values

Recovery actions: Activities undertaken to achieve recovery objectives and minimise threat to values

Figure 1. *Bushfire recovery framework. The threats are described with an expanded schematic in Figure 2.*

3.2 Threats to values – water supply

The threats to water supply can be separated into short-term and longer-term impacts on sediment contaminant transport.

- Short term threats are those that are linked to surface runoff from hillslopes, which cause erosion of topsoil and headwater gullies. The threat is primarily linked to soil hydraulic properties and vegetation cover. Most of the erosion occurred within the first 2-years but remains elevated for up to 5 years after bushfire. The threat depends on the sequence of rainfall events following a bushfire. A high intensity thunderstorm (return interval in the order 2-5years) in the first year after bushfire is likely to trigger large erosion events and impact like those following the 2003 bushfire.
- Longer-term threats are associated with changes to floodplain structure, sediment availability, and contaminant sources along waterways. Degradation of floodplain, riparian zones and bogs can lead to changes in the rates of channel incision and lateral migration. Increased abundance of vertebrate pests can exacerbate the degradation, whilst also increasing the concertation of Cryptosporidium in waterways. These threats can persist in the landscape for several decades.

The approach to mapping post-bushfire risk to water quality will be underpinned by the processes and threats described in Figure 2.

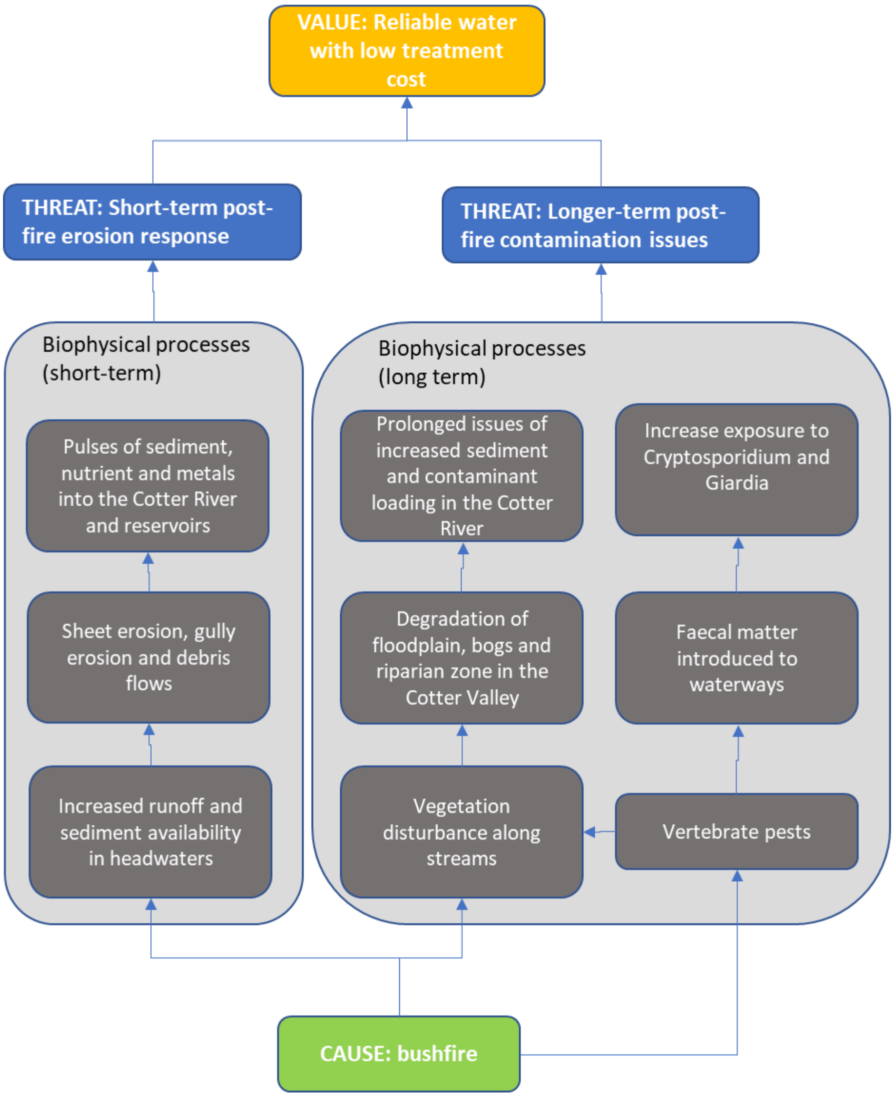


Figure 2. *Threat to water supply after bushfire*

3.3 Orroral Valley Fire

The Orroral Valley fire burnt 87,923 ha in the ACT with extensive areas in Namadgi National Park (NNP) comprising the southern region of the Cotter Water Supply Catchment (Figure 3). The entire Corin catchment was burned. About 30% of the Bendora catchment was burned. Though fire severity varied considerably within the affected lands of the Upper Cotter Catchment, there is generally an overlay with the same areas that burnt in 2003.

The fire began in grassland on Monday 27 January 2020 in Namadgi National Park (NNP). Suppression operations and rain across the fire ground (~158 mm between 10 and 14 February) led to containment.

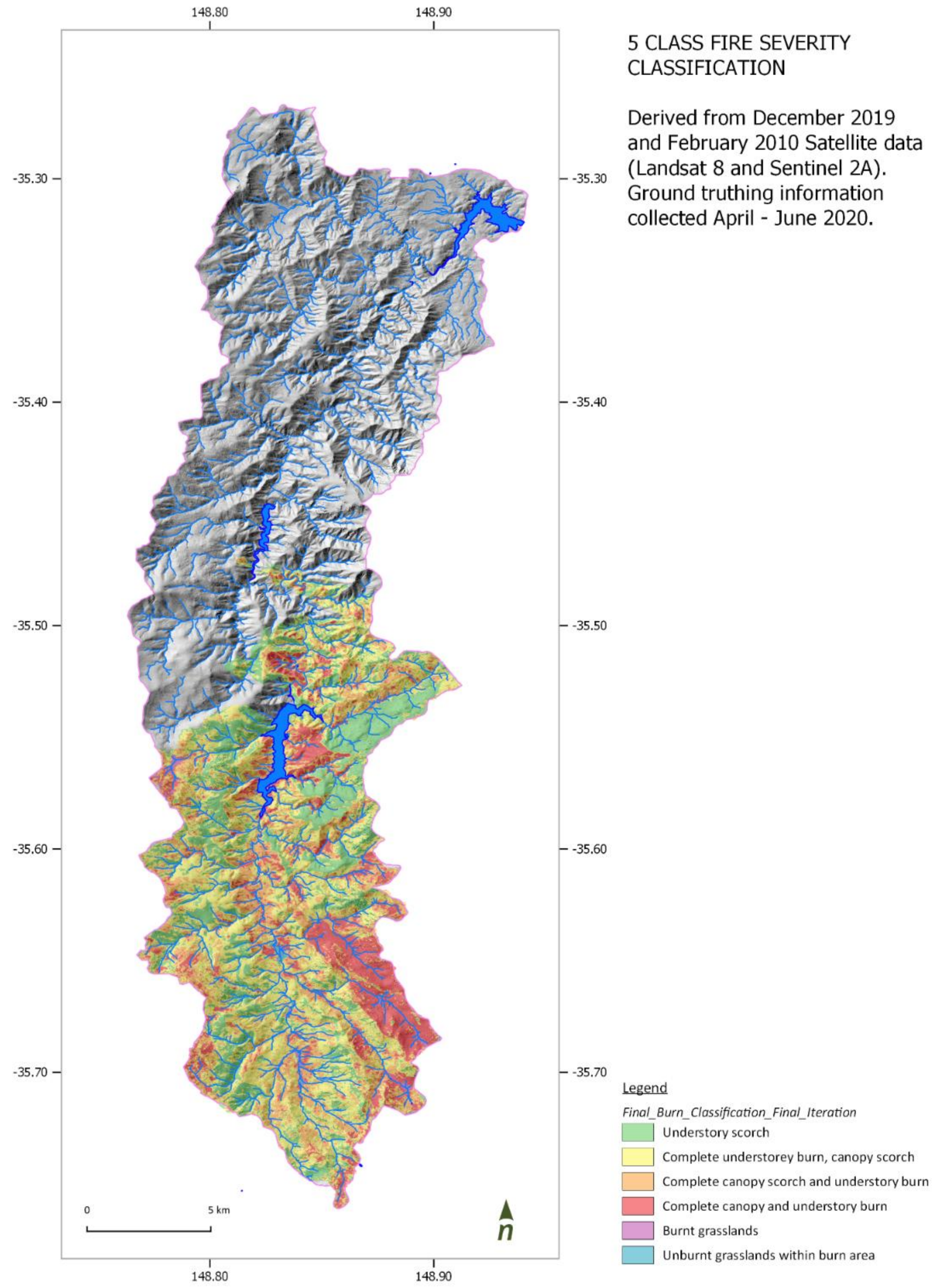


Figure 3. *Fire severity mapped by Icon Water (Tony Sparks). Details in Appendix B.*

4 Methods: Mapping erosion risk following the Orroral Fire

This section describes a method for mapping water quality risk that is aligned with the risk framework in Figure 2. There are three components that are linked to different sources of risk. By considering hillslopes, gullies, and channels separately, the method is consistent with the framework used to map erosion risk in the ACWA plan. This means that the approach to mapping risk in burned and unburned settings is underpinned by similar assumptions around processes and sediment sources.

4.1 Hillslope erosion risk in headwaters

RUSLE model

Erosion risk from erosion in headwater is determined using the RUSLE model. The parameters for this model were developed for the Cotter catchments as part of the ACWA plan. The parameters are related to soil erodibility, rainfall erosivity, vegetation and terrain. A commonly used method to assess catchment scale sediment generation processes is the Revised Universal Soil Loss Equation (RUSLE). Benefits of using RUSLE include the requirement of a modest number of parameters that can be derived from commonly available datasets, it has been adapted to Australian conditions and the factor-based nature allows individual contributing factors to be easily analysed (Lu et al, 2011). The RUSLE determines mean annual soil loss (A, t/ha/yr) as a product of six factors as shown below:

$$A=R*K*LS*C$$

Where:

- A is the annual average soil loss per unit of area (tonne per hectare per year),
- R is the rainfall erosivity factor,
- K is the soil erodibility factor,
- L is the slope length factor,
- S is the slope steepness factor,
- C is the cover management factor and

The equation helps determine where within a catchment hillslope sediment generation is likely to occur. All the data are available at 5m resolution but should be resampled to 25 m to be consistent with fire severity data. The equation helps determine where within a catchment hillslope sediment generation is likely to occur. Data for applying RUSLE are listed in Table 1.

Table 1. Datasets used to assess hillslope erosion risk.

Data	Name	Description
R	Rusle_r_z55_clipped_5mres	Rainfall erosivity
K	Rusle_k_z55_clipped_5mres	Soil erodibility
C	Rusle_c factor_z55	Vegetation cover factor
LS	Rusle__LS_z55	Slope length and steepness factor
SDR	delivery ratio	Sediment delivery ratio
WQ_risk	Geol_Mass_Fraction	Risk categories based on geology
Sub-catchments	Creek_CatchmentsFINMGA55	Sub catchment (produced by Icon)

Fire adjustment to C factor

For the burned setting we use information on fire severity (or dNBR) to adjust the vegetation cover parameter (C) according to methods outlined in Blake et al. (2020). First, the burn severity (dNBR) layer is categorised and used to assign new C values to RUSLE based on the rules in Table 2.

Table 2. C factor adjustment to account for fire-effects

Description*	C- factor adjustment according to burn severity
Unburnt to understory scorch	The lesser of 0.01 and background RUSLE C factor
Complete understorey burn, partial canopy scorch	The lesser of 0.05 and background RUSLE C factor
Complete canopy scorch and understory burn	The lesser of 0.1 and background RUSLE C factor
Complete canopy and understory burn	The lesser of 0.2 and background RUSLE C factor
Tussock grasslands regenerating. regeneration of grasses along	The lesser of 0.05 and background RUSLE C factor

Sediment property adjustment based on Geol Mass Frac

The local erosion rate from RUSLE was weighted by water quality categories in 'Geol Mass Frac' dataset to account for the different grain size and dispersibility of source material. This weighting factor was determined after consultation with Icon Water on the relative risk of high, moderate, and low water quality risk categories in the Geol Mass Frac dataset. The following weighting (Table 3) was assigned after analysis of fine fraction in the three water quality risk categories.

Table 3. Erosion risk weighting factor to account for different fine fraction as determined by parent material (i.e. geology)

Risk category	Weighting
High	1
Moderate	0.41
Low	0.24

Aggregation to sub catchment scale

The weighted hillslope erosion (A_{fire}) is then aggregated to the sub-catchment scale (using Creek_CatchmentsFINMGA55.shp) to give a summary for each catchment. These catchments were ranked into risk categories based on their median erosion risk. We assigned categories based on the distribution of values across the 40 sub catchments.

Table 4. Range of erosion risks used to assign risk categories to sub catchments.

Risk category	Range
Very high	>6
High	4-6
Moderate	2-4
Low	<2

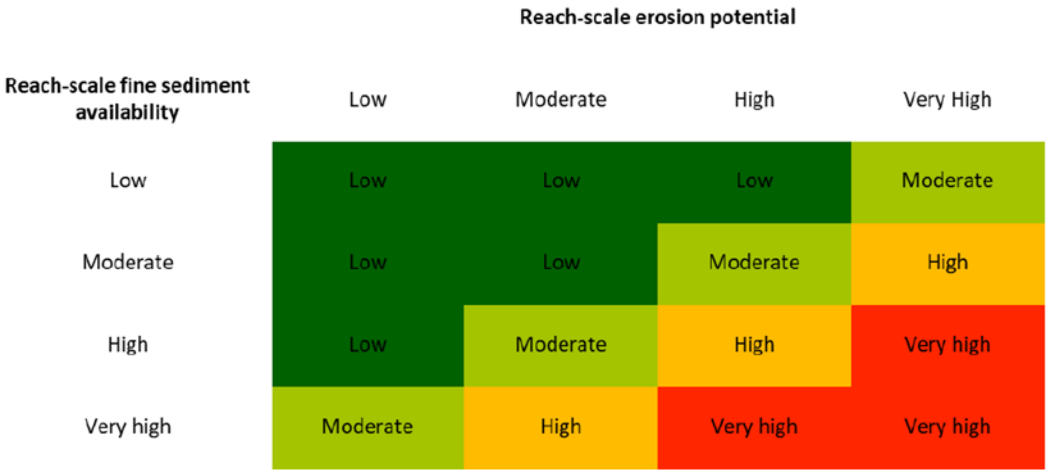
4.2 Gully erosion in headwaters (or sub-catchments)

The risk to water quality from gully erosion within sub catchments was assumed to be proportional to the risk metric produced for hillslope erosion by RUSLE. This assumption is based on observations and the review, which indicate that most gullies are eroded by the same erosion events that cause widespread hillslope erosion. The dominant process for erosion and sediment transport – shear stress from overland flow - is the same for both.

4.3 Channel erosion along Cotter mainstem and other larger streams outside sub catchments

Sediment availability along channel reaches was mapped as part of the ACWA plan. In ACWA, these data on sediment availability was combined with erosion potential (determined from visual assessment of exposed sediment/vegetation disturbance), to determine channel erosion risk.

In this post-fire risk assessment, we use the data on fire severity to adjust erosion potential. First, we constructed a 5m buffer around the stream reaches, then extract the median fire severity from those buffers. For low, moderate, and high burned severity we set erosion potential to low, moderate and high. The fire adjusted erosion risk was then determined from the matrix:



	Reach-scale erosion potential			
Reach-scale fine sediment availability	Low	Moderate	High	Very High
Low	Low	Low	Low	Moderate
Moderate	Low	Low	Moderate	High
High	Low	Moderate	High	Very high
Very high	Moderate	High	Very high	Very high

Figure 4. *Risk matrix used to in the Cotter Catchment Actions for Clean Water (ACWA)*

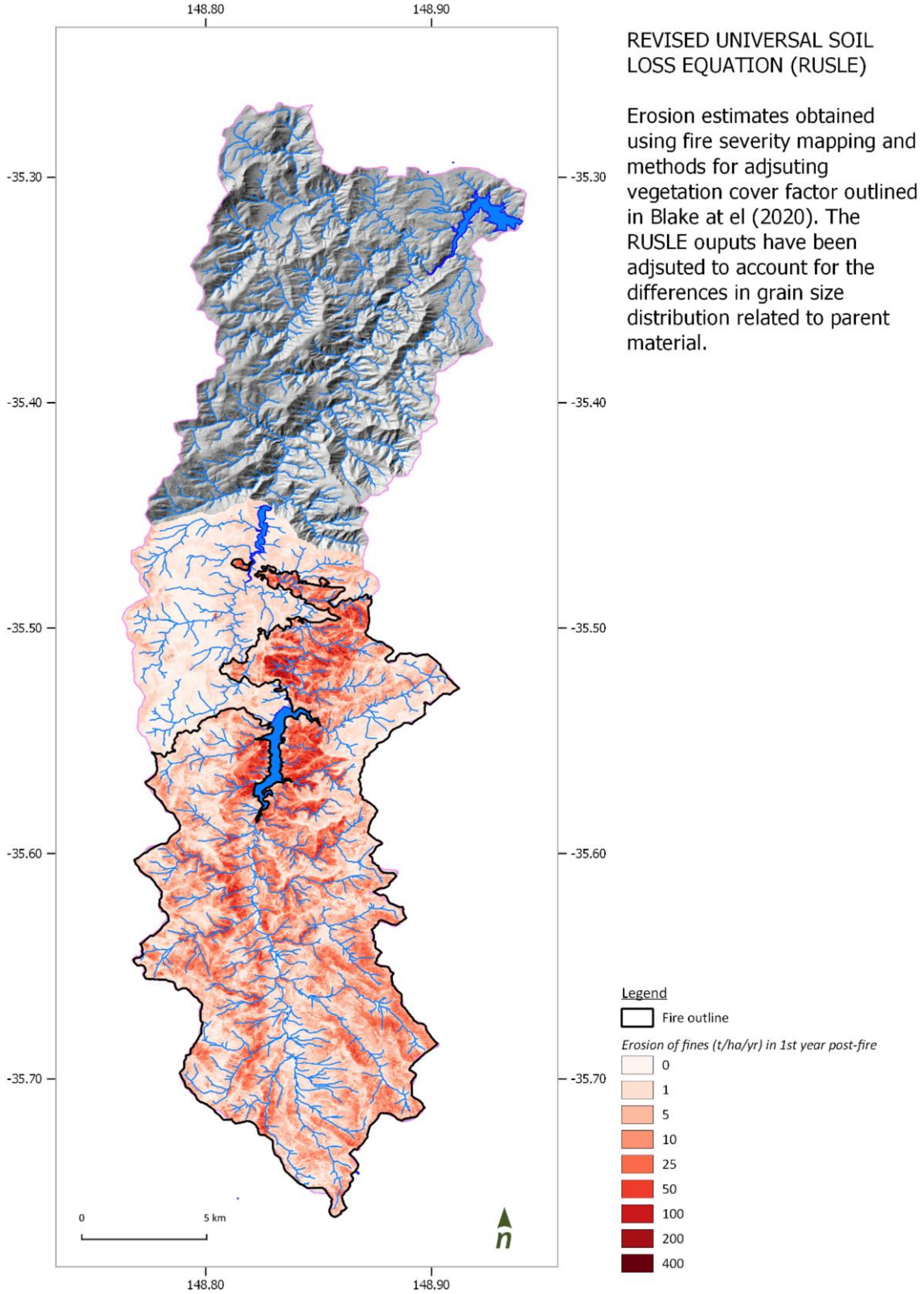
4.4 Degradation of bogs/swamps

Here we identified areas where bushfire and bogs/swamps overlap, then use proximity to stream (from sediment delivery ratio), to rank these areas in terms of threat to water quality. The risk is high, moderate, and low for areas within 10m, 30m and greater than 30m of a waterway. For this assessment we used fire as a binary variable because fire severity form remote sensing metrics (e.g. dNBR) are not well suited to picking up on differences in bushfire-impact in systems where the fire burns through grasses and organic deposits.

5 Results: Erosion risk following the Orroral Fire:

5.1 Hillslope erosion

The water quality risk stemming from hillslope erosion is concentrated in steep catchment areas where the severity has caused complete canopy burn or scorch (Figure 5).



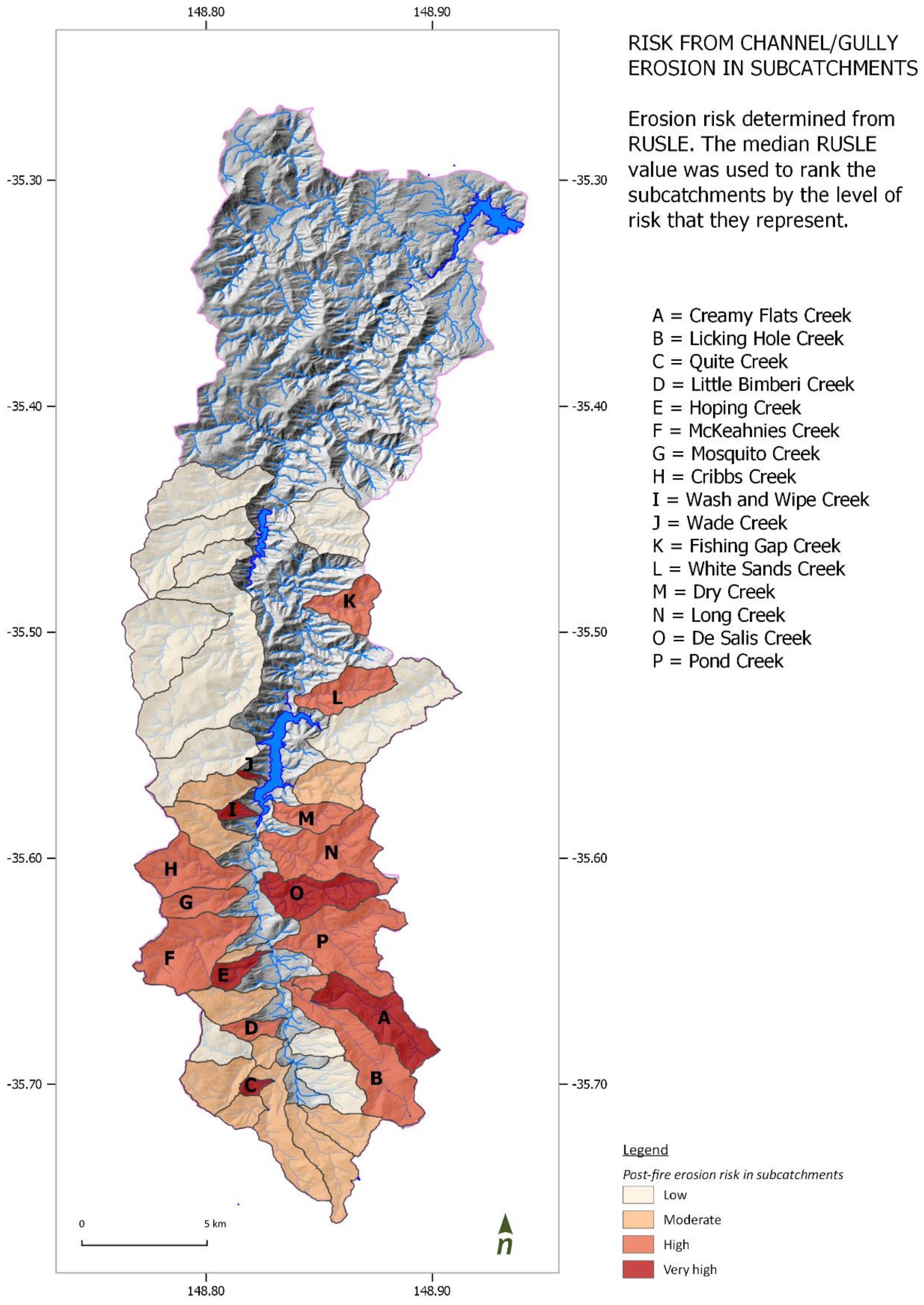
REVISED UNIVERSAL SOIL LOSS EQUATION (RUSLE)

Erosion estimates obtained using fire severity mapping and methods for adjsuting vegetation cover factor outlined in Blake at el (2020). The RUSLE ouputs have been adjsuted to account for the differences in grain size distribution related to parent material.

Figure 5. *Water quality risk from hillslope erosion determined using RUSLE, fire severity and data on fine fraction in source sediments.*

5.2 Channel and gully erosion in headwaters (or sub-catchments)

The sub catchment where gully erosion is most likely were determined by aggregating RUSLE outputs to sub catchment-scale (Figure 6). This assessment provides an indicator of relative risk, considering those factors that go into our RUSLE risk model: fire severity, fine sediment fraction, topography and soil erodibility and rainfall erosivity.



RISK FROM CHANNEL/GULLY EROSION IN SUBCATCHMENTS

Erosion risk determined from RUSLE. The median RUSLE value was used to rank the subcatchments by the level of risk that they represent.

A = Creamy Flats Creek
B = Licking Hole Creek
C = Quite Creek
D = Little Bimberi Creek
E = Hoping Creek
F = McKeahnies Creek
G = Mosquito Creek
H = Cribbs Creek
I = Wash and Wipe Creek
J = Wade Creek
K = Fishing Gap Creek
L = White Sands Creek
M = Dry Creek
N = Long Creek
O = De Salis Creek
P = Pond Creek

Legend

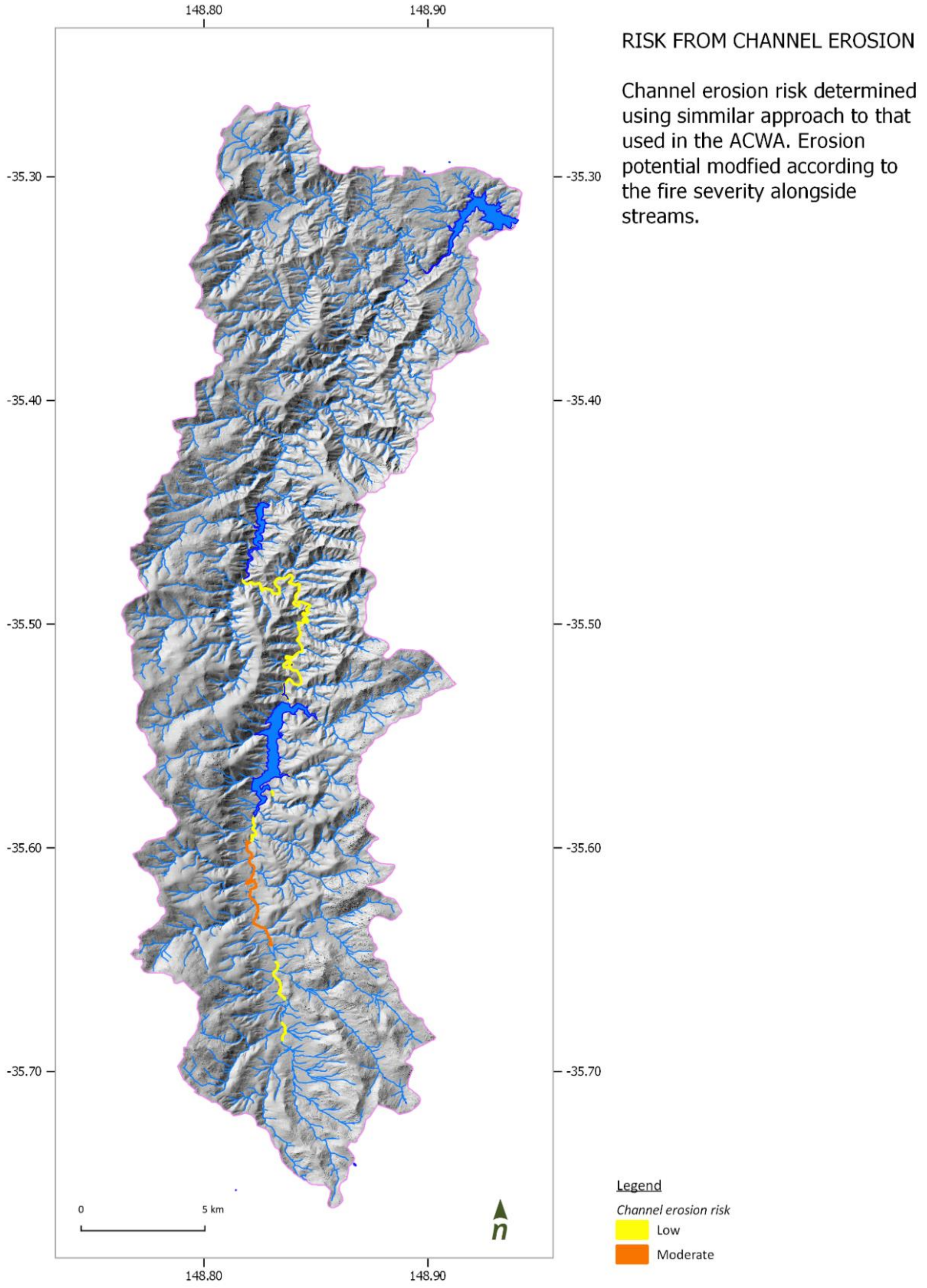
Post-fire erosion risk in subcatchments

- ▨ Low
- ▨ Moderate
- ▨ High
- ▨ Very high

Figure 6. *Risk of gully and channel erosion in sub catchments determined by ranking catchments based on their aggregated RUSLE risk rating.*

5.3 Channel erosion along Cotter mainstem

With our assessment of channel erosion risk, there was one reach of the Cotter River, upstream of Corin dam, where the erosion risk has changed from low to moderate because of the bushfire. This assessment does not consider possible changes in peak flows. It also aggregates the fire impact to the reach scale, ignoring local effect that may trigger increased erosion.



RISK FROM CHANNEL EROSION

Channel erosion risk determined using simmilar approach to that used in the ACWA. Erosion potential modfied according to the fire severity alongside streams.

Figure 7. *Post-fire channel erosion risk along the Cotter River.*

5.4 Degradation of bogs and riparian zones

There are many swamps and bogs that have been burned and which represent risk to water quality. There is 30ha, 50ha and 160ha of high, moderate, and low risk bogs/swamps. Nearly all of which are located in the Corin Catchment. A detailed assessment on impacts of fire on bogs is provided in Hope & Keany (2020).

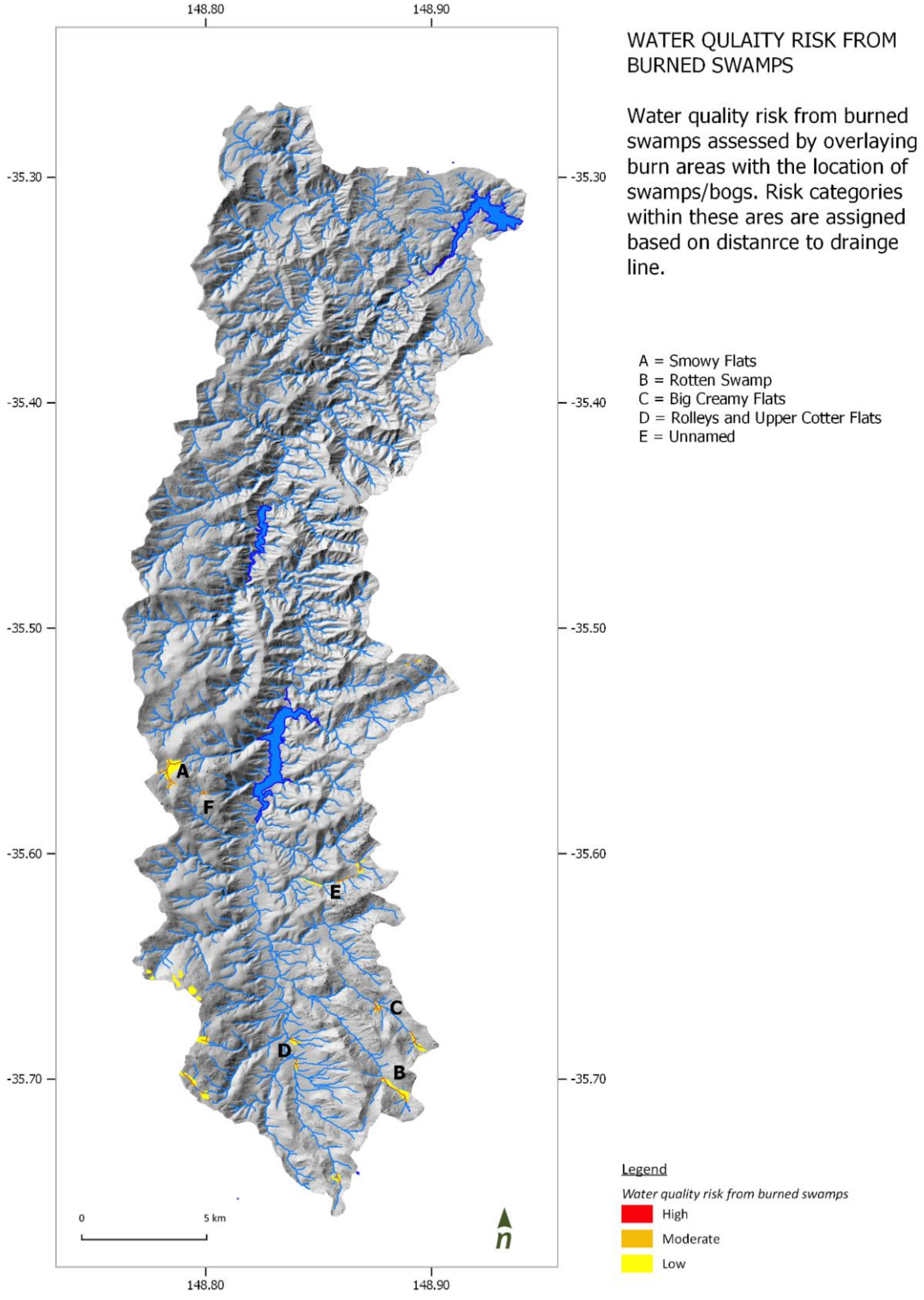


Figure 8. *Swamps and bogs that have been burned and which represent risk to water quality.*

6 Method reflections

The risk maps have been developed using the best available data and models that can be applied without detailed information on hydrological parameters and process understanding.

The outputs should be interpreted in a qualitative sense in that we are not predicting actual impacts on water quality in terms of suspended sediment, nutrient concentrations, etc. Our approach, however, is underpinned by strong conceptual understanding of key processes that are likely to operate in the catchments. Our understanding comes from our review, conducted as part of this project, and past research on post-fire erosion and water quality impacts in SE Australia (Nyman et al., 2019; Smith et al., 2011; White et al., 2006).

The risk maps provide robust input to assist with focusing and prioritising recovery efforts.

Some key limitations with our approach include:

- Along the Cotter in the flats and wetlands, the biggest sediment sources are from upstream and the tributaries, but also from bank collapse. Our approach does not provide a strong basis for evaluating where localised bank collapse might be causing water quality issues. Field observations indicate that bank collapse along streams in wetlands is occurring on large scale across the burned area.
- The RUSLE approach does not consider the connectivity between sediment source areas and the reservoir. The model does not quite relate to what is going on in the environment. There is complexity in processes and spatial heterogeneity that our modelling approach does not capture. With further research and model development more sophisticated tools for assessing risk can be developed. If rates of deposition can be estimated, then there is potential to accumulate erosion rate with increasing area.
- None of our models consider recovery. We provide a snapshot of risk following the fire. As recovery processes unfold, the spatial patterns in risk are likely to play out through complex interactions between fire severity, moisture availability and other biophysics factors, including the potential disturbance from pigs, horses, deer and rabbits. Incorporating recovery processes into erosion models is a high priority.
- Rocky slopes of the ranges on the eastern side of the catchment have an unburnt RUSLE C-factor value of 0.12 (very high) for vegetation that could be crudely described as open native woodlands on moderate to steep rocky slopes. The value seems rather high for this community and may be giving a higher result for the pre-fire environment.
- Our approach does not consider changes in channel erosion along the main Cotter River due to increases in peak flows following fire.
- Our approach identifies bogs/swamps where water quality and degradation issues might emerge. We do not have a strong understanding of the processes occurring in these parts of the landscape and what it might mean for water quality.
- We do not have the grain-size data to understand to what degree channel/floodplain derived sediments represent risk to water quality. More generally there is a lack of these data on gain-size throughout the Upper Cotter catchments.
- We do not use models that operate on event-based time scales, which can be important to understand the risk coming from pulses of sediment that are delivered during short periods of time.

7 Risk management – strategies, principles, and techniques

7.1 Strategies for risk management

Building knowledge through partnerships, research, and model development
Insights from applied research on forest hydrology, post-fire sediment transport and erosion control are critical to informing a post-fire erosion management plan. Using models to identify *where* in the catchment problematic erosion will occur is central to effective risk mitigation. The cost of catchment intervention is high. Widespread intervention throughout an entire water supply catchment is not cost-effective and probably not feasible. The effectiveness of the management plan is therefore contingent on robust models. Continued refinement of post-fire erosion models, through monitoring, evaluation, and research, although outside the scope of this work, should form part an adaptive approach to managing risk. Investment in research and model development, and knowledge sharing amongst water utilities, are key components to knowledge generation.

Building capacity within Icon Water to use research to inform risk management
A well targeted, timely and cost-effective response to post-fire erosion is contingent on the capacity within Icon Water to generate, interpret and respond to information on water quality risk. Each fire scenario is unique and requires detailed modelling of erosion risk using information on fire severity and catchment attributes. Through training and workshops, Icon Water will benefit from developing in-house capacity to respond to bushfire emergency in water supply catchments. There are several outcomes that a training program should focus on:

- In-house expertise to conduct risk assessments using fire severity and water quality risk models in catchments that are recovering from bushfire.
- Technical capabilities to understand and interpret results and apply them to inform an emergency response.
- Developing an understanding of erosion control strategies in burned areas and the factors that should be considered when developing a post-fire emergency response plan.

Building bushfire preparedness through investment in infrastructure, catchment works and rehabilitation efforts
An effective post-fire response is contingent on Icon Water understanding the options, benefits and cost of erosion management. Investment in infrastructure and catchment works will be guided by outputs from this report, which draws on the best available data and our current understanding of suitable options for erosion management. Further work is required to understand cost and benefits of these options.

7.2 Guiding principles for management of post-fire erosion

Each bushfire emergency will present unique challenges and opportunities with regards to managing water quality risk. A cost-effective and fit-for-purpose risk management response will therefore be developed based on the circumstances and parameters of a given bushfire event. Based on our review and input from subject experts, we advise that four principles are applied when developing a post-fire water quality risk management plan:

1. Mitigation *targets hotspots* at the source and where most runoff and erosion are likely to be generated. Typically, 90% of the erosion is from 10% of the catchment area. This provides a basis for prioritising and focusing interventions.
2. Mitigation through a *multipronged approach* that reduces sediment delivery to the reservoir by interventions along the entire transport pathway between source (hillslopes) and asset (reservoir).
3. The *reduction in risk is quantifiable* so the benefits can be evaluated against economic costs, safety, and environmental impacts.

4. Mitigation forms part of an *adaptive management approach* with clear pathways for evaluating benefits and refining strategies and methods for erosion control as new information and data come available.

In addition to these specific principles around erosion control, there are important broader considerations regarding feasibility, maintenance, cost, access, safety, and potentially conflicting interest with regards to other values that land and waterways are managed for:

- *Access* is often a major constraint and any intervention that requires ground crew will be dictated in large part by the road network.
- *Safety* of personnel also presents major constraints on feasibility and access to erosion hotspots because of steep slopes and hazardous trees.
- *Legislative/statutory requirements*, arising from the zoning under the national park management policies are a high-level consideration and any management plan to mitigate water quality impacts will need to be developed in close consultation with the land ACT Parks and Conservation Service.

7.3 Techniques for management of post-fire erosion and water quality impacts

Overview
Risk mitigation can target different pathways that contribute to risk. There is strong evidence in the peer-reviewed literature that the post-fire erosion risk can be reduced with erosion control (deWolfe et al., 2008; Robichaud & Ashmun, 2013). See attached letter (Appendix C) from Peter Robichaud (leading expert on post-fire hydrology and erosion from the US Forest Service) outlining efforts and evidence in the US Forest Service on mitigation of post-fire erosion. Erosion risk management as deWolfe et al. (2008) points out, is most effective when multiple strategies are implemented in combination and where they operate in synergy with one another. In other words, the whole strategy is greater than the sum of the parts.

In steep landscapes like the Cotter Catchment, sediment retention approaches are extremely difficult to implement and poorly designed erosion and sediment control structures can be counterproductive and exacerbate the erosion problem (deWolfe et al., 2008). Furthermore, on a broad scale, the use of methods such as coir logs, trapping sediment and limiting the transport of fine sediment is likely not an economically or physically feasible proposition. These efforts would need to be highly targeted at those areas where the threat of erosion is very high. Most benefits are likely to be gained by participating in the rehabilitation of the swamps and riparian zones in the catchment, as although the bog sites are geographically disparate, the terrain in which they sit is a little more accessible.

Promote vegetation recovery in riparian zones and bogs that are prone to degradation
Strategies to promote vegetation and streambank stability will fast track the recovery of bogs, wetlands, and streams. Hope & Keany (2020) recommend using stacked coir logs as barriers in the streams and rivulets that dissect the bogs. They also suggest using locally derived rock gabions to build in-stream barriers that can withstand larger flows. These can be built 20 cm above the channel to encourage water to spread onto the peatland during floods. They also propose a program of transplanting of moss, restiads and sedges to hasten the colonisation of bare peat and to form nuclei for Sphagnum hummock return.

In riparian zones along larger streams, the main strategy for promoting recovery would be revegetation programs in zones where tree mortality is high. In areas where trees remain, and growing back from epicormic shoots or lignotubers, the roots systems are likely to provide stability to streambanks. No management intervention would be required in these settings.

Vertebrae pest management is a critical component of managing recovery in bogs and in sensitive riparian zones.

Reducing peak flows from hillslopes
This includes hillslope treatments such as mulching and barriers (e.g. coir logs) that add roughness to the hillslope. These strategies will 1) increase the water storage potential on the hillslope and 2) reduce the velocity of overland flow. Both reduce the peak flows on hillslopes and in downstream channels (Robichaud et

al., 2008; Robichaud & Ashmun, 2013; Istanbulluoglu et al., 2003). This means that the flow is less erosive and rainfall thresholds for initiation of gully erosion increase as a result. Effectiveness of this strategy depends on application rate, rainfall events, and the type of materials used to treat the hillslopes (Wilson et al., 2018).

Reducing erosion by trapping coarse sediments with debris barriers

Trapping of coarse sediment in channels can be achieved with structures such as constructed log jams or robust debris barriers. By trapping coarse sediment, the peak flow of the event is reduced (Banihabib & Forghani, 2017). This in turn reduces the shear stress of the flow as it progresses down the channel network (Kean et al., 2016). This means that the flow is less likely to erode into sediment that is stored in channels. To be effective, the barriers would need to be constructed to withstand large flow events, including debris flows. Straw bales or coir logs are not suitable for in-channel erosion control in steep, burned catchments.

Limiting transport of fine sediment between source areas and the reservoir

Use of check dams and small ponds to provide opportunities for fine sediment to settle/deposit prior to reaching the water offtake. In-channel structures such as log jams and road embankments reduce flow velocities and provide opportunities for water to pond, resulting in sediment settling out of the flow (Verstraeten & Poesen, 2000).

Figure 9. *Techniques for erosion and sediment control in burned catchments. If appropriate, wood mulch or wood-shred can be used together with coir logs for a more intensive intervention strategy.*

8 Monitoring and research

8.1 General framework for monitoring and evaluation of risk mitigation

The aim of monitoring and evaluation is to help understand how a management and recovery plan achieve their objective, which in this case is to ensure supply of water that is treatable at minimal cost. Monitoring and evaluation should provide data for adaptive management through assessments of effectiveness, progress, benefit, cost and safety, and improvement opportunities. An adaptive management approach should consider:

- Scope and objectives of monitoring and evaluation must be clearly defined in relation to the desired management outcomes.
- Perspectives and approaches to catchment management and recovery strategies will vary. The program for monitoring and evaluation should be inclusive and cognisant of the diversity of views amongst stakeholders.
- Accepting that progress stems from ‘learning by doing’. Incomplete science is not a justification for inaction. However, when knowledge gaps are large, the adaptive framework should be approached so that feedback loops are short, allowing for quick and continuous improvement.
- Ensure monitoring is targeted, efficient and coordinated, so that it provides information on progress against the core objectives of the plan.

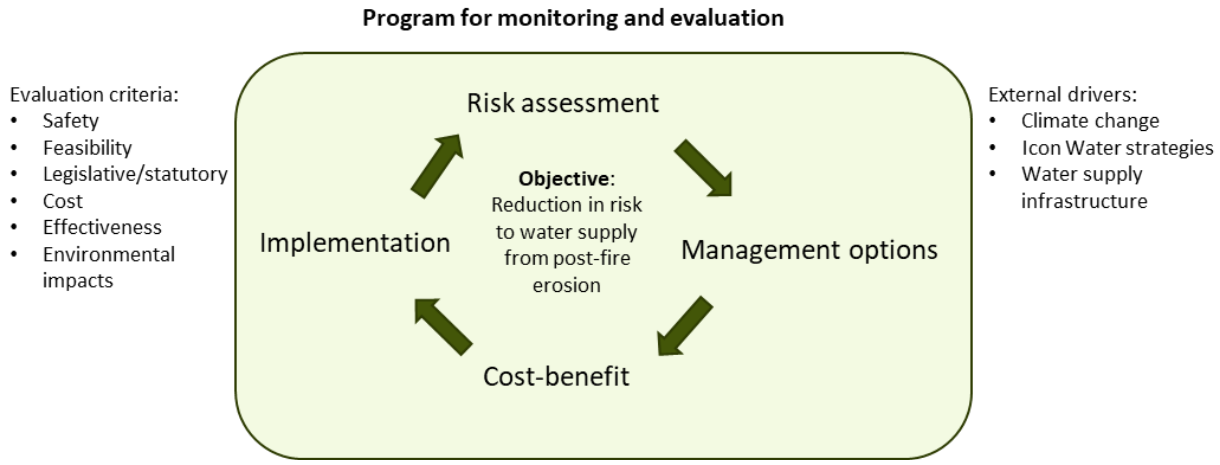


Figure 10. *Evaluation criteria, external drives and processes for monitoring and evaluation.*

8.2 Immediate opportunities for monitoring and research

There are several areas where monitoring will help guide recovery and improve preparedness for future events:

- Collect data on water quality (turbidity, TSS, organics, nutrients, metals and pathogens) in reservoirs and downstream of high-risk areas, focusing on capturing response to significant rainfall events.
- Use satellite imagery (Landsat or Sentinel) to monitor vegetation change over time.
- Use repeat topographic surveys (photogrammetry, lidar, erosion pins) in strategic locations to construct sediment budgets and identify sediment sources and sinks. Bathymetric surveys of dams could be recommended as way to assess what sediment infill has occurred and how this may affect water availability.
- Monitoring gully erosion through regular field surveys and identify the rainfall intensities when key events such as debris flows are triggered.

- Sample sediment to analyse geochemistry with the aim to identify the degree with which nutrients and metals are transported in association with ash and sediments.
- Carefully designed monitoring system for evaluating the effectiveness of any management intervention that is pursued.

In designing and prioritising monitoring and research activities, the framework in Figure 11 provides some guidance on the different aspects of risk and the mitigation measures that can be implemented. Ultimately, any investment in monitoring and research should be embedded in and inform the well-established four-phase disaster management approach of prevention (planning), preparedness, response and recovery (Canning et al, 2020).

Figure 11. *Framework for predicting post-fire contamination risk. From Nunes et al (2018)*

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Appendix A: Literature Review Summary Findings

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Publication	What are the links to water quality and bushfire in the Cotter Catchment?	What are the relevant processes or impacts being described? What regulates this process? In terms of frequency, magnitude, recovery, timescales etc.	In what way (if at all) does this document help inform a risk framework?	Any recommendations on solutions to the issues raised in the publication	What is the timescale of processes and potential management response	Other notes?
Fire in the Alps						
Fire History of the Australian Alps: Prehistory to 2003	There are no links water quality in this document. This document contains a list detailing fires that occurred in the Australian Alps pre 1960	Vegetation change following European settlement and reduction/ prevention of aboriginal burning practices. Soil loss resulting from low intensity fires burning off the herbaceous layer and exposing the soil to erosion forces. (magnified by the introduction of hard hooved animals)	This document aims to document what is normal in terms of fire severity and regularity.			The general trend for all vegetation types across South Eastern Australia is that fire frequency/intensity prior to European influence was significantly less than it was during the early European period, but slightly greater than it is currently.
Cotter Context						
Cotter – Namadgi Hydrological Resource values	'Planned and unplanned fire – and allied measures such as clearing and tracking. Fire, per se, has the effect of reducing water quality' 'fire on steep slopes, particularly those on dry, and apparently fire prone west facing slopes in all reaches below Corin dam and in areas such as the Clear Range has a major impact on water quality'		Identifies the impoundment storage of Bendora and Corin Dams			Fire management is often in conflict with hydrological values. Leaf litter and ground cover represent both fuel loads and erosion protection
Wetland and bogs						
Progress Report for the Restoration of Sphagnum Bogs in Namadgi National Park	Sphagnum bogs act as a filtering system, removing sediments and nutrients before slowly releasing water.	Sphagnum bog threatening processes include, dry periods, hard hooved animals, wind-borne weed infestation (can occur after burning)	Identifies techniques to aid in the recovery of Sphagnum bogs	Proposed techniques include: Retain and spread water within the bog system Protect live Sphagnum from the effects of Ultraviolet exposure and dehydration Enhance the recovery of Sphagnum. Ongoing feral horse, pig and goat control programs was recommended to be implemented	Work was to be funded for 5 years with priority area work completed by December 2003	
Response of Sphagnum bogs to Montane Fire Regime	Damage to swamps represents a reduction in landscape detention storage capacity and efficiency.	Providing there is a total absence of fire and grazing, Sphagnum bogs that do recover from fire will take a minimum of 20 years				
2003 Cotter – WQ						
Impacts of the January 2003 Wildfires on ACT Water Supply Catchments: Water Quality in the Cotter Storages and Catchment Yield	This paper describes the impacts on catchment water yields and dam water quality as well as the works, monitoring and studies being undertaken to better understand and manage the catchment response to fire.	Turbidity, iron and manganese levels at the bottom of the reservoirs peak in late autumn each year due to depletion of oxygen in bottom waters and sediments. The 2003 fires resulted in a 30-fold increase from normal event levels.		To handle the deterioration in water quality due to the large sediment and ash loads in runoff from the denuded catchment, a water filtration treatment plant was constructed Rehabilitation works that were documented to have commenced include: decommissioning of some forestry roads, strategic placement of significant numbers of drainage culverts and gabion protection works, the construction of wetlands and settling basins and the replanting of riparian zones and steep slopes to native vegetation rather than pines.	Design and construction of the filtration treatment plant took 18 months	Major bushfires of greater than 5000 ha have been recorded in the summers of 1920, 1926, 1939, 1983 and 2003, and generally have corresponded with El Nino droughts.

Publication	What are the links to water quality and bushfire in the Cotter Catchment?	What are the relevant processes or impacts being described? What regulates this process? In terms of frequency, magnitude, recovery, timescales etc.	In what way (if at all) does this document help inform a risk framework?	Any recommendations on solutions to the issues raised in the publication	What is the timescale of processes and potential management response	Other notes?
Sources of Turbidity in Bendora Reservoir Final report 2004	During 2003 about 5.7 times the sediment entered Bendora Reservoir compared to a non-fire year	It is not anticipated that the fan deposits will be stabilised by vegetation and will continue to act as a source of turbidity in Bendora Reservoir	Describes the makeup of the fan deposits that were formed post 2003 fire and storm events	Manually establishing vegetation on the fan/deltas to stabilise them. Alternatively, maintaining a fairly constant storage level would accelerate reestablishment of riparian vegetation, at least for backwater reaches Install sediment fences across the fan/deltas, and possibly upstream of the fan/deltas to stop fresh deposition near the reservoir. Maintenance and removal of accumulated sediment behind the fences will be essential		Every year during thermal stratification flocs of iron and manganese produced by bacteria that reduce iron and manganese diffuse into the bottom waters of the reservoir
Turbidity and Contaminent loads in Bendora Reservoir, Cotter river ACT	Chapter 1 details the impacts of fire and rainfall on reservoir water quality Increased catchment runoff levels and sediment loads in streams have regularly been observed following fire and consequent heavy rainfall events fire-based disturbance events were found to trigger much poorer water quality conditions in bottom water depths than those created by lone rainfall events	Sheet erosion Soils become hydrophobic through fire action and thus exhibit very low infiltration rates. Stratified systems are discussed Riparian zones and most hill slopes in the Cotter catchment are likely to take at least 5 years to recover from the fires	Identifies water quality parameters. These include turbidity, total iron, total manganese, total phosphorus and total nitrogen. Details the geology and soils, climate, vegetation, land use and fire history of the Cotter catchment. Provides data on the relationship between rainfall and turbidity; Iron; Manganese; Phosphorus; nitrogen at varying reservoir depths	Recommended that aeration and mixing processes be implemented within the reservoir to maintain dissolved oxygen Levels at concentrations that discourage releases of contaminants, at all depths of the reservoir. Recommends that filtration processes be installed to lower the turbidity levels of the waters. Recommends that a high frequency (at least once in 2 weeks),sampling regime be implemented, that samples all water quality parameters	Sampling is recommended to be conducted once every 2 weeks, year-round	The severity of impacts can depend on several factors including the intensity and extent of burns, the intensity and frequency of subsequent rainfalls, the dryness of preceding weather conditions and the physical characteristics of the site parameters studied were more vulnerable to rainfall events within the catchment that followed fire rather than lone rainfall event Bendora catchment is able to withstand a fire with an extent of 5,800 hectares without significant changes to water quality or the need for long recovery times.
Natural Pollution of Cotter River Dams: Implications for loading of biologically reactive contaminants derived from the Cotter Watershed	Destabilised landscape following drought or fire has the potential to deliver a large flux of material into streams.	Natural equilibrium process and contaminant profile of materials washed off catchment Background to redox (oxidation – reduction) reactions taking place in Cotter watershed				
Iron and Manganese in the Cotter Catchment- Upper Cotter Field Trip 1 March 2004			Provided information on the possible reason for iron and manganese in Cotter tributaries			The source of iron (and probably manganese) in the seeps in tributaries of the Cotter is from dissolved reduced iron (and manganese) from ground and possibly soil water.
2003 Cotter – vegetation, soil, and bogs						
Cotter Catchment Fire Remediation Project: Project: WF 30032 Report February 2004 Cotter Catchment Fire Recovery Mapping - 7 September 2004 Report	The second part of this report details impacts vegetation response will have on water quality Partial vegetation recovery has seen improvements in water quality	factors controlling the recovery of the vegetation relate to the initial fire severity, type and fire sensitivity of the vegetation, and available moisture. Some natural vegetation recovery was observed during the first 12 months, however areas where more severely impacted by the fire may continue to contribute turbidity and groundwater linked iron and manganese problems. Full recovery may take up to a decade.	Within each sub-catchment this report identifies areas severely impacted by the fires that are most likely to contribute to water quality issues	The most severely burnt dry (west and north facing) slopes warrant surveillance for several years, as they will remain a major likely source of water quality deterioration		Digital processing of satellite imagery combined with ground survey was used to map the vegetation recovery 12 months after the fire.

Publication	What are the links to water quality and bushfire in the Cotter Catchment?	What are the relevant processes or impacts being described? What regulates this process? In terms of frequency, magnitude, recovery, timescales etc.	In what way (if at all) does this document help inform a risk framework?	Any recommendations on solutions to the issues raised in the publication	What is the timescale of processes and potential management response	Other notes?
ACTEW – Cotter Catchment Fire Remediation Project – Impact of the fires of January 2003 on the vegetation of the cotter river catchment: early assessment and monitoring	Vegetation plays a stabilisation role in the landscape, preventing erosion and related water quality issues		The report provides a 'snapshot' of vegetation condition one year on from the 2003 fires with descriptions of the catchment's vegetation communities.	Management through monitoring and, where necessary, special measures in respect of control of the fire regime and of forest fuels, of each extensive vegetation type vegetation type, is recommended	At least 5 years	
Revegetation of water supply catchments following bushfire: A review of the scientific literature relevant to the Lower Cotter catchment	Loss of vegetation resulting from the 2003 fire has led to an increase in erosion processes which impact on water quality.	The loss of vegetative cover from the Lower Cotter catchment after the 2003 bush-fires has resulted in an increased rate of soil erosion from both hillslope and gully sources, impacting negatively upon water quality. Eroded sediments in waterways can lead to elevated nutrient levels increasing the likelihood of algal blooms. Chemical reactions may be triggered resulting in the release of stored manganese and iron into the waterway.	Provides a fire history of the cotter catchment Provides detail on the catchment hydrology, soils, geomorphology and road networks. Provides detail on catchment post fire responses	The removal and better drainage of roads is highly likely to have a beneficial impact upon water quality in the Lower Cotter Catchment in the short and long term. Returning riparian vegetation to the landscape Constructed wetland are a priority for management in the short term. The Cotter Reservoir could be managed to encourage the formation of a stable wetland at its backwater zone. A budget of sediment within the stream and reservoir is an urgent priority for monitoring and research.		Loss of vegetation during the 2003 bushfires will have altered the catchment's hydrologic balance. This is likely to result in a short term (3-7 year) increase in catchment water yield. Beyond this and under re-establishment of either native forest or introduced pine species, water yields are likely to decline in the medium term (7–50+ years) as this vegetation grows and its water use increases.
A report on the state of the mountain mires of the Australian Capital Territory after fires 14-22 January 2003	Describes how a loss of peatlands due to fires can result in extensive erosion events, impacting on waterways.	Vegetation change in the form of A shift towards sedge and grass dominance will increase runoff during showers, which may increase stream incision and other erosion processes Peatlands moderate runoff, filtering mineral sediment and steadily releasing clean water for extended periods of time (months) following rainfall	Details the location of bogs and swamps located in the cotter catchment and the impact that the 2003 fire had on them. Describes how a loss of peatlands due to fires can result in extensive erosion events, impacting on waterways.	To assist the regeneration of drained mires, feral horses, goats and pigs need to be removed and the flow redirected through the use of barriers at natural nick points out onto the bog surfaces.		Almost all the montane mires in the ACT have been affected by the January 2003 fires with the burnt area varying from 55-100% of the mire surface
ACT Bushfire summaries – Effects of varying fire regimes on hydrological processes	'The mobilisation of organic and inorganic sediment after a severe fire poses the greatest threat to water chemistry of water reservoirs, including increases in turbidity, manganese, iron, and biological oxygen demand (BOD) well above national water standards'.	The effects of fire regimes on water quality section is not included in this document	'Preliminary results gleaned from the scientific literature indicate that a ground cover load of 6-7 tonnes per hectare covering at least 70% of the ground prevents major soil movement following storms of high intensity, between 60 and 100 mm per hour.' Cotter catchment 2003 firer severity map provided	There is a section in the table of contents for management solutions but this is not included in this document		
Sparks: Ecowise Cotter Fire Recovery Mapping – TasWater 09	All significant fires within the catchment have resulted in degradation of the landscape immediately after the fire event with subsequent loss in water quality.	Erosion processes following fire and storms 30-fold increases in turbidity, iron and manganese resulting from post fire storm sediment influxes.	Provides a description of land uses in the cotter catchment Provides an indication of areas that will naturally recover quicker i.e. eastern slopes	Rehabilitation activities such as road upgrades and redundant road closures, removal of pines, and native planting and seeding, within the lower Cotter areas has significantly improved water quality in recent years.		Fires are a normal recurring event in the Cotter catchment typically occurring after drought
Interim report – January 2003 fires impact of vegetation change on hydrological values of the cotter river watershed		Vegetation change	Provides vegetation units of the cotter catchment Provides time frames for natural regeneration of each vegetation unit		Continuous management of every vegetation type for at least five years is recommended E. delegatensis and E. fastigata, need to be managed for a period of 15 – 25 years.	Suppression of the development of the mature stages of understorey formation and fuel build up would require fuel reduction burning that would maintain soil surfaces at increased erodibility levels for more time.

Publication	What are the links to water quality and bushfire in the Cotter Catchment?	What are the relevant processes or impacts being described? What regulates this process? In terms of frequency, magnitude, recovery, timescales etc.	In what way (if at all) does this document help inform a risk framework?	Any recommendations on solutions to the issues raised in the publication	What is the timescale of processes and potential management response	Other notes?
2003 Cotter – erosion						
Major Erosion Events and Past Fires in the Cotter River Catchment	Vegetation and leaf litter protect the landscape from erosion events. Bushfires remove this vegetation and have an impact on the soil properties increasing the landscapes vulnerable to erosion during rain events.	Erosion – fires amplify most hillslope erosion processes Fire is a frequent component of the Namadgi landscape – events similar to 2003 although infrequent are not unique. The most recent event of a similar nature occurred approximately 400 years ago and far outweighed the scale of the 2003 event Previous studies cited in the report documented that it took 5 to 6 years for stream water turbidity to return to pre fire conditions	Discusses how the 2003 events were not unique			
REPORT # 3 - Rain Event Survey 21 February 2003	Impact of runoff on water quality – increased turbidity from ash and charcoal runoff Potential for storage eutrophication to occur following the February 8, 2003 storm	The rate of recovery of the landscape will be related to a complex mixture of climatic condition (temperature, rainfall intensity and interval), fire intensity, landform, edaphic (soil) factors, and vegetation recovery processes. Turbidity in water storages should clear up within a couple of weeks following rain events, fire material may take slightly longer to settle out.	Provides detail on water quality issues that can impact water storages following similar events to that of the 2003 fires and subsequent			
PRELIMINARY REPORT # 2 Covering Period 7 - 14 February 2003	Erosion events during the storms following the 2003 fires have been attributed predominantly to loss of protecting vegetation as a direct result of the fires.	Study examined sheet and aeolian erosion. Nutrient loss from slopes mobilised by erosion process will result in implications to vegetation recovery. Instream sediment loads – large instream deposits will be mobilised during the next bank full event Under normal circumstances flow events similar to the one experienced in 2003 would occur at an interval of every 1 to 2 years, however changes in hydraulic characteristics due to fire has resulted in higher discharges in shorter timeframes with higher erosion potential.	Illustrates losses in vegetation cover can lead to large erosion events that have ongoing impacts to the ecosystem Provides documentation of events that occurred following the 2003 fires			'The erosion that occurred during the storm was, in terms of the range of landforms affected and the amount of material moved, the most severe witnessed in thirty-five years by Barry Starr. The severity was obviously a combination of conditioning by drought and fire and the extreme nature of the rainfall event.'
Cotter Catchment - Fire And Storm **An Analysis of the Impact of the January 2003 Wildfire and Following Rainfall Events on the Stability of Upper Cotter Catchment and Management Recommendations** **Produced for and on behalf of ActewAGL by BARRY STARR**	The purpose of this report is to provide some predictive capacity as to the impact of fires on the water quality in the cotter catchment. Investigates the impact of back burning on water quality Details the impacts of fire and following rainfall events. 'Loss of groundcover, provision of material for mobilisation in the form of ash, charcoal and organic matter, and hydrophobicity, all ensured that mobilisation would occur in a high rainfall event'	Erosion and movement of fine sediment There magnitude of the erosion event following the 2003 fires and subsequent storms has been severe (sheet erosion) The risk of large volumes of material export will continue until vegetation on slopes and along drainage lines has recovered.	This document details how the cotter catchment was impacted following the 2003 fires and subsequent storm events. This knowledge can be used to inform the development of preventative measures to reduce future mass erosion events.	Construction of sediment fences for the purpose of monitoring movement of eroded soil, fine debris and organic matter. It is anticipated that mass movement of eroded material will continue for an extended period of time following a fire event.	Revegetation of side slopes is likely to take at least 18 months. Streambank revegetation will take longer, at least three years.	The swamps and bogs, suffered high to extreme fire damage.

Appendix B: Fire Severity Mapping

Appendix B: 2020 Fire Severity Analysis

Background

This analysis is limited to the Upper Cotter catchment (upstream of the Bendora Dam wall) on the western side of the ACT. The analysis aims to provide a fire severity assessment of the fire effected lands as well as a comparison with pre-existing knowledge of the soils within the Upper Murrumbidgee and their risks to water quality as sampled and mapped between 2003 and 2012. This analysis does not include areas within the Namadgi National Park further to east of the Cotter Catchment.

Basic premise of the severity analysis was that a difference could be detected between two different dates, a pre fire and a post fire image. The process to undertake this analysis is well defined and has been widely used for many decades, however, results can be degraded if care is not taken in the selection of the image dates and calibration of images and results.

The analysis used, a normalised burn index/ratio to utilise the difference in the ratio of the near infrared (NIR) and short wave infrared (SWIR) areas of the spectrum for a pre-fire and post-fire image pair as shown in the equation below.

NBR = (NIR-SWIR)/(NIR+SWIR)

A severity analysis is then derived by a difference/ratio of a pre-fire NBR and a post-fire NBR.

The NIR and SWIR requirement dictates which sensors are capable of providing data suitable for the analysis. This also rules out the commonly used high resolution sensors that provide near photographic products as these do not typically cover the SWIR parts of the spectrum.

The dates available for post fire Image selection are confined by a rain event in the beginning of March 2020, meaning that imagery acquired after that date will likely have a green flush going through the fire effected lands and degrading the potential to map fire severity. This will be particularly be the case on more protected slopes (south east facing) where recovery tends to be more intense even when rain has not occurred. It would also be worth noting that excess shadow would become an issue.

Pre-fire imagery was made more difficult due to the amount of smoke haze affecting the region in the lead up to the fire. Conditions were best in the first half of December, though all pre-fire imagery available is affected to some degree by smoke haze. Smoke does however tend to affect the shorter wavelength frequencies more than the longer wavelengths seen in the NIR and SWIR image bands.

Two pre-fire and three post-fire images were selected from two different image sources, Sentinel 2 and Landsat 8. Though no scene was perfect, a combination of these images will allow near complete coverage of the Cotter Catchment. To simplify the analysis, the post fire scenes were matched to a pre-fire image from the same source with the resulting derived indices mosaicked.

Local Date	Sensor and Bands Utilised	Resolution (NIR/SWIR)	Coverage	Cloud/Haze
10 December 2019	Sentinel 2 (Bands 8A and 12)	20m	Complete	Minor haze. Will not affect the result.
16 December 2019	Landsat 8 (90/85) Bands 5 and 7	30m	Complete	Minor haze. Will not affect the result.
23 February	Sentinel 2 (Bands 8A and 12)	20m	Complete	Cloud and haze significantly affecting the area of interest
25 February	Landsat (91/85) Bands 5 and 7	20m	Complete	Cloud and haze partially affecting the area of interest
26 February	Sentinel 2 (Bands 8A and 12)	20m	Partial	Completely cloud and haze free over the area of interest

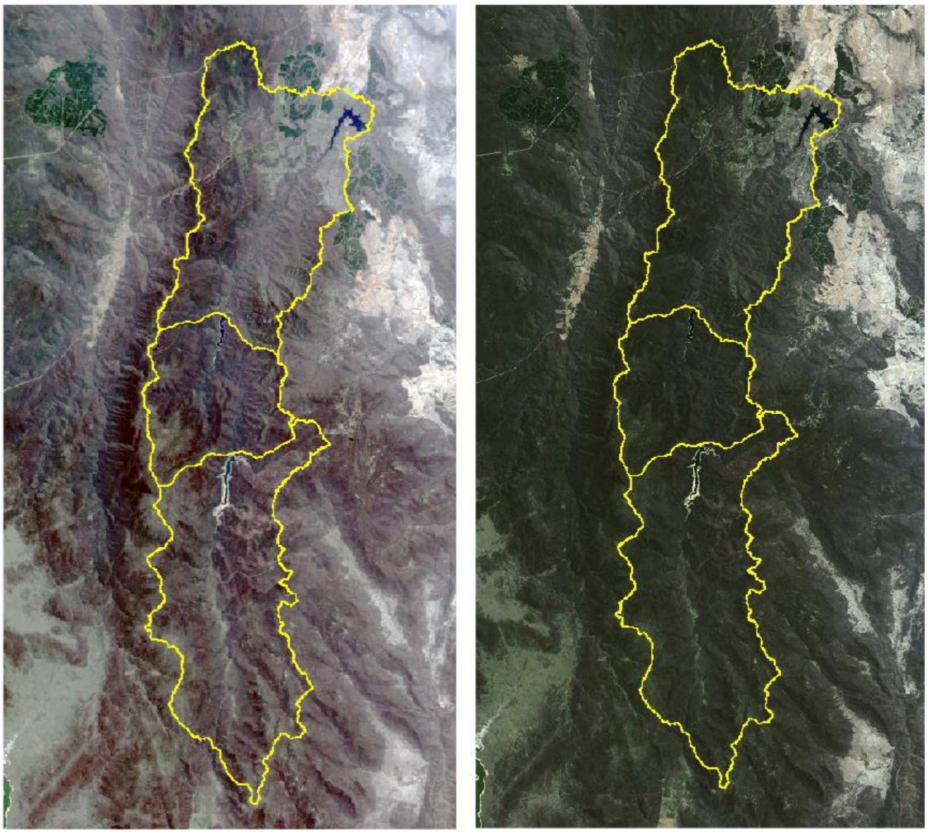


Figure 12. Sentinel 2 (left) and Landsat 8 (right) prefire satellite imagery acquired in December 2019. Some minor haze is present in the imagery but should not limit the abaility to undertake the analysis.

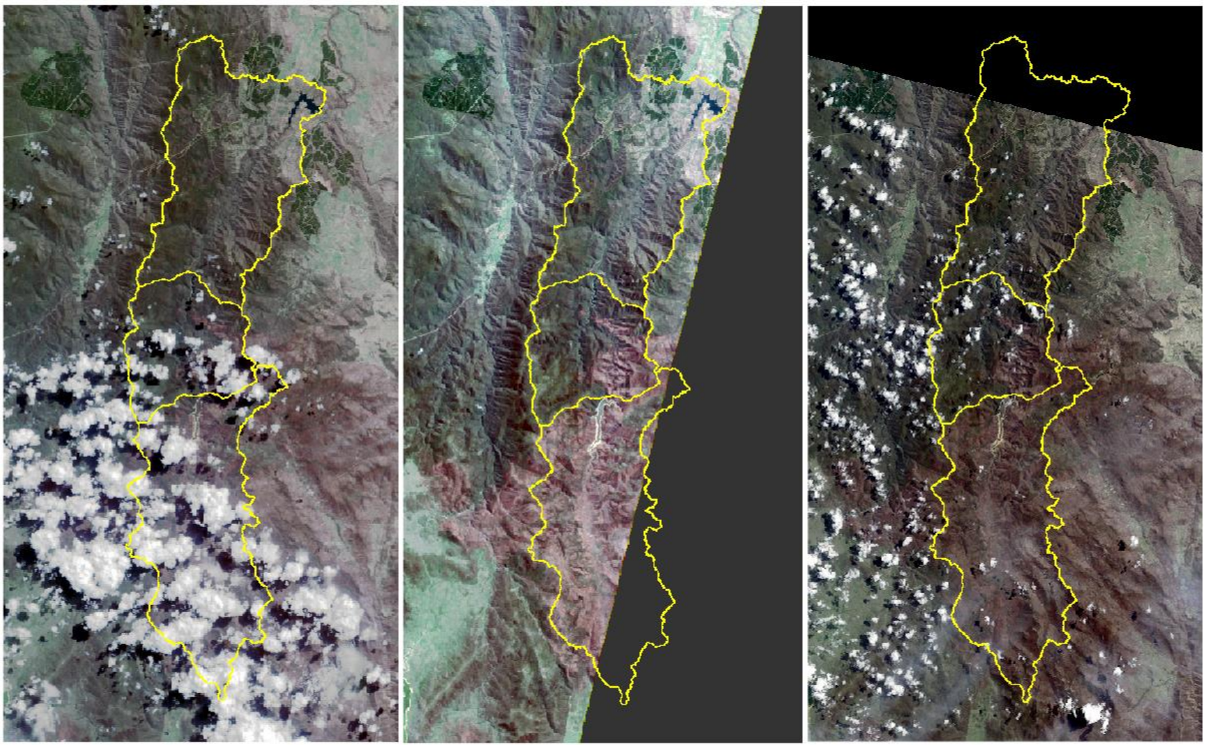


Figure 13. 24 February Sentinel 2 (left), 27 February Sentinel 2 (centre) and Landsat 8 (right) post-fire satellite imagery acquired in February 2020 201. Though no acquisition provides full coverage of the fire effected lands of the Cotter

Catchment, a mosaic of the burn severity analyses for each post fire image will provide near complete coverage of the catchment.

Incorporation of ACT Parks Fire Severity Index

The small areas of cloud and shadow that remained in the original analysis was patched using the fire severity index that had been prepared for the whole of the Orroral Valley fire area. Though the Parks interpretation did not have cloud, the approach of patching the Icon Water analysis was used as the Icon Water analysis had less noise and did not saturate as quickly. This difference is purely a result of Icon Water focusing its analysis in on a smaller area and therefore did not have the constraints the ACT Parks had to operate under.

The patch from the ACT Parks severity index was matched to the Icon Water severity index using the same methodology as that used to merge the Icon Water index components as previously discussed. The patch was then applied to ensure complete coverage of the Icon Water severity index.

Image Analysis

Spatial adjustment

All imagery was referenced to the 2003 fire analysis to simplify comparisons between events. The positional accuracy of the 2003 analysis has been previously verified in other studies to within approximately ten metres. The errors observed between all images used for the analysis were within one pixel (20 meters for the Sentinel imagery and 30 meters for the Landsat imagery).

Fire analysis

Post fire imagery were paired to a matching reference pre-fire image. The pairs are listed below:

- 1. Pre-fire Sentinel 2 – Post-fire Sentinel 2 (23 February 2020)
- 2. Pre-fire Sentinel 2 – Post-fire Sentinel 2 (26 February 2020)
- 3. Pre-fire Landsat 8 – Post-fire Landsat 8

Though the coverage was incomplete, for the second pair listed above, this was considered the primary or reference analysis due to the quality of the imagery. The other two analyses were matched to this analysis over areas that were not adversely affected by cloud. It was noticed that the 23rd Feb Sentinel analysis could be matched the reference with a basic linear scale/offset correction, however the Landsat analysis required a non-linear correction.

The resulting analyses were mosaicked together to produce a draft fire severity index.

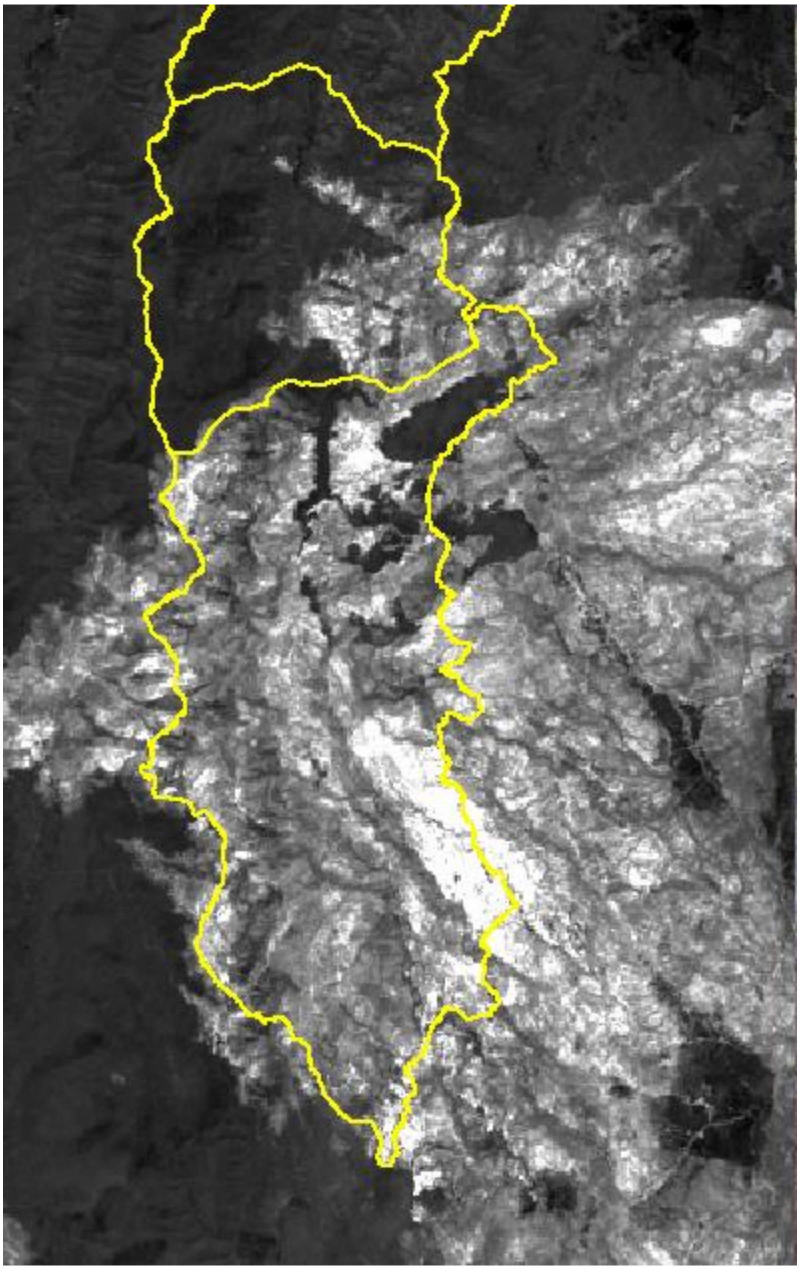


Figure 14. Fire severity index of the 2020 fire event over the Cotter Catchment consisting of a mosaic of three different image analyses.

Visual analysis

Two components of a visual analysis were undertaken being:

- Identification of the northern fire extent
- Likely draft categories to delineate different levels of fire severity

The visual analysis was largely undertaken using the Sentinel 2A imagery acquired on the 26th of February due to the image quality and the availability of higher resolution multispectral imagery (10m). Through this analysis, a five-class fire severity map (Map 1) has been completed to a draft state.

The classes are:

- Unaffected catchment

- Unburnt to low intensity understory only burn within the extent of the fire
- Moderate Intensity Burn, Often incomplete canopy scorch
- High Intensity Burn, complete canopy scorch
- High Intensity Burn. Complete canopy destruction

These class names and the classification interpretation within the imagery would be significantly improved through the use of ground truth information.

Field Survey

A preliminary planning day with ACT Parks and Icon Water staff was undertaken to share experience of the fire ground and how the landscape is recovering within the larger Namadgi National Park with attention given to the Gudgenby and Cotter catchments on May 5th 2020. This was a valuable exercise for Icon Water to fully appreciate the fire event as it occurred and allowed some targeting of certain areas of the Cotter catchment and commence planning of the use of the drone to cover the flats and to attempt to identify where sediment within the Cotter River was being sourced.

Four specific field survey days were undertaken to develop the fire severity mapping and to document sediment sources. These surveys concentrated on specific areas of the catchment and are summarised as follows:

1. June 4th, 2020. The catchments of Kangaroo Creek (Corin Dam sub-catchment) and White Sands Creek (Bendora Dam sub-catchment, both accessed from Corin Road. Ground survey only.
2. June 10th 2020. Upper Cotter above Corin Dam including the lower reaches of Licking hole creek catchment, Cotter, Upper Cotter and Rollys Flats. Drone acquisitions were taken on all flats and on Licking Hole Creek
3. June 18th, 2020. Lick Hole Road, Pond creek catchment and Mt Franklin Road. Ground survey only.
4. June 26th, 2020. Cotter River downstream of Corin Dam. Drone survey only to observe sediment within the Cotter River at the confluence with White Sands Creek.

Field observations

The field surveys allowed for the collection of fire severity information and evidence of sediment movement within the catchment. Each fire severity field site was documented and classified to a particular fire severity as listed in the Table below while sediment movement information included the nature of erosion/deposition observed, regolith observed on site, and likely source of material observed within the drainage. Detailed survey notes that were prepared following each day of survey.

The fire severity classes derived during the field survey were aligned with observations following the 2003 fire event to ensure that a direct comparison can be made between years. The classes are summarised in the Table below.

Table 5. Fire severity categories and descriptions utilised in the 2020 analysis while retaining compatibility with the work undertaken in 2003

Class	Name	Description
1	Understorey Scorch	A low intensity fire that has burnt the grasses left the understorey scorched. The fine branch structures in the understorey vegetation often remain. The canopy essentially remains unaffected.
2	Complete understorey burn, partial canopy scorch	A moderate intensity fire that has completely burnt the understorey and partially scorched the canopy. Areas classified as this class exhibit as a mosaic of scorched and unscorched crowns.

Class	Name	Description
3	Complete canopy scorch and understorey burn	A high intensity burn where the understory is completely destroyed often leaving only relatively thick stems behind. The canopy is completely scorched. The fine branch structures in the canopy often remain. Leaf litter from the scorched canopy often present.
4	Complete canopy and understory burn	A very high intensity burn where all vegetation was completely burnt. The understorey is generally burnt back to the main stem and, in places burnt to ground level. Vegetation recovery was particularly poor for this category.
5	Burnt Grassland	A burnt class that represents the presence of fire on the flat/wetland.
6	Unburnt grasslands within burn area	An unburnt class that represents the absence of fire on the flat/wetland.

Though these classes are relatively simple, there are situations observed in the field that have the potential to confound the result. The main issues are listed below:

- The Class One category essentially covers all areas from unburnt to that described in the category description above. Therefore, it is expected that small refugia exist, particularly around Yaouk Gap, Kangaroo Creek, and along the edges of the fire ground. It is difficult to further refine the analysis due to the canopy and understorey obscuring the underlying vegetation.
- Due to regrowth following the 2003 fires, it can be difficult to define what understorey vegetation is structurally where young eucalypts below the main canopy are burnt while the canopy is only scorched.
- Remotely collected information (e.g. observed on slopes away from the road or via drone) is limited due to the potential to miss classify the landscape. Where possible, sites registered to the road were shifted into the surrounding vegetation.

Vegetation Recovery up to June 2020
In addition to the fire severity observations, recovery was also documented for many sites visited in June 2020. Despite the short time that had elapsed since the fire and the dry summer conditions prevalent before the fire, recovery could be assessed and compared with the nature of the landscape and the severity of the fire event. The following recovery observations were noted:

- Class 1 severity impacted areas have typically the most recovery of all severity classes. In areas of particularly low severity, it can be difficult to ascertain whether the area was burnt at all.
- Class 2 severity burnt areas had variable recovery dependent on the severity of the burn. The canopy regeneration through Epicormic growth was well established though understorey regeneration was limited. Understorey and ground cover regeneration is variable dependent on the intensity of the burn, the site orientation and available moisture.
- Class 3. Severity burnt areas have generally poor recovery of the understorey and grasses but mature eucalypts are showing significant recovery within the canopy through epicormic regrowth. The nature of the recovery can often allow the differentiation of class 3 and class4 fire severity classes.
- Class 4 severity burns tend to have very poor levels of recovery, often with little ground cover regeneration on the slopes and limited and often failed epicormics growth. Most common regeneration of eucalypts is via basal sprouting.
- Areas where available moisture such as along streams are showing intense grass regrowth though typically less than ½ meter in height. From previous experience (2003), this grass regeneration can exceed 2 metres in height after 12 months.

- The flats that have been burnt have tussock grass regeneration but cover still remains limited. River bank collapse remains a significant concern on all flats visited.

Analysis of Field Survey Data
As discussed previously, all sites have a spatial position that allow them to be directly compared to the Fire Severity Index. This comparison allows the index to be classified into the fire severity classes listed above. The exception to this being the grasslands/wetlands which were incorporated via on-screen digitising, and the use of previous mapping of wetlands mapping.

Sixty-seven fire severity sites have been utilised for the preparation of the final classification of the fire severity index. These sites are summarised in the Table below. Though there is an unequal number of sites for each class, there are sufficient to identify class cut offs for each of the fire severity class. As with any analysis of this type, there is a certain degree of overlap and this is evident in the summary table below.

Table 6. Summary of fire severity field sites when compared to the fire severity index. The Fire Severity Index Range values are based on the 20th and 80th percentiles.

Class	No. Ground Sites	Min	Max	20th %ile	80th %ile	Fire Severity Index Range
1	13	0.75	1.81	1.052	1.554	**<1.6**
2	20	1.5	2.45	1.614	2.286	**1.6 – 2.2**
3	22	1.66	3.97	2.176	2.948	**2.2 – 3.0**
4	12	2.4	5.1	3.076	4.044	**> 3.0**
All	67	0.75	5.1			

As can be seen in this summary, the 20th and 80th percentiles have been utilised to define the ranges applied to the fire severity index to provide a final classification.

Fire Severity Statistics

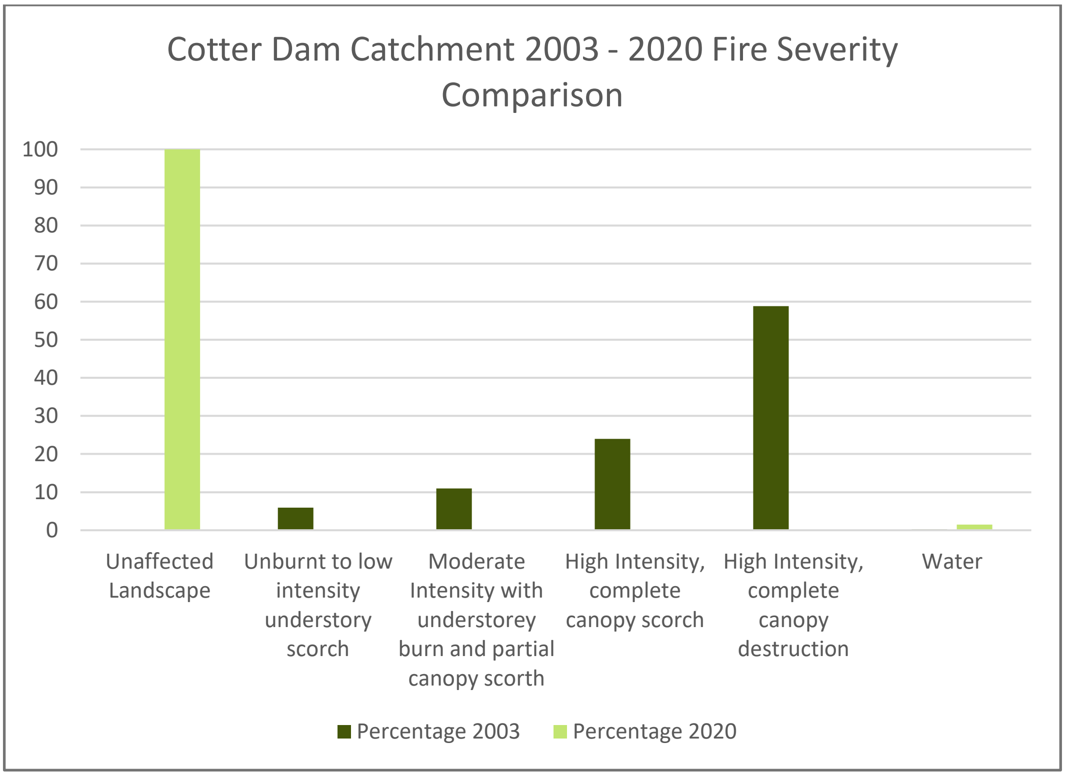
Statistics were calculated to provide a comparison of the 2003 and 2020 fires for each sub-catchment. The area statistics for the sub-catchments are derived from raster histograms computed for each sub-catchment. Minor errors are inherent in the generation of these statistics and are the result of pixel versus polygon comparisons.

Although the Cotter Dam sub-catchment was unburnt in 2020, it is included in this analysis for reference purposes. Additionally, the charts do not contain the grasslands classes as these were not included in the 2003 fire severity analysis.

The 2020 fire severity results when compared to those of 2003 analysis further emphasises the difference in extent and the higher degree of canopy destruction in the upper reaches. As expected, the percentage of the Bendora Dam sub-catchment that suffered a high intensity burn is significantly lower (approximately 80% in 2003 vs 10% in 2020). In contrast, Corin Dam catchment has similar levels of low and moderate intensity burn, but a higher level of canopy destruction in 2020. This is likely to be higher as grasslands/wetlands were incorporated into the highest level of fire severity in the 2003 analysis. The anomaly within this catchment however, is the high intensity canopy scorch category where there is a significantly lower area impacted.

Table 7. Comparison of the fire severity of the 2003 and 2020 fires within the Cotter Catchment – Cotter Dam sub-catchment.

Fire Severity Category	Area 2003 (ha)	Area 2020 (ha)	2003%	2020%
Unaffected landscape	0	19235.38	0	100
Unburnt to low intensity understory only scorch	1143.81	0	5.95	0
Moderate Intensity Burn, Complete understorey burn and partial canopy scorch	2110.22	0	10.97	0
High Intensity Burn, complete canopy scorch	4610.42	0	23.97	0
High Intensity Burn. Complete canopy destruction	11323.74	0	58.87	0
Burnt Grassland				
Unburnt Grassland				
Water	46.94	263.45[3]	0.25	1.47
Total	19235.38	19235.38	100	100



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[3] The expansion of Cotter Dam is the primary cause of the increase in surface area of the water class

Table 8. Comparison of the fire severity of the 2003 and 2020 fires within the Cotter Catchment – Bendora Dam sub-catchment.

Fire Severity Category	Area 2003 (ha)	Area 2020 (ha)	2003%	2020%
Unaffected landscape	0	6445.17	0	70.44
Unburnt to low intensity understory only scorch	587.51	679.68	6.42	7.43
Moderate Intensity Burn, Complete understorey burn and partial canopy scorch	1484.37	1067.76	16.22	11.67
High Intensity Burn, complete canopy scorch	3477.94	583.72	38.01	6.38
High Intensity Burn. Complete canopy destruction	3520.52	234	38.47	2.56
Burnt Grassland	Not assessed	Not in fire ground		
Unburnt Grassland	Not assessed	Not in fire ground		
Water	79.82	79.82	0.87	0.87
Total	9150.46	9150.46	100	100

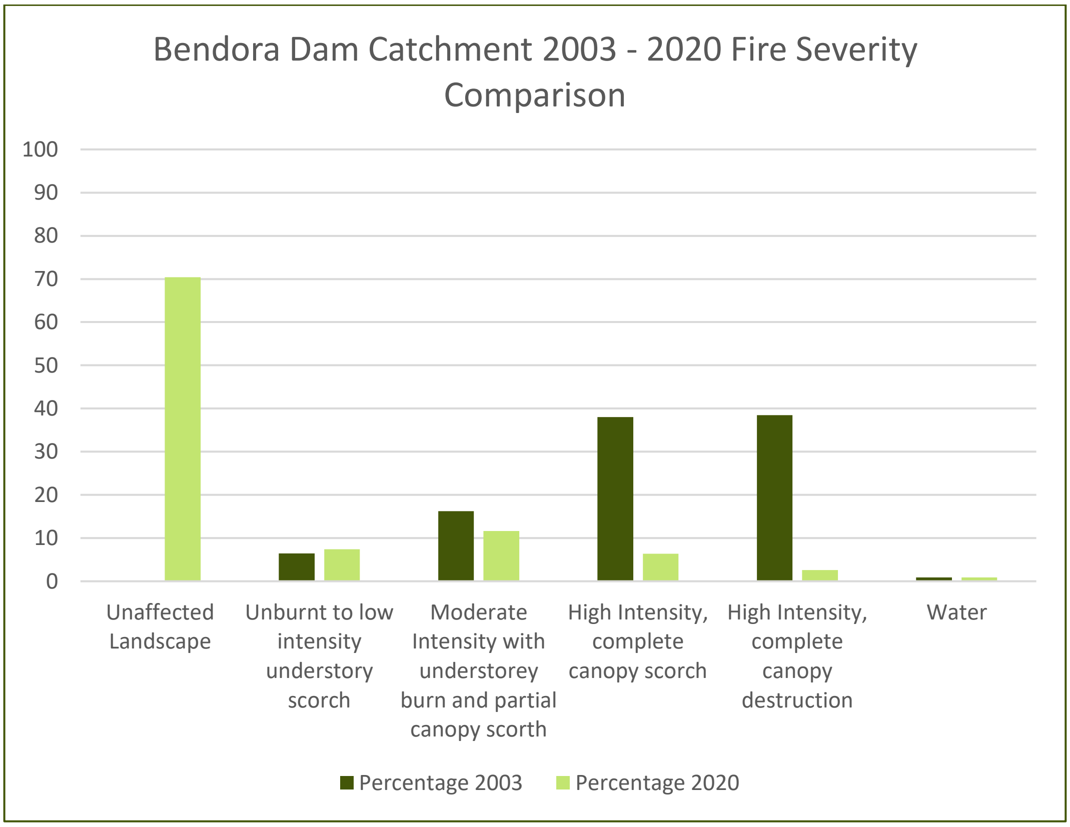
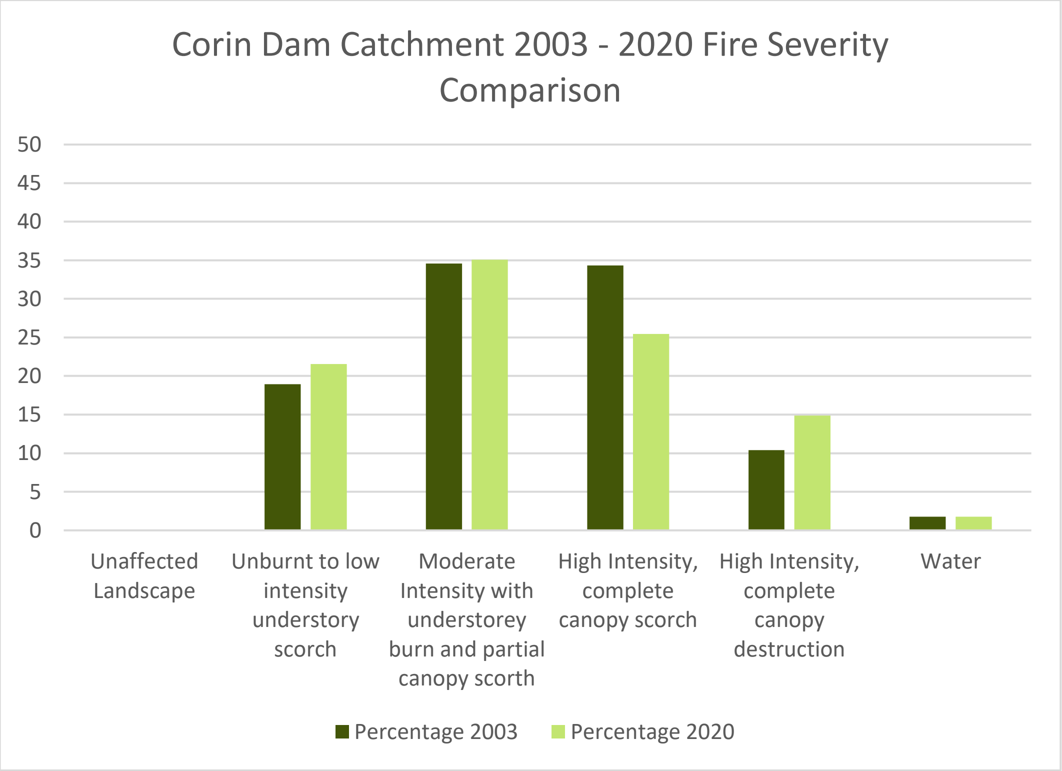


Table 9. Comparison of the fire severity of the 2003 and 2020 fires within the Cotter Catchment – Corin Dam sub-catchment.

Fire Severity Category	Area 2003 (ha)	Area 2020 (ha)	2003%	2020%
Unaffected landscape	0	122.5	0.00	0.62
Unburnt to low intensity understory only scorch	3733	4237.4	19.00	21.56
Moderate Intensity Burn, Complete understorey burn and partial canopy scorch	6819.4	6895.3	34.70	35.09
High Intensity Burn, complete canopy scorch	6767.2	5003.2	34.44	25.46
High Intensity Burn. Complete canopy destruction	2047.8	2920.9	10.42	14.86
Burnt Grassland	Not assessed	158.5	Not assessed	0.81
Unburnt Grassland	Not assessed	29.6	Not assessed	0.15
Water	282.4	282.4	1.44	1.44
Total	19638.1	19649.8	0.00	0.62



Appendix C: Letter from US Forest Service

United States Department of Agriculture **Forest Service** **Rocky Mountain Research Station** **1221 S. Main Street Moscow ID 83843**

Date: 14 January 2020

To: Dr. Petter Nyman
Alluvium Consulting
Melbourne, Australia

From: Peter Robichaud PhD PE
Research Engineer
USDA Forest Service
Rocky Mountain Research Station
Moscow, Idaho USA

Re: Melbourne Water Bushfire and Sediment Risk

What to do about sedimentation risk related to bushfires?

Pre-Fire Modeling

Reducing fuels leads to reduce fire severity and soil burn severity which is key to reduce sediment input to reservoirs. There are various tools to determine how much fuel reduction is needed to reduce risk, we have a few online tools that can help calculate the sediment yields from fuel treated hillslopes verses wildfire affected hillslopes for the US (https://forest.moscowfsl.wsu.edu/fswepp/ navigate to FuME, Fuel Management). We have evaluated this for a California watershed (Elliot et al. 2016). Another way to address and evaluate fuel treatments is to look at changes in fire behavior due to fuel treatment during past mega-wildfires in the US (Hudak et al. 2011). We have also looked at coupling fire spread modeling with probabilistic erosion modeling (ERMiT, Erosion Risk Management Tool) in Italy to address changes in erosion risk with fuel treatments (Salis et al. 2019).

Post Fire Modeling

Identifying the likely high erosion risk areas after a bushfire is key as often 90% of the erosion is from 10% of the land. We recently developed a Soil Burn Severity Model for generating a soil burn severity map for unburned areas in which a wildfire can be modeled. We are using a Random Forest approach that is trained from nearby past wildfires BARC (Burned Area Reflectance Classification) map or Soil Burn Severity map (if available). This is not publicly available yet but should be in the April 2020, we could possible do some modeling for you if interested in this approach.

We have various tools (https://forest.moscowfsl.wsu.edu/fswepp/) such as QWEPP for running the WEPP watershed model in GIS platform and the WEPPcloud tool for watershed analysis but without the cumbersome GIS software. These tools have been made for the continental US. If you have a soil burn severity map (Parsons et al. 2010) or a methods to generate one (Elliot et al 2016, Salis et al. 2019) for some of the Melbourne's watersheds then you can run our experimental version of WEPPcloud PEP AU

(Wepp Cloud Postfire Erosion Predictor for Australia) (https://forest.moscowfsl.wsu.edu/fswepp/) navigate to WEPPcloud PEP AU.

I was in contact with Rebecca Gibson, Remote Sensing Scientist, Remote Sensing and Regulatory Mapping Science Division, Department of Planning, Industry and Environment from NSW regarding soil burn severity mapping for Sydney's Municipal Water Supply fire-affected catchment within the Gospers Mountain Bushfire. There was some interest in estimating ash contamination for their catchments. Since Rebecca is busy with active fire mapping, I had my colleague at the USGS, Kurtis Nelson, produce a BARC map for the Gosper Mountain Fire (download the package here: https://edcftp.cr.usgs.gov/project/fire/BAER/gospersmtn_deliver.zip). We are now running WEPPcloud PEP AU and our ash transport model . Both products will provide information as to where the "hot spots" are for erosion and ash transport (Nunes et al. 2018). The ash transport model will predict the amount of ash transported by runoff into the reservoir among other outputs. We are actively running the model for fire affected catchments.

Post-fire Treatments Modeling and Treatment Effectiveness

The Erosion Risk Mangement Tool (ERMiT) is a probabilistic model of hillslope erosion that can easily compare treatments (https://forest.moscowfsl.wsu.edu/fswepp/ navigate to ERMiT; Robichaud et al. 2007). The ERMiT Batch spreadsheet model allows for larger areas to be model by running ERMiT on each hillslope and compiling results into a spreadsheet. This allow for quickly determining which hillslopes have the highest erosion risk and allows for comparing erosion control treatments (i.e. mulch) to the determine the benefits of the treatments. We have validated the model results with field data with acceptable results (Robichaud et al. 2016).

Mitigating high-magnitude erosion risk where both hillslope and channels are delivering sediment to the reservoir after a bushfire.

Hillslopes

There are numerous treatments available to reduce sedimentation, Napper (2006) compiled a catalog of treatment which are in three categories hillslope, channel, road treatments (available to download at https://forest.moscowfsl.wsu.edu/BAERTOOLS/ navigate to catalogs). It is often more effective to reduce erosion risk at the source rather than try to capture sediment downstream. In recent years, US land management agencies (Forest Service, Bureau of Land Management, National Park Service, Fish and Wildlife Service, and Bureau of Indian Affairs) have been using mulches as onsite erosion control with less emphasis on log erosion barriers and seeding as a method to reduce sediment from the source (Peppin et al. 2011; Robichaud et al. 2010 and 2014). Only in the last decade has wood shreds been more adaptively used. The National Park Service will use weed-free mulches or other techniques for reducing the erosion risk for critical values at risk that they are trying to protect. To assist in determine values at risk, we have developed an value at risk calculation tool (https://forest.moscowfsl.wsu.edu/BAERTOOLS/ navigate to VAR Calculation Tool and VAR Tool Lite; Calkin et al. 2007).

Wood shreds have been evaluated for its performance (Robichaud et al. 2013b and 2013c) especially as compared to agricultural straw mulch. Wood shreds tend to last longer and performed better while continuously reducing sediment yields in the post-fire years and there are no introduced weeds either.

Remote sensing imagery can be used to determine mulch cover as well (Lewis et al. 2011). We have written a "How-To Manual" for wood shreds (Robichaud et al. 2013a) which describes the details of using commercial forestry tub grinders to make desirable wood shred products as well as some do's and don'ts.

With various mulches, we wanted to be sure of the long-term consequences with changes in nitrogen cycling, grass forbs and shrub regrowth, and tree seedling survival (Morgan et al. 20 14; Jonas et al. 2019). Overall we have limited impact or long-term consequences with the wood shreds (Jonas et al. 2019) and even with agricultural straw mulch (Bontrager et al. 2019). Thus, wood shreds are a good mulch to consider and can be made from forest fuel reduction forestry operations and post fire onsite dead trees.

Regarding the nutrient transport due to hillslope erosion after wildfires, we found some effects on nutrient transport but not a major concern (Pierson et al. 2019).

Channels

Channel treatments reduce sediment delivery by trapping sediment and "slowly" metering sediment over a longer time span. Our assessments of channel treatment effectiveness have found that strawbale checks dams reduce only a limited amount of sediment (Robichaud et al. 2019). We observed that the check dams filled during the first events and after that provided little additional benefit. With the addition of more check dams more sediment storage capacity would have likely been achieved. In our study, we had no failures of the strawbale check dams but that does occur (Robichaud et al. 2000).

I have been asked what the combined effect is of using hillslope mulches (agricultural straw or wood shreds) and channel treatments (check dams, detention pond, etc.). We have not evaluated the combine effects; however, it is likely to reduce sediment transport, but I am unsure of the magnitude.

Summary

Various methods are available to evaluate the risk of sedimentation into reservoirs. Mitigation treatments can reduce the risk of erosion and sedimentation but not eliminate all risk. Targeting treatment to the highest erosion potential areas is the most cost-effective methods to reduce sedimentation.

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These are all available on our website https://forest.moscowfsl.wsu.edu/library/ search under my name and the PDF can be downloaded. However, the newer (2019) publications have not been added to the web site yet. I have attached those for your use.

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