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FINAL REPORT:

Googong Dam catchment Actions for Clean Water Plan

December 2018

icon WATER

Upper Murrumbidgee Catchment Network UMCN

Molonglo Conservation Group

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Disclaimer:

Access to private land was sought through the Queanbeyan Palerang Regional Council and the South East Local Land Service but landowner contact details could not be provided. As a consequence, field assessments in Priority Management Zones were restricted to public roads and there was limited access to channel and gully sites.

Executive Summary

Icon Water engaged Alluvium Consulting Australia (Alluvium) to develop an Actions for Clean Water (ACWA) Plan to establish a baseline understanding of the sources and quantum of the sediment loads entering the Queanbeyan River and Burra Creek upstream of the Googong Reservoir. The ACWA Plan (this report) will be used to direct efforts to stabilise and remediate sites over time, based on a prioritisation of risk to water quality in the receiving environment.

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

Phase One: Project inception	Phase Two: Assessment of catchment physiology and background information	Phase Three: Assessment of erosion processes within the catchment	Phase Four: Prioritisation	Phase Five: Recommended works

As part of Phase Two, a stakeholder workshop was held to inform understanding of historical catchment developments and current erosion issues in the Googong Catchment. Information gained from the stakeholder workshop and a review of relevant background information was synthesised to describe the catchment context (Section 4).

Phase Three, the assessment of erosion processes within the catchment, involved a desktop assessment to assess hillslope, channel and gully erosion occurring across the Googong catchment (Section 5). At the conclusion of Phase Three, sub-catchment profiles were developed that summarised the desktop erosion assessment (Appendix A). The sub-catchment profiles were used to identify priority sub-catchments that were the focus of a field assessment program in Phase Four.

Lack of access to private land meant that the field assessments were restricted to public roads and therefore some sites could not be inspected. Phase Four included a risk assessment to prioritise sites in the catchment, based on the desktop and field assessments (Section 6). Project recommendations (Phase Five) are provided in Section 7, based on the risk assessment and available management options.

The Burra Creek (G2) and Googong Foreshore (G9) sub-catchments had the highest hillslope, channel and gully erosion risks (see table below). As a result, these were classified as priority sub-catchments for management.

Sub-catchment	Area	Main waterways	Hillslope erosion risk	Channel erosion risk	Gully erosion risk
G1 Urialla Creek	76 km²	Queanbeyan River and Urialla Creek	Moderate	Low	Low
G2 Burra Creek	99 km².	Burra Creek	High	Moderate - High	Moderate
G3 Lighthouse Creek	60 km²	Queanbeyan River and Lighthouse Creek	Low - Moderate	Low	Low
G4 Tinderry Creek	156 km²	Queanbeyan River and Tinderry Creek	Low - Moderate	Low	Low
G5 Ballinafad Creek	75 km²	Ballinafad Creek	Low - Moderate	Low	Low
G6 Sherlock Creek	96 km²	Queanbeyan River, Sherlock Creek, Crow Valley Creek, Two Mile Creek and Careys creek	Low - Moderate	Low	Low

G7 Roberts Creek	101 km²	Queanbeyan River, Roberts Creek, Lyons Creek, Sandy Flat creek and Limekiln Gully	Moderate	Low	Low
G8 Towneys Creek	136 km²	Queanbeyan River and Towneys Creek,	Moderate	Low	Low
G9 Googong Foreshore	90 km²	Queanbeyan River	High	Low - Moderate	Moderate

Within these two priority sub-catchments, key zones of erosion risk were identified and classified as Priority Management Zones. These zones were the subject of a targeted field investigation to complete a more detailed risk assessment and prioritisation exercise. A summary of the risk assessment for the priority management zones in each priority sub-catchment is shown below.

Priority management zone	**Likelihood**	**Consequence**	**Trajectory**	**Risk**
G2 Burra Creek Sub-catchment				
1 - Western tributary of Burra Creek running parallel to Williamsdale road	3	3	3	27 - Moderate
2 – Western tributaries of Burra Creek in vicinity of Macdiarmid and Plummers Roads	3	2	2	12 - Low
3 – Northern most western tributary of Burra Creek	3	2	2	18 - Moderate
4 – Eastern tributary of Burra Creek adjacent Boundary Trail	3	2	4	18 - Moderate
5 – Upstream reach of Burra Creek parallel to Burra Rd near Captain Robertson Drive	4	3	4	48 - Very high
G9 Googong Foreshore catchment				
6 – Western tributaries entering Googong dam adjacent The Hut" and western foreshore walk	4	3	3	36 - High

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

- Stock exclusion measures
- Revegetation works
- Bank battering and / or toe protection on more severe erosion sites

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. Two options for riparian management of varying cost have been developed and their effect on risk within each priority management zone analysed.

Option 1 involves stock exclusion and facilitated revegetation. Stock exclusion can involve any number of methods for keeping stock from within an approximate 40 m riparian buffer zone. Stock access to the riparian zone should be restricted through fencing. Defined watering points could be included in the design of a stock management plan. 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.

Option 2 involves stock exclusion, isolated bank reprofiling, isolated toe protection and revegetation works. This option would also involve keeping stock from within the 40 m riparian zone each side of the waterway; however, the 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.

To decrease the risk within priority management zones 3, 4 and 6 to *Low*, the implementation of Option 1 would be sufficient. The risk rating of priority management zone 2 is already at *Low*, so Option 1 would also be sufficient. To reduce the risk rating within priority management zone 1 to *Low*, Option 2 would need to be implemented. Implementing Option 1 within priority management zone 5 would reduce the risk rating to *High*; however implementing Option 2 would further reduce this to *Moderate* (see table below).

	Existing risk analysis			Option 1 risk analysis		Option 2 risk analysis	
Priority management zone	*Likelihood*	*Consequence*	*Risk*	*Revised likelihood*	*Risk*	*Revised likelihood*	*Risk*
1 - Western tributary of Burra Creek running parallel to Williamsdale road	Moderate	Moderate	Moderate	Unlikely	Moderate	Rare	Low
2 – Western tributaries of Burra Creek in vicinity of Macdiarmid and Plummers Roads	Moderate	Minor	Low	Unlikely	low	Rare	Low
3 – Northern most western tributary of Burra Creek	Moderate	Minor	Moderate	Unlikely	Low	Rare	Low
4 – Eastern tributary of Burra Creek adjacent Boundary Trail	Moderate	Minor	Moderate	Unlikely	Low	Rare	Low
5 – Upstream reach of Burra Creek parallel to Burra Rd near Captain Robertson Drive	Likely	Moderate	Very high	Moderate	High	Unlikely	Moderate
6 – Western tributaries entering Googong dam adjacent The Hut" and western foreshore walk	Likely	Moderate	High	Moderate	Low	Unlikely	Moderate

Many of the reaches within the Googong catchment have been classified as having low to moderate sediment generation potential. However, despite the low rates of channel adjustments and/or sediment availability, collectively these reaches still represent a major sediment source to Googong Reservoir. As a result, improved riparian management (protection or restoration of riparian vegetation, exclusion fencing, weed/pest management, stock management etc.) in these reaches remains a critical part of ongoing sediment reduction programs. Restricting ground management responses to the priority reaches discussed above is unlikely to achieve the desired level of catchment reductions in sediment loads.

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Glossary

Accretion	The progressive deposition of sediment on a landscape surface.
Alluvial channel	A stream with deformable bed and banks that moves across their floodplain over time. Bank erosion is a natural process of alluvial channel behaviour.
Bed load	Transport of sediment along a stream bed by rolling, sliding or saltation.
Bench	A fine-grained sediment deposit which occurs between a river bed and floodplain, attached to the bank.
Bank erosion	Scour or slumping of a waterway bank caused by energy of the flowing water or saturation of the bank.
Bed lowering	Channel bed erosion resulting in a lowering of the bed and higher banks, initiated by headcuts (these move in the upstream direction).
Cross-section	A channel survey that identifies geomorphic units of the channel and floodplain.
Degradation	Channel bed erosion that deepens a channel and can result in channel widening and increased channel capacity.
Diffuse source turbidity	Landscape scale activities that lead to non-discrete point sources of sediment that impact on turbidity.
Pile fields	Energy retarding structures that are driven into the stream bed to reduce erosion processes.
Point source turbidity	Discrete sources of turbidity which induce significant rates of sedimentation.
Riparian vegetation	Vegetation located on a river or stream bank.
Rock beaching	Energy retarding structures comprised of rocks that are located on stream banks to reduce bank erosion.
Sedimentation	Deposition of material of varying size, away from its original location.
Sodic/ dispersive soils	Sodic soils are those which slake (collapse) and disperse when saturated, due to the presence of excess sodium ions in the soil profile. Exchangeable Sodium Percentage (ESP) is used to define the degree of soil sodicity. The parameters are: non-sodic soils – have an ESP of less than 6; sodic soils – have an ESP of 6-14; highly sodic soils have an ESP of greater than 15.
Stream order	A stream numbering system, developed by Strahler, which is used to identify streams and their tributaries. First order streams are defined as the smallest headwater tributaries. Where two first order streams meet, the classification becomes a second order stream. Where two second order streams meet, the classification becomes a third order stream and so on. Stream order only increases at the confluence of two streams with the same order. In situations where two streams with a different order meet, the stream maintains the highest classification.
Turbidity	Turbidity is a measure of water clarity. It is influenced by the amount of total suspended solids (which includes suspended sediments) in a water column.

1 Introduction

Googong Reservoir is part of the water supply infrastructure in the Australian Capital Territory (ACT). It forms a major component of a network of other dams, reservoirs, treatment plants and pump stations managed by Icon Water. The reservoir represents 43% of Canberra's water supply storage capacity.

Icon Water engaged Alluvium Consulting Australia (Alluvium) to develop an Actions for Clean Water (ACWA) Plan to establish a baseline understanding of the sources and quantum of the sediment loads entering the Queanbeyan River and Burra Creek upstream of the Googong Reservoir. The ACWA Plan (this report) will be used to direct efforts to stabilise and remediate sites over time, based on a prioritisation of risk to water quality in the receiving environment.

Sediment transport to, and accumulation in, water storages used in the potable water supply system imposes costs on Icon Water as the manager and operator of the system. These costs result from increased water treatment of inflows with high sediment and nutrient concentrations and lost water storage capacity as the dam fills with sediment transported from the upstream catchment. To reduce operational and maintenance costs and the risks associated with flood management, Icon Water have a direct interest in ensuring:

- inflows of water to the dam have low concentrations of sediment and nutrients, and do not require additional water treatment. Reducing treatment effort is likely to be of significant long-term benefit to Icon Water with chemical and power costs predicted to increase substantially into the future.
- sediment yield to the dam is minimised to reduce the rate sediment accumulates in the dam. Sediment infilling has been estimated to cost $3-6 / tonne assuming an alternative new dam site is available. If no alternative dam site is available dredging has been estimated to cost $30 / tonne (pers. comm Dr Adrian Volders).
- flood waves enter the dam at a relatively low velocity so that releases to the lower Queanbeyan River downstream of the dam occur at a lower peak discharge, with a consequent reduction in the risk of flood inundation to downstream communities and dam safety risks. The speed of flood waves is impacted by a number of factors including channel size, channel slope and hydraulic roughness.

In addition to treatment costs and loss of storage, sediment entering dams has a range of other impacts including enhanced algal and weed growth, loss of fish stock, methane production and reduced recreational value for the local community. The geomorphic and hydrologic processes collectively pose substantial impacts on the operational and financial risk profile of the operation of Googong Reservoir.

1.1 The Actions for Clean Water Plan process

An ACWA Plan is a report to identify and prioritise erosion hotspots in terms of risk to water quality. The ranking in the report provides guidance to prioritising investment in stabilisation or remediation. This ACWA plan 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 within a catchment supplying sediment, and the transport and storage of sediment within the catchment and floodplain is important to inform decision-making on where and how to reduce sediment loads to downstream receiving waters. There has been significant investment across Australia in modelling and monitoring research to better understand catchment sediment dynamics and the effectiveness of management actions to guide 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 predict the generation of sediment and nutrients 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 are too coarse to effectively inform decisions about investment in erosion control at the site and reach-scales.

Typically, planners use 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 across a catchment based on their risks to water quality.

1.2 The project objectives

The objective of this project was to develop an ACWA Plan that establishes a baseline for the sources and quantum of sediment loads entering the Queanbeyan River and Burra Creek upstream of the Googong Reservoir and helps direct efforts to stabilise and remediate sites over time, based on a prioritisation of risk to water quality in the receiving environment.

The specific objectives of the ACWA Plan are to:

1. Provide an overview of sediment sources within the Googong Reservoir catchment and identify the issues that need to be addressed to minimise sediment loads entering Googong Reservoir
2. Draw on existing strategies from earlier planning undertaken in the region
3. Identify high priority sites using existing guidelines to develop a prioritised series of management strategies
4. Utilise the framework developed for Upper Murrumbidgee ACWA to rank sites and adaptively manage water quality in the catchment
5. Prioritise on-ground actions over the short, medium and long term
6. Provide a monitoring and evaluation framework.

2 Background

2.1 Study area

The Googong Dam catchment is located in New South Wales, to the south-east of Canberra and is part of the larger Queanbeyan River catchment. Googong Dam was completed in 1978 and upon closure formed the Googong Reservoir. The catchment area to the Dam is 875 km^2, extending approximately 70 km south from the Dam to Gourock National Park (Figure 1).

The catchment is bounded by the Tinderry Range in the west and south and the Gourock Range to the east. Elevations within the catchment vary from over 1,600 m AHD in the surrounding ranges to 580 m AHD at the catchment outlet at Googong Dam (Figure 26).

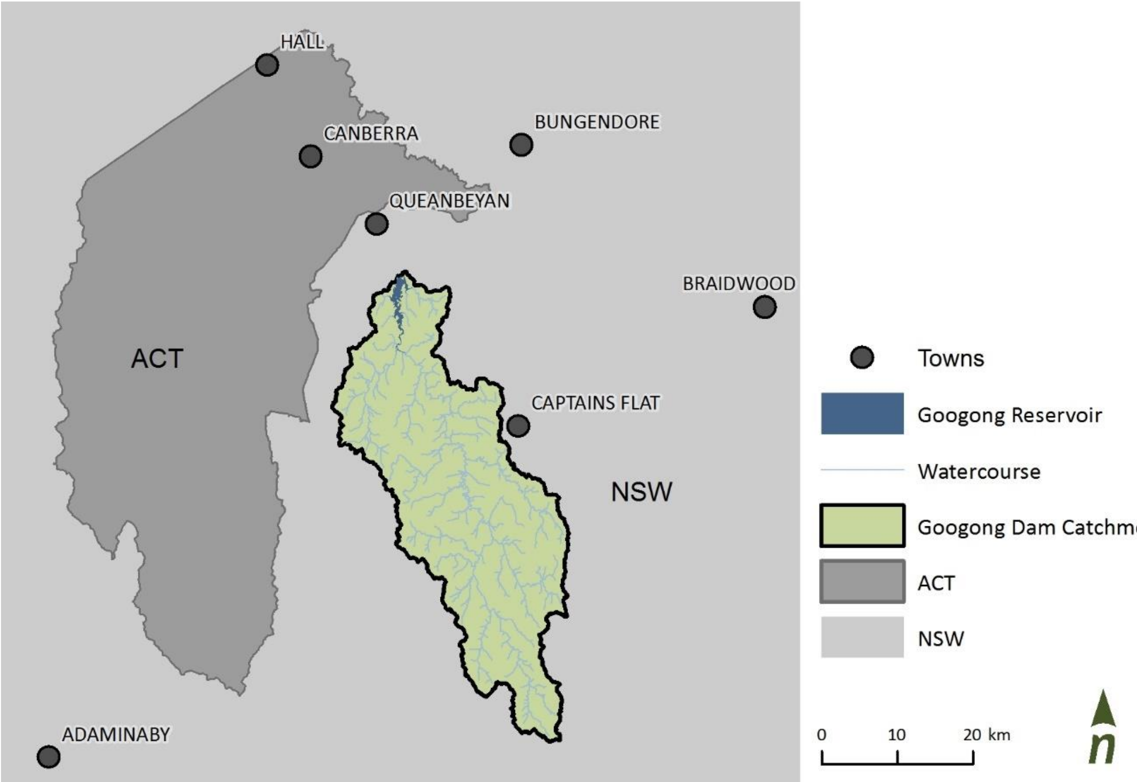


Figure 1. *Location map of the Googong catchment*

The Queanbeyan River, with its headwaters rising in the Gourock Range in the south of the catchment, drains the majority of the catchment into Googong Reservoir. It flows south to north through the centre of the catchment and is fed by several tributaries that drain the ranges to the east and west. The main tributaries of the Queanbeyan River include Burra, Urialla, Tinderry, Ballinafad, Groggy, Woolpack, Sherlock, Lyons, Towneys and Mile Creeks. Burra Creek, which flows in a northerly direction drains the north-west of the catchment and a number of small waterways drain directly to Googong Reservoir.

2.2 Catchment management arrangements

The Googong Dam Area was acquired by the Commonwealth Government in the 1970s under the Commonwealth legislation, *Canberra Water Supply (Googong Dam) Act 1974*. The Googong Dam Area includes the reservoir, Googong Dam, the Queanbeyan River immediately below the dam and the surrounding Googong Foreshore area. The main purpose of the management of the Googong Dam Area is to protect the water-quality for the supply of potable water for Canberra and Queanbeyan.

The ACT Government manages the Googong Dam area under a 150-year lease with the Commonwealth Government. The area is directly managed by the ACT Parks and Conservation Service and a Googong

Foreshores Plan of Management was completed in 2012 [1]. The entire Foreshores area remains within NSW and is subject to NSW legislation.

Waterways and natural resources in the Googong catchment are managed by NSW Government (South-east Local Land Services) and NSW Local Government (Queanbeyan-Palerang Regional Council and Snowy Monaro Regional Council). Community groups, including the Upper Murrumbidgee Catchment Network and Molonglo Catchment Group also play a role in the management of the catchment.

There is also an ACT and Region Catchment Management Coordination Group, which includes the above groups and ACT and Commonwealth governments and is a statutory body under the *Water Resources Act 2007* (ACT).

As part of the Murrumbidgee to Googong (M2G) water transfer project, there has been some monitoring of sites along Burra Creek. Findings from the most recent monitoring report [2] have been included in the risk assessment process.

3 Method

3.1 Overview

The project was undertaken in five phases (Figure 2).

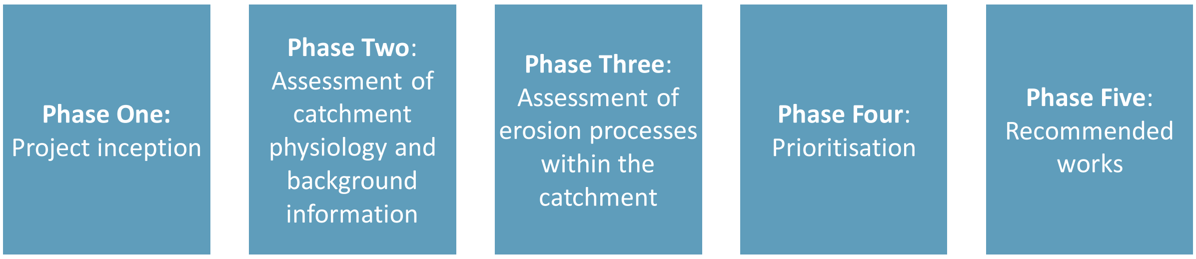


Figure 2. *Project phases*

Representatives from relevant government agencies and organisations were engaged in the course of the project to provide catchment context, feedback on project deliverables, and supply project data. Representatives from the following organisations have been involved:

- South-east Local Land Services (LLS)
- Queanbeyan Palerang Regional Council
- Snowy Monaro Regional Council
- Molonglo Catchment Group
- ACT Government

As part of Phase Two, a stakeholder workshop was held on 7 May 2018 in the Icon Water offices, Canberra, to inform the understanding of historical catchment developments and current erosion issues in the Googong Catchment. Workshop participants included representatives from relevant government organisations and volunteer groups. Information gained from the stakeholder workshop, analysis of spatial data describing the catchment physiography, climate and land use and a review of relevant background information was synthesised to describe the catchment context (Section 4).

Phase Three, the assessment of erosion processes within the catchment, involved a desktop assessment to assess hillslope, channel and gully erosion occurring across the Googong catchment. Technical details of the methods used are provided in the following section, and the results are presented in Section 5.

At the conclusion of Phase Three, sub-catchment profiles were developed that summarised the desktop erosion assessment (see Appendix A). These sub-catchment profiles were provided to relevant government agencies and catchment organisations, so they could provide feedback and additional information.

The sub-catchment profiles were used to identify priority sub-catchments that were the focus of the field assessment program in Phase Four. Field assessment was undertaken on 15 August 2018 by Elisa Zavadil and Jacob Dearlove. Lack of access to private land meant that the field assessments were restricted to public roads and therefore some sites could not be inspected.

Based on the field and desktop assessments, Phase Four included a risk assessment to prioritise sites in the catchment to meet the requirements of an ACWA plan. The risk assessment method is presented below (Section 3.3) and the results are presented in Section 6. Based on the risk assessment and management options, recommendations (Phase Five) are provided in Section 7.

3.2 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 Googong Dam Catchment. Three types of erosion processes were assessed: hillslope erosion, gully erosion and channel erosion. An overview of factors that commonly affect erosion is provided in Appendix B. The approach uses similar methods and data to the previous Upper Murrumbidgee ACWA study [3], with some modifications and extensions (Table 1).

Table 1. Summary of erosion assessment method compared to Upper Murrumbidgee ACWA Plan approach

Erosion type	Method for Upper Murrumbidgee ACWA Plan	Method for Googong ACWA Plan (this report)
Hillslope erosion	Soil Regolith Stability Classification layer	Revised Universal Soil Loss Equation (RUSLE) – expands on Soil Regolith Stability Classification approach to include local climate, topography, soil type, vegetation cover and management interventions.
Gully erosion	SedNet Model Data (2004); NSW Erosion Data (2003) Murrumbidgee River Styles Data (2011).	Similar approach using high resolution aerial imagery and LiDAR data. Also included an assessment of whether gullies are active or dormant.
Channel erosion		Approach developed by Alluvium to extend previous approach, using River Styles data and aerial imagery.

Data sources

The following data sources were used for the desktop erosion assessment:

- Aerial imagery: 2018 data provided by Icon Water and 2008 data accessed from NSW public imagery layer [4]
- 2009 LiDAR Digital Elevation Model (DEM)
  - Geoscience Australia – 5m grid
  - ACT Government 1m grid
- Murrumbidgee River Styles Data (2011)
- Soil mapping (ASC NSW, 2017)
- NSW land use layer (Office of Environment and Heritage 2011)
- Modelled Hillslope Erosion over New South Wales (Office of Environment and Heritage 2018)

Hillslope erosion assessed using the Revised Universal Soil Loss Equation

Hillslope erosion in the Googong Dam catchment 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 that:

- a modest number of model parameters is required
- the RUSLE model parameters can be derived from commonly available datasets, and
- the RUSLE model has been adapted to Australian conditions and the factor-based nature allows individual contributing factors to be easily analysed [5]

The RUSLE determines mean annual soil erosion as a product of six parameters (Table 2). By mapping the spatial distribution of the parameters, the location of likely hillslope erosion and sediment generation within a catchment can be estimated.

The methods and data sets used to estimate the RUSLE parameters across the Googong Catchment are shown below (Table 2) with more detail provided in Appendix C. There are state-wide layers available for each of the RULSE parameters, with 20m resolution [6]. Where these layers were considered the best available data for a given parameter, the layers were adopted for the assessment and spatially resampled from a 20m to a 2m grid resolution.

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 should be used with some caution.

Table 2. RUSLE parameters used in the Googong Hillslope erosion assessment

Factor	Method
Rainfall erosivity (R)	NSW state-wide layer spatially re sampled to 2 m grid resolution
Soil erodibility (K)	NSW state-wide layer spatially re sampled to 2 m grid resolution
Slope length (L)	Length and Steepness layer generated from a compiled 2 m Digital elevation Model
Slope steepness (S)	
Cover management (C)	C factors applied based on NSW land use layer
Erosion control practice (P)	1 (assuming no erosion control)

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

Waterway 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 2009 DEM and soil mapping information.

These factors are combined into an overall rating of sediment generation potential using the following matrix.

Reach-scale fine sediment availability	Reach-scale erosion potential: 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 3. *Matrix used to define reach-scale sediment generation potential*

Gully erosion assessment assessed from aerial imagery

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 (2008 and 2018 aerials and 2009 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 provided.

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 10-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. It should be noted that ideally this assessment would be ground-truthed; however, owing to site access constraints this was not possible. The overall percentage of gully coverage for each sub-catchment (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 sub-catchment as either Low, Moderate, High or Very High based on the spatial distribution of gullies.

3.3 Risk assessment

For consistency, a risk assessment approach similar to the approach used in the Upper Murrumbidgee ACWA Plan [3] has been adopted. 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

Value = Water Quality for human consumptive use. This is the same value for every risk assessment, 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, 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

The risk assessment ratings for likelihood, consequence and trajectory are provided below (Table 3). 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 and field erosion assessment.

Table 3. Risk assessment ratings (adopted from Upper Murrumbidgee 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 4).

Table 4. 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

It is important to understand the history of the Googong Dam catchment as it provides insight into historic erosion and sediment transport processes in the catchment and informs the development of an understanding of the 'baseline' conditions for the catchment. A summary of the catchment characteristics and processes is provided in this section, and graphically presented in **Figure 5** and Figure 6. In 2000, Barry Starr assessed changes in the state of drainage networks and catchment condition since 1944 [7]. This work is referred to throughout the following section.

4.1 Climate

Average annual rainfall across the Googong Dam catchment ranges from 1,100 mm/year along the Gourock Range in the south-east to 600 mm/year in the north part of the catchment (Appendix D, Figure 27) [8]. The catchment has also undergone a number of flood and drought events, as shown in Figure 6 below.

Climate change is expected to impact soils through changes in both soil erosion and rainfall erosivity. Recent work by the Office of Environment and Heritage has used the projections from NARCliM to provide information on the projected impacts of climate change on soil erosion and rainfall erosivity in the near future (2030) and far future (2070) [9]. The results of this analysis for the far future scenario is provided below, showing a 10-20% increase in annual mean rainfall erosivity in the Googong catchment.

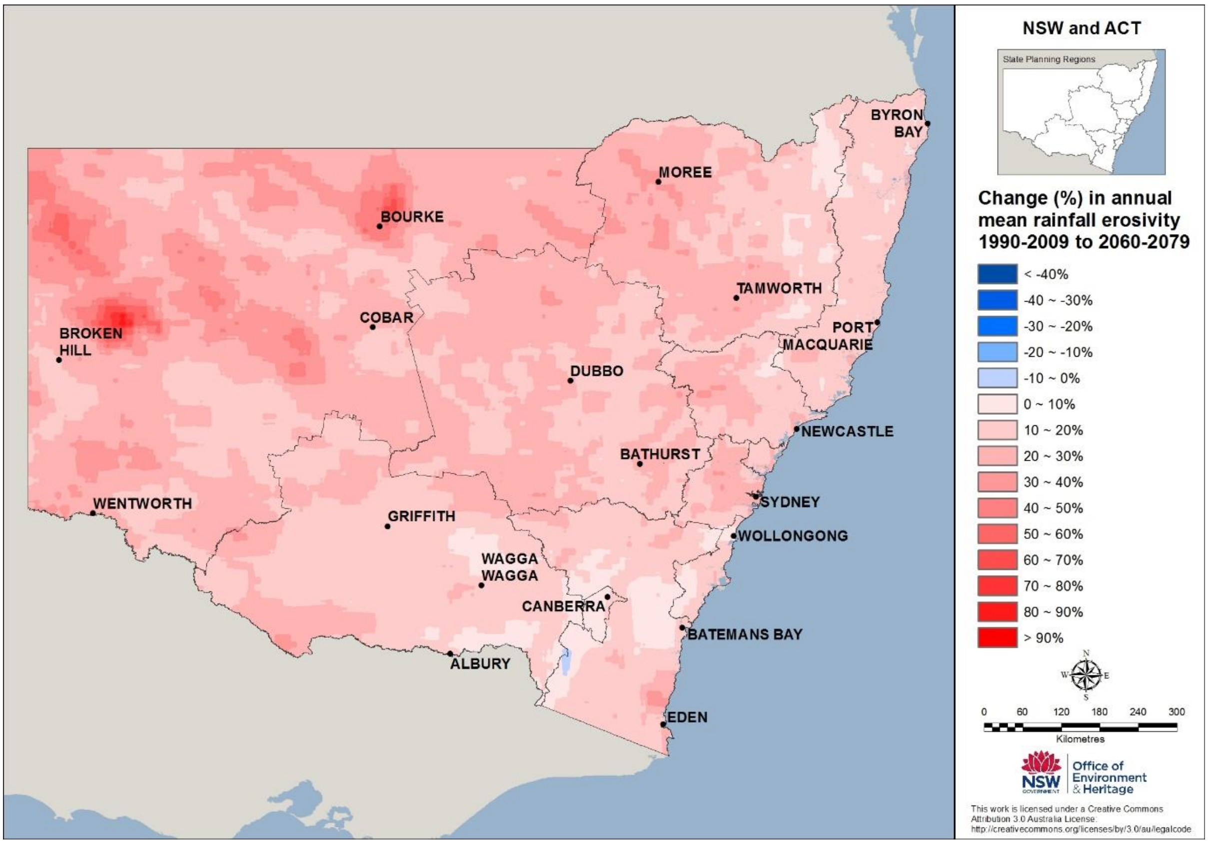


Figure 4. *Change (%) in annual mean rainfall erosivity 1990-2009 to 2060-2079 [Source: Office of Environment and Heritage]*

4.2 Land use

Understanding the land use types throughout Googong Dam catchment is important in determining the dominant erosion processes supplying sediment within the catchment, as particular land use types have different degrees of impact on erosion process. Generally, the Nature Conservation areas will supply less sediment than grazed areas. It is also important to understand the land use types as they will directly affect the development and implementation of management actions aimed at reducing downstream sediment loads.

The principle land use type in the Googong Dam catchment is *Nature Conservation* (Tallaganda, Yuntununbeyan and Gourock National Parks; and Tinderry and Yuntununbeyan Nature Reserves) which covers 30% of the catchment. The next most dominant land use types are classified as *Other minimal use* (areas that have residual native cover) and *Grazing native vegetation*, each covering 22% of the total catchment area. *Grazing modified pastures* accounts for 12% of the catchment area and *Production forestry* 10% (Appendix D, Figure 28).

European settlement and subsequent landscape alteration commenced in the catchment in the 1820s. Land use consisted of grazing and cropping and generally increased in intensity through the mid-20th Century, with a reduction since the 1970s. Clearing of vegetation was significant, with evidence of a significantly degraded state in the 1940s, but regeneration has been observed in the decades since then (Starr 2000).

In more recent years there has been a shift in land use in the downstream part of the catchment, with an increase in smaller rural-residential blocks associated with the growing townships of Googong and Burra. In general, this type of land use can decrease pressures from land management but can also lead to water quality issues through septic tanks and stormwater runoff.

4.3 Erosion processes and waterway modification

Prior to the 1820s the lower reaches of the Queanbeyan River and its tributaries consisted of chain-of-ponds style systems. As land use and land clearing intensified, these chain-of-ponds systems became more channelised, resulting in channel erosion. Land clearing also resulted in gullying throughout the catchment.

In middle of the 20th Century, there was significant modification of drainage in the Googong catchment, including substantial farm dam construction. In the 1970s and 1980s, soil conservation projects were implemented under the Lake Burley Griffin Protection Scheme. This included 613 gully control structures, 127 km of bank works and 95 km of gully shaping works. The projects also included fencing, construction of access tracks, and associated land management works [10].

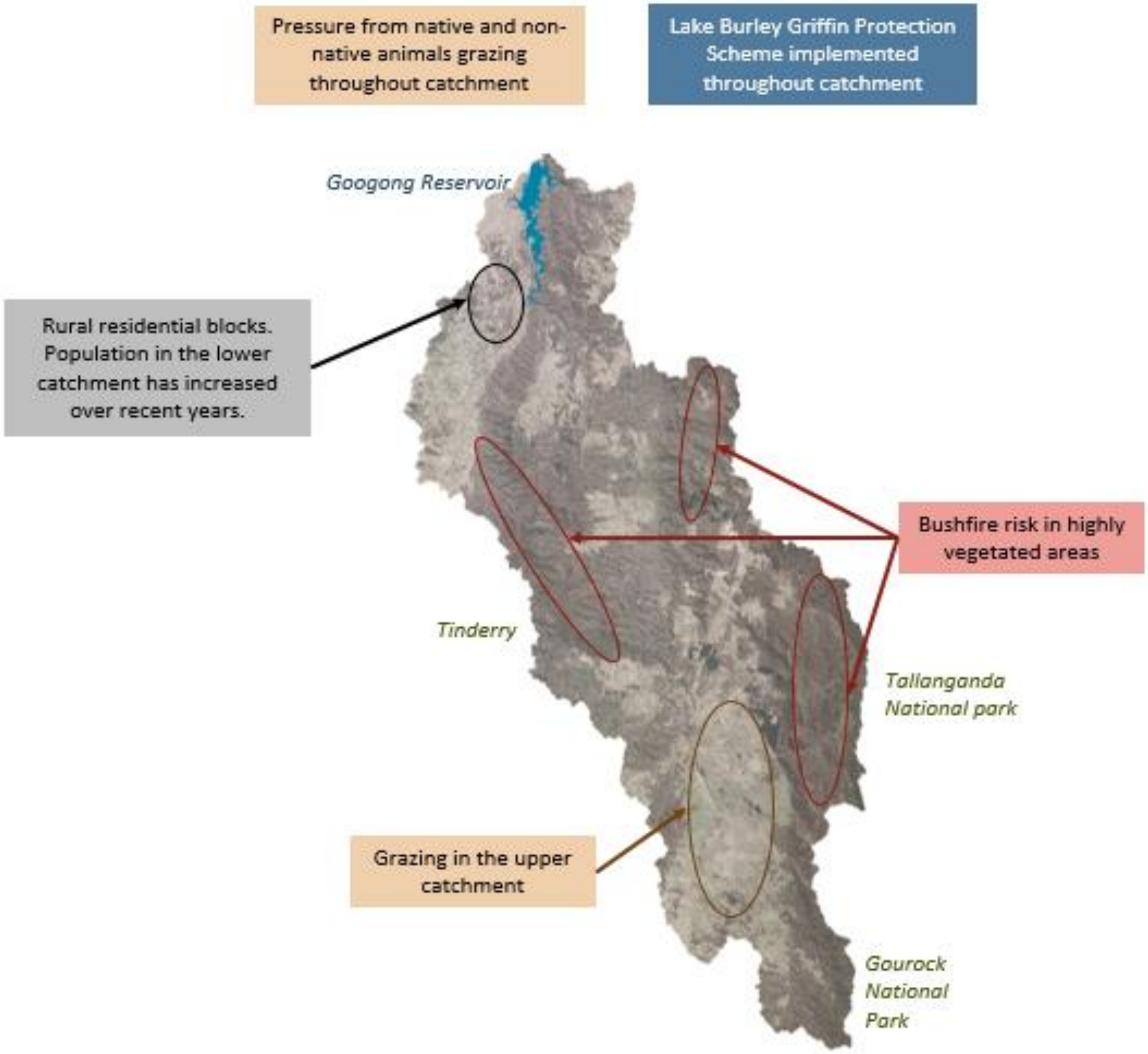


Figure 5. *Overview of Googong catchment*

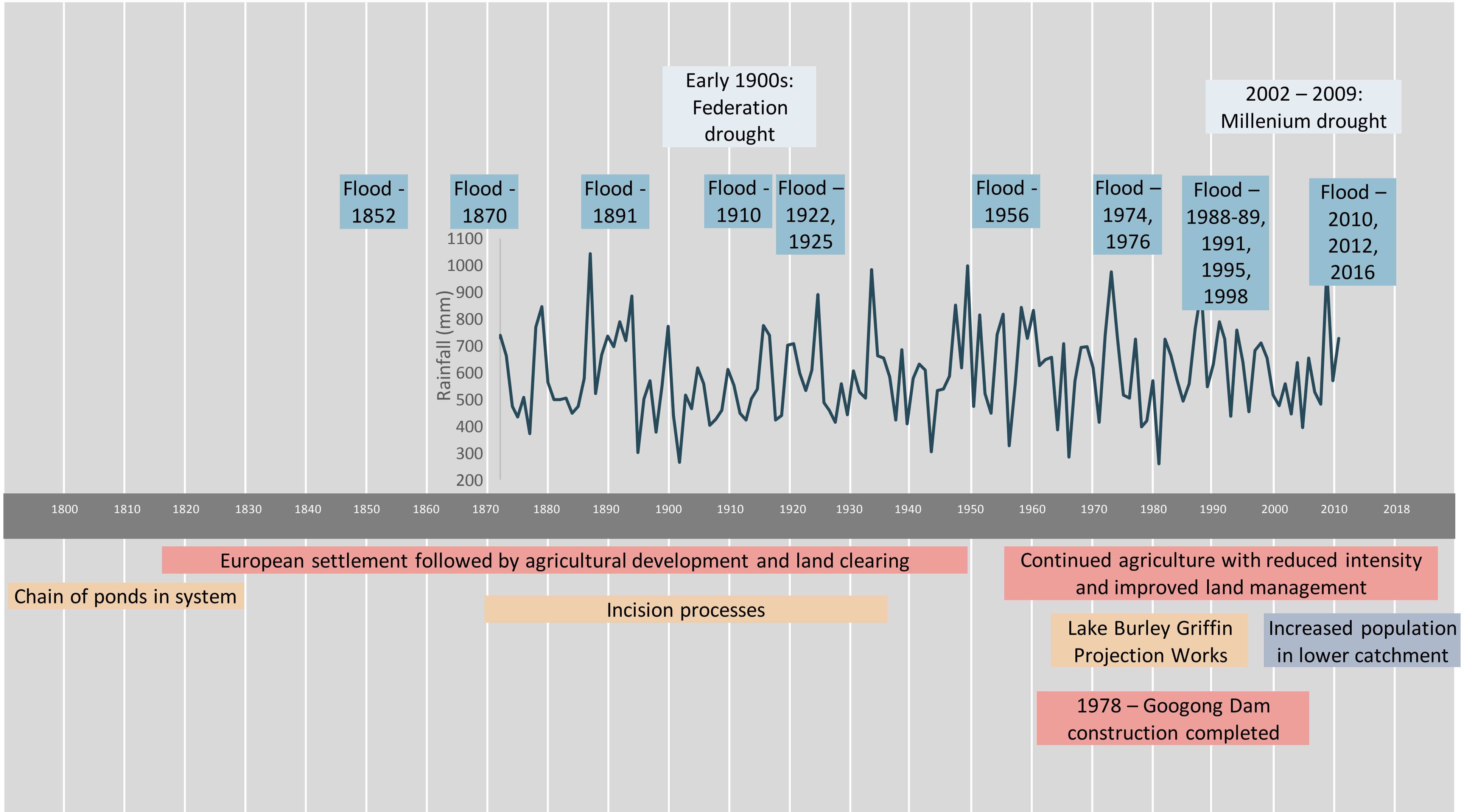


Figure 6. *Googong Dam catchment timeline*

A summary of the findings from Starr (2000) on the erosion processes in the catchment is presented in the text box below.

Googong Catchment findings (Starr 2000)

Queanbeyan River main channel:

- The stability of the Queanbeyan River has not been impacted since 1994
- Some changes have been detected in the active channel of the river and are associated with bedload movement

Main tributary Creeks

- The main tributary creeks remain as efficient transport channels
- Colonisation by vegetation occurs and is often subsequently stripped away during flood events
- A reach of Tinderry Creek had been identified as a major sediment source in a 1990 study, but in 2000, the erosion was deemed not as extensive

Tributary major gullies and valley floor channels

- Many valley floor channels have transitioned from sediment sources to deposition systems
- There are grassy swamps and wet tussock depressions that have remained intact. These are important for trapping fine sediment. They are not being threatened by current land management practices.

More recently, the South East LLS and regional councils have provided advice to landholders regarding land management practices, including revegetation and fencing of waterways. A project is underway, *Rivers of Carbon – Burra Banks, Bush and Biodiversity*, to fence out waterways, revegetate riparian areas, undertake strategic erosion control works to improve water quality, and link wildlife habitat.

4.4 Catchment geology and soils

A large proportion of the catchment is underlain by sandstone with a large Granodiorite band extending from the south midway through the catchment. There are notable areas of granite in some of the elevated areas and a large band of tuff along the north-west of the catchment. There are also areas of schist and shale in the north of the catchment (Appendix D, Figure 29). 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 types throughout the catchment are Kurosols as well as areas of Kandosols, Rudosols and Tensosols (Appendix D, Figure 30). There are also some smaller areas of Sodosols, Tenosols and Ferrosols. Kurosols are extremely erodible and consist of a sandy loam topsoil underlain by a markedly contrasting heavy clay subsoil. Kandosols are highly erodible and are relatively uniform throughout their profile with a loamy topsoil increasing in clay content with depth. Rudosols and Tensosols are stony soils that are generally found on steeper slopes where finer grains have been transported away. They are also highly erodible.

4.5 Other factors potentially contributing to erosion

Bushfires directly affect a range of physical characteristics and processes. They cause almost an instantaneous change in the hydrologic and geomorphic response to rainfall, which can see increases in runoff and sediment loads to waterways. Based on the Snowy Monaro and lake George Bush Fire Risk management Plans, the Googong catchment has significant areas in the upper catchment that have not burned in over 25 years.

There are many unsealed roads in the catchment, including council roads, tracks for forestry management, and tracks constructed for bushfire management. These tracks can be a source of sediment to the system.

There is anecdotal evidence of significant native animal populations (kangaroos) and non-native species such as deer that may influence erosion through grazing of groundcover vegetation.

5 Sub-catchment erosion assessment

5.1 Sub-catchment assessments

The results of the erosion assessment are summarised in Table 5 and are presented spatially below (Figure 7 and Figure 8). Detailed profiles are provided for each sub-catchment in Appendix A.

Table 5. Summary of desktop erosion assessment for each sub-catchment

Sub-catchment	Area	Main waterways	Hillslope erosion risk	Channel erosion risk	Gully erosion risk
G1 Urialla Creek	76 km^2	Queanbeyan River and Urialla Creek	Moderate	Low	Low
G2 Burra Creek	99 km^2.	Burra Creek	High	Moderate - High	Moderate
G3 Lighthouse Creek	60 km^2	Queanbeyan River and Lighthouse Creek	Low - Moderate	Low	Low
G4 Tinderry Creek	156 km^2	Queanbeyan River and Tinderry Creek	Low - Moderate	Low	Low
G5 Ballinafad Creek	75 km^2	Ballinafad Creek	Low - Moderate	Low	Low
G6 Sherlock Creek	96 km^2	Queanbeyan River, Sherlock Creek, Crow Valley Creek, Two Mile Creek and Careys creek	Low - Moderate	Low	Low
G7 Roberts Creek	101 km^2	Queanbeyan River, Roberts Creek, Lyons Creek, Sandy Flat creek and Limekiln Gully	Moderate	Low	Low
G8 Towneys Creek	136 km^2	Queanbeyan River and Towneys Creek,	Moderate	Low	Low
G9 Googong Foreshore	90 km^2	Queanbeyan River	High	Low - Moderate	Moderate

Seven of the nine sub-catchments were identified as having low gully and channel erosion risk and low to moderate hillslope erosion risk and were thus classed as low priority.

Burra Creek (G2) and Googong Foreshore (G9) have moderate-high and low-moderate channel erosion risk respectively. Both sub-catchments were rated as having a moderate overall gully erosion risk and high overall hillslope erosion risk. As a result, these sub-catchments were classified as priority sub-catchments for management. A description of these priority sub-catchments is provided in the following section.

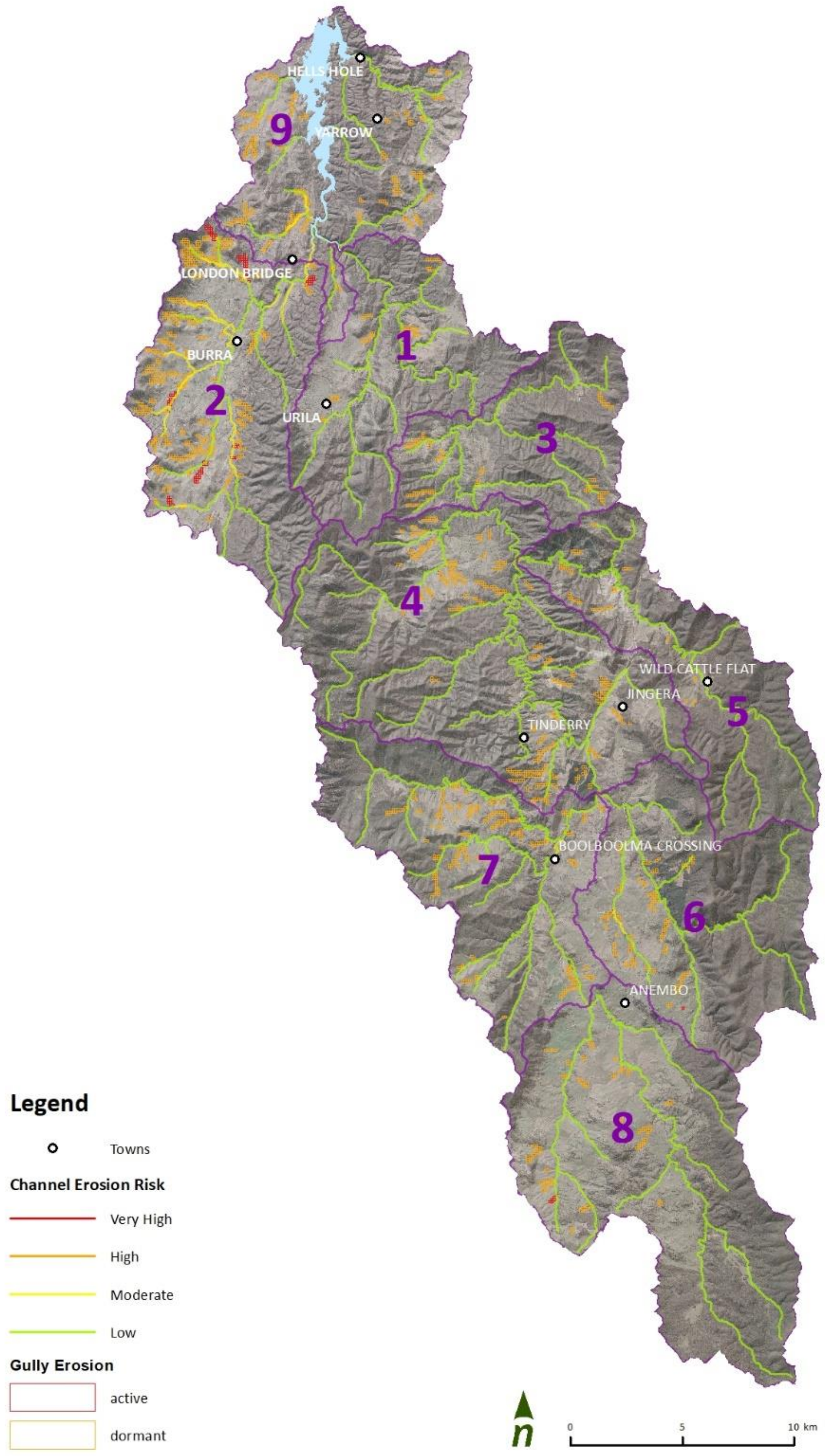


Figure 7. *Googong erosion assessment: channel and gully erosion assessment results with sub-catchments shown in purple*

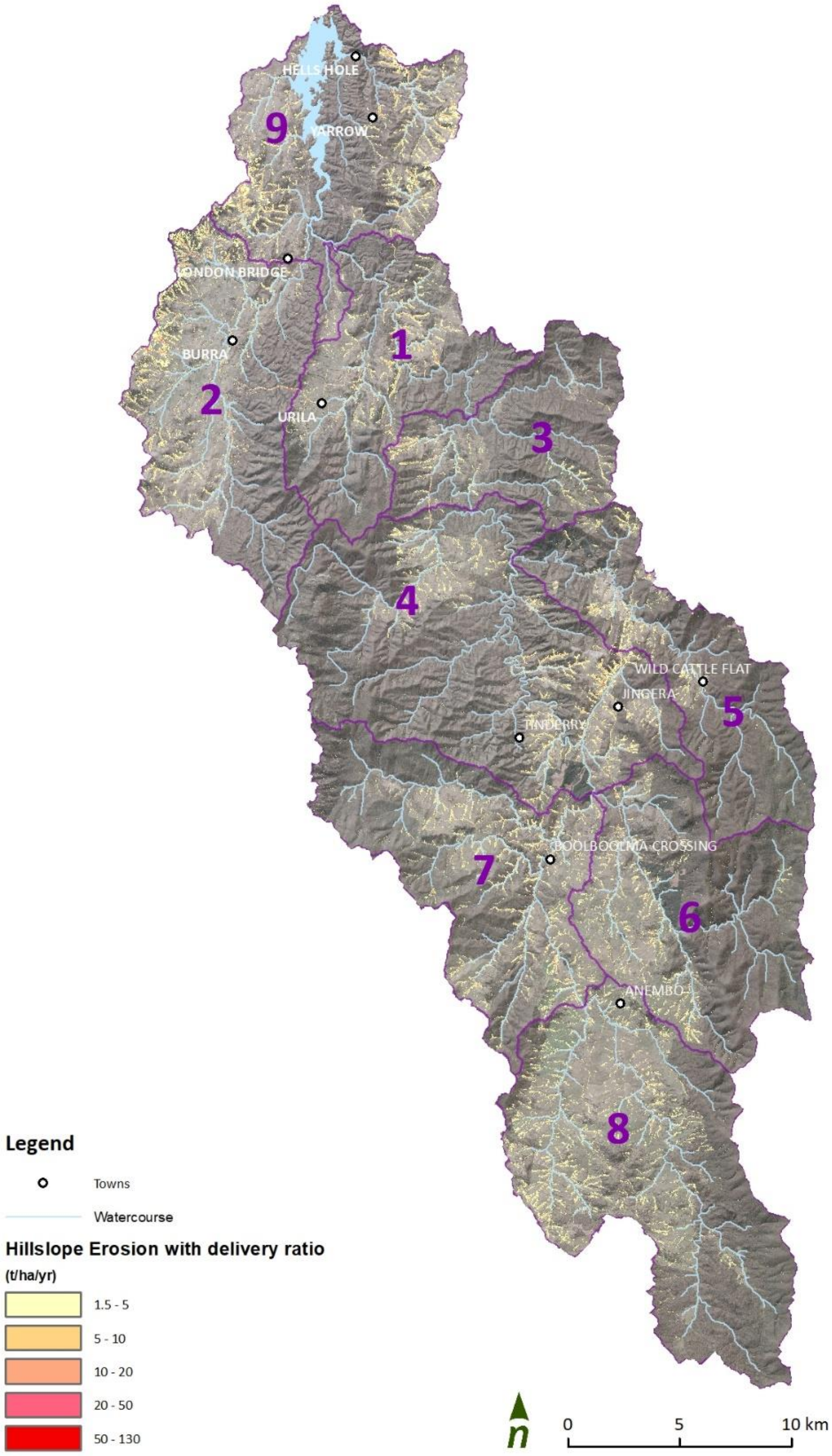


Figure 8. *Googong erosion assessment: hillslope erosion assessment results with sub-catchments shown in purple*

5.2 Priority sub-catchments

As described above, G2 – Burra Creek and G9 – Googong Foreshore were identified as priority sub-catchments based on the desktop erosion assessment. A description of these priority sub-catchments is provided below, and specific management zones are discussed in Section 6 – Risk assessment.

Burra Creek sub-catchment

The desktop channel erosion risk assessment investigation identified a significant number of reaches within the sub-catchment as having *very high, high* or *moderate* channel erosion risk. These reaches were identified as having minor to moderate instabilities, which corresponds to moderate to high erosion potential as well as having high or very high sediment availability.

It should be noted that the accuracy of this desktop assessment was limited by the data provided, which included 2018 (poor resolution) and 2010 aerial and 2018 LiDAR data. Following field assessments, it was evident that the initially assigned moderate or minor instability ratings assigned to some streams needed to be changed to stable or minor. This had the effect of lowering the channel erosion risks from very high and high to high and moderate, as illustrated below (Figure 9).

The majority of the moderate risk reaches are the tributaries of Burra Creek that drain the western extent of the catchment. There is also a short reach in the south-west of the catchment and another reach in the north-east identified as being moderate risk. A large reach of Burra Creek in the south is identified as being moderate-high risk. The soils and underlying geology within these moderate to high-risk areas is dominated by highly erodible kurosols and soft tuff. The field inspection confirmed this, as the soil was mostly highly erodible fine sediments interspersed with larger grain sands and gravels. In addition, the majority of these reaches are located within land use areas that have been modified and have poor riparian vegetation coverage; hence the higher risk of erosion.

The gully erosion risk for the sub-catchment is classed as moderate. Gully erosion covers approximately 7% of the sub-catchment. Of this, 6% has been assessed as dormant (i.e. inactive in the last 10 years) whilst 1% has been identified as active gully erosion. 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, land use changes, etc.) this risk can increase or even decrease.

Gully erosion is primarily active in the western half of the sub-catchment and is particularly concentrated along the western hillslopes. Active gully erosion has been identified adjacent to several of the western tributaries of Burra Creek and the lower reaches of some of the eastern tributaries. The soils in these areas consist of highly erodible Kurosols which, with little coverage from vegetation, are highly susceptible to gully erosion caused by overland runoff and direct rainfall. The lack of vegetation also provides little structural support for the soils leading to further erosion.

The RUSLE analysis indicated relatively high rates of hillslope erosion along the steeper western slopes of the sub-catchment. 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. While this distance was considered as part of this analysis, the numerous farm dams which exist along these streamlines were not. These dams have the potential to act as sediment traps and possibly reduce sediment delivery to the stream; however, further investigation of sedimentation within these privately-owned dams would be necessary to determine their effect. Road areas are also highlighted as erosional hotpots, particularly where they intersect with stream lines.

Googong Foreshore sub-catchment

The initial channel erosion risk assessment identified two reaches in the south-west of the catchment that were identified as having *high* channel erosion risk. These reaches were identified from the desktop assessment as having minor instabilities that corresponds to moderate erosion potential and a very high sediment availability. The remaining reaches within the sub-catchment were identified as having *low* channel erosion risk. These reaches were identified from the desktop assessment as being stable which corresponds to low erosion potential and low sediment availability.

It should be noted that this desktop assessment was limited by the data provided, which was comparison between 2018 (poor resolution) and 2010 aerial and one set of lidar (2018 data). Following field assessments, it was evident that the initially assigned moderate or minor instability ratings given to some streams had to be changed to stable or minor. Therefore, the channel erosion risk ratings were lowered from *very high* and *high* to *high* and *moderate*.

The underlying geology to the east of this sub-catchment consists of mainly of sandstone, mudstone, shale, quartzite, phyllite, slate, schist and quartzite. The land use in the majority of the reaches in the east is either conservation land or has not been heavily modified, and as a result the reaches have moderate to good riparian vegetation coverage. The combination of generally resistant geology and moderate to good riparian vegetation means most of the reaches in the east of the sub-catchment have a low risk of erosion. In contrast, most of the western area of the catchment has been more highly modified and has poor riparian vegetation coverage, leading to reaches in this area to be given a *high* risk of erosion.

The gully erosion risk for the sub-catchment is classed as moderate. Gully erosion covers approximately 4% of the sub-catchment, primarily in the western half. All gully erosion was identified as being dormant (i.e. inactive in the last ~10 years). 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, land use changes, etc.) this risk can increase or even decrease.

Most of the identified gully erosion is situated within, or adjacent to, land that is classed as grazing (modified pastures and native vegetation). The soils in this area consist of highly erodible Kurosols, which, with little coverage from vegetation, are highly susceptible to erosion from direct rainfall. The lack of vegetation also means there is little structural support for the soils leading to further erosion.

6 Risk assessment

Burra Creek (G2) and Googong Foreshore (G9) were classified as priority sub-catchments on the basis of the risk assessment for channel, gully and hillslope erosion (Section 5.1). Within each of these sub-catchments the key zones of erosion risk were identified and have been classified as Priority Management Zones. The zones are shown in Figure 9 and Figure 9 (and in further details of specific site locations in Appendix E).

These zones were the subject of a targeted field investigation to complete a more detailed risk assessment and prioritisation exercise. The risk assessment approach is described in Section 3 above. A summary of the risk assessment for each priority management zone is provided in Table 6, with more detail on the following pages.

Table 6. Summary of risk assessment results

Priority management issue/zone	Likelihood	Consequence	Trajectory	Risk
G2 Burra Creek Sub-catchment				
1 – Western tributary of Burra Creek running parallel to Williamsdale road	3	3	3	27 - Moderate
2 – Western tributaries of Burra Creek in vicinity of Macdiarmid and Plummers Roads	3	2	2	12 - Low
3 – Northern most western tributary of Burra Creek	3	2	3	18 - Moderate
4 – Eastern tributary of Burra Creek adjacent Boundary Trail	3	2	3	18 - Moderate
5 – Upstream reach of Burra Creek parallel to Burra Rd near Captain Robertson Drive	4	3	4	48 - Very high
G9 Googong Foreshore catchment				
6 – Western tributaries entering Googong dam adjacent The Hut" and western foreshore walk	4	3	3	36 - High

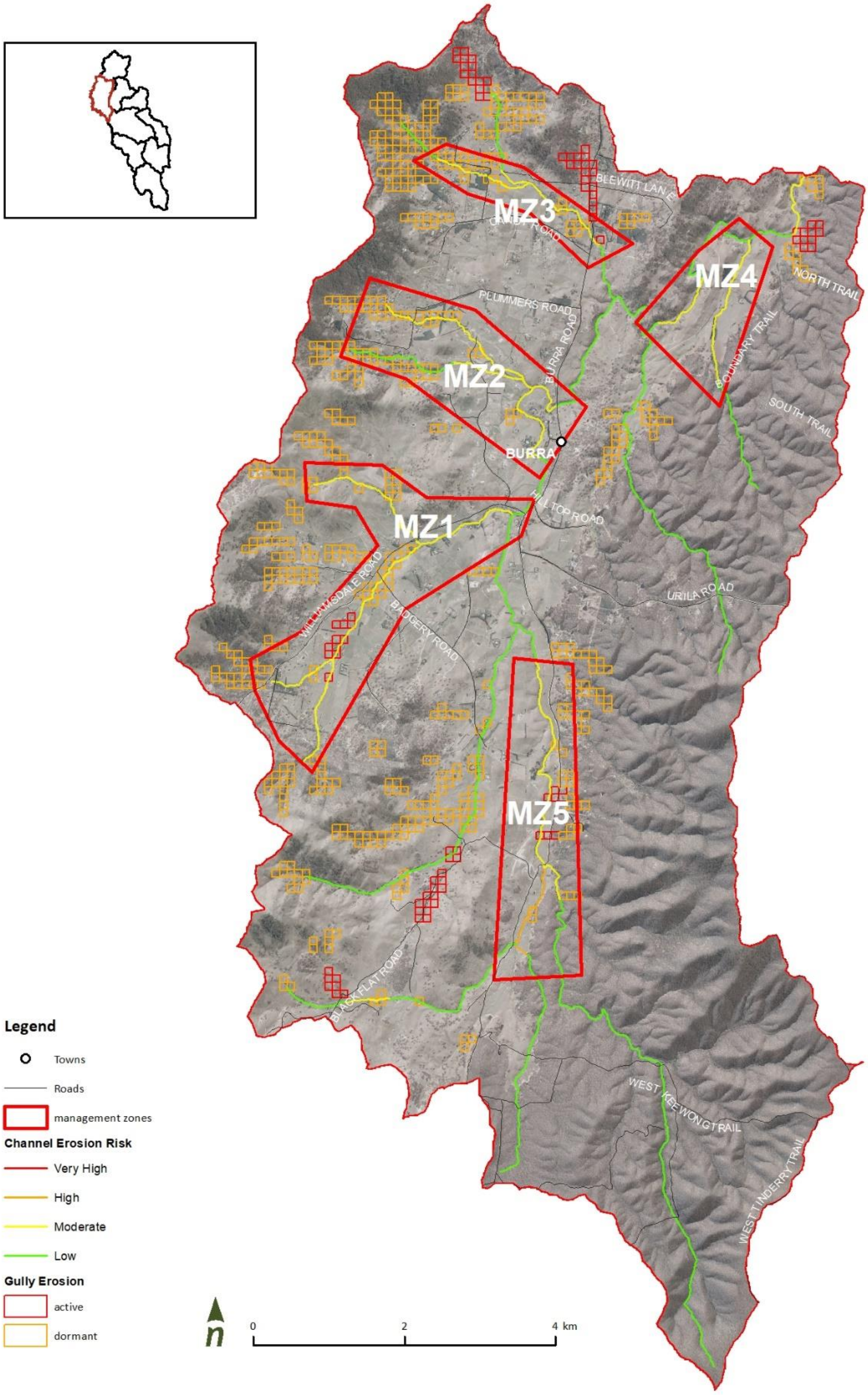


Figure 9. *Overview of management zones in Burra Creek Sub-catchment*

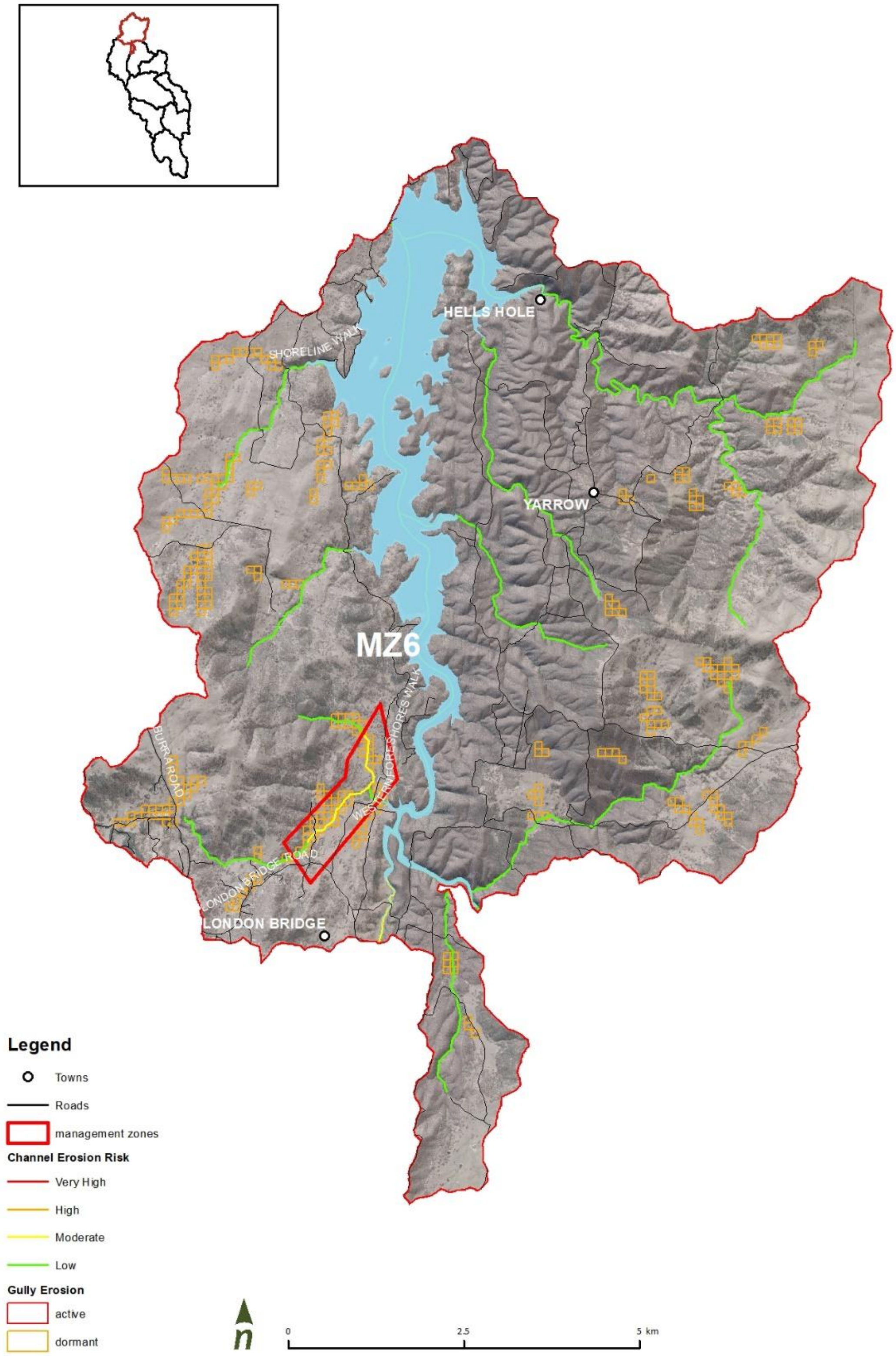


Figure 10. *Overview of management zones in Googong Foreshore Sub-catchment*

<table>
<tr><th colspan="3">Priority management zone 1 – Burra Creek sub-catchment</th></tr>
<tr><td colspan="3">Priority management zone 1 consists of one of the main tributaries entering Burra Creek from the west that runs parallel to Williamsdale Road, including its tributaries. Field investigations were restricted to public road access. Two sites were assessed as part of this management zone. Note that this management zone includes sites BUR 1c, 2a and 2 from the Murrumbidgee Ecological Monitoring Program 2015-21. There were no observable geomorphic changes at these sites between the spring 2015 and Spring 2017 monitoring periods.</td></tr>
<tr><th colspan="3">Condition assessment</th></tr>
<tr><td>Site MZ1a</td><td>Site MZ1a is located along the main Burra Creek tributary that runs parallel to Williamsdale road where it crosses under Badgery Road. The site was initially classed as having moderate instabilities which in turn resulted in it being classed as having a high channel erosion risk. However, following on the ground field assessment of the reach it was identified that the instabilities within the reach were better classed as minor instabilities which lowered the channel erosion risk to moderate.

The site photo (right) show a section of the reach immediately upstream and downstream of Badgery Road. The reach appears to have undergone significant deepening due to incision into the highly erodible soils. The area is almost completely devoid of vegetation due to post 1800s clearing for agricultural purposes. Although there are still some incision processes occurring within the low flow channel, the mid to upper banks appear of low grade, apart from some isolated areas of active gully erosion due to stock impacts.</td><td>
Site MZ1a Looking downstream from Badgery Road bridge</td></tr>
<tr><td>Site MZ1b</td><td>Site MZ1b is located along a tributary of the above-mentioned main Burra Creek tributary where it crosses under Williamsdale Road. The reach is shown in Figure 31 (Appendix E) and was initial classed as having moderate instabilities which in turn resulted in it being classed as having a high channel erosion risk. However, following the ground field assessment of the reach it was identified that the instabilities within the reach were better classed as minor instabilities which lowered the channel erosion risk to moderate. The photos below show a section of the reach immediately upstream and downstream of Williamsdale Road. The reach appears to be largely stable upstream of the crossing, however, beyond this short section and further up the valley, near vertical unstable banks were identified. It is thought that backwater effects from the road crossing and subsequent vegetation establishment (mainly willows) in the accumulated sediments dropping out of the water column has stabilised this particular section. However, this is not representative of the whole reach. Looking downstream of the Williamsdale Road crossing it can be seen that the channel has undergone deepening and is now widening. Again, the area is almost completely devoid of vegetation due to post 1800s clearing for agricultural purposes. There is some grass coverage on the upper banks and revegetation has been attempted. This reach is more representative of the reach as a whole, which has been classified as having a moderate channel erosion risk.</td><td>
Site MZ1b Looking upstream from Badgery Road bridge</td></tr>
</table>

Priority management zone 1 – Burra Creek sub-catchment			
	 *Site MZ1b looking downstream of Williamsdale Road towards confluence with main tributary. Note some revegetation effort*		 *Site MZ1b looking upstream of Williamsdale Road*
Risk assessment			
Likelihood	*Consequence*	*Trajectory*	*Overall Score / risk*
3	3	3	27 – Moderate
Management options			
Bank battering on more severe erosion sites and revegetation works in combination with stock exclusion measures for whole reach.			

<table>
<tr><th colspan="3">Priority management zone 2 – Burra Creek sub-catchment</th></tr>
<tr><td colspan="3">Priority management zone 2 consists of two tributaries of Burra Creek that enter from the northwest of the Burra Creek sub-catchment. Field investigations were restricted to public road access. Two sites were assessed as part of this management zone.</td></tr>
<tr><td colspan="3">Condition assessment</td></tr>
<tr><td>Site MZ2a</td><td>Site MZ2a is located along the southern tributary within the wider priority management zone 2 area where it crosses MacDiarmid Road. The site was initial classed as having moderate instabilities, which in turn resulted in it being classed as having a high channel erosion risk. However, following on the ground field assessment of the reach it was identified that the instabilities within the reach were better classed as minor, which lowered the channel erosion risk to moderate. The figures to the right and below show a section of the reach immediately upstream and downstream of MacDiarmid Road. The reach appears to be largely stable upstream of the crossing, however, beyond this short section and further up the valley, near vertical unstable banks were identified (exposed red/orange soil banks in photos). It is thought that backwater effects from the road crossing has helped in stabilizing this particular section, which is not representative of the whole reach. Looking downstream of the MacDiarmid Road it can be seen that the channel has undergone deepening and widening with some near vertical 3 m banks. Immediately downstream of the crossing, stabilisation works have been implemented in the form of large rock beaching protection in order to prevent undercutting of the road.</td><td>
Site MZ2a looking upstream of MacDiarmid Road</td></tr>
<tr><td>Site MZ1b</td><td>Site MZ2b is located along the northern tributary within the wider priority management zone 2 area where it crosses MacDiarmid Road. The site was initial classed as having moderate instabilities, which in turn resulted in it being classed as having a high channel erosion risk. However, following on the ground field assessment of the reach, it was identified that the instabilities within the reach were better classed as minor, which lowered the channel erosion risk to moderate. The figures to the right and below show a section of the reach immediately upstream and downstream of MacDiarmid Road. The reach appears to be largely stable upstream of the crossing, however, beyond this short section and further up the valley near vertical unstable banks were identified. It is thought that backwater effects from the road crossing has helped in stabilizing this particular section, which is not representative of the whole reach. Looking downstream of the MacDiarmid Road it can be seen that the channel has undergone some deepening and widening, however not as much as the southern tributary at site MZ2a. There is some sediment accumulation along the left bank downstream of the culvert that has been held in place by what appear to be recent stabilisation works in the form of large rock beaching protection.</td><td>
Site MZ2b looking upstream of MacDiarmid Road</td></tr>
</table>

Priority management zone 2 – Burra Creek sub-catchment			
 *Site MZ2a looking downstream of MacDiarmid Road*		 *Site MZ2b looking downstream of MacDiarmid Road*	
Risk assessment			
Likelihood	*Consequence*	*Trajectory*	*Overall Score / risk*
3	2	2	12 – Low
Management options			
Bank battering on more severe erosion sites and revegetation works in combination with stock exclusion measures for whole reach.			

Priority management zone 3 – Burra Creek sub-catchment			
Priority management zone 3 includes a north-western tributary of Burra Creek located near Moore Road and Candy Road. Field investigations were restricted to public road access and, as a consequence, moderate and high-risk channel and gully erosion areas were unable to be directly assessed in the field.			
Condition assessment			
Based on the desktop assessment, the reaches in this management zone were identified as having *moderate* risk of channel erosion. Review of aerial imagery and the DEM indicates that there are possible erosion hotspots on some of the bends, with near vertical banks of up to 3m high. There are also areas of gully erosion identified in the upstream and downstream reaches within this management zone. The area contains agricultural land and is devoid of vegetation coverage.			
Risk assessment			
Likelihood	*Consequence*	*Trajectory*	*Overall Score / risk*
3	2	3	18 – Moderate
Management options			
Bank battering on more severe erosion sites and revegetation works in combination with stock exclusion measures for whole reach.			

Priority management zone 4 – Burra Creek sub-catchment			
Priority management zone 4 includes Burra Creek and a southern tributary near the London Bridge Homestead and the Boundary Trail adjoining the Googong Foreshore reserve. Field investigations were restricted to public road access and, as a consequence, moderate and high-risk channel and gully erosion areas were unable to be directly assessed in the field. Note that this management zone includes site BUR 2c from the Murrumbidgee Ecological Monitoring Program 2015-21. The following information was provided in the report: *There was some slumping of the steep bank adjacent to the riffle habitat between the autumn 2015 and spring 2015 sampling periods. In the subsequent monitoring rounds (autumn 2017 and spring 2017) there has been little or no further slumping in this section of the bank, which may be related to the low rainfall and low flows over this period. Downstream of the main pool, the banks appear to be relatively stable due to the large areas of the face of the bank being vegetated by various grass species. There have been no obvious changes to the channel morphology since the last monitoring period.*			
Condition assessment			
Based on the desktop assessment the reaches in this management zone were identified as having moderate risk of channel erosion. Review of aerial imagery and the DEM indicates that there are possible erosion hotspots on some of the bends, with near vertical banks of up to 5m high. The DEM also indicates that there is potentially large storages of erodible material within the inset units of the floodplains.			
Risk assessment			
Likelihood	*Consequence*	*Trajectory*	*Overall Score / risk*
3	2	3	18 – Moderate
Management options			
Bank battering on more severe erosion sites and revegetation works in combination with stock exclusion measures for whole reach.			

Priority management zone 5 – Burra Creek sub-catchment		
Priority management zone 5 comprises the upstream reach of Burra Creek in the south of the Burra Creek sub-catchment. Field investigations were restricted to public road access. Three sites were assessed as part of this management zone. Note that this management zone includes site BUR 1a from the Murrumbidgee Ecological Monitoring Program 2015-21. There were no observable geomorphic changes at this site between the spring 2015 and Spring 2017 monitoring periods.		
Condition assessment		
Site MZ5a	Site MZ5a is located along a tributary of Cassidy's Creek, where Burra Road crosses the stream. The site is classed as being stable, which in turn resulted in it being classed as having a *Low* channel erosion risk. This site was assessed as it provided the closest access point to the nearby upper reaches of Burra Creek where there is a *high* channel erosion risk. The nearby site MZ5b was slightly up the road from site MZ5a along the same reach. It simply provided a higher vantage point from which to view Cassidy's Creek. From the road crossing looking upstream (photo on right) it can be seen that this reach is stable, most probably in part due to the crossing preventing the head cut from migrating any further upstream. Figure below right looking downstream of the crossing indicates deepening (downstream of the crossing is approximately 2m lower than the upstream side) and widening has occurred. Just downstream of the crossing erosion is exacerbated as this is the location of the confluence for two main tributaries and a further unmapped tributary.	 Site MZ5a looking upstream from Burra Road crossing
Site MZ5b	Examining the photos taken from site MZ5b it can be seen that there are unstable near vertical banks all throughout this reach. The soils in the area consisted of highly dispersible clayey sands interspersed with sands and gravels. There were also notable outcrops of hard bedrock, probably granites. The extent of this bedrock throughout the system is unable to be determined without a more thorough field investigation with access to more of the reach.	 Site MZ5b looking from Burra road towards Cassidy's Creek. Note eroding right bank running through centre of picture. Estimates based on banks upstream and from lidar puts this bank at 3-5m vertical.

Priority management zone 5 – Burra Creek sub-catchment		
Site MZ5c	Site MZ5c is located along Burra Creek just downstream of its confluence with Cassidy's Creek, where the Burra Road crosses the creek. The site is classed as having minor instabilities, which in turn resulted in it being classed as having a *moderate* channel erosion risk. Although the reach immediately upstream of the Burra Road crossing is stable, this is again the backwater effects of the crossing. Eroded banks could be seen approximately 50 m further upstream. Looking downstream from the Burra Creek crossing it could be seen that there were some instabilities overall, with some near vertical banks on the outside bends. Soils in this area were highly dispersible interspersed with sands and larger gravels and cobbles/boulders. Bedrock outcrops were also present in the base of the channel in areas.	 *Site MZ5c Burra Creek looking upstream from Burra Road crossing*

Site MZ5b

Site MZ5b

Site MZ5c Burra Creek looking downstream from Burra Road crossing

Risk assessment			
Likelihood	*Consequence*	*Trajectory*	*Overall Score / risk*
4	3	4	48 – Very High (Based on site MZ5b)

Management options

Bank battering on more severe erosion sites and revegetation works in combination with stock exclusion measures for whole reach.

Priority management zone 6 – Googong Foreshore sub-catchment

Priority management zone 6 comprises the western tributaries entering Googong dam adjacent "The Hut" and western foreshore walk. Field investigations were restricted to public road access. One site was assessed as part of this management zone.

Condition assessment

Site MZ6a	Site MZ6a is located along a small tributary that enters Googong reservoir from the south-west adjacent "The Hut" foreshore area. Overall, the site is classed as having minor instabilities, which in turn resulted in it being classed as having a *moderate c*hannel erosion Risk. As the upper photo on right looking downstream shows, there is some erosion where the stream abuts valley margins and erodible bank material. The material consists of highly erodible soils with interspersed gravels and larger cobbles/boulders. Looking upstream (lower photo) it can be seen that there is a wide floodplain but again in the distance is some near vertical banks indicating erosion on a bend. It should be noted that this tributary outfalls to a smaller dam (that is not part of the main Googong Reservoir) before entering Googong Reservoir. Although this dam would act as a sediment sink for some eroded material entering from upstream, finer sediments are still likely to pass through the system and during high flow events the sediment loads of all fractions will be high. As well as the identified channel erosion management zones there are large areas of hillslope erosion that should be managed by changes in land use practices.	 *Site MZ6a*  *Site MZ6a*

Risk assessment

Likelihood	*Consequence*	*Trajectory*	*Overall Score / risk*
4	3	3	36 – High

Management options

Bank battering on more severe erosion sites and revegetation works in combination with stock exclusion measures for whole reach.

7 Management options

7.1 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 is given in Table 7.

Table 7. 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, and as outlined in Table 7, 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:
    - o 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 Googong 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 11.

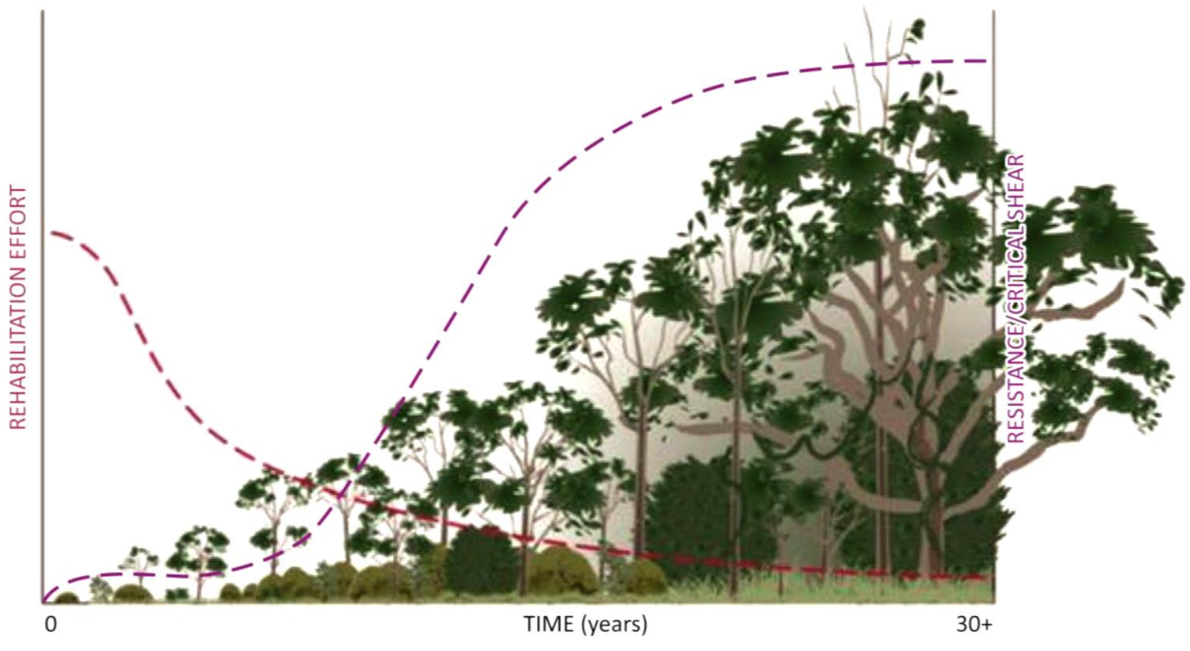


Figure 11. *Progressive long-term improvement in river health and erosion resistance with gradual reduction in rehabilitation effort (source: Department of Sustainability and Environment (2004)). This is the trajectory concept.*

Large lengths of stream bank within the priority management zones are currently steep with exposed erodible soil deposits. 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 Googong Reservoir as well as reduce the impact on adjacent land uses.

Improved management of riparian zones and allowing vegetation establishment throughout the priority management zones will reduce sediment loads. However, vegetation establishment is currently threatened through unrestricted stock access to waterways within the zones.

7.2 Effect of stock on waterways

The impacts of stock on waterways in the priority management zones, and in particular the effect they are having on increased sediment supply to the downstream receiving system, were apparent during the field inspections. Direct structural damage and weakening of the banks caused by stock together with the destruction of riparian vegetation was observed throughout the management zones.

Stock destroy riparian plants by consuming or simply trampling them. As well as providing a barrier between bare soil and direct rainfall and flow, the roots of riparian vegetation are important for providing structural support within soils. Stock also cause direct structural damage to the underlying soils via trampling the banks as they access water and vegetation. This damage can lead to mass failure as well as gullying along stock paths. As well as their impacts on bank stability, stock also cause pollution to waterways through defecation into streams.

Evidence of unrestricted stock access, causing bank instabilities and therefore acting as sources of sediment within the management zones, are shown below in Figure 12.

Figure 12. *Example of stock impacted waterways within Googong catchment. Note informal tracks along banks*

7.3 Recommended management options

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

- Stock exclusion measures
- Revegetation works
- Bank battering and / or toe protection on more severe erosion sites

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. Two options for riparian management of varying cost have been developed and their effect on risk within each priority management zone analysed.

Option 1 involves stock exclusion and facilitated revegetation (Figure 13). Stock exclusion can involve any number of methods for keeping stock from within an approximate 40 m riparian buffer zone. Stock access to the riparian zone should be restricted through fencing. Defined watering points could be included in the design of a stock management plan. 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.

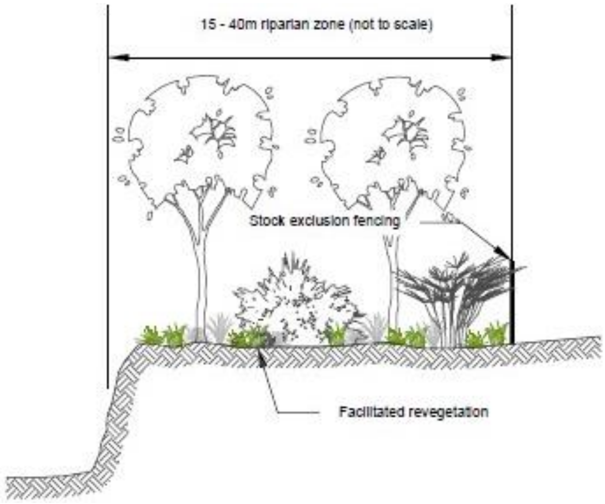


Figure 13. *Option 1 - Stock exclusion and facilitated revegetation*

Option 2 involves stock exclusion, isolated bank reprofiling, isolated toe protection and revegetation works (Figure 14). This option would also involve keeping stock from within the 40 m riparian zone each side of the waterway; however, the 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 and / 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.

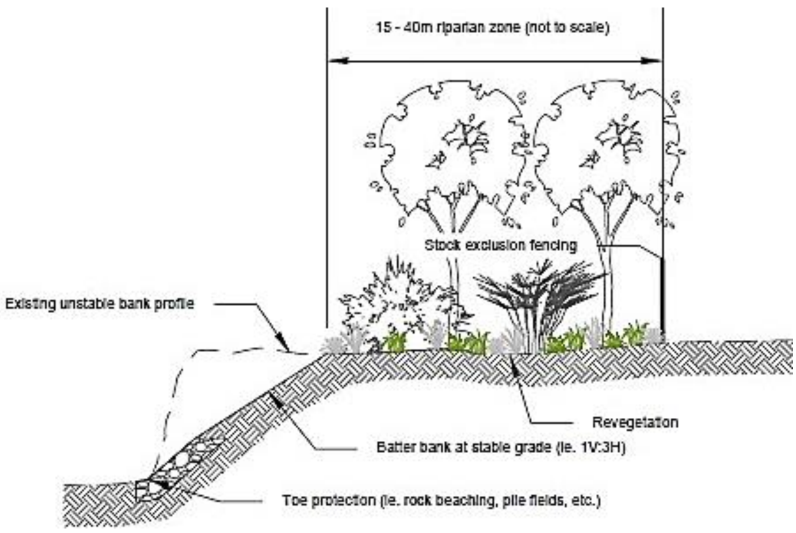


Figure 14. *Option 2 - Stock exclusion, isolated bank reprofiling, isolated toe protection and revegetation works*

To assess the outcome that each of the two 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 8.

To decrease the risk within priority management zones 3, 4 and 6 to *Low*, the implementation of Option 1 would be sufficient. The risk rating of priority management zone 2 is already at *Low*, so Option 1 would also be sufficient.

To reduce the risk rating within priority management zone 1 to *Low*, Option 2 would need to be implemented.

Implementing Option 1 within priority management zone 5 would reduce the risk rating to *High*; however implementing Option 2 would further reduce this to *Moderate*.

The recommended works for each priority management zone based on the revised risk assessment is shown in Figure 15. The short-, medium- and long-term priority of each management zone is also outlined in Figure 16. The priority assessment is based on the current level of risk.

Table 8. 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	
Priority management zone	*Likelihood*	*Consequence*	*Risk*	*Revised likelihood*	*Risk*	*Revised likelihood*	*Risk*
1 – Western tributary of Burra Creek running parallel to Williamsdale road	Moderate	Moderate	Moderate	Unlikely	Moderate	Rare	Low
2 – Western tributaries of Burra Creek in vicinity of Macdiarmid and Plummers Roads	Moderate	Minor	Low	Unlikely	low	Rare	Low
3 – Northern most western tributary of Burra Creek	Moderate	Minor	Moderate	Unlikely	low	Rare	Low
4 – Eastern tributary of Burra Creek adjacent Boundary Trail	Moderate	Minor	Moderate	Unlikely	low	Rare	Low
5 – Upstream reach of Burra Creek parallel to Burra Rd near Captain Robertson Drive	Likely	Moderate	Very high	Moderate	High	Unlikely	Moderate
6 – Western tributaries entering Googong dam adjacent The Hut" and western foreshore walk	Likely	Moderate	High	Moderate	Moderate	Unlikely	Moderate

Many of the reaches within the Googong catchment have been classified as having low to moderate sediment generation potential. However, despite the low rates of channel adjustments and/or sediment availability, collectively these reaches still represent a major sediment source to Googong Reservoir. As a result, improved riparian management (protection or restoration of riparian vegetation, exclusion fencing, weed/pest management, stock management etc.) in these reaches remains a critical part of ongoing sediment reduction programs. Restricting ground management responses to the priority reaches discussed above is unlikely to achieve the desired level of catchment reductions in sediment loads.

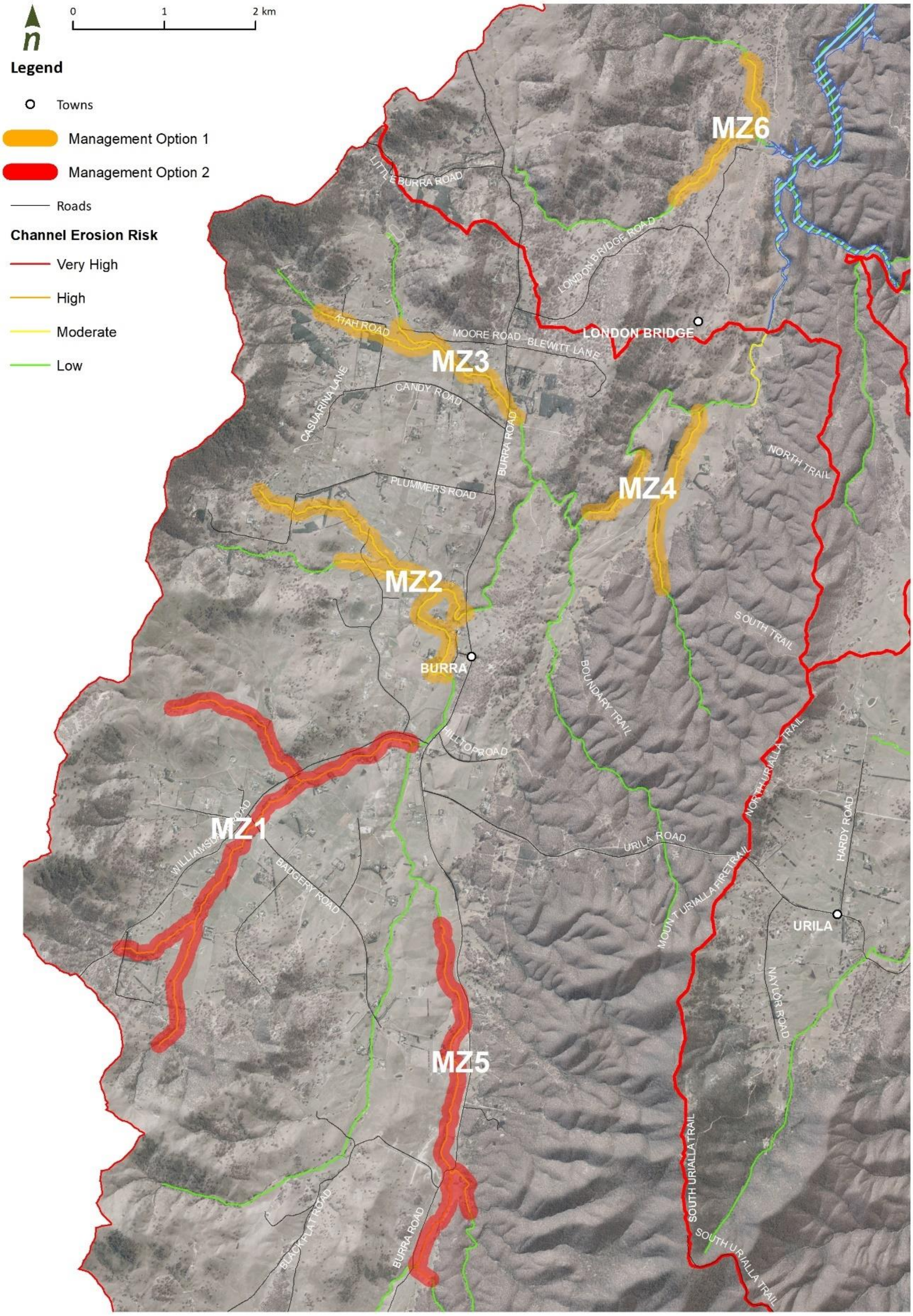


Figure 15. *Recommended management options for each management zone within Googong catchment*

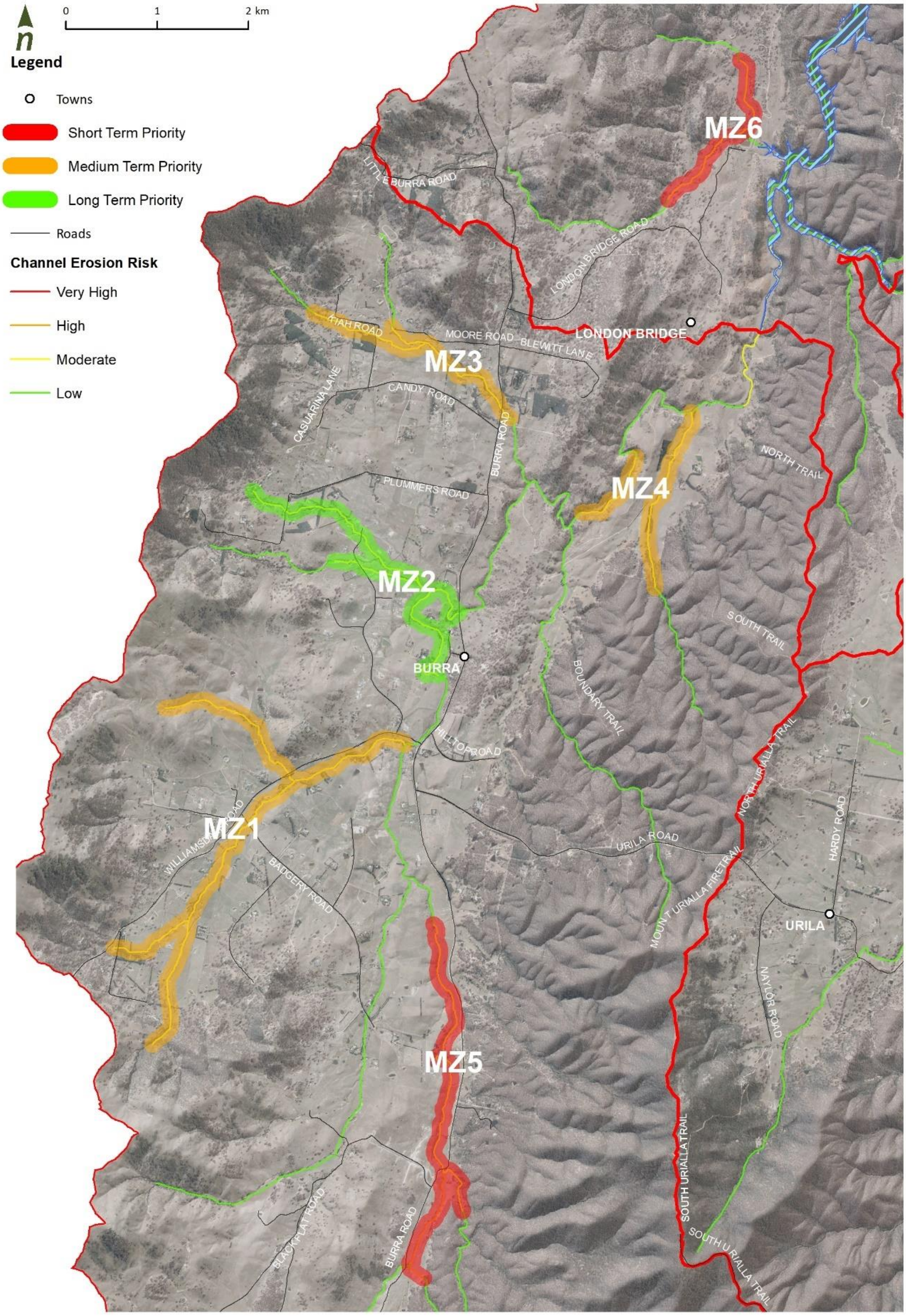


Figure 16. *Priority ratings for each management zone within Googong catchment*

7.4 Monitoring and maintenance

Establishing a monitoring and maintenance program is an important component of implementing the proposed works. Regular maintenance of the works is required to ensure their integrity is retained and longevity maximised. A specific maintenance program is required that clearly defines routine maintenance schedules, especially early on when vegetation is becoming established, and addresses specific flow event inspections and responses.

Monitoring the condition of works will be important for identifying any new issues and quantitatively assessing the success or failure of the works. A specific monitoring program should be developed that can be used to monitor condition across all the works.

The works should be routinely inspected approximately every month during the first year and following high flow events during the vegetation establishment stage (first 2 to 3 years). Following this stage, inspections should be event-driven.

8 Bibliography

[1] Environment and Sustainable Development Directorate, "Conservation Planning and Research, Program Report 2011 - 2013," ACT Government, Canberra, 2013.

[2] GHD, *GHD 2018, Murrumbidgee Ecological Monitoring Program 2015-21 Sentinel Monitoring - Autumn 2018. Report prepared for Icon Water,* 2018.

[3] Murrumbidgee Catchment Management Authority, "Upper Murrumbidgee Actions for Clean Water Plan," State of New South Wales, Department of Trade and Investment, Regional Infrastructure Services, Wagga Wagga, NSW, 2012.

[4] " https://maps.six.nsw.gov.au/arcgis/rest/services/public/NSW_Imagery/MapServer," [Online].

[5] H. Lu, J. Gallant, I. Prosser, C. Moran and G. Priestley, "Prediction of sheet and rill erosion over the Australian Continent, incorporating monthly soil loss distribution. CSIRO Land and Water Technical Report_13/01," CSIRO Land and Water , 2001.

[6] Office of Environment and Heritage, 2018. [Online]. Available: https://datasets.seed.nsw.gov.au/dataset/aea6e148-2c60-4de3-8233-2bc7ade4b4d2.

[7] B. Starr, "Googong Catchment, The state drainage network and trends in catchment condition since 1944, Prepared for ACTEW Corporation by Barry Starr Pty Ltd., Torrens, ACT," 2000.

[8] Bureau of Meteorology, "Period 1961 - 1990".

[9] NSW Government - Department of Environment and Heritage, "Soil Erosion," 2018. [Online]. Available: https://climatechange.environment.nsw.gov.au/Impacts-of-climate-change/Soil/Soil-Erosion.

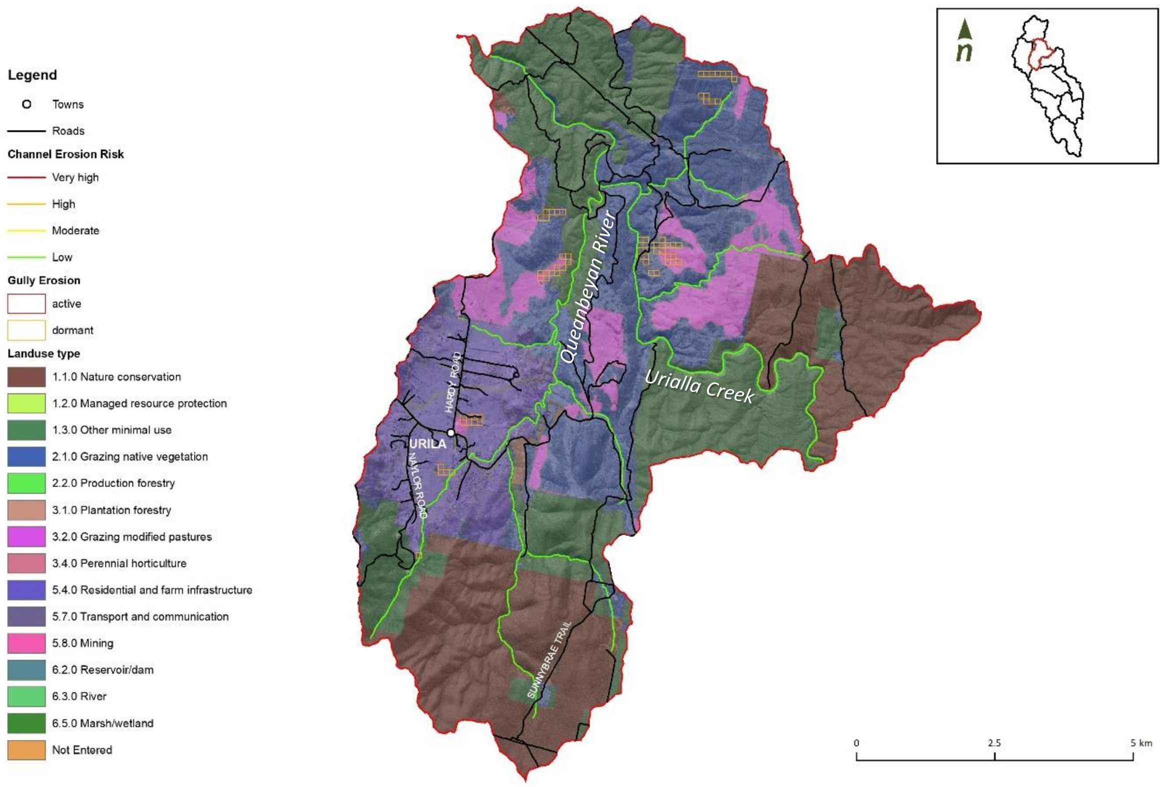
[10] *The Lake Burley Griffin Catchment Protection Scheme 1965-1998, A Short History.*

Appendix A
Sub-catchment profiles

Sub-catchment overview: G1 (Urialla Creek)

The G1 (Urialla Creek) sub-catchment forms the north east extent of the overall Googong catchment and covers approximately 76 km². The main waterways within the sub-catchment are: the Queanbeyan River, which flows through the sub catchment from south to north where it discharges at the sub catchment outlet directly to Googong reservoir; and Urialla Creek which flows through the west of the catchment from south to north and then discharges into the Queanbeyan River. The geology and topography of the sub catchment creates primarily confined streams throughout the ranges that extend across the majority of the sub catchment.

The main land use type within the sub catchment is Nature Conservation, covering 58% of the area. Grazing native vegetation and Other minimal use each cover 16%.



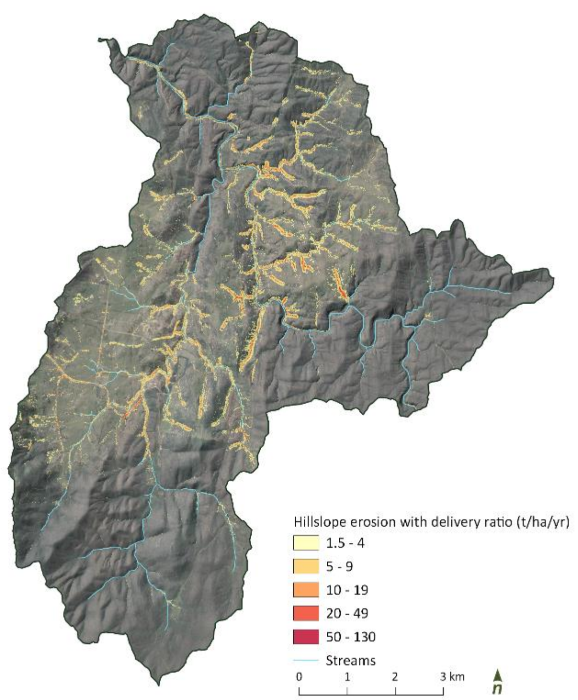
Hillslope erosion risk — Moderate

Hillslope erosion hotspots occur predominantly within the cleared agricultural land west and north west of Corner Hill. The steeper valleys within the range to the north of the Queanbeyan River display the highest sediment losses. Other hotspots lie where streams run adjacent to road surfaces, such as those along Urila Rd in the south -west.

Channel erosion risk — Low

The overall channel erosion risk for the sub-catchment has been classed as low. All reaches within the sub-catchment have been classified as a low channel erosion risk. From the desktop assessment, these reaches were identified as being stable, which corresponds to low erosion potential as well as having low sediment availability.

The low channel erosion risk is due to the underlying geology and the riparian vegetation coverage. The underlying geology within the catchment is mainly sandstone, mudstone, slate and granite. Most of the reaches within the catchment are located within land use areas that have not been heavily modified and as a result have good to moderate riparian vegetation coverage. Where the land is grazed it is classed as *grazing native vegetation* which may account for the better riparian vegetation compared to more intensively grazed land use areas.



Gully erosion risk — Low

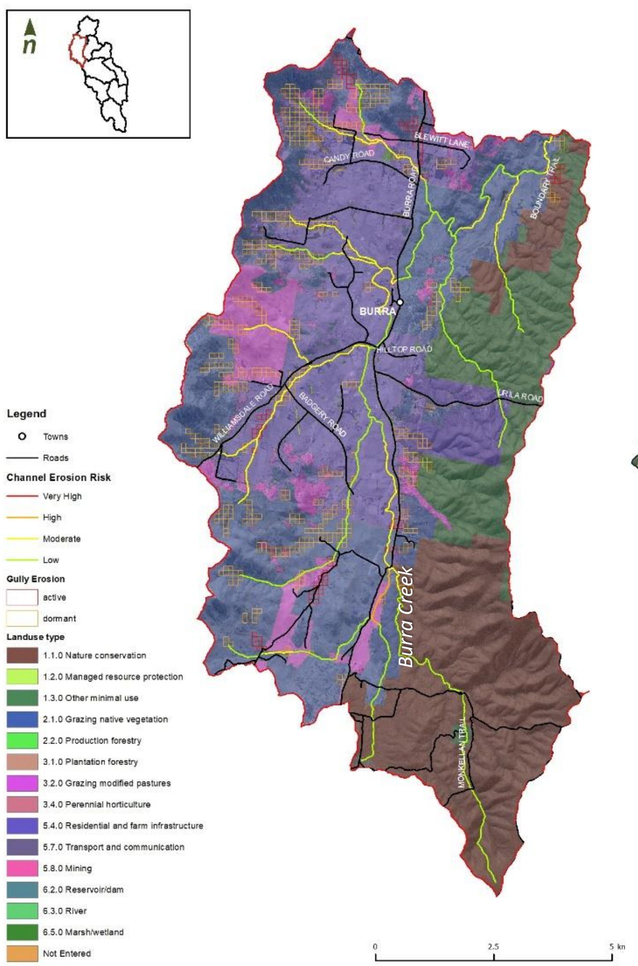
The overall gully erosion risk for the sub catchment is classed as low: gully erosion cover less than 1% of the entire sub-catchment. All of the identified gully erosion has been assessed as dormant (i.e. inactive in the last 10 years). No active gully erosion was identified from the desktop assessment. It should be noted that the current gully erosion assessment can only be used as a prediction for future gully erosion risk across the sub-catchment based on current conditions. As conditions change throughout the catchment (i.e. changes in rainfall patterns, land use changes, etc.) this risk can increase or even decrease.

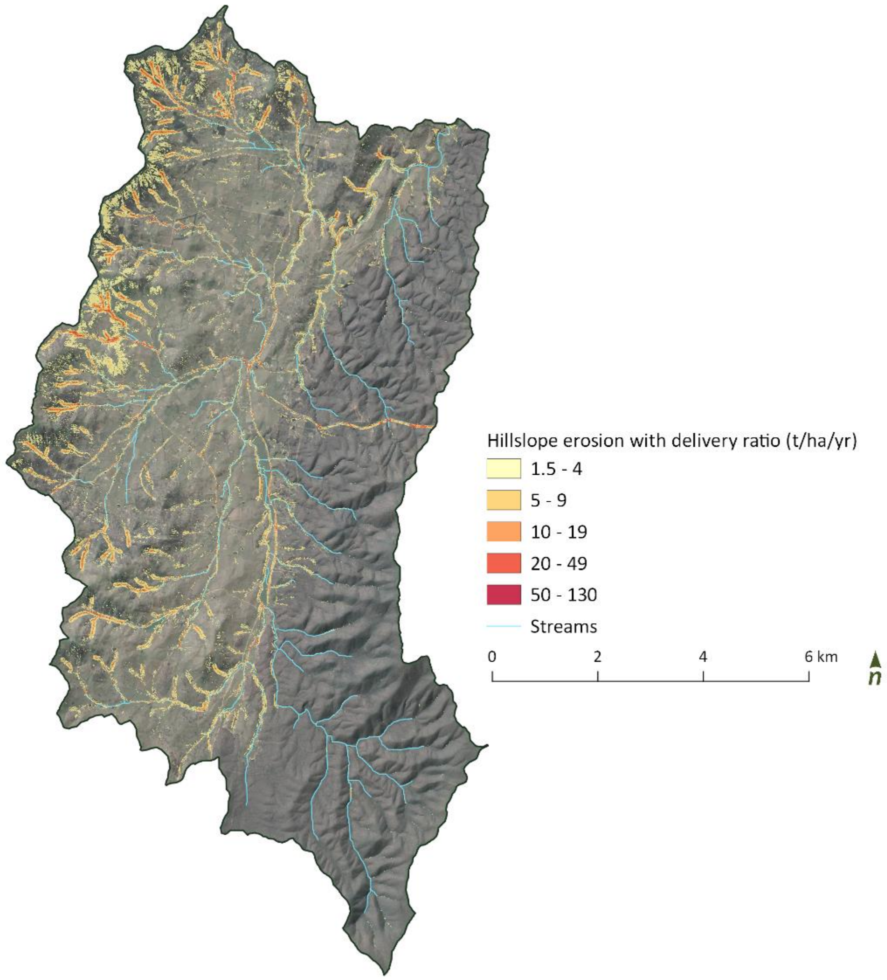
Gully erosion is primarily present throughout the north of the sub-catchment as well as a couple of isolated areas in the west. The majority of the identified gully erosion is situated within grazing land (modified pastures and native vegetation). The soils in this sub-catchment consist of highly erodible Kurosols. With little coverage from vegetation, Kurosols are highly susceptible to erosion from direct rainfall. The lack of vegetation also provides little structural support for the soils leading to further erosion.

Sub-catchment overview: G2 (Burra Creek)

The G2 (Burra Creek) sub-catchment forms the north west extent of the overall Googong catchment and covers approximately 99 km². The main waterway within the sub-catchment is Burra Creek which drains south to north where it discharges directly to Googong reservoir. The geology and topography of the sub catchment creates primarily confined streams throughout the ranges that border the east of the catchment while the streams in the lower parts of the catchment and lower relief ranges bordering the west of the sub catchment are slightly confined (terrace) or unconfined.

The main land use type throughout the sub-catchment is Nature Conservation which covers 36%. Other minimal use (areas that have residual native cover) comprises another 32% and grazing native cover spans 22%.





Hillslope erosion risk — High

The RUSLE analysis revealed relatively high rates of erosion along the steeper western slopes of the sub catchment. The applied delivery ratio highlights the key areas in proximity to streamlines where sediment transport is most likely to occur. Numerous farm dams exist along these streamlines, which were not considered as part of this analysis. Road areas are also highlighted as erosional hotpots, particularly where they intersect with stream lines.

Channel erosion risk — Moderate – High

The channel erosion risk assessment has identified a significant number of reaches within the sub catchment as having *very high, high* or *moderate* channel erosion risk. These reaches were identified from the desktop assessment as having minor to moderate instabilities which corresponds to moderate to high erosion potential as well as having high or very high sediment availability.

The majority of the high and very high risk reaches consist of the tributaries of Burra Creek that drain the western extent of the catchment. There is also a short reach in the south west of the catchment and another reach in the north east identified as being very high risk. A large reach of Burra Creek in the south is identified as being moderate risk. The soils and underlying geology within these high risk areas, which consist of mainly highly erodible kurosols and soft Tuff. combined with the fact that most of these reaches are located within land use areas that have been modified and as a result have very poor riparian vegetation coverage explain why these reaches are higher risk.

Gully erosion risk — Moderate

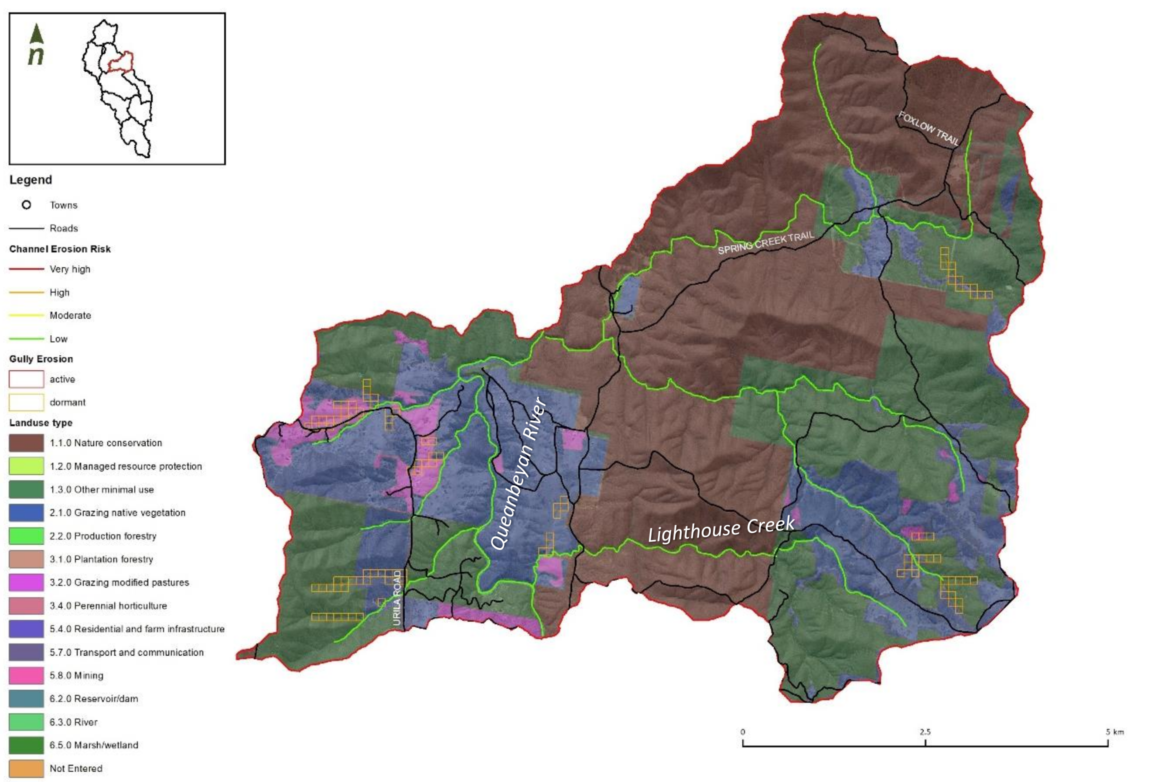
The Gully erosion risk for the sub catchment is classed as moderate: gully erosion cover approximately 7% of the sub-catchment. Of this identified gully erosion, 6% has been assessed as dormant (i.e. inactive in the last 10 years) whilst 1% has been identified as active gully erosion. It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment for current conditions. As conditions change throughout the catchment (i.e. changes in rainfall patterns, land use changes, etc.) this risk can increase or even decrease.

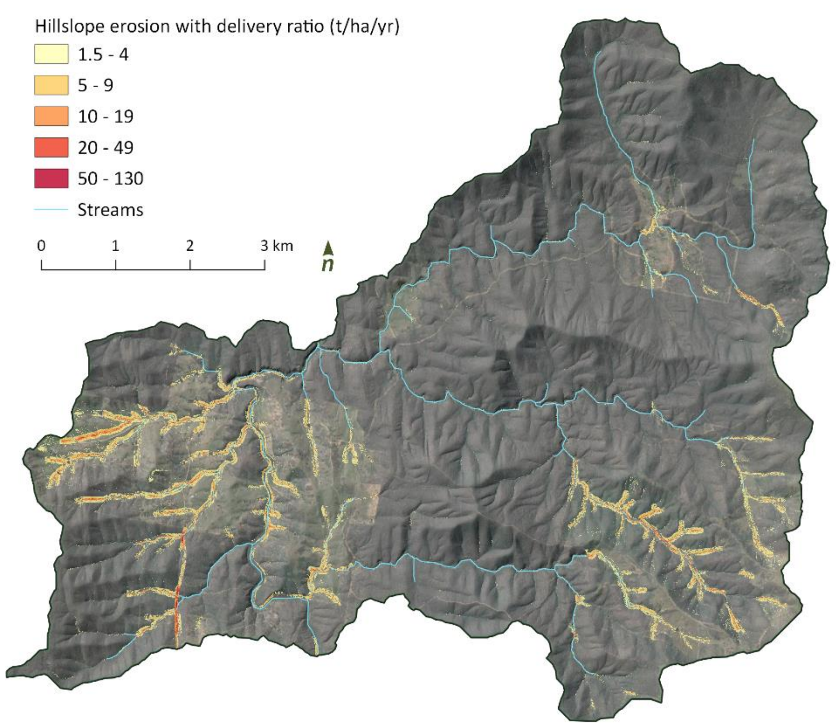
Gully erosion is primarily present throughout the western half of the sub catchment and is particularly concentrated along the western hillslopes. Active gully erosion has been identified adjacent to a number of the western tributaries of Burra Creek as well the lower reaches of some of the eastern tributaries. The soils in these areas consist of highly erodible Kurosols which, with little coverage from vegetation, are highly susceptible to gully erosion caused by overland runoff and direct rainfall. The lack of vegetation also provides little structural support for the soils leading to further erosion.

Sub-catchment overview: G3 (Lighthouse Creek)

The G3 (Lighthouse Creek) sub-catchment is located along the eastern edge of the main Googong catchment and covers approximately 60 km². The main waterways within the sub-catchment are the Queanbeyan River, which flows through the sub catchment from south to north and lighthouse Creek which drains the mountain ranges in the south east of the sub-catchment before discharging into the Queanbeyan River. There are also two unnamed tributaries that drain the ranges to the east and north east of the catchment. The geology and steep topography of the sub catchment creates confined and significantly confined streams throughout the entire sub catchment.

Nature Conservation comprises most of the sub catchment (76%). The remainder is made up of Other minimal use (17%), Grazing native vegetation (7%) and Grazing modified pastures (1%).





Hillslope erosion risk — Low - moderate

Hillslope erosion hotspots are located predominantly where land clearing has occurred and there is relatively little vegetative cover. These include the eastward drainage lines which intersect Urila road in the west and the streams running within the eastern agricultural areas and intersecting the Ballinfade and Spring Creek fire trails.

Channel erosion risk — Low

The channel erosion risk assessment has identified all reaches within the sub-catchment as having *low* channel erosion risk. These reaches were identified from the desktop assessment as being stable which corresponds to low erosion potential as well as having low sediment availability.

The underlying geology within this catchment, which consists of mainly of sandstone, mudstone, slate and granite, combined with the fact that most of the reaches within the catchment are located within land use areas that are either conservation or have not been heavily modified and as a result have good to moderate riparian vegetation coverage explain why these reaches are low risk. Where the land is grazed it is classed as *grazing native vegetation* which may account for the better riparian vegetation compared to more intensively grazed land use areas.

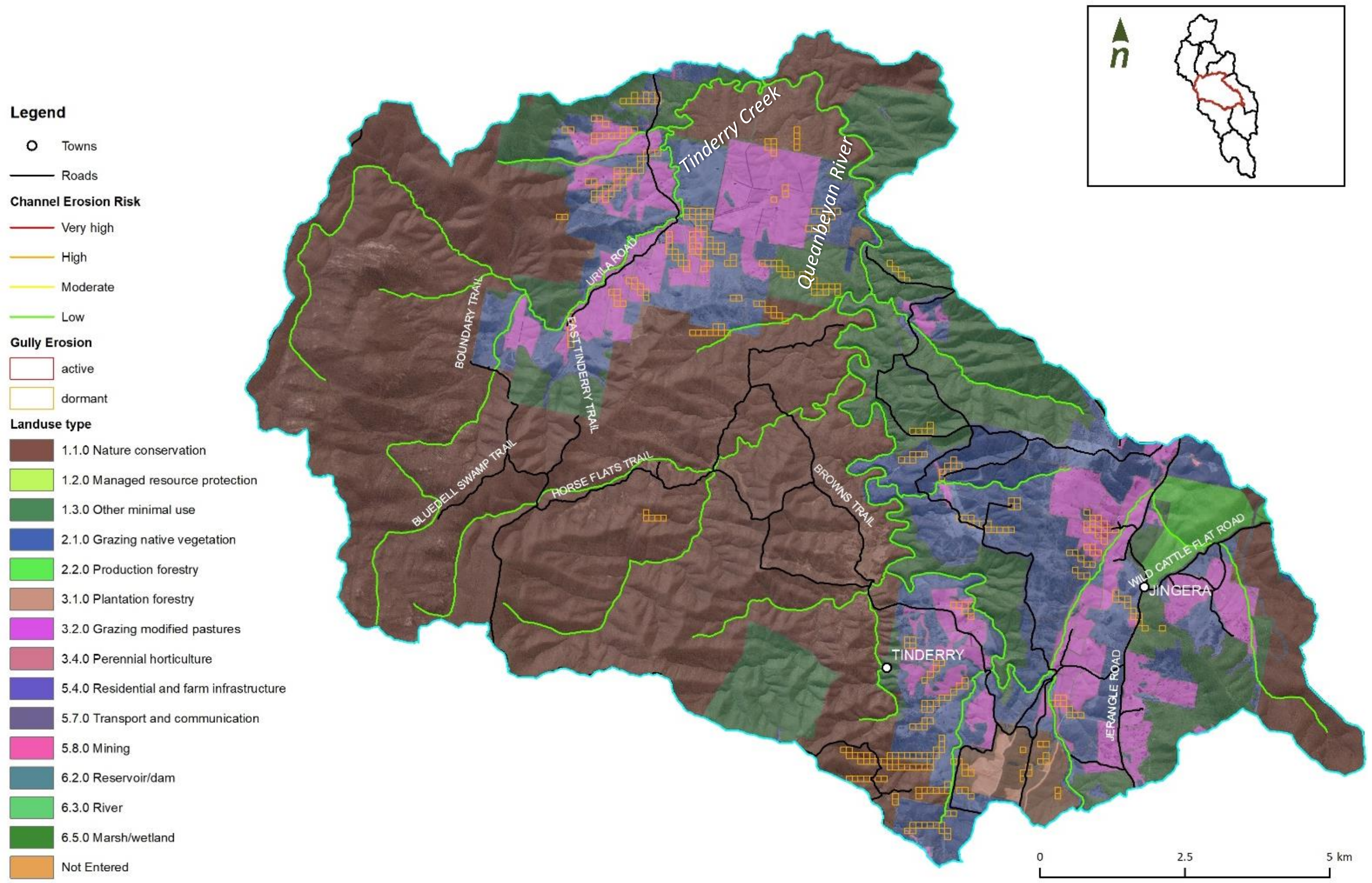
Gully erosion risk — Low

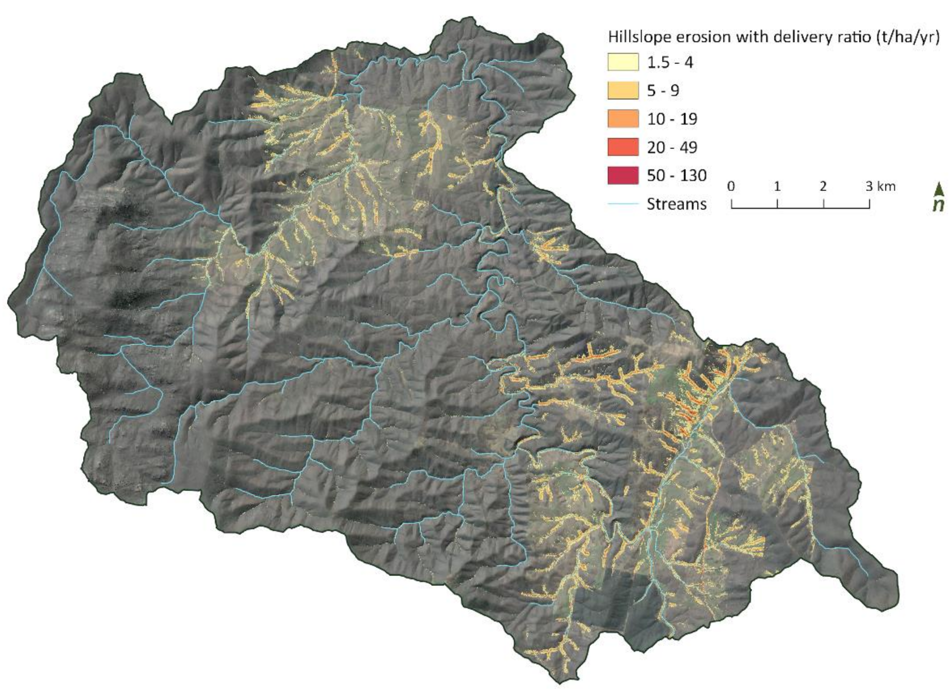
The Gully erosion risk for the sub catchment is classed as low: gully erosion cover less than 2% of the entire sub-catchment. All of the gully erosion has been identified as being dormant (i.e. inactive in the last 10 years). No active gully erosion was identified from the desktop assessment. It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment for current conditions. As conditions change throughout the catchment (i.e. changes in rainfall patterns, land use changes etc.) this risk can increase or even decrease.

Gully erosion is primarily present along tributaries that enter the Queanbeyan River from the west. The majority of the identified gully erosion is situated within, or adjacent to, land that is classed as grazing (modified pastures and native vegetation).

Sub-catchment overview: G4 (Tinderry Creek)

The G4 (Tinderry Creek) sub-catchment is located towards the centre of the overall Googong catchment and is the largest sub-catchment, covering approximately 156km². The main waterways within the sub-catchment are the Queanbeyan River, which flows through the sub-catchment from south to north and Tinderry Creek which drains the mountain ranges in the east of the sub-catchment before discharging into the Queanbeyan River. The geology and steep topography of the sub-catchment creates confined and significantly confined streams throughout the entire sub-catchment. Nature Conservation comprises most of the sub-catchment (76%). The remainder is made up of Other minimal use (12%), Grazing native vegetation (7%), Grazing modified pastures (3%) and Transport & communication (0.5%).





Hillslope erosion risk — Low-Moderate

Hillslope Erosion hotspots are located predominantly where clearance has occurred, particularly within Tindery Park, Big Tinderry and in the south-east, along the cleared slopes draining south-east towards Jerangle Rd. The steep slopes of docking creek and its tributaries are hotspots despite their vegetative cover.

Channel erosion risk — Low

The channel erosion risk assessment has identified all reaches within the sub-catchment as having *low* channel erosion risk. These reaches were identified from the desktop assessment as being stable which corresponds to low erosion potential as well as having low sediment availability.

The underlying geology within this catchment, which consists of mainly of sandstone, mudstone, shale, quartzite, phyllite, slate in the west and granites in the east, combined with the fact that most of the reaches within the catchment are located within land use areas that are either conservation or have not been heavily modified and as a result have good to moderate riparian vegetation coverage explain why these reaches are low risk. Where the land is grazed it is primarily classed as *grazing native vegetation* which may account for the better riparian vegetation compared to more intensively grazed land use areas

Gully erosion risk — Low

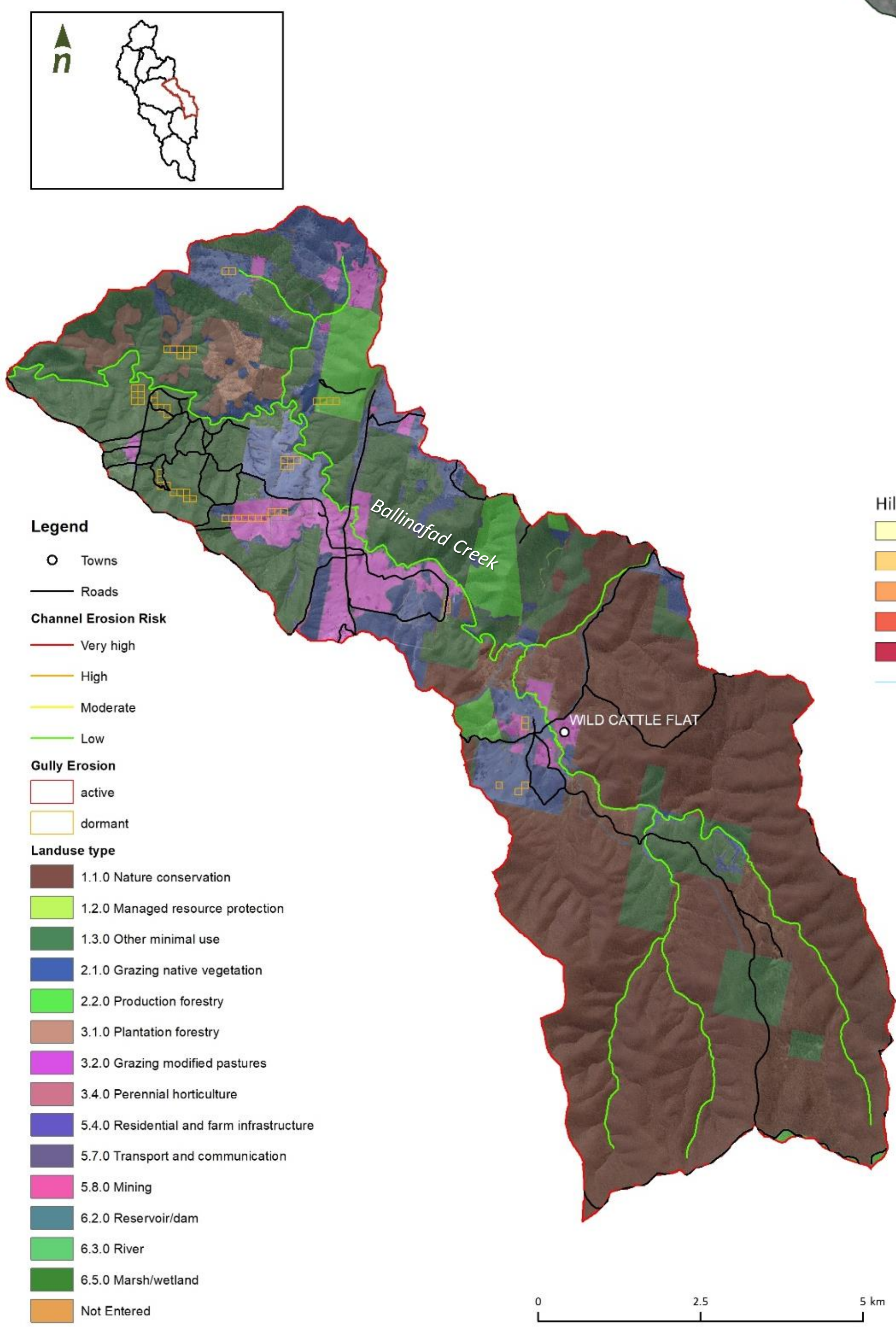
The gully erosion risk for this sub-catchment is classed as low: gully erosion cover less than 2% of the entire sub-catchment. All of the gully erosion has been identified as dormant (i.e. inactive in the last 10 years). No active gully erosion was identified from the desktop assessment. It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment for current conditions. As conditions change throughout the catchment (i.e. changes in rainfall patterns, land use changes, etc.) this risk can increase or even decrease.

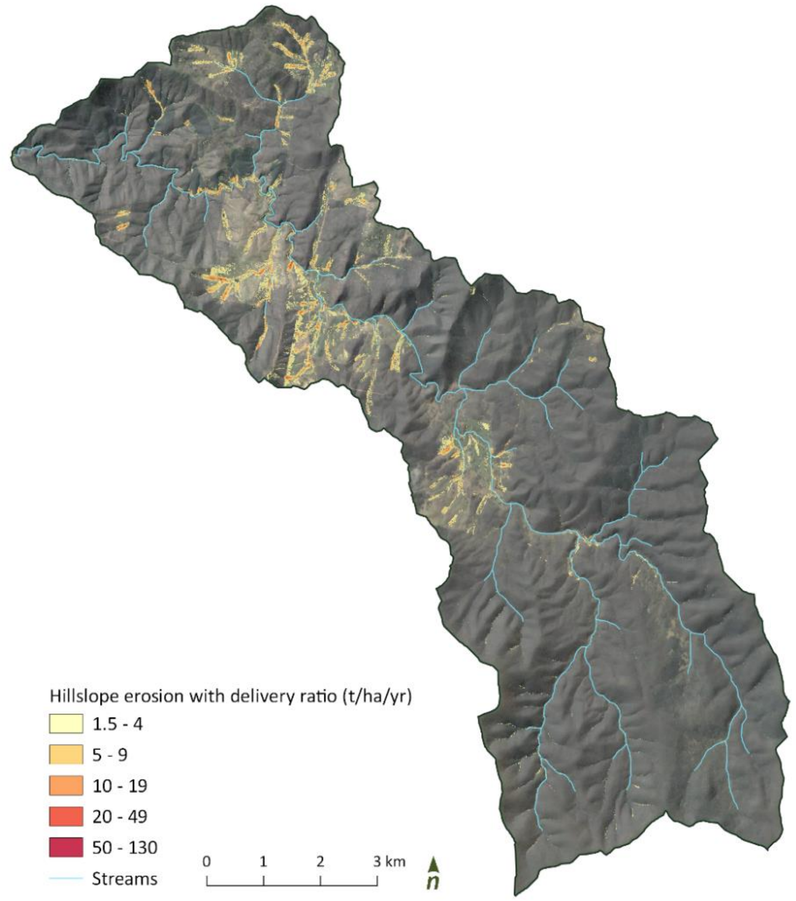
Gully erosion is primarily throughout the lower reaches of the catchment. The majority of the identified gully erosion is situated within, or adjacent to, land that is classed as grazing (modified pastures and native vegetation). Soils throughout the catchment are primarily Kurosols in east and Kandosols in the west, both are highly erodible if vegetation coverage is poor.

Sub-catchment overview: G5 (Ballinafad Creek)

The G5 (Ballinafad Creek) sub-catchment is situated along the east of the Googong catchment and covers approximately 75km². The main waterway within the sub-catchment is Ballinafad Creek which drains south to north where it discharges at the sub-catchment outlet to the Queanbeyan River. The geology and topography of the sub-catchment creates primarily confined and partly streams throughout the ranges that border the east of the catchment. There are some reaches towards the valley areas that are unconfined.

Nature Conservation comprises almost half of the sub-catchment (47%). Production forestry constitutes 32% and the remainder is comprised of Other minimal use (14%), Grazing native vegetation (5%) and Grazing modified pastures (1%).





Hillslope erosion risk	Low - Moderate

The hillslope erosion assessment has indicated there are erosional hotspots located predominantly where clearance has occurred, particularly along streams which intersect Jerangle road those draining towards Ballina fad creek to the north and also the cleared drain lines along wild cattle flat.

Channel erosion risk	Low

The channel erosion risk assessment has identified all reaches within the sub-catchment as having *low* channel erosion risk. These reaches were identified from the desktop assessment as being stable which corresponds to low erosion potential as well as having low sediment availability.

The underlying geology within this catchment, which consists of mainly of sandstone, mudstone, shale, quartzite, phyllite and slate, combined with the fact that most of the reaches within the catchment are located within land use areas that are either conservation or have not been heavily modified and as a result have good to moderate riparian vegetation coverage explain why these reaches are low risk. Where the land is grazed it is primarily classed as *grazing native vegetation* which may account for the better riparian vegetation compared to more intensively grazed land use areas

Gully erosion risk	Low

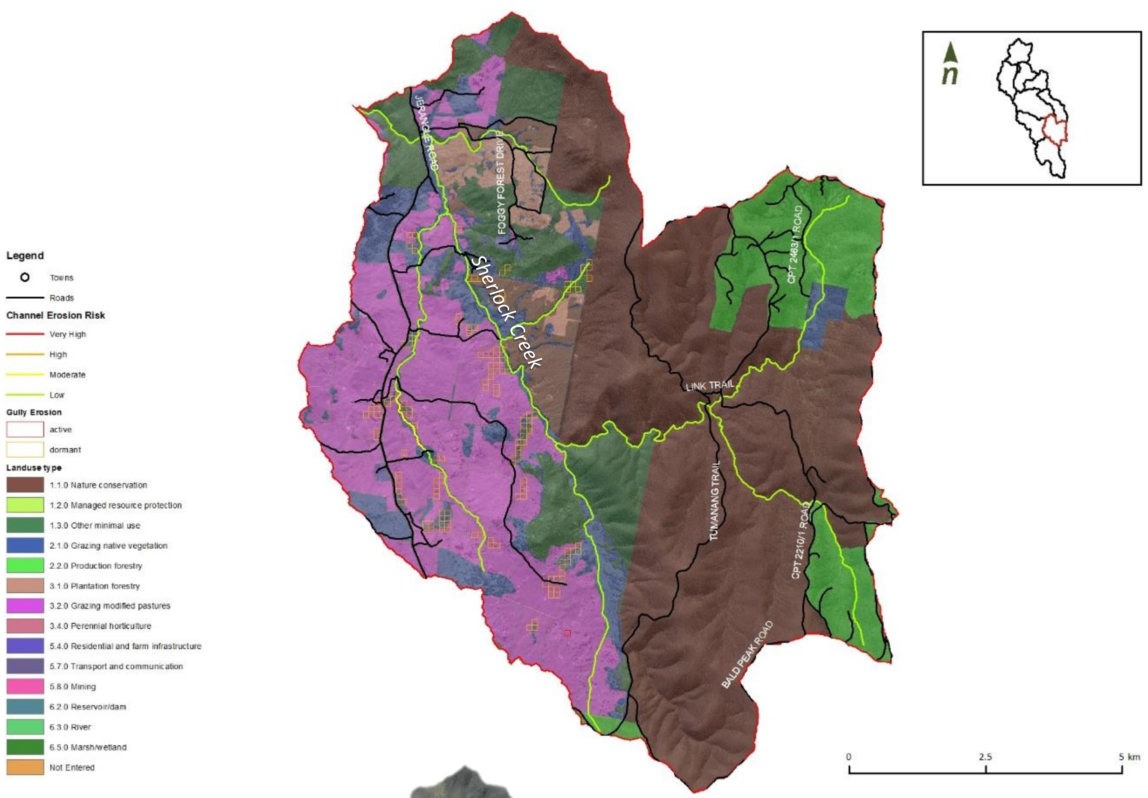
The gully erosion risk for the sub-catchment is classed as low, gully erosion cover less than 1% of the entire sub-catchment and of this all of it has been identified as being dormant (i.e. inactive in the last ~10 years) No active gully erosion was identified from the desktop assessment. It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment for current conditions. As conditions change throughout the catchment (i.e. changes in rainfall patterns, land use changes, etc.) this risk can increase or even decrease.

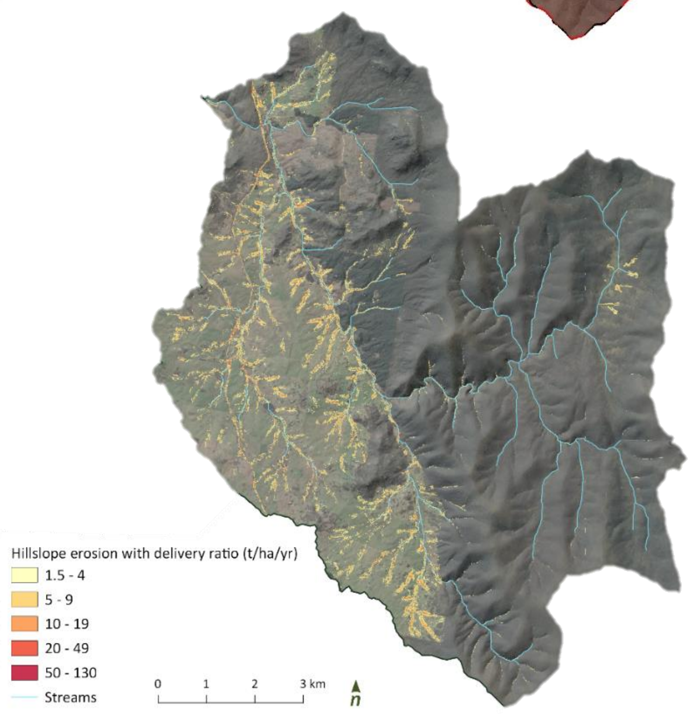
Gully erosion is primarily throughout the lower reaches of the catchment. The majority of the identified gully erosion is situated within, or adjacent to, land that is classed as grazing (modified pastures and native vegetation). Soils throughout the catchment are primarily Kurosols across the majority of the catchment and Kandosols in the south, both are highly erodible if vegetation coverage is poor.

Sub-catchment overview: G6 (Sherlock Creek)

The G6 (Sherlock Creek) sub-catchment is located in the south east of the overall Googong catchment and covers approximately 96km². The main waterways within the sub-catchment are Sherlock Creek which flows south to north through the centre of the catchment and discharges to the Queanbeyan River, Crow Valley Creek and Two Mile Creek which drain the ranges along the east of the catchment before discharging into Sherlock Creek, and Careys creek which drains the western half of the catchment before discharging to Sherlock Creek. the Queanbeyan River. Crow Valley and Two Mile Creeks are primarily confined and partly confined systems due toe the steep topography and underlying geology. The lower reaches of Careys and Sherlock Creeks are mostly partly confined whilst the upper reaches of both creeks are unconfined.

Half (50%) the sub-catchment is assigned to Nature Conservation. Production forestry constitutes 34% and the remaining 16% is comprised of Grazing modified pastures (7%) and grazing native vegetation (3%).





Hillslope erosion risk | Low - Moderate

Erosional hotspots are scattered throughout where clearance has occurred and roughly correlate to where a stepped increase in gradient is observed. Most of these hotspots highlight gullies on agricultural land.

Channel erosion risk | Low

Overall the channel risk for this sub-catchment has been classed as Low. There was one reach along Careys Creek that was identified as having *moderate* channel erosion risk. This reach was identified from the desktop assessment as having minor instabilities which corresponds to moderate erosion potential as well as having very high sediment availability. The remaining reaches within the sub-catchment were identified as having *low* channel erosion risk. These reaches were identified from the desktop assessment as being stable which corresponds to low erosion potential as well as having low sediment availability.

The underlying geology within this catchment, which consists of mainly of sandstone, mudstone, shale, quartzite, phyllite, slate, granodiorite and adamellite combined with the fact that most of the reaches within the catchment are located within land use areas that are either conservation or have not been heavily modified and as a result have good to moderate riparian vegetation coverage explain why most of the reaches within the sub-catchment are low risk. The underlying soils of the high risk reach along Careys Creek consists of mainly highly erodible Rudosols and Tenosols, combined with the fact that this reach is located within land use area classed as *grazing modified pastures* and as a result has very poor riparian vegetation coverage explain why this reach is high risk.

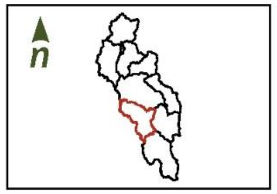
Gully erosion risk | Low

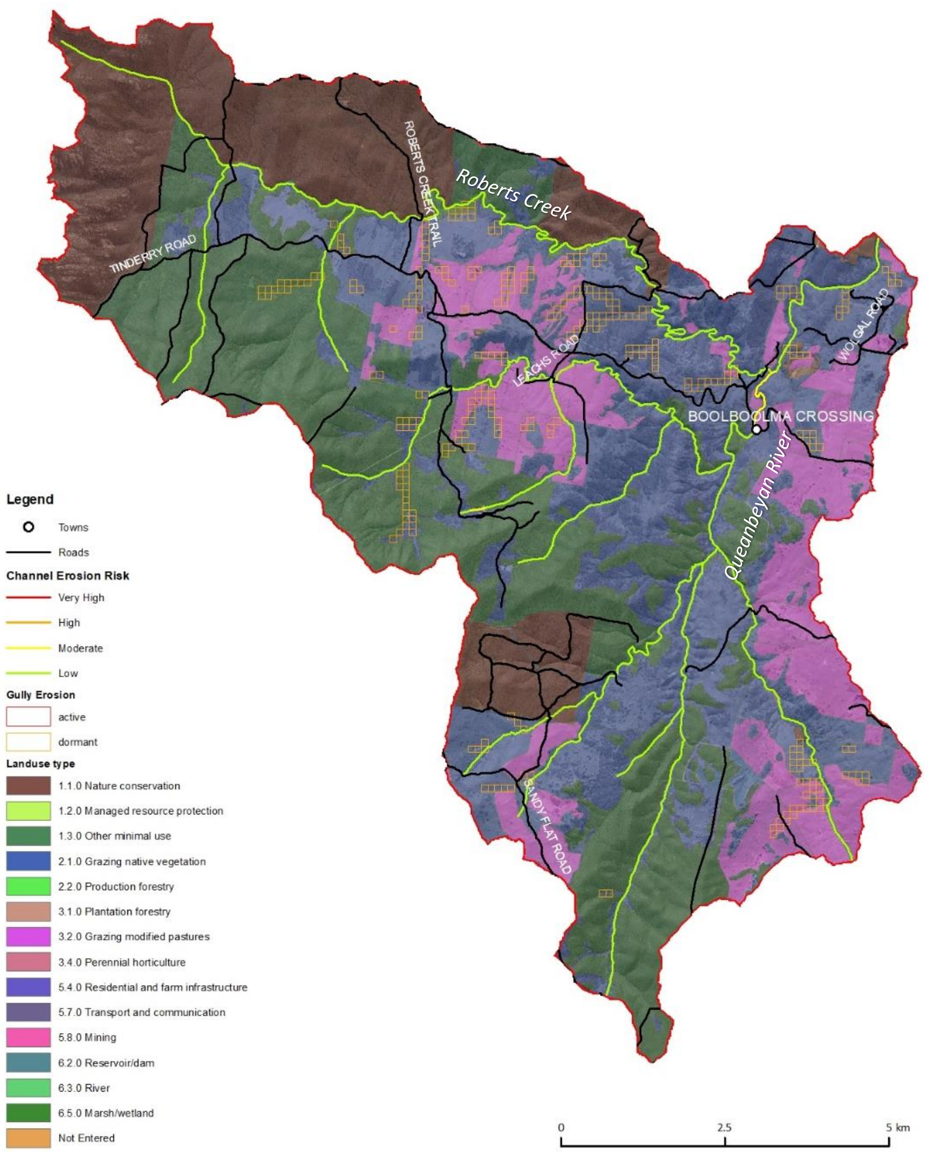
The Gully erosion risk for the sub-catchment is classed as low, gully erosion cover less than 1% of the entire sub-catchment, most of which has been identified as being dormant (i.e. Inactive in the last ~10 years). One small area of active gully erosion was identified. It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment for current conditions. As conditions change throughout the catchment (i.e. Changes in rainfall patterns, land use changes, etc.) this risk can increase or even decrease.

Gully erosion is primarily present throughout the western half of the catchment. The majority of the identified gully erosion is situated within, or adjacent to, land that is classed as grazing (modified pastures and native vegetation). The Soils in this area consist of highly erodible Rudosols and Tenosols which with little coverage from vegetation are highly susceptible to erosion from direct rainfall. The lack of vegetation also provides little structural support for the soils leading to further erosion.

Sub-catchment overview: G7 (Roberts Creek)

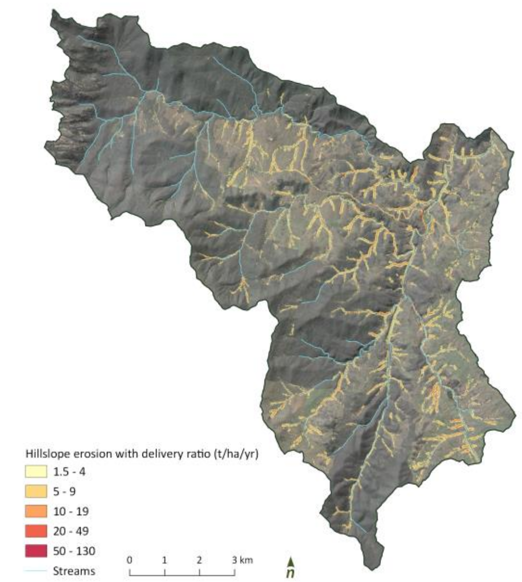
The G7 (Roberts Creek) sub-catchment is located in the south west of the overall Googong catchment and covers approximately 101km². The main waterways within the sub-catchment are the Queanbeyan River which runs south to north through the east of the catchment and Roberts, Lyons, and Sandy Flat creeks and Limekiln Gully which form the tributaries of the Queanbeyan River that drain the western half of the catchment. The geology and topography of the sub catchment creates primarily confined streams throughout the Queanbeyan River and the mid to lower reaches of the western tributaries. In the upper and mid reaches, within the elevated low grade valley floors, of the western tributaries there are some reaches that are classed as the swampy meadow group. These are relatively flat discontinuous low energy swampy reaches. Nature Conservation comprises 40% of the sub-catchment. Other minimal use constitutes 37% and Grazing native vegetation (15%). Other land uses include Grazing modified pastures (6%), Plantation forestry (1%) and Transport and communication (1%).





Hillslope erosion risk — Moderate

Hillslope erosion hotspots occur predominantly where a marked increase in hillslope coincides with. This is particularly the case along the confined streams adjoining the Queanbeyan in the south and north as well as along Roberts and Lyons creek in the north.



Channel erosion risk — Low

Overall the channel risk for this sub-catchment has been classed as moderate. There was one reach along the Queanbeyan River that was identified as having *high* channel erosion risk. This reach was identified from the desktop assessment as having minor instabilities which corresponds to moderate erosion potential as well as having very high sediment availability. The remaining reaches within the sub-catchment were identified as having *low* channel erosion risk. These reaches were identified from the desktop assessment as being stable which corresponds to low erosion potential as well as having low sediment availability.

The underlying geology within this catchment, which consists of mainly of sandstone, mudstone, shale, quartzite, phyllite, slate, granodiorite and adamellite combined with the fact that most of the reaches within the catchment are located within land use areas that are either conservation or have not been heavily modified and as a result have good to moderate riparian vegetation coverage explain why most of the reaches within the sub-catchment are low risk. The underlying soils of the high risk reach along Careys Creek consists of mainly highly erodible Rudosols and Tenosols, combined with the fact that this reach is located within land use area classed as *grazing modified pastures* and as a result has very poor riparian vegetation coverage explain why this reach is high risk.

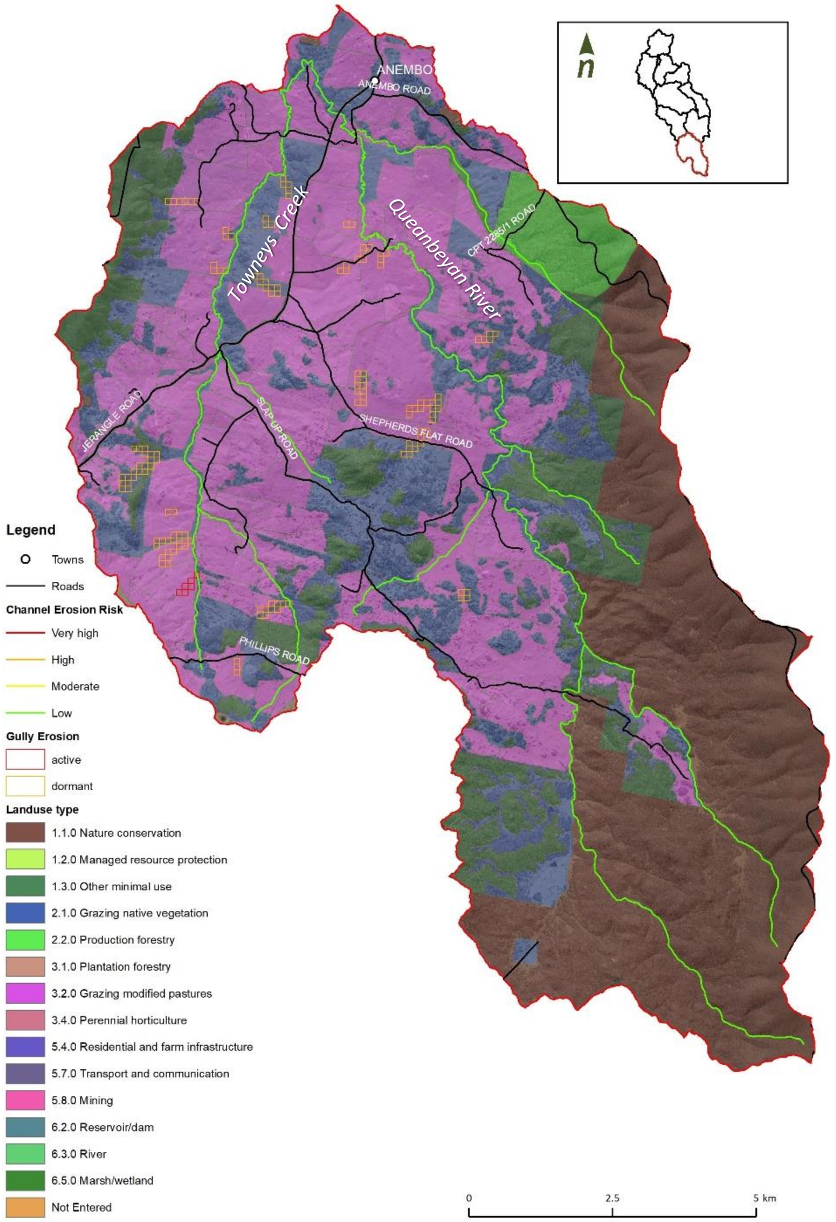
Gully erosion risk — Low

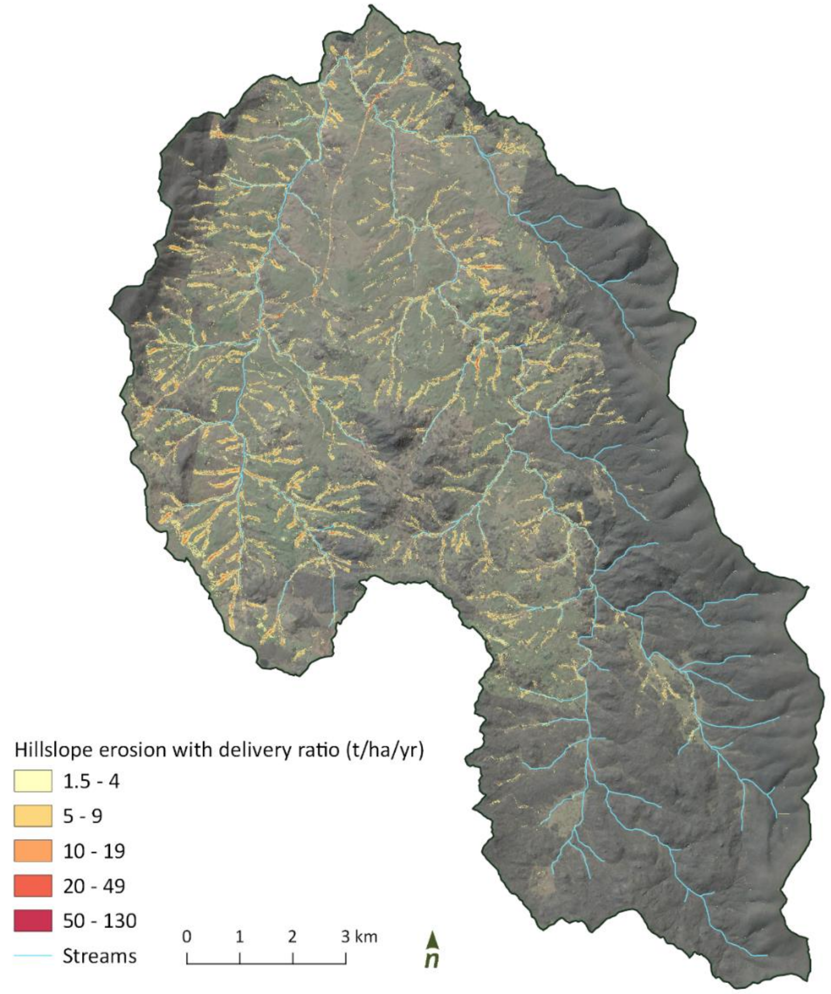
The Gully erosion risk for the sub-catchment is classed as low, gully erosion cover less than 3% of the entire sub-catchment and of this all of it has been identified as being dormant (i.e. Inactive in the last ~10 years) No active gully erosion was identified from the desktop assessment. It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment for current conditions. As conditions change throughout the catchment (i.e. Changes in rainfall patterns, land use changes, etc.) this risk can increase or even decrease.

Gully erosion is primarily located throughout the lower reaches of the catchment, in the north adjacent Roberts and Lyons Creeks. The majority of the identified gully erosion is situated within, or adjacent to, land that is classed as grazing (modified pastures and native vegetation). Soils throughout this area are primarily Kurosols which are highly erodible if vegetation coverage is poor.

Sub-catchment overview: G8 (Towneys Creek)

The G8 (Towneys Creek) sub-catchment forms the southern extent of the overall Googong catchment and covers approximately 136km². The main waterways within the sub-catchment are the Queanbeyan River rises in the ranges that border the south of the sub-catchment and Towneys Creek which drains the west of the catchment and discharges to the Queanbeyan River. The geology and topography of the sub catchment creates primarily confined and partly confined reaches throughout the Queanbeyan River and the higher reaches of the eastern tributaries. Towneys Creek and the mid reaches of the two tributaries that form the headwaters of the Queanbeyan River in the south consist of primarily unconfined and swampy meadow group reaches. These are relatively flat discontinuous low energy swampy reaches. Nature Conservation comprises 43% of the sub-catchment and Production forestry constitutes another 30%. The remaining 27% is allocated to Grazing modified pastures (14%), Grazing native vegetation (7%), Other minimal use (5%) and Transport and communication (1%).





Hillslope erosion risk | Moderate

The RUSLE hillslope erosion risk analysis revealed erosional hotspots are scattered throughout where clearance has occurred and roughly correlate to where a stepped increase in gradient is observed. Most of these hotspots highlight gullies which are widespread across this section of agricultural land.

Channel erosion risk | Low

The channel erosion risk assessment has identified all reaches within the sub-catchment as having *low* channel erosion risk. These reaches were identified from the desktop assessment as being stable which corresponds to low erosion potential as well as having low sediment availability.

Although a large proportion of this sub-catchment consists grazing modified pastures the underlying geology within this catchment, which consists of mainly granodirite, combined with the fact that the topography is fairly low grade means that most reaches within these areas are unconfined or swampy meadow type reaches that have low energy and therefore stable or low erosion potential.

Gully erosion risk | Low

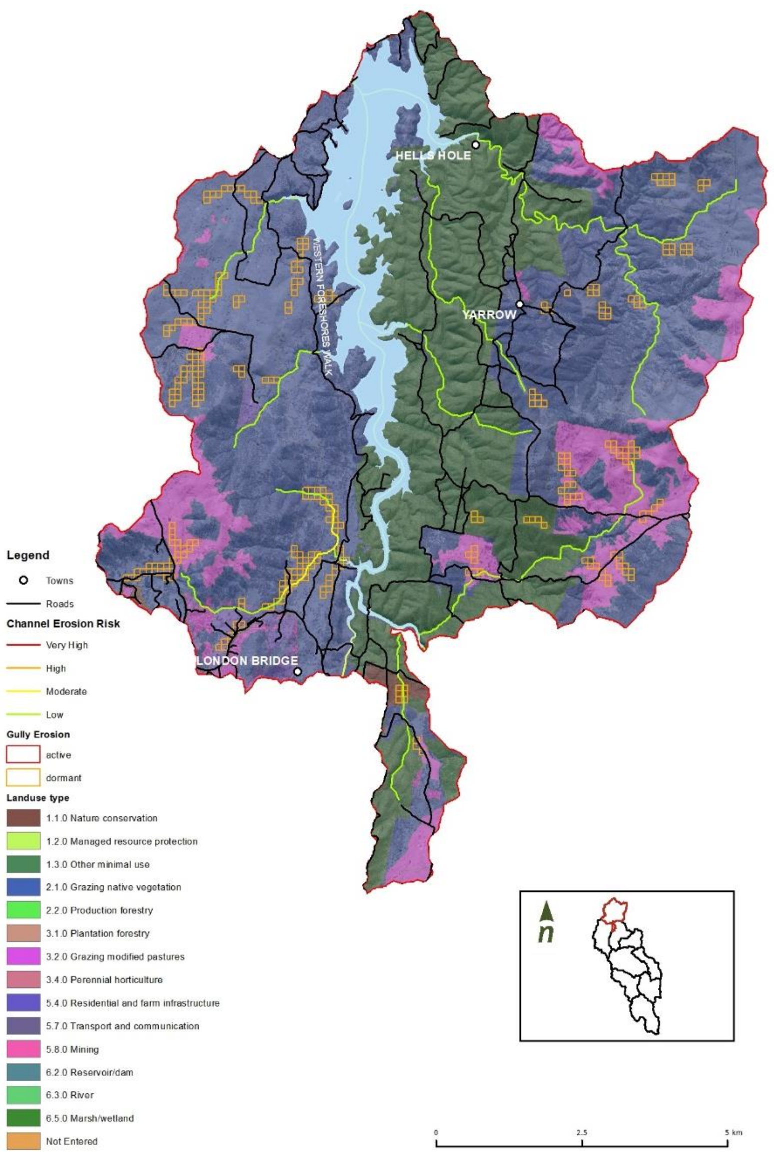
The Gully erosion risk for the sub catchment is classed as low, gully erosion cover less than 1% of the entire sub-catchment, most of which has been identified as being dormant (i.e. Inactive in the last ~10 years). One small area of active gully erosion, in the upper reaches of Towneys Creek was identified. It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment for current conditions. As conditions change throughout the catchment (i.e. Changes in rainfall patterns, land use changes, etc.) this risk can increase or even decrease.

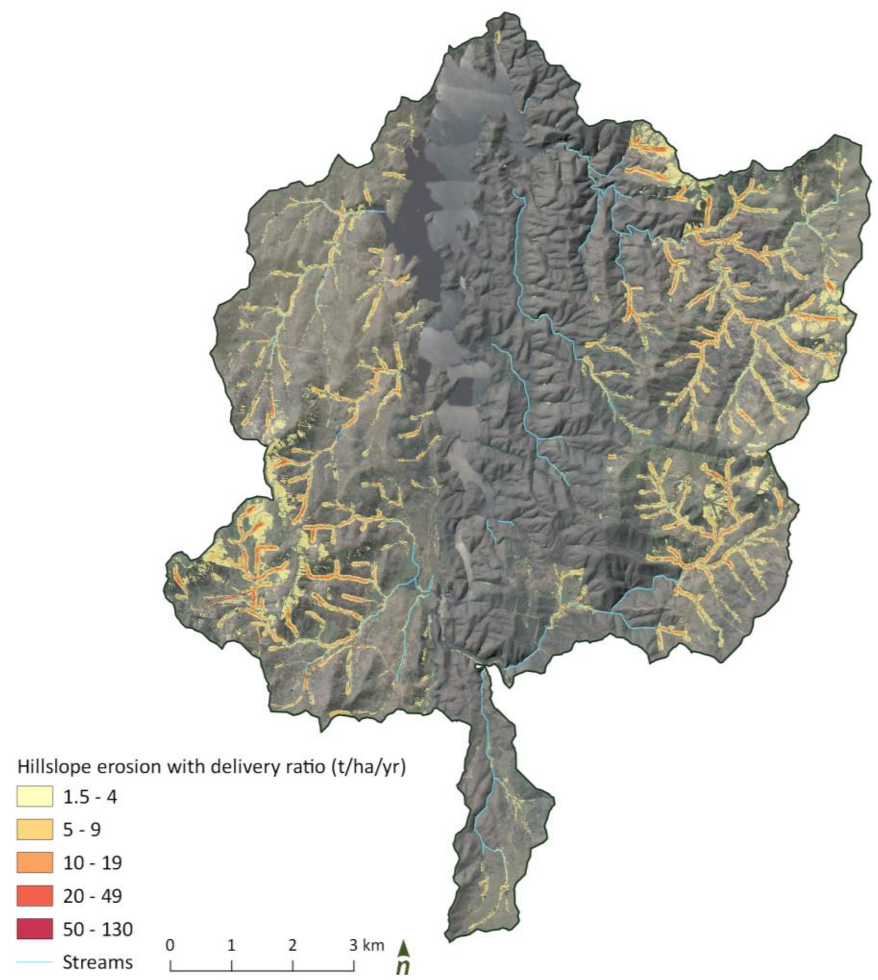
Gully erosion is primarily present throughout the western half of the catchment. The majority of the identified gully erosion is situated within, or adjacent to, land that is classed as grazing (modified pastures and native vegetation). The Soils in this area consist of highly erodible Rudosols, Tenosols and Kurosols which with little coverage from vegetation are highly susceptible to erosion from direct rainfall. The lack of vegetation also provides little structural support for the soils leading to further erosion.

Sub-catchment overview: G9 (Googong Foreshore)

The G9 (Googong Foreshore) sub-catchment forms the northern extent of the overall Googong catchment and covers approximately 90km². There are a number of smaller waterways within this sub-catchment which discharge directly to Googong Reservoir from the east and west. The geology and topography of the sub catchment creates primarily confined and partly confined streams. The stream to the south west of the catchment has some slightly confined (terrace) or unconfined reaches.

The predominant land use within the sub catchment is Grazing native vegetation (47%) followed by Other minimal use at 23%. This catchment holds the reservoir which makes up 4%, Nature conservation comprises only 2%, Residential and farm infrastructure 1.5% and Transport and communication 1%.





Hillslope erosion risk — High

The RUSLE hillslope erosion risk analysis revealed Erosional hotspots occur primarily in the higher reaches where clearance has occurred and a stepped increase in gradient is observed. Particular areas of note include the slopes running north and south west off Mt Molongo as well as Tin Hut Creek along Burra road.

Channel erosion risk — Low - Moderate

Overall the channel risk for this sub-catchment has been classed as moderate. There were two reaches in the south west of the catchment that was identified as having *high* channel erosion risk. These reaches were identified from the desktop assessment as having minor instabilities which corresponds to moderate erosion potential as well as having very high sediment availability. The remaining reaches within the sub catchment were identified as having *low* channel erosion risk. These reaches were identified from the desktop assessment as being stable which corresponds to low erosion potential as well as having low sediment availability.

The underlying geology to the east of this sub catchment, which consists of mainly of sandstone, mudstone, shale, quartzite, phyllite, slate, schist and quartzite combined with the fact that most of the reaches in the east are located within land use areas that are either conservation or have not been heavily modified and as a result have good to moderate riparian vegetation coverage explain why most of the reaches within the east of the sub catchment are low risk. Throughout the western extents of the catchment the land has been more highly modified as evidenced by the poor riparian vegetation coverage which explain why there are some high risk reaches in this area. reach is high risk.

Gully erosion risk — Moderate

The Gully erosion risk for the sub catchment is classed as moderate, gully erosion covers approximately 4% of the entire sub-catchment, all of which has been identified as being dormant (i.e. Inactive in the last ~10 years) No active gully erosion was identified from the desktop assessment. It should be noted that current gully erosion can only be used as a prediction for future gully erosion risk across the sub-catchment for current conditions. As conditions change throughout the catchment (i.e. changes in rainfall patterns, land use changes, etc.) this risk can increase or even decrease.

Gully erosion is primarily present throughout the western half of the catchment and the far east, beyond the nature conservation areas. The majority of the identified gully erosion is situated within, or adjacent to, land that is classed as grazing (modified pastures and native vegetation). The Soils in this area consist of highly erodible Kurosols which with little coverage from vegetation are highly susceptible to erosion from direct rainfall. The lack of vegetation also provides little structural support for the soils leading to further erosion.

Appendix B
Factors affecting erosion

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 Googong 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 17).

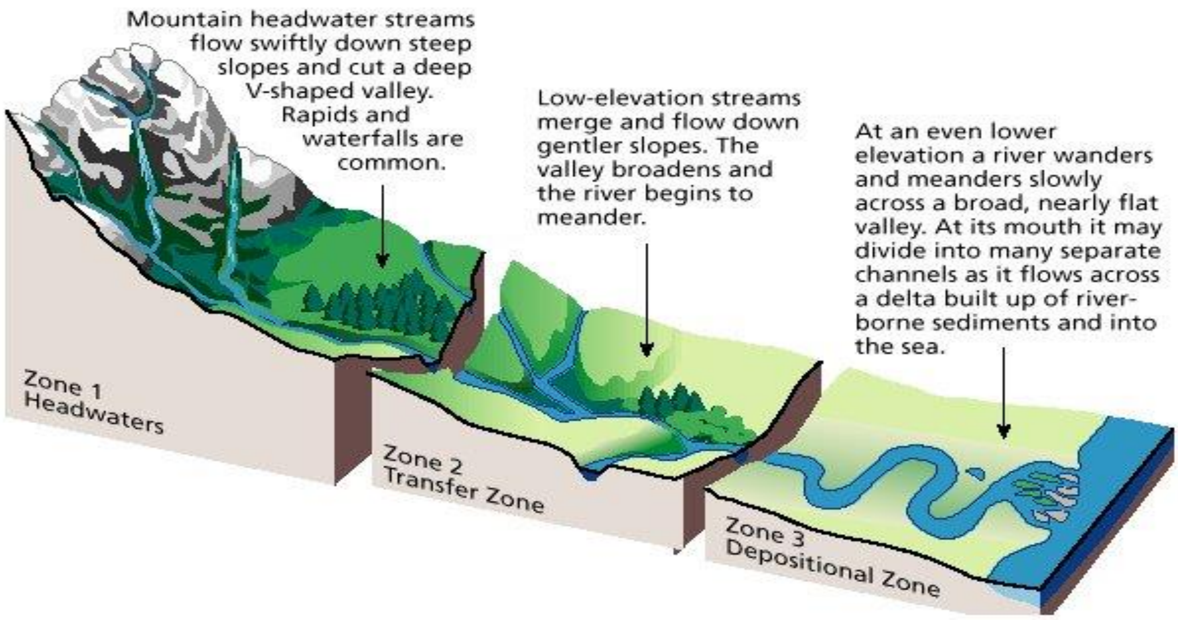


Figure 17. *Sediment zones in a typical catchment. Image reproduced from the Federal Stream Corridor Restoration Handbook (FISRWG, 1998)*

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 18).

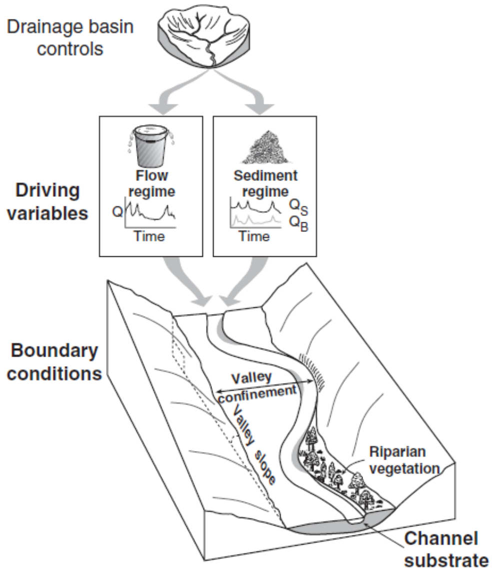


Figure 18. *Schematic representation of the factors influencing channel form and geomorphic process in alluvial rivers (reproduced from Charlton 2008)*

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 19).

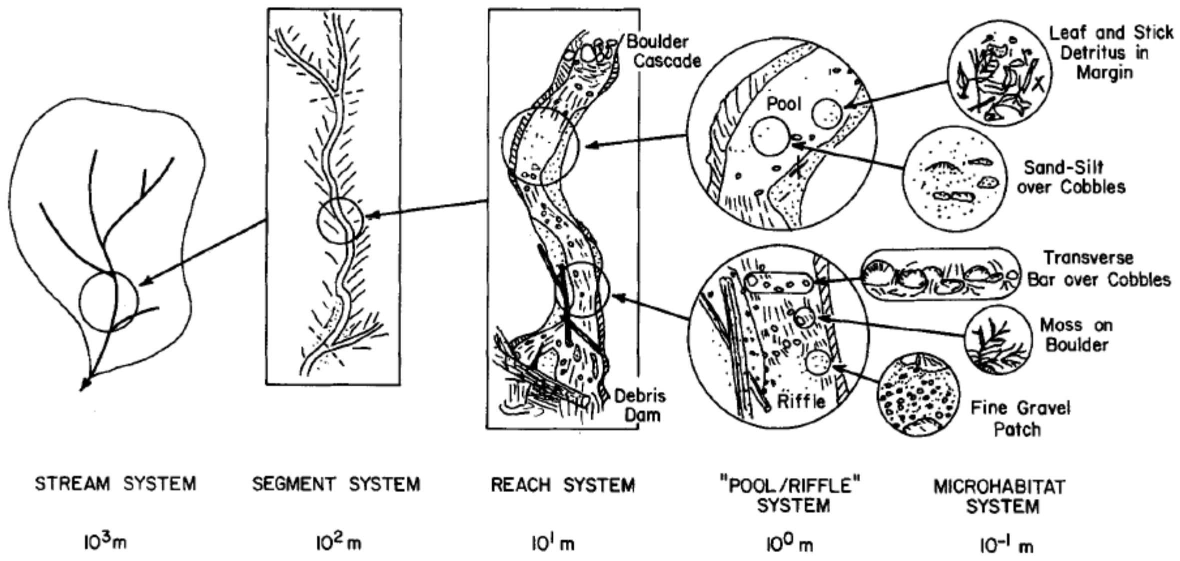


Figure 19. *Hierarchical organization of a spatial scales in a stream system (from Frissell et al 1986).*

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, their drivers, and their likely future magnitude is central to effectively reducing sediment yield.

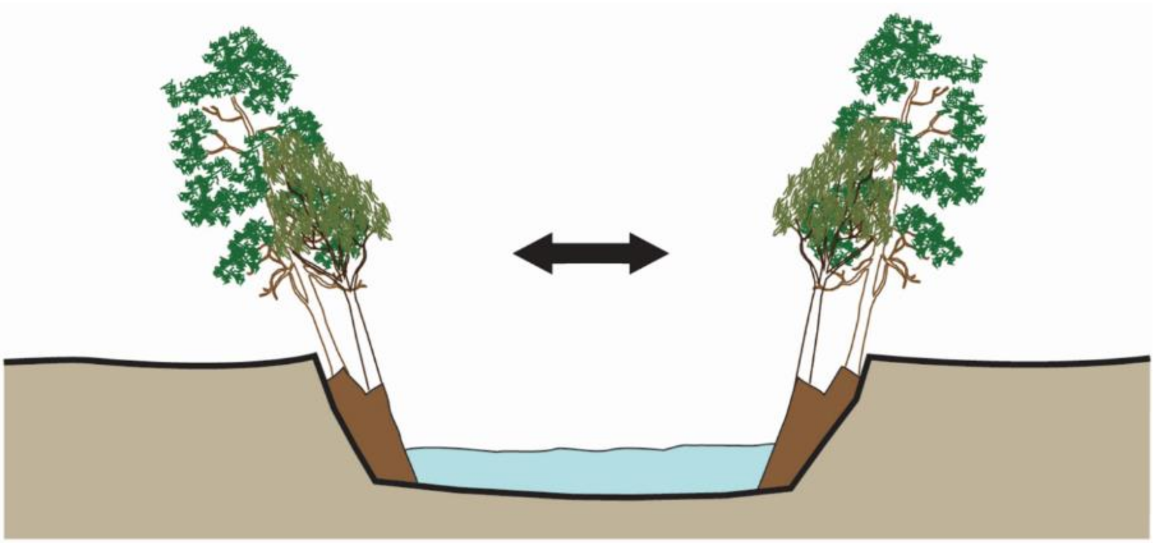
Bank erosion is a ubiquitous geomorphic process in alluvial channels. Bank erosion is important in the development of different channel forms, while the migration of channels across their floodplains involves a combination of bank erosion on one side and deposition on the other (which is often expressed 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:

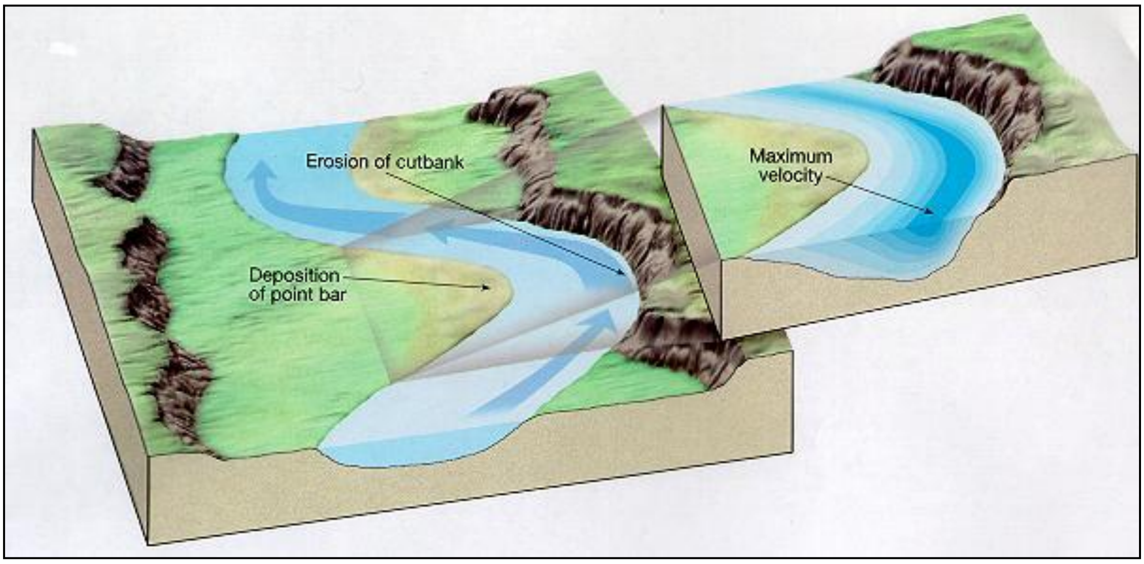
5. Pre-weakening processes such as repeated cycles of wetting and drying or cattle trampling of the substrate, which ‘prepare’ the bank for erosion.
6. Fluvial processes, where individual particles of sediment are directly entrained (mobilised) by flowing water.
7. Processes of mass failure, which include 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.

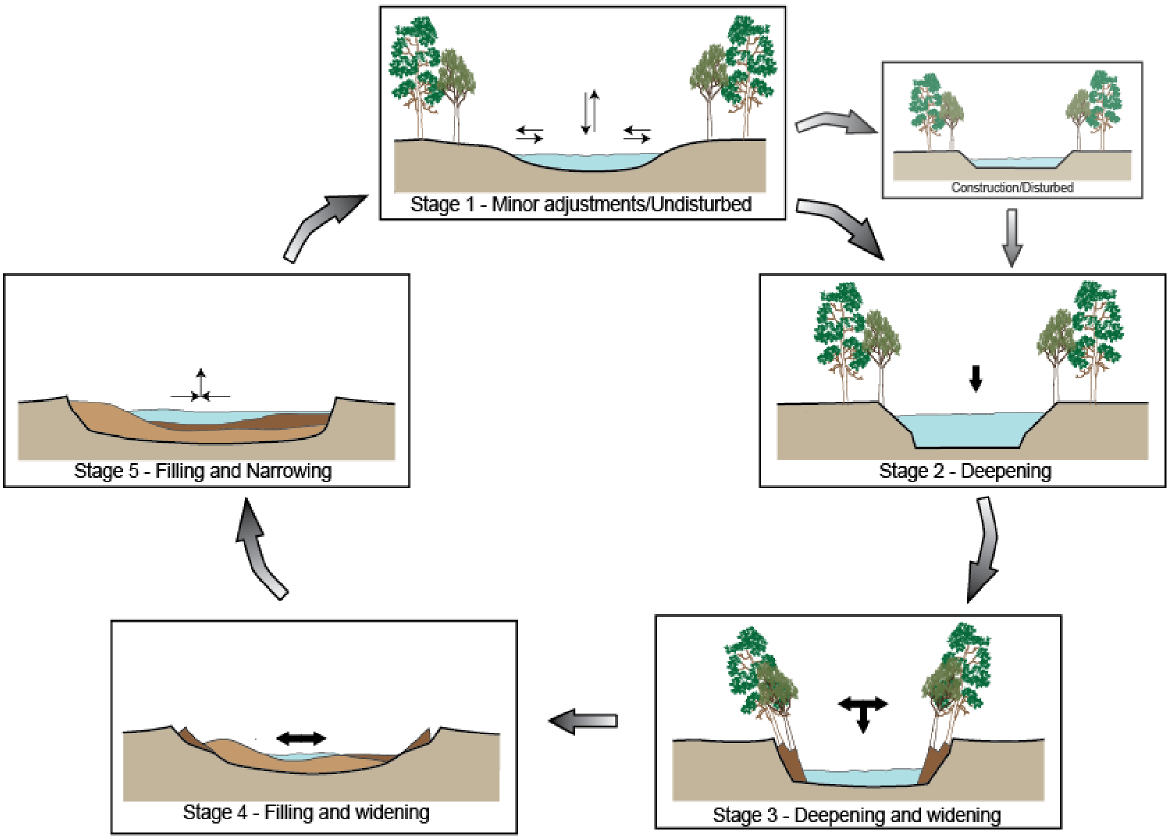
Channel widening occurs when river banks erode on both sides of a channel. Channel widening is often a symptom of a wider scale process, such as an increase in in-channel flow, arising from river regulation, channelisation, deforestation urbanisation or channel incision.



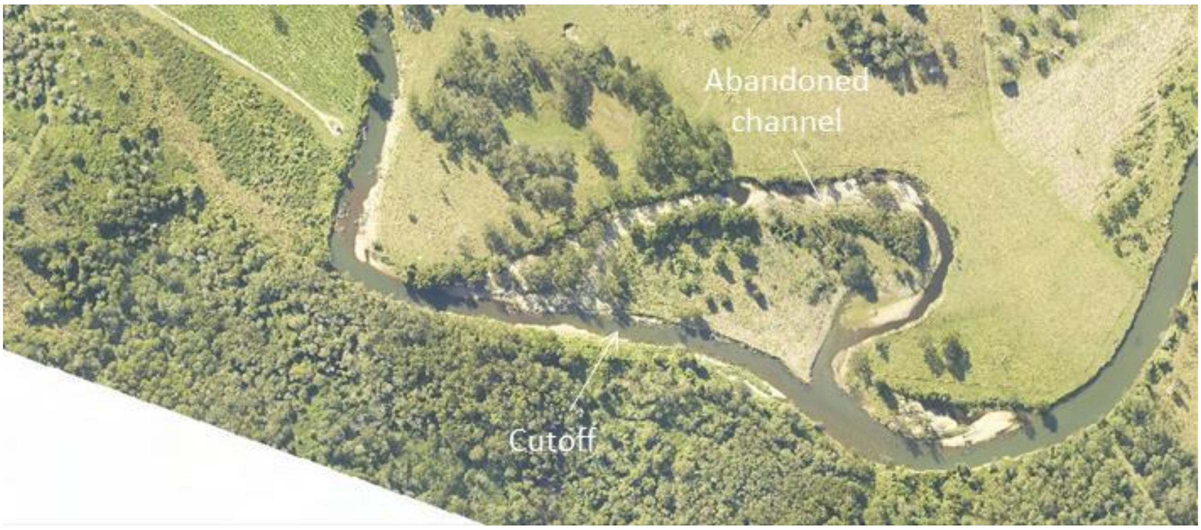
Channel migration is often associated with **meander migration** and is caused by erosion on one bank and deposition on the other (FISRWG, 1998).



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.



Appendix C
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 the state, 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 Googong 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 Googong Catchment are shown in Table 9 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 9. RUSLE parameters used in the Googong Hillslope erosion assessment

Factor	Method
Rainfall erosivity (R)	State layer re sampled to 2m
Soil erodibility (K)	State layer re-sampled to 2m
Slope length (L)	LS layer generated from a compiled 2m DEM
Slope steepness (S)	

Cover management (C)	C factors applied to land use layer
Erosion control practice (P)	1 (assuming no erosion control)

Rainfall Erosivity (R)
The layers currently available on the Queensland Government data portal have been developed applying the method outlined in Yang & Yu (2015) to calculate rainfall erosivity (R) using gridded rainfall data across NSW over the period 1961 - 2012 (inclusive).

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 applied the Yang & Yu (2015) method to both daily rainfall and SILO data from gauge stations within proximity to the Googong catchment. 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. The difference in gauge values was to be expected given that the State layer is based on gridded SILO data. The difference in SILO values is attributed to the fact that the SILO data set has been updated since the State layer was created. From this analysis it was concluded that no extra value would be provided by creating a localised rainfall erosivity grid and the state R layer was resampled from 90m to 2m and used for the RUSLE calculation.

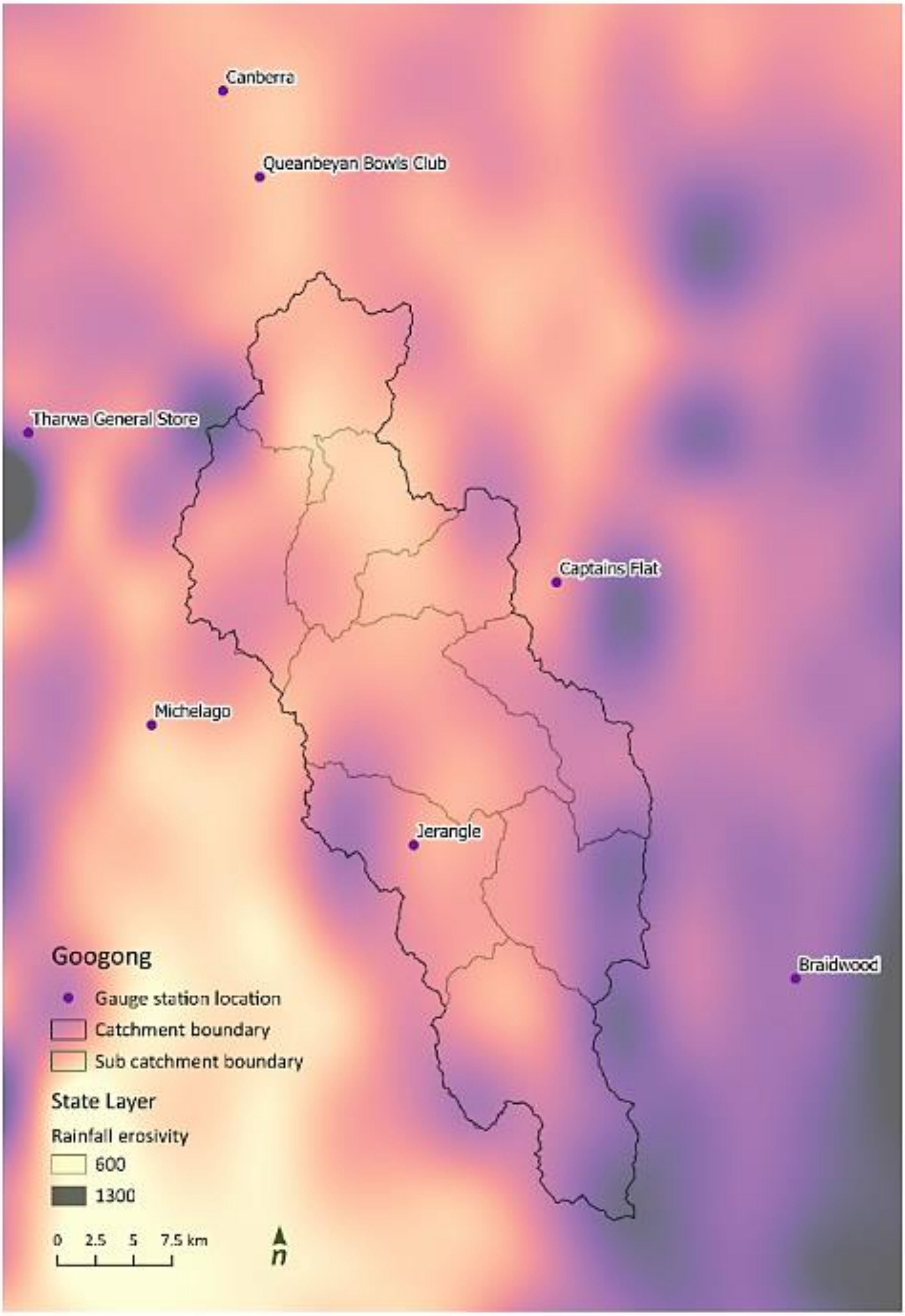


Figure 20. *Selected locations for R factor analysis*

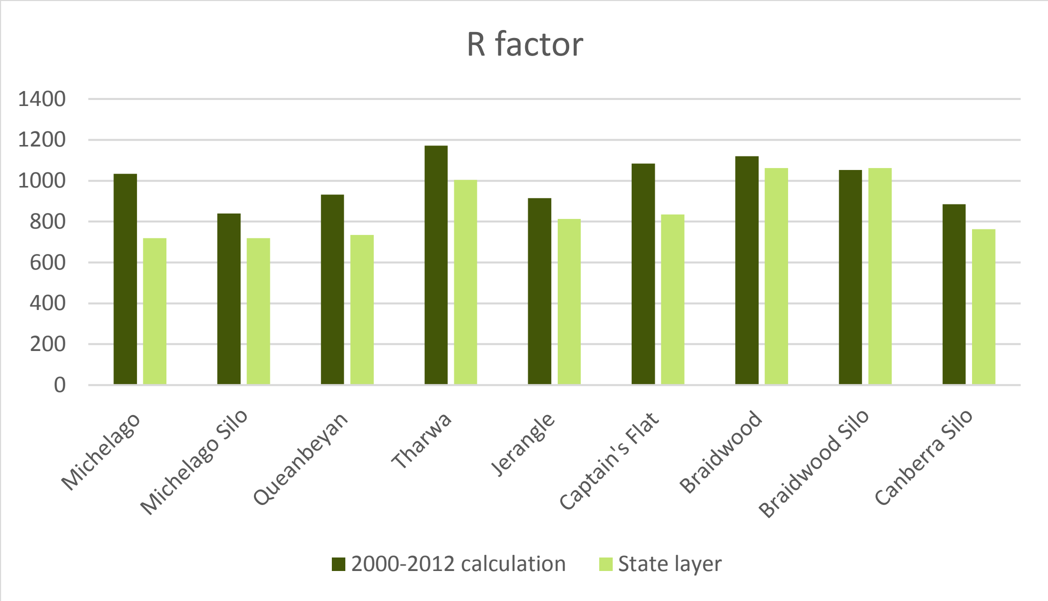


Figure 21. *Comparison of R calculation methods for selected locations*

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 (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.

Figure 22 shows the distribution of the soil erodibility (K) factor across the Googong Catchment as applied in the RUSLE calculations.

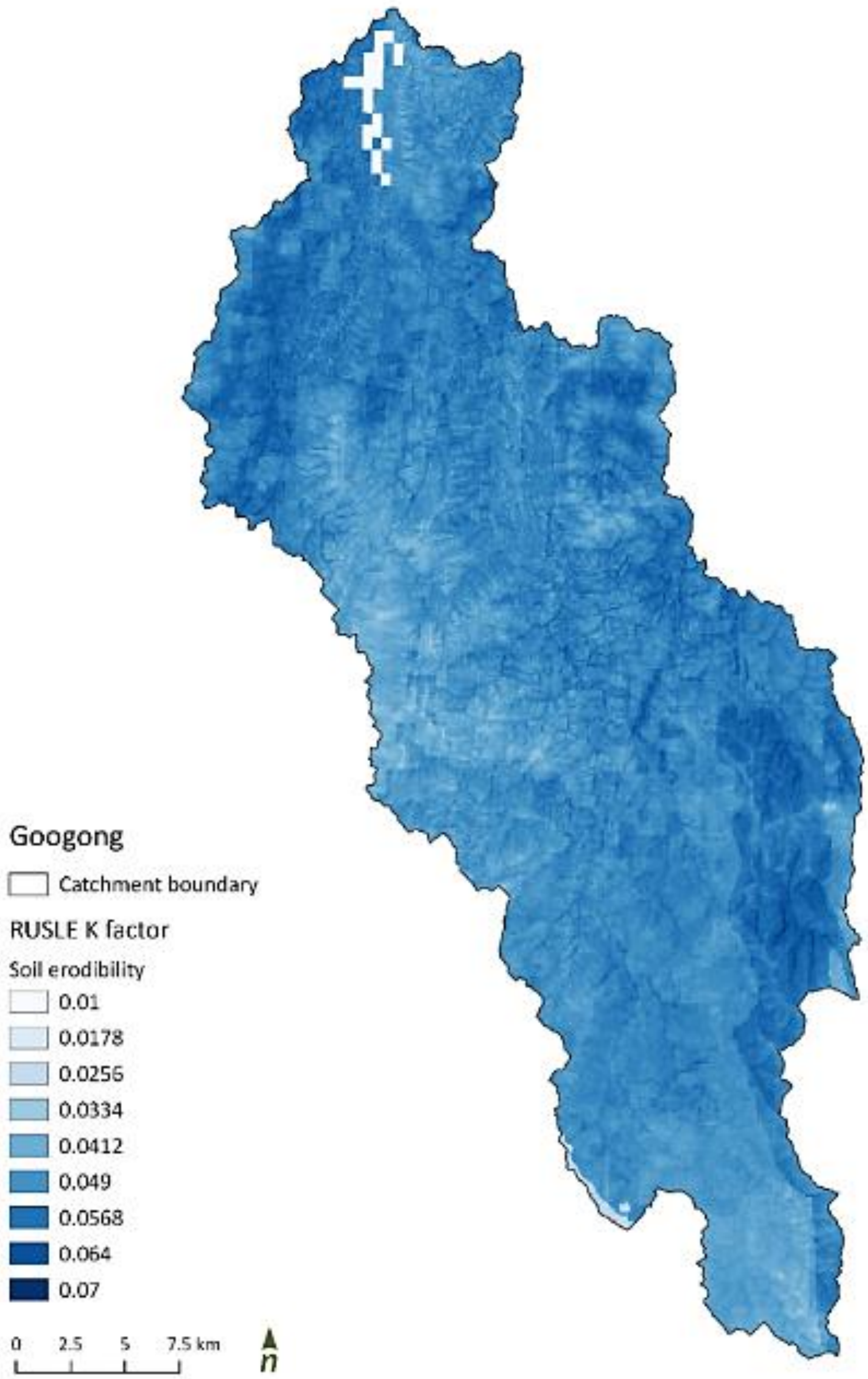


Figure 22. *Googong Soil erodibility (K) factor, 90m resolution*

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 Googong 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 2m.

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

Figure 23 and Figure 24 show the distribution of LS values for the whole of the Googong catchment and a sample area.

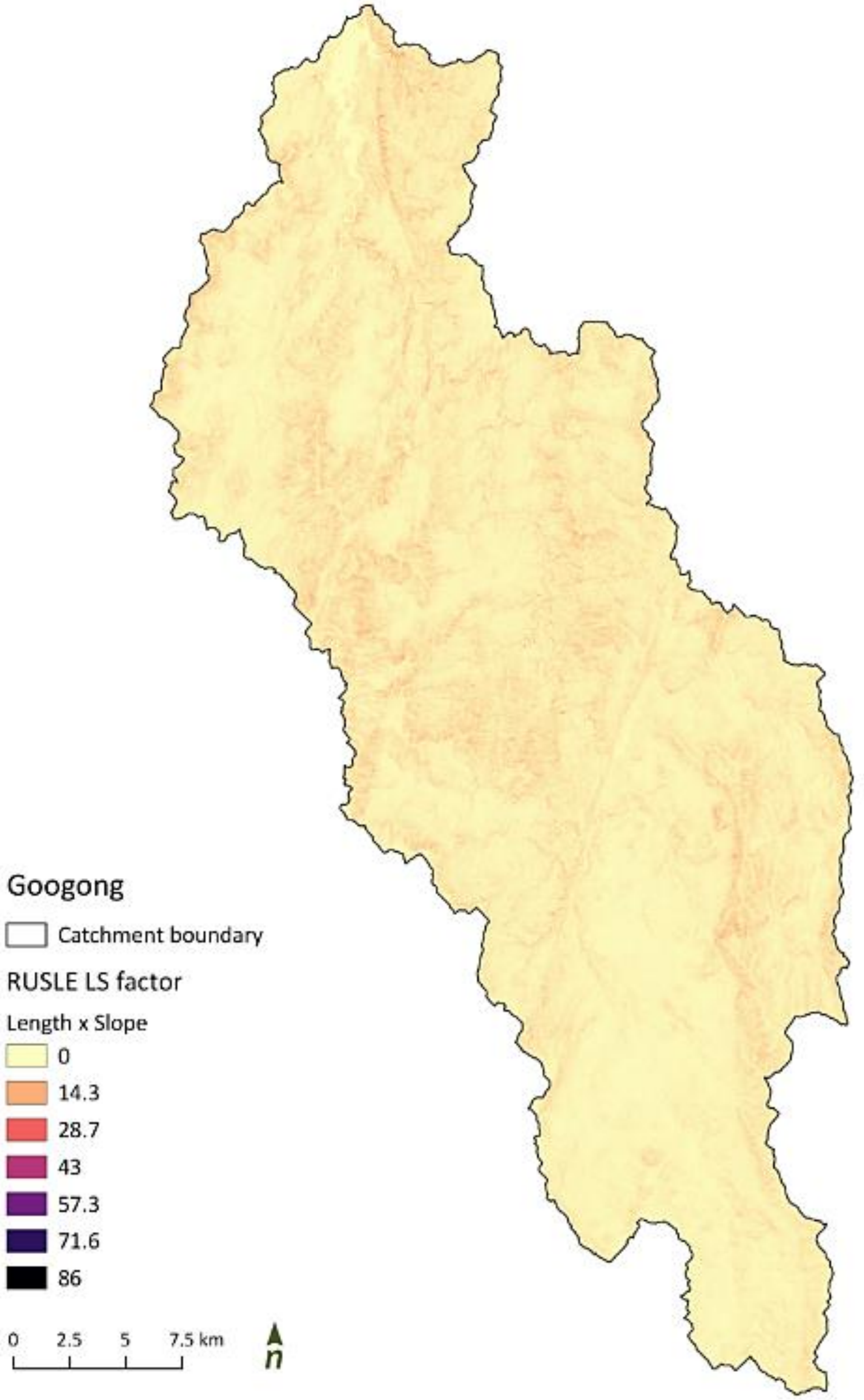


Figure 23. *SEQ Slope length (LS) factor, 5m resolution*

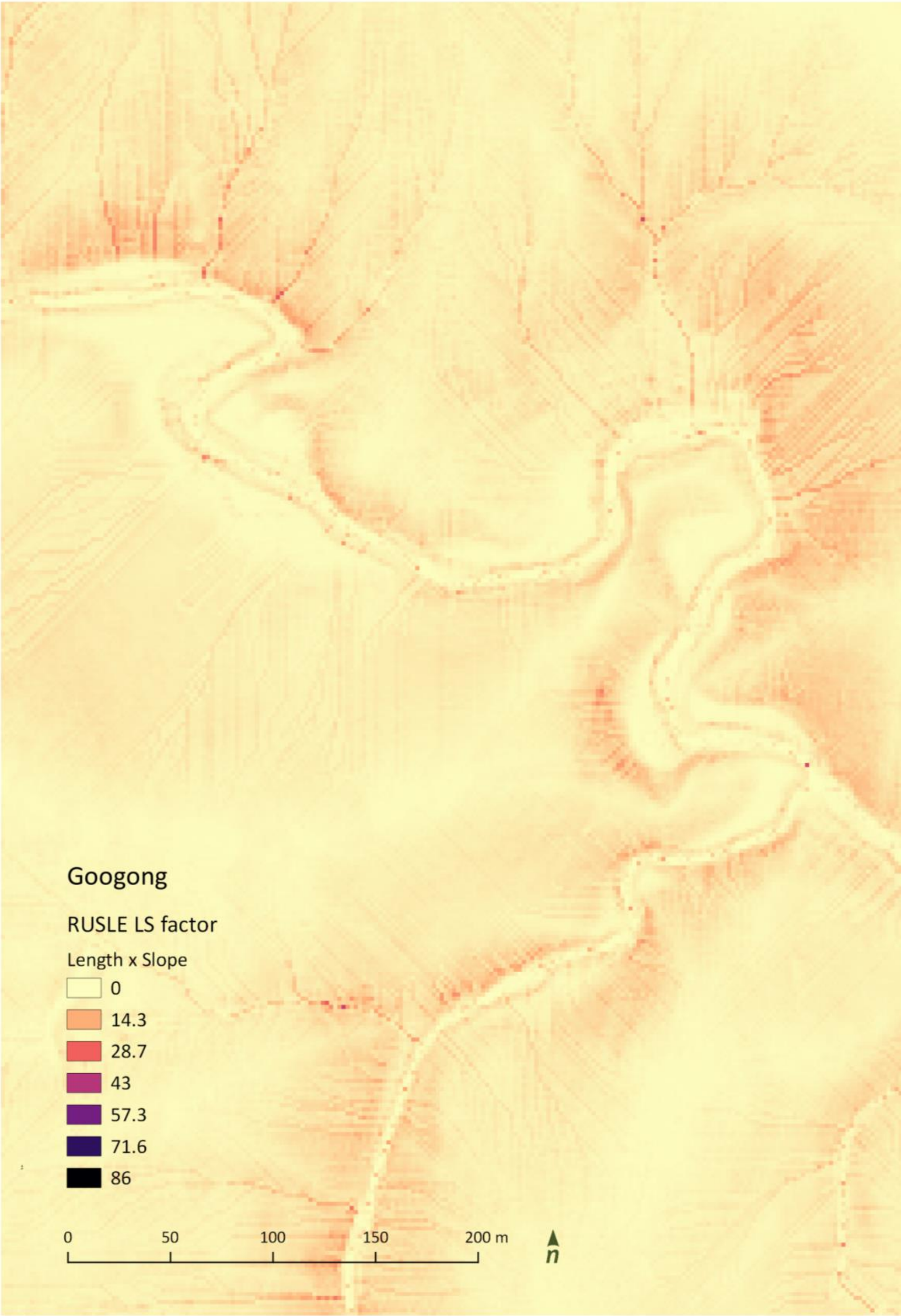


Figure 24. *SEQ Slope length (LS) factor, 5m resolution*

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 land use types (Pal and Samanta 2012). For this project, these values were applied to the 2013 NSW land use spatial layer, which is comprised of a combination of aerial and satellite imagery mapped between 2000-2013. C-factor value application of provides a finer level of detail than the current C factor layer used in the State RUSLE calculation. Table 10 shows the C factor applied to each landcover code based on similar land use types and Figure 25 illustrates how this has been applied. It is worth noting that the current land-use layer does not account for the extent of all dirt road surfaces within the catchment. These surfaces are given the highest C factor of 0.5.

Table 10. C factor applied to each landcover type

Code	Primary	Secondary	Tertiary	Landcover	Land use (matched)	C factor
1	B Non-vegetated areas	B1 Terrestrial non-vegetated	B15 Built-up and associated area	Impervious Road Surface	Barren land (construction)	0.5
2	NA	NA	NA	Cloud	NA	0.2
3	B Non-vegetated areas	B2 Aquatic non-vegetated	B28 Inland or marine water	Ocean	Water	0
5	B Non-vegetated areas	B1 Terrestrial non-vegetated	B15 Built-up and associated area	Mine | Quarry | Industrial	Barren land (construction)	0.5
6	B Non-vegetated areas	B2 Aquatic non-vegetated	B28 Inland or marine water	Waterbody	Water	0
8	B Non-vegetated areas	B2 Aquatic non-vegetated	B27 Artificial water bodies	Canal	Water	0
9	A Vegetated	A1 Vegetated terrestrial	A12 Natural and semi vegetation	Native Forest	Forest (vegetated)	0.004
10	A Vegetated	A1 Vegetated terrestrial	A11 Cultivated terrestrial	Plantation	Forest (vegetated)	0.004
11	A Vegetated	A1 Vegetated terrestrial	A12 Natural and semi vegetation	Non-forest Native Vegetation	Forest (vegetated)	0.004
13	B Non-vegetated areas	B1 Terrestrial non-vegetated	B18 Bare areas	Sand | Mud Bank	Barren land (construction)	0.5
14	A Vegetated	A1 Vegetated terrestrial	A11 Cultivated terrestrial	Grass	Dry land pasture/shrub land (agriculture)	0.05
15	A Vegetated	A1 Vegetated terrestrial	A11 Cultivated terrestrial	Tree Crop	Forest (vegetated)	0.004
16	A Vegetated	A1 Vegetated terrestrial	A11 Cultivated terrestrial	Irrigated Crop and Pasture	Irrigated Pasture	0.125
17	A Vegetated	A1 Vegetated terrestrial	A11 Cultivated terrestrial	Dryland Crop	Dry land pasture/shrub land (agriculture)	0.05
18	B Non-vegetated areas	B1 Terrestrial non-vegetated	B18 Bare areas	Natural Rock | Cliff	Barren land (construction)	0.5
19	B Non-vegetated areas	B1 Terrestrial non-vegetated	B15 Built-up and associated area	Non-vegetated	Settlement (urban)	0.002

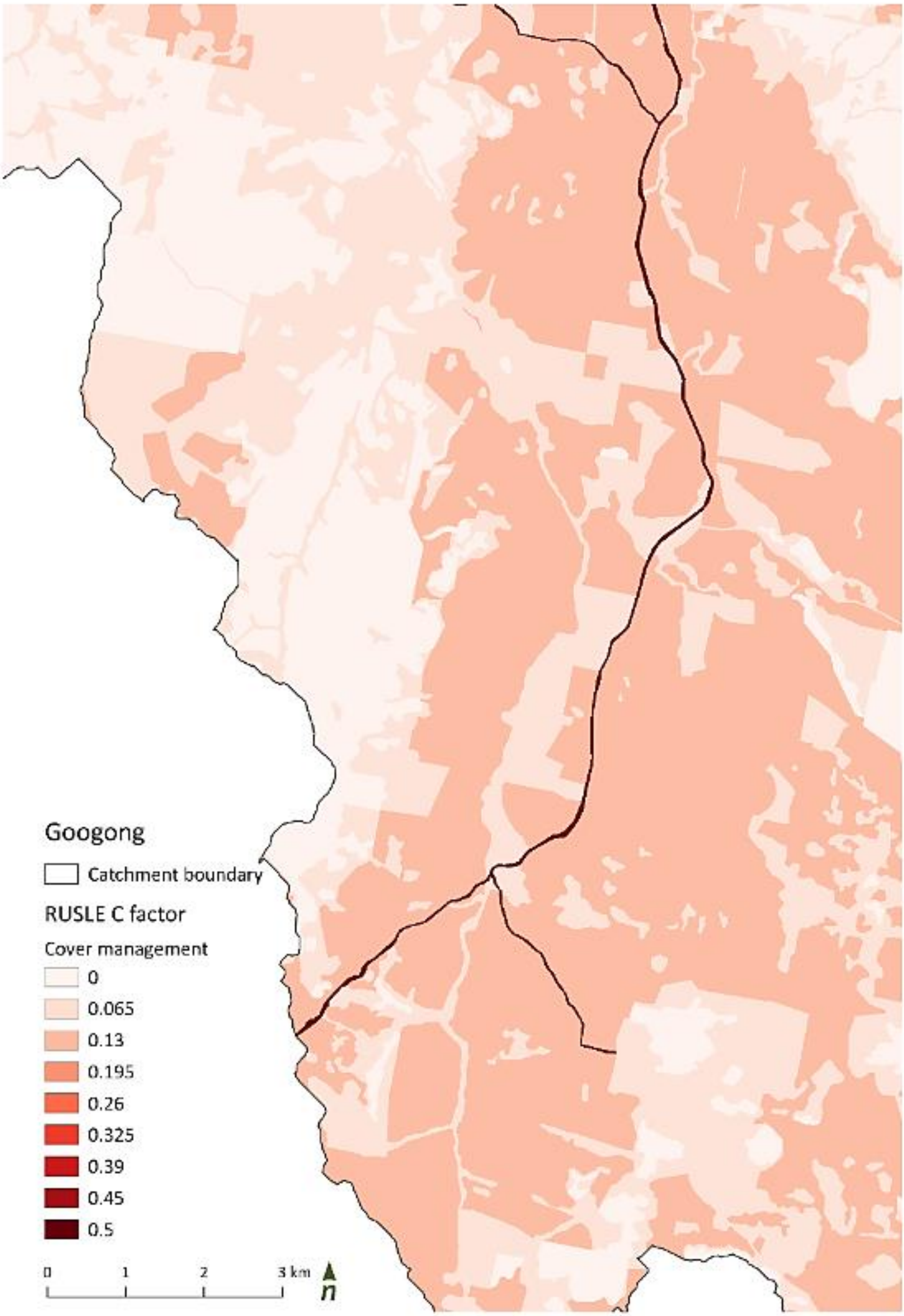


Figure 25. *Googong Land cover (C) factor, 2m resolution*

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 Googong sub-catchment. These estimates provide an indication of the relative loads (see Table 11) and can be used in combination with the spatial layers which allow the identification of sites with potentially high risk of hillslope erosion.

Table 11. Summary of RUSLE derived sediment yield for the Googong catchment

Catchment	Catchment area (ha)	% area Googong	Mean sediment generation (t/ha/yr)	Mean sediment delivery (t/ha/yr)	Catchment yield (t/yr)	Delivered to waterway (t/yr)	Proportion of Googong delivered
1	7567.44	8.50%	2.2	0.5	16400	3400	8.08%
2	9898.76	11.12%	3.3	0.7	32800	6700	15.91%
3	6044.68	6.79%	1.6	0.3	9500	2000	4.75%
4	15586.44	17.50%	1.8	0.4	28700	6100	14.49%
5	7499.08	8.42%	1.4	0.3	10700	2100	4.99%
6	9612.48	10.80%	1.8	0.4	16900	3500	8.31%
7	10113.8	11.36%	2.4	0.5	24200	5300	12.59%
8	13634.56	15.31%	2.4	0.5	32200	6500	15.44%
9	9085.6	10.20%	3.7	0.7	33400	6500	15.44%
TOTAL	89042.84	100%	20.5	4.2	204800	42100	100%

References

Fu, B., Newham, L.T.H., Ramos-Scharron C.E., (2010) A review of surface erosion and sediment delivery models for unsealed roads. *Environmental Modelling and Software 25* (2010) 1-14

Lu, H., Gallant, J. Prosser, I., Moran, C. & Priestley, G. (2001) Prediction of sheet and rill erosion over the Australian Continent, incorporating monthly soil loss distribution. CSIRO Land and Water Technical Report_13/01 http://www.clw.csiro.au/publications/technical2001/tr13-01.pdf

Pal, B., Samanta S., (2012) Morphometric and hydrological analysis and mapping for Watut watershed using Remote Sensing and GIS techniques, *International Journal of Advances in Engineering & Technology*. ISSN: 22313

Wischmeier, WH., and Smith, DD., (1978) Predicting rainfall erosion losses—a guide to conservation planning. *U.S. Department of Agriculture*. Handbook No. 537

Yang, X., Gray, J., Chapman, G., Qinggaozi, Z., Tulau, M., McInnes-Clarke, S., (2018) Digital Mapping of soil erodibility for water erosion in New South Wales, Australia, Soil Research, 56, 158-170.

Yang, X (2015) Digital mapping of RUSLE slope length and steepness factor across New South Wales, *Soil Research* 53, 216–225

Yang, X., and Yu, B., (2015) Modelling and mapping rainfall erosivity in New South Wales, Australia, Soil Research, 53, 178-189

Zhang, H., Wei, J., Yang, Q., Baartman, JEM., Gai, L., Yang, X., Li, S. Yu, J., Ritsema, CJ. Geissen, V., (2017) An improved method for calculating slope length (λ) and the LS parameters of the Revised Universal Soil Loss Equation for large watersheds, *Geoderma* 308 (2017) 36–45.

Appendix D
Catchment context maps

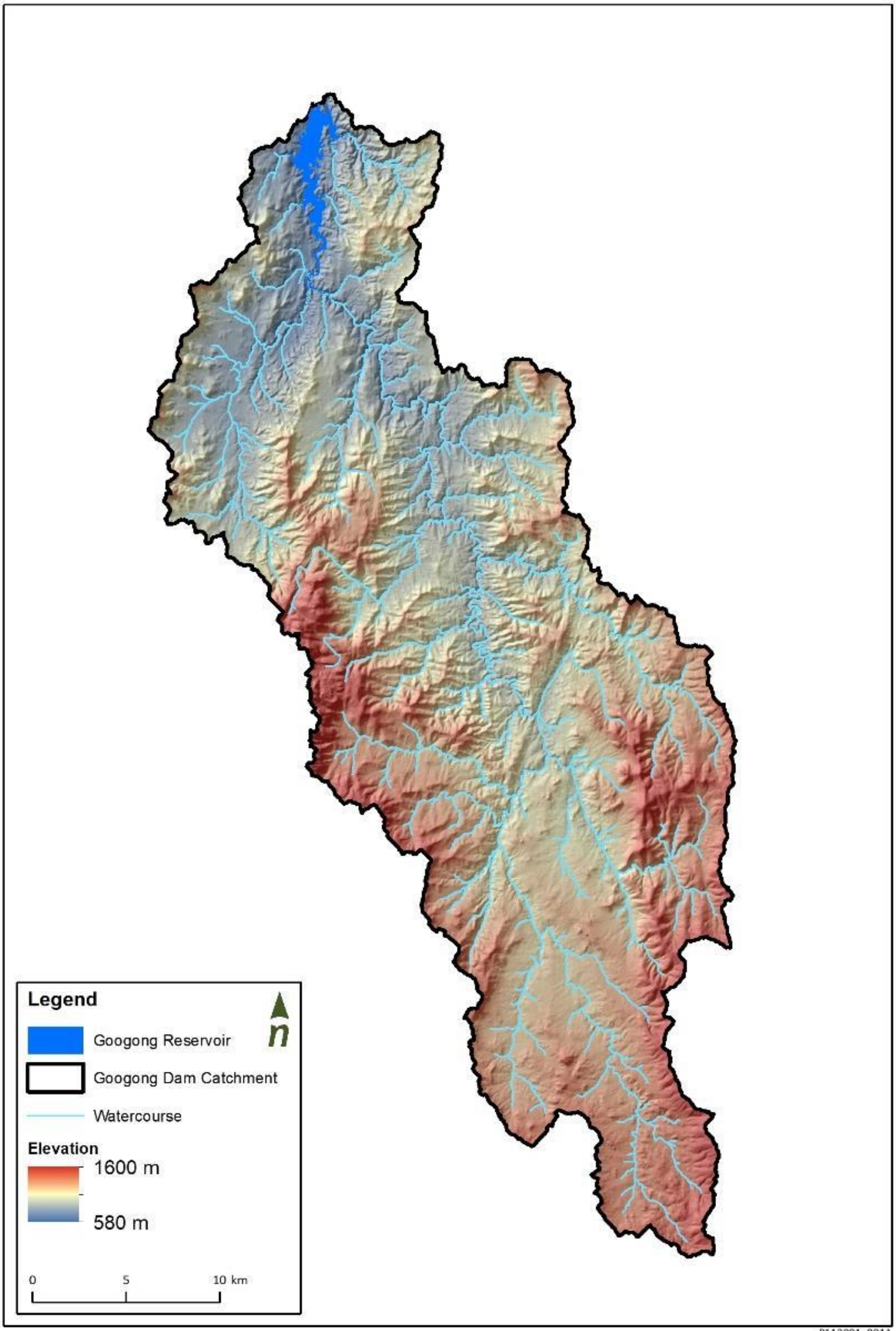


Figure 26. *Googong catchment topography*

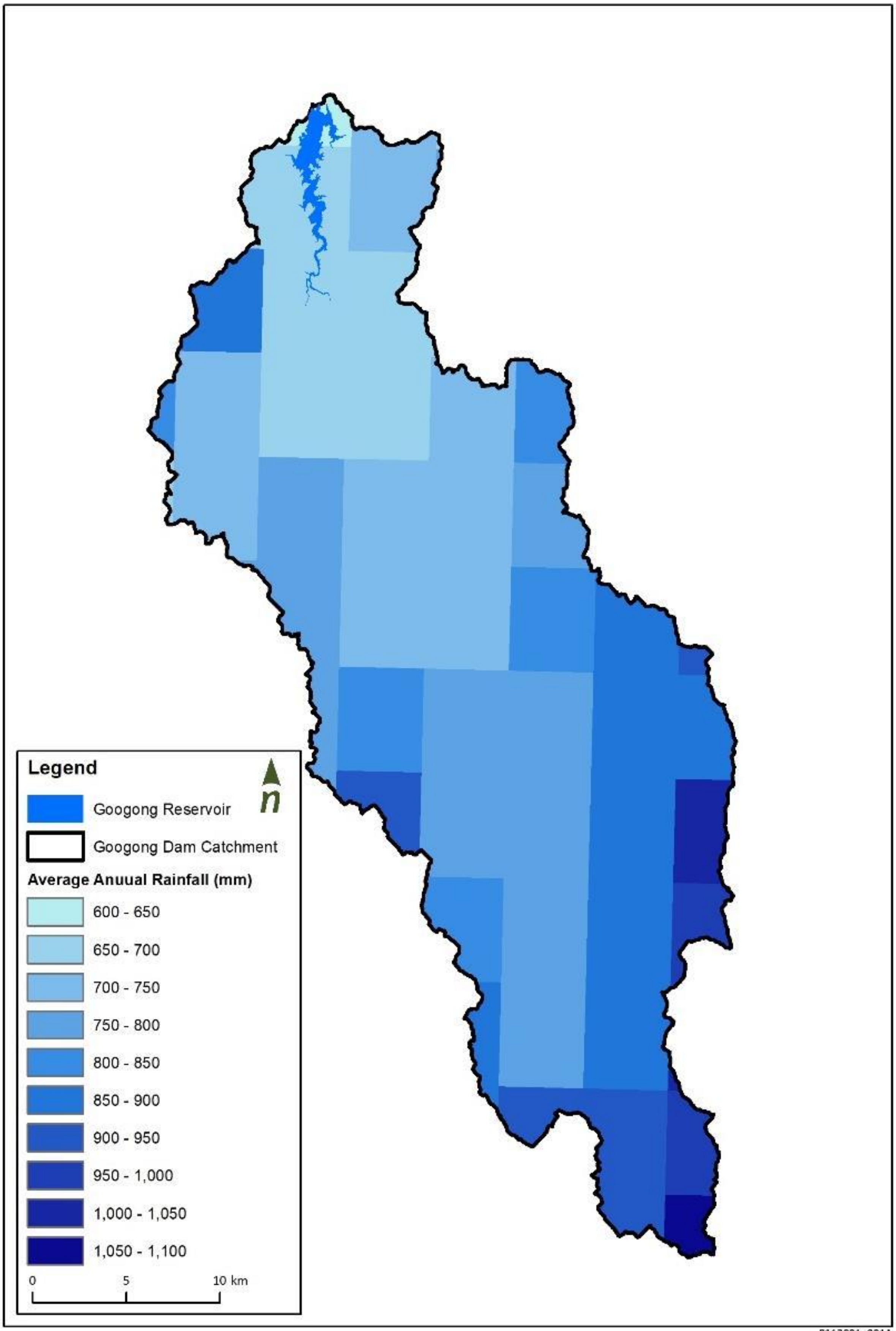


Figure 27. *Average yearly rainfall (mm/year), BoM 1961 - 1990*

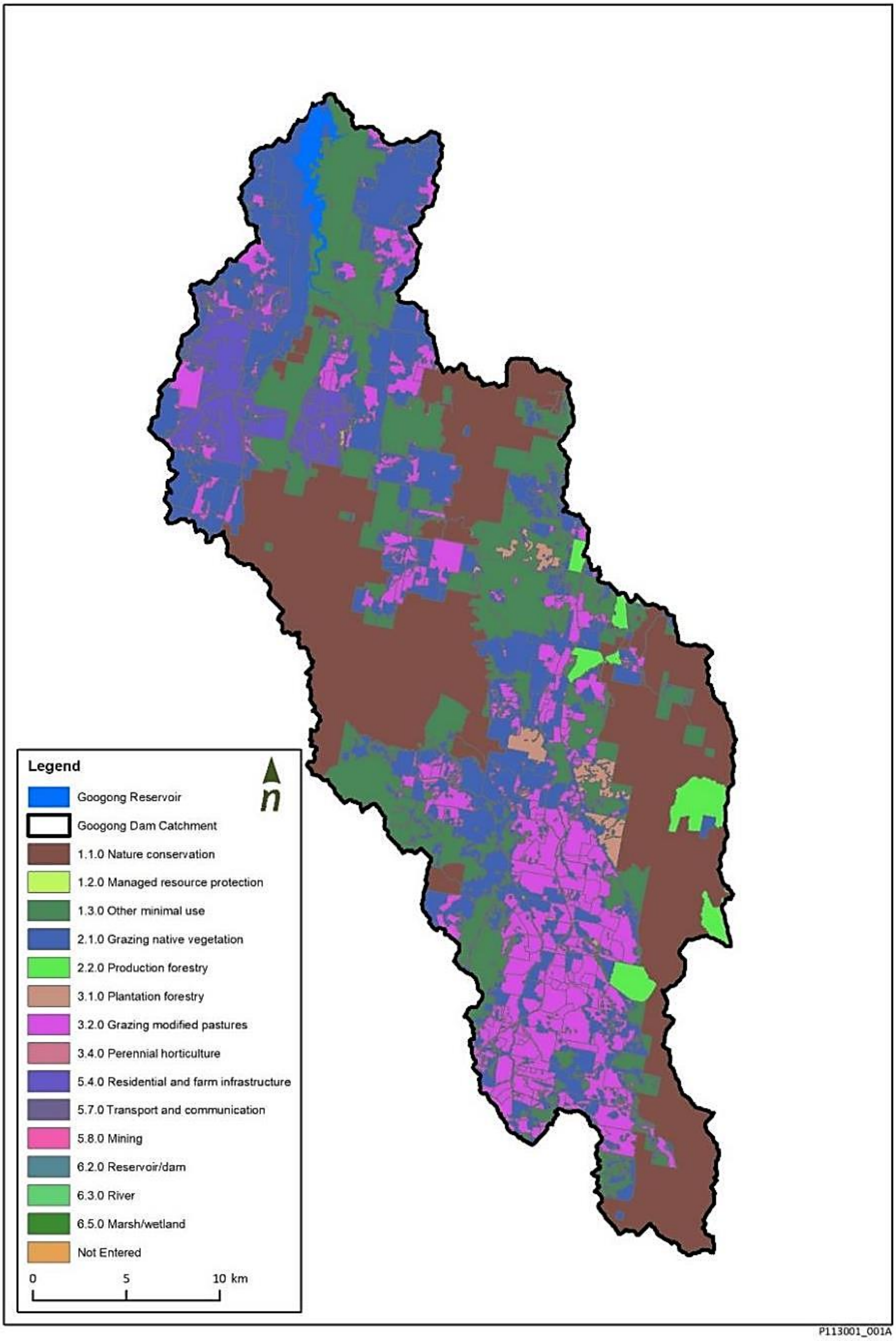


Figure 28 *Googong Dam catchment land use mapping*

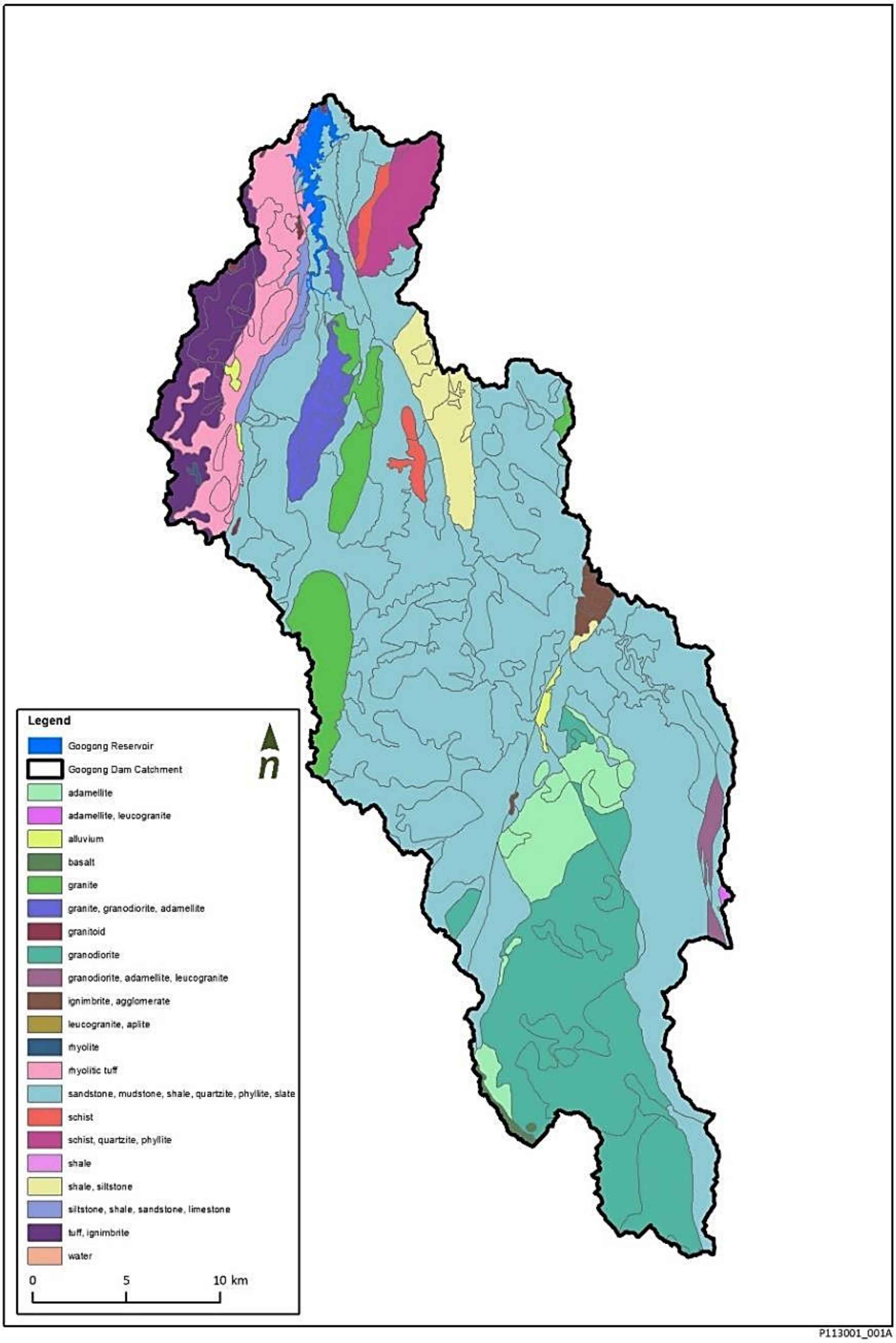


Figure 29 - *Googong Dam catchment geology*

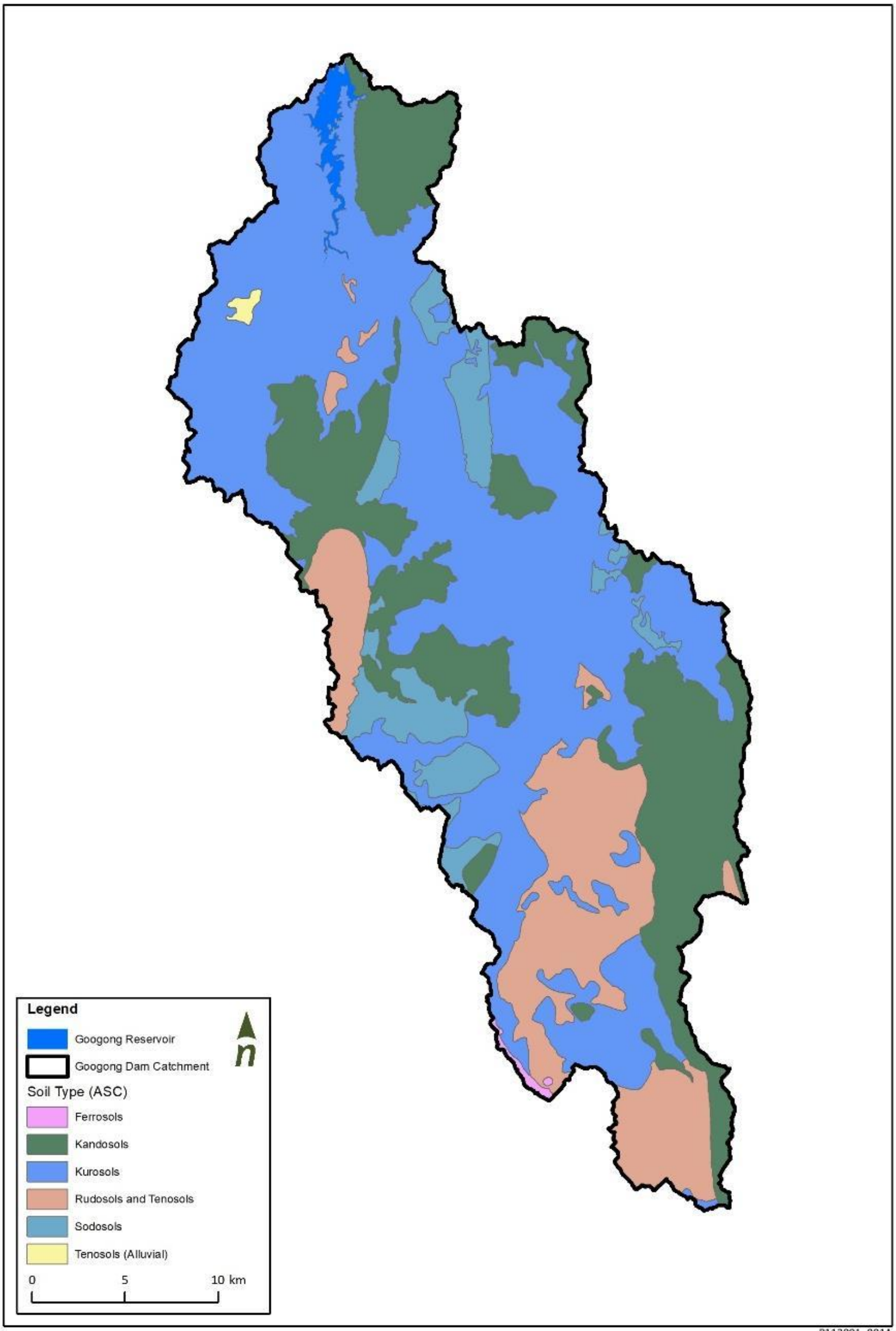


Figure 30 - *Googong Dam catchment soil types*

Appendix E
Location of priority management zones

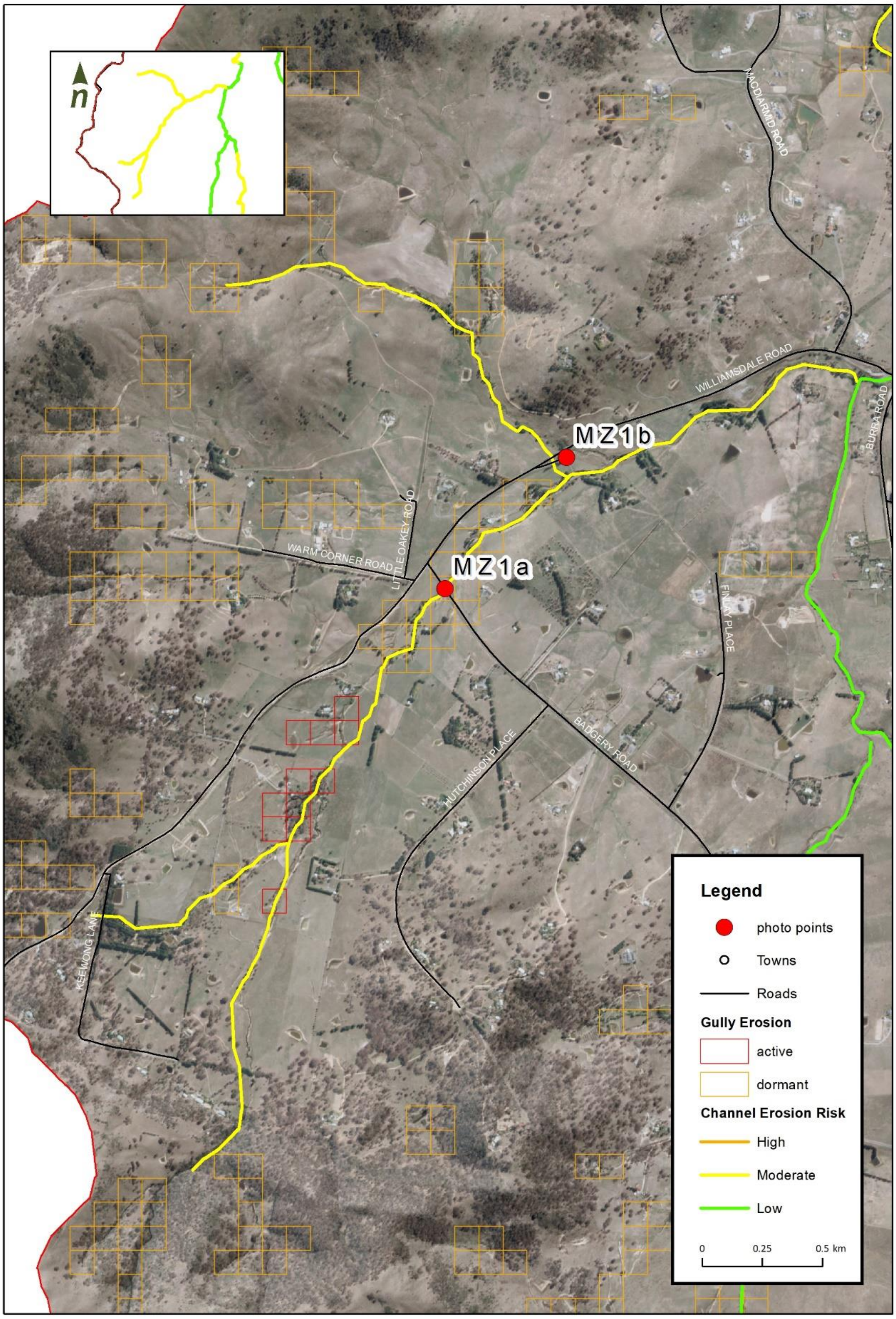


Figure 31. *Priority Management Zone 1*

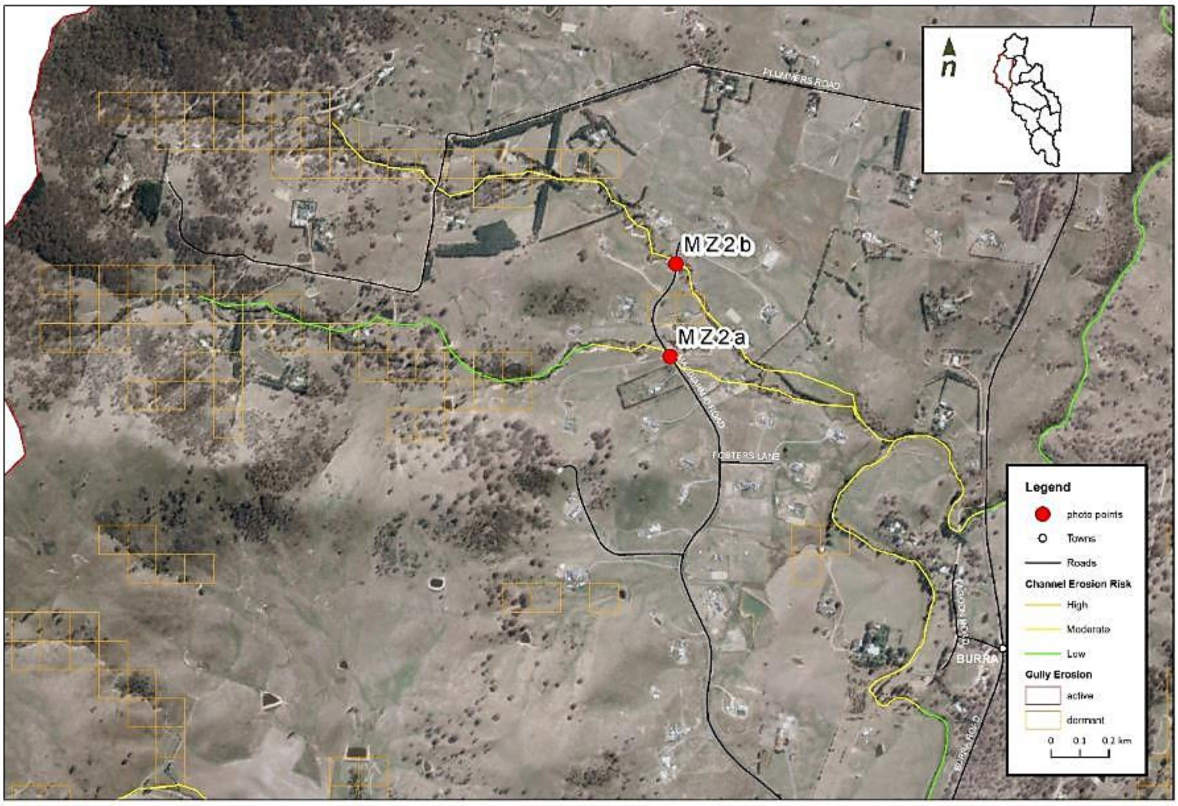


Figure 32. *Priority Management Zone 2*

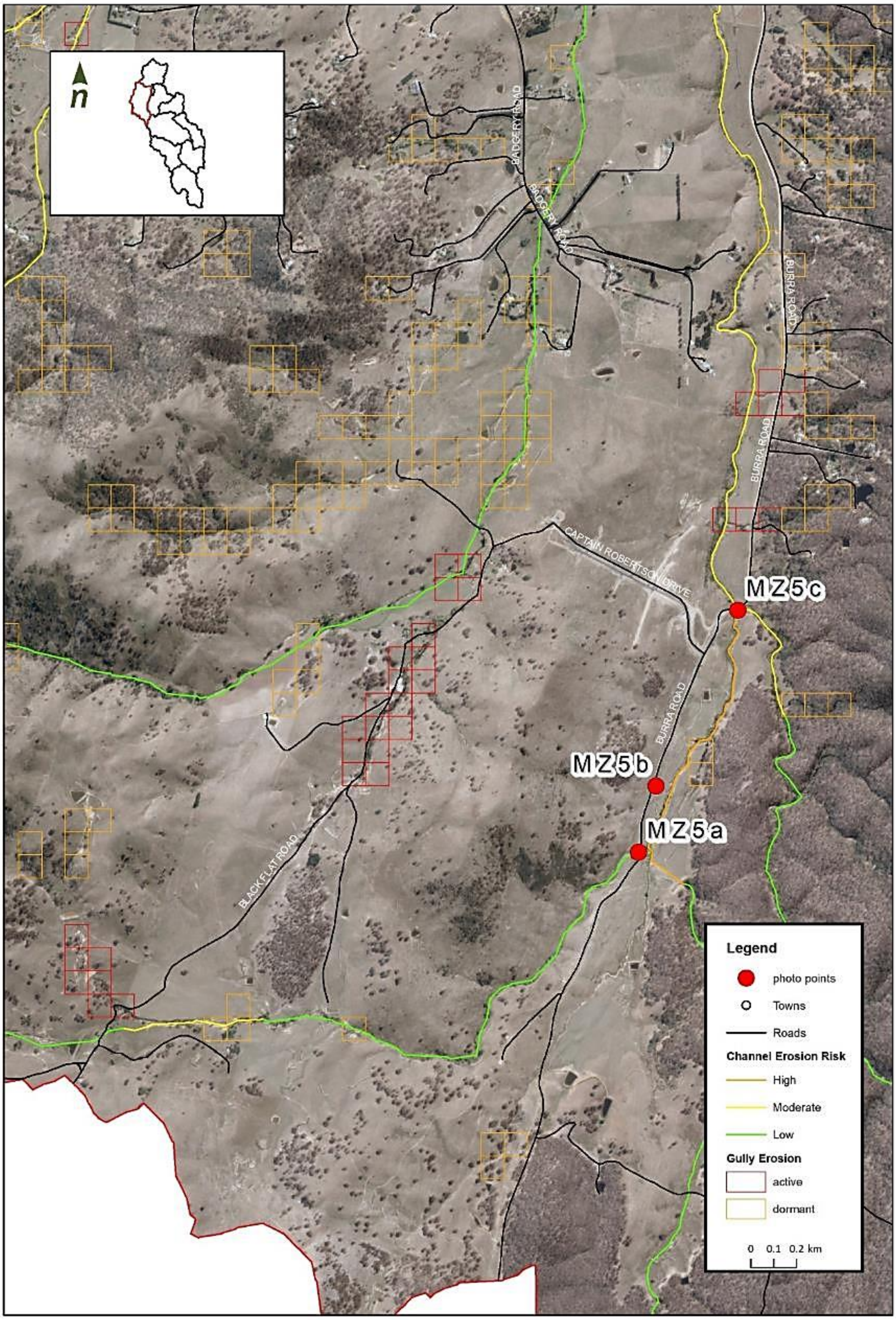


Figure 33. *Priority Management Zone 5*

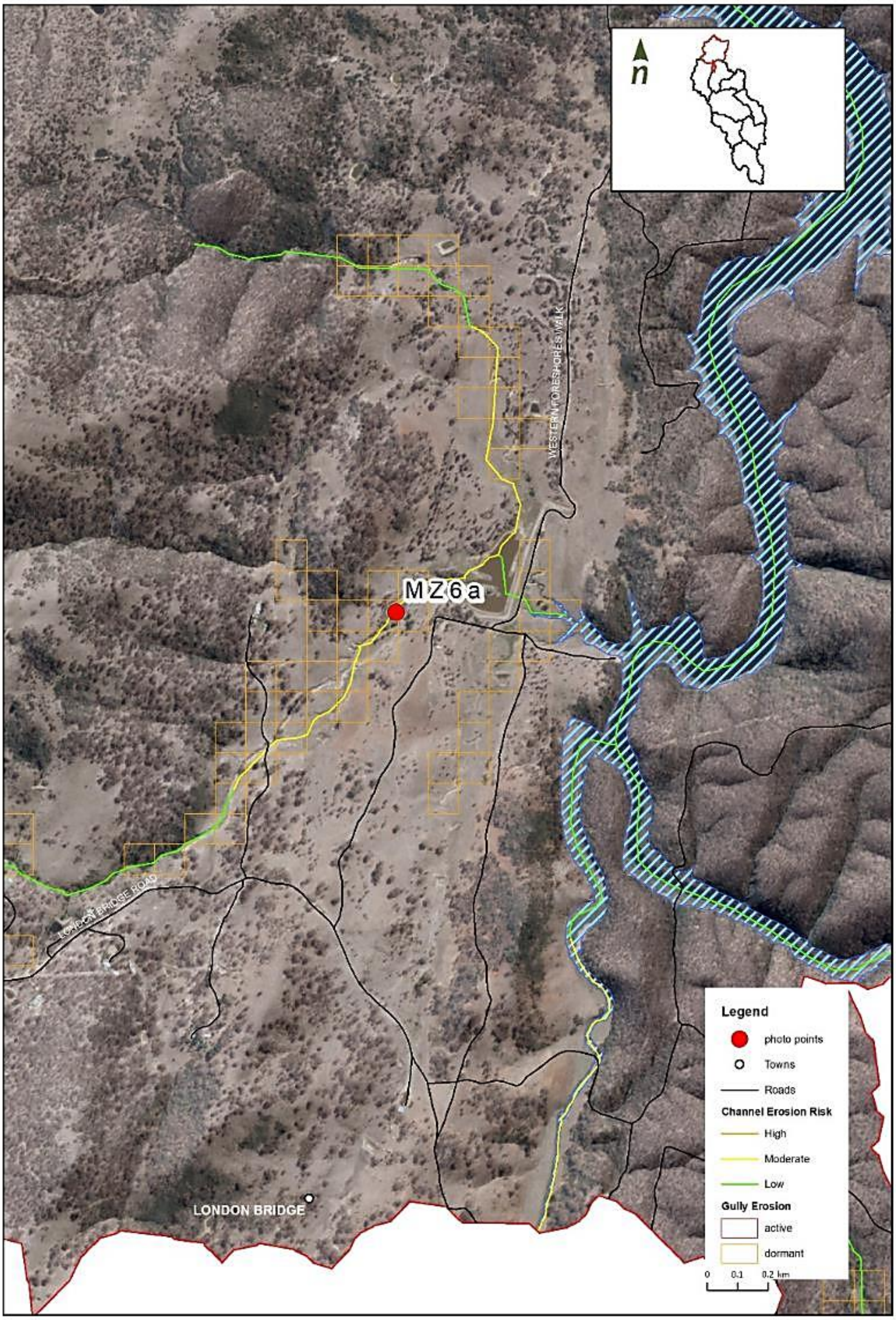


Figure 34. *Priority Management Zone 6*