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FINAL REPORT:

Cotter Catchment Actions for Clean Water Plan

March 2020

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Executive summary

Under the Australian Capital Territory Water Resources Act 2007, the ACT Water Strategy Plan was developed to guide the management of water resources. Key to the outcomes of this plan is healthy catchments and water bodies. An outcome of the Implementation Plan was that Icon Water nominated to take the lead in the developing catchment Actions for Clean Water (ACWA) plans, including the Upper Murrumbidgee, Googong and Cotter catchments. The Upper Murrumbidgee and Googong catchment ACWA plans are now complete and the Cotter is the final catchment to be assessed as part of the ACT Government Water Strategy.

Alluvium Consulting Australia Pty Ltd (Alluvium) was engaged by Icon Water to develop the Cotter catchment ACWA Plan to help direct efforts to stabilise and rectify erosion risk sites over time in the Cotter catchment based on a prioritisation of the risk they pose to water quality in the receiving environment (Cotter Dam).

The project was undertaken in five phases as shown below. Representatives from relevant government agencies and organisations were engaged over the course of the project to provide catchment context, feedback on project deliverables, and to supply project data.

Phase One: Project inception and data review

Phase Two: Assessment of catchment physiology and background

Phase Three: Assessment of erosion processes within the catchment

Phase Four: Prioritisation

Phase Five: Reporting

As part of Phase Two, a stakeholder workshop was held to inform understanding of historical catchment developments and current erosion issues in the Cotter catchment. Information gained from the stakeholder workshop and a review of relevant background information was synthesised to describe the catchment context.

Phase Three, the assessment of erosion processes within the catchment, involved a desktop investigation to assess hillslope, channel and gully erosion occurring across the Cotter catchment followed by field inspection of identified high priority channel erosion sites (Section 3.1).

Phase Four involved an assessment of the relative risk of each of the erosion processes across the catchment to identify priority subcatchments, (Section 3.2). Recommended management actions are provided in Section 9 based on the risk assessment and available management options.

Overall, all the Lower Cotter subcatchments (Pierces Creek, Cotter Dam Condor Creek and Lees Creek) scored highest in terms of relative erosion risk (see table below). The top four were classified as priority subcatchments for management.

Erosion risk assessment by subcatchment and erosion type

Subcatchment	Area (Ha)	Main waterways	Hillslope erosion risk	Channel erosion risk	Gully erosion risk
Pierces Creek	2281	Pierces Creek and Dry Creek	Very High	Moderate	Very High
Cotter Dam	1280	Cotter River (Dam)	High	Low	High
Condor Creek	4709	Condor Creek, Musk Creek, Wombat Creek, Fastigata Creek and Coree Creek	Moderate	Moderate	Moderate
Lees Creek	2560	Lees Creek and Blundells Creek	Moderate	Moderate	Moderate

Bullock Head	8425	Cotter River, Bullock Head Creek, Burkes Creek, Burkes Creek North, Burkes Creek South, Bushrangers Creek, Bendora Creek, Cow Flat Creek Collins Creek and Little Collins Creek	Moderate	Moderate	Low
Kangaroo Creek	4986	Kangaroo Creek, Snowy Flat Creek, Clear Hills Creek and Dry Creek	Low	Moderate	Low
White Sands Creek	3558	Cotter River and White Sands Creek	Low	Moderate	low
Ginini Creek	3584	Ginini Creek and Stockyard Creek	Low	Moderate	Low
Cribbs Creek	7357	Cotter River, Cribbs Creek, Gingera Creek, Long Creek, De Salis Creek, Pond Creek, Mosquito Creek and McKeahnie Creek	Low	Low	Low
Lick Hole Creek	2178	Lick Hole Creek and Creamy Flats Creek	Low	Low	Low
Porcupine Creek	5076	Cotter River, Porcupine Creek, Bimberi Creek, Jacks Creek, Little Bimberi Creek and Drag Creek	Low	Low	Low
Franklin Creek	1937	Cotter River and Franklin Creek	Low	Low	Low

Within the four priority sub-catchments, key zones of erosion risk were identified and classified as Priority Management Zones. The recommended management options for the priority management zones involve implementing one or more of the following actions:

- Revegetation works
- Bank battering and/or toe protection on more severe streambank erosion sites
- Gully remediation by reshaping and drop structures.

These options should be implemented as a package through a riparian management program. The degree of riparian management intervention can have a significant impact on implementation cost as well as the overall change in risk rating in priority management zones. Three options for riparian management of varying cost have been developed and their effect on risk within each priority management zone analysed.

Option 1 involves facilitated revegetation. Facilitated revegetation entails allowing vegetation to establish via natural means and is reliant on there being a good source of seedbank supply in the area. This option requires less effort and financial investment. However, the seedbank supply that is naturally available for facilitated revegetation is not guaranteed and therefore it is difficult to ascertain the effectiveness of this technique. It should be noted that this option would also permit continued erosion of unstable banks, and therefore release of sediments, until a stable equilibrium is reached.

Option 2 involves isolated bank reprofiling, isolated toe protection and revegetation works. This option would also include more intensive revegetation efforts to establish a robust riparian vegetation community. In areas that exhibit bank instabilities, direct bank stabilisation works would be implemented in the form of bank battering or toe protection (large wood, pile fields, rock beaching etc.). This option requires higher financial investment and there are greater ongoing maintenance requirements. However, by stabilising unstable banks directly and increasing the likelihood of riparian vegetation establishment, this option generates a better chance of long-term success.

Option 3 involves reshaping gully scarps, the installation of erosion control structures, and revegetation works. This option involves earthworks to form a stable gradient across gully drainage pathways. While relatively cost intensive, the design of erosion control structures can be tailored to meet the long-term hydrologic characteristics of the gully catchment, thus enhancing the likelihood of long-term stabilisation and optimising the overall cost-benefit.

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Abbreviations

ACWA	Actions for Clean Water
ACT	Australian Capital Territory
DEM	Digital elevation model
NSW	New South Wales
Lidar	Light Detection and Ranging
RUSLE	Revised Universal Soil Loss Equation

1 Introduction

1.1 Project background

Alluvium Consulting Australia Pty Ltd (Alluvium) was engaged by Icon Water to develop a Cotter Catchment Actions for Clean Water (ACWA) Plan to help direct efforts to stabilise and rectify erosion risk sites over time in the Cotter catchment based on a prioritisation of the risk they pose to water quality in the receiving environment (Cotter Dam).

An ACWA Plan is a report that documents erosion hotspots and applies a standard algorithm in order to rank erosion point sources in terms of risk to water quality. The ranking in an ACWA report provides guidance to prioritising investment in stabilisation or remediation. The final report will assist government and natural resource management organisations to link future investment to science-based models they are familiar with and are consistently applied by various departments and agencies.

Understanding the dominant erosion processes supplying sediment within a catchment and how those loads are transported and stored within the catchment and across a floodplain is important for informing decision making and designing targeted management actions aimed at reducing downstream sediment loads. In recent years, there have been multiple research and modelling projects across Australia to assess catchment-based initiatives and to quantify their impacts as well as to identify sediment risk areas for guiding future planning and investment within catchments.

The sediment risk to water quality can vary both in type and spatial distribution across a catchment. As a result, identifying and prioritising different risks across a region presents challenges. Catchment models typically use broad scale land use and topographic data to assess pollutant generation across a region. These models can be excellent at identifying the relative contribution of different processes or land uses in each catchment. However, these outputs do not help planners inform decision making regarding investment at the site and reach scales. Typically, planners use a range of in-house knowledge and reach scale technical assessments to inform decision making at the site or reach scale. While these methods are effective for site or reach scale management, they can be less useful in regard to prioritising projects in different areas based on their risks to water quality.

1.2 Project objectives

The project objective is to investigate and identify strategies to address water quality issues and sources of water quality variability in the Cotter catchment. This ACWA Plan will help to direct efforts to stabilise and rectify sites over time based on a prioritisation of risk to water quality in the receiving environment.

The ACWA Plan objectives are to:

1. Provide an overview of water quality issues within the Cotter Catchment and frame the issues that need to be addressed
2. Draw on existing information sources, including strategies, plans, data, research, Auditor General and Commissioner for Sustainability and Environment reports
3. Identify high priority sites using previously adopted methodology to improve the water quality in Cotter Catchment, particularly the Cotter reservoir
4. Develop a prioritised series of management strategies using the framework developed for previous ACWAs to rank sites in the catchment
5. Prioritise on-ground actions over the short, medium and long term, and
6. Identify other actions (community engagement, incentives or policy changes) which contribute directly to the goals of the project.

2 Study context

2.1 Study area

The Cotter catchment is located along the western border of the Australian Capital Territory (ACT). The downstream extent is approximately 16 km west of the city of Canberra and the catchment covers an area of 480 km^2. The Cotter River has its headwaters in the Brindabella Range and the catchment extends to Cotter Dam which is just upstream of the Murrumbidgee River. The catchment extends approximately 12 km east to west and 55 km north to south and is situated mostly in the ACT; however, a small section in the north-west is within NSW (Figure 2).

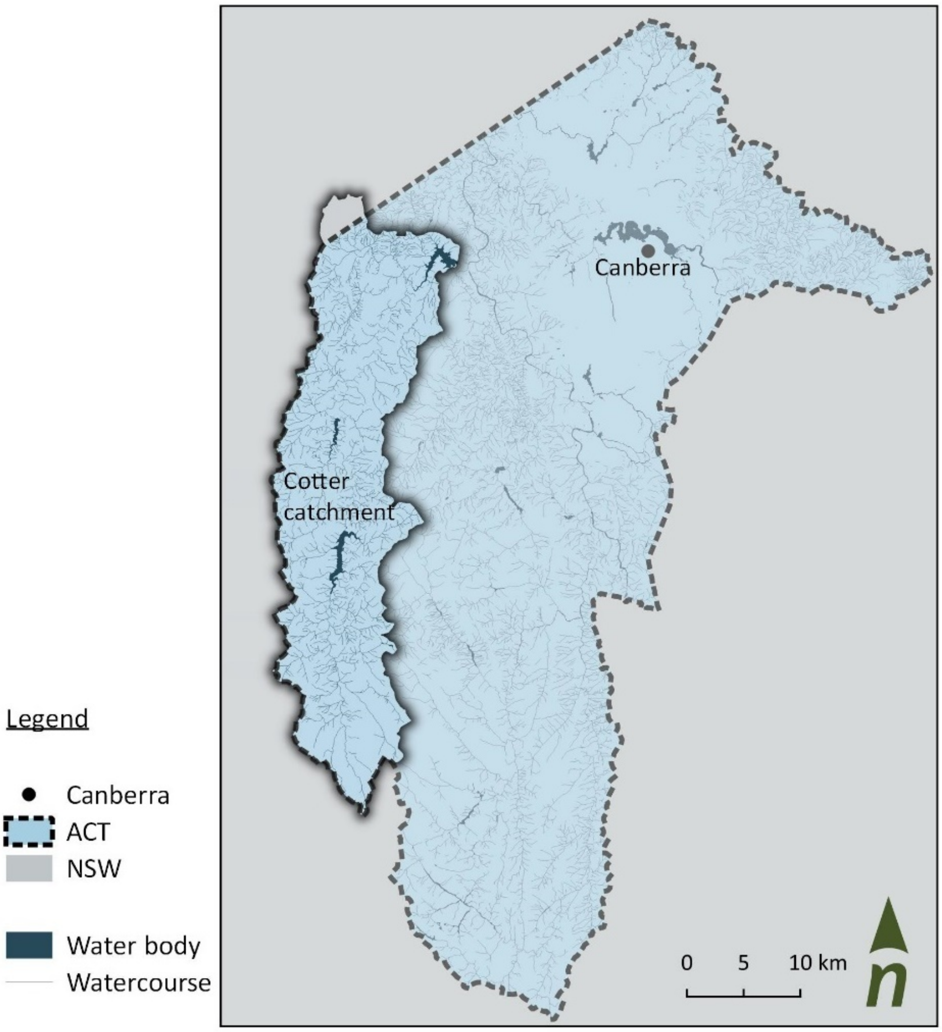

Figure 1. *Overview of Cotter Catchment location*

The western boundary of the Cotter Catchment (and the ACT) is formed by the Brindabella Range. The Cotter River flows generally north then, below the Cotter Dam, flows to the east into the Murrumbidgee River at Casuarina Sands.

There are three Dams along the Cotter River. Corin, Bendora and Cotter Dams are often used to divide the catchment into three broad subcatchments. The Cotter catchment has also been divided into 12 subcatchments by the ACT Government, which have been used as spatial units for prioritisation in this study. The original Cotter Dam was formed in 1912 and the wall was raised in 1951 [1]. The Bendora Dam was formed in 1961 and Corin Dam was formed in 1968 [1]. A project to enlarge the Cotter Dam from 4 GL to 79.4 GL capacity was completed in 2013, with a new 80 m high dam wall constructed approximately 100 m downstream of the existing wall [2].

2.2 Catchment management

The Cotter Catchment is managed by the ACT Government Parks and Conservation Services (PCS). The water resources in the dams are abstracted by Icon Water for the purpose of the supply of potable water. The Traditional Owners of the catchment, the Ngunnawal people, also have a role in contributing to the management of the catchment. The Brindabella National Park to the north is managed by NSW National Parks and Wildlife Service.

Three management plans are of relevance to the catchment's management:

- Lower Cotter Catchment Reserve Management Plan 2018
- Namadgi National Park Plan of Management 2010
- Brindabella National Park and State Conservation Area Plan of Management 2009.

The management objectives for these plans are listed in Table 1.

Table 1. Management objectives of the Catchment by protected area [1] [3] [4]

Lower Cotter Catchment Reserve Management Plan 2018	Namadgi National Park Plan of Management 2010	Brindabella National Park and State Conservation Area Plan of Management 2009
1. to protect existing and future domestic water supply 2. to conserve the natural environment 3. to provide for public use of the area for education, research and low-impact recreation	National park 1. To conserve the natural environment 2. To provide for public use of the area for recreation, education and research. Bimberi Wilderness area 1. To conserve the natural environment in a manner ensuring that disturbance to that environment is minimal 2. To provide for the use of the area (other than by vehicles or other mechanised equipment) for recreation by limited numbers of people, so as to ensure that opportunities for solitude are provided.	1. protection of the park as part of the system of protected areas of the Australian Alps, with emphasis on maintaining ecological relationships with the park and adjoining and nearby protected areas 2. protection of catchments and water quality within the park, with priority to the protection of Canberra's domestic water supply 3. protection of the range of plant and animal communities within the park, with particular attention to the maintenance of populations of threatened or regionally significant species 4. provision of a limited number of visitor facilities at a basic standard consistent with remote use of the park by an increasing number of people 5. development and maintenance of close ties and cooperative land management operations with adjoining public and private land managers 6. management of a large area of remote bushland to maintain and enhance opportunities for recreation, while ensuring the maintenance of natural processes.

The management of all or parts of the Cotter catchment have also been investigated through a number of reports, studies and evaluations including:

- The Heroic and the Dammed – Lower Cotter Catchment Restoration Evaluation conducted by the Commissioner for Sustainability and the Environment in 2018 [5]
- Progress Report on the Restoration of the Lower Cotter Catchment conducted by the Auditor General in 2017 [6]
- Erosion Potential Mapping Report conducted by URS for the former ACT Government Parks, Conservation and Lands in 2009 [7]

3 Project method

3.1 Assessment of erosion processes within the catchment

Our approach to assessing erosion processes in the catchment is outlined in this section. The approach is based on best practice assessment methodologies, tailored to the available datasets for the Cotter catchment. The types of erosion processes assessed were hillslope, channel and gully erosion. An overview of factors that commonly affect erosion is provided in Appendix A. The approach uses similar methods and data to the Upper Murrumbidgee ACWA and the Googong Dam Catchment ACWA, with some modifications.

Data sources

The following data sources were used for the desktop erosion assessments.

Table 2. Data sources

Erosion assessment type	Data sources
Hillslope erosion	Modelled hillslope erosion over NSW 2018 downloaded from data.nsw.gov.au [8] DEM of ACT 2015 Lidar data (1m) downloaded from ELVIS (resampled to 5m) [9] DEM of NSW 2018 Lidar data (2m) downloaded from ELVIS (resampled to 5m) [10] C factors applied based on URS 2009, supplied by ACT Government [7]
Channel erosion	NSW River Styles 2012 data downloaded from data.gov.au [11] DEM of ACT 2015 Lidar data (1m) downloaded from ELVIS [9] DEM of NSW 2018 Lidar data (2m) downloaded from ELVIS [10]
Gully erosion	Aerial imagery 2015 (20cm) downloaded from ACTmapi [12] Aerial imagery 2017 (10cm) downloaded from ACTmapi [13] DEM of ACT 2015 Lidar data (1m) downloaded from ELVIS [9] DEM of NSW 2018 Lidar data (2m) downloaded from ELVIS [10]

Hillslope erosion method

Hillslope erosion was estimated using the Revised Universal Soil Loss Equation (RUSLE). RUSLE is an established and commonly used method to assess catchment scale sediment generation processes, with several benefits including:

- a modest number of model parameters is required.
- the RUSLE model parameters can be derived from commonly available datasets
- the RUSLE model has been adapted to Australian conditions and the factor-based nature allows individual contributing factors to be easily analysed.

The RUSLE method determines mean annual soil loss (Y, t/ha/yr) as a product of six factors (rainfall erosivity, soil erodibility, slope length, slope steepness, cover management and erosion control practices). By mapping the spatial distribution of the parameters, the location of likely hillslope erosion and sediment generation within a catchment can be estimated.

While generic values are available for some parameters, rainfall erosivity was calculated using daily SILO rainfall data, and slope length and steepness generated using the Digital Elevation Models. From this information the mean annual soil loss in each subcatchment was assessed.

There is some uncertainty in the estimate of the RUSLE parameters, particularly the site-specific nature of soil erodibility and erosion control practice. In the absence of a rigorous field validation, the outputs from the RUSLE method should be used with some caution.

Table 3. RUSLE parameters used

Factor	Method
Rainfall erosivity (R)	NSW State-wide layer spatially resampled to 5 m grid resolution [8]
Soil erodibility (K)	NSW State-wide layer spatially resampled to 5 m grid resolution [8]
Slope length (L)	Slope length layer generated from a compiled 5 m DEM [8]
Slope steepness (S)	Slope steepness layer generated from a compiled 5 m DEM [8]
Cover management (C)	C factors applied based on 2009 C factor for ACT [7]
Erosion control practice (P)	1 (assuming no erosion control)

Additional information on the hillslope erosion assessment method is provided in Appendix A.

Channel erosion assessment

The assessment of channel erosion is based on the approach developed and applied by Alluvium for other catchments around Australia. An assessment of the *stream type* using the River Style© framework is used to characterise at a reach-scale the geomorphic form of the waterway, the erosion potential (i.e. geomorphic trajectory of the stream) and the sediment availability (i.e. the volume of sediment likely to be eroded).

The two primary factors that influence reach-scale channel derived sediment generation potential are:

1. **Reach-scale erosion potential –** The potential for erosion (i.e. the trajectory of the stream) in future high flow events. This will be dependent on the geomorphic form (i.e. the type of stream) and condition, combined with a range of different hydrogeomorphic parameters (i.e. stream power, hydrology, channel resistance etc.). For this assessment we used multitemporal aerial imagery analysis (where available) and site inspections to assess these factors and inform the assessment of erosion potential.

2. **Reach-scale sediment availability –** The volume of sediment available to be eroded by channel erosion processes. This will be dependent on the volume of alluvial deposits that are within the likely channel erodible zone (i.e. floodplain, benches, islands etc.). For this assessment we used the 2015 DEM of the ACT and the 2018 DEM of NSW (specified above) and soil mapping information.

These factors are combined into an overall rating of sediment generation potential using the following 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 2. *Matrix used to define reach-scale sediment generation potential*

Gully erosion method

Gully erosion throughout the catchment was assessed by creating a $100m^2$ grid over the entire catchment and through visual inspection of multitemporal aerial imagery analysis (2015 and 2017 aerials and 2015 and 2018 LiDAR data). Each grid was classed as either having no gully erosion present, active gully erosion present or dormant gully erosion present. The accuracy of the gully erosion assessment is limited to the accuracy of the DEM available.

In order to assess whether gully erosion was dormant or active, the multitemporal aerial imagery was analysed to assess any change between the two datasets over the 2-3-year period. Where sites did not change in this time, they were classified as dormant, and where clear progression of gullies could be observed, they were classified as active. The overall percentage of gully coverage for each subcatchment (for both dormant and active gullies) was then calculated in order to provide a means for classifying the gully erosion risk for each. We classified the gully erosion risk in each subcatchment as either Low, Moderate, High or Very High based on the spatial distribution of gullies.

3.2 Risk assessment

For consistency, a risk assessment approach similar to the approach used in the Upper Murrumbidgee ACWA Plan has been adopted [14]. The risk assessment approach estimates risk based on five criteria:

Risk = Value x Threat x Consequence x Likelihood x Trajectory

Definitions of the criteria are provided in the text box below, which is taken from the Upper Murrumbidgee ACWA Plan.

Extract from the Upper Murrumbidgee ACWA Plan [14]

Value = Water Quality for human consumptive use. This is the same value for every risk assessment and therefore it is attributed a multiplier of “1”.

Threat = Threat posed by turbidity on water quality. This is the same value for every risk assessment and therefore it is attributed a multiplier of “1”.

Consequence = This rating relates to the consequence of a specific erosion issue on water quality. It considers the size fraction of sediment eroded and volume that is being exported from an eroding area. For example, fine silts mobilised are going to have a higher consequence on turbidity than coarse sediment.

Likelihood = This rating relates to the proximity of a specific erosion issue to the water extraction point or the likelihood that a specific stream has the ability to deliver sediment to the water extraction point. Implicit within this is an assessment of sediment connectivity from the area of erosion to the water extraction point.

Trajectory = This rating refers to the level of erosion activity identified at a site and its stage of development. For example, is there evidence that a site is in the early stages of erosion as evident by incision and presence of active head cuts, has it proceeded to the next stage where it is now eroding its banks or is the evidence that the site has reached a quasi-stable state.

The risk assessment ratings for likelihood, consequence and trajectory are provided below (Table 5). The consequence rating refers to the amount of fine sediment that could potentially be mobilised such that the different erosion processes can be compared between sites. The assessment considers likelihood, consequence and trajectory based on the desktop erosion assessment.

Table 4. Risk assessment ratings (adopted from Upper Murrumbidgee ACWA Plan and Googong Catchment ACWA Plan)

Component	Score	Rating	Definition
Likelihood	5	Almost certain	High connectivity, close proximity to extraction point
	4	Likely	High connectivity, direct input into major waterway
	3	Moderate	Moderate connectivity
	2	Unlikely	Low sediment connectivity, high potential for sediment storage
	1	Rare	Disconnected from tributary and major waterway
Consequence	5	Catastrophic	Fine sediment, large volume, erosion over several 100 m or kms
	4	Major	Fine sediment, large volume, localised erosion
	3	Moderate	Fine sediment, moderate volume, localised erosion
	2	Minor	Fine sediment/small volume or coarse sediment
	1	Insignificant	Coarse sediment
Trajectory	5	Early degradation phase	Stream incising bed, active head cuts
	4	Degradation and widening	Bed still incising and banks also eroding (vertical or undercut)
	3	Widening and aggradation	Bed aggrading, erosion of banks (vertical or undercut)
	2	Partially stabilised	Toe of banks and bed partially stabilised with vegetation
	1	Stabilised	Stable channel configuration

The overall risk score is calculated by multiplying Likelihood, Consequence and Trajectory scores. The higher the risk score, the higher the priority of a specific site or issue. The overall risk rating can then be defined using the following classifications (Table 6).

Table 5. Relative risk ratings (adopted from Upper Murrumbidgee ACWA Plan)

Risk rating	*Extreme*	*Very High*	*High*	*Moderate*	*Low*
Risk score	64 - 125	43 - 63	34 - 42	15 - 33	<15

4 Catchment context

4.1 Catchment history

It is important to understand the history of the Cotter Catchment as it provides insight into previous erosional processes within the catchment as well as helping to understand 'baseline' conditions for the catchment. The catchment features and changes discussed below are presented in Figure 3 and Figure 5.

The Traditional Owners of the catchment are the Ngunnawal people. There is evidence of Aboriginal occupation of the land from over 25,000 years ago, with many Aboriginal heritage sites including rock art, stone arrangements, campsites and quarry sites in the Namadgi National Park [3].

European settlement and subsequent landscape alteration commenced in the catchment in the 1820s-30s. Clearing of native vegetation for grazing occurred in flatter areas, primarily in the Lower Cotter Catchment, and some pastoral land use also existed in parts of the upper catchment. The removal of native vegetation in parts of the catchment left soils vulnerable to erosion and pastoral uses introduced weed species to the landscape [3].

In 1911, Canberra was declared as the site for the Australian capital city and in 1912 the original Cotter Dam was constructed for the purpose of supplying the city with water. Bendora Dam and Corin Dam were added to the Cotter River in 1961 and 1968 respectively [1].

The designation of the Cotter Catchment as the water supply for Canberra was a catalyst for changes in the catchment to protect the water supply and improve water quality. Livestock grazing was removed through termination of leases, and pine plantations were established in the cleared areas of the Lower Cotter as an erosion control measure and for timber extraction. The mostly natively vegetated middle and upper reaches of the Cotter have been protected since 1914, under the *Cotter River Ordinance 1914*, for the purpose of ensuring a safe and secure water supply. The Ordinance excluded certain land uses including camping and picnicking; however, other land uses were permitted. Leases were issued for ski lodges and timber harvesting. Livestock were also permitted to pass through the catchment on route to snow leases in NSW until 1969 [3].

Roads, firebreaks and forestry huts were established in the 1920s to support industry and land management. Native forests continued to be cleared and converted to plantation forestry till the late 1960s. The last cleared areas typically regenerated fastest due to better soils, higher rainfall and available seed stock. The Lower Cotter Catchment was opened to public recreational use in 1968. Pine plantations in the Lower Cotter continued until the bushfires of 2003. Some of the catchment continues to be managed as a pine plantation. Once harvested, the intension is to return these areas to native vegetation [15]. There is limited recreational use in the catchment in the protected middle and upper reaches of the Cotter within the Namadgi National Park, which was gazetted in 1984 [3].

In 2003, the Canberra bushfires devastated the Cotter Catchment and other parts of Canberra. Shortly after the fires, severe storms resulted in significant erosion and increased turbidity in the reservoirs. Open land was more vulnerable to gullying, particularly in the Lower Cotter. Following this event, restoration efforts have included replanting native vegetation in areas that previously had pine plantations; however, this work has been constrained by funding availability.

The 2020 Orroral fire that burnt almost all of the Corin Catchment and part of the Bendora Catchment occurred after the investigations and analyses described in this report were undertaken and findings and recommendations developed. The impact of that fire on erosion risk in the Cotter Catchment, and recommendations for targeted actions in response to the fire, are described in Addendum 1.

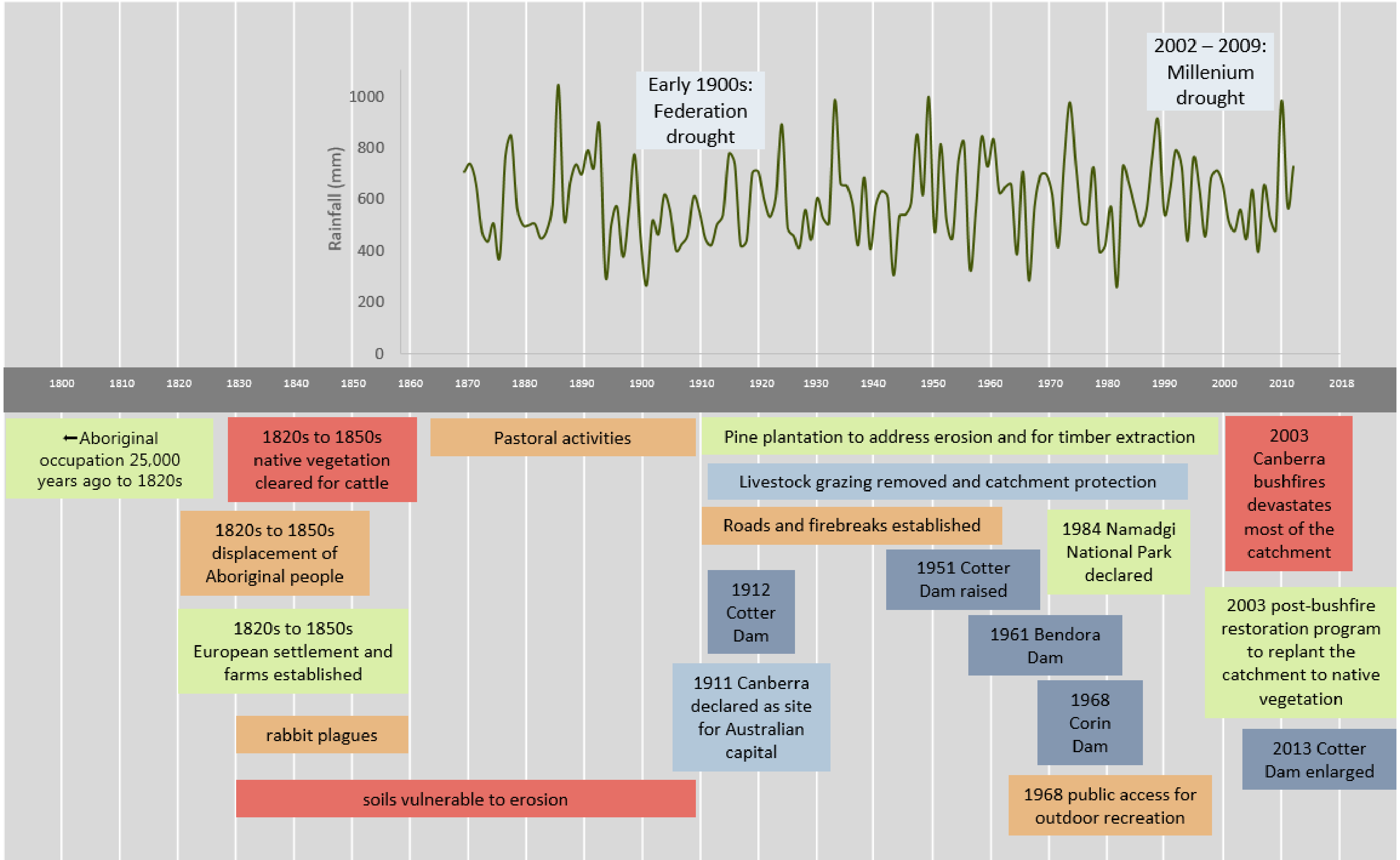

Figure 3. *Cotter Catchment timeline*

4.2 Factors affecting water quality

Climate change

Average annual rainfall (for the period 1961-1990) in the Cotter Catchment ranges from 700 mm to 1300 mm, compared to 688 mm in Canberra [16] (Figure 8). The catchment has also undergone several flood and drought events as shown in Figure 3. The mean minimum and maximum temperatures across all months are 3.5°C and 11.8 °C respectively [16].

Climate change is expected to impact soils through changes in both soil erosion and rainfall erosivity. Recent work by the former NSW Office of Environment and Heritage used projections from the NARCliM model to provide information on the predicted impact of climate change on soil erosion and rainfall erosivity in the near future (2030) and far future (2070) [17]. The results of this analysis for the far future scenario is provided below (Figure 5), showing a 0-10% increase in annual mean rainfall erosivity in the Cotter catchment [17].

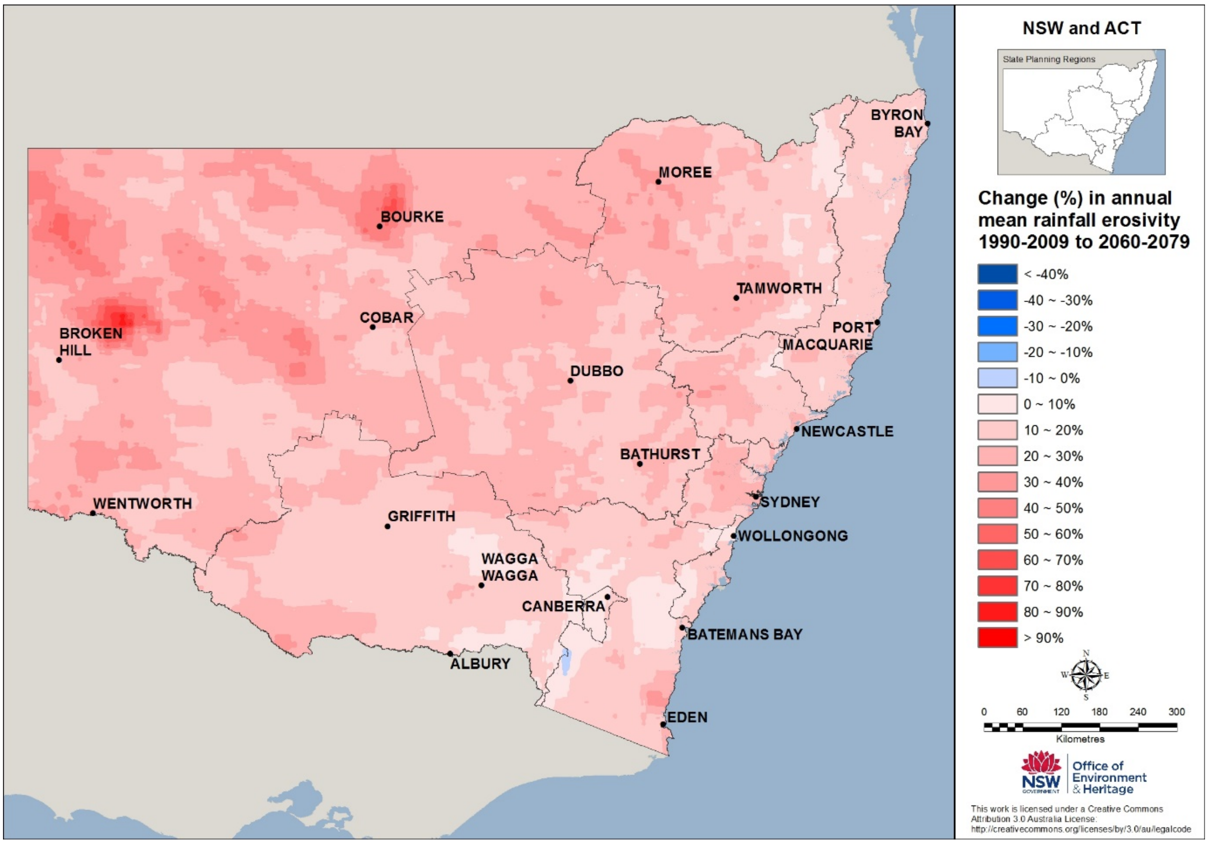

Figure 4. *Predicted Change in annual mean rainfall erosivity from 1990-2009 to 2060-2079* **[17]**

Land use

Understanding the land use types throughout the Cotter Catchment is important in determining the dominant erosional processes supplying sediment within the catchment, as land use types have varying degrees of impact on erosional processes. Generally, vegetated areas will contribute considerably less sediment than cleared areas. It is also important to understand extant land use types when developing and implementing management actions aimed at reducing downstream sediment loads.

Nature conservation is currently the predominant land use in the Cotter Catchment. The catchment is mostly protected by the Namadgi National Park. The park covers the mid and upper Cotter River, and part of the lower Cotter River below Bendora Dam. The Lower Cotter Catchment in the north is outside the national park and is managed for the protection of water supply. The small section of the catchment in NSW is part of the Brindabella National Park.

The Namadgi National Park is protected for its natural and cultural heritage and provides regional ecological connectivity through its links to NSW. The park's snow gum woodlands, subalpine fens and bogs, grasslands and montane forest communities provide habitat for a diverse range of species [3]. Namadgi National Park is part of a greater network of reserved areas known as the Australian Alps national parks [3].

The catchment also supports various recreation activities. The use of the catchment for recreation is being managed to minimise impact and to protect land values including water supply [1] [3].

Unsealed roads, fire breaks and trails contribute to risk of erosion and sediment movement into the reservoirs, particularly in the Lower Cotter Catchment where a large number of access routes were developed in association with earlier forestry [1]. The Auditor General recommended that the road and trail network in the Lower Cotter Catchment be reviewed and a road improvement plan developed to minimise roads and fire trails [6]. The ACT Government subsequently developed the Lower Cotter Catchment Road Network Improvement Plan. The Plan prioritises roads based on their importance for fire and land management to determine whether they will be maintained, dormant or extinct. This plan needs to be kept updated and the road network progressively rationalised as the catchment area continues to be rehabilitated.

Catchment geology and soils

The catchment is underlain by mostly Ordovician sedimentary rocks in the mid catchment, with Silurian granites in the upper catchment and some Silurian to Devonian felsic volcanics in the lower catchment in the north (Figure 9). The type of geology and depth at which it lies under the soils layer determines the extent and timeframe over which erosion processes can impact the catchment. A highly weathered sandstone layer for example will provide less resistance to erosion processes than a granite outcrop.

The dominant soil type throughout the catchment is Kurosols. The upper catchment boundary has areas of Rudosols and Tenosols which extend north along the western boundary to the mid catchment. There are also some smaller areas of Kandosols (Figure 9). Kurosols are extremely erodible and consist of a sandy loam topsoil underlain by a markedly contrasting heavy clay subsoil. Rudosols and Tenosols are stony soils that are generally found on steeper slopes where finer grains have been transported away and are highly erodible. Kandosols are also highly erodible and are relatively uniform throughout their profile with a loamy topsoil increasing in clay content with depth.

Bushfires

Bushfires directly affect a range of physical characteristics and processes and cause almost an instantaneous change in the hydrologic and geomorphic response to rainfall, which can see increases in runoff and sediment loads to waterways. The 2003 Canberra bushfires affected the entire catchment and, in conjunction with the severe storms that followed, caused significant erosion and sedimentation of the Cotter Dam in particular. The impact of bushfires on erosion processes is discussed as part of appendix A.

Hard hooved pest animals

Hard-hooved pest animals in the catchment also increase the risk of erosion. The stakeholder workshop identified that hard-hooved pest animals are an increasing threat to the Cotter catchment water quality, particularly following fire events that open the vegetation and increase the range of accessible bushland. Wild brumbies are known to cross from NSW in the western part of the catchment. Deer and pigs are also present in the catchment, contributing to erosion and contamination of water sources.

Other factors affecting water quality

Unsealed roads, tracks for recreation and fire breaks constructed for bushfire management can also be a source of sediment to the Cotter system. In addition, the Commissioner for Sustainability and the Environment's 2018 Restoration Evaluation report raised the issue of car related ignitions in the catchment [5]. This issue is particularly prevalent where access is available closest to urban populations. High-impact recreation activities that are prohibited in the catchment such as dirt-biking and four-wheel driving also contribute to erosion.

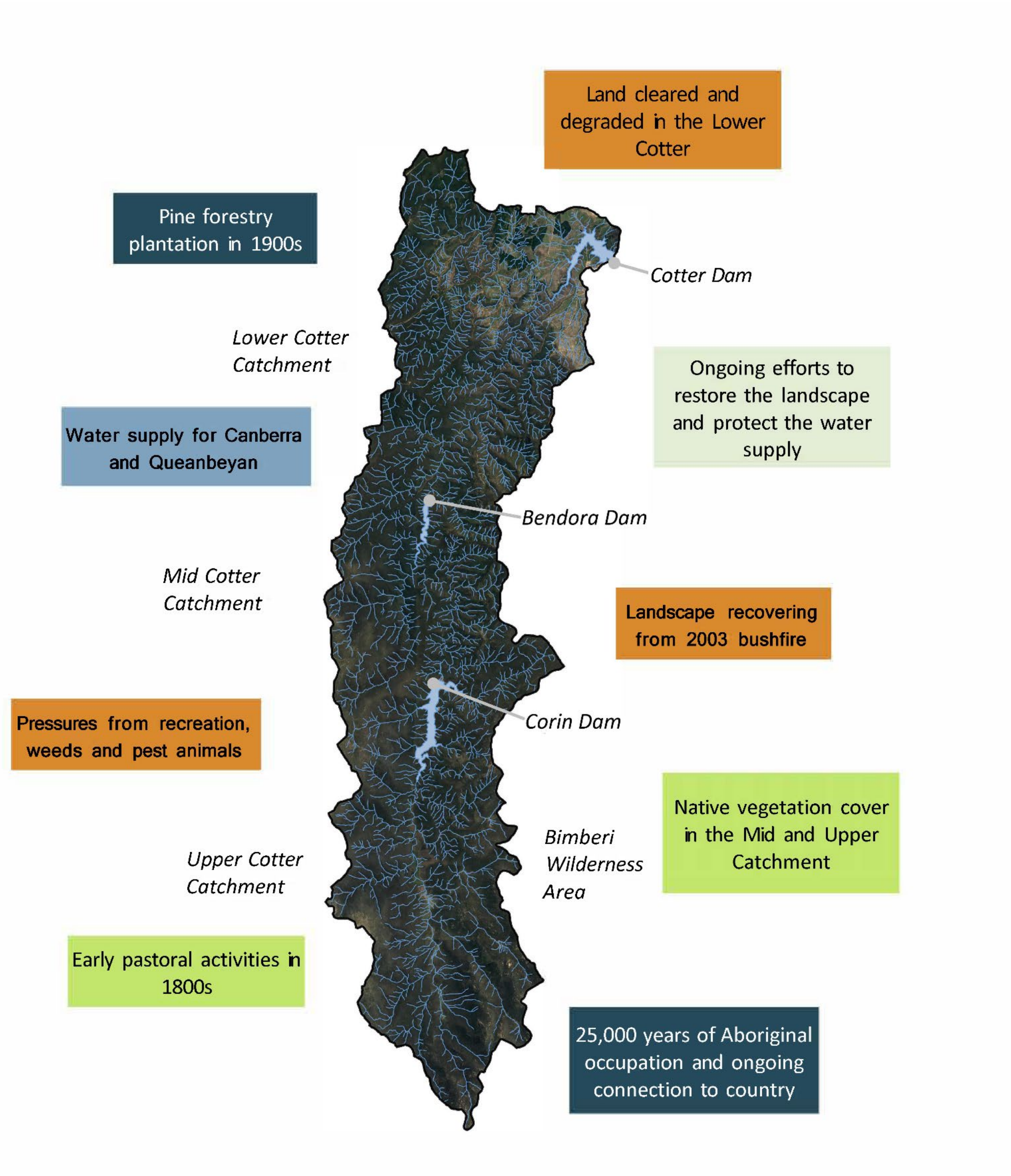

Figure 5. *Overview of Cotter Catchment*.

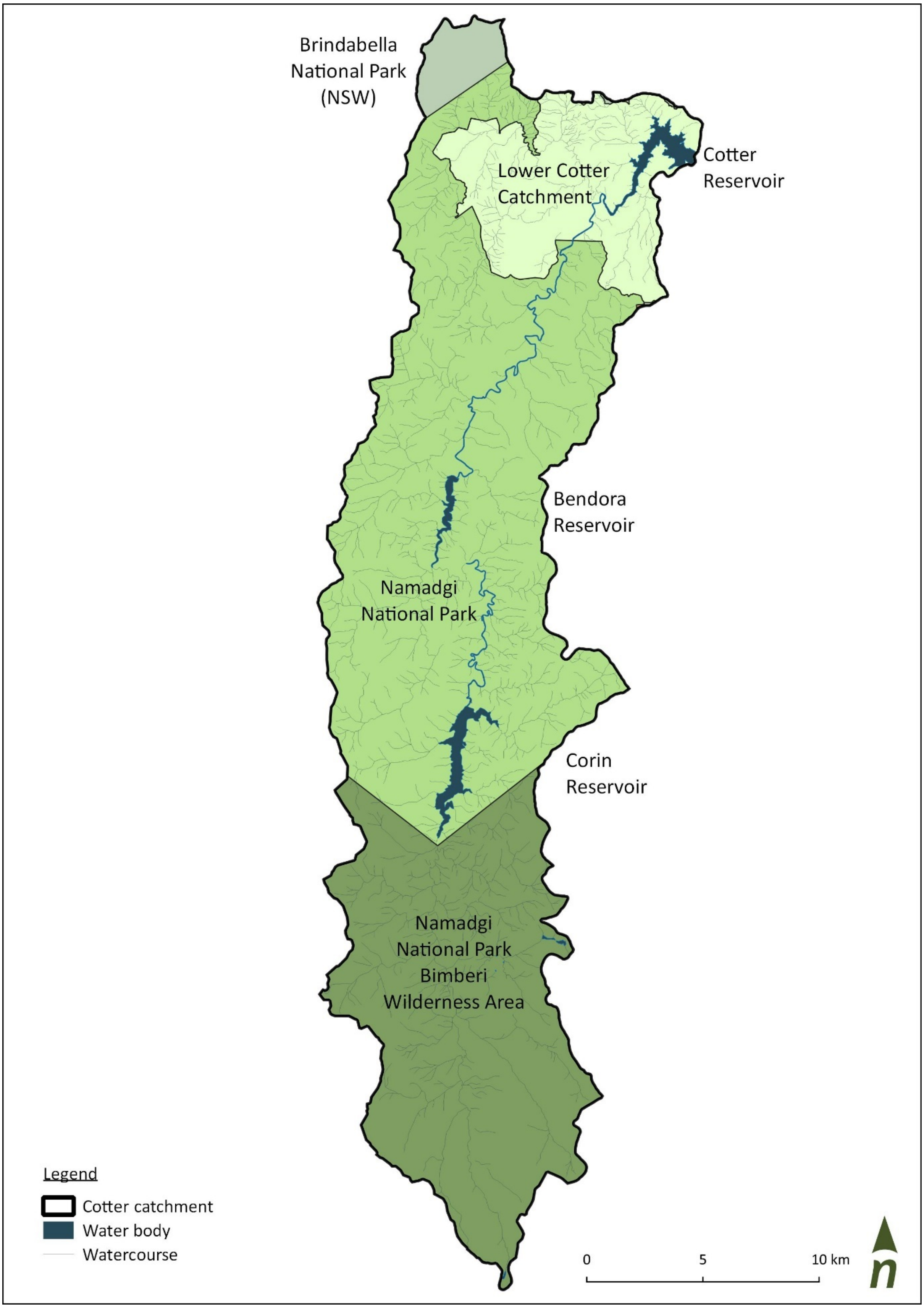

Figure 6. *Cotter Catchment land tenure*

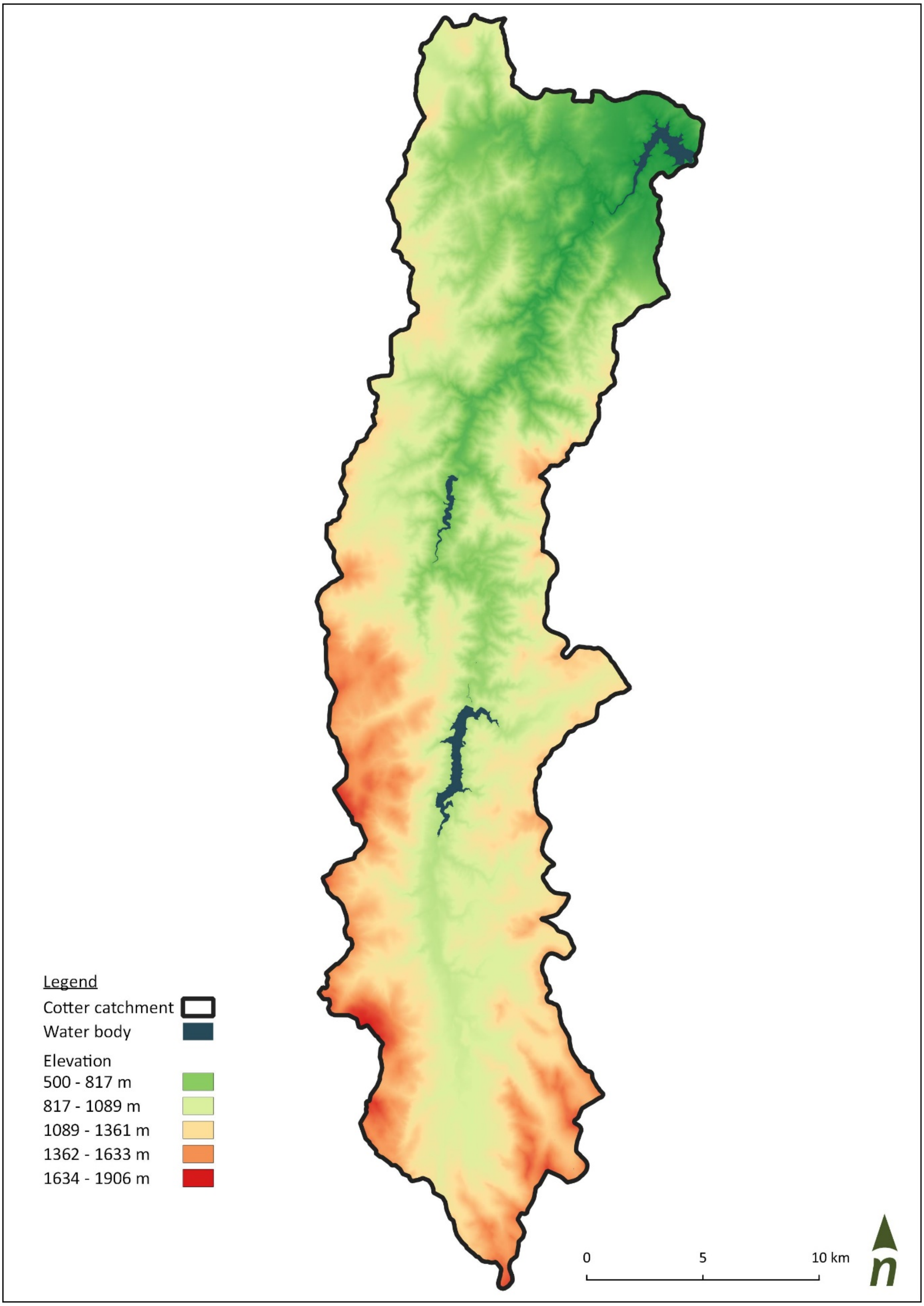

Figure 7. *Cotter Catchment topography*

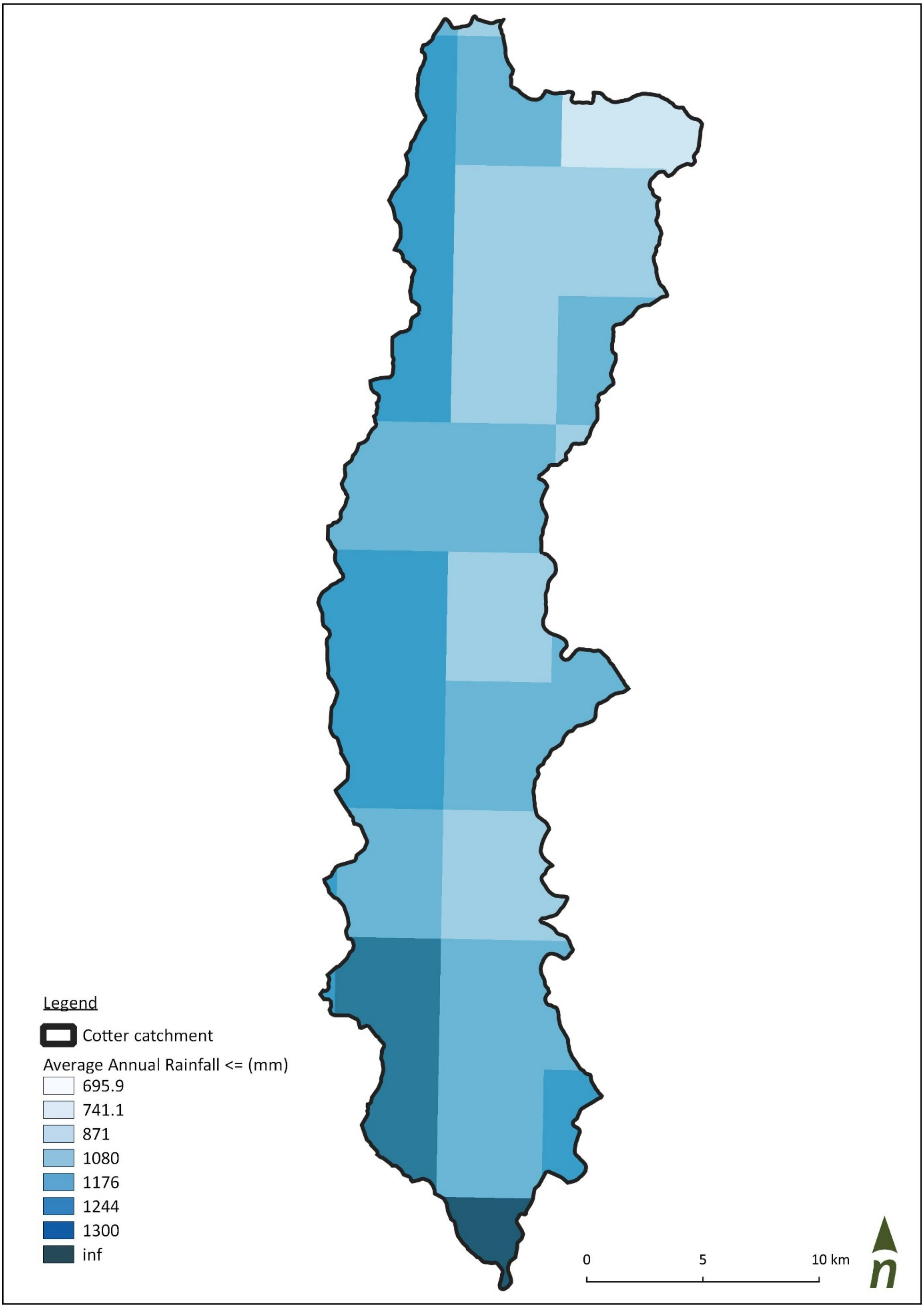

Figure 8. *Average annual rainfall (mm/year), BoM 1961 - 1990*

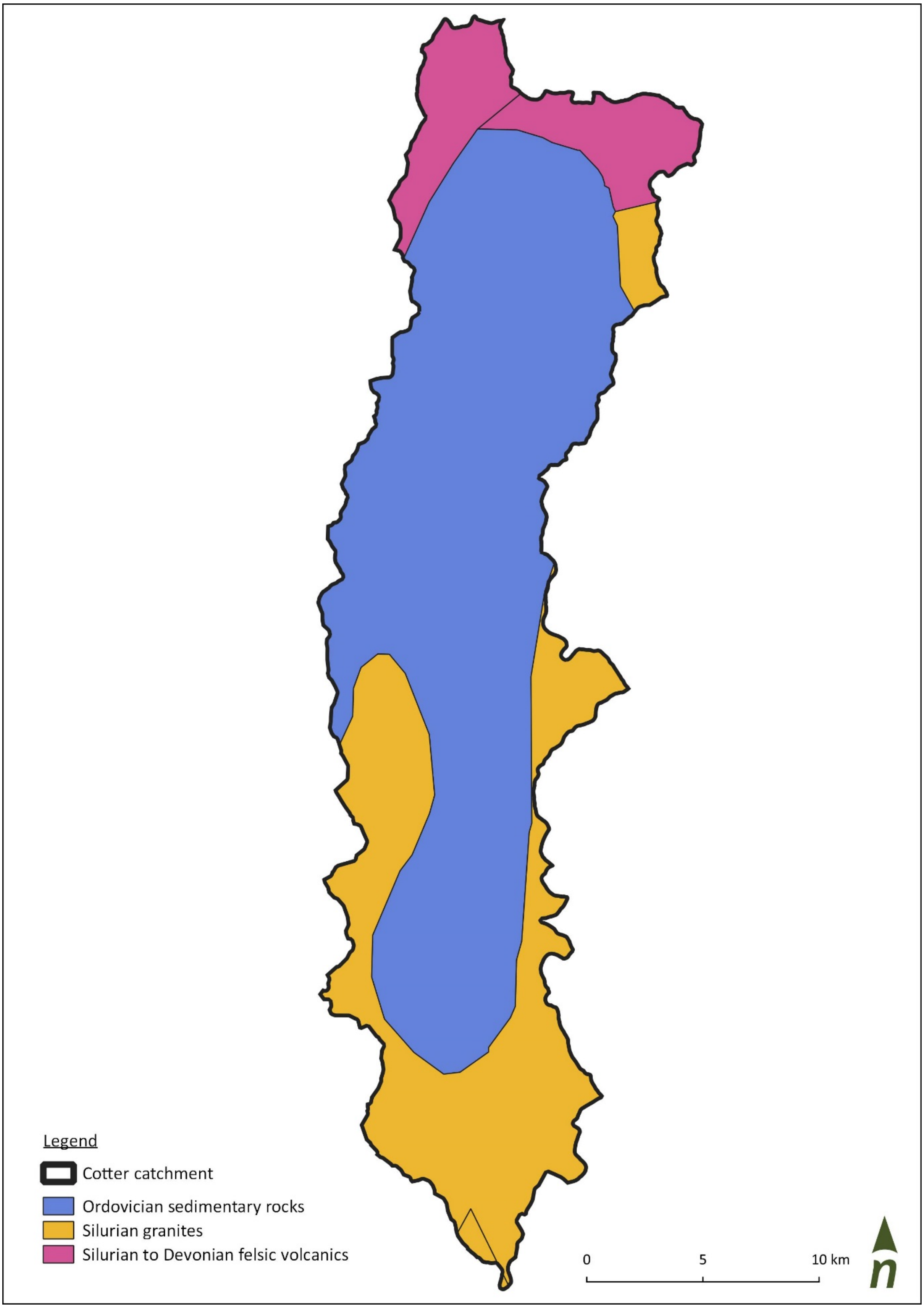

Figure 9. *Cotter Catchment geology*

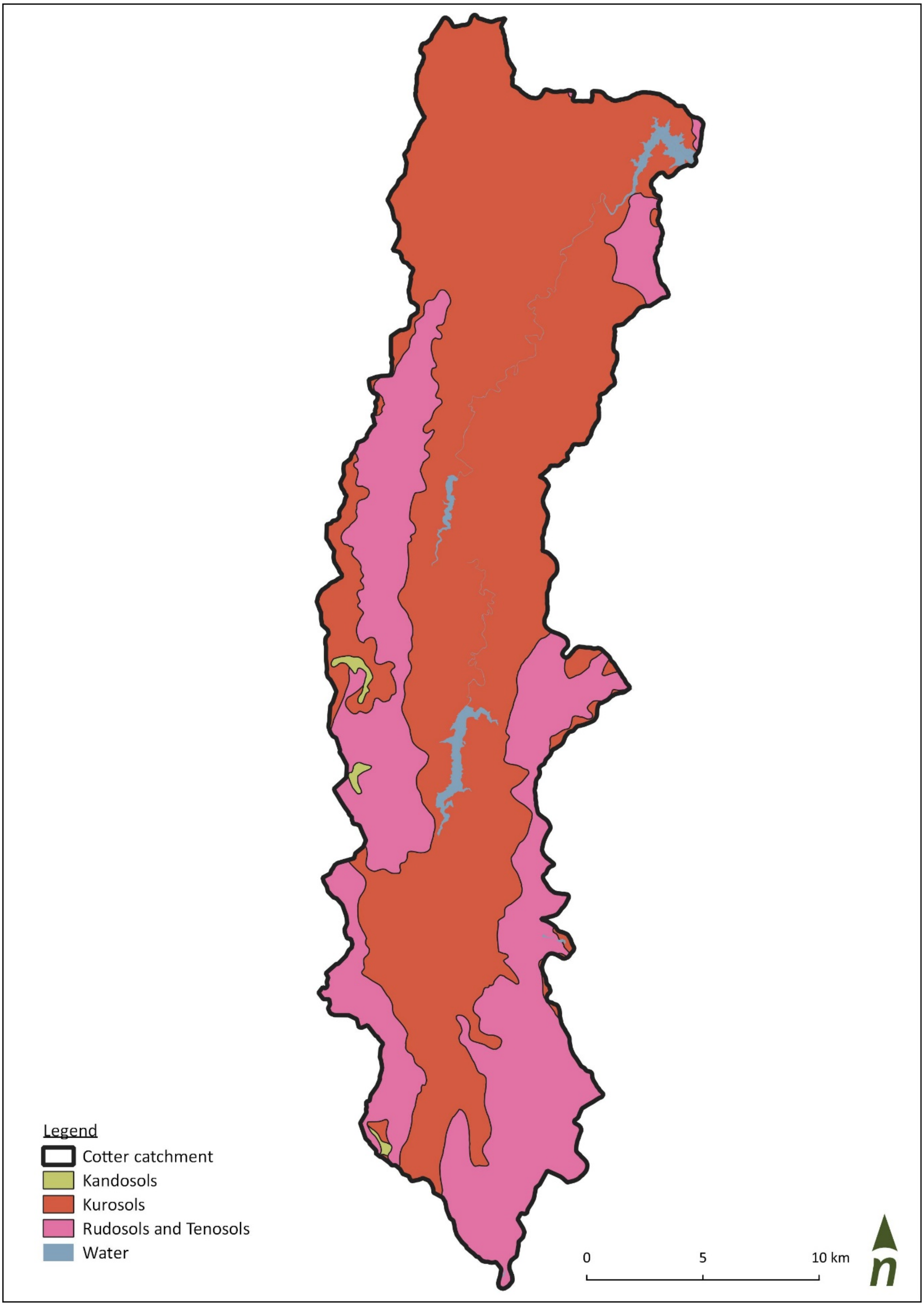

Figure 10. *Cotter Catchment soil types*

5 Subcatchment erosion assessment

5.1 Subcatchment assessments

The results of the erosion assessment are summarised in Table 6 and are presented spatially below (Figure 11, Figure 12, Figure 13 and Figure 14).

Table 6. Erosion risk assessment by subcatchment and erosion type

Subcatchment	Area (Ha)	Main waterways	Hillslope erosion risk	Channel erosion risk	Gully erosion risk
Pierces Creek	2281	Pierces Creek and Dry Creek	Very High	Moderate	Very High
Cotter Dam	1280	Cotter River (Dam)	High	Low	High
Condor Creek	4709	Condor Creek, Musk Creek, Wombat Creek, Fastigata Creek and Coree Creek.	Moderate	Moderate	Moderate
Lees Creek	2560	Lees Creek and Blundells Creek	Moderate	Moderate	Moderate
Bullock Head	8425	Cotter River, Bullock Head Creek, Burkes Creek, Burkes Creek North, Burkes Creek South, Bushrangers Creek, Bendora Creek, Cow Flat Creek Collins Creek and Little Collins Creek	Moderate	Moderate	Low
Kangaroo Creek	4986	Kangaroo Creek, Snowy Flat Creek, Clear Hills Creek and Dry Creek	Low	Moderate	Low
White Sands Creek	3558	Cotter River and White Sands Creek	Low	Moderate	low
Ginini Creek	3584	Ginini Creek and Stockyard Creek	Low	Moderate	Low
Cribbs Creek	7357	Cotter River, Cribbs Creek, Gingera Creek, Long Creek, De Salis Creek, Pond Creek, Mosquito Creek and McKeahnie Creek	Low	Low	Low
Licking Hole Creek	2178	Licking Hole Creek and Creamy Flats Creek	Low	Low	Low
Porcupine Creek	5076	Cotter River, Porcupine Creek, Bimberi Creek, Jacks Creek, Little Bimberi Creek and Drag Creek	Low	Low	Low
Franklin Creek	1937	Cotter River and Franklin Creek	Low	Low	Low

The subcatchments of the Lower Cotter Catchment (Pierces, Cotter Dam, Condor Creek and Lees Creek) scored the highest in terms of all three types of erosion risk. As a result, these subcatchments were classified as priorities for management. The Bullock Head subcatchment also scored highly in terms of hillslope erosion risk but scored somewhat less for channel and erosion risk. This was due to the fact that there remains a greater proportional extent of intact native cover within the Bullock head subcatchment.

The remaining subcatchments within the Bendora and Corin catchments scored considerably lower and were therefore classed as low priority. However, it should be noted that three of these (White Sands Creek, Kangaroo Creek and Ginini Creek) were assessed as having moderate channel erosion risk.

Note that the 2020 Orroral fire that burnt almost all of the Corin Catchment and part of the Bendora Catchment occurred after the investigations and analyses described in this report were undertaken and findings and recommendations developed. The impact of that fire on erosion risk in the Cotter Catchment, and recommendations for targeted actions in response to the fire, are described in Addendum 1.

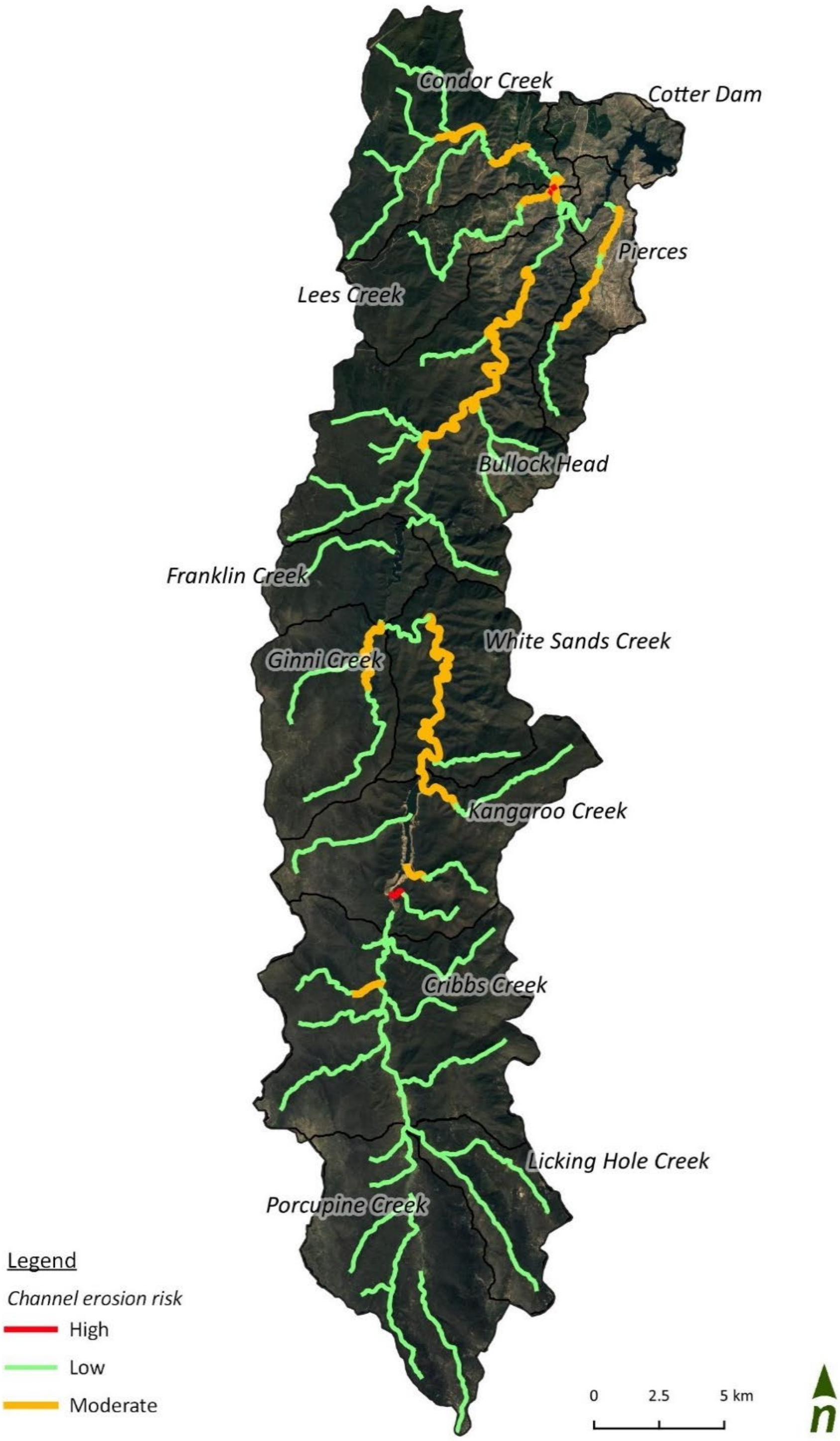

Figure 11. *Channel erosion risk of mapped Riverstyles waterways* **[11]**

Figure 12. *Mapped gully erosion across the Cotter catchment, which includes previously mapped gullies in the lower catchment* **[18]**

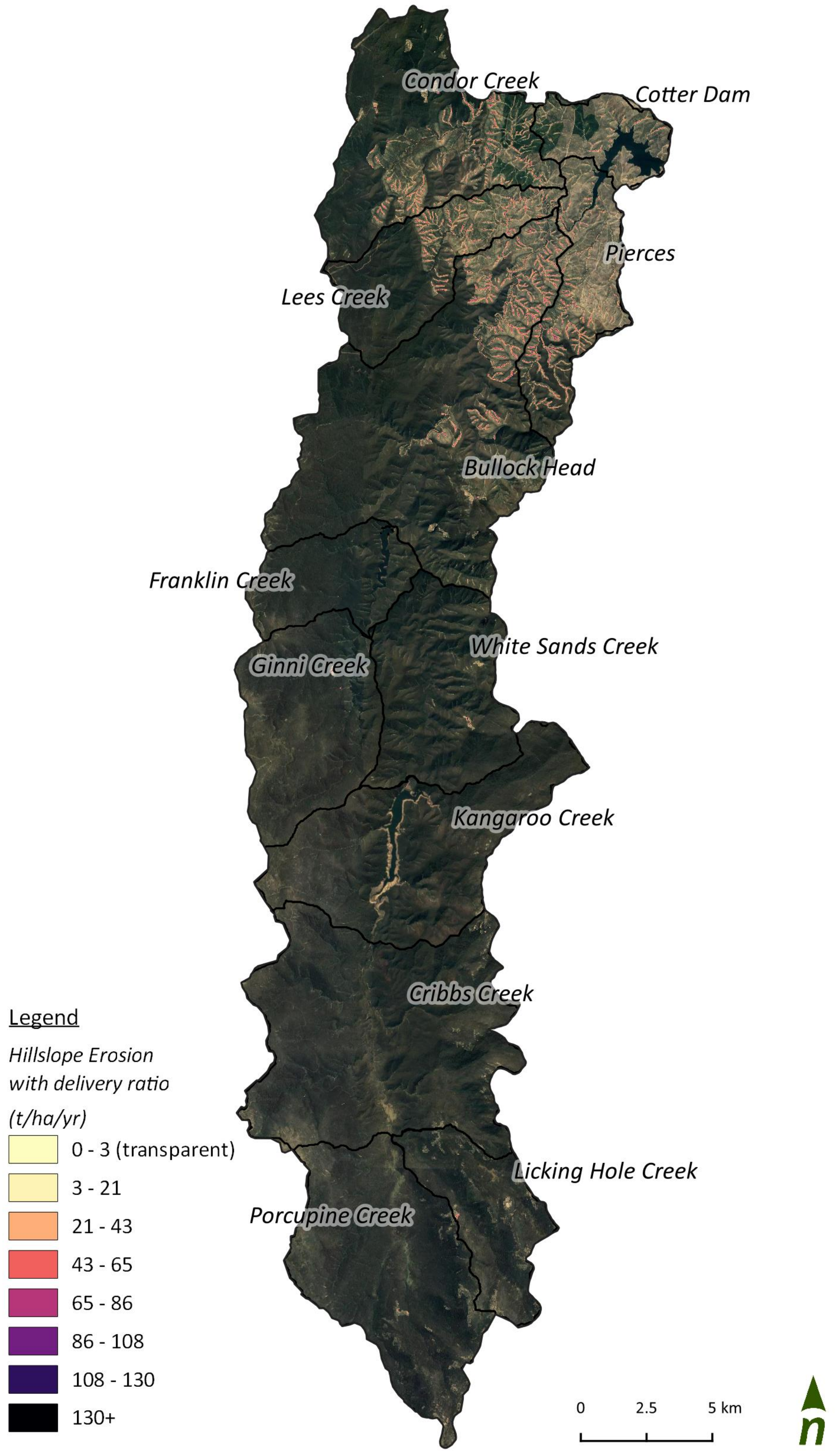

Figure 13. *Cotter erosion assessment: hillslope erosion results with subcatchments outlined in black*

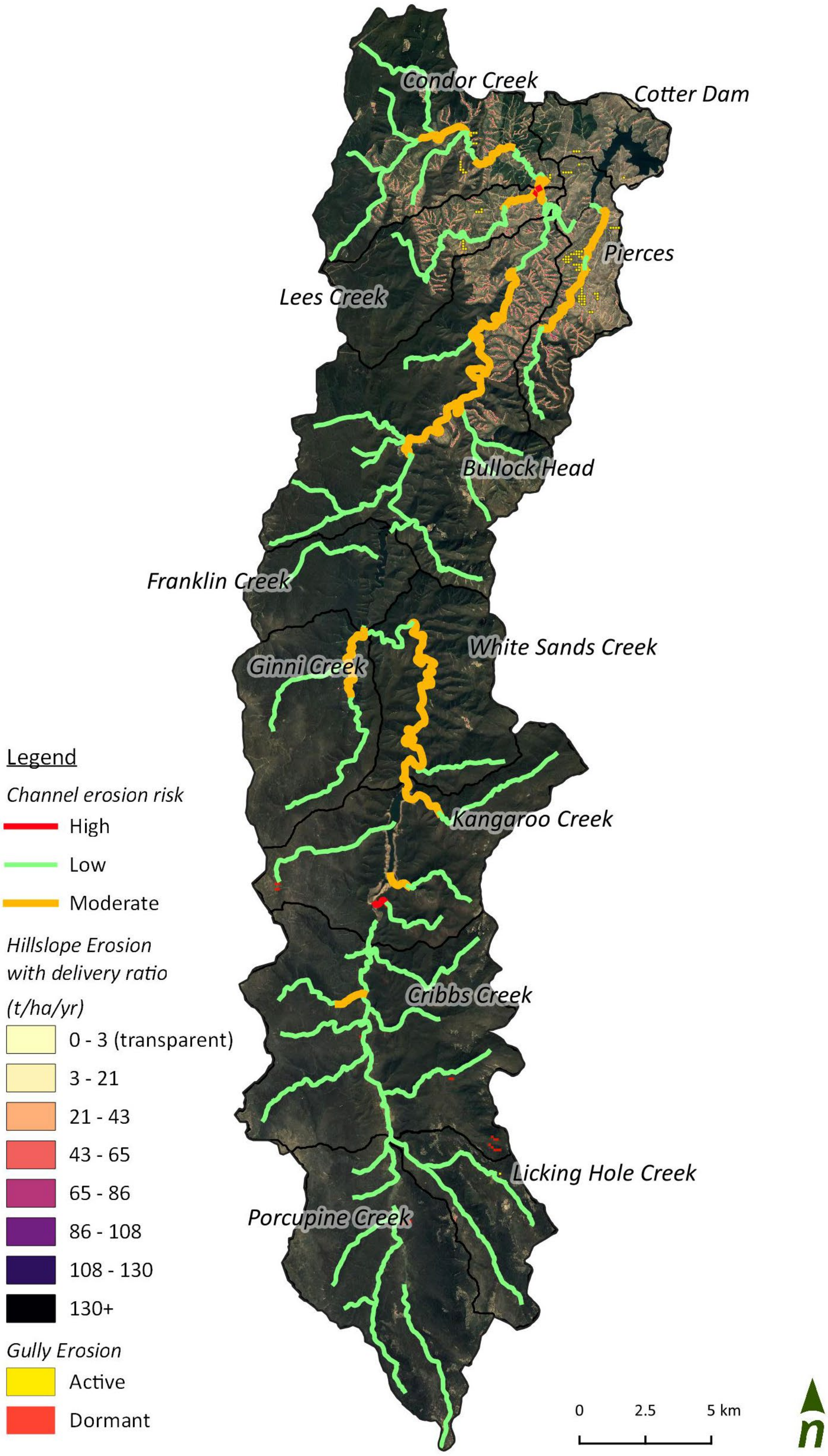

Figure 14. *Combined Channel, Hillslope and Gully erosion risk distributions across the Cotter catchment*

6 Priority subcatchments

As described above, the four lower Cotter subcatchments of Pierces, Cotter Dam, Condor Creek and Lees Creek were identified as priority subcatchments based on the desktop erosion assessment. A description of these priority subcatchments is provided below. Specific management zones are discussed in Section 7.

It should be noted that the accuracy of these desktop assessments is limited by the available data, which here included 2015/2017 aerial and 2015/2019 and LiDAR data.

Pierces subcatchment
The desktop channel erosion risk assessment identified this subcatchment as having the greatest proportion of reaches facing *high to moderate* channel erosion risk in close proximity to Cotter Dam. These consisted of two high risk reaches along Pierces Creek with a combined length of 2.5km. Field verification however warranted a reduction in rating from *high* to *moderate* given the high incidence of bedrock controls, good riparian continuity combined with a low incidence of exposed or unstable bank surfaces.

The soils and underlying geology within these *moderate* reaches consist of well drained rudosols (alluvials) and moderate to poorly drained bleached-mottled Yellow Kurosols, all which atop late Silurian felsic granite. Drainage pathways are reported to often be incised; however previous literature has not observed any significant streambank erosion [19]. The field visit clarified this, while there remains the presence of deeply incised drainage pathways, the relatively steep terrain has restricted the degree to which meandering or widening can occur, thus moderating streambank erosion. Nevertheless, given the depth of exposed highly dispersive subsoil (up to 4m deep) and concentrated flows along incised/failed contour banks, there remain multiple flow entry points along tributaries which will experience streambank erosion into the future.

Gully erosion risk for this subcatchment is classed as *very high*. The subcatchment contains the highest proportion of active gullies by far (62 1Ha cells active in Pierces followed by 18 in Condor Creek and then 4 in Cotter Dam). It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment given current conditions. As conditions change throughout the catchment (i.e. changes in rainfall patterns, naturalisation continues, etc.) this risk can increase or even decrease.

Gully erosion is primarily active in the southern half of the sub-catchment and is particularly concentrated along hillslopes downslope of access trails. The soils in these areas consist of highly erodible and bleached Yellow, Brown and occasional Red Chromosols which, with concentrated flows from access tracks, are highly susceptible to gully erosion caused by overland runoff and direct rainfall [19]. The success and/or failure of gully remediation works undertaken in 2016 and 2017 can be indicative of the likelihood of effectively remediating the remaining active gullies into the future [1]. While some of the works appear to have remained intact under recent high flows, others are at risk. This is particularly the case where the weathering profile is deep between stabilisation efforts. Such depth has made it difficult to effectively tie grade control structures into the stable terrain, enabling knick-points to develop and threaten upstream works or allowing for outflanking to destabilise the structure itself.

The RUSLE Analysis indicated relatively high rates of hillslope erosion along the steeper southern slopes of the subcatchment (See Appendix A). While these rates are high for the steeper surfaces, not all of the sediment eroded enters the streamline. The applied delivery ratio accounted for this by assuming that the fraction of sediment delivered to the waterway is proportional to its distance from the closest streamline. It is, however, likely that the delivery in the southern half of the catchment is less than modelled, given the extent of vegetative cover and the increased likelihood of minimal anthropogenic disturbance into the future.

Cotter Dam subcatchment
The initial desktop analysis for the Cotter Dam catchment yielded a relatively low overall risk score when compared to the other sub-catchments. This was largely due to the limited length of channels mapped for erosion risk, the small proportion of relative hillslope area and the high level of sediment management actions (Contour banks, log placement, sediment control structures etc) since 2003.

The RUSLE Analysis suggested that relatively high rates of hillslope erosion occur along the northern and north-western half of the subcatchment (See Appendix A). As observed during the field inspection, these areas may be subject to a higher degree of contour bank failure and subsequent rill erosion. For this reason, the hillslope erosion risk was revised from *moderate* to *high*. While the hillslope erosion rates are high for steeper surfaces in general, not all of the sediment eroded enters the streamline. The RUSLE analysis accounts for this through the application of a delivery ratio which assumes that the fraction of sediment delivered to the waterway is proportional to its distance from the closest streamline. It is, also however possible that the delivery of hillslope derived sediment will reduce over time, especially since current management objectives aim to return the subcatchment to a less disturbed landscape.

The subcatchment geology consists of Silurian volcanics which have given rise Red Kandosols on the mid-slopes and Brown Chromosols and Brown Kandosols along lower slopes and drainage lines[1]. The terrain is highly disturbed due to its history of land use, with much of the original topsoil removed as a result of plantation operations. Consequently, severe gullying has occurred in many of the drainage lines, many of which have received extensive rehabilitation work. The inspection however revealed that at least one of the remaining mapped active gullies is active, progressing into readily available dispersive, fine sediment. Given the high connectivity of drainage lines to Cotter Dam, the gully erosion risk was revised from *moderate* to *high*, despite the relatively low number of mapped active gullies mapped within this subcatchment.

Condor Creek subcatchment

The initial channel erosion risk assessment identified two reaches (total length 2.8km) toward the eastern end of the catchment as having *high* channel erosion risk. These reaches were initially identified from the desktop assessment as having moderate instabilities, which corresponds to very high erosion potential and a moderate sediment availability. The remaining reaches within the sub-catchment were primarily identified as having *low* channel erosion risk, with one *moderate* reach in the middle of the catchment of 2.2 km in length.

Field verification has subsequently led to a downgrading of all high-risk channels to moderate. This is due to the presence of extensive bedrock controls and high-quality riparian vegetation. The occurrence of isolated instabilities within these reaches of moderate risk remains a possibility. The geology underlying the reaches facing high channel erosion risk comprises a complex assemblage of faulted Silurian volcanics and some metasediments, each giving rise to a corresponding variety of soils, ranging from Yellow Sodosols to Grey Chromosols along drainage lines, much of which is highly erodible. The field inspection confirmed this, as the soil where encountered was mostly highly dispersive fine clays.

The terrain is highly disturbed due to its history of land use, with much of the original topsoil removed as a result of plantation operations. Consequently, severe gullying has occurred in many of the drainage lines [20]. Gully erosion for this catchment was classed as moderate, with the second highest proportion of active gully development when compared to other subcatchments. Eighteen 1ha cells were considered active and most of these were situated along steep tributaries draining into Condor Creek midway along the catchment. The field inspection of these gullies revealed that bedrock controls are restricting any further incision. Given the steep terrain, bedrock control and presence of vegetation, these gullies are relatively restricted in their ability to widen, even though recent high flows have evidently led to considerable destabilisation, tree fall and subsequent soil mobilisation. It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment given current conditions. As conditions change throughout the catchment (i.e. changes in rainfall patterns, naturalisation continues, etc.) this risk can increase or even decrease

The RUSLE Analysis indicated relatively high rates of hillslope erosion, particularly along the eastern half of the subcatchment (See Appendix A). While these rates are high for the steeper surfaces, not all of the sediment eroded enters the streamline. The applied delivery ratio accounted for this by assuming that the fraction of sediment delivered to the waterway is proportional to its distance from the closest streamline. It is, however,

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[1] Jenkins, B.R. 2000. *Soil Landscapes of the Canberra.* 1:100 000 Map Sheet, Sydney: Department of Land and Water Conservation.

possible that the delivery of hillslope derived sediment will reduce over time, given the current management objectives which aim to return the subcatchment to a less disturbed landscape.

Lees Creek subcatchment

The desktop channel erosion risk assessment originally identified this subcatchment as retaining the second greatest proportion (2.3km) of reaches facing *high* channel erosion risk. The subsequent field inspection led to a re-classification of these reaches, reducing the high-risk length to only 230m. This is due to presence of extensive bedrock controls and high riparian longitudinal connectivity/structural diversity. There does however remain the potential for isolated instabilities. Existing channel stabilisation works near the confluence appear to have only partially withstood recent high flows. The remaining reaches mapped within the sub-catchment (85%) were primarily identified as having low channel erosion risk.

The underlying geology the reaches facing moderate to high channel erosion risk comprises a complex assemblage of faulted Silurian volcanics and some metasediments, each giving rise to a corresponding variety of soils, ranging from Yellow Sodosols to Grey Chromosols along drainage lines, much of which is highly erodible. The terrain is highly disturbed due to its history of land use, with much of the original topsoil removed as a result of plantation operations. Consequently, severe gullying has occurred in many of the drainage lines [20]. The gully erosion risk for this catchment is considered *moderate*, with the third highest proportion of active gully development when compared to other subcatchments. Nine 1ha cells were considered active, all of which were situated in the lower third of the subcatchment along the fault boundary between the Silurian volcanics and Ordovician metasediments. It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment given current conditions. As conditions change throughout the catchment (i.e. changes in rainfall patterns, naturalisation continues, etc.) this risk can increase or even decrease.

Field verification of mapped active gullies was limited by time constraints. Nevertheless, aerial imagery and on ground observations from downstream of the mapped gullies suggest that the gully activity is exacerbated by a disused trail parallel to the drainage pathway. While some roll over banks have been put in place along the trail to direct flows into the original tributary channel, the dispersive nature of the exposed subsoil coupled with poor vegetation establishment appears to have led to roll over bank failure and rill erosion.

The RUSLE Analysis indicated moderate rates of hillslope erosion, with higher rates in previously disturbed areas particularly along the north-eastern half of the subcatchment (See Appendix A). While these rates are high for the steeper surfaces, not all of the sediment eroded enters the streamline. The applied delivery ratio accounted for this by assuming that the fraction of sediment delivered to the waterway is proportional to its distance from the closest streamline. It is, however, possible that the delivery of hillslope derived sediment will reduce over time, given the current management objectives which aim to return the subcatchment to a less disturbed landscape

7 Risk assessment

The Pierces, Cotter Dam, Condor Creek and Lees Creek subcatchments were classified as priority sub-catchments on the basis of the risk assessment for channel, gully and hillslope erosion (Section 5.1). The risk assessment approach is described in Section 3 above.

Within each of these sub-catchments, key zones of erosion risk were identified and have been classified as Priority Management Zones. The zones are shown in Figure 15 below. These zones were the subject of a targeted field investigation to compete a more detailed risk assessment and prioritisation exercise. Cell ID numbers gathered from existing gully mapping for the Lower Cotter catchment have been used assist in identifying the gully in question, as not all 'active' gullies were able to be field assessed due to time constraints. A summary of the risk assessment for each priority management zone is provided in Table 7, with more detail on the following pages.

Table 7. Priority management issues and risk rating

Priority management issue/zone	Likelihood	Consequence	Trajectory	Risk
Pierces subcatchment				
1 – Extensive gully development along a tributary to the west of Pierces Creek, primarily adjacent to Pipeline Rd. Further gullying occurs adjacent to Pierces Creek at the upstream end of the reach. (Cell ID 70916)	5	4	5	100 - *Extreme*
2 – Extensive gully development to the east of Pierces Creek within former pine plantation (Cell ID 73129)	5	4	4	80 - *Extreme*
3 – Gully development along old trail, east of Pierces Creek (Cell ID 79141)	3	3	2	18 - Moderate
4a - Gully development along tributary flowing directly into Cotter Dam (Cell ID 69789)	4	3	2	24 - Moderate
Cotter Dam subcatchment				
4b - Gully development along tributary flowing directly into Cotter Dam (Cell ID 71426)	5	4	4	80 - *Extreme*
Condor Creek subcatchment				
5 – Longitudinal gully development along unnamed tributary of Condor Creek along Brindabella Rd. Located east of the Wombat Creek confluence (Cell ID: 47275)	3	3	3	27 - Moderate
Lees Creek subcatchment				
6 – Stream bank erosion along lower section of Lees Creek before Condor Creek confluence	2	2	2	8 - Low
7 – Active gully development 700m northwest of the Warks Rd crossing of Lees Creek (Cell ID: 51136)	3	4	4	48 – Very High

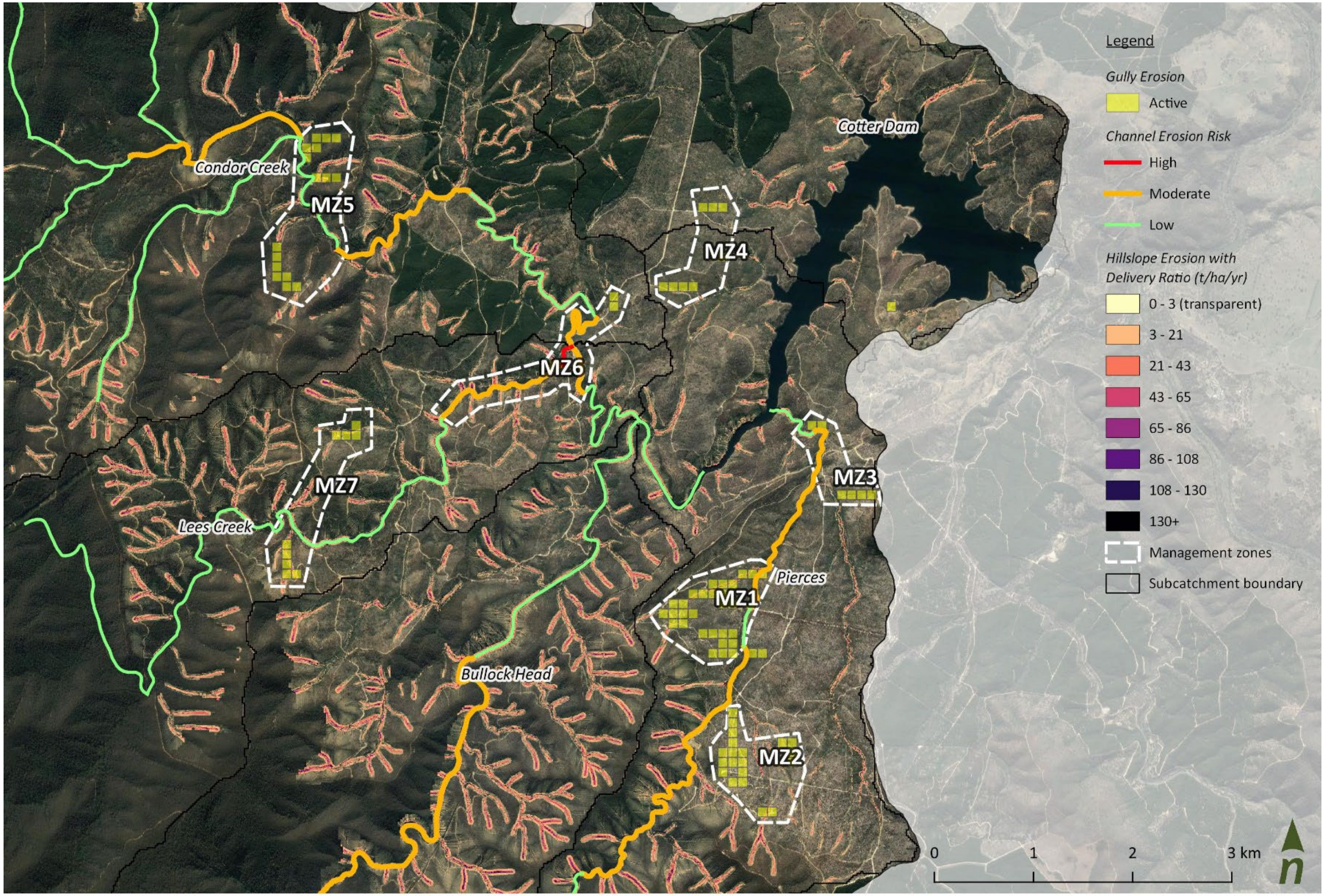

Figure 15. *Overview of Priority Management Zones 1 to 7 within the Pierces, Condor Creek and Lees Creek sub-catchment*

Priority management zone 1 – Pierces Creek sub-catchment Location (E672840, N6086389 GDA94Z55)		
Priority management zone 1 consists of a series of longitudinal gullies along three steep tributaries entering Pierces Creek from the south west. Given time constraints, not all mapped 'active' gully cells were field assessed. Nevertheless, what appeared to be the most at-risk section was assessed as part for this management zone and reported below		
Condition assessment		
Site MZ1	Site MZ1 is located along the main Pierces Creek tributary that runs parallel to Pipeline Rd road where it crosses East West Break. The soils in this area are dispersive fine sandy clays which display evidence of tunnelling. The site has already had significant stabilisation works; however recent rain has revealed the presence of channel instabilities in multiple locations. Furthermore, contour banks along tributary hillslopes have incised and failed, leading to further destabilisation. Outflanking of existing structures also appears to be occurring at the East-West Break Rd crossing, suggesting the need for road runoff management to protect existing works. The site photo (right) shows how recent flows have scoured stabilisation works thus threatening their long-term stability. This is but one example of at least two head cuts between works along this gully line. While vegetative cover does provide some structural support, the steep grade of the channel, dispersive substrate and the lack of bedrock control mean that these instabilities are likely to worsen over time without intervention.	 *Site MZ1a looking upstream from 50 south of East West Break crossing*

Priority management zone 1 – Pierces Creek sub-catchment Location (E672840, N6086389 GDA94Z55)		
	 *Site MZ1a: Another head cut progressing towards stabilisation works further upstream*	 *Site MZ1a: Approx. 2m deep incision along contour banks down stream of East West Break road crossing*

Priority management zone 2 – Pierces Creek sub-catchment Location (E674448, N6087374 GDA94Z55)		
Priority management zone 2 consists of two main tributaries of Pierces Creek that run roughly parallel to Quandry Road. Given time constraints on the field investigation, the gully system was assessed at a general level and not all mapped 'active' gully cells were inspected.		
Condition assessment		
Site MZ2	Site MZ2 is located along a south to north running tributary of Pierces Creek. The site consists of a series of longitudinal gullies which have incised into steep, sandy and extremely weathered granitic terrain. Gully mapping classified this gully system as active which was confirmed by the site assessment. The figure to the right shows a section of the gully near Pierces Creek road, where vertical banks and meander development will lead to continue to sediment mobilisation downstream immediately upstream. The figure in the bottom left is an example of some of the bed rock exposures within the gully channels, which should be taken into consideration when determining the placement of rock chutes. The figure in the bottom right is an example of outflanking which has occurred at least two gabions placed within the gully system, thus illustrating the need for well designed, keyed in stabilisation structures moving forward. While hydraulically designed and keyed in rock chutes are more expensive, their probability of long stabilisation is much higher.	 *Site MZ2 looking downstream near Pierces Creek Rd*

Priority management zone 2 – Pierces Creek sub-catchment Location (E674448, N6087374 GDA94Z55)		
	 *Site MZ2 looking upstream towards Pierces Creek Rd*	 *Site MZ2 looking across stream near Quandry Rd*

Priority management zone 3 – Pierces Creek sub-catchment		
Gully development along old trail, east of Pierces Creek (E674449, N6087346 GDA94Z55)		
Condition assessment		
Site MZ3	Site MZ3 features a shallow, narrow longitudinal gully along a disused trail. It is located 550 metres south east from the Vanity's Road/Pierces Creek crossing and is identified as an active gully (Cell ID 79141). Runoff from the disused trail is concentrating flow through the system. The field inspection confirmed that the gully is active only in minor sections, where two to three small head cuts from 0.25 to 0.5m in depth appear progressing upstream. The rate of progression may be relatively slow due to colluvium at the foot slope of the adjacent hill, as well as the presence of blackberry. The figure to the right shows one of the head cuts mid-way along the system, within finer dispersive substrate amidst blackberry. The bottom figures illustrate how the disused trail concentrates flow over the first head cut, also swamped by blackberry. Without intervention (assisted revegetation and head cut stabilisation) the system is likely to continue to deliver fine sediment downstream, albeit a relatively smaller amount when compared the to the previous two sites	 *Site MZ3 looking upstream. Head-cut within finer substrate near Dry Creek Rd*

Priority management zone 3 – Pierces Creek sub-catchment		
	 *Site MZ3 looking upstream/east with head-cut in foreground.*	 *Site MZ3 looking west/ downslope along eroding trail with head-cut in background*

Priority management zone 4 – Pierces Creek sub-catchment		
Gully development along drainage pathway, west of Cotter Dam (E672536, N6089465 GDA94Z55)		
Condition assessment		
Site MZ4a	Site MZ4a features gully development along a drainage pathway with direct connectivity to Cotter Dam. Extensive blackberry growth obscures much of the gully head cut and original rock stabilisation. Whether existing stabilisation works have failed or not remains unclear. The rock in places appears to have slumped, suggesting the head cut has outflanked and progressed further upstream. The bottom left figure shows a minor head-cut on the flank of the gully, revealing potential for further radial gully development upslope. A review of previous management activities for this gully can provide an indication of gully activity to date and help inform if monitoring is necessary to determine the degree of gully activity. If gully is active, reshaping and erosional control structures will be beneficial given the proximity of this gully to the dam and the extent of available sediment upstream.	 *Site MZ4a looking downstream along gully obscured by blackberry*

Priority management zone 4 – Pierces Creek sub-catchment

Site MZ4a slumping at radial head cut toward the upper end of the gully

Site MZ4a looking upslope along gully trunk obscured by blackberry

Priority management zone 4 – Cotter Dam sub-catchment		
Gully development along drainage pathway, west of Cotter Dam (E672979, N6090248 GDA94Z55)		
Condition assessment		
Site MZ4b	Site MZ4a features gully development along a drainage pathway adjacent to Bracks Hole Rd. The head cut is approximately 0.75m deep and is followed by a secondary incision phase into the sub-soil horizon, adding another 0.5m in depth. The soils consist of very fine dispersive clays which extend for at least another 150m upslope, providing an ample supply of fines with direct connectivity to Cotter Dam The figure in the bottom right displays evidence of feral animal browsing, possibly pigs. Any facilitated revegetation that accompanies gully stabilisation works at this site will need to take into consideration feral animal management.	 *Site MZ4b: looking upstream at head cut within drainage depression*

Priority management zone 4 – Cotter Dam sub-catchment		
	 *Site MZ4b secondary incision working through sub soil*	 *Site MZ4b Evidence of feral animal disturbance – possibly feral pigs*

<table>
<tr><td colspan="3">Priority management zone 5 – Condor Creek sub-catchment</td></tr>
<tr><td colspan="3">Longitudinal gully development along Condor Creek tributary (E668549, N6089787 GDA94Z55)</td></tr>
<tr><td colspan="3">Condition assessment</td></tr>
<tr><td>Site MZ5</td><td>Longitudinal gully development along unnamed tributary of Condor Creek along Brindabella Rd. Located east of the Wombat Creek confluence.

While this site is classified as a gully according to pre-existing gully activity mapping, the field inspection revealed that is more akin to a heavily scoured, bedrock-controlled drainage pathway. Recent flows appear to have contributed to large fluvial scours into the exposed, near vertical stream banks, as shown in the figures to the right and bottom right.

Considering the presence of bedrock, steepness and accessibility of the terrain, immediate remediation works at this site are not a priority. However, given the presence of other ’active’ gullies within the same management zone, it would be beneficial as a priority action to assess these as well in order to determine where and if erosion stabilisation structures would be most cost effective. It is likely that the most effective measure would be stabilisation of the head cut through a rock chute, if the head cut is still progressing upstream and incision is bedrock controlled.

If all mapped active gullies in this management zone are similar in the sense that that bear a narrow gauge, are bedrock controlled and are well vegetated then any intervention is likely to lead to more sediment loss than what is already occurring. In terms of fine sediment control, the only other option then would be to treat the symptom rather than the cause, which would be the construction of wetlands further downstream, however given the confined nature of the channel downstream to the dam, there remains little opportunity for such an installation.</td><td>
Site MZ5 looking upstream. Significant fluvial scour to bedrock</td></tr>
</table>

Priority management zone 5 – Condor Creek sub-catchment

Site MZ5 looking upstream. Narrow gully with significant bedrock control

Site MZ5. Fluvial scour contributing to widening of the channel

Priority management zone 5 – Lees Creek sub-catchment		
Stream bank erosion along lower section of Lees Creek (E668549, N6089787 GDA94Z55)		
Condition assessment		
Site MZ6	Site MZ6 consists of minor stream bank erosion along lower section of Lees Creek before Condor Creek confluence. As shown the figure to the right, minor sections of the existing streambank stabilisation works have been washed out by recent high flows. Toe stabilisation and facilitated revegetation of damaged areas can assist in consolidating the riparian zone and minimising the possibility of flows outflanking of existing works.	 *Site MZ6: Looking upstream Lees Creek, with washed out rehabilitation works in foreground*

Priority management zone 7 – Lees Creek sub-catchment		
Longitudinal gully development along Condor Creek tributary (E668549, N6089787 GDA94Z55)		
Condition assessment		
Site MZ7	Site MZ7 consists of two mapped 'active gully' systems. Aerial imagery (as shown in the bottom right figure) and on ground observations (Figures to the right and bottom left were taken downstream) suggest that the most active gully in this subcatchment occurs along a disused trail adjacent to a tributary of Lees Creek. While some roll over banks have been put in place to direct flows into the original tributary channel, the dispersive nature of the exposed subsoil coupled with poor vegetation establishment appears to have led to bank failure and rill erosion An inspection of all active gully systems (Cell IDs: 51136 and 47854) would be able to determine where the most cost-effective gully stabilisation measures may be installed.	 *Site MZ4a looking downstream along gully obscured by blackberry*

Priority management zone 7 – Lees Creek sub-catchment		
	 *Site MZ7. Rill erosion along the disused track downstream of the shown in the image to the right.*	 *Site MZ7. Aerial imagery of gully development along disused trail*

8 Management options

Management options are provided in Section 8.3 based on the typical approaches to Riparian and Gully management outlined in the Sections 8.1 and 8.2, respectively.

8.1 Riparian management

The riparian zone can be defined as the land that adjoins, directly influences or is influenced by a river or stream. By properly managing the riparian zone, and in particular riparian vegetation, we can see an increase in the geomorphic stability of the channel, which results in reductions in sediment runoff and improvements in water quality. Riparian vegetation also has a range of other ecological benefits to both aquatic and terrestrial communities.

Riparian vegetation plays an important role in minimising the rates of erosion in each of the three primary erosion categories: mass failure, fluvial scour and subaerial preparation. However, for each category, different types of vegetation influence the processes differently. Furthermore, as highlighted by Abernethy and Rutherfurd (1998), the means by which different types of vegetation influence erosional channel change is also dependant on their location within the catchment. A summary of how different vegetation types limit each of the three erosion categories are given in Table 8.

Table 8. Vegetation and its influence on the three erosional processes (adapted from Abernethy and Rutherfurd, 1998)

Erosion process	Vegetation interaction
Mass failure	Root reinforcement – Riparian trees strengthen bank substrate and tend to resist mass failure. The extent of reinforcement is dependent on root strength and the density of the root structure. The effect of the roots is to increase the effective cohesion of the sediments. The longer and more extensive the root network the greater the degree of reinforcement. As a result, smaller shrubs and grasses are less effective at limiting mass failure. (Abernethy and Rutherfurd 2000) Bank moisture – Saturated banks are less stable than unsaturated banks as water increases the weight of the bank, encouraging mass failure. All vegetation types decrease the level of bank saturation by intercepting precipitation and by transpiration (Abernethy and Rutherfurd 2000)
Fluvial scour	Resistance of bank material – Vegetation on the bank increases cohesion and bank strength through the root networks. Smaller shrubs and grasses, which have limited impact on mass failure processes, are more effective at limiting the ability of bank sediments to be entrained due to their more extensive coverage of the bank surface area (Blackham 2006). Near bank velocities – Vegetation increases hydraulic roughness, which reduces near bank velocities. The shear force exerted against the bank is thus reduced. The impact of vegetation on hydraulic roughness is complex and varies with type of vegetation and discharge. At low flow, grasses and shrubs that stand rigid have a high wetted surface area and provide hydraulic resistance (Blackham 2006). As discharge increases, the herbaceous vegetation often cannot withstand the force and is flattened against the bank. Hydraulic resistance is reduced but the vegetation protects the bank substrate from erosion (Abernethy and Rutherfurd 1999). Large trees provide minimal resistance during low flow but as discharge increases their large trunks and branches provide the majority of the resistance once the herbaceous vegetation has been flattened.
Sub-aerial preparation	Piping – Seepage of water can lead to leeching and softening of the bank material making the bank more susceptible to mass failure. Vegetation can reduce the onset of saturated flow through evapotranspiration. However, cavities from decomposed roots can encourage subsurface flow. The risk of this can be reduced with an appropriate suite of riparian vegetation. Desiccation – Dry and cracking banks are more susceptible to mass failure. Vegetation can reduce desiccation by binding the substrate together. (Wynn and Mostaghimi 2006).

Importantly, for these different forms of erosion, vegetation plays two critical roles in limiting channel change:

1. Hydraulic (frictional) resistance: According to Anderson and Rutherfurd (2003), riparian vegetation adds additional resistance elements in the main channel and on the floodplain of waterways such that flow velocity and conveyance are reduced. As a result:
    - In-channel stream power is lower in vegetated reaches compared to systems with bare banks
    - Near bank stream velocity is lower in vegetated reaches compared to systems with bare banks, and
    - Flood wave speed is also reduced through vegetated channel networks.
2. Structural protection to the stream bank: The vegetation provides structural reinforcement to the bank material increasing the cohesive properties of the soil.

A single vegetation type will generally not limit erosion and downstream flood wave speed; a suite of vegetation types is required. This suite of vegetation includes instream vegetation, stream bank ground covers, shrub species and trees. This suite of vegetation is typical of south eastern Australia's remnant native riparian vegetation.

The establishment of high quality, structurally diverse riparian vegetation across the identified priority management zones can achieve, or assist in achieving, the management objective of reducing sediment inputs into the Cotter Reservoir by:

1. Increasing the erosion resistance of channel bed, banks and floodplain
2. Increasing the hydraulic roughness of the channel which will reduce the sediment transport capacity
3. Stabilising instream and floodplain sediment deposits through root reinforcement
4. Trapping lateral inflows of sediment and nutrients from adjacent floodplains

It should be noted that riparian vegetation will take time to reach a level of maturity, structural diversity and robustness that allows it to perform the desired functions outlined above. The change in the function provided by vegetation through time is referred to as its trajectory of change, or trajectory, and is illustrated conceptually below in Figure 18.

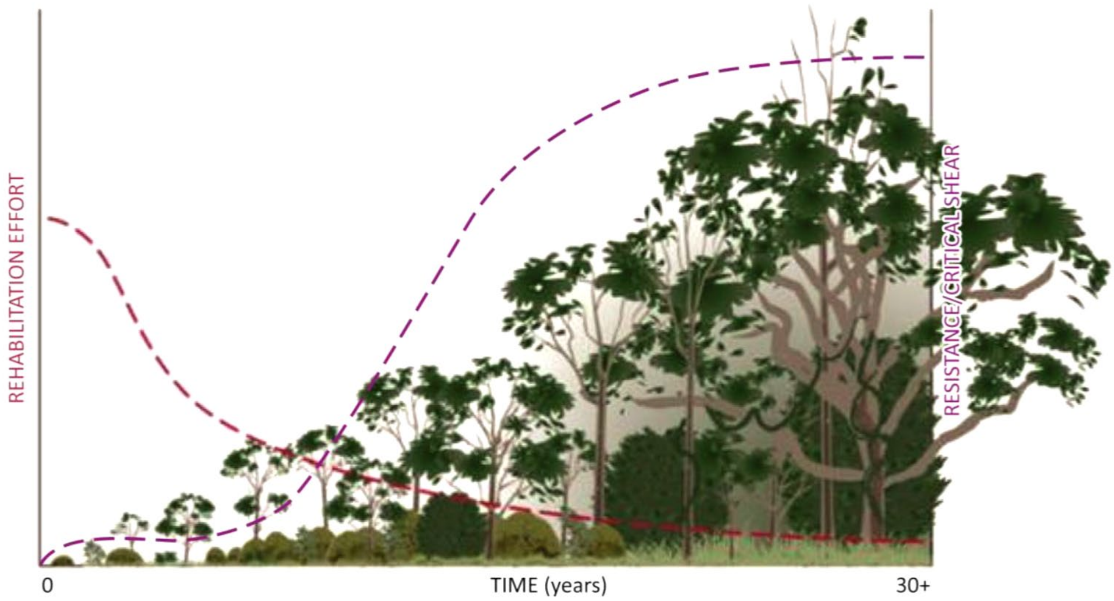

Figure 16 *Progressive long-term improvement in river health and erosion resistance with gradual reduction in rehabilitation effort (source: Department of Sustainability and Environment (2004)). This is the trajectory concept.*

Large lengths of stream bank within the priority management zones are currently steep with exposed erodible soil deposits.[2] These banks are highly vulnerable to fluvial scour and mass failure processes. Riparian vegetation will provide root reinforcement and protection against fluvial scour. The establishment of riparian vegetation will significantly reduce rates of bank retreat and assist in maintaining the current channel alignment during future flood events. The reduction in lateral adjustment will significantly reduce the amount of sediments being transported into the Cotter Reservoir as well as reduce the impact of adjacent land uses.

The improved management of riparian areas by assisted vegetation establishment throughout priority management zones will reduce sediment loads. While the LCC is already progressing along a restoration trajectory as guided by the 2018 LCC Reserve Management Plan, pine wildling competition, macropod grazing, hard hooved feral species in open areas and drying climatic conditions are likely to continue to threaten the development of structurally diverse native riparian vegetation within these zones.

8.2 Gully management

Gullies often result from degradation of riparian vegetation due to land clearing, grazing and drought-flood-fire cycles. A gully can be initiated when a steep/vertical wall develops at a track (i.e. wheel, stock or fence line grader track), within a drainage line, or where soil erosion resistance is reduced due to seepage (during and after rainfall) [21]. The gully then propagates upslope due to the unstable near-vertical wall.

Gully erosion is largely driven by three interacting processes (i) upslope surface runoff or seepage, (ii) direct rainfall, and (iii) fluvial scour within the gully. Gully erosion is generally most severe (i.e. extensive and rapid) in areas characterised by less-stable soil (e.g. sodosols) and low to moderate slopes adjacent to river channels [21].

Two primary gully morphological variants are the linear gully and dendritic gully. Linear gullies generally have an elongated planform morphology and are likely initiated by the formation of a preferential flow path and antecedent conditions (i.e. loss of vegetation, increases in flow and/or cattle/hard hooved impacts). The initial disturbance results in knickpoint development due to excess shear stress and channel deepening. The channel deepening results in an increase in channel capacity, and as a result stream power, which leads to further deepening and widening. The steep high banks are then prone to geotechnical failure which can lead to ongoing widening. Comparatively, dendritic gullies generally have an elongated branched planform and are likely initiated by overland flow due to either local runoff or return flow resulting from overbank flooding [22].

The three primary objectives of gully erosion control are to increase sediment trapping within the gully, reduce gully wall erosion, and reduce surface runoff and seepage into gullies. Improved vegetation cover reduces flow velocity (promoting sediment deposition) and provides erosion control functions. Gully erosion management interventions include fencing, reprofiling, revegetation, porous check dams, and gully head drop structures (i.e. rock chutes). The objective of each of these treatments is summarised below [21]:

- Hard hooved pest exclusion (fencing) promotes natural processes of revegetation (removing pressure from pest species such as deer and brumbies).
- Reprofiling of gullies to a more stable grade enables revegetation to re-establish. Soil amelioration should be undertaken along with reprofiling to stabilise dispersive and slaking sub-soils.
- Revegetation reduces runoff velocity by increasing surface roughness, increases gully wall stability through root reinforcement, and provides soil cover (resistance against erosion).
- Porous check dams reduce flow velocity and ameliorates soil condition within gullies by promoting deposition of fine sediment, nutrients and seed stock.
- Rock chute structures can prevent both continues upslope propagation of a head cut and secondary incision of a gully bed.

[2] based on desktop assessment

8.3 Recommended management

Management options for the priority management zones involve implementing one or more of the following actions:

- Revegetation works
- Bank battering and / or toe protection on more severe erosion sites
- Gully remediation by reshaping and sediment control structures

A range of management options have already been exercised within the Cotter River catchment in an attempt to remedy issues pertaining to water quality since the 2003 bushfires. Evaluation of these efforts by the Commissioner for Sustainability and the Environment in 2018 outlined the need to fund such activities into the future to ensure long term water security.

As such, the following management approaches are recommended in line with high priority management actions 7, 8 and 19 in the Lower Cotter Catchment Reserve Management Plan. Three options for riparian and gully management of varying cost have been developed and their effect on risk within each priority management zone analysed, this assessment is subject to confirmation through site assessment.

Option 1

Option 1 involves facilitated revegetation and feral species exclusion where necessary. Feral pest exclusion can involve any number of methods for keeping hard hooved feral species within an approximate riparian buffer zone. While at times possibly unnecessary, riparian zones are likely to face extra grazing pressure during extended dry periods. Facilitated revegetation involves allowing vegetation to establish via natural means and is reliant on there being a good source of seedbank supply in the area. This option requires less effort and financial investment. However, the seedbank supply that is naturally available for facilitated revegetation is not guaranteed and therefore it is difficult to ascertain the effectiveness of this technique. It should also be noted that this option would also allow for continued erosion of unstable banks, and therefore release of sediments, until a stable equilibrium was reached.

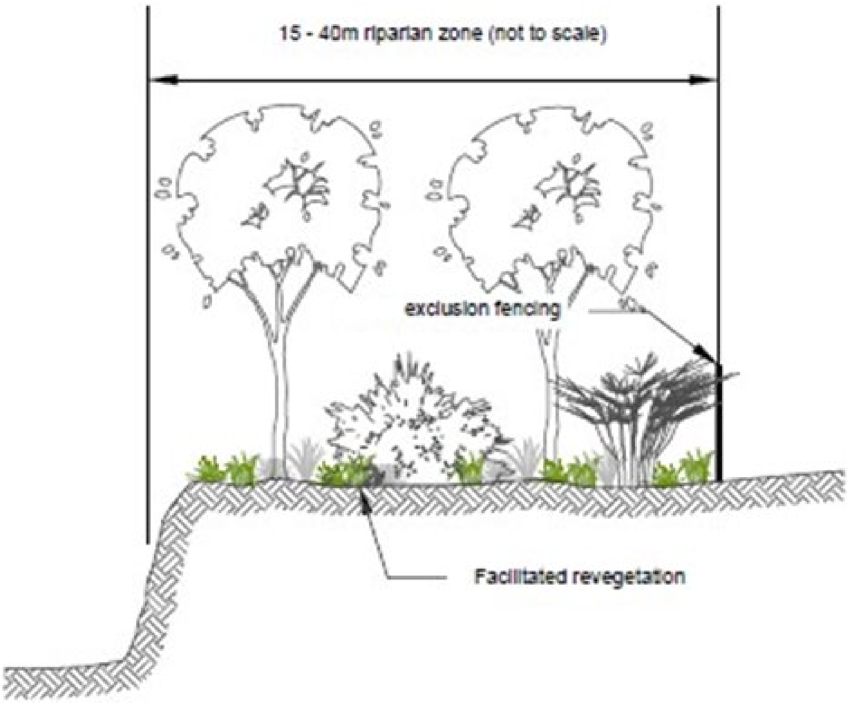

Figure 17. *Option 1 – feral species exclusion and facilitated revegetation*

Option 2
Option 2 involves isolated bank reprofiling, isolated toe protection and revegetation works. This option would also involve more intensive revegetation efforts to establish a robust riparian vegetation community. In areas that exhibit bank instabilities, direct bank stabilisation works would be implemented in the form of bank battering or toe protection (large wood, pile fields, rock beaching etc.). This option requires higher financial investment and higher ongoing maintenance requirements. However, by stabilising unstable banks directly and increasing the likelihood of riparian vegetation establishment, this option would have a much better chance of long-term success.

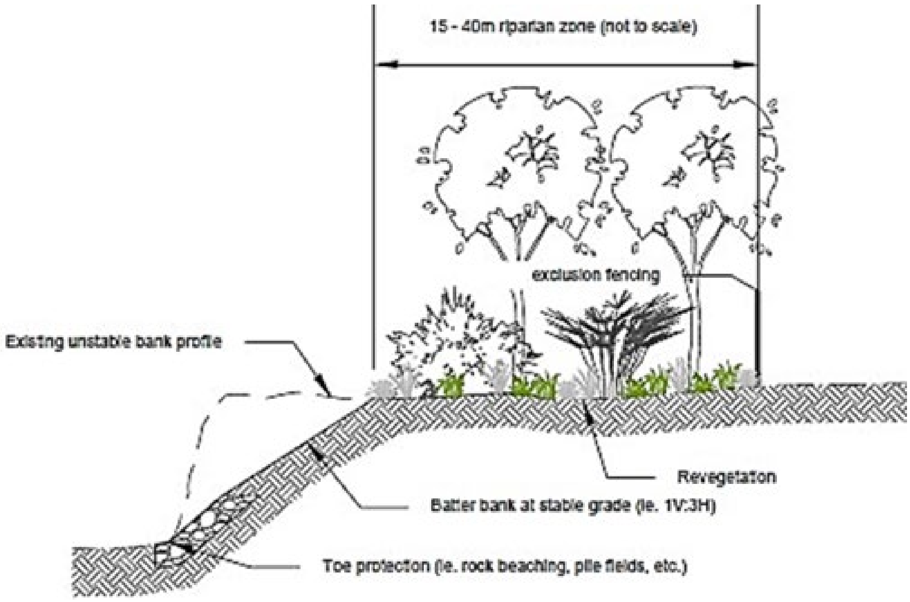

Figure 18. *Option 2 – Feral species exclusion, isolated bank reprofiling, isolated toe protection and revegetation works*

Option 3
Option 3 involves reshaping gully scarps, the installation of erosion control structures, revegetation works and exclusion fencing where necessary. This option involves earthworks to form a stable gradient across gully drainage pathways. While relatively cost intensive, the careful design of erosion control structures can meet the long-term hydrologic characteristics of the gully catchment and thus avoid over or under engineered solutions. Considering the extensive works already completed, transfer of the lessons learnt from these works will significantly increase the likelihood of long-term stabilisation and optimise the overall cost.

To assess the outcome that each of the three management options would have for each of the priority management zones, an adapted risk assessment was conducted. The revised risk ratings are shown below in Table 9.

Table 9. Adapted risk assessment for each of the priority management zones to consider management option effects

	Existing risk analysis			Option 1 risk analysis		Option 2 risk analysis		Option 3 risk analysis	
Priority management zone	*Likelihood*	*Consequence*	*Risk*	*Revised likelihood*	*Risk*	*Revised likelihood*	*Risk*	*Revised likelihood*	*Risk*
1 – Extensive gully development along a tributary to the west of Pierces Creek, primarily adjacent to Pipeline Rd.	Almost certain	Major	Extreme	Almost certain	Extreme	Likely	Extreme	Unlikely	High
2 – Extensive gully development to the east of Pierces Creek within former pine plantation	Almost certain	Major	Extreme	Almost certain	Extreme	Likely	Extreme	Unlikely	Moderate
3 – Gully development along old trail, east of Pierces Creek	Moderate	Moderate	Moderate	Unlikely	Low	Rare	Low	Rare	Low
4a – Gully development along tributary flowing directly into Cotter Dam	Almost Certain	Major	Extreme	Likely	Extreme	Moderate	Very high	Unlikely	Moderate
4b – Gully development along tributary flowing directly into Cotter Dam	Likely	Moderate	Moderate	Moderate	Moderate	Unlikely	Moderate	Rare	Low
5 – Longitudinal gully development along unnamed tributary of Condor Creek	Moderate	Moderate	Moderate	Moderate	Moderate	Unlikely	Moderate	Rare	Low
6 - Stream bank erosion along lower section of Lees Creek before Condor Creek confluence	Unlikely	Moderate	Low	Rare	Low	Rare	Low	Rare	Low
7 - Active gully development 700m northwest of the Warks Rd crossing of Lees Creek	Moderate	Major	Very High	Moderate	Very High	Moderate	Very High	Unlikely	Moderate

9 Recommended management actions

The Cotter ACWA Plan represents an opportunity for the natural resource managers of the Cotter Catchment to work together, consolidating and building upon the existing studies and initiatives to improve the supply of clean water to Canberrans.

Implementation of the actions outlined in this plan will require strong leadership, appropriate resources and collaboration between the land and water managers and various stakeholders including the community.

The dominant theme that came through the stakeholder workshop was that the Lower Cotter Catchment is undoubtedly the highest priority for improving water quality, which also came out in the spatial risk assessments. There was also a strong willingness from the land managers to do the work required to achieve the long-term vision of a restored Cotter catchment that is completely National Park. The capacity to implement the actions outlined here, and in the plans referenced throughout this study, will be an ongoing issue. The exact timing of the implementation of these actions will depend on the availability of necessary funding.

The recommended actions detailed below are grouped into on-ground management actions and strategic management actions, including community engagement, incentives and policy changes. The on-ground management actions have been assigned a priority of short-, medium- or long-term. A short-term action should be undertaken as soon as resources allow, while medium-term (in the next 5 years) and long-term priorities (in the next 5-20 years) are not as urgent.

It should be noted that from the field inspection it became obvious that gully 'activity' is variable across the catchment. While not all 'active' cells were assessed during the field inspection, it is thoroughly recommended that follow up monitoring of all active cells within the priority subcatchment be undertaken to ensure judicious investment in stabilisation works.

On-ground management actions

Action no.	Action	Priority
1	Implement rehabilitation of the high priority Pierces Creek subcatchment. Implement the specified management actions at priority management zones including: MZ1 – A detailed assessment of all active gullies to inform the placement, design and construction of gully reshaping, large scale stepped rock chutes and other erosion control structures (such as reno matts) to stabilise head-cuts which pose a significant threat to existing stabilisation works and water quality in general (Cell ID 70916). The assessment will need to especially consider: the amelioration of sodic soils, geofabric efficacy, collapsing all existing tunnel erosion, rock chute stabilisation of incised contour banks along adjacent hillslopes, reno matt placement where possible to reduce overall costs and the reshaping existing road drains to avoid flows outflanking existing and future stabilisation structures. MZ2 – A detailed assessment of all active gullies to inform the design and construction of a series of large-scale stepped rock chutes with facilitated vegetation (Cell ID: 73129). MZ3 – Isolated grade control/bank reprofiling at head-cuts and facilitated revegetation. More thorough field assessment of mapped active gully to determine if further works necessary (Cell ID:71980)	Short term
2	Implement rehabilitation of the high priority Cotter Dam subcatchment. Implement the specified management actions at priority management zones including: MZ4a – Design and construction of keyed in erosion control structures to stabilise head-cut. Facilitated revegetation and pest exclusion (Cell ID 69789). MZ4b – Monitor gully development. Current blackberry coverage inhibits adequate understanding of gully system. If gully is active, construction of keyed in erosion control	Short term

	structures to stabilise head-cut in conjunction with facilitated revegetation and pest exclusion (Cell ID 71426). More thorough field assessment of mapped active gully to determine if further works necessary (Cell ID: 77487 and 81318)	
3	Implement rehabilitation of the high priority Condor Creek subcatchment. Implement the specified management actions at priority management zones including: MZ5 – Inspect all active gully systems to the top of their catchment (Cell ID: 48911 and 49463) to determine where (if possible at all) the most cost-effective bank or grade stabilisation structures may be installed. MZ6 – Facilitate to protection and revegetation of damaged bank stabilisation works near confluence.	Short term
4	Implement rehabilitation of the high priority Lees Creek subcatchment Implement the specified management actions at priority management zones including: MZ7 – Inspect all active gully systems (Cell ID: 51136 and 47854) to determine where the most cost-effective gully stabilisation measures may be installed.	Short-term

Strategic management actions

Action no.	Action	Priority
5	Coordinate the community engagement for the whole Cotter Catchment, building upon the recommendation 60 in the LCC Reserve Management Plan 2018. *60. Develop and implement education and communication strategies to improve.* *community knowledge about the values of the LCC, appropriate use, and the* *importance of access restrictions in protecting water quality.*	Medium-term
6	Coordinate the engagement with Aboriginal groups and explore opportunities for co-management of land across the whole Cotter catchment in line with implementation of recommendations 61 and 63 in the LCC Reserve Management Plan 2018. *61. Continue to support community involvement and input from Aboriginal groups in revegetation and other environmental improvement activities.* *63. Enhance partnerships with Aboriginal groups in managing the reserve.*	Medium-term
7	Work to enhance the partnerships and data sharing arrangements between the land and water managers in the catchment including Icon Water, ACT Government Parks and Conservation Service and NSW National Parks and Wildlife Service (building upon the recommendation 64 in the LCC Reserve Management Plan 2018). *64. Enhance partnerships with neighbours in managing reserve boundaries.*	Medium-term
8	Develop a coordinated approach to addressing the risks posed by hard-hooved animals including brumbies, deer and pigs in the catchment. Continually monitor the impact of potential overgrazing by Macropods	Medium-term
9	Continue to implement the Lower Cotter Catchment Road Network Improvement Plan to minimise the number of surplus unsealed roads that are a contributing factor to poor water quality.	Medium-term
10	Continue to implement the recommendations in the Lower Cotter Catchment Reserve Management Plan 2018.	Various
11	Continue to implement the five recommendations from the Commissioner for Sustainability and the Environment's Lower Cotter Catchment Restoration Evaluation Report. *Recommendation 1: monitoring and evaluation implementation* *Recommendation 2: funding and resources commitment* *Recommendation 3: governance improvements* *Recommendation 4: coordination of efforts* *Recommendation 5: legislative interventions*	Various

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Appendix A -
Additional information on hillslope erosion assessment

Hillslope sediment generation and delivery

Sediment generation, transport and delivery within a catchment is influenced by many factors including local climate, topography, soil type, vegetation cover and management interventions. By understanding the processes and their interactions both qualitative and quantitative methods can be used to estimate where sediment is being generated within a catchment, and its potential for reaching catchment outlets.

The NSW government data portal provides spatial layers for NSW which can be used to estimate hillslope sediment generation across both the state and ACT at a spatial resolution of 90m grid size. Through a review of the process used to generate the Government's spatial layers, this project explored options for improving quantification of hillslope sediment generation across the Cotter Catchment.

This study has focussed on developing a spatial distribution of risk of hillslope sediment generation and the likelihood of any mobilised sediment reaching waterways, and ultimately being discharged at catchment outlets. An estimate of sediment loads has been calculated, noting the limitations of current methods to estimate sediment generation and delivery.

Assessment of sediment generation

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:

$$A = RKLSCP$$

Where:

- A is the annual average soil loss per unit of area (ton 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
- P is the erosion control practice factor.

The equation helps determine where within a catchment hillslope sediment generation is likely to occur.

Methods to calculate each of the RUSLE factors across the Cotter Catchment are shown in Table 10 and discussed in detail below. There is some uncertainty in the RUSLE factors, particularly the site-specific nature of soil erodibility and erosion control practice. Therefore, without a rigorous field validation of these conditions the results should be used with some caution.

Table 10. *RUSLE parameters used in the Cotter Hillslope erosion assessment*

Factor	Method
Rainfall erosivity (R)	State layer re sampled to 5m
Soil erodibility (K)	State layer re-sampled to 5m
Slope length (L)	LS layer generated from a compiled 5m DEM

Slope steepness (S)	
Cover management (C)	State layer re-sampled to 5m
Erosion control practice (P)	1 (assuming no erosion control)

Rainfall erosivity (R)
Rainfall erosivity is defined as the mean annual sum of individual storm rainfall intensity (EI_{30}) values, where EI_{30} is the total storm energy (E) multiplied by the maximum 30-minute rainfall intensity (I_{30}). Continuous rainfall intensity data, such as pluviograph data, for at least 20 years (Wischmeier and Smith 1978) is required to compute EI_{30}. Given the limited spatial extent of pluviograph data over 20-year periods in NSW, several studies have demonstrated the suitability of using daily rainfall to estimate storm erosivity.

$$\hat{E}_j = \alpha[1 + \eta \cos(2\pi f j - \omega)] \sum_{k=1}^{N} R_k^{\beta} \qquad when\ R_k > R_0$$

Where:

$\hat{E}_j$ is rainfall erosivity for the month j

R_k is the daily rainfall amount

R_0 is the threshold rainfall amount (12.7 mm)

ω is the phase parameter which accounts for seasonal variability ($\pi/6$)

f gives the fundamental frequency (1/12)

N is the number of rain days

j is the month (eg January $= 1$)

α , η and β are calibration factors with a recommended set of parameter values:

$\alpha = 0.395\left[1 + 0.0980 \exp\left(3.26\frac{S}{P}\right)\right], \beta - 1.49,\ \eta = 0.29$

(where *S* is mean summer rainfall (November-April) and *P* is the mean annual rainfall)

Monthly rainfall erosivity values were summed to give an annual time series of rainfall erosivity, and the average of these was taken to give the annual average rainfall erosivity, the R factor.

This study utilised the results from a previous study by Alluvium of the Googong catchment, approximately 30km to the East of Cotter. The Googong study applied the Yang & Yu (2015) method to both daily rainfall and SILO data from gauge stations close to the Googong catchment. The study found that the calculated values did not match the state layer given. Gauge and SILO calculations were on average 20% and 10% higher than the state layer respectively (Figure 21 and Figure 22). This difference in gauge values was to be expected given that the State layer is based on gridded SILO data, however the difference in SILO values is attributed to the fact that the SILO data set has been updated since the State R layer was created. As with the Googong study, it was concluded that no extra value would be provided by creating a localised rainfall erosivity grid. Therefore, the state R layer was resampled from 90m to 5m and used for the Cotter RUSLE calculation.

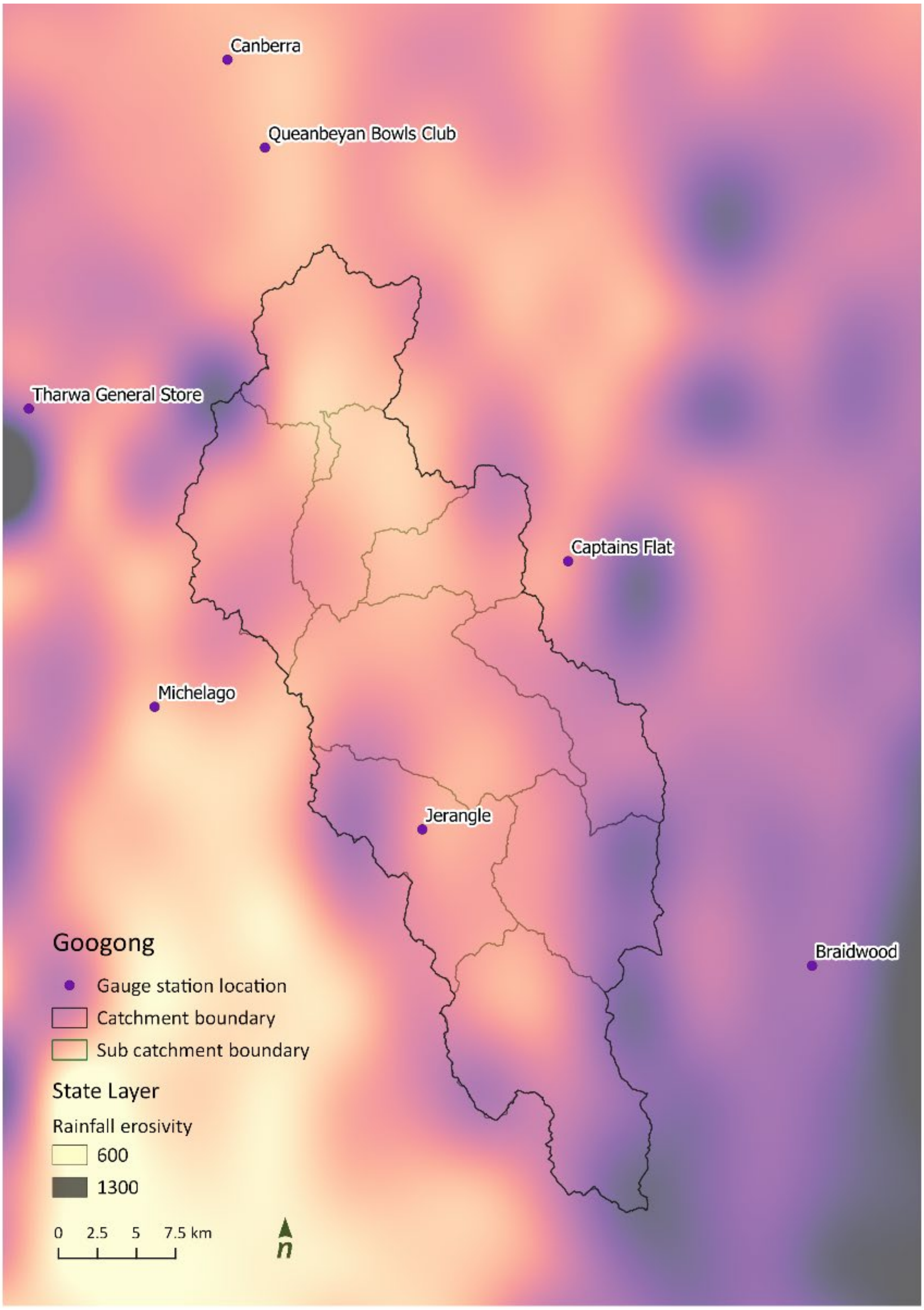

Figure 19. *Selected locations for R factor analysis*

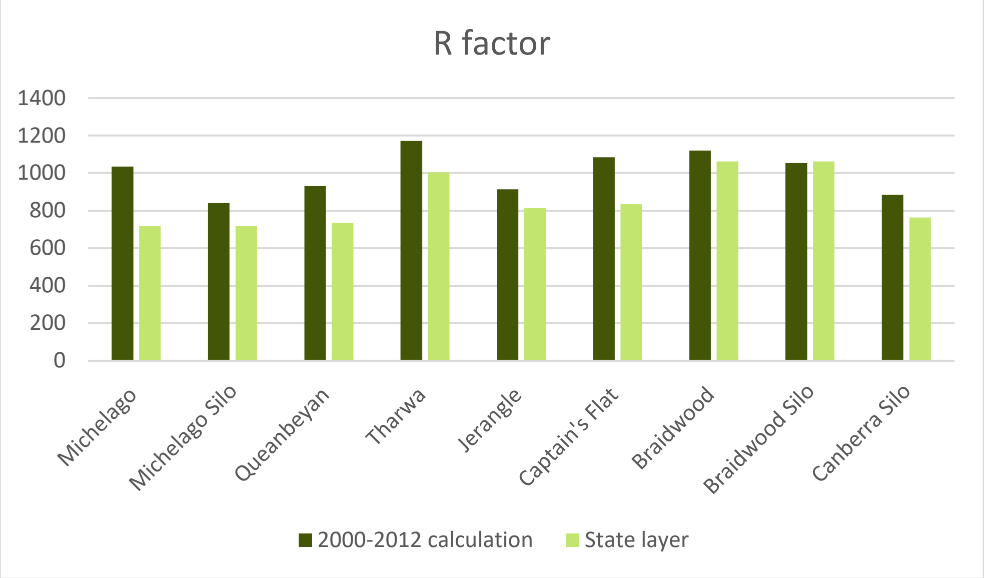

Figure 20. *Comparison of R calculation methods for selected locations*

Soil erodibility factor (K)
The K factor layer currently available on the NSW government data portal is calculated from recently compiled 90m resolution soil maps for a wide range of soil properties across NSW and ACT (Yang et al 2017). A desktop review of the K layer revealed a strong correlation between k values and existing catchment soils and geology. We therefore adopted the existing K factor layer as outlined above.

The distribution of the soil erodibility (K) factor across the Cotter Catchment as applied in the RUSLE calculations is shown below (Figure 23).

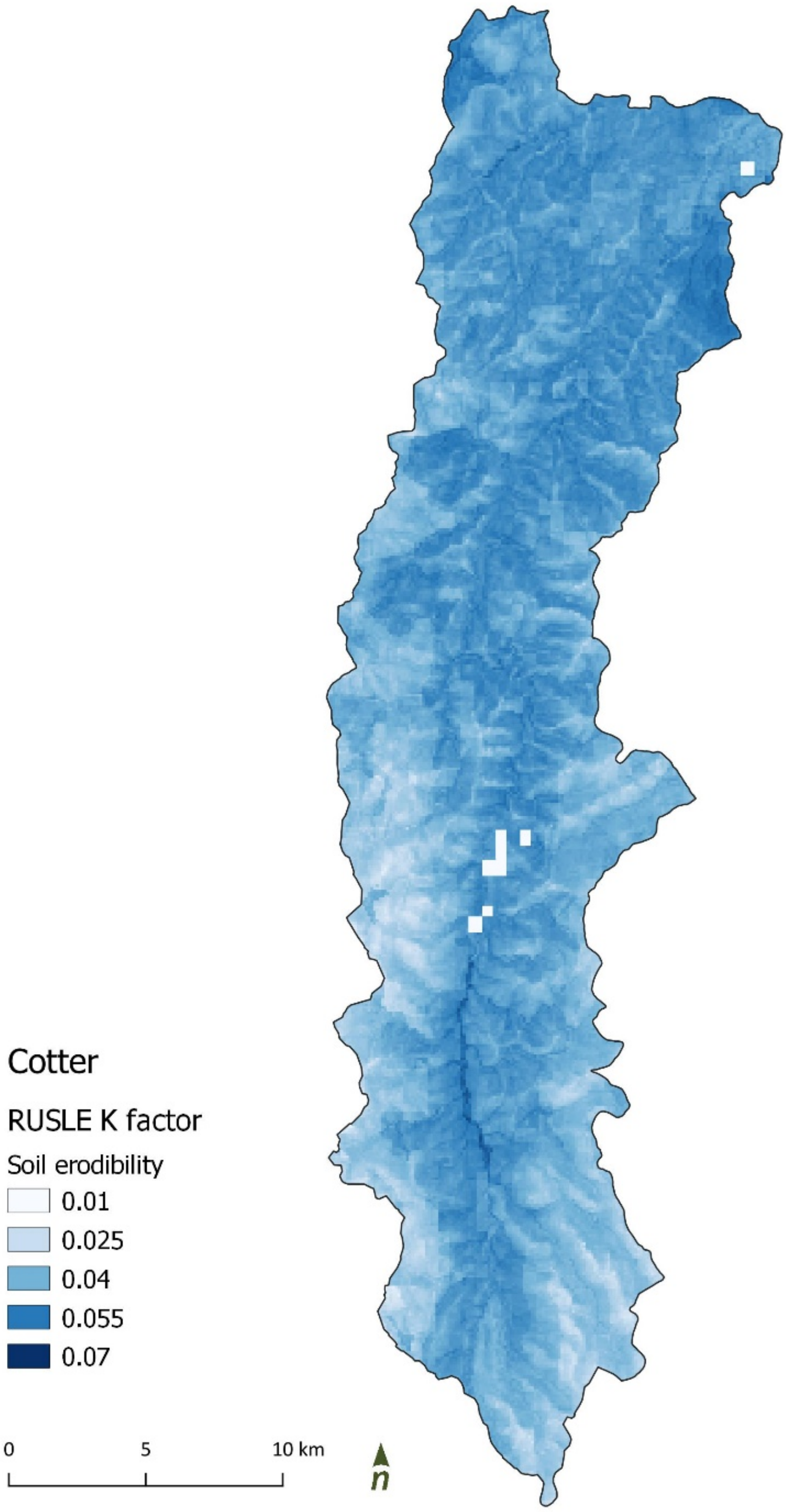

Figure 21. *Cotter Soil erodibility (K) factor, 90m resolution*

Slope length factor and slope steepness factor (LS)
The L factor (slope length) and S factor (steepness) are often combined as LS, representing the effect of topography on hillslope erosion rates (Yang 2017).

The L factor and S factor layers currently available on the NSW government data portal use smoothed 1 second (~30m) Shuttle Radar Topography Mission (SRTM) Derived Digital Elevation Model (DEM) to calculate the L factor and S factor separately, which can be multiplied to give the LS factor with a 90m grid (Yang 2017).

Various GIS based algorithms have been developed for calculating a combined LS factor using high resolution DEMs. The combined LS factor in RUSLE represents the ratio of soil loss on a given slope length and steepness to the soil loss from a unit slope that has a length of 22.13m and a steepness of 9%, where all other conditions are the same (Yang 2015).

1m and 2m resolution elevation data is available for most of the Cotter catchment. These datasets were used where available to create a 2m grid DEM for the entire catchment. The LS factor was calculated using the SAGA LS factor tool, which requires a layer of contributing area for each point in the grid, and a layer of slope. These layers were developed using TauDEM (Terrain Analysis Using Digital Elevation Models), a set of tools developed by Utah State University for the analysis of terrain using digital elevation models. The tools can be used as a plug-in to most mapping software. The calculated LS layer improves the cell resolution from the state layer to 5m.

The following steps were undertaken to develop the LS factor layer:

1. TauDEM: Pit removal of the 2m DEM to ensure hydraulic connectivity within the watershed
2. TauDEM: Computation of flow directions and slopes using the D8 method which selects which adjacent grid cell water will flow to for each cell in the grid
3. TauDEM: Contributing area using the D8 flow direction method
4. SAGA: LS factor tool in Terrain>Hydrology to convert slope and contributing area layers to the LS factor layer

The distribution of LS values for the whole of the Cotter catchment is shown below (Figure 24).

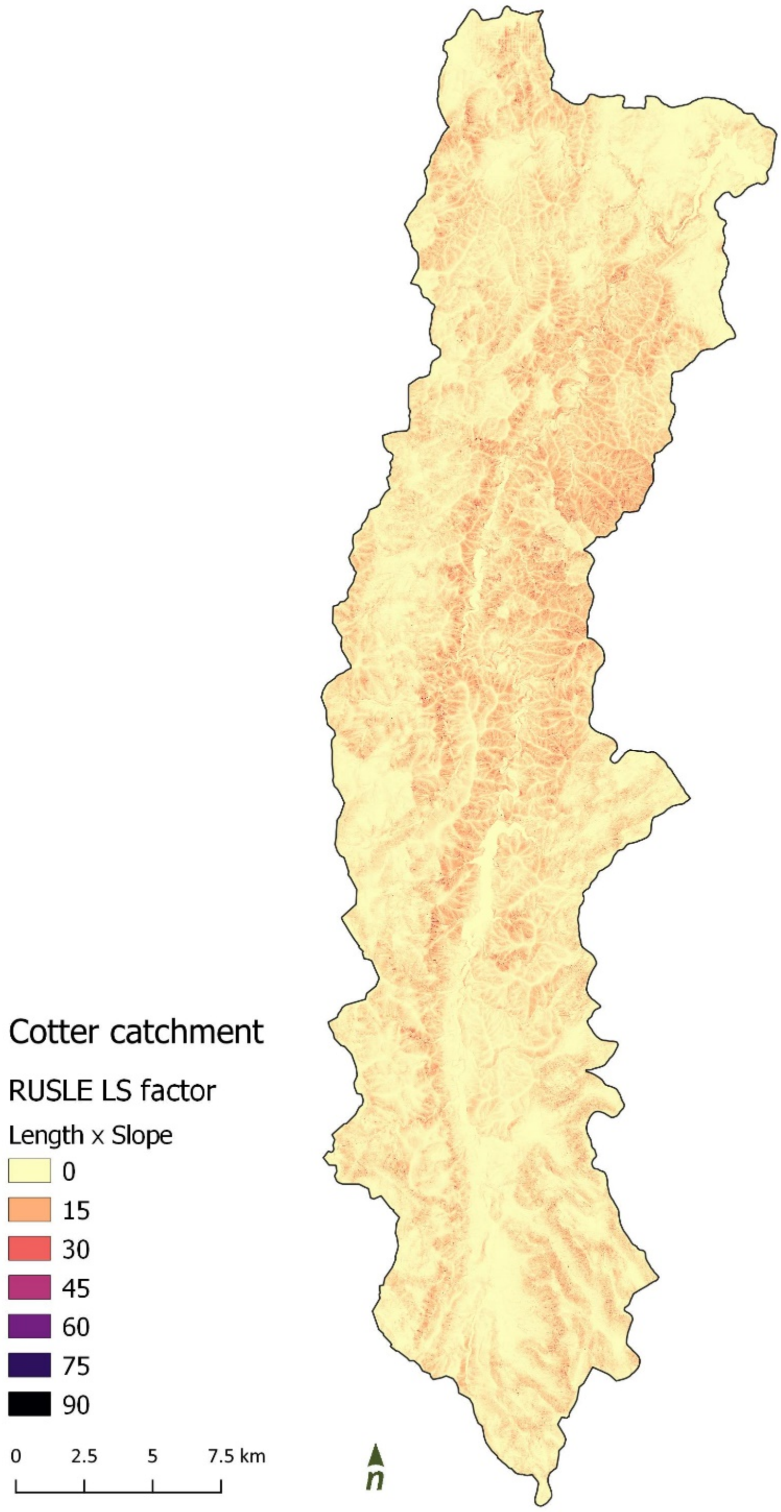

Figure 22. *Cotter Slope length (LS) factor, 5m resolution*

Cover management factor (C)
There are number of methods currently used to estimate the C factor based on ground cover estimates or land use layers. Previous studies have determined C factor values to be applied to various types of groundcover (URS 2009) (Table 11).The 2009 territory-wide RUSLE analysis provides a higher resolution representation of cover across the cotter catchment when compared to the NSW state-wide C factor layer. Considering this, the territory C layer was considered favourable for this analysis (Figure 25).

Table 11. *C factor values which were applied to each subformation category type across ACT* **[7]**

Vegetation Subformation	C factor
Wetlands	0.001
Wet forest	0.002
Upland montane forest	0.003
Montane woodland	0.013
Riparian Woodland	0.013
Subalpine Woodland	0.013
Grassland	0.042
Dry Forest	0.09
Plantation/Arboretum	0.09
Modified Grassland/ Urban vegetation complex	0.1
Table land woodland	0.1
Urban	0.01
Woodland	0.1
Dry heath shrubland complex	0.12
Former Pine Plantation Post 2003	0.14
Former Pine Plantation Pre 2003	0.14

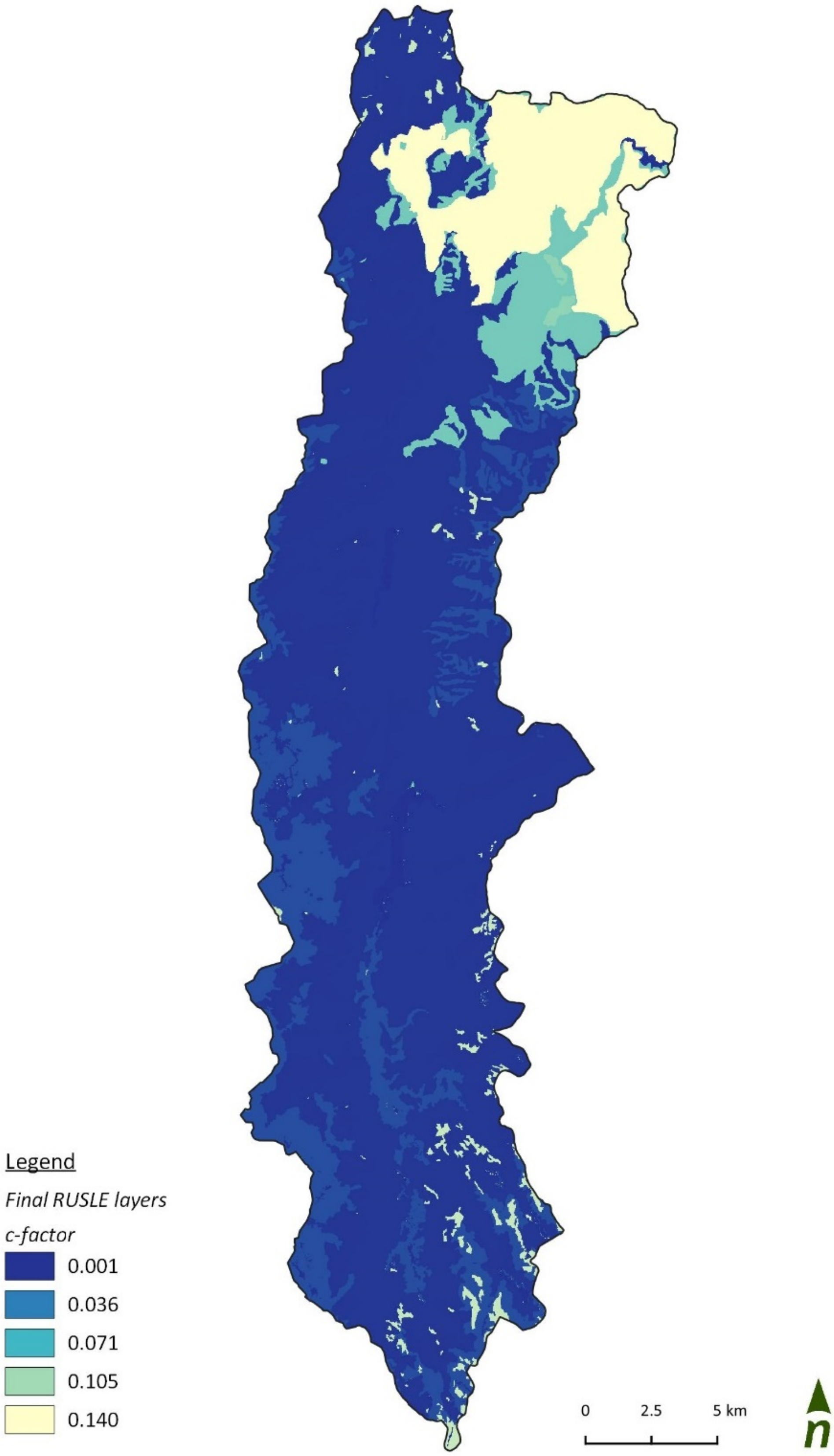

Figure 23. *Cotter Land cover (C) factor values as provided by URS (2009)*

Erosion control practice factor (P)
No adjustment has been applied to account for erosion control practices.

Assessment of sediment delivery ratio

Not all sediment generated from hillslope erosion processes will enter waterways, or discharge at catchment outlets.

In Fu et al (2010) an assessment of the delivery of sediments from unsealed roads in forested catchments showed that the distance of the source of sediment to the stream was a critical measure of delivery ratio. Based on this research and similar studies, it was assumed that for sediment generated within 10m, 30m and greater than 30m of a waterway, 100%, 35% and 10%, respectively, of generated sediment would enter the waterway.

Estimation of sediment loads from hillslope erosion

The analysis described above shows that there are various assumptions and multiple levels of uncertainty involved in the estimation of hillslope erosion generation and delivery rates. The following table provides an estimation of sediment loads from hillslope erosion for each Cotter subcatchment. These estimates provide an indication of the relative loads (see Table 12) and can be used in combination with the spatial layers which allow the identification of sites with potentially high risk of hillslope erosion.

Table 12. Summary of RUSLE derived sediment yield for the Cotter catchment

Catchment	Catchment area (ha)	% area Cotter	Mean sediment generation (t/ha/yr)	Mean sediment delivery (t/ha/yr)	Catchment yield (t/yr)	Delivered to waterway (t/yr)	Proportion of Cotter delivered
Bullock Head	8425	18%	9.23	1.86	77800	15600	31%
Pierces Creek	2281	5%	20.21	4.30	46100	9800	19%
Condor Creek	4709	10%	10.61	2.06	50000	9700	19%
Lees Creek	2560	5%	12.53	2.59	32100	6600	13%
Cotter Dam	1280	3%	9.18	1.69	11800	2200	4%
Cribbs Creek	7357	15%	1.15	0.18	8500	1300	3%
White Sands Creek	3558	7%	1.87	0.33	6700	1200	2%
Porcupine Creek	5076	11%	1.85	0.23	9400	1200	2%
Ginini Creek	3584	7%	1.18	0.22	4200	800	2%
Kangaroo Creek	4986	10%	0.88	0.16	4400	800	2%
Licking Hole Creek	2178	5%	3.16	0.37	6900	800	2%
Franklin Creek	1937	4%	1.01	0.20	2000	400	1%
Totals	**47931**				**259900**	**50400**	

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Appendix B - Factors affecting erosion

Erosion processes in alluvial rivers

Rivers that flow through unconsolidated sediments are known as alluvial rivers. These rivers are shaped by their flow regime, base level, sediment inputs and boundary strength. The boundary strength refers to the resistance of the bed and banks of the stream to scour and is controlled by the characteristics (size) of the bed and bank sediments and the riparian vegetation condition.

The erosion, transport and deposition of sediment in alluvial river systems has been the subject of much scientific research. The study of the interactions between the physical forms and sediment transport processes is known as fluvial geomorphology (geomorphology for convenience in this study).

The sediment processes are of particular interest to Icon Water. In particular, Icon Water are interested in reducing the sediment yield—the total amount of sediment and associated nutrients that are discharged into Cotter Reservoir.

Sediment yield

The amount of sediment delivered to the outlet (or any other location in a catchment) is controlled by the rate of erosion and by the rate of transport to the location. A catchment can be considered in three broad zones: sediment supply, sediment transport and sediment storage (Figure 26).

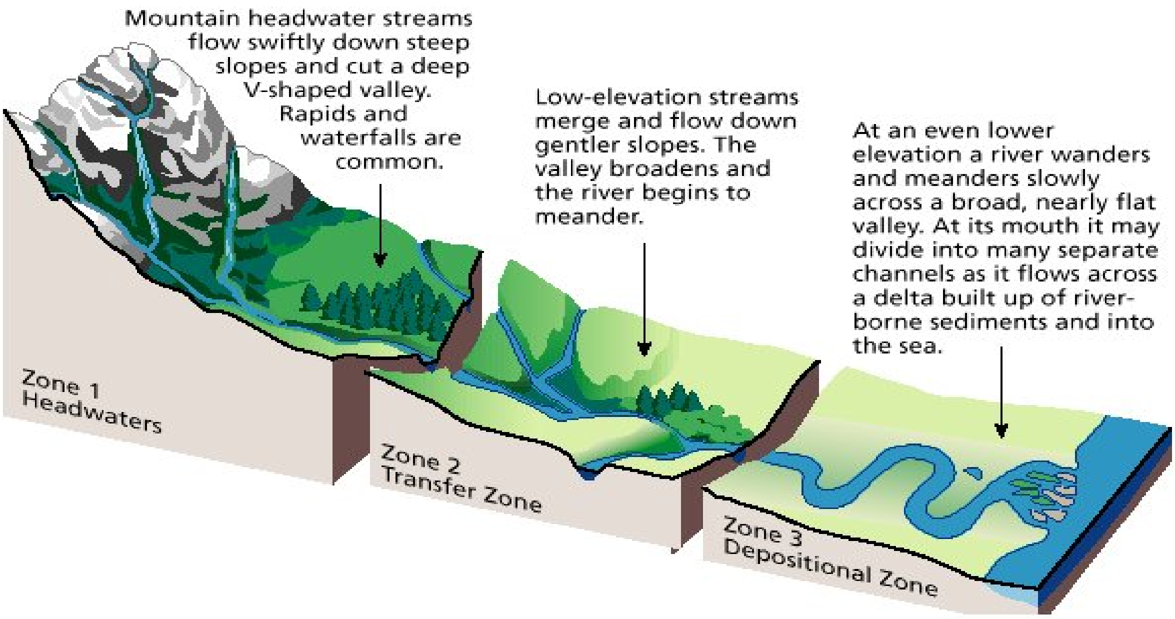


Figure 24. *Sediment zones in a typical catchment. Image reproduced from the Federal Stream Corridor Restoration Handbook (FISRWG, 1998)*

The sediment yield to a location in a catchment is a function of the rate of erosion from source area and transport to the location of interest. Sediment is generated by erosion of hillslopes and headwaters in the upper catchment and transferred downstream through the channel network.

The form of a channel is largely a function of the water and sediment supplied to it. Adjustments to channel form occur as a result of process feedbacks that exist between channel form, flow and sediment transport. At the reach-scale, the type of adjustment that can take place is constrained by the valley setting, the nature of bed and bank materials, and bank vegetation. This gives rise to a wide diversity of different channel forms.

Channel bed and bank erosion throughout the catchment contributes to the sediment entering a river system. The rate of channel erosion is controlled by factors including the flow regime (channel erosion can increase dramatically during floods), the supply of sediment to a reach, the size, shape and slope of the channel, and the strength of the bed and banks. Riparian vegetation influences a number of these factors. Tree root systems increase the strength of bank material, and above ground vegetative structures slow the flow of water and shield bank sediment from erosion. The valley width also constrains channel erosion by limiting the lateral extent of erosion.

The driving variables and boundary conditions that influence channel form and geomorphic processes are illustrated schematically (Figure 27).

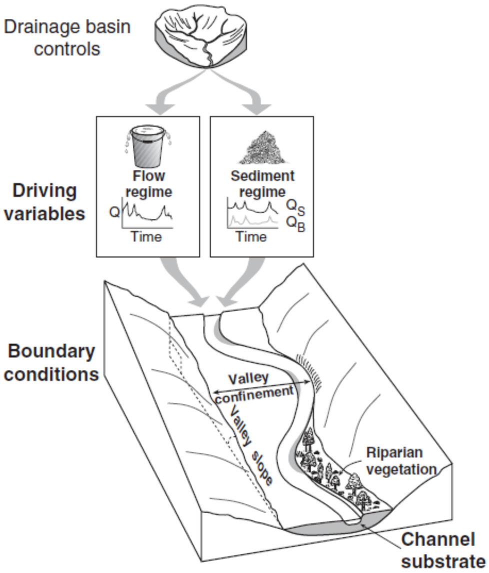


Figure 25. *Schematic representation of the factors influencing channel form and geomorphic process in alluvial rivers (reproduced from Charlton 2008)*

The rate at which sediment is transported through a river system is controlled by:

- The flow regime (more sediment is transported if there are a sequence of large flows than during a long drought)
- The energy (or stream power) in the system (a steep, powerful river will transport more sediment faster than a flat, slow flowing system, everything else being equal)
- The size of the sediment (fine sediment in suspension is transported more quickly than gravels or cobbles).

Only a small proportion of the sediment eroded typically leaves a catchment, because a significant volume of the sediment is stored in transient sediment sinks as it is deposited throughout the catchment. These sediment sinks include floodplain depressions, in-channel islands, bars and benches or floodplains (vegetation can help lock sediment into these sinks). Sediment can be released from storage when it is reworked at a later stage. An individual particle of sediment can be stored and remobilised many times as it is transported through a river system. Changes to land management practices (e.g. clearing of riparian and catchment vegetation) can significantly increase the proportion of sediment that leaves a catchment.

The geomorphic processes that drive sediment transport operate across different spatial scales, from drainage basin or catchment to individual particles of sediment. The relationship between different spatial scales can be considered schematically (Figure 28).

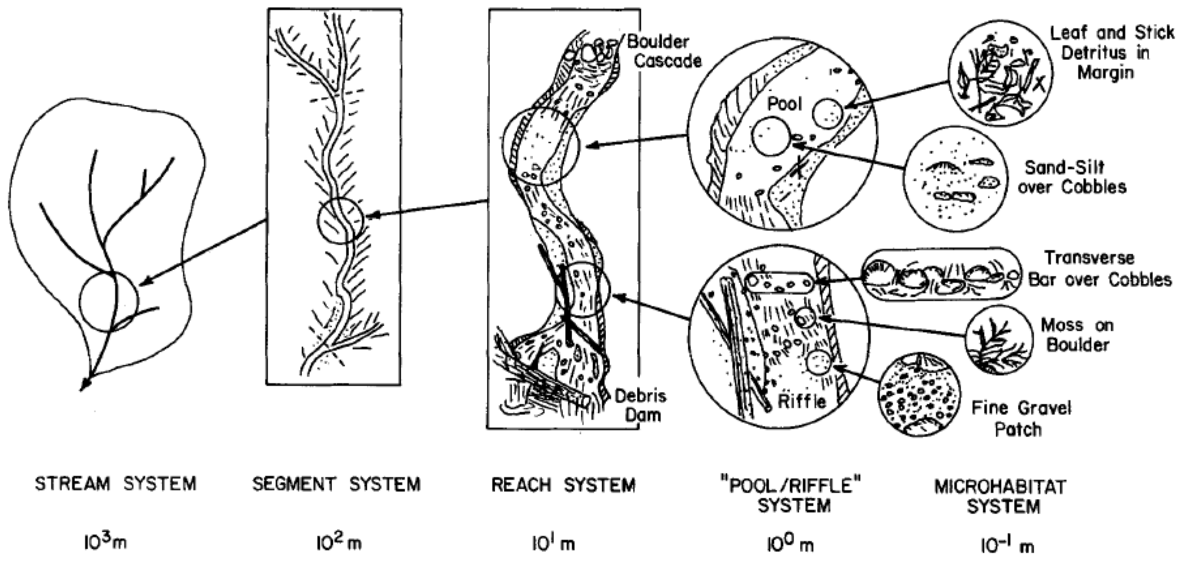


Figure 26. *Hierarchical organization of a spatial scales in a stream system (from Frissell et al 1986).*

Understanding sediment erosion and transport processes is critical to developing a management plan that will reduce sediment yield to a receiving environment. The spatial scales most relevant to managing sediment yield are catchment to reach-scale. A range of fluvial geomorphic processes operate across these scales (see boxes below). Understanding the location of these processes in a catchment, what's driving them, and their likely future magnitude is central to effectively reducing sediment yield.

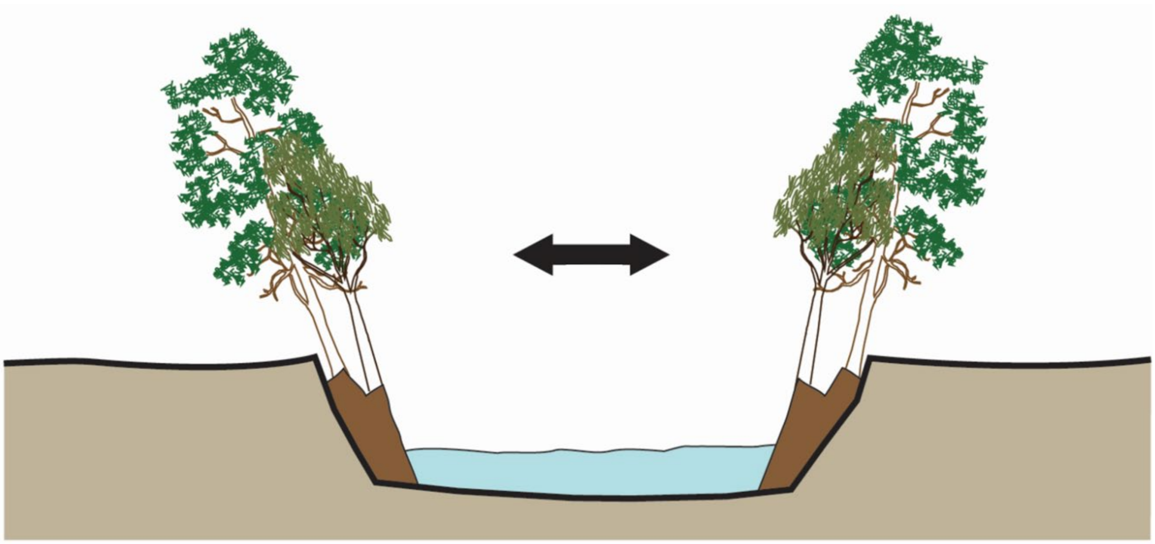
Bank erosion is a ubiquitous geomorphic process in alluvial channels. Bank erosion is important in the development of different channel forms, while the migration of channels across their floodplains involves a combination of bank erosion on one side and deposition on the other (which is often expressed through meander migration. Bank erosion can also create management problems when bridges, buildings, agricultural lands and roads are undermined or destroyed. Large volumes of sediment can be generated and made available for transport to downstream reaches.

Bank erosion is often caused by a number of different geomorphic processes that can operate separately or in combination, and can be considered in three groups:

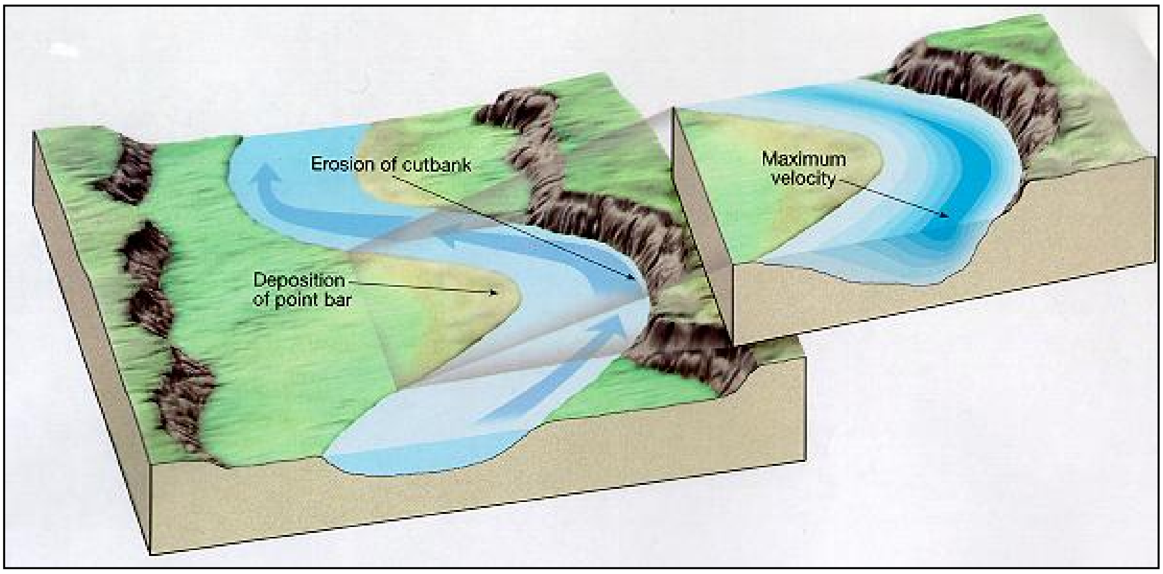
1. Pre-weakening processes such as repeated cycles of wetting and drying or cattle trampling of the substrate, which 'prepare' the bank for erosion.
2. Fluvial processes, where individual particles of sediment are directly entrained (mobilised) by flowing water.
3. Processes of mass failure, which include the collapse, slumping or sliding of bank material into the channel.

Bank erosion is an important contributor to geomorphic related management issues due to the amount of sediment it can release, and its direct impact on floodplain assets and property.

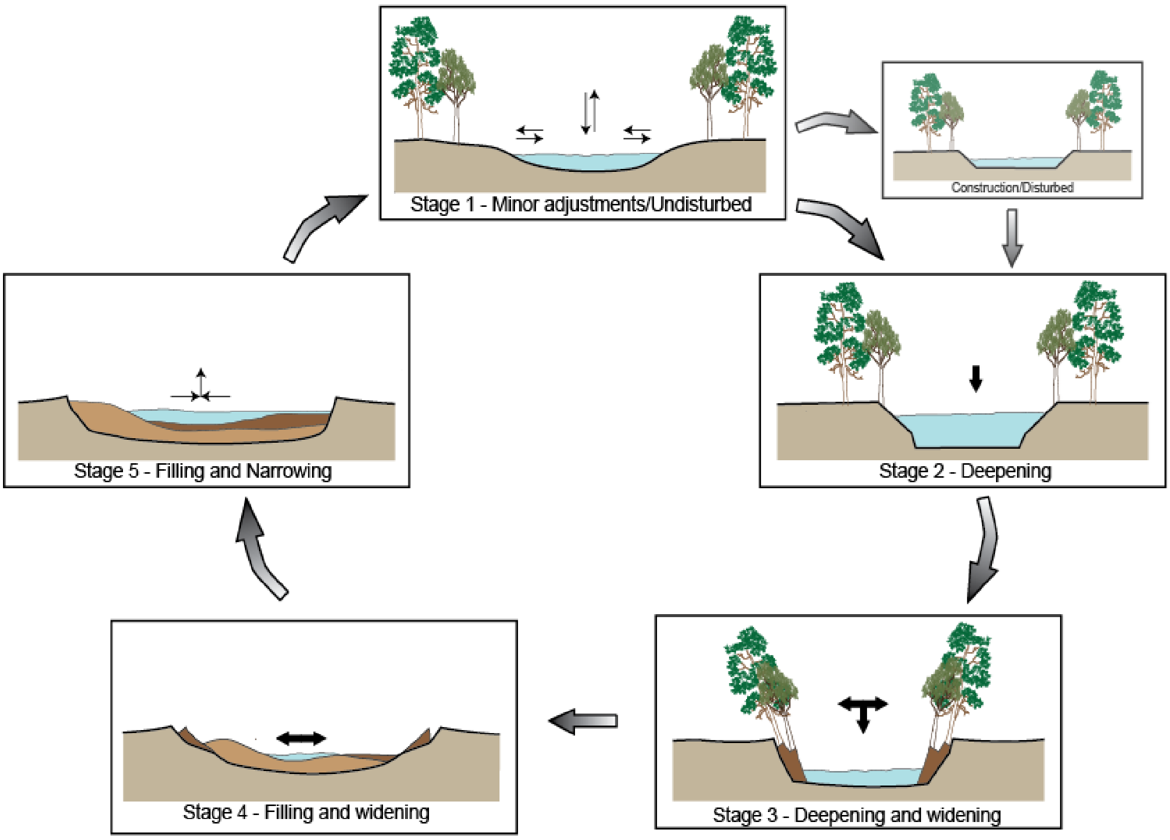
Channel widening occurs when riverbanks erode on both sides of a channel. Channel widening is often a symptom of a wider scale process, such as an increase in in-channel flow, arising from river regulation, channelisation, deforestation urbanisation or channel incision.



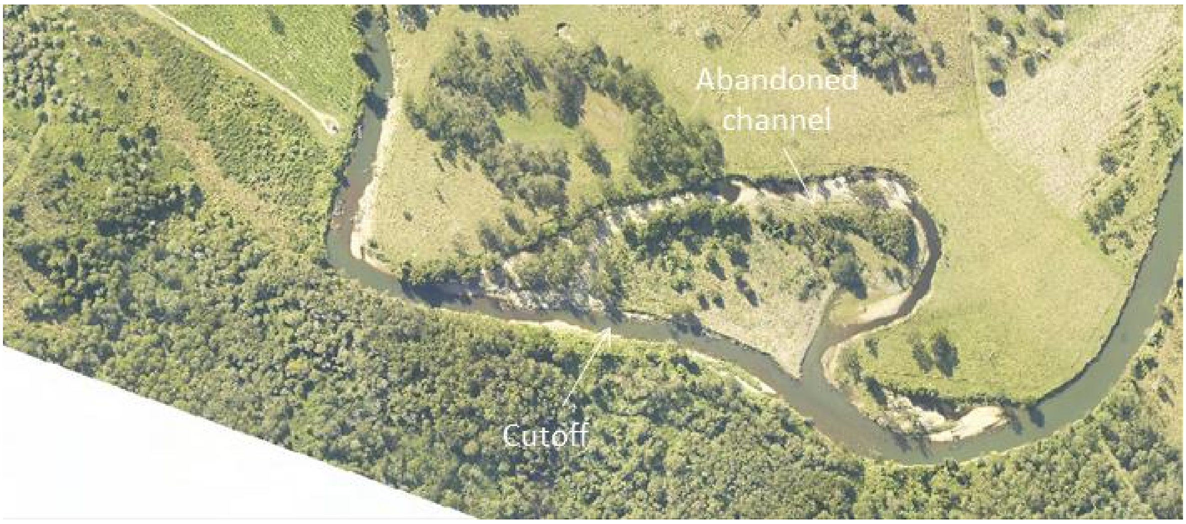
Channel migration is often associated with **meander migration** and is caused by erosion on one bank and deposition on the other (FISRWG, 1998).



Channel incision occurs when the bed of the channel cuts down and causes reach-scale deepening of the channel. The deepening is then normally followed by widening.



Avulsions and meander cut offs are both floodplain processes where a new, often shorter, channel is scoured leaving the previous course abandoned.



Impact of bushfires on erosion processes

The changes in hillslope process following a bushfire can be illustrated conceptually (Figure 29). In general, bushfires lead to an increase in the volume of runoff and erosion from hillslopes. Runoff and erosion increase as a result of a number of specific changes to vegetation and soil.

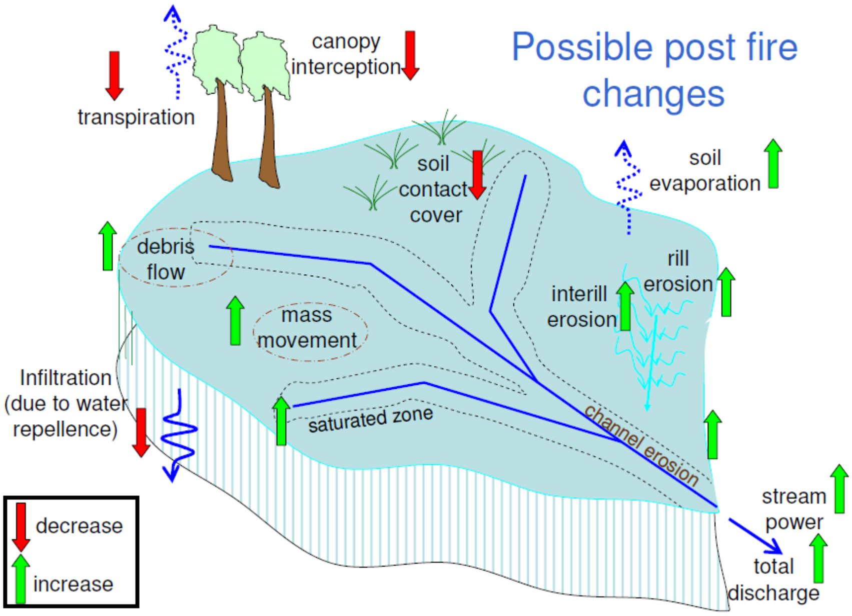


Figure 27. *Schematic representation of possible post-bushfire changes in hydrologic processes (taken from Smith et al. 2011a)*

In addition to the complexity of predicting responses from numerous, interrelated processes, the impact on the processes changes over time as—for example—burned vegetation on hillslopes regenerates. While bushfires cause almost instantaneous change in the hydrologic and geomorphic response to rainfall, the (general) increase in runoff and erosion changes over time as vegetation regeneration, bioturbation and leaf litter accumulation restores soil structure, infiltration rate and canopy storage to pre-bushfire levels (Brunsden and Thornes, 1979). The restoration of the physical characteristics (and consequently runoff and erosion processes) after a bushfire is referred to as ***relaxation*** and the duration between a bushfire and the point at which runoff and erosion has returned to pre-bushfire levels as the ***window of disturbance*** (Prosser and Williams, 1998). These concepts are important when considering post-bushfire effects and can be illustrated by considering the change in runoff (as a measure of hydrologic response) before and after a fire (Figure 30).

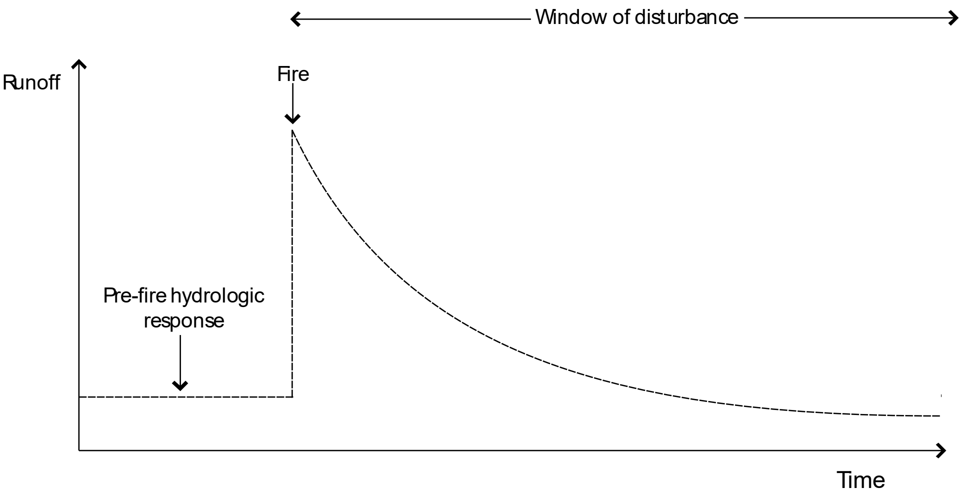


Figure 28. *Hypothetical effect of bushfire on runoff, illustrating the window of disturbance concept. Runoff is measured as the volume of runoff for a given rainfall event.*

Addendum 1 -
Impact of the 2020 Orroral fire on erosion risk in the Upper Cotter Catchment