APPENDIX O.2

CENOZOIC GEODIVERSITY ASSESSMENT

Cenozoic Geodiversity Assessment Report

Snowy 2.0 Main Works

A report prepared for EMM

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Frontispiece: View of a periglacial block stream upslope of Lobs Hole Ravine Road, northern Kosciuszko National Park. (Photo source: I. Percival)

Executive Summary

Introduction

Snowy 2.0 is a large-scale pumped hydro-electric storage and generation project which would increase hydro-electric capacity within the existing Snowy Mountains Hydro-electric Scheme (Snowy Scheme) by almost 50%. Snowy 2.0 proposes to link the existing Tantangara and Talbingo reservoirs within the Snowy Scheme through a series of tunnels and an underground hydro-electric power station (Figure 1.1). The first stage of Snowy 2.0, the Exploratory Works, includes an exploratory tunnel and portal and other exploratory and construction activities primarily in the Lobs Hole area of the Kosciuszko National Park (KNP). The second stage is termed the Main Works, and includes the major construction elements of Snowy 2.0 and its subsequent operation.

The Snowy 2.0 project area is located within the Australian Alps, in southern NSW, about mid-way between Canberra and Albury (Figure 1.2). Most of the proposed infrastructure is located within northern Kosciuszko National Park (KNP), with key locations for surface works being Tantangara and Talbingo reservoirs, the Lobs Hole area, and the Marica area (Figure 1.3). Works will also include establishing or upgrading access tracks and roads and electricity connections to construction sites.

This geodiversity assessment has been prepared to accompany an application and supporting EIS (Environmental Impact Statement) for the Snowy 2.0 Main Works. The Exploratory Works have been assessed in a separate EIS and were approved in February 2019. This is one of two geodiversity assessments conducted for the Main Works EIS. The other, by Dr Ian Percival (2019), focuses on geodiversity within the much older Palaeozoic era rocks of the project area. The current report includes:

1. A review of Cenozoic geodiversity in the Main Works project area, with a particular focus on the two documented sites within and near the project disturbance area.
2. An assessment of the sensitivities, risks and opportunities associated with Cenozoic geodiversity in the context of the project.
3. Recommendations for the management of Cenozoic geodiversity during the project, to mitigate and avoid associated impacts on geodiversity values (summarised in Table 5.1).

Assessment context

Geodiversity is the equivalent of biodiversity but pertaining instead to non-living elements of the natural world encompassing the natural range of geological (bedrock), geomorphological (landform) and soil features, assemblages, systems and processes (Commonwealth of Australia 2002). Geodiversity significance can be assessed on the basis of a variety of criteria including rarity, scientific importance, aesthetic or landscape values, educational value and cultural value. Sites are assessed as significant at a particular scale of reference which may be local, regional, national or international. KNP management documents consider geodiversity conservation and management. The KNP Plan of Management identifies numerous significant geological and geomorphological features that occur within the park (Schedule 1, NPWS 2006). This plan and the subsequent KNP Geodiversity Action Plan (KGAP, OEH 2012) outline the actions required to ensure such features are protected, conserved and promoted, and these documents were used as a starting point in the current assessment.

The Cenozoic is the geological era extending from 66 million years ago (Ma) to the present. The geology of the Snowy 2.0 project area mainly comprises Palaeozoic era rocks deposited during the Ordovician to Devonian periods (approximately 485 to 360 Ma) with mid-Cenozoic to younger cover deposits occurring in some areas. No deposits from the long intervening time span extending from the late Palaeozoic to the early Cenozoic are known from the project area, when erosion was the dominant process. Notable Cenozoic deposits documented within the area include Miocene epoch volcanic rocks (largely basaltic lava flow deposits forming ridge-tops and plateaus due to topographic inversion), fossiliferous Miocene alluvial and lacustrine sediments which underlie or are interbedded with lava flow deposits, and Late Pleistocene (last ice age) periglacial block streams. During the Cenozoic, the area was subject to periods of tectonism that has left its mark on the landscape through uplift, fault movement, and impacts on drainage and erosion patterns.

Assessment methods

This assessment is based on literature review, spatial data review, and observations made during a site visit to Cenozoic geodiversity features in the vicinity of Lobs Hole Ravine Road in northern KNP. The literature reviewed included recent geological and geotechnical reports undertaken for Snowy 2.0 in addition to the abundant past literature on the geology of the project area, and KNP management documents. Spatial data examined included newly-acquired aerial photos and LiDAR-derived DEM, in addition to existing geological mapping and other relevant data. The new remotely-sensed data was used, along with other available information including limited field data, to interpret the extent and context of Cenozoic geodiversity features within the project area.

Cenozoic geodiversity impacted by the project

Two sets of Cenozoic geodiversity features identified as significant in KNP management documents (NPWS 2006, OEH 2012) occur within or close to the project disturbance area. These are Pleistocene periglacial block streams and Quaternary tufa deposits, both of which occur in the vicinity of Lobs Hole Ravine Road, near Ravine. Detailed descriptions of these features are provided in this report including their locations, lithological features, mode of formation, geological context, geodiversity significance, current condition and potential susceptibility to impacts. Revised maps of both sets of features are also presented.

The Ravine periglacial block streams comprise linear deposits of boulder to cobble-size basalt blocks occupying steep slopes. They are elongate downslope, and range from around 6 m to 100 m wide, with the longest example around 370 m long (Figure 4.2). Deposit thicknesses are believed to typically be between 1-2 m, but may range up to 5 m. The block streams are visually striking features and include extensive unvegetated areas. They formed as a result of frost-induced fracture of Miocene-age basalt outcrops capping the ridge to the east of the features and subsequent en masse down-slope movement of the coarse rock debris under the influence of interstitial ice. Age-dating of these deposits has confirmed that they formed approximately 23 to 17 thousand years ago during the Late Pleistocene at the peak of the last ice age, similar to the few other dated examples of such features in south-eastern Australia (Barrows et al. 2004). The Ravine block streams are clearly visible from numerous sites along Lobs Hole Ravine Road which crosses five block streams. Periglacial block streams are not common in south-eastern Australia although they occur quite widely in KNP above 1000 m elevation in association with basalt ridge-tops. They provide the most impressive evidence of Late Pleistocene periglacial activity in the area, the scientific study of which has contributed to the understanding of regional and global cold climates and past climate change (Galloway 1989). The Ravine block streams are a very prominent example of these features due to their accessibility for future geotourism, scientific significance as a dated reference site and scenic landscape values, and are assessed to have geodiversity significance at regional to national level.

The Ravine tufa comprises deposits of secondary limestone formed from precipitation of calcium carbonate minerals (probably mainly calcite) from spring or surface water inferred to be sourced from the underlying Devonian Lick Hole Formation which contains common limestone beds. Spectacular cliff-edge tufa deposits occur at eight sites in Lick Hole Gully, Cave Gully, and Wallaces Creek where streamlines emerge at a prominent sandstone cliff-line, and pale 'cascades' of tufa have built out over the cliffs, in places forming deposits more than 100 m wide and extending tens of metres down and out from the cliff-face (Figures 4.3, 4.4). This tufa exhibits a variety of forms including stalactites and constructional caverns. Very active deposition at these sites was observed in the relatively recent past including onto native flora (Andrews 1901). The upper age limit of the deposits is unknown but is likely to extend into thousands of years. Tufa deposits also line gullies upstream of the cliff-edge sites, extending hundreds of metres, but are mainly low grade. Lobs Hole Ravine Road bisects two of these tufa-lined gullies, one of which includes some modest higher-grade tufa (Tufa B). Tufa is not common in south-eastern Australia and the cliff-edge tufa sites are the largest known tufa deposits in the region. They are visually spectacular features with high potential for future geotourism, and have untested but strong potential for future scientific interest. They are assessed to have geodiversity significance at regional to national level.

There is some potential for undocumented Cenozoic geodiversity features to occur within the project area, including additional notable periglacial features, fossil-rich Miocene sediments underlying basalt, and Cenozoic deposits affected by neotectonics (relatively recent faulting); however, no specific sites have been identified to date within the project disturbance area and the possibility that such sites exist within that area is assessed to be low. This study has identified numerous previously unreported basalt block deposits of probable Pleistocene periglacial origin, including block streams, from remotely-sensed data and limited field reports (Figures 4.5 and 4.6). These occur within the project area but outside the disturbance area.

Potential impacts and benefits of the Main Works

Prior to Snowy 2.0, Lobs Hole Ravine Road has comprised a narrow, unpaved, single lane road corridor constructed by cut and fill. Road works assessed and approved for the Exploratory Works include a minor upgrade to the road involving upslope encroachment of around 2 m on block streams adjacent to the road and no additional impacts on the tufa. A much more substantial upgrade and widening of this road are proposed for the Main Works, with a typical disturbance area 80 m wide around the current road alignment in the vicinity of the block stream and tufa sites.

For the block streams, road widening and associated construction works affecting an area of this width would have a substantial additional impact, with five block streams partially, and one wholly, within the disturbance area. Direct impacts within this area are likely to include excavation and covering of blocks. Other potential impacts on this geodiversity site include degradation of landscape values, imposition of viewing limitations through covering of blocks, and affects on local block stability. There are large areas of block stream outside the project disturbance area, mostly on the upslope side of the road, and total removal of the features is not a risk.

Two areas of tufa lie within the project disturbance zone and are likely to be impacted directly by the roadworks. Of these, one is a low-grade gully deposit (Tufa A) and the other a small, higher grade deposit (Tufa B). The very high-value, cliff-edge tufa deposits occur downstream of the road outside the defined project disturbance area but may be subject to indirect impacts from roadworks several hundred metres upstream. Tufa deposits are fragile and typically highly dependent on the maintenance of natural hydrology and vegetation. Specific concerns around roadwork impacts include: unnatural changes in water flow, turbidity and chemistry; mechanical damage; and sedimentation due to construction activities including land clearing in tufa catchments.

The road upgrade will improve access to the Ravine area Cenozoic geodiversity sites and presents an opportunity to provide visitor viewing areas and information for these significant sites, potentially within a regional geotrail initiative. This could provide some compensation for negative impacts on the natural values of the area arising from project construction activities. There also may be opportunities to facilitate scientific study of the geodiversity sites, the results of which could have management and educational benefits in addition to scientific benefits. This could be facilitated by alerting nominated specialists to the new opportunities for site access post-construction (e.g. new road cuts through the block streams) and sharing new geological information and other relevant project data.

Summary of recommended mitigation strategies

Recommendations relating to the management of Cenozoic geodiversity features during Snowy 2.0 Main Works are presented in Table 5.1 of this report. They are grouped into five broad categories, and include design principles for road sections through the block streams (GEO1) and tufa deposits (GEO3); and measures to include in management plans for the block streams (GEO2), tufa (GEO4), and any undocumented Cenozoic geodiversity features identified during the project (GEO5).

For the Ravine block stream sections, road design priorities should include the following measures:

- minimise the road footprint through these sections as far as practicable;
- limit excavation into the block streams to the minimum required for road safety;
- avoid covering the upslope block streams with shotcrete or other materials that would permanently preclude viewing of the blocks;
- consider the visual impact of the road upgrade in the block stream sections and implement road design that will maintain landscape values.

For the Ravine tufa sections, road design priorities should include the following:

- limit direct impacts on roadside tufa features where possible, in particular those that display notable intact natural structures;
- maintain drainage in as natural state as possible where the road crosses tufa-lined gullies;
- implement strict water and sediment controls during roadworks within the Lick Hole Gully and Cave Gully catchments upstream of the cliff-edge tufa deposits; and
- minimise vegetation clearing within the Lick Hole Gully and Cave Gully catchments upstream of the cliff-edge tufa deposits.

Management plans for both the block stream and tufa sites should include the following measures:

- regularly monitor for impacts during construction, and implement contingency measures in the event that unexpected impacts are identified;
- facilitate development of a safe stopping space and interpretive signage within the proposed road and disturbance footprint post-construction to enhance opportunities for geotourism viewing;
- facilitate the potential scientific study of the features post-construction including, if required, sharing of relevant project data.

For undocumented Cenozoic geodiversity sites, a management plan should include: Cenozoic geodiversity awareness training for relevant personnel; field checking for Cenozoic geodiversity at newly exposed construction sites; guidelines in the event that new sites are recognised; and a requirement for reporting of such sites to NPWS.

Conclusions

The Main Works project area includes some high value Cenozoic geodiversity features which occur within a national heritage-listed, national park landscape. As detailed in this report, the Ravine periglacial block streams and tufa deposits also have wider regional to national geodiversity significance. New infrastructure associated with Snowy 2.0 Main Works will undoubtedly have some adverse impact on parts of these sites. With careful management, including well-considered infrastructure design, it should however be possible to reduce the impacts of the project on these features to an acceptable level. Potential opportunities presented by the project for scientific study and improved access and facilities for educational groups and tourists would also help ameliorate the negative impacts.

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1 Introduction

1.1 The project

Snowy Hydro Limited (Snowy Hydro) proposes to develop Snowy 2.0, a large-scale pumped hydro-electric storage and generation project which would increase hydro-electric capacity within the existing Snowy Mountains Hydro-electric Scheme (Snowy Scheme). Snowy 2.0 is the largest committed renewable energy project in Australia and is critical to underpinning system security and reliability as Australia transitions to a decarbonised economy. . Snowy 2.0 will link the existing Tantangara and Talbingo reservoirs within the Snowy Scheme through a series of underground tunnels and a new hydro-electric power station will be built underground.

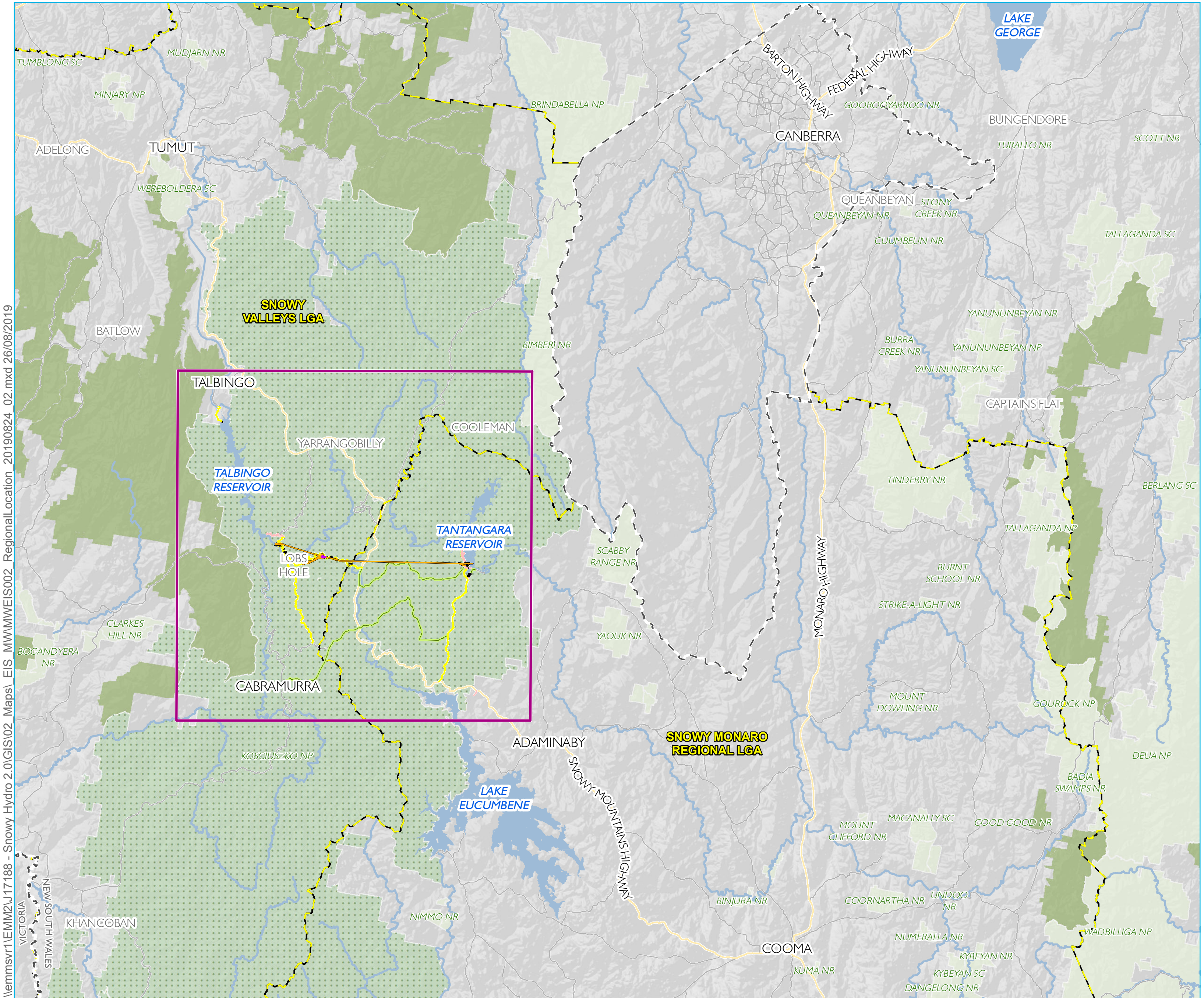
Snowy 2.0 has been declared to be State significant infrastructure (SSI) and critical State significant infrastructure (CSSI) by the former NSW Minister for Planning under Part 5 of the NSW Environmental Planning and Assessment Act 1979 (EP&A Act) and is defined as CSSI in clause 9 of Schedule 5 of the State Environmental Planning Policy (State and Regional Development) 2011 (SRD SEPP). CSSI is infrastructure that is deemed by the NSW Minister to be essential for the State for economic, environmental or social reasons. An application for CSSI must be accompanied by an environmental impact statement (EIS).

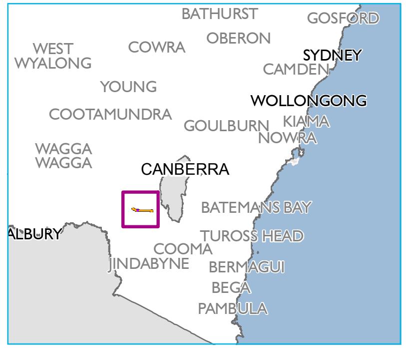
Separate applications are being submitted by Snowy Hydro for different stages of Snowy 2.0 under Part 5, Division 5.2 of the EP&A Act. This includes the preceding first stage of Snowy 2.0, Exploratory Works for Snowy 2.0 (the Exploratory Works) and the stage subject of this current application, Snowy 2.0 Main Works (the Main Works). In addition, an application under Part 5, Division 5.2 of the EP&A Act is also being submitted by Snowy Hydro for a segment factory that will make tunnel segments for both the Exploratory Works and Main Works stages of Snowy 2.0.

The first stage of Snowy 2.0, the Exploratory Works, includes an exploratory tunnel and portal and other exploratory and construction activities primarily in the Lobs Hole area of the Kosciuszko National Park (KNP). The Exploratory Works were approved by the former NSW Minister for Planning on 7 February 2019 as a separate project application to DPIE (SSI 9208).

This geodiversity assessment has been prepared to accompany an application and supporting EIS for the **Snowy 2.0 Main Works**. As the title suggests, this stage of the project covers the major construction elements of Snowy 2.0, including permanent infrastructure (such as the underground power station, power waterways, access tunnels, chambers and shafts), temporary construction infrastructure (such as construction adits, construction compounds and accommodation), management and storage of excavated rock material and establishing supporting infrastructure (such as road upgrades and extensions, water and sewage treatment infrastructure, and the provision of construction power). Snowy 2.0 Main Works also includes the operation of Snowy 2.0.

Snowy 2.0 Main Works is shown in Figure 1.1. If approved, the Snowy 2.0 Main Works would commence before completion of Exploratory Works.





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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY

- Project area

Snowy 2.0 Main Works operational elements

- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements

- Temporary construction compounds and surface works
- Temporary access road

Existing environment

- Main road
- Local road
- Watercourse
- Waterbodies
- Kosciuszko National Park
- NPWS reserve
- State forest
- Local government area boundary
- State boundary

Regional setting

Snowy 2.0
Cenozoic geodiversity report
Main Works
Figure 1.1

The Snowy 2.0 Main Works do not include the transmission works proposed by TransGrid (TransGrid 2018) that provide connection between the cableyard and the NEM. These transmission works will provide the ability for Snowy 2.0 (and other generators) to efficiently and reliably transmit additional renewable energy to major load centres during periods of peak demand, as well as enable a supply of renewable energy to pump water from Talbingo Reservoir to Tantangara Reservoir during periods of low demand. While the upgrade works to the wider transmission network and connection between the cableyard and the network form part of the CSSI declaration for Snowy 2.0 and Transmission Project, they do not form part of this application and will be subject to separate application and approval processes, managed by TransGrid. This project is known as the HumeLink and is part of AEMO's Integrated System Plan.

With respect to the provisions of the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), on 30 October 2018 Snowy Hydro referred the Snowy 2.0 Main Works to the Commonwealth Department of the Environment and Energy (DEE) and, on a precautionary basis, nominated that Snowy 2.0 Main Works has potential to have a significant impact on MNES and the environment generally.

On 5 December 2018, Snowy 2.0 Main Works were deemed a controlled action by the Assistant Secretary of the DEE. It was also determined that potential impacts of the project will be assessed by accredited assessment under Part 5, Division 5.2 of the EP&A Act. This accredited process will enable the NSW Department of Planning, Industry and Environment (DPIE) to manage the assessment of Snowy 2.0 Main Works, including the issuing of the assessment requirements for the EIS. Once the assessment has been completed, the Commonwealth Minister for the Environment will make a determination under the EPBC Act.

1.2 Project location

Snowy 2.0 Main Works are within the Australian Alps, in southern NSW, about mid-way between Canberra and Albury. Snowy 2.0 Main Works is within both the Snowy Valleys and Snowy Monaro Regional local government areas (LGAs).

The nearest large towns to Snowy 2.0 Main Works are Cooma and Tumut. Cooma is located about 50 kilometres (km) south east of the project area (or 70 km by road from Providence Portal at the southern edge of the project area), and Tumut is located about 35 km north west of the project areas (or 45 km by road from Tumut 3 power station at the northern edge of the project area). Other townships near the project area include Talbingo, Cabramurra, Adaminaby and Tumbarumba. Talbingo and Cabramurra were built for the original Snowy Scheme workers and their families, while Adaminaby was relocated in 1957 to make way for the establishment of Lake Eucumbene.

The location of Snowy 2.0 Main Works with respect to the region is shown in Figure 1.2.

The pumped hydro-electric scheme elements of Snowy 2.0 Main Works are mostly underground between the southern ends of Tantangara and Talbingo reservoirs, a straight-line distance of 27 km. Surface works will also occur at locations on and between the two reservoirs. Key locations for surface works include:

- **Tantangara Reservoir** - at a full supply level (FSL) of about 1,229 metres (m) to Australian Height Datum (AHD), Tantangara Reservoir will be the upper reservoir for Snowy 2.0 and include the headrace tunnel and intake structure. The site will also be used for a temporary construction compound, accommodation camp and other temporary ancillary activities;

- **Marica** - this site will be used primarily for construction including construction of vertical shafts to the underground power station (ventilation shaft) and headrace tunnel (surge shaft), and a temporary accommodation camp;

- **Lobs Hole** - the site will be used primarily for construction but will also become the main entrance to the power station during operation. Lobs Hole will provide access to the Exploratory Works tunnel, which will be refitted to become the main access tunnel (MAT), as well as the location of the emergency egress, cable and ventilation tunnel (ECVT), portal, associated services and accommodation camp; and

- **Talbingo Reservoir** - at a FSL of about 546 m AHD, Talbingo Reservoir will be the lower reservoir for Snowy 2.0 and will include the tailrace tunnel and water intake structure. The site will also be used for temporary construction compounds and other temporary ancillary activities.

Works will also be required within the two reservoirs for the placement of excavated rock and surplus cut material. Supporting infrastructure will include establishing or upgrading access tracks and roads and electricity connections to construction sites.

Most of the proposed pumped hydro-electric and temporary construction elements and most of the supporting infrastructure for Snowy 2.0 Main Works are located within the boundaries of KNP, although the disturbance footprint for the project during construction is less than 0.25% of the total KNP area. Some of the supporting infrastructure and construction sites and activities (including sections of road upgrade, power and communications infrastructure) extends beyond the national park boundaries. These sections of infrastructure are primarily located to the east and south of Tantangara Reservoir. One temporary construction site is located beyond the national park along the Snowy Mountains Highway about 3 km east of Providence Portal (referred to as Rock Forest).

The project is described in more detail in Chapter 2.

1.2.1 Project area

The project area for Snowy 2.0 Main Works has been identified and includes all the elements of the project, including all construction and operational elements. The project area is shown on Figure 1.3. Key features of the project area are:

- the water bodies of Tantangara and Talbingo reservoirs, covering areas of 19.4 square kilometres (km^2) and 21.2 km^2 respectively. The reservoirs provide the water to be utilised in Snowy 2.0;

- major watercourses including the Yarrangobilly, Eucumbene and Murrumbidgee rivers and some of their tributaries;

- KNP, within which the majority of the project area is located. Within the project area, KNP is characterised by two key zones: upper slopes and inverted treelines in the west of the project area (referred to as the 'ravine') and associated subalpine treeless flats and valleys in the east of the project area (referred to as the 'plateau'); and

- farm land southeast of KNP at Rock Forest.

The project area is interspersed with built infrastructure including recreational sites and facilities, main roads as well as unsealed access tracks, hiking trails, farm land, electricity infrastructure, and infrastructure associated with the Snowy Scheme.

1.3 Proponent

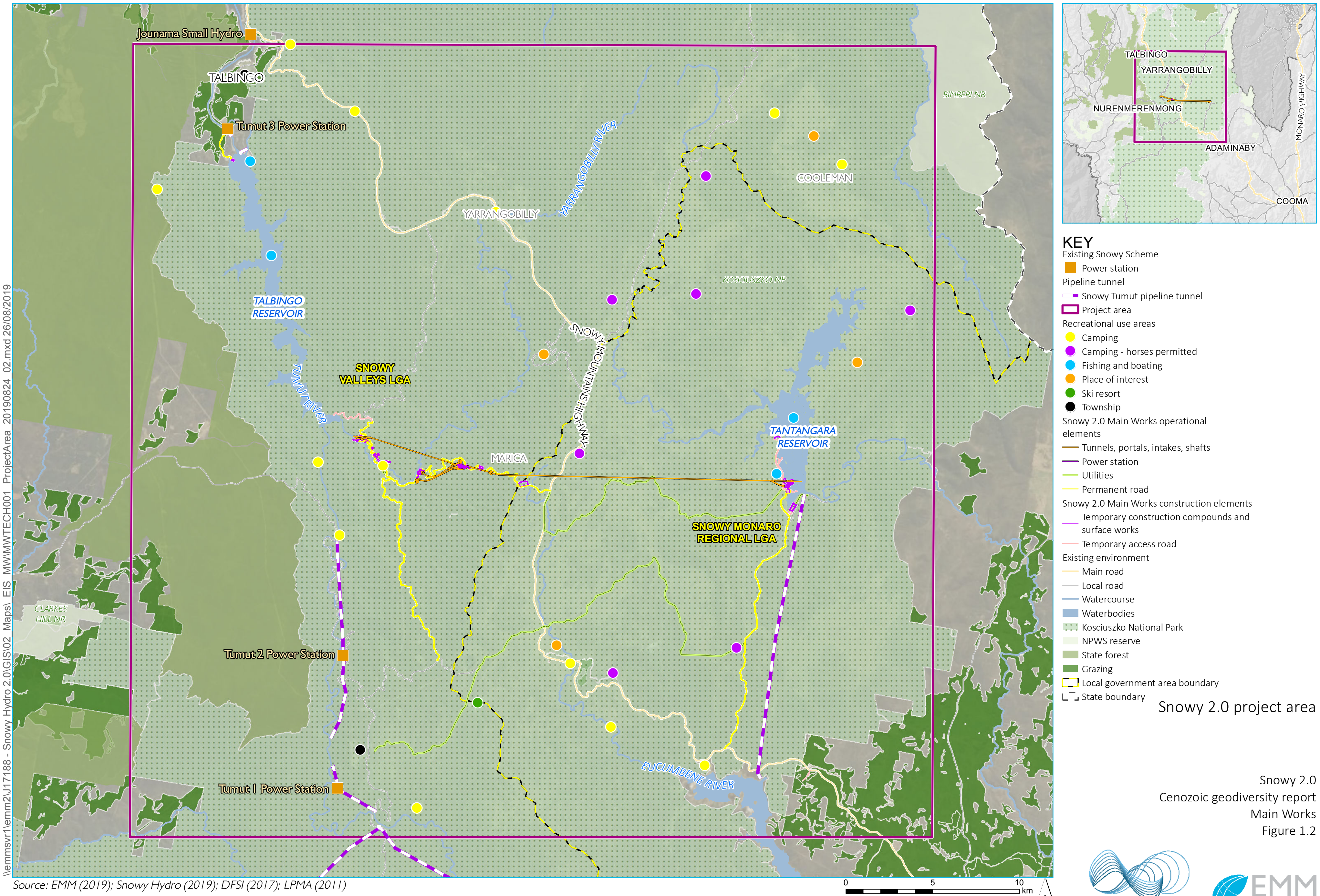
Snowy Hydro is the proponent for the Snowy 2.0 Main Works. Snowy Hydro is an integrated energy business – generating energy, providing price risk management products for wholesale customers and delivering energy to homes and businesses. Snowy Hydro is the fourth largest energy retailer in the NEM and is Australia's leading provider of peak, renewable energy.

1.4 Purpose of this report

This Cenozoic Geodiversity Assessment Report (GAR) supports the EIS for the Snowy 2.0 Main Works. It is one of two GARs prepared for the Snowy 2.0 Main Works EIS; a companion Palaeozoic GAR has been produced by Dr Ian Percival. The geology of the project area is comprised mainly of Palaeozoic rocks with less extensive areas of much younger Cenozoic deposits. Rocks from the intervening Mesozoic era are not known from the area. The nature and mode of formation of the Palaeozoic and Cenozoic geology are distinct and their study requires different approaches and expertise, hence the separate reporting. This GAR documents the Cenozoic geodiversity assessment methods and results, initiatives built into the project design to avoid and minimise associated impacts to Cenozoic geodiversity, and the mitigation, and management measures proposed to address any unavoidable residual impacts.

The specific objectives of this assessment are to:

- describe the known Cenozoic geodiversity sites potentially impacted by the project, including their geological context and geodiversity significance;
- identify and/or assess the potential for additional undocumented Cenozoic geodiversity sites which may be impacted by the project;
- identify constraints within and impacts arising from the Snowy 2.0 Main Works on Cenozoic geodiversity;
- provide mitigation and management measures to reduce the impacts from the project on Cenozoic geodiversity wherever possible; and
- indicate opportunities and benefits for Cenozoic geodiversity that could arise from the Snowy 2.0 Main Works which could potentially provide some compensation for any negative impacts.



Snowy 2.0 project area

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

Snowy 2.0
Cenozoic geodiversity report
Main Works
Figure 1.2

1.4.1 Assessment guidelines and requirements

This geodiversity assessment has been prepared in accordance with the Secretary's Environmental Assessment Requirements (SEARs) for Snowy 2.0 Main Works, issued on 31 July 2019, as well as relevant government assessment requirements, guidelines and policies, and in consultation with the relevant government agencies. The SEARs must be addressed in the EIS. Table 1.1 lists the matters relevant to this assessment and where they are addressed in this report.

Table 1.1 Relevant matters raised in SEARs

Requirement	Section addressed
An assessment of impacts of the project on: • The geodiversity values of the site, including potential impacts on karst systems, fossil beds and boulder streams;	Tufa associated with Ravine area karst: Sections 4.7, 5 Ravine periglacial boulder (block) streams: Sections 4.6, 5

To inform preparation of the SEARs, the DPIE invited relevant government agencies to advise on matters to be addressed in the EIS. These matters were taken into account by the Secretary for DPIE when preparing the SEARs.

1.5 Related projects

There are three other projects related to Snowy 2.0 Main Works, they are:

- Snowy 2.0 Exploratory Works (SSI-9208) – a Snowy Hydro project with Minister's approval;
- Snowy 2.0 Transmission Connect Project (SSI-9717) – a project proposed by TransGrid; and
- Snowy 2.0 – Segment Factory (SSI-10034) – a project proposed by Snowy Hydro.

While these projects form part of the CSSI declaration for Snowy 2.0 and Transmission Project, they do not form part of Snowy Hydro's application for Snowy 2.0 Main Works. These related projects are subject to separate application and approval processes. Staged submission and separate approval is appropriate for a project of this magnitude, due to its complexity and funding and procurement processes. However, cumulative impacts have been considered in this report where relevant.

1.6 Other relevant reports

This Cenozoic geodiversity assessment has been prepared with reference to other technical reports that were prepared as part of the Snowy 2.0 Main Works EIS. The other relevant reports referenced in this Cenozoic geodiversity assessment are listed below.

- Biodiversity development assessment (EMM 2019)
- Heritage assessment and statement of heritage impact (NSW Archaeology 2019)
- Noise and vibration impact assessment (EMM 2019)
- Palaeozoic geodiversity assessment (Percival 2019)
- Water assessment (EMM 2019)

2 Description of the project

This chapter provides a summary of the Snowy 2.0 Main Works project. It outlines the functional infrastructure required to operate Snowy 2.0, as well as the key construction elements and activities required to build it. A more comprehensive detailed description of the project is provided in Chapter 2 (Project description) of the EIS, which has been relied upon for the basis of this technical assessment.

2.1 Overview of Snowy 2.0

Snowy 2.0 will link the existing Tantangara and Talbingo reservoirs within the Snowy Scheme through a series of underground tunnels and a new hydro-electric power station will be built underground. An overview of Snowy 2.0 is shown on Figure 2.1, and the key project elements of Snowy 2.0 are summarised in Table 2.1.

Table 2.1 Overview of Snowy 2.0 Main Works

Project element	Summary of the project
Project area	The project area is the broader region within which Snowy 2.0 will be built and operated, and the extent within which direct impacts from Snowy 2.0 Main Works are anticipated.
Permanent infrastructure	Snowy 2.0 infrastructure to be built and operated for the life of the assets include the: • intake and gate structures and surface buildings at Tantangara and Talbingo reservoirs; • power waterway tunnels primarily comprising the headrace tunnel, headrace surge structure, inclined pressure tunnel, pressure pipelines, tailrace surge tank and tailrace tunnel; • underground power station complex comprising the machine hall, transformer hall, ventilation shaft and minor connecting tunnels; • access tunnels (and tunnel portals) to the underground power station comprising the main access tunnel (MAT) and emergency egress, communication, and ventilation tunnel (ECVT); • establishment of a portal building and helipad at the MAT portal; • communication, water and power supply including the continued use of the Lobs Hole substation; • cable yard adjacent to the ECVT portal to facilitate the connection of Snowy 2.0 to the NEM; • access roads and permanent bridge structures needed for the operation and maintenance of Snowy 2.0 infrastructure; and • fish control structures on Tantangara Creek and near Tantangara Reservoir wall.
Temporary infrastructure	Temporary infrastructure required during the construction phase of Snowy 2.0 Main Works are: • construction compounds, laydown, ancillary facilities and helipads; • accommodation camps for construction workforce; • construction portals and adits to facilitate tunnelling activities; • barge launch ramps; • water and wastewater management infrastructure (treatment plants and pipelines); • communication and power supply; and • temporary access roads.
Disturbance area	The disturbance area is the extent of construction works required to build Snowy 2.0. The maximum disturbance area is about 1,680 hectares (ha), less than 0.25% of the total area of KNP. Parts of the disturbance area will be rehabilitated and landformed and other parts will be retained permanently for operation (operational footprint).

Table 2.1 Overview of Snowy 2.0 Main Works

Project element	Summary of the project
Operational footprint	The operational footprint is the area required for permanent infrastructure to operate Snowy 2.0. The maximum operational footprint is about 99 ha. This is 0.01% of the total area of KNP.
Tunnelling and excavation method	The primary tunnelling method for the power waterway is by tunnel boring machine (TBM), with portals and adits using drill and blast methods. Excavation for other underground caverns, chambers and shafts will be via combinations of drill and blast, blind sink, and/or raise bore techniques.
Excavated rock management	Excavated rock will be generated as a result of tunnelling activities and earthworks. The material produced through these activities will be stockpiled and either reused by the contractor (or NPWS), placed permanently within Tantangara or Talbingo reservoirs, used in final land forming and rehabilitation of construction pads in Lobs Hole, or transported offsite.
Construction water and wastewater management	Water supply for construction will be from the two existing reservoirs (Talbingo and Tantangara) and reticulated via buried pipelines (along access roads). Raw water will be treated as necessary wherever potable water is required (eg at accommodation camps). Water to be discharged (comprising process water, wastewater and stormwater) will be treated before discharge to the two existing reservoirs (Talbingo and Tantangara) as follows: • treated process water will be reused onsite where possible to reduce the amount of discharge to reservoirs, however excess treated water will be discharged to the reservoirs; • collected sewage will be treated at sewage treatment plants to meet the specified discharge limits before discharge and/or disposal; and • stormwater will be captured and reused as much as possible.
Rehabilitation	Rehabilitation of areas disturbed during construction including reshaping to natural appearing landforms or returning to pre-disturbance condition, as agreed with NPWS and determined by the rehabilitation strategy. This includes construction areas at Lobs Hole which comprise surplus cut materials that are required for the construction. Areas to be used by Snowy Hydro in the long-term may be re-shaped and rehabilitated to maintain access and operational capabilities (eg intakes and portal entrances).
Construction workforce	The construction workforce for the project is expected to peak at around 2,000 personnel.
Operational life	The operational life of the project is estimated to be 100 years.
Operational workforce	The operational workforce is expected to be 8-16 staff, with fluctuations of additional workforce required during major maintenance activities.
Hours of operation	Construction of Snowy 2.0 will be 24/7 and 365 days per year. Operation of Snowy 2.0 will be 24/7 and 365 days per year.
Capital investment value	Estimated to be $4.6 billion.

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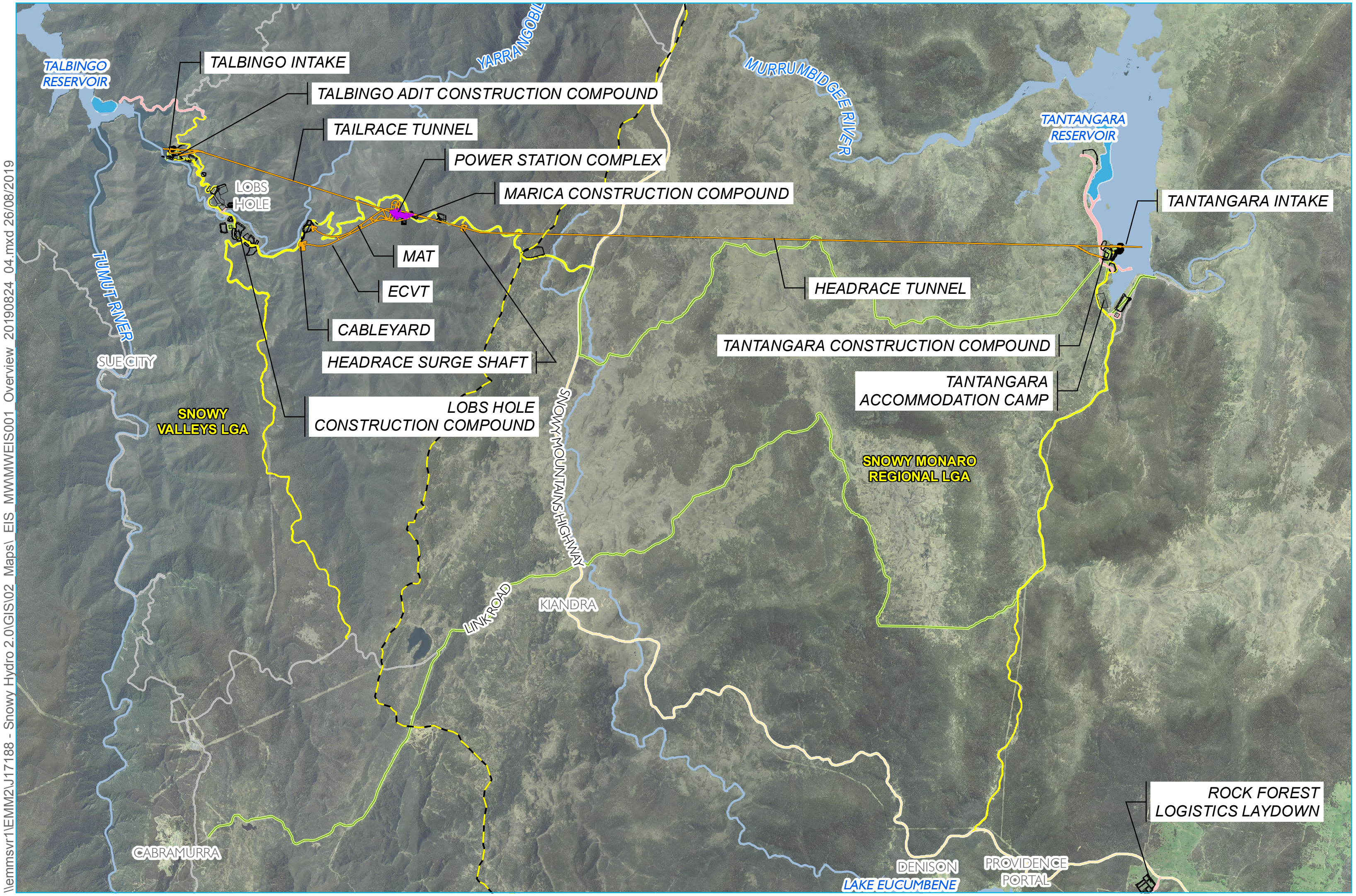
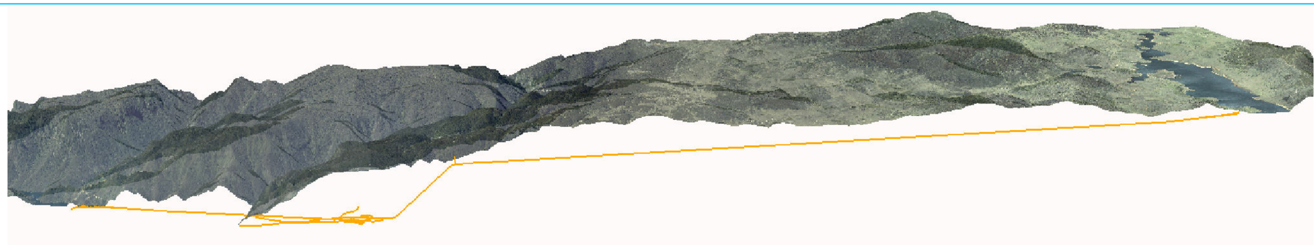




Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

0 2.5 5 km
GDA 1994 MGA Zone 55
N

KEY

Existing environment
- Main road
- Local road
- Watercourse
- Waterbodies
- Local government area boundary

Snowy 2.0 Main Works operational elements
- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements
- Temporary construction compounds and surface works
- Temporary access road
- Indicative rock emplacement area

Snowy 2.0 project elements

Snowy 2.0
Cenozoic geodiversity report
Main Works
Figure 2.1

snowy2.0

EMM creating opportunities

2.2 Construction of Snowy 2.0

A number of construction activities will be carried out concurrently, and across a number of different sites. Specific details on these activities as well as an indicative schedule of construction activities is provided in Chapter 2 (Project description) of the EIS. This section summarises the key construction elements of the project.

Table 2.2 provides an overview of the construction elements, their purpose and location within the Project area.

Table 2.2 Snowy 2.0 construction elements

Construction element	Purpose	Location
Construction sites	Due to the remoteness of Snowy 2.0, construction sites are generally needed to: • Provide ancillary facilities such as concrete batching plants, mixing plants and on-site manufacturing; • Store machinery, equipment and materials to be used in construction; • Provide access to underground construction sites; and • Provide onsite accommodation for the construction workforce.	Each construction site needed for Snowy 2.0 is shown on Figures 2.2 to Figure 2.6.
Substations and power connection	One substation is required to provide permanent power to Snowy 2.0, at Lobs Hole. This substation is proposed as part of a modification to the Exploratory Works with a capacity of 80 mega volt amp (MVA). It will continue to be used for Main Works, however requires the establishment of further power supply cables to provide power to the work sites and TBM at Tantangara, as well as Talbingo, in particular to power the TBMs via the MAT, ECVT, Talbingo and Tantangara portals.	The supporting high voltage cable route mostly follows access roads to each of the work sites, using a combination of aerial and buried arrangements.
Communications system	Communications infrastructure will connect infrastructure at Tantangara and Talbingo reservoirs to the existing communications system at the Tumut 3 power station (via the submarine communications cable in Talbingo Reservoir established during Exploratory Works) and to Snowy Hydro's existing communications infrastructure at Cabramurra.	The cable will be trenched and buried in conduits within access roads. Crossing of watercourses and other environmentally sensitive areas will be carried out in a manner that minimises environmental impacts where possible, such as bridging or underboring.
Water and waste water servicing	Drinking water will be provided via water treatment plants located at accommodation camps. Water for treatment will be sourced from the nearest reservoir. There are three main wastewater streams that require some form of treatment before discharging to the environment, including: • Tunnel seepage and construction wastewater (process water); • Domestic sewer (wastewater); and • Construction site stormwater (stormwater).	Utility pipelines generally follow access roads. Water treatment plants (drinking water) will be needed for the accommodation camps and will be located in proximity. Waste water treatment plants will similarly be located near accommodation camps. Process water treatment plants will be at construction compounds and adits where needed to manage tunnel seepage and water during construction.

Table 2.2 Snowy 2.0 construction elements

Construction element	Purpose	Location
Temporary and permanent access roads	Access road works are required to: • provide for the transport of excavated material between the tunnel portals and the excavated rock emplacement areas; • accommodate the transport of oversized loads as required; and • facilitate the safe movement of plant, equipment, materials and construction workers into and out of construction sites. The access road upgrades and establishment requirements are shown on Figure 2.2 to Figure 2.6. These roads will be used throughout construction including use of deliveries to and from site and the external road network. Some additional temporary roads will also be required within the footprint to reach excavation fronts such as various elevations of the intakes excavation or higher benches along the permanent roads.	The access road upgrades and establishment requirements are shown across the project area. Main access and haulage to site will be via Snowy Mountains Highway, Link Road and Lobs Hole Ravine Road (for access to Lobs Hole), and via Snowy Mountains Highway and Tantangara Road (for access to Tantangara Reservoir) (see Figure 2.1).
Excavated rock management	Approximately 9 million m^3 (unbulked) of excavated material will be generated by construction and require management. The strategy for management of excavated rock will aim to maximise beneficial reuse of materials for construction activities. Beneficial re-use of excavated material may include use for road base, construction pad establishment, selected fill and tunnel backfill and rock armour as part of site establishment for construction. Excess excavated material that cannot be re-used during construction will be disposed of within Talbingo and Tantangara reservoirs, used in permanent rehabilitation of construction pads to be left in situ in Lobs Hole, or transported for on-land disposal if required.	Placement areas are shown on Figure 2.2 and Figure 2.6.
Barge launch facilities	Barge launch facilities on Talbingo Reservoir will have already been established during Exploratory Works for the placement of the submarine communications cable, and will continued to be used for Main Works for construction works associated with the Talbingo intake structure. The Main Works will require the establishment of barge launch facilities on Tantangara Reservoir to enable these similar works (removal of the intake plug).	Barge launch sites are shown on Figure 2.2 and Figure 2.6.
Construction workforce	The construction workforce will be accommodated entirely on site, typically with a FIFO/DIDO roster. Private vehicles will generally not be permitted and the workforce bused to and from site.	Access to site will be via Snowy Mountains Highway

The key areas of construction are shown on Figure 2.2 to Figure 2.6 and can be described across the following locations:

- Talbingo Reservoir – Talbingo Reservoir provides the lower reservoir for the pumped hydro-electric project and will include the tailrace tunnel and water intake structure. The site will also be used for temporary construction compounds and other temporary ancillary activities;

- Lobs Hole – this site will be used primarily for construction (including construction of the MAT and ECVT portals and tunnels to the underground power station and the headrace tunnel (and headrace tunnel surge shaft), underground tailrace surge shaft and a temporary accommodation camp);

- Marica – the site will be used primarily for construction to excavate the ventilation shaft to the underground power station as well as for the excavation and construction of the headrace surge shaft;

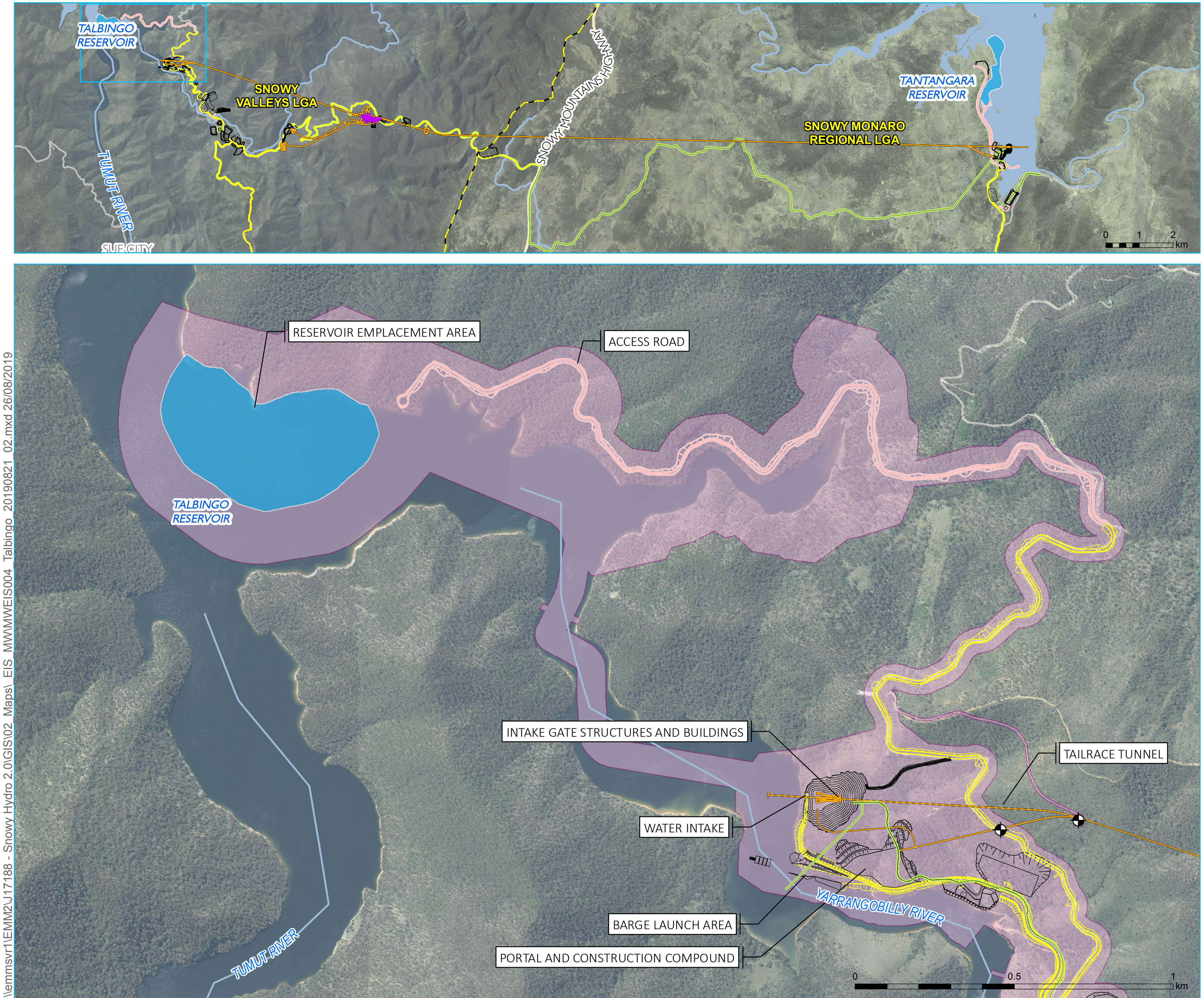
- Plateau – the land area between Snowy Mountains Highway and Tantangara Reservoir is referred to as the Plateau. The Plateau will be used to access and construct a utility corridor and construct a fish weir on Tantangara Creek;

- Tantangara Reservoir – Tantangara Reservoir will be the upper reservoir for the pumped hydro project and include the headrace tunnel and intake structure. The site will also be used for a temporary construction compound, accommodation camp and other temporary ancillary activities; and

- Rock Forest – a site to be used temporarily for logistics and staging during construction. It is located beyond the KNP along the Snowy Mountains Highway about 3 km east of Providence Portal.

During the construction phase, all work sites will be restricted access and closed to the public. This includes existing road access to Lobs Hole via Lobs Hole Ravine Road. Restrictions to water-based access and activities will also be implemented for public safety and to allow safe construction of the intakes within the reservoirs. Access to Tantangara Reservoir via Tantangara Road will be strictly subject to compliance with the safety requirements established by the contractor.

A key construction element for the project is the excavation and tunnelling for underground infrastructure including the power station, power waterway (headrace and tailrace tunnels) and associated shafts. The primary methods of excavation are shown in Figure 2.7 with further detail on construction methods provided at Appendix D of the EIS.



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Source: *EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)*

GDA 1994 MGA Zone 55

N

KEY

Existing environment

- Main road
- Local road
- Watercourse
- Waterbodies
- Local government area boundary

Snowy 2.0 Main Works operational elements

- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

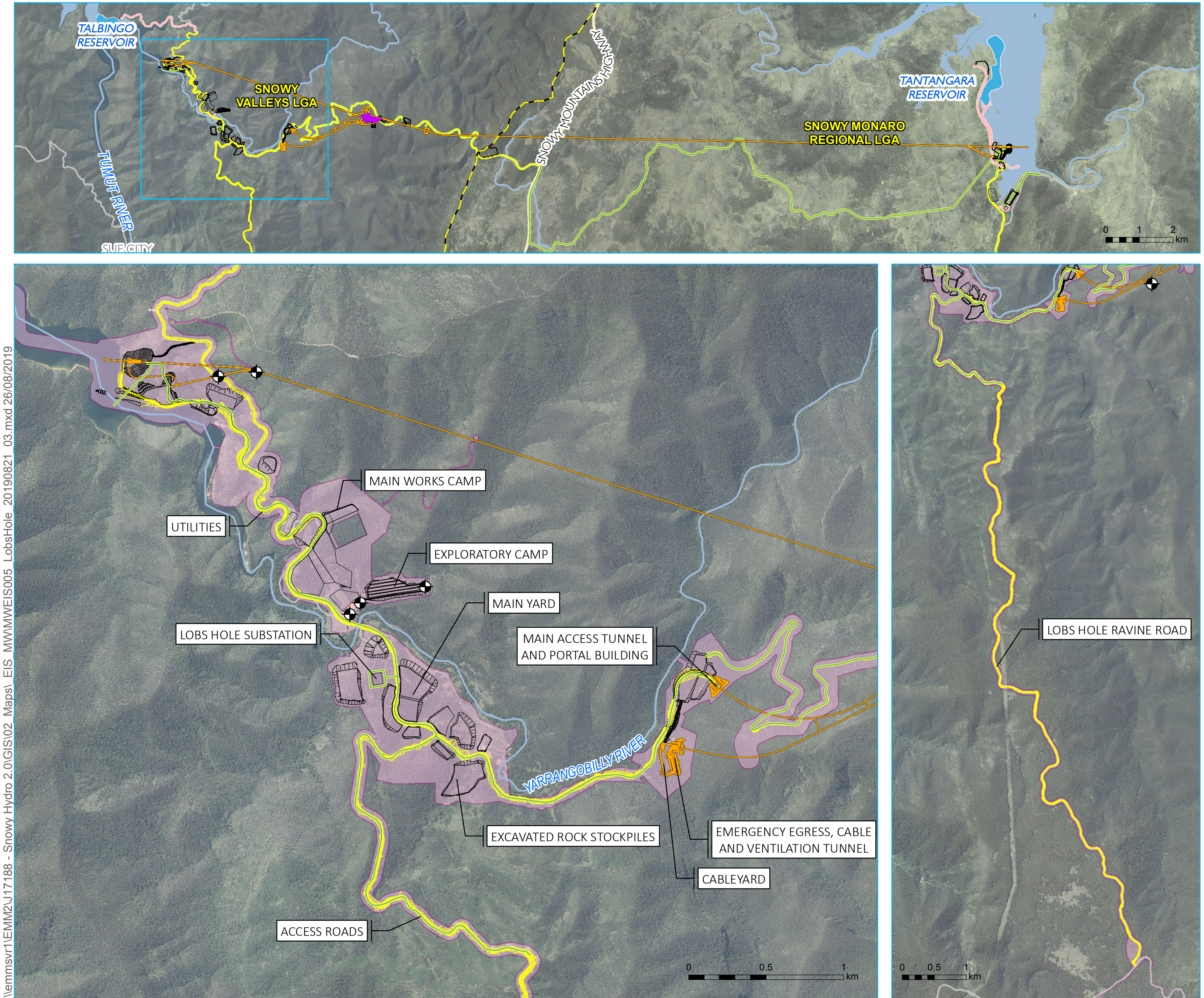
Snowy 2.0 Main Works construction elements

- Temporary construction compounds and surface works
- Temporary access road
- Geotechnical investigation
- Indicative rock emplacement area
- Disturbance area*

Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Talbingo Reservoir - project elements, purpose and description

Snowy 2.0
Cenozoic geodiversity report
Main Works
Figure 2.2



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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

GDA 1994 MGA Zone 55

N

KEY

Existing environment
- Main road
- Local road
- Watercourse
- Waterbodies
- Local government area boundary

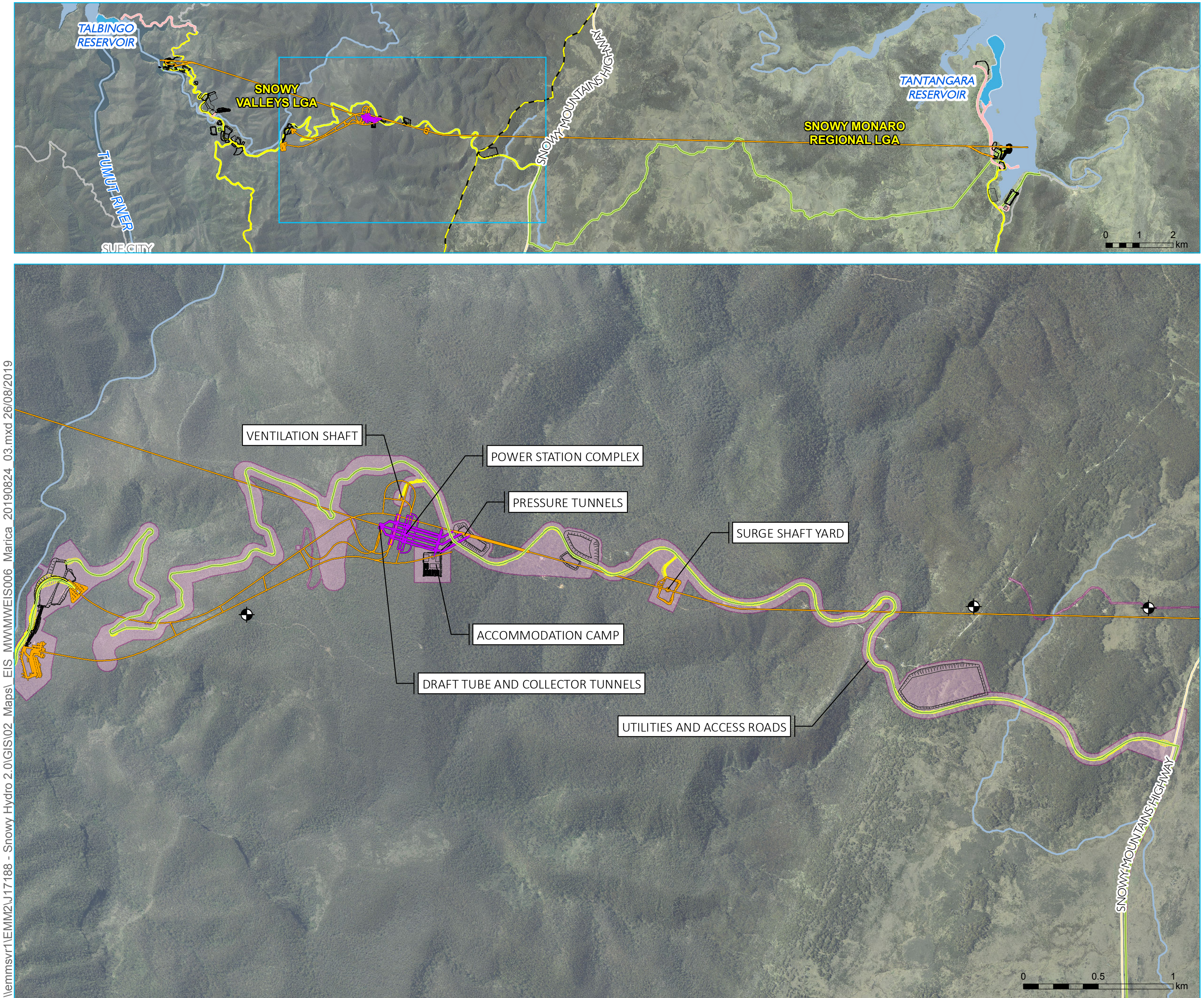
Snowy 2.0 Main Works operational elements
- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements
- Temporary construction compounds and surface works
- Temporary access road
- Geotechnical investigation
- Indicative rock emplacement area
- Disturbance area*

Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Lobs Hole - project elements, purpose and description

Snowy 2.0
Cenozoic geodiversity report
Main Works
Figure 2.3



Source: *EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)*

GDA 1994 MGA Zone 55

N

KEY

Existing environment
- Main road
- Local road
- Watercourse
- Waterbodies
- Local government area boundary

Snowy 2.0 Main Works operational elements
- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements
- Temporary construction compounds and surface works
- Temporary access road
- Geotechnical investigation
- Indicative rock emplacement area
- Disturbance area*

Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Marica - project elements, purpose and description

Snowy 2.0
Cenozoic geodiversity report
Main Works
Figure 2.4

snowy 2.0

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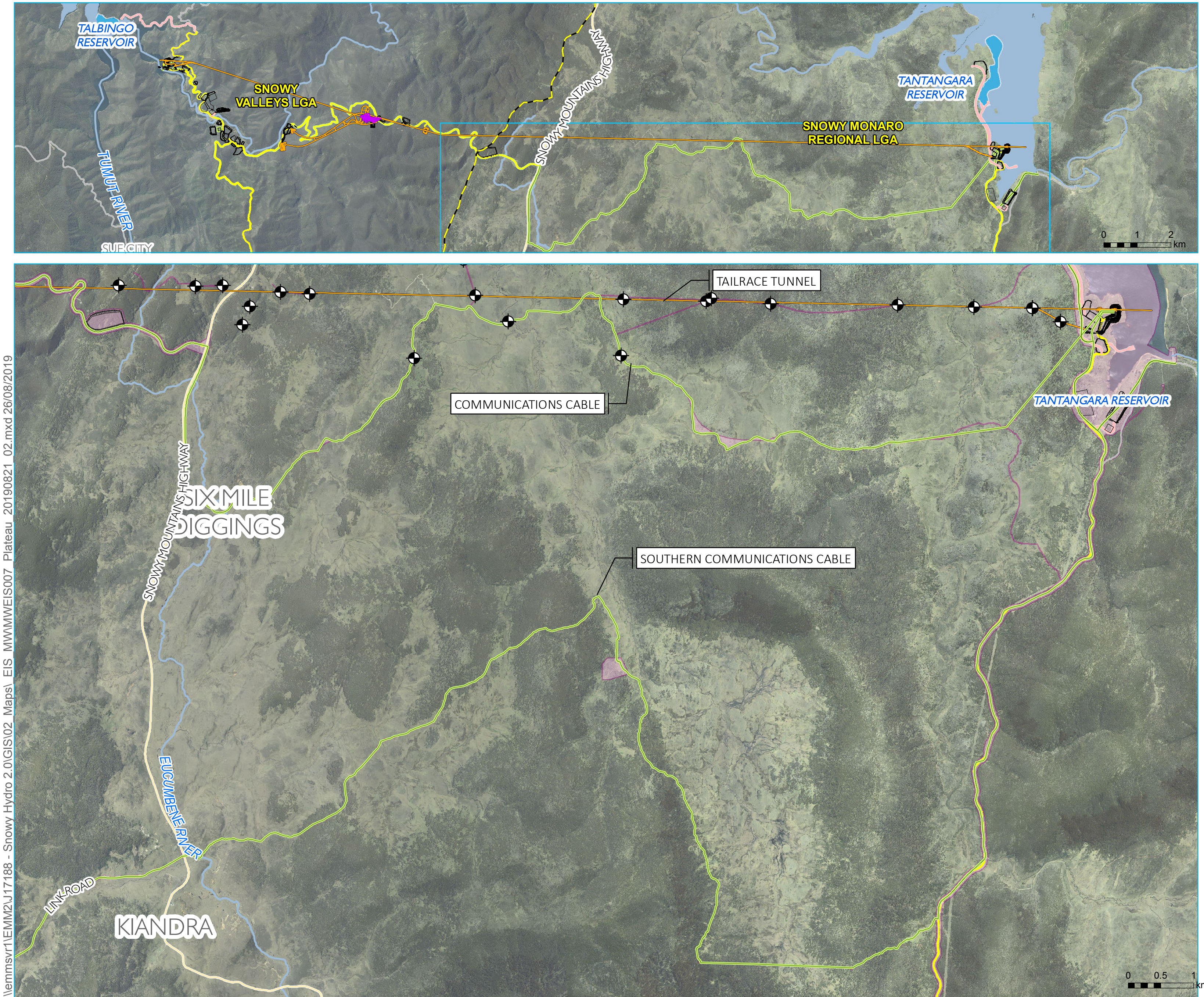


Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

GDA 1994 MGA Zone 55

N

KEY

Existing environment

- Main road
- Local road
- Watercourse
- Waterbodies
- Local government area boundary

Snowy 2.0 Main Works operational elements

- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

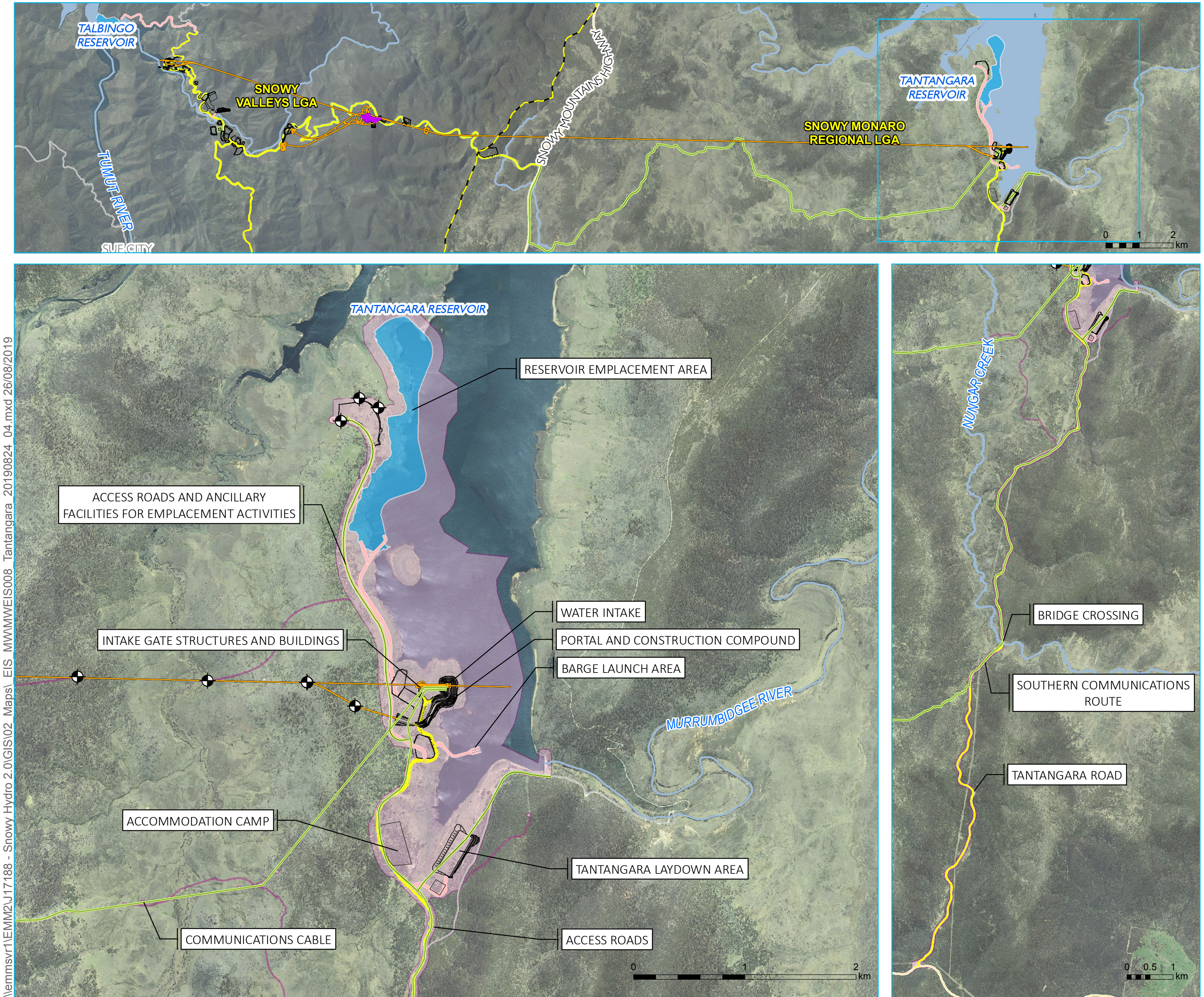
Snowy 2.0 Main Works construction elements

- Temporary construction compounds and surface works
- Temporary access road
- Geotechnical investigation
- Indicative rock emplacement area
- Disturbance area*

Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Plateau - project elements, purpose and description

Snowy 2.0
Cenozoic geodiversity report
Main Works
Figure 2.5



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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

GDA 1994 MGA Zone 55

N

KEY

Existing environment

- Main road
- Local road
- Watercourse
- Waterbodies
- Local government area boundary

Snowy 2.0 Main Works operational elements

- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements

- Temporary construction compounds and surface works
- Temporary access road
- Geotechnical investigation
- Indicative rock emplacement area
- Disturbance area*

Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Tantangara Reservoir - project elements, purpose and description

Snowy 2.0
Cenozoic geodiversity report
Main Works
Figure 2.6

KEY

Existing environment
- Main road
- Local road
- Watercourse

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Utilities
- Permanent road

Snowy 2.0 contruction elements
- Temporary construction compounds and surface works
- Temporary access road
- Geotechnical investigation
- Disturbance area*

Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Rock Forest - project elements, purpose and description

Snowy 2.0
Cenozoic geodiversity report
Main Works
Figure 2.7

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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

GDA 1994 MGA Zone 55

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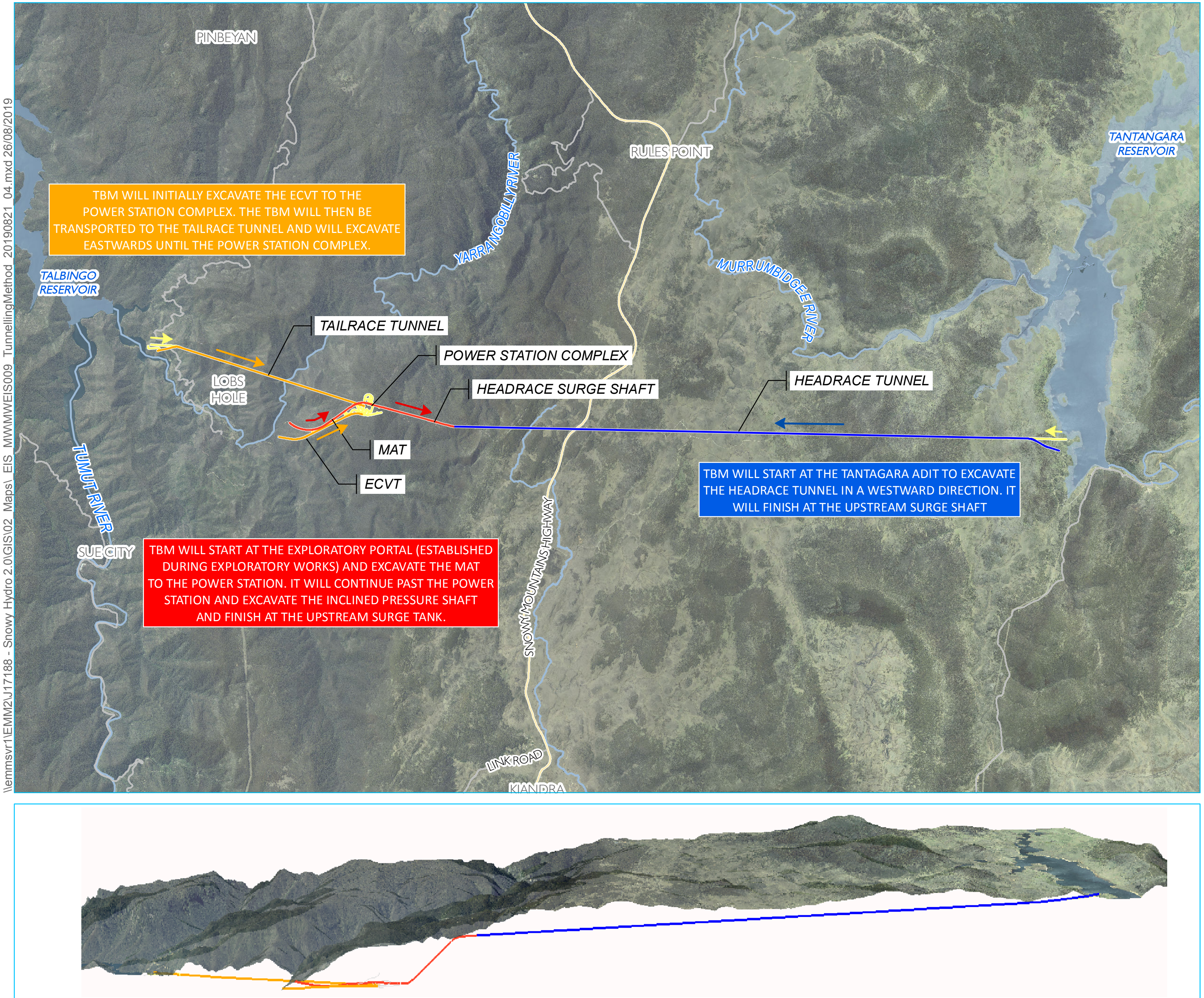
snowy 2.0

EMM creating opportunities



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KEY

Tunnelling method
- Drill and blast
- TBM 1
- TBM 2
- TBM 3
- Tunnelling direction

Existing environment
- Main road
- Local road
- Watercourse
- Waterbodies

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

Primary excavation methods – drill and blast and tunnel boring machine

Snowy 2.0
Cenozoic geodiversity report
Main Works
Figure 2.8

snowy 2.0

EMM creating opportunities

2.3 Operation of Snowy 2.0

2.3.1 Scheme operation and reservoir management

Snowy 2.0 would operate within the northern Snowy-Tumut Development, connecting the existing Tantangara and Talbingo reservoirs.

Tantangara Reservoir currently has the following operational functions within the Snowy Scheme:

- collects releases from the Murrumbidgee River and the Goodradigbee River Aqueduct,
- provides a means for storage and diversion of water to Lake Eucumbene via the Murrumbidgee-Eucumbene Tunnel, and
- provides environmental releases through the Tantangara Reservoir river outlet gates to the Murrumbidgee River.

Talbingo Reservoir currently has the following operational functions:

- collects releases from Tumut 2 power station,
- collects releases from the Yarrangobilly and Tumut rivers,
- acts as head storage for water pumped up from Jounama Pondage, and
- acts as head storage for generation at Tumut 3 power station.

Due to its historic relationship to both the upstream Tumut 2 Power Station and downstream Tumut 3 Power Station, Talbingo Reservoir has had more operational functions than Tantangara Reservoir in the current Snowy Scheme.

Following the commencement of the operation of Snowy 2.0, both Tantangara and Talbingo reservoirs will have increased operational functions. Tantangara Reservoir will have the additional operational functions of acting as a head storage for generation from the Snowy 2.0 power station and also acting as a storage for water pumped up from Talbingo Reservoir. Talbingo Reservoir will have the additional operational function of acting as a tail storage from Snowy 2.0 generation.

As a result of the operation of Snowy 2.0, the water level in Tantangara Reservoir will be more variable than historically. Notwithstanding this, operations will not affect release obligations under the Snowy Water Licence nor will it involve any change to the currently imposed Full Supply Levels (FSLs). No additional land will be affected by virtue of the inundation of the reservoirs through Snowy 2.0 operations. Water storages will continue to be held wholly within the footprint of the existing FSLs.

2.3.2 Permanent access

Permanent access to Snowy 2.0 infrastructure is required. During operation, a number of service roads established during construction will be used to access surface infrastructure including the power station's ventilation shaft, water intake structures and gates, and the headrace tunnel surge shaft. Permanent access tunnels (the MAT and ECVT) will be used to enter and exit the power station. For some roads, permanent access by Snowy Hydro will require restricted public access arrangements.

2.3.3 Maintenance requirements

Maintenance activities required for Snowy 2.0 will be integrated with the maintenance of the existing Snowy Scheme. Maintenance activities that will be required include:

- maintenance of equipment and systems within the power station complex, intake structures, gates and control buildings;
- maintenance of access roads (vegetation clearing, pavement works, snow clearing);
- dewatering of the tailrace and headrace tunnel (estimated at once every 15 to 50 years, or as required); and
- maintenance of electricity infrastructure (cables, cable yard, cable tunnel).

2.4 Rehabilitation and final land use

A Rehabilitation Strategy has been prepared for Snowy 2.0 Main Works and appended to the EIS.

It is proposed that all areas not retained for permanent infrastructure will be revegetated and rehabilitated. At Lobs Hole, final landform design and planning has been undertaken to identify opportunities for the reuse of excavated material in rehabilitation to provide landforms which complement the surrounding topography in the KNP.

Given that most of Snowy 2.0 Main Works is within the boundaries of the KNP, Snowy Hydro will liaise closely with NPWS to determine the extent of decommissioning of temporary construction facilities and rehabilitation activities to be undertaken following the construction of Snowy 2.0 Main Works.

3 Geological context

3.1 Regional setting

The project area is located within the south-east portion of the Lachlan Orogen (Fold Belt) of NSW. The Lachlan Orogen comprises a suite of Ordovician (485 million years) to Devonian (359 million years) sedimentary, igneous and metamorphic rocks that have developed during multiple orogenic periods associated with extensive faulting forming major geotectonic structures throughout the area.

The geology of the broader assessment area comprises Ordovician to early Devonian granites, volcanics, occasionally fossiliferous sedimentary rocks and metamorphosed sedimentary sequences that have formed faulted, stepped ranges at the point where the South Eastern Highlands (part of the Lachlan Orogen) in NSW transition west into Victoria (NPWS 2003). The region was uplifted during the Middle Devonian Tabberabberan Orogeny and no further sedimentary deposition or igneous activity occurred until the Neogene Period, when basalts extruded over the exposed and eroded landscape burying river valleys and lakes. During the Pleistocene epoch (2.6 Ma to 12 thousand years ago), the Australian Alps Bioregion was the only part of the Australian mainland to have been affected by glaciation, resulting in a variety of unique glacial and periglacial landforms above 1,100 m altitude (NPWS 2003). The general structural trend in this bioregion is north-south and the topography strongly reflects this (NPWS 2003).

Outcropping and subcropping Ordovician to Devonian units of the region are commonly extensively weathered, with widespread development of residual soils and colluvium. Weathered Neogene basalt deposits are erosional remnants of Early Miocene lava flows, and mostly occur capping ridges and plateaus. In some areas, basalt is underlain or interbedded with unconsolidated fluvial and lacustrine deposits of a similar age.

The area of the Main Works program between Talbingo and Tantangara reservoirs is structurally deformed with numerous folds and several major faults associated with the north-south trending Long Plain Fault. The broader Main Works project area comprises two distinct geological terrains (incised ravine area and the plateau area), separated by an escarpment caused by movement on the Long Plain Fault (see Figure 3.1). The incised ravine area is situated on the western side of this fault structure whereas the plateau area is to the east.

The broader Snowy 2.0 Main Works project area intercepts two major structural blocks, separated by the regional Long Plain Fault. These are the Tumut Block in the west composed of predominantly Silurian rocks, and the mainly Ordovician Tantangara Block in the east.

Folding is well developed across the project area and is a consequence of the significant tectonic activity and east-west compression across the Tumut and Tantangara geological blocks.

3.2 Review of geological studies of the Snowy Mountains region

Early detailed geological studies in the Snowy Mountains were often focussed on localities characterised by mineral deposits, e.g. Andrews (1901) on the gold at Kiandra, Carne (1908) on the copper deposits at Lobs Hole, and Carne & Jones (1919) on the limestone deposits at Ravine, Yarrangobilly and Cooleman Plain. As all these areas now are located within the boundaries of the Kosciuszko National Park, the impetus for mining and mineral exploration has been removed. However, they remain of interest as significant sites showcasing the geodiversity of the Snowy Mountains region.

A second major theme in the early days of geological research in the region was description and interpretation of the glacial features recognised in the high country in the vicinity of Mount Kosciuszko, e.g. David et al. (1901). The significance of this area was its identification as the only place on the Australian mainland that had been glaciated during the last Ice Age of the late Pleistocene. These pioneering studies have subsequently been expanded by detailed reappraisals of the Pleistocene glacial and periglacial features and climate history (e.g. Galloway 1963; Costin 1972; Barrows et al. 2001, 2004).

Modern geological investigations of previously unknown and largely inaccessible areas of the Snowy Mountains commenced with the inception of the original Snowy Mountains Scheme in 1949, culminating in a series of publications documenting the results of reconnaissance mapping that appeared in the Technical Reports series of the Geological Survey of New South Wales (GSNSW) between 1953 and 1962 (e.g. Hall & Lloyd 1954; Adamson 1957, 1958). This work was summarised by Moye et al. (1969).

Regional geological mapping of the Snowy Mountains and surrounding areas published at the standard 1:100,000 commenced in the 1970s, when geologists from the Commonwealth Bureau of Mineral Resources, Geology & Geophysics (BMR), the GSNSW and the Geology Department of the Australian National University mapped the eastern side of KNP bounded to the west by longitude 148°30´. The resulting Brindabella and Tantangara sheets (Owen & Wyborn 1979a, 1979b, 1979c) and Berridale sheet (White, Williams & Chappell 1976) supplemented by the Tumut sheet (Basden 1990) covering the northeast corner of KNP and northwards to Tumut, greatly added to geological knowledge of the region. The Yarrangobilly, Kosciuszko and Jacobs River 1:100,000 geological maps remain unpublished. There was considerable focus on interpreting the complex igneous history of the area, with multiple phases of silica-rich intrusions occurring through the late Silurian and early Devonian involving the newly recognised S-type and I-type granites. Complementary palaeontological studies in the late 1960s and early 1970s concentrated on the Lower Devonian limestone of the Lobs Hole area (e.g. Flood 1969), with minor work undertaken on the Yarrangobilly Limestone (Cooper 1977). The rich fossil flora found within Cenozoic sediments in the Kiandra area were well studied during the mid-20th century (e.g. Cookson 1945, 1954; Gill & Sharp 1957), and a number of more recent palaeontological studies have also been published (e.g. Owen 1988; Paull & Hill 2003; Tarran et al. 2018).

Compilation of all geological mapping and thesis studies to the end of the 1980s resulted in the first geological map covering the entire extent of Kosciuszko National Park at 1:250,000 scale (Wyborn et al. 1990), which remains the best publicly-available hard copy geology map for the project area. However, there have been subsequent revisions in the digital geology data available for the area, as reflected in the Statewide Seamless Geology Digital Data, a compilation of the state's best available geological mapping data in an internally consistent format (Colquhoun et al. 2018). These revisions include greater detail in some Palaeozoic units to the east of the project area, based on data from the Eastern Lachlan Orogen Digital Data Set (Glen et al. 2007).

A number of geological studies of the project area have been undertaken in preparation for Snowy 2.0 including field mapping of the area around the project alignment and geotechnical studies focussed mainly on the subsurface. The findings from geological studies conducted to date have been summarised by SMEC (2018). This report includes geology maps at 1:10,000 extending 2 km around the project alignment from Tantangara to Talbingo reservoirs and an additional sheet covering a broader segment of the central project area around Marica. These maps include revisions to the extent and structure of some units, mainly in the Palaeozoic geology.

3.3 Cenozoic geology of the project area

The Cenozoic geology of the project area is straightforward in comparison to the complex Palaeozoic geology which it overlies, with only six Cenozoic geological units mapped in the regional geology data, most of which have a very limited areal extent (Figure 3.1). Erosion was the dominant process from the late Palaeozoic to early Cenozoic and deposits from these periods are not known from the area (Wyborn et al. 1990; Colquhoun et al. 2018; SMEC 2018).

The most widespread Cenozoic unit is olivine basalt (coded CZuc__g in the regional geology data) which, in places, is associated with contemporaneous sedimentary deposits mapped as Neogene alluvial sediments (GN_a). The basalt formed as lava flows in the Early Miocene, mainly flowing down valleys and covering stream and lake sediments which have been preserved beneath and interbedded with the basalt. Lava remnants occur most extensively east and north-east of Cabramurra, around Kiandra, and north of Six Mile

Diggings. These occur mainly as flat-topped, sheet-like deposits with common vertical columnar joints, capping plateaus and ridges. They vary in thickness with an upper range of around 100 m on New Chum Hill at Kiandra (Owen & Wyborn 1979c). The associated Miocene sediments are typically well-bedded and unconsolidated. They are composed predominantly of sand and clay with minor gravel and carbonaceous layers, including lignite, and in places are up to 100 m thick (Gill & Sharp 1957). Fossil plant material is abundant in some horizons, including wood, leaves and pollen, and a highly diverse range of plant types have been identified (e.g. Gill & Sharp 1957; Owen 1988). The range of plant types indicates a much wetter and warmer climate in the Early Miocene than exists in the area today (Owen 1988).

Other Cenozoic units mapped within the region are small areas of Neogene ferruginised residuum (GN_rf) and Quaternary alluvium (Q_a, Q_ath). The ferruginised residuum occurs on the Cooleman Plain overlying limestone, as thin patches of pebbles composed of limonite or hematite cemented by limonite, possibly of Miocene age (Owen & Wyborn 1979a, 1979c). Quaternary alluvium is widespread in modern river valleys and is mapped where it occurs most extensively.

Other Cenozoic deposits identified in the literature but not mapped on the regional geology are Pleistocene periglacial features and small areas of Quaternary tufa. Periglacial deposits formed during the Late Pleistocene glacial period have been documented at sites in northern KNP in the Ravine and Cooleman Plains areas. Quaternary tufa is known only from sites in the Ravine area associated with Devonian limestone.

Numerous faults cross the project area, including some of regional significance and extent such as the Long Plain Fault (see Figure 3.1), and date originally from Palaeozoic orogenic events. Some are inferred to have been re-activated during the mid to late Cenozoic in association with regional uplift (DrQuigs Geological Hazards Consulting 2018). Based on landscape features and Cenozoic basalt distribution, this tectonism has been inferred to have resulted in differential uplift across the area impacting drainage and geomorphic development (e.g. Sharp 2004; Young, McDougall & Sharp 2004).

Note that the term ‘Tertiary’, used in historical literature for the first period of the Cenozoic era (66 million years ago (Ma) to 2.6 Ma), has officially been abandoned as a stratigraphic term and replaced with the terms Paleogene (66-23 Ma) and Neogene (23-2.6 Ma). Modern usage is followed in this report, except where previous literature is quoted.

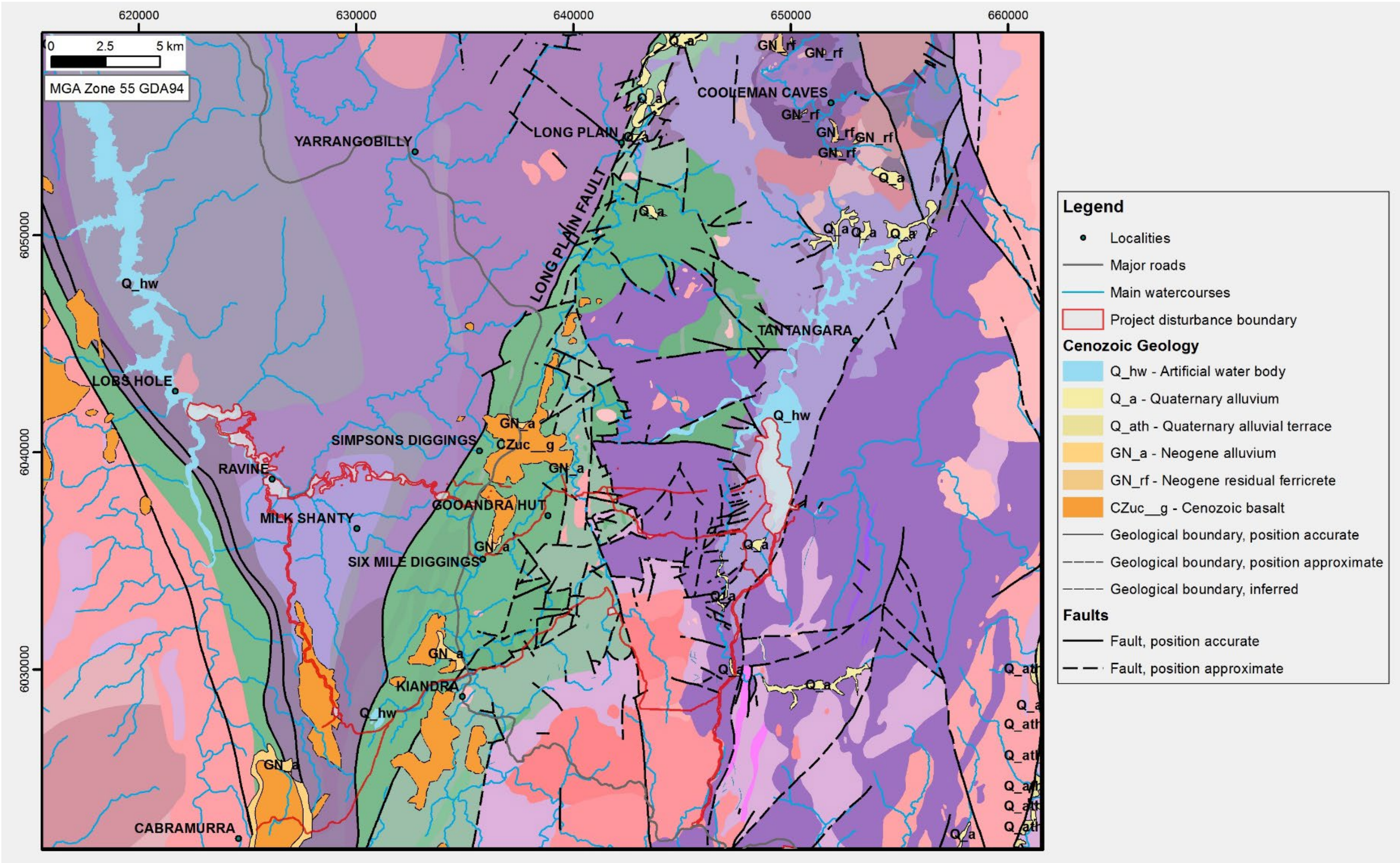

Figure 3.1 Project area regional geology map from the NSW Statewide Seamless Geology digital data (Colquhoun et al. 2018). Only Cenozoic units are labelled and shown in the main legend. Older Palaeozoic (Ordovician to Devonian) geology units are shades of purple, pink and green; a legend for these units is provided on the next page.

Paleozoic geology units

SILURIAN TO MID DEVONIAN BASINS - DEVONIAN

- Dba - Boraig Group
- Dbrm - Mountain Creek Volcanics
- Dbrm_m - Mountain Creek Volcanics - megabreccia
- Dby - Byron Range Group
- Dulk - Kellys Plain Volcanics
- Dulr - Rolling Grounds Latite

EARLY DEVONIAN INTRUSIONS

- D__l - Lobs Hole Monzogranite
- Db_j - Jackson Granite
- Dbob - Bogong Granite
- Dcmc - Coolamine Igneous Complex
- Dcmg -Gurrangorambla Granophyre
- Dfrf - Free Damper Monzogranite
- Dfrp - Pennyweight Monzogranite
- Duu - Unassigned Devonian intrusions

SILURIAN TO MID DEVONIAN BASINS - SILURIAN

- Scpb - Blue Waterhole Formation
- Scpc - Crack Hardy Point Monzodiorite
- Scpo - Pocket Formation
- Scpo_l - Pocket Formation - limestone
- Scpp - Peppercorn Formation
- Sdoo - Goobarragandra Volcanics
- Stu - Tumut Pond Group
- Stuk - Kings Cross Formation
- Suer - Ravine beds
- Sufo_t - Blowering Formation - tuff
- Sufy - Yarrangobilly Limestone

MIDDLE TO LATE SILURIAN INTRUSIONS

- Sbp__c - Boggy Plain Suite - cumulophyric textured intrusion
- Sbp__i - Boggy Plain Suite - intrusion
- Sbpb - Boggy Plain Granitic Complex
- Sbpb_g - Boggy Plain Granitic Complex - granodiorite phase
- Sbpb_q - Boggy Plain Granitic Complex - gabbro phase
- Sbpc - Crack Hardy Point Monzodiorite
- Sbph - Hell Hole Creek Monzogranite
- Sbuf - McLaughlins Flat Granodiorite
- Sbur - Lucas Creek Granite
- Sjiu - Bugtown Tonalite
- Smch - Half Moon Peak Monzogranite
- Smcm - McKeahnie Monzogranite
- Stgh - Green Hills Granodiorite
- Stgr - Rough Creek Tonalite
- Sugb - Bimberi Leucogranite
- Sui__l - Unassigned Silurian Intrusions - leucogranite
- Sui__p - Unassigned Silurian Intrusions - porphyry
- Sui__t - Unassigned Silurian Intrusions - tonalite
- Sukg - Gang Gang Monzogranite
- Suyp - Starvation Point Monzogranite
- Suys - Spicers Creek Granodiorite

EARLIEST SILURIAN BASINS

- Syaa - Tantangara Formation
- Syaa_q - Tantangara Formation - quartzite

MACQUARIE ARC

- Okig - Gooandra Volcanics
- Okig_a - Gooandra Volcanics - basalt
- Okig_i - Gooandra Volcanics - gabbro
- Okig_s - Gooandra Volcanics - siltstone
- Okin_b - Nine Mile Volcanics - basalt
- Okin_f - Nine Mile Volcanics - arenite
- Okin_t - Nine Mile Volcanics - tuff
- Okit_a - Temperance Formation - agglomerate
- Okit_b - Temperance Formation - basaltic tuff
- Okit_c - Temperance Formation - chert
- Okit_m - Temperance Formation - monzonite
- Okit_t - Temperance Formation - tuff
- Ouog - Geordies Spur Gabbro
- Ouos - Shaw Hill Gabbro

LATE ORDOVICIAN - BENDOC & MARGULES GROUPS

- Obew - Warbisco Shale

EARLY TO MIDDLE ORDOVICIAN - LACHLAN SUPERGROUP

- Oada - Abercrombie Formation

PALEOZOIC UNDIFFERENTIATED

- PZui__i - Unassigned Palaeozoic Intrusions - dykes

4 Geodiversity features

4.1 Review methods, data and approach

4.1.1 Literature review

The literature review has included use of the following sources:

1. Relevant environmental management documents for KNP including the KNP Plan of Management 2006 (PoM), the KNP Geodiversity Action Plan 2012-2017 (KGAP) and appendices to that plan.

2. DIGS (Digital Imaging Geological System), the Geological Survey of NSW online repository of geological and mining reports, maps and other documents (https://digsopen.minerals.nsw.gov.au/digsopen/).

3. Geoscience Australia online report and data repository.

4. Relevant scientific literature relating to the geology of the project area and surrounding region, the geology of periglacial block streams and tufa deposits, and assessment of geodiversity and geoheritage in New South Wales and Australia.

5. Reports produced for the project including geological and geotechnical studies supplied by EMM, SMEC and Snowy Hydro.

The aims of the literature review included gaining a detailed understanding of both the Cenozoic geology of KNP generally and the nature of known Cenozoic geodiversity features, in particular those with potential to be impacted by the Main Works; assessing gaps in knowledge with respect to Cenozoic geology for the project area; and understanding the context for the assessment of geodiversity significance.

4.1.2 Spatial data review

A further part of this review has involved compilation and examination of relevant spatial data for the project area. This data, detailed in Appendix A, included aerial imagery, high resolution LiDAR-derived DEM and derivatives of this data (hillshade, slope), existing digital geological map data, base data (roads, waterways, etc.), the disturbance area of the Main Works, and mapped locations of known geodiversity features which occur within the project area. Site data for the project area was also downloaded from Minview, the Geological Survey of NSW online portal for spatial geological data. The spatial data was compiled into a GIS and used for the purposes listed below.

1. Comparison of the geology map with the remotely sensed data (DEM and aerial imagery) to assess the nature and accuracy of the mapped Cenozoic geology.

2. Examination of the remotely sensed data to gain familiarity with the expression of Cenozoic features within that data.

3. Assessment of the geological context and mapped accuracy of known Cenozoic geodiversity features within or near the project disturbance area, and remapping of these features where necessary.

4. Checking within the project disturbance area for indications of previously unidentified Cenozoic features with potential geodiversity significance.

5. Production of maps for this report.

4.1.3 Field visit

A field visit was undertaken on 30 May 2019. The visit was facilitated by EMM and Snowy Hydro Pty Ltd. The focus of the field visit was the geodiversity features identified previously along Lobs Hole Ravine Road, namely periglacial block streams and tufa. The deposits were somewhat snow-covered at the higher elevation sites, but the features were visible nonetheless.

The purpose of the site visit was to make observations on feature characteristics, extents and condition, and better enable visualisation of potential impacts of the proposed works. Field activities included examination of documented geodiversity features in the vicinity of the road, note taking, recording of waypoints at observation sites using a hand-held GPS unit, and photography. Field observations are integrated into this report. Field photos referenced in the text are provided in Appendix B.

4.2 Definition of geodiversity

The Australian Natural Heritage Charter (Commonwealth of Australia 2002) defines geodiversity as: 'the natural range (diversity) of geological (bedrock), geomorphological (landform) and soil features, assemblages, systems and processes. Geodiversity includes evidence of past life, ecosystems and environments in the history of Earth as well a range of atmospheric, hydrological and biological processes currently acting on rocks, landforms and soils'. Geodiversity is described in that document as the equivalent of biodiversity but pertaining instead to non-living elements of the natural world.

Management of geodiversity within KNP is addressed in the KNP Plan of Management (PoM) (National Parks & Wildlife Service 2006) and the KNP Geodiversity Action Plan 2012-2017 (KGAP). The PoM includes an objective to protect rocks, landforms and geological processes at risk of disturbance. It also specifies the most significant geodiversity features identified in the park. The KGAP provides a more detailed conservation strategy for geodiversity in KNP. Geodiversity assessment was undertaken previously for the Snowy 2.0 Exploratory Works EIS (EMM 2018b; Percival 2018; Opdyke 2018).

4.3 Assessment of geodiversity significance

The Australian Natural Heritage Charter (Commonwealth of Australia 2002) defines 'natural significance' in relation to geodiversity (and biodiversity) as referring to 'existence' value as well as value to current and future generations in terms of scientific, social, and aesthetic considerations. In addition to these considerations, the KGAP notes that conservation of geodiversity is integral to the maintenance of biodiversity, and is important for educational, cultural and economic values (OEH 2012).

Brocx & Semeniuk (2007) provide a useful framework for the assessment of geoheritage significance which may equally be applied to geodiversity as the concepts are similar. In their scheme, significance can be evaluated on the basis of how common a feature is within a particular scale of reference (local/regional/national/international), and how important it is intrinsically or culturally. This approach, in concert with the range of values listed in the previous paragraph, is used in this report to assess geodiversity significance.

4.4 Geodiversity conservation and management within KNP

Geodiversity conservation and management in KNP is considered within the KNP PoM (NPWS 2006) and the KNP Geodiversity Action Plan 2012-2017 (KGAP) and appendices (OEH 2012). These issues were addressed after wide stakeholder consultation identified that geodiversity features of the park are 'significant and highly regarded by the community for their aesthetic, rarity, scientific, educational, socio-economic and recreational values'.

The PoM outlines policies and actions to protect and manage geodiversity features. These include providing maximum protection to features that are deemed to be of national significance and sensitive to disturbance, prohibiting developments that are likely to significantly impact on the integrity of such features, assessing potential impacts on geodiversity values during approval processes for proposed developments, and rehabilitating disturbed sites. Additional objectives are to enhance visitor appreciation and understanding of the geodiversity of the park, and to facilitate research on geodiversity. The PoM separately outlines a Karst Management Strategy (Section 6.4) that provides a framework for protection of karst areas, which have specific management issues.

The PoM identifies numerous geological and geomorphological features with national, state or regional significance that occur within the park. These include: numerous features within the Ordovician to Devonian rocks of the Lachlan Fold Belt; several 'Tertiary' geological features associated with Miocene basalt and sedimentary deposits; and glacial and periglacial features associated with Pleistocene glaciations. The most significant geodiversity features are listed in Schedule 1 of the PoM.

A Geodiversity Action Plan (KGAP) was subsequently developed for the park, effective from 1st July 2012 (OEH 2012). The plan applies to the significant geological and geomorphological features identified in Schedule 1 of the PoM and a limited number of additional features. The main purpose of the plan is to outline the actions required to ensure these features are protected, conserved and promoted. Some key sites were the subject of 'rapid condition assessments' in 2012 as documented in Appendix 1 of the KGAP. The basis for this monitoring is outlined in Appendix 2, which describes the KNP Geodiversity Monitoring Program (KGMP).

Table 4.1 lists significant Cenozoic geodiversity sites and features within northern KNP (north of Cabramurra) identified in the PoM and KGAP, along with their geographic extent and geological context. Key sites singled out for monitoring in the KGAP are noted.

The KGAP identifies poorly designed or located infrastructure amongst a range of activities that pose a potential threat to geodiversity sites within KNP, with possible impacts including complete or partial loss of an element of geodiversity, physical damage, interruptions to natural land forming processes, impeded or lost access to significant sites, changes in erosion rates and water pollution.

KNP is within the Australian Alps National Parks and Reserves, which is a listed National Heritage Place. Some of the geodiversity features and values of the KNP may contribute to the heritage values of the Australian Alps National Parks and Reserves. An assessment of impacts to National Heritage Places from the Snowy 2.0 Main Works is provided in the Snowy 2.0 Main Works Historic Cultural Heritage Assessment Report (NSW Archaeology 2019).

Table 4.1 Summary of Cenozoic geodiversity features identified in northern KNP by NPWS in the PoM and KGAP

No	Feature type	Geographic extent	Close to or within project disturbance area	Geological context and age	Subject to NPWS monitoring
1	Quaternary tufa deposits	Sites in gullies draining the hill south of the Yarrangobilly River, Ravine area	Yes	Recent secondary limestone deposits associated with Devonian limestone sequences	Yes, at two sites: Lick Hole Gully and Cave Gully
2	Periglacial block streams	Two sites: adjacent to Lobs Hole Ravine Rd, south of Ravine, and near Blue Holes, Cooleman Plain area	Yes, Ravine block streams only	Formed by periglacial processes during the Late Pleistocene glacial period	Yes, both sites
3	Solifluction terraces	One site in the Cooleman Plain area	No	Formed by periglacial processes, most likely during the Late Pleistocene glacial period	No
4	'Tertiary' (Neogene?) ferruginous gravels	Two sites in the Cooleman Plain area	No	Thin deposits of unconsolidated to cemented ferruginous gravel overlying limestone; probable Neogene age	No
5	Remnant 'Tertiary' (Miocene) basalt flows	A number of areas across central northern KNP	No	Early Miocene lava flow deposits overlying Palaeozoic sequences and/or Miocene sedimentary deposits	No
6	Basalt columns	Sites include those at Link Road north of Cabramurra, Kiandra and Yarrangobilly	No	Well exposed structures within Miocene basalt	Yes, one site on Link Road north of Cabramurra
7	'Tertiary' (Miocene) sediments and plant fossils	A number of sites across central northern KNP associated with remnant Tertiary basalt	No	Early Miocene stream and lake deposits preserved by overlying basalt lava flow deposits	Yes, at one site at New Chum Hill, near Kiandra

4.5 Cenozoic geodiversity sites in the project area

Two sets of Cenozoic geodiversity features identified in the KGAP lie within or adjacent to the Snowy 2.0 Main Works disturbance area. These are the Ravine periglacial block streams and Quaternary tufa deposits, both of which occur in the vicinity of Lobs Hole Ravine Road (Figure 4.1). Detailed descriptions and assessments of these features are presented below in Sections 4.6 and 4.7.

Geodiversity features listed in the PoM and KGAP were identified on the basis of institutional knowledge within NPWS and literature review. It is understood that field surveys additional to this process have not been conducted except to assess the condition of already identified features. It is possible that other significant Cenozoic geodiversity features exist within the KNP but are undocumented in the KGAP (OEH 2012, Appendix 3).

Review of literature for the project area has not revealed any other documented Cenozoic geodiversity sites; however, there are substantial knowledge gaps. In relation to Cenozoic geology, the available geological map data is fairly coarse in many areas and omits some known features such as periglacial deposits. Regional geology maps are produced on the basis of extensive interpretation in between field study sites, and the project area includes tracts of previously undisturbed bushland where geological field studies may not have been undertaken in the past. Geological field studies have been conducted in the vicinity of the project alignment in preparation for Snowy 2.0 (e.g. SMEC 2018) but new findings are restricted largely to Palaeozoic geology. A recent study of faulting within the project area based mainly on LiDAR DEM data has identified some sites associated with Cenozoic deposits which may provide evidence of neotectonic (post-Miocene) fault activity (DrQuigs Geological Hazards Consulting 2018). These sites could potentially hold geodiversity significance.

Review of spatial data for the project area has confirmed that the regional map data for Cenozoic basalt and sediments is quite coarse but can be refined on the basis of the high-resolution DEM and aerial imagery now available. The mapped extents of periglacial block streams and tufa deposits have been refined and extended based on the available spatial data and new field observations.

In summary, gaps in knowledge around the geology of some areas have been identified as a potential risk posed to geodiversity by the Snowy 2.0 Main Works. Therefore, a brief assessment of the risk of encountering undocumented Cenozoic geodiversity features within the project area is presented in Section 4.8.

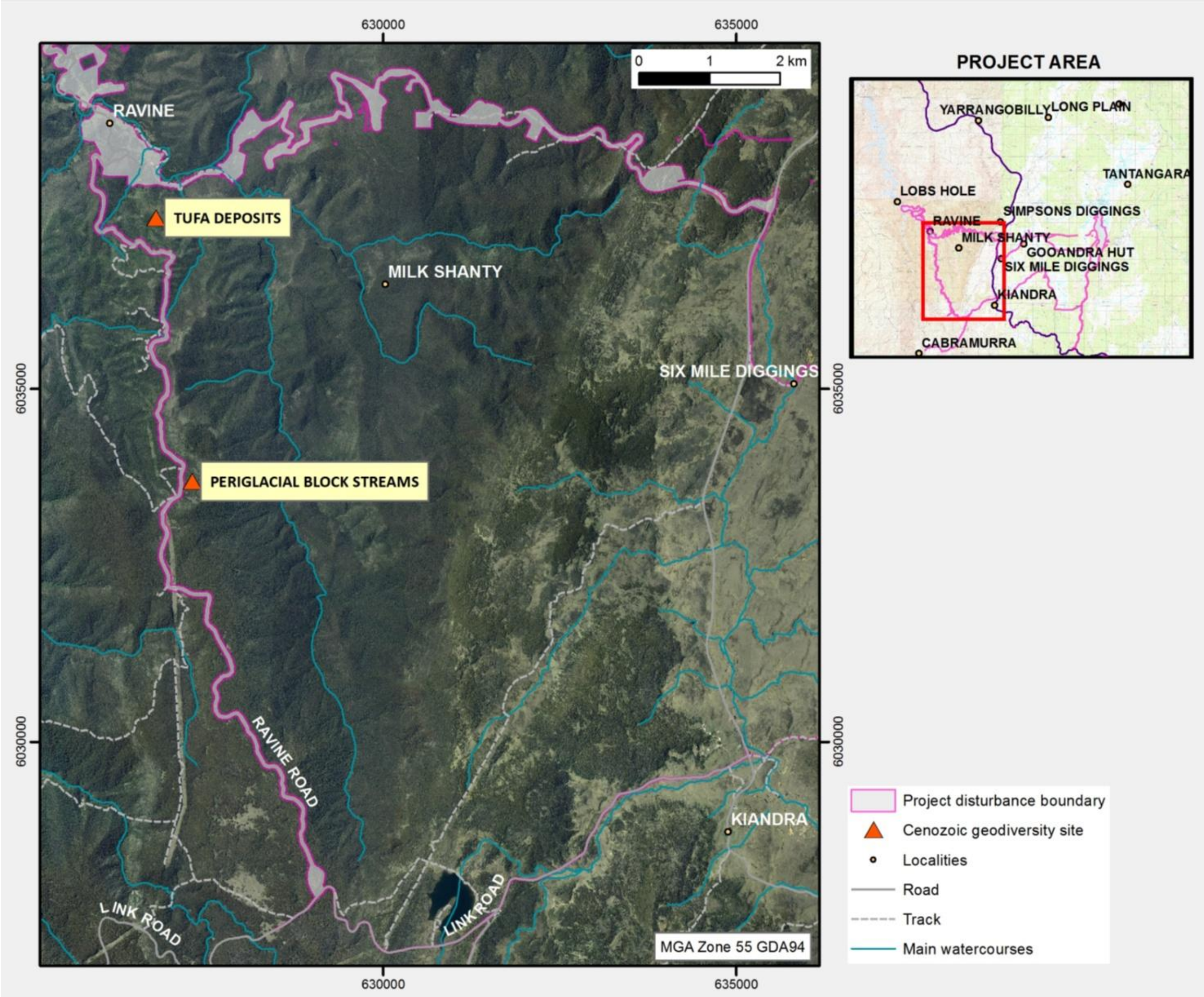

Figure 4.1 Map of general locations of documented Cenozoic geodiversity features within or near the project disturbance area

4.6 Ravine periglacial block streams

4.6.1 Definition of block streams

Block streams are linear deposits of boulders and cobbles with a down-slope alignment, formed where periglacial conditions have promoted the frost-induced fracture of bedrock outcrops and subsequent en masse down-slope movement of the coarse rock debris under the influence of interstitial ice (Wilson 2007). They are one of a class of block deposits that may develop in periglacial environments, where freeze-thaw activity is able to modify the landscape in a significant way.

Block streams may occupy hill-slopes or valley axes. They are physically different from talus (scree) deposits in that typically they do not show sorting of block size with distance down-slope, may occupy shallower slopes, have an elongate shape unlike typical cone-shaped talus aprons, and may occur detached from an upslope free face or bedrock cliff. Block streams may also exhibit characteristic surface morphologic features including arcuate ridges, lobes and pits (Wilson 2007).

4.6.2 Location

A number of block streams occur in the Ravine area adjacent to Lobs Hole Ravine Road in northern KNP, on steep west to southwest facing slopes below the northern extension of Section Ridge (Figure 4.2). Lobs Hole Ravine Road bisects five of the block streams (labelled A to E in the figure). The lower section of one additional block stream (B2) has been identified within the project disturbance area; it appears to terminate upslope of the road. A basalt block feature (labelled X), which may be a block stream, occurs on the downslope side of the road to the south of the main group, and is encroached at the top by the disturbance area. All other block streams terminate higher up the slope to the east.

The block stream extents indicated in Figure 4.2 are based on remote interpretation of aerial and DEM imagery with some ground-truthing provided by SMEC geologists in July 2019, and by the author of this report at most road/block stream intersections. The mapped extents are substantially modified from an earlier version used in the Exploratory Works EIS reports. Some boundaries may be imprecise and it is possible that additional limited areas of block stream may exist and are masked from remote interpretation by vegetation. Additional block streams (not shown, and discussed later in this report) occur around the northern and eastern side of Section Ridge distant from the Main Works disturbance area and will not be considered further in this section.

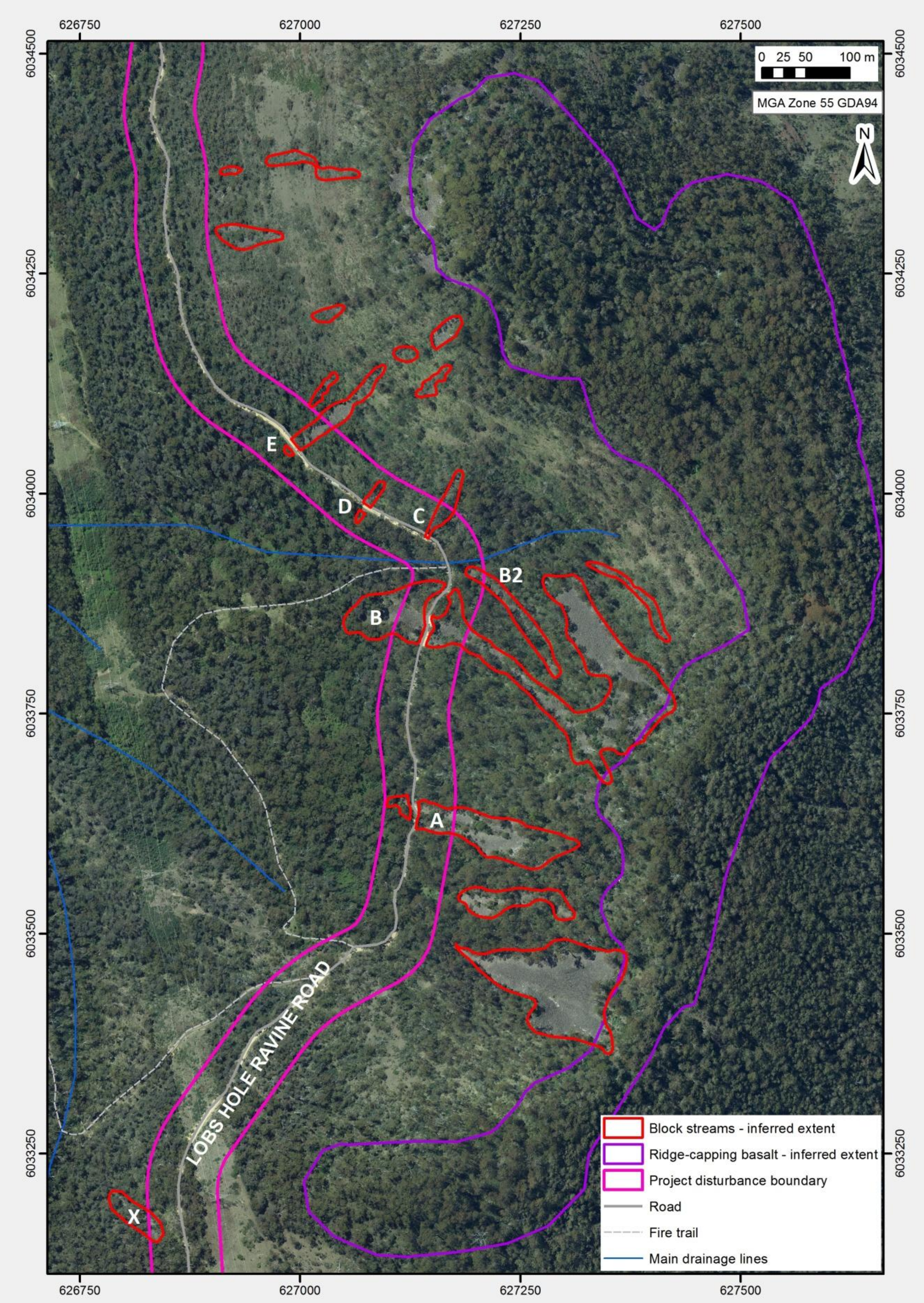

Figure 4.2 **Inferred extents of periglacial block streams adjacent to Lobs Hole Ravine Road overlaid on aerial imagery. The project disturbance area and inferred extent of ridge-capping basalt are also shown.**

4.6.3 Description

The main Ravine block streams are visually striking landforms and can be viewed from a number of locations along Lobs Hole Ravine Road. Expanses of unvegetated blocks stand out clearly from surrounding forested slopes both upstream and downstream of the road (Photos 1 and 2). The block streams are elongate downslope, range from around 6 m to 100 m wide, and the longest example (B) is around 370 m long. They extend across an altitudinal range of approximately 1045 m to 1215 m above sea level. Block stream surface slopes are mainly within the range 22-34°.

In places, low relief curved ridges perpendicular to the slope and other surface micro-topography are visible on the block streams. From the road, these are best observed on lower Block Stream B (Photo 2). Barrows et al. (2004) also observed some well-preserved arcuate ridges that extend the width of a Ravine block stream. These features are inferred to have formed by block flow during ice age deposition of the blocks (Barrows et al. 2004) and are characteristic of periglacial block streams (Wilson 2007).

The block streams consist of mainly sub-angular to sub-rounded interlocking basalt cobbles and boulders. Block sizes vary from around 0.08 m to greater than 1 m in diameter, but are typically in the 0.2-0.5 m range. Some very large surface blocks (>0.8 m) were observed in a few places at the surface of the block streams, and some blocks exhibit columnar jointing inherited from the ridge-top lava flow deposit from which they were sourced (e.g. Photo 3). No size sorting of blocks was noted in road cut exposures.

Block stream thickness can be hard to estimate accurately due to uncertainty around the depth to the underlying substrate. Where block stream bases could be observed in road cuttings the features are typically 1-2 m thick, as previously estimated by Barrows et al. (2004); however, a range in thickness was observed from around 0.2-0.5 m (one layer of boulders) at block stream edges, to greater than 4 m in the central part of southern Block Stream B.

Vegetation around the block streams is largely eucalypt forest with an understory of smaller trees and shrubs. In some areas, particularly around their edges, block streams are lightly to thickly-vegetated with trees and shrubs, making the full extent of the deposits hard to determine precisely from aerial imagery. Based on limited observations at road cuttings, it seems that vegetation is absent to sparse where block stream deposits are relatively thick, with vegetation colonising areas of block stream where the deposits are thin.

The features mapped and defined here as block streams are confined to areas of matrix-free blocks, i.e. boulders and cobbles with no interstitial fine-grained material. Basalt blocks buried in the upper soil profile to a variable depth, but in places around 1 m, can be observed in some road cuttings both underlying matrix-free blocks and where surficial matrix-free blocks are absent (Photos 4 and 5). The latter situation was observed immediately adjacent to some block stream edges and at some sites downslope of block streams that do not intersect the road. The buried blocks may represent a lower layer of the block stream structure, or (less likely) may be older colluvial slope deposits. It is unclear whether the block streams are invariably underlain by such deposits, as it is only possible to observe the substrate underlying the block streams in a few localities; however, a lower layer of blocks with a matrix of fine-grained material has been reported in studies of block stream structure elsewhere in KNP (Caine & Jennings 1968, further details below), and overseas (Wilson 2007).

All five of the block streams bisected by Lobs Hole Ravine Road occupy shallow gullies where they are intersected by the road (e.g. Photo 4). Some block streams higher up the slope and not intersected by the road appear to lie on ungullied hillslopes based on DEM imagery.

4.6.4 Geological context

Dating of six samples from three sites along Ravine Block Stream B using a cosmogenic isotope surface exposure method produced ages ranging from 17.2 ± 1.2 to 22.7 ± 1.4 thousand years old (Barrows et al. 2004). The dating results indicate that the block stream was deposited during a single periglacial episode of the last glacial maximum (i.e. the peak of the last ice age), a particularly cold period in Quaternary earth history. Landforms and associated deposits record glaciation in the higher elevation Kosciuszko-Main Range area just to the south at this time, the only such occurrence on the Australian mainland known from the Quaternary. Periglacial conditions were more extensive, and relict periglacial deposits and landforms dating from that period are relatively widespread in KNP above 1000 m and include terracing, slope deposits, solifluction lobes and shattered boulders in addition to block deposits (Galloway 1963, 1965, 1989; Costin & Polach 1971; Costin 1972; Slee & Shulmeister 2015). Only very limited periglacial processes such as frost heaving have been recorded under modern climatic conditions in the Main Range, and are unknown elsewhere in mainland Australia.

On the regional geology map, Cenozoic basalt capping Section Ridge is shown to terminate south of this area, although discontinuous basalt is shown to extend further north along the ridge-top on unpublished Snowy Mountains Authority maps (e.g. Drawing B1, reproduced in SMEC (2018)). It is clear from comments in Barrows et al. (2004) and from inspection of aerial photographs and LiDAR DEM imagery that Cenozoic basalt forms the ridge top immediately above the block streams. The basalt boulders and cobbles forming the block streams evidently originated from this deposit, the inferred extent of which is shown on Figure 4.2. This geological setting is typical, as block streams appear to form preferentially from outcrops of well-jointed metamorphic and igneous rocks (Wilson 2007), with basalt being by far the most common source rock for block stream production in mainland south-eastern Australia (Slee & Shulmeister 2015).

Caine & Jennings (1968) described the internal structure of a block stream in the Toolong Range, near the upper Tumut River, within KNP. The Toolong block stream was similarly sourced from a basalt capped ridge and is likely comparable to those at Ravine. They documented an upper layer of matrix-free blocks, 1-1.5 m thick; a middle layer of blocks surrounded by black humic (organic-rich) material, 0.2-0.6 m thick; and a lower layer of blocks infilled with silty sand up to 0.5 m thick. The block stream was directly underlain by weathered bedrock, and the water table coincided with the upper surface of the middle layer. Studies of the internal structure of relict block streams from other parts of the world commonly indicate decreasing block size with depth, and a lack of interstitial fine material in at least the upper part of the deposit (Wilson 2007).

Based on the regional geology data and SMEC (2018), Early Devonian sedimentary sequences of the Byron Range Group form the bedrock underlying the ridge-top basalt and block stream deposits. Residual or colluvial soils may be developed locally on these sequences, and are expected to underlie the block streams.

4.6.5 Geodiversity significance

In the KNP PoM, periglacial phenomena in the park are included in a list of geological and geomorphological features with national significance, and described as ‘amongst the most striking in Australia and demonstrate the widespread effects of cold climate in the Quaternary and recent past’ (p.44, NPWS 2006). Periglacial features, specifically including block streams, are listed in Schedule 1 (Significant natural and cultural features) of the PoM (NPWS 2006). In the KGAP, the Ravine block streams are included in a list of key KNP geodiversity features selected for rapid condition assessment (OEH 2012). Such assessments were undertaken on sites representative of significant geological features listed in Schedule 1 of the PoM and identified for future management focus including potential use for interpretation purposes.

On the basis of evidence presented in the current report, the Ravine block streams have intrinsic value as outstanding landscape features and are currently well preserved apart from the narrow road corridor impacting on the lower reaches of five block streams. While this is one of a number of periglacial block stream sites in KNP, it is possibly the most accessible in the park for visitation and viewing, amongst the lowest in elevation, the best documented block stream site in northern KNP, and is extensive with numerous distinct block streams present. Of additional interest are the visible ridges on the surface of Block Stream B which can be inferred to relate to ice age depositional processes. As such, the Ravine block streams have local and regional significance for their cultural value due to their potential use in geo-tourism and earth science education, as foreshadowed in the KGAP (OEH 2012). They are part of the story of the ice age heritage of the park, a spectacular example of the effects of periglacial processes, and a prominent testament to late

Quaternary climate change. Excellent views of the block streams can be obtained at various points on Lobs Hole Ravine Road in the vicinity of the features.

The Ravine block streams have scientific significance as the only directly dated block stream site in NSW and one of only two in mainland Australia, based on the work of Barrows et al. (2004). Isotopic dating locations can be considered to hold significant geodiversity value as scientific reference sites, equivalent to a stratigraphic type section or fossil locality, for the contribution they make to a wider understanding of natural history (Osborne et al. 1998). Late Pleistocene periglacial block deposits also have regional scientific significance as part of a suite of glacial and periglacial features in the Australian Alps which provide evidence of regional climatic conditions during the last ice age and have been used to infer last glacial maximum climatic conditions around 9°C cooler than today for the region (Galloway 1965; Costin & Polach 1971; Slee & Shulmeister 2015).

Periglacial block deposits are not common regionally, although a recent study has documented periglacial block deposits of inferred Late Pleistocene age in highland areas of southeastern Australia up to northern NSW (Slee & Shulmeister 2015), confirming earlier inferences from Galloway (1965). Although some very minor modern periglacial activity is known in association with the highest parts of the Main Range, there is no evidence of modern periglacial block activity in Australia. Block activity requires much colder conditions than occur currently and all such deposits are relict features formed during Pleistocene ice ages (Galloway 1989; Barrows et al. 2004; Slee & Shulmeister 2015). Due to continued climatic warming, formation of periglacial block streams is highly unlikely to occur again in Australia in the foreseeable future.

In summary, the Ravine block streams are considered by KNP management to have very high (regional to national) geodiversity significance, as a prominent example of the periglacial features in the park, which are the most extensive on mainland Australia. On the basis of the relative scarcity of block streams in south-eastern Australia, their status as relict features, and the intrinsic landscape value, representativeness, scientific and educational value of the Ravine block streams, this view of their significance appears justified.

4.6.6 General susceptibility to impacts

Block streams are amongst the most striking and robust periglacial features in KNP with generally good potential for future preservation if minimally disturbed. The Ravine block streams are composed of hard cobbles and boulders of basalt which rest against each other with abundant void space in between blocks. Radiometric age data together with the presence of intact surface morphological features (e.g. arcuate ridges perpendicular to the slope) suggests that the block streams are structurally stable features which have not moved significantly since the end of the periglacial episode during which they formed, around 17 thousand years ago (Barrows et al. 2004). Further evidence that these and other periglacial block stream deposits in eastern Australia have long been inactive includes such features as weathering rinds, colonisation by vegetation at the edges, and accumulation of organic debris between blocks (Barrows et al. 2004). Notwithstanding this apparent natural stability of the deposit overall, there is potential for individual blocks to be destabilised by the removal or disturbance of adjacent or nearby blocks as has occurred in places along Lobs Hole Ravine Road.

The aesthetic values of the Ravine block streams are susceptible to visual impact from unsympathetic design in the event of road widening and stabilising, excessive removal or covering of blocks, and removal of natural vegetation.

Due to the large amount of void space between the basalt blocks, the block streams are likely to have very high permeability and porosity. All of the block streams intersected by Lobs Hole Ravine Road occur in association with drainage lines on moderate to steep slopes. These features should be considered in the design of any developments that impact the block streams as impeding drainage through the deposits may have a localised impact on block stability.

4.6.7 Existing and approved impacts

Existing impacts on the block streams are confined to the road corridor of Lobs Hole Ravine Road in the five areas where it bisects the features. This is an unpaved single lane road constructed by cut and fill. It was initially constructed in the late 19th century although current road cuts and surfacing would be more recent. Typical impacts on the features are illustrated in Photos 6 and 7, and can be summarised as follows:

- On the upslope side of the road, block stream material and in some cases the underlying substrate has been excavated, in places forming road cuts up to ~ 2m high;
- Filling has been placed on top of block stream deposits below the excavated area to build up a level road surface with a steep down-slope batter.

Some impacts on the Ravine block streams have been approved to occur in association with widening and upgrade of Lobs Hole Ravine Road for Snowy 2.0 Exploratory Works (EMM 2018a, 2018b; Opdyke 2018). The approved works through the block stream sections involve building up the road surface vertically, constructing a retaining wall on the downslope into the block streams, and some encroachment on the upslope sections of block stream, typically of around 2 m width and mainly through placement of fill (Opdyke 2018).

4.6.8 Potential impacts from proposed works

Snowy 2.0 Main Works include a planned upgrade of Lobs Hole Ravine Road. An 80 m wide disturbance area has been identified as the maximum extent of impact to the Ravine block streams by the Main Works (Figure 4.2). This disturbance area includes: currently unimpacted up- and down-slope areas of the five block streams bisected by the road; the lower end of a narrow intact block stream just north of Block Stream B on the upslope side (labelled B2 in Figure 4.2); and the upper end of a possible block stream to the south (labelled X). Other minor unmapped areas of vegetated block stream may also lie within the disturbance area. The proposed works are expected to negatively impact the block streams through the permanent removal and covering of blocks. This has potential to substantially impact the extent and aesthetic values of the block streams. The mapping in Figure 4.2 demonstrates that even with the maximum impact occurring, a significant extent of block streams would remain present in the Ravine area. Through the implementation of appropriate road design and other recommendations outlined in Section 5 of this report, the presence and geodiversity values of these features would be maintained.

4.7 Ravine tufa deposits

4.7.1 Definition of tufa

Tufa is a type of limestone formed when calcium carbonate minerals (principally calcite) precipitate out from a spring or surface water that is at ambient temperature. Capezzuoli et al. (2014) summarise the typical characteristics of tufa deposits as follows:

- high porosity (> 40%);
- poorly developed bedding;
- lenticular profiles, symmetrical around stream axes;
- association with secondary carbonate deposits (cements and speleothems);
- biotic associations and abundant fossil remains;
- depositional rates in the range of mm to cm/year;

- association with alkaline, calcium bicarbonate-rich water; and
- occurrence at sites with variable, rainwater-dependant flow.

Tufa can occur in a wide variety of forms depending on factors such as underlying topography, water flow regime, and biota present. Deposit morphologies can include fans, cones, mounds, terraces, cascades, stalactites, rimmed pools and valley-fills (Viles & Goudie 1990).

4.7.2 Location

Spatial data supplied by the National Parks and Wildlife Service (NPWS) identifies eleven tufa sites in the Ravine area of northern KNP (Figure 4.3). The sites occur within gullies on north and east facing slopes south of the Yarrangobilly River. Three sites (A, B East, B West) are beside Lobs Hole Ravine Road where the road crosses Lick Hole Gully and tributary gullies. The remaining sites are remote from the road or other tracks and occur against a prominent, mid-slope cliff line. Of these, five sites (C to G) occur downstream of the road within Cave Gully, Lick Hole Gully and tributary gullies. The three remaining sites occur within tributary gullies of Wallaces Creek (H, J, K), and are separated from Lobs Hole Ravine Road by a ridge.

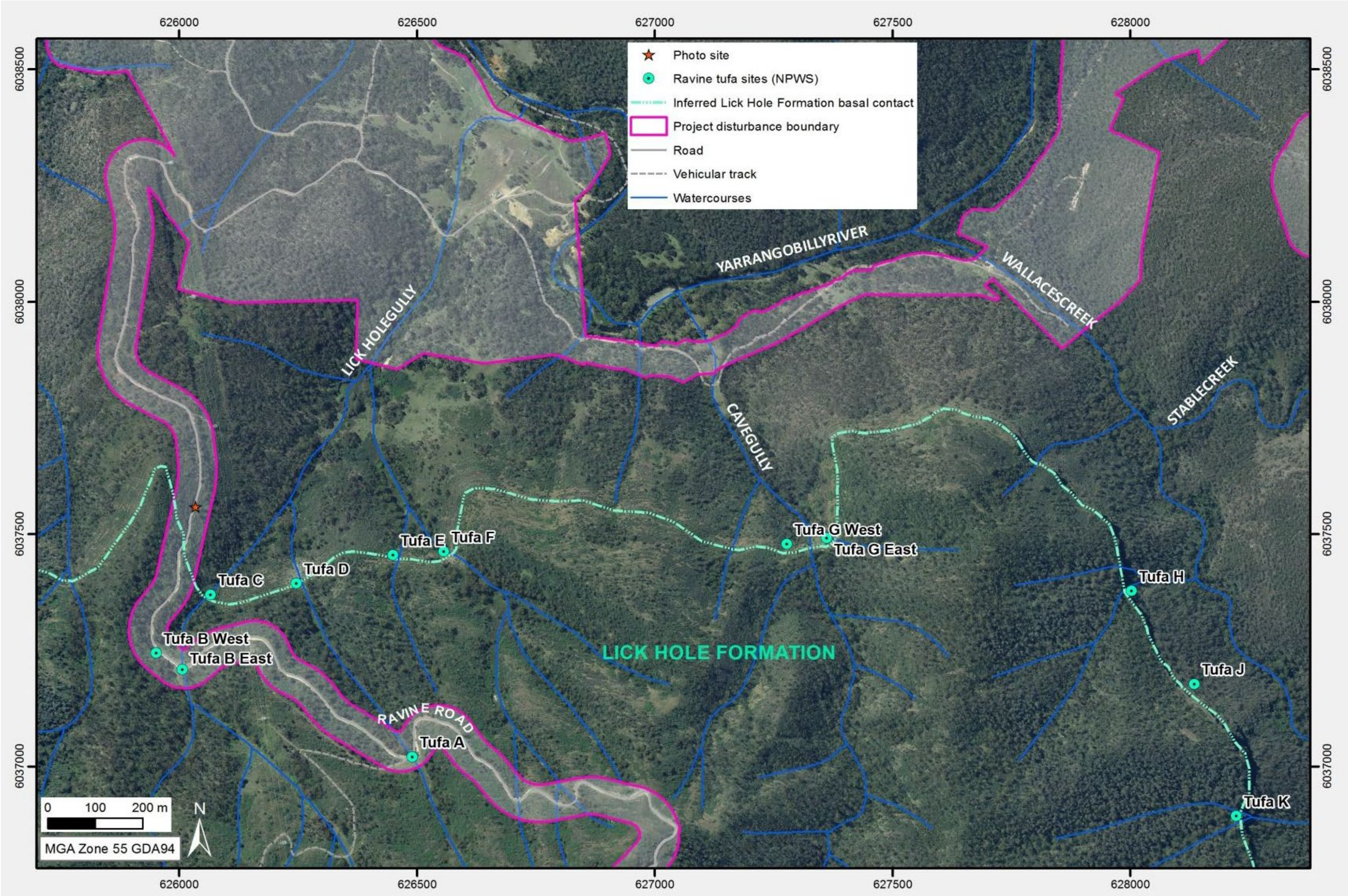

Figure 4.3 **Map of Ravine tufa locations as supplied by NPWS, overlaid on aerial imagery. The most extensive and spectacular tufa deposits (C to K) occur at a prominent cliff line formed from Milk Shanty Formation sandstone the top of which coincides with the base of the overlying Lick Hole Formation.**

Recent field studies by geologists working on Snowy 2.0 have revealed that, while the point localities described above may be the most obvious tufa deposits, tufa is not restricted to these sites and in places extends along the associated gully floors for hundreds of metres, as shown in Figure 4.4. The tufa extents indicated are based on field mapping by SMEC (2019) of Tufa A, B and G, augmented by aerial and DEM imagery interpretation by the current author. Tufa deposits may be more extensive than shown, for example they may extend up-gully from cliff-edge Tufa E, further upstream in Cave Gully, and downstream of the main cliff-edge tufa deposits in some areas. In these areas the remote data is equivocal and no ground-truthing has been undertaken except downstream of the cliff-edge Cave Gully site, where no tufa deposits were observed but investigations were hampered by thick blackberry infestation (SMEC 2019). The known extent of tufa spans around 2300 m east-west and 800 m north-south, with an elevation range of 630 m to 860 m above sea level.

4.7.3 Description

Tufa in the Ravine area was first described by Andrews (1901) who painted a vivid picture of the deposits. He reported 'masses of travertine encrusting the strata underlying the bedded limestone at Lobbs Hole' (note that the term travertine is now typically reserved for limestone deposits precipitated from hot springs). He described living plants including tea-tree and thick 'mossy growth' which were in places wholly or partially covered or even buried by tufa deposits. He observed that the tufa varied in character with some areas where vegetation was being buried being light and porous, and other areas being composed of more compacted limestone. He also described one prominent tufa deposit as being 100 feet (~30 m) high, 200 feet (~60 m) wide, and extending 70-100 feet (~20-30 m) beyond the quartzite cliff against which it was forming. The basal part of this deposit contained 'large caverns' with 'beautiful stalactitic growths'. Spate & Baker (2018) described the tufa as 'large banks containing some caves of construction, massive stalactites, and other karst forms'.

Photo 8 of the spectacular main Cave Gully tufa deposit (Tufa G East) shows some of the features described above including caves and stalactites. Based on examination of the aerial imagery this appears to be the largest cliff-edge tufa deposit, spanning around 100 m of the cliff line and extending out from the cliff and downslope for at least 40 m. The cliff-edge deposits in Lick Hole Gully and its tributaries are visible from Lobs Hole Ravine Road and have a similar morphology to the Cave Gully example, forming prominent pale bulges extending beyond the well-bedded cliffs (Photos 9, 10, 11).

The roadside tufa sites are less visually impressive than the remote tufa sites with Tufa A in particular having limited visual interest. At this site, a gully-floor tufa deposit has been excavated and exposed in a low road cut around 15 m wide and up to 1.2 m high (Photos 12 and 13). The tufa is fairly poorly exposed with grass, topsoil or colluvium covering the deposit in places, and no more than a 0.5 m thickness of tufa visible (e.g. Photo 14). The tufa here is brown-grey where weathered but grey in fresh exposures (Photo 15), and is relatively weakly cemented and soft. It appears structureless, apart from numerous pores up to 2 cm in diameter evident in some areas. On account of its relatively dark colour and apparent lack of structure it is inferred to be relatively impure, low grade tufa.

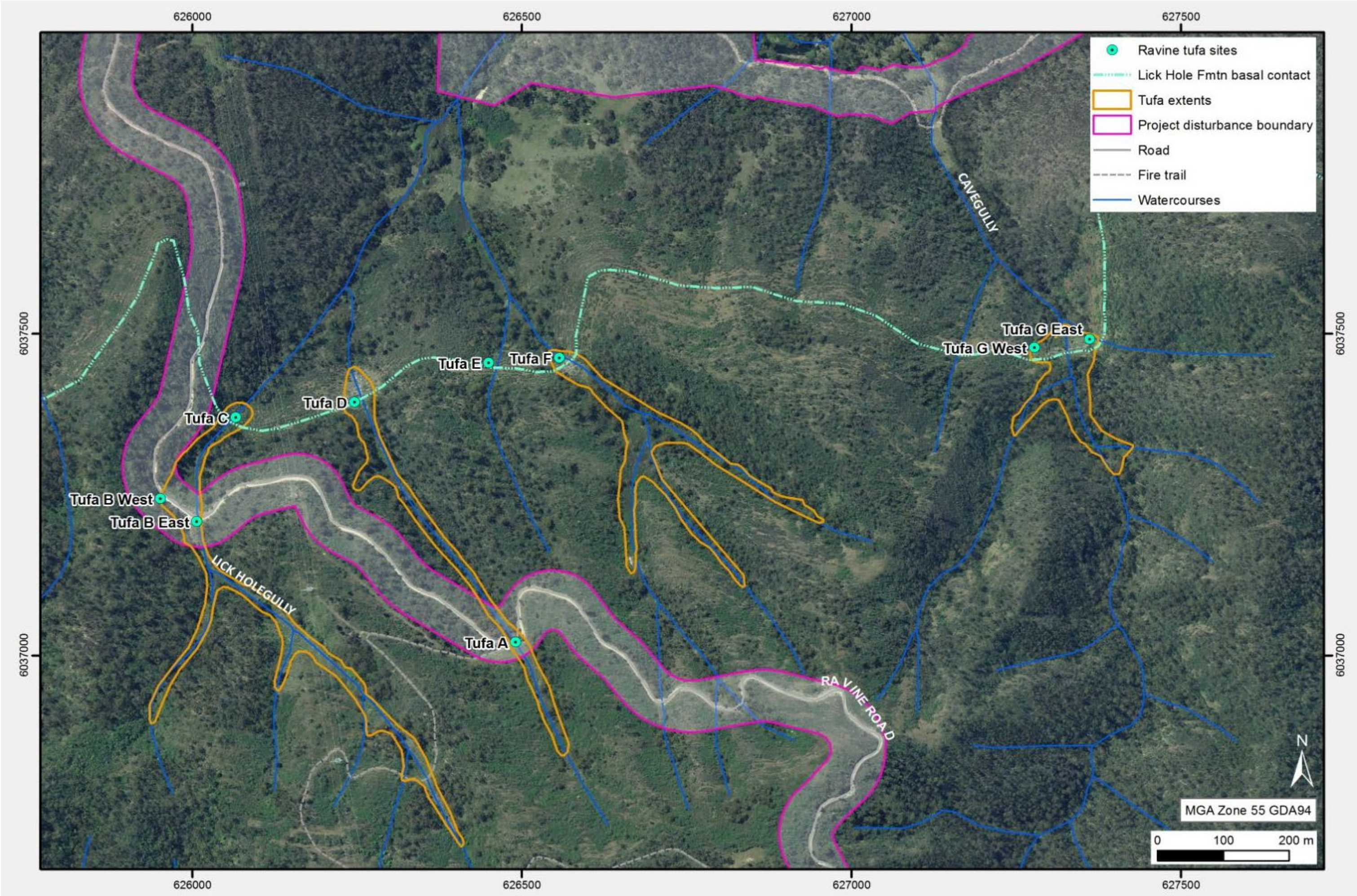

Figure 4.4 **Map showing inferred and established tufa extents along gullies associated with sites A, B, C, D, F and G, based on data in SMEC (2019) and interpretation of aerial and DEM imagery. Note that some deposits may be more extensive than shown (see text for details).**

Upslope from the Tufa A road cut, similar tufa deposits line the gully floor for at least a further 180 m along the gully axis (SMEC 2019). The gully floor is fairly level across its width, 20-25 wide and with a typical axial slope of 10-15°. It is largely devoid of trees but thickly vegetated with grass and in places, blackberry, with some trees (tall eucalypts) and shrubs growing on the hillslopes lining the gully beyond the tufa boundary (Photo 16). Tufa can be observed up to 1.1 m below the ground surface in cavities and localised narrow erosion gullies, and cavities and sinkholes in places connected by tunnels or piping are common throughout the area (SMEC 2019). In the gully immediately downslope from the road at Tufa A, no tufa or associated features were observed in the 100 m length explored by SMEC personnel in May 2019. It is possible that tufa does occur here but that thick vegetation and cover deposits precluded observation.

The second roadside tufa site (Tufa B) occurs where Ravine Road crosses Lick Hole Gully. On the upslope (south) side of the road there are two sections of tufa separated by soil landslips, termed Tufa B East and B West on Figures 4.3 and 4.4 (see Photo 17). Tufa B West consists of natural tufa cliffs rather than a road cut; Tufa B East may be a rough road cut (Photo 18). Compared to Tufa A, the tufa at this site is paler and is inferred to be higher grade (purer). It is also much better exposed and includes a variety of interesting structures.

The tufa is typically medium grey, light grey or cream in colour. It has a highly variable texture; in places it appears sponge-like and somewhat porous, some parts have abundant large pores and are very low density, elsewhere it is denser. At Tufa B East, discontinuous layering and pillow-like structures are present (Photo 19) with some surface structures of criss-crossing tubes (e.g. Photo 20). At Tufa B West a wider range of structures were observed including stalactites, natural overhangs and cavities, layering, and delicate structures of intricate branching tubes (Photos 21 to 24). In tufa cliffs immediately below the road at Tufa B West there are structures resembling branching corals (Photo 24). Stepped tufa outcrops have also been reported at this location (SMEC 2019).

SMEC field mapping has revealed that an extensive and continuous network of gully-floor tufa extends at least 150 m downstream and 700 m upstream of the Tufa B deposits (see Figure 4.4). Upstream these deposits feature areas of piping and sinkholes exceeding 2 m deep, with observations within sinkholes revealing tufa at least 2.5 m thick and sites where tens of centimetres of alluvium overlie tufa (SMEC 2019). Photos indicate that the gully-floor tufa typically resembles the low-grade deposit in the road cut at Tufa A. The tufa-lined gully floors up and downstream of Tufa B are vegetated with grass, ferns and in places thick blackberry infestations, with the edge of the tufa coinciding with the tree-line (SMEC 2019).

Bedded limestone, possibly interbedded with fine-grained clastic sediments, occurs in road cuts to the east of Tufa A and on either side of Tufa B and is attributable to the Devonian Lick Hole Formation. Tufa deposits up to ~8 cm thick encrust one such road cut adjacent to Tufa B East, providing evidence that deposition has occurred here in recent decades, assuming a post-1950s age for the road cut (Photos 25 and 26). Stream flow was not observed at any of the tufa sites visited or observed in May 2019. SMEC personnel observed standing water at two locations, upstream of Tufa A and Tufa B.

4.7.4 Geological context

No age dating of the tufa has been reported in the literature. Based on observations by Andrews (1901) of tufa encrusting and burying growing plants, it can be inferred that active deposition extended into modern times for some of the remote cliff-edge deposits. Limited evidence of recent deposition was also observed at Tufa B East adjacent to Lobs Hole Ravine Road. The upper age limit of the tufa deposits is unclear. They have been described as Quaternary in the literature (e.g. Spate & Baker 2018), a period which spans the last 2.6 million years, but given their dependence on groundwater and likely much drier conditions during the late Pleistocene glacial period, they may be a Holocene phenomenon in their current form (i.e. restricted to the last 12,000 years in age or less).

The tufa is associated with an identified karst area defined by the extent of the Lick Hole Formation, a geological unit containing limestone beds, known only from the area to the south of Ravine. The Lick Hole Formation is part of the Byron Range Group, a broader geological unit of Devonian age that occupies most of the Lobs Hole – Ravine valley floor and forms surrounding ridges to the south, north and east (Colquhoun et al. 2018; SMEC 2018). The Byron Range Group consists of three conformable formations. Lowermost is the Milk Shanty Formation, a thick to massive-bedded succession of clastic rocks, which is overlain by the Lick Hole Formation consisting of limestone interbedded with siltstones and shales with a total thickness of over 400 m, and is overlain by the Round Top Formation which consists of sandstone and siltstone forming ridge-tops to the south (Flood 1969, 1973; Moye et al. 1969). The Byron Range Group sequences dip shallowly to the south to southeast through the Ravine area (Flood 1973).

The regional geological map does not differentiate the Byron Range Group formations, however, based on a more detailed geology map of the Ravine area published in Flood (1973), confirmed by map data in SMEC (2018), the contact between the Lick Hole Formation and underlying Milk Shanty Formation coincides with the top of the prominent mid-slope, sub-horizontal cliff-line developed across this area known as 'The Walls'. This boundary is indicated in Figure 4.3, based on interpretation of the aerial and DEM images. (Note that a karst area GIS layer supplied to the author, sourced from NPWS, maps this unit boundary with lower accuracy). The most impressive and well-developed tufa sites (C to K) occur around this contact, where gully lines intersect the cliff and tufa deposits have built out over it. The alkaline, calcium-rich water from which the tufa precipitates would be sourced from dissolution of limestone beds in the Lick Hole Formation. The change in lithology from softer, more permeable, lime-rich rocks within the Lick Hole Formation above to relatively hard, impermeable, cliff-forming sandstone of the Milk Shanty Formation below provides the opportunity for extensive deposition of high-grade tufa where the water flows slowly over the cliff face. Tufa B is a smaller-scale cliff-edge deposit, and occurs within the Lick Hole Formation rather than at the base of it. Tufa A is an example of the lower grade tufa that occurs extensively on gully floors upstream of the main cliff-edge sites in association with the Lick Hole Formation. It is unclear whether tufa deposition is reliant mainly on surface run-off from the ephemeral creeks which occupy these gullies, or whether groundwater springs, perhaps in the vicinity of the cliff-edge deposits, also play a significant role.

4.7.5 Geodiversity significance

The Ravine tufa deposits have intrinsic value within KNP as impressive and potentially active karst features, and as a special element of the wider karst landscapes of the park. The tufa has been identified as having national or regional significance in the KNP PoM (p.50), and prominent cliff-edge sites within Cave Gully and Lick Hole Gully are listed in the KGAP as significant geodiversity features (OEH 2012). The tufa deposits of Lick Hole Gully, Cave Gully and Wallaces Creek are included in a list of key geodiversity features selected for rapid condition assessments (KGAP, OEH 2012), indicating that they had been identified as sites for future management focus including potential use for interpretation purposes.

The Ravine tufa deposits have been described as possibly the largest deposits of tufa in Australia south of Far North Queensland in a review of the karst values of KNP (Spate & Baker 2018). Recent mapping by SMEC (2019) indicates that tufa deposits in the area are much more extensive than previously realised.

The tufa deposits have been little studied and have potential but untested value to scientific studies. Of particular interest might be their value to palaeo-environmental reconstructions. An understanding of their hydrology and of their interaction and association with specific plant and algae communities would be of value to their long-term preservation and management.

The tufa deposits could potentially be used for geotourism and earth science education and in this context have local to regional geodiversity significance for their cultural value. They would be a worthy inclusion in a regional geotrail if a safe viewing area was developed.

In summary, the Ravine tufa deposits have regional and, potentially, national geodiversity significance on account of their rarity and potential scientific value, as well as potential tourism value.

4.7.6 General susceptibility to impacts

The tufa deposits are delicate and easily susceptible to disturbance including erosion and sedimentation. The deposits may remain active so impacts that could affect continued tufa deposition must also be considered.

Hydrological changes that impact on natural water flow, turbidity, chemistry and biotic associations could have a very negative impact on the tufa. It is likely that the deposits form in a very specific range of hydrological and biotic conditions, and significant changes in these could result in active deposits becoming inactive or eroded.

Excess unnatural sedimentation in the tufa-lined gullies may lead to burial of the deposits, vegetation changes or other potentially adverse impacts.

Vegetation changes, especially those associated with weed infestations, may impact on the deposits due to the effects on hydrology, native biota, soils and site microclimates. Deposition of tufa is highly sensitive to the nature of organic matter present, hydrological regime and microclimate, all of which could be affected by weed infestation (Spate & Baker 2018).

Due to the fragility of tufa, mechanical damage such as cracking or breaking off parts of the formations is a concern. Such damage could potentially be caused by nearby construction activity including vibrations or blasting. Unregulated close visitation could also lead to damage, either inadvertently or due to vandalism and souveniring. The most spectacular deposits are situated up cliffs distant from tracks so are relatively inaccessible, however, the Cave Gully and Lick Hole Gully tufa sites are only 350 - 500 m upslope from the project disturbance area and Mine Trail within the valley at Ravine and may be visible from that area, increasing the likelihood of visitation.

4.7.7 Existing impacts

The Lobs Hole – Ravine area has been disturbed by considerable human impacts since the late 19th century when the road was built and Lobs Hole copper mine developed in the valley at Ravine. Subsequent environmental impacts occurred due to grazing and timber cutting prior to inclusion of the area in KNP.

Lobs Hole Ravine Road crosses a number of gullies containing tufa deposits downstream, and in two gullies (at Tufa A and B) road construction has involved direct impacts on tufa deposits including excavation and placing of fill. Lick Hole Gully and its tributaries traverse a north-facing hillslope across which there is evidence in the aerial image of extensive land-clearing. Widespread weed infestations in these gullies and reported alluvial deposits overlying tufa (SMEC 2019) probably relate to this impact. These factors along with associated changes in hydrological regime may have impacted active tufa deposition in these gullies. The upper Cave Gully catchment is traversed by Lobs Hole Ravine Road and there is some evidence of land clearing on surrounding hills so it may be impacted similarly though to a lesser degree, however, there are no current observations from this area.

Visually the Lick Hole Gully and Cave Gully cliff-edge sites remain spectacular deposits in relatively remote settings surrounded by natural forest. However, it is probable that land-clearing and road-building upstream has affected hydrology, sedimentation and vegetation in the vicinity of these deposits. Andrews (1901) described extensive deposition of tufa on 'tea trees' which flourished in the tufa at these sites on both the cliff tops and vertical faces. No subsequent observations have been discovered during review of the literature for this report, so the history of active tufa deposition since that time is unknown. A rapid condition assessment of the Cave Gully site conducted in May 2019 did not record tufa-encrusted live vegetation, or signs of stream flow or active deposition (SMEC 2019), however, such flow is likely to be intermittent. Areas below the Lick Hole Gully and Cave Gully tufa deposits are reportedly impacted by weeds, including blackberry, and there are existing concerns that this could pose a threat to natural development of the deposits (OEH 2012; Spate & Baker 2018).

There is currently no field information on the condition of the three documented cliff-edge tufa sites overlooking Wallaces Creek (Tufa H, J, K). These sites appear to be remote from human impacts and may be in an effectively natural state. If so, they would potentially provide good control sites for any studies of the level of impact on the Lick Hole Gully and Cave Gully tufa deposits.

Minor road widening through the roadside tufa sections are approved for the Snowy 2.0 Exploratory Works, but these will avoid direct impacts to the tufa and no impacts on the roadside tufa are currently approved.

4.7.8 Potential impacts from proposed works

The proposed upgrade of Lobs Hole Ravine Road for the Main Works will directly impact the roadside tufa deposits. An 80 to 85 m wide disturbance area around the existing road has been identified as the maximum extent of impact at Tufa A and B (see Figures 4.3 and 4.4). The proposed works are expected to negatively impact the tufa at these locations through the permanent removal and covering of tufa. There is potential for impacts to occur outside the identified disturbance area on the downstream tufa deposits, mainly as a result of sediment and water runoff, but with careful management impacts on the high-value cliff-edge tufa should be negligible. Potential impacts are discussed further and mitigations addressed in Section 5 of this report.

4.8 Undocumented Cenozoic geodiversity

4.8.1 Approach and limitations

As outlined in Section 4.5, there is potential for undocumented geodiversity sites to be present within the project area. This section presents a desktop assessment of the nature of undocumented Cenozoic geodiversity sites most likely to occur. This assessment is based on review of the available literature and spatial data, and is limited by the accuracy and detail of the existing geology data, the unavailability of airborne geophysical data for the region, and lack of field checking.

4.8.2 Assessment of types of deposits

Cenozoic geodiversity features identified to date in northern KNP in management documents fall into four categories: Quaternary tufa deposits, Pleistocene periglacial features, Neogene ferruginous gravel deposits, and features associated with Miocene basalt and sediments. The tufa and ferruginous gravel deposits are localised phenomena associated with limestone sequences and are unlikely to occur elsewhere within the project area so will not be considered further here. Pleistocene periglacial features and Miocene features are evidence of Cenozoic environments very different from today which left an imprint on the region. They have geodiversity significance in the context of KNP and more widely in some cases (NPWS 2006; OEH 2012), and both will be considered in this assessment.

Another process which is inferred to have left a mark on the project area during the Cenozoic is tectonic activity (e.g. Sharp 2004). A recent study has identified some sites at which Cenozoic deposits may provide important evidence of such activity (DrQuigs Geological Hazards Consulting 2018), and as such could be significant geodiversity features.

4.8.3 Assessment of possible location of deposits

The only periglacial features documented in the northern KNP area to date are block streams near Ravine and on the Cooleman Plain in the far north of the area (see Table 4.1), however, it does not appear that systematic documentation of periglacial features has been undertaken across the area.

Periglacial features have been widely identified above 1000 m elevation in the Australian Alps (Costin 1972). A large part of the Snowy 2.0 project area lies above this elevation, as indicated in Figure 4.5, making it potentially prospective for such features, however, other conditions such as ice age microclimates and underlying geology would need to have been suitable to enable their formation. During SMEC field mapping undertaken in the vicinity of the project alignment, basalt block deposits were identified at two sites on slopes below basalt-capped hills in the Gooandra area (R. Goldsmith, SMEC, pers. comm.), the only such features identified during their field activities to date. Inspection of aerial imagery has revealed numerous other similar-looking block features on slopes around basalt-capped hills and ridges within the project area as mapped in Figure 4.5. A late Pleistocene periglacial origin is probable for these features, some of which have distinctive block stream morphology, whereas others appear to be block fields, rimming the edge of basalt outcrops. Such features are quite widespread around the basalt-capped hills north of Six Mile Diggings and near Kiandra. Some were also identified along the eastern side of Section Ridge, east of Lobs Hole Ravine Road, as mapped in Figure 4.6. Such features may be more extensive than shown on the eastern side of this ridge which is thickly vegetated making remote interpretation difficult.

None of the newly documented basalt block features lie within the project disturbance area although some are within a few hundred metres of it near access roads which will be upgraded and widened for the project, including sites around Kiandra and Gooandra to Six Mile Diggings, and one site along Section Ridge. No block features have been observed in the thickly vegetated and previously untracked Marica area during SMEC geological mapping activities and the area lacks Cenozoic basalt so such features are inferred to be unlikely to occur through that area.

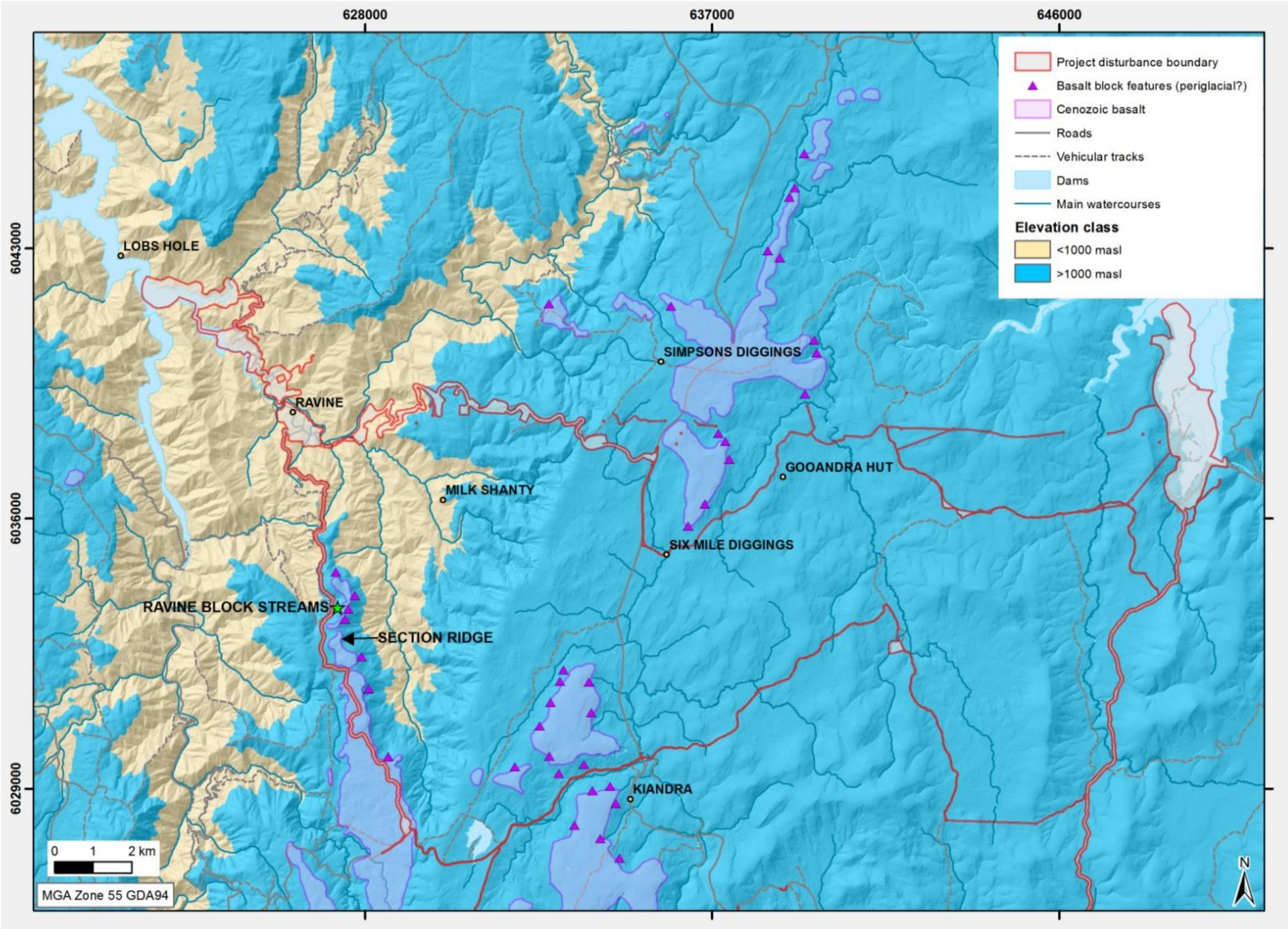

Figure 4.5 Map of project alignment area indicating land >1000 m elevation (based on DEM), which may be prospective for periglacial features, and sites of previously undocumented block deposits around basalt-capped hills and ridges, which are most likely Pleistocene (ice age) periglacial deposits.

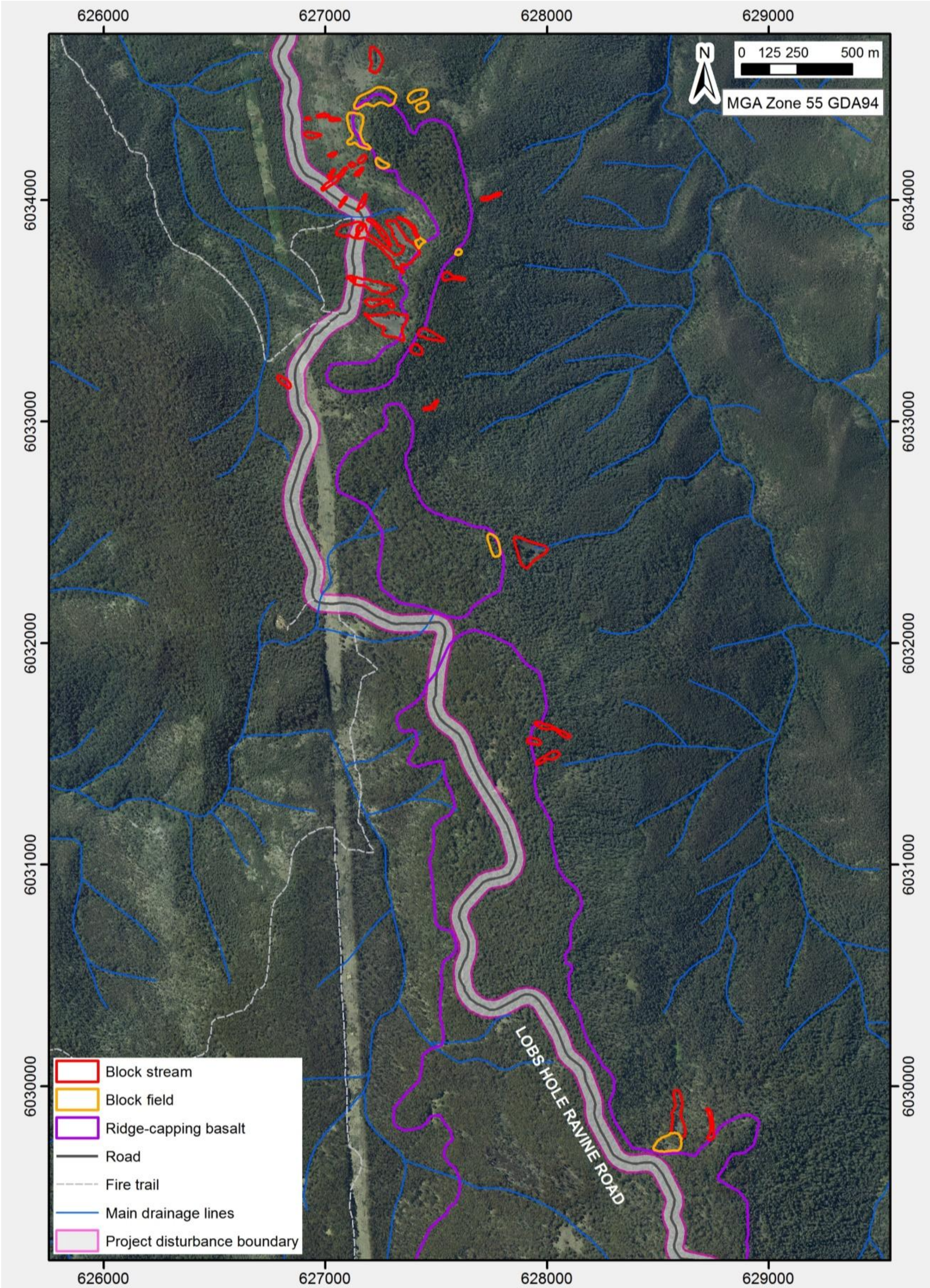

Figure 4.6 **Extents of basalt block deposits mapped around Section Ridge. The Ravine block streams are at top left. Block streams and block fields are differentiated.**

Block streams are amongst the most obvious periglacial features in KNP and, where unvegetated or lightly vegetated, are readily identifiable in the field and on aerial photographs. Other types of periglacial deposits documented previously in KNP include solifluction lobes and terraces, sliding and shattered boulders, and periglacial slope deposits (Costin & Polach 1972; Costin 1972; Galloway 1989; NPWS 2006). Such features have not been reported in the project disturbance area but they may be smaller scale or more subtle than block deposits, so less readily identified in remote data or in the field.

In the regional geology data, Miocene sediments have been mapped abutting and underlying basalt at a few localities in the project area, but based on some reports in the literature they may occur more widely. Some authors report that such sediments occur beneath the majority of Cenozoic basalt deposits in the area (e.g. Hall & Lloyd 1954), and that abundant basalt talus around the margins of basalt outcrops tends to conceal their presence (Gill & Sharp 1957). The sediments are typically unconsolidated to poorly consolidated so are eroded easily where the protective cover of basalt has been removed, as occurred around Kiandra and other areas where buried leads at the base of the deposits were worked for gold in the 19^{th} century.

The only known basalt exposures within the project disturbance area are those capping Section Ridge, which is crossed by the southern part of Lobs Hole Ravine Road. No Miocene sediments have been mapped in association with this basalt deposit in the past, and Sharp (2004) states that unlike the basalt cappings at Eight Mile to the west and Kiandra to the east this deposit has no associated sediments. Furthermore, no Miocene sediments have been reported in reconnaissance mapping by SMEC or in preliminary geotechnical investigations conducted along Lobs Hole Ravine Road (SMEC 2018; GHD 2019), although investigations have been very limited to date. Overall, the likelihood of significant Miocene sediments occurring in association with this basalt is inferred to be low, but cannot be ruled out as past investigations are unlikely to have been exhaustive. Mapped extents of this deposit indicated in Figure 4.7 are inferred from aerial and DEM imagery on the basis of geomorphic expression and vegetation, guided by a Snowy Mountains Authority map reproduced in Sharp (2004). Two areas where the road may intersect the basalt contact are highlighted in Figure 4.7, as these would be the most prospective sections for Miocene sediments. They include an area ~5.1-5.6 km north of the Link Road intersection, and another area on Link Road just east of this intersection. There is also some (very limited) potential for such sediments to occur elsewhere along southern Lobs Hole Ravine Road if the basalt contact is encountered or excavated.

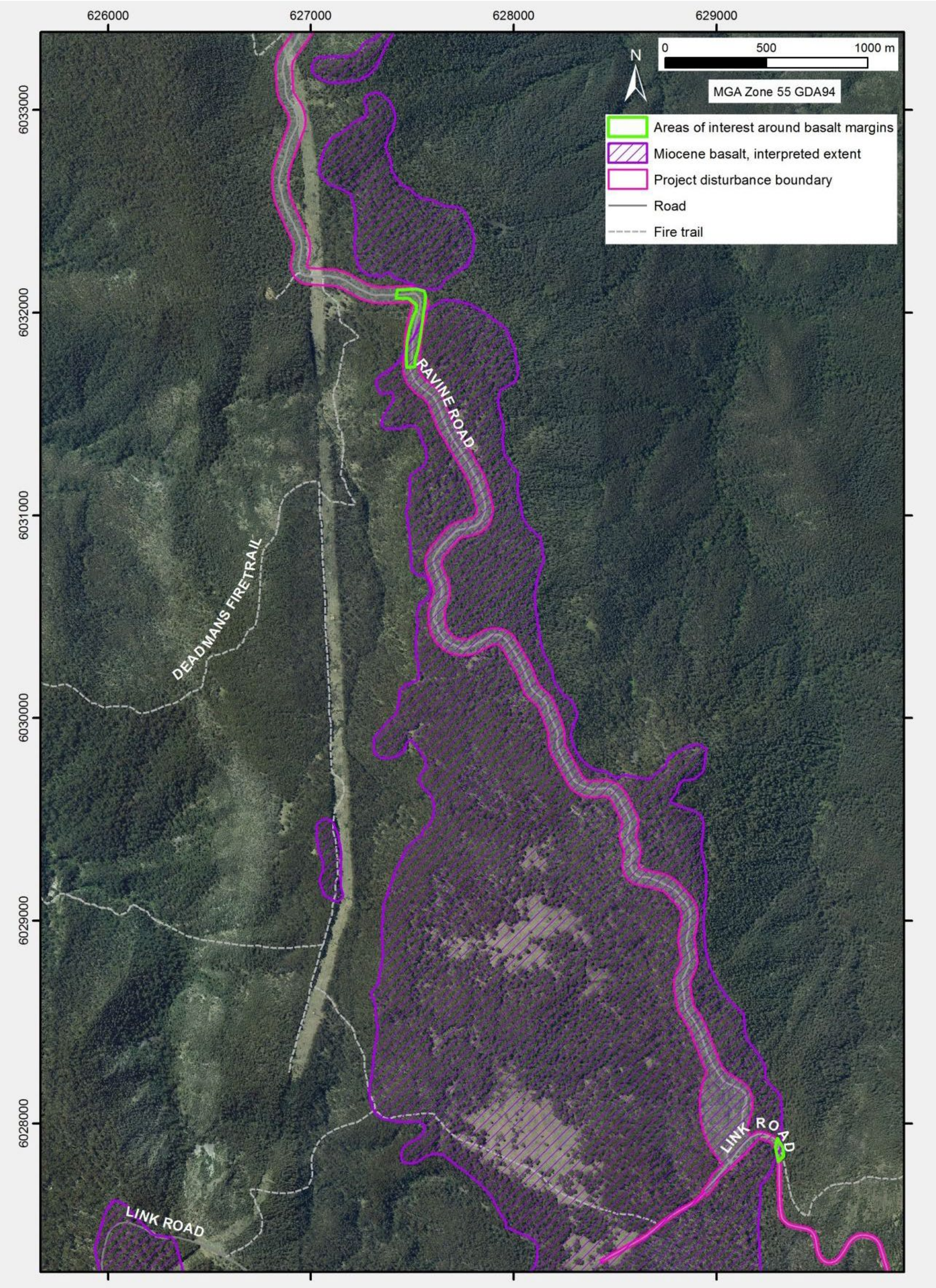

Figure 4.7 The inferred extent of Miocene basalt through the southern section of Lobs Hole Ravine Road overlaid on aerial imagery. The green polygons indicate road section which may cross the base of the basalt and where underlying Miocene sediments could be encountered, if present.

No undocumented Cenozoic basalt has been detected elsewhere in the project disturbance area in either the review of remote sensing data conducted for this report, or in geological investigations undertaken to date for Snowy 2.0 (SMEC 2018) and the likelihood of finding substantial new Miocene basalt and associated sediment deposits with potential to be impacted by the project is inferred to be minimal.

A study by DrQuigs Geological Hazards Consulting (2018) has identified some sites within the project area at which Cenozoic deposits have potentially been affected by and provide evidence for neotectonics. Their identification of these sites is based on interpretation of LiDAR DEM data, and it is understood that no field checking has been undertaken to date to confirm the remote interpretation (R. Goldsmith, SMEC, pers. comm.). They identified three such sites within Cenozoic basalts. These occur several kilometres north of the project alignment so will not be impacted by the project.

4.8.4 Potential geodiversity significance of undocumented features

Periglacial features and 'Tertiary' (Miocene) features including columnar basalt pinnacles and sediments are identified specifically within KNP PoM Schedule 1 as 'Significant Natural and Cultural Features' of the park, so any undocumented examples of these features may be considered to have at least local geodiversity significance.

Previously undocumented periglacial block streams have been identified in the project area (Figures 4.5 and 4.6) and would likely be of local interest to KNP management and may be of regional scientific interest. None of the features identified occur within the project disturbance area. Other more subtle types of periglacial features may occur within the project disturbance area (e.g. periglacial slope deposits), but would be much less visually impressive than block streams and are likely to occur much more extensively throughout the area so are unlikely to have similar geodiversity significance.

Past scientific studies of Miocene sediments and associated fossils from the project area have provided important evidence of Early Miocene environmental conditions in the area and a notably large range of fossil plant types. Fresh samples of Miocene sediments may have value for future palaeontological studies.

Some Cenozoic basalt and alluvial deposits provide important evidence for studies seeking to reconstruct the tectonic history of the area, including neotectonic fault activity (e.g. Sharp 2004; Young, McDougall & Sharp 2004; DrQuigs Geological Hazards Consulting 2018). Any sites confirmed to indicate neotectonics activity would have geodiversity significance at some level.

In summary, if any newly discovered periglacial features, fossil-rich Miocene deposits, or Cenozoic deposits providing clear evidence for tectonic activity are identified in the project area, they would have local intrinsic geodiversity significance and potential regional geodiversity significance based on their scientific value and possibly other inherent values.

4.8.5 General susceptibility to impacts of undocumented features

Undocumented periglacial features may include such features as solifluction lobes and terraces which are composed of a mix of soil and rock and may be moderately susceptible to erosion. The KGAP notes that periglacial features in the Main Range area are generally robust but that some are likely to become less visible through time due to rainwash and vegetation growth (OEH 2012). Removal of vegetation around or on periglacial features on slopes may lead to unnatural and damaging sedimentation and/or erosion.

The Miocene sediments of the area consist largely of unconsolidated sand, silt and gravel, and are highly susceptible to erosion and landslips once exposed from beneath a basalt capping. The historic gold workings around Kiandra provide a good example of this. Kiandra Miocene sediments also include lignite beds which have been damaged by fire (OEH 2012).

Cenozoic deposits displaying evidence of tectonic activity may include basalt and alluvium. Their susceptibility to erosion would depend on their level of induration or cementation and geographic situation.

Undocumented Cenozoic geodiversity features would be at risk of significant damage if subject to excavation or covered due to construction activities.

5 Management of geodiversity

5.1 Risks and sensitivities relating to Cenozoic geodiversity features

5.1.1 Ravine blocks streams

In the vicinity of the block streams, the indicative project disturbance area associated with the upgrade of Lobs Hole Ravine Road is typically around 80 m wide (plan view) around the road centreline, with the road alignment largely unchanged (Figure 4.2). Road widening and associated construction works affecting an area of this width would have a substantial additional impact on the block streams. Specific risks and sensitivities include:

1. Damage to the integrity of the block streams due to removal of blocks during road widening.

2. Disruption to the stability of blocks in the vicinity of roadworks due to removal of adjacent or nearby blocks.

3. Introduction of new materials which contaminate the integrity of the features.

4. Covering of areas of the block streams for construction purposes.

5. Road design that detracts from the intrinsic scenic and landscape values of the block streams.

6. Changes in hydrology of the block deposits if roadworks substantially impede natural drainage through the deposits in the vicinity of the road, potentially affecting stability.

7. Introduction of access or viewing limitations which impact on future use of the block streams for educational, tourism or scientific purposes.

Based on the block stream mapping shown in Figure 4.2, large parts of the lower sections of block streams A, B, C and E, and the whole of Block Stream D lie within the project disturbance area. The exact nature of the disturbance within this area is not currently defined but potentially includes extensive excavation and fill placement. This would have a considerable impact on the integrity of these features. There are large areas of block stream outside the project disturbance area, mostly on the upslope side of the road, and total removal of the features is not a risk. Nonetheless, road design which minimises both excavation and permanent covering of the block stream features is desirable as much as is practicable while maintaining safety and stability of the road. A further aim should be to minimise permanent impacts on the features beyond the extent of the widened road, even where this lies within an approved disturbance area.

At block streams A, B and D, block deposits extend across the width of the project disturbance area, and impacts on the down- and up-slope would appear equal, in the absence of information on design options. The basal part of Block Stream B downslope of the road (pictured in Photo 2) preserves interesting surface topography features which are readily visible from the current road and are interpreted to be associated with ice age block flow, and it is suggested that preservation of this section in an intact state should be a priority, as far as practicable. For the road section passing though block streams C to E, impacts on block stream integrity could be reduced by undertaking road widening on the downslope side of the road where block stream deposits are less extensive, but this area is very steep so upslope cut and fill may prove more practical.

Creation of a much wider road corridor through the block streams would negatively affect the aesthetic and landscape values of this geodiversity site, and road design which minimises visible and unnatural-looking infrastructure is desirable.

Stability issues associated with roadwork impacts on local block stability and drainage through the deposits could be addressed by suitable engineering solutions. Where block stream deposits require retaining for stability purposes, materials that maintain viewing access should be considered, and materials that completely cover the deposits or are unsightly, such as shotcrete, should be avoided where possible.

5.1.2 Ravine tufa deposits

The project disturbance area associated with the planned upgrade of Lobs Hole Ravine Road crosses tufa-lined gullies at Tufa A and Tufa B (East and West) as indicated on Figure 4.4. The disturbance area is ~85 m wide at Tufa A, but offset to the north with a wider impact of around 60 m on the downslope side. At Tufa B the disturbance area is ~80 m wide around the road centreline. Other areas of tufa lie outside the project disturbance area but the downslope deposits in Cave Gully, Lick Hole Gully and associated tributary gullies could be impacted adversely by road construction works upstream.

Specific risks and sensitivities associated with the tufa include:

1. Mechanical damage due to blasting, construction vibration or, in the case of the roadside deposits, excavation.

2. Covering of roadside tufa deposits by fill or other materials.

3. Hydrological impacts in tufa catchments including changes to natural surface and groundwater flow regimes, changes in water chemistry including chemical contamination and pH changes, changes in stream lines and drainage impedance.

4. Increased sedimentation associated with land clearing or earthworks in tufa catchments.

5. Vegetation changes which adversely impact active tufa deposition.

6. Direct damage to delicate tufa features due to increased visitation, either inadvertent or deliberate.

7. The low level of understanding of the tufa deposits, including the severity of existing impacts on tufa depositional activity, hydrology and tufa-associated vegetation.

Road design plans are not currently available but it is clear that that the roadside tufa deposits will be directly impacted by road construction activities. This will potentially include excavation and placement of fill and other materials to enable construction of a wider roadway. The Tufa A site appears to consist of relatively impure tufa forming a vegetated gully floor deposit that has been excavated previously for the existing road. It is unclear if tufa deposition is still occurring at this site. Some additional direct impact in the form of further excavation of this deposit should not diminish the overall significance or value of the Ravine tufa deposits.

The Tufa B deposits are composed of higher grade, purer tufa exhibiting a range of structures and textures, and include natural outcrop (e.g. Photos 20-24). There is evidence that tufa deposition has occurred at this site in relatively recent times. This is also the only easily accessible, documented example of good quality tufa. For all these reasons, this site is assessed as being higher value than Site A. Road design that enables preservation of at least some of the tufa features at this site should be considered if practical.

The highest geodiversity values can be attributed to the large, high-quality cliff-edge tufa deposits which occur in gullies downstream from the road, and any adverse impacts on these deposits should be avoided. Specific impacts to avoid or minimise include water and sediment release into Cave Gully, Lick Hole Gully and tributary gullies downstream of the road. An assessment and proposed mitigations to reduce impacts to surface water flows and sedimentation are outlined in the Main Works Surface Water Assessment (EMM 2019).

The Noise and Vibration Impact Assessment has assessed potential impacts to the tufa from blasting during road construction (EMM 2019). This assessment identified a blast offset zone for vibration sensitive receivers. The roadside tufa (A and B) were identified as being within the blast offset zone and have potential to be impacted by vibration above the criteria levels. The cliff-edge tufa (C-G) are located well outside of the blast offset zone and would not be impacted above the criteria levels for vibration impacts.

There is minimal information available on recent or current tufa depositional activity levels, and the tufa systems as a whole are poorly understood. The cliff-edge deposits are physically linked to upstream tufa-lined gullies and may even be dependent on them for maintaining tufa depositional activity. It is possible that historic human impacts since the early 20th century have already wrought substantial change from pre-existing natural systems, for example due to sedimentation and weed infestation in the tufa-lined gullies. Any activities that might lead to further adverse impacts on the tufa-lined gullies should therefore be avoided where possible. Weeds are an existing significant issue in these gullies. The potential for the project to impact further on weeds and relevant controls have been addressed in the Main Works Biodiversity Development Assessment Report (EMM 2019).

A large temporary works camp is being built in the Lobs Hole area for use during Snowy 2.0 Exploratory Works and Main Works, and while it lies outside and downstream of the tufa, will result in increased visitation to the area. Potential risks to the tufa from damage by visitors could be managed by enacting visitation restrictions during construction.

5.1.3 Undocumented geodiversity sites

As discussed in Section 4.7, some potential exists for previously undocumented significant Cenozoic geodiversity features to occur within the project disturbance area. The main risk posed by the project to such features is the possibility that they are not recognised by construction personnel and are damaged or destroyed by construction activities, or covered by construction works as a result.

5.2 Opportunities arising from Snowy 2.0 Main Works for Cenozoic geodiversity

Snowy 2.0 Main Works present a number of opportunities for Cenozoic geodiversity within KNP in relation to science, education and tourism.

5.2.1 Scientific opportunities

New remotely sensed data collected for Snowy 2.0 in the form of high-resolution aerial photography and LiDAR DEM has, along with limited field studies, made it possible to map the Ravine block streams and tufa deposits and better understand their context in the landscape, but much more remains to be learnt about these features. New remotely-sensed data and field data collected for Snowy 2.0 along with new excavations associated with the proposed works, could provide fresh opportunities for scientific studies of these features and other aspects of Cenozoic geology in the project area if the new data and other information was made available to interested scientists.

For example, geotechnical investigations and roadworks through the Ravine block streams may enable the opportunity for further scientific investigations of these features, including their stratigraphy (internal structure) and the nature of the underlying substrate. These features, which cannot be accessed in intact block streams and of which there appear to be only a few descriptions in the scientific literature, may provide clues regarding their mode of formation, some aspects of which appear to be poorly understood. There are academics with past interest in these and other southeast Australian block streams who could be approached to gauge interest in this research opportunity.

The Lobs Hole – Ravine tufa deposits have never been studied in any detail. Access to new remotely-sensed data and other relevant data collected for Snowy 2.0 may encourage and facilitate research into these deposits. Improved understanding of their hydrology, biotic interactions, activity levels and current impacts would better enable future preservation and management. A study of palaeoenvironmental records contained in the tufa could potentially provide new insights into local and regional climatic, hydrological and landscape changes through the period of deposition. Academics with interests in karst features and palaeoenvironmental reconstructions could be approached with regard to this opportunity in the post-construction phase of the project.

Investigation and construction activities associated with Snowy 2.0 Main Works including geotechnical testing, excavations, new road cut exposures along existing roads and road development in previously untracked areas may reveal previously undocumented geodiversity features. In terms of Cenozoic features, there is very minor potential for the discovery of new Miocene sediment sites which could present the opportunity to collect fresh samples containing plant fossils for use in future paleontological studies. There is some potential for the discovery of previously undocumented periglacial features in areas above around 1000 m elevation. If recognised, the documentation of such features would extend the knowledge of periglacial landforms of KNP (identified as a significant geodiversity element of the park). Subsequent scientific studies of such features could lead to improved understanding of Late Quaternary climatic changes in the region. There is also potential for the recognition of sites that provide evidence of neotectonic fault activity. There is ongoing scientific interest in this fault activity as it has implications for both engineering applications and for the understanding of tectonics and landscape development in eastern Australia. Documentation and study of such sites for engineering purposes could potentially be extended to provide the opportunity to assess their wider scientific significance.

5.2.2 Geotourism and educational opportunities

Snowy 2.0 Main Works include a planned upgrade of Lobs Hole Ravine Road along which there are three documented geodiversity sites: the Ravine block streams and tufa deposits as detailed in this report, and a Devonian fossil site in a road cutting (OEH 2012; EMM 2018; Percival 2019). Tourism potential of the area has been limited to date by poor access, which has been four-wheel drive only. Improved access to the Ravine area geodiversity sites would provide better opportunities post-construction for educational and tourism visitation. The proposed development should consider opportunities to enhance the geotourism potential of the known geodiversity sites, for example by providing suitable viewing areas and associated educational material. With such facilities in place, these sites could potentially be included in a regional geotrail, as suggested in the KGAP (Key Action 5.2 and Appendix 1). This action would help fulfil two of the aims of the KGAP, i.e. to promote opportunities for increasing visitation to interesting and/or significant geological sites, and to increase awareness, appreciation and understanding of the geodiversity of KNP (p.5). The close proximity of three geodiversity sites in the Ravine area provides the potential to make this a focus area of a regional geotrail.

5.3 Recommendations for management of Cenozoic geodiversity features

As detailed in this report, the Ravine periglacial block streams and tufa deposits are highly valued geodiversity features of KNP and also have wider regional to national geodiversity significance. New infrastructure associated with Snowy 2.0 Main Works will undoubtedly have some adverse impact on these features, particularly the block streams and roadside tufa deposits. With careful management, including well-considered infrastructure design, it should however be possible to reduce the impacts of Snowy 2.0 on these features to an acceptable level. Potential opportunities presented by the project for scientific study and improved access and facilities for educational groups and tourists would also help ameliorate the negative impacts.

Key recommendations relating to the management of Cenozoic geodiversity features during Snowy 2.0 Main Works are presented in Table 5.1. They are grouped into five categories which include design principles for road sections through the block streams (GEO1) and tufa deposits (GEO3), and measures to include in management plans for the block streams (GEO2), tufa (GEO4), and any undocumented Cenozoic geodiversity features identified during the project (GEO5). Justifications for each measure are also outlined in the table.

Table 5.1 Key measures for protection of Cenozoic geodiversity within or near the project disturbance area

Impact/risk	ID#	Measure(s)	Justifications	Timing	Responsibility
Ravine block streams	GEO1	Implement the following design principles for detailed design of road sections that intersect the Ravine block streams:		Design and construction	Contractor
		• undertake detailed field mapping of the scale and extent of the block streams within the project disturbance area;	• Block stream mapping (Fig. 4.2) is based partly on remote interpretation; a ground-truthed map is required on which to base designs around the features and to mitigate the risk of finding new block stream areas during construction.		
		• minimise the road footprint through the block stream sections as far as practicable;	• This will limit the impact on and maintain integrity of the features as far as possible.		
		• utilise construction techniques which avoid or minimise impacts outside the road footprint in block stream sections;	• This will limit permanent impacts on the block streams and their surrounds thereby maintaining landscape aesthetics and integrity.		
		• limit excavation into the block streams to the minimum required for road safety;	• This will limit the impact on and maintain integrity of the features as far as possible.		
		• avoid covering the upslope block streams with shotcrete or other materials that would permanently preclude viewing of the blocks, and where permanent covering is required materials with low visual impact should be used where practical;	• This will maintain viewing access and aesthetic values of the block streams.		
		• consider the visual impact of the road upgrade in the block stream sections and implement road design that will maintain landscape values; and	• Prominent, unsightly infrastructure would detract from the visual appeal and landscape values of the block streams.		
		• minimise vegetation clearing associated with roadworks in the block stream sections.	• This would reduce the visual impact on the surrounding environment, and may help maintain stability of blocks.		

Impact/risk	ID#	Measure(s)	Justifications	Timing	Responsibility
Ravine block streams	GEO2	Develop a management plan that includes measures to: • carry out regular monitoring and assessment of block stream sections including for impacts on structure extents, integrity and aesthetics; the plan should include contingency measures in the event that unexpected impacts are identified; • facilitate development of a safe stopping space and interpretive signage within the proposed road and disturbance footprint where practical; consult with NPWS regarding enhancing the geotourism potential of the site, including consideration of including the site in a geotrail; and • facilitate scientific study of the block streams post-construction by contacting specified academics who may be interested in the features and releasing relevant project data (e.g. geological and geotechnical reports, aerial imagery and LiDAR DEM, other relevant spatial data) to these academics if required.	• This would help to ensure that works are being carried out within design parameters and are not unnecessarily impacting on the features. • Interpretive signage and a stopping space would enable safe visitor appreciation of the features, post-construction. A regional geotrail would provide a new tourism drawcard to the area. Relevant information collected during Snowy 2.0 could be used in development of materials and signage if made available. • Aspects of block stream formation remain poorly understood as their structure has rarely been investigated due to difficult access; the new road cuts and data collected for Snowy 2.0 may present an opportunity to advance scientific knowledge of block streams and periglacial environments in Australia.	Construction and operation	Contractor

Impact/risk	ID#	Measure(s)	Justifications	Timing	Responsibility
Ravine tufa	GEO3	Implement the following design principles for detailed design of road sections that impact directly on roadside tufa and could impact indirectly on cliff-edge tufa: • limit direct impacts on roadside tufa features where possible, in particular those that display notable intact natural structures; • maintain drainage in as natural state as possible where the road crosses tufa-lined gullies; • implement strict water and sediment controls during roadworks within the upper Lick Hole Gully and Cave Gully catchments to avoid downstream release of unnatural water or sediment loads; and • minimise vegetation clearing within the upper Lick Hole Gully and Cave Gully catchments (i.e., above cliff-edge tufa deposits C, D, E, F and G as shown in Figure 4.4).	• This would minimise unnecessary damage to geodiversity features. • Significant changes in the natural surface water flow regime may impact adversely on tufa activity levels. • Tufa deposits, including at downstream high value cliff-edge sites, could be adversely impacted by unnatural hydrological changes (including in water chemistry, turbidity, and flow rates) or by increased sedimentation. • Vegetation clearing would likely lead to increased erosion and sedimentation in these gullies which could impact on tufa depositional activity or bury existing deposits.	Design and construction	Contractor

Impact/risk	ID#	Measure(s)	Justifications	Timing	Responsibility
Ravine tufa	GEO4	Develop a management plan that includes measures to: • Undertake baseline assessment of high value cliff-edge tufa deposits at sites C, D, E, F and G. Parameters to be assessed should include water flow, vegetation/tufa interactions, and evidence for recent tufa depositional activity and alluvial sedimentation on tufa deposits. • Implement regular assessment and monitoring of tufa deposits during construction, including high value cliff-edge deposits in Lick Hole Gully and Cave Gully (C to G) for changes from baseline assessment observations outside expected natural variations. The plan should include contingency measures in the event that unexpected impacts are identified. • Enact and enforce visitation restrictions to cliff-edge tufa sites except for monitoring and assessment purposes. • Facilitate development of a safe stopping space and interpretive signage within the proposed road and disturbance footprint where practical; consult with NPWS regarding enhancing the geotourism potential of the site, including consideration of including the site in a geotrail. • Facilitate scientific study of the tufa post-construction by contacting specified academics who may be interested in the features and releasing relevant project data (e.g. geological and geotechnical reports, aerial imagery and LiDAR DEM, other relevant spatial data) to these academics if required.	• Baseline assessment would provide better context for subsequent monitoring of impacts during the construction phase. • Regular monitoring would identify actual or potential impacts of the roadworks on the high value cliff-edge tufa, and protocols providing for contingency measures would assist with mitigating any impacts identified. • A large number of personnel will be housed in the Ravine area construction camp; visitation restrictions will minimise the risk of accidental or deliberate damage to the fragile tufa deposits. • This would enable visitor appreciation of the features and provide a new tourism drawcard to the area. • The tufa is little studied; better knowledge of the tufa would have benefits for management and may reveal new insights into local and regional palaeo-environmental conditions during the period of deposition.	Construction and operation	Contractor

Impact/risk	ID#	Measure(s)	Justifications	Timing	Responsibility
Undocumented geodiversity sites	GEO5	Develop a management plan that includes the following measures: • management guidelines in the event that previously undocumented Cenozoic geology sites with potential geodiversity significance are discovered during the investigation and construction phases; • awareness training in relation to Cenozoic geodiversity for relevant personnel; • field checking by a geologist for previously undocumented Cenozoic geodiversity sites where warranted within or near the project disturbance boundary; • any newly discovered geodiversity sites should be documented and reported to NPWS.	• Clear guidelines would assist in limiting any project delays that may otherwise arise due to such findings. • Undocumented Cenozoic sites with geodiversity significance may be present and may be at risk of damage or destruction if not recognised prior to works occurring; awareness training and field checking would reduce this risk. • The requirement to report such finds would help ensure the dissemination and use of new knowledge.	Design and construction	Contractor

6 Conclusions

Two previously identified Cenozoic geodiversity sites of regional to national significance occur within or close to the Snowy 2.0 project disturbance area in the vicinity of Lobs Hole Ravine Road, near Ravine. These are Late Pleistocene periglacial block streams and Quaternary tufa deposits. The proposed upgrade and widening of Lobs Hole Ravine Road for the Main Works will directly impact parts of both sites. It is possible that other currently undocumented Cenozoic geodiversity sites exist within or near the project disturbance area, although the potential for such occurrences is assessed to be very low.

This report outlines a range of specific risks, sensitivities and opportunities for Cenozoic geodiversity within the context of Snowy 2.0 Main Works, relating mainly to the two documented Cenozoic geodiversity sites. This assessment has informed a series of management measures, summarised in Table 5.1, which, if implemented, would mitigate the impacts of the project on the features and have potential to provide some benefits to Cenozoic geodiversity in KNP in the longer term.

The Main Works project area includes some high value geodiversity sites which occur within a national heritage-listed national park landscape. With careful design, construction practices and monitoring, impacts on geodiversity can be minimised and opportunities for education, scientific research and public appreciation of geodiversity enhanced by the project.

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Appendices

A Details of spatial data sets

Data type	Dataset name	Data format	Metadata
Digital aerial photo	snowy2-0_2018oct26-28_rgb_10cm_z55	ecw raster	Orthorectified digital aerial photo image captured 26-28 October 2018 for Snowy Hydro by Photomapping Services Pty Ltd. 10 cm resolution, 30 cm accuracy.
DEM	J17188_LiDAR_Surfaces.gdb	raster grid	1 m resolution DEM based on LiDAR data captured May 2017 for Snowy Hydro by Photomapping Services Pty Ltd.
Geodiversity feature area	BoulderScree_01pg_EMMDigitise_20180406	shape file	Interpreted areas of periglacial block stream deposits supplied by EMM, digitised from a combination of ground-truthed vegetation survey and LiDAR-derived surface.
Geodiversity feature sites	GeodiversityIndex_01pt_EMM_20180606	shape file	Approximate locations of geodiversity features based on NPWS data, sourced from KGAP (2012).
Geodiversity feature area	Karst_01pg_SH_20170809	shape file	Interpreted surface area of karst zone supplied by Snowy Hydro. Apparently sourced from Lishmund et al. (1986), a report on limestones in NSW.
Geodiversity feature sites	TufaRavineLocations_01pt_NPWS_20190409	shape file	Locations of Ravine tufa deposits, sourced from National Parks and Wildlife Service.
Digital geology map data	NSW_SeamlessGeology_GDA94_v1.gdb	geodatabase	Statewide Seamless Geology Digital Data version 1 (Colquhoun et al. 2018), Geological Survey of NSW.

B Field photos

Photo 1 **Block Stream E immediately upslope of Lobs Hole Ravine Road showing a typical view of unvegetated matrix-free blocks up the main axis of the block stream.**

Photo 2 **Block Stream B immediately downslope of Lobs Hole Ravine Road. Low relief surface topography is subtly delineated by variations in snow cover, and includes across-slope ridges. These features were probably formed by block flow at the time of deposition, ~22-17 thousand years ago.**

Photo 3 Block sizes are mainly in the 0.2-0.5 m diameter range but a few are much larger including this elongate boulder around 1.2 m long at the surface of Block Stream A on the upslope side of Lobs Hole Ravine Road. The block exhibits columnar jointing inherited from the ridge-top basalt lava flow deposit from which it was sourced.

Photo 4 Road cut at the northern edge of Block Stream E, upslope of Lobs Hole Ravine Road. In the foreground, basalt blocks are embedded in soil. Matrix-free surface blocks occupy a shallow gully beyond that to the right; pink streamers mark the roadside extent of surface blocks.

Photo 5 **A layer of basalt blocks within the upper soil profile adjacent to the southern edge of Block Stream B, where matrix-free surface blocks are absent. The camera case is 14 cm long.**

Photos 6 & 7 **Block Stream B where it is crossed by Lobs Hole Ravine Road, illustrating the existing impact of the road on the features. On the upslope side the block stream, and in places the underlying substrate, have been excavated. Fill has been placed on the block stream below the cutting to create a level road surface with a steep batter sloping down to the lower section of the block stream.**

Photo 8 **The main Cave Gully tufa deposit (Tufa G East) viewed from the north (Photo source: SMEC 2019).**

Photo 9 **View of Tufa D (right arrow) and Tufa F (left) looking southeast from Lobs Hole Ravine Road. The site at which the photo was taken is shown on Figure 3.3. Tufa C is out of shot to the right.**

Photos 10 & 11 **Closer views of Tufa D (top) and Tufa F (base) looking southeast from Ravine Road. These deposits occur in the same geological context as Tufa G, where gullies intersect a prominent cliff-line.**

Photos 12 & 13 **Views of Tufa A looking east (upper image) and south-southeast (lower image) exposed in a low road cut in a shallow gully on the south side of Lobs Hole Ravine Road. (Source for lower image: SMEC 2019)**

Photo 14 **Weathered brown-grey, valley-fill tufa exposed in the Tufa A road cut. Notebook is 19 cm long.**

Photo 15 **Fresh grey tufa at Tufa A road cut.**

Photo 16 **Blackberry-infested, tufa-lined gully upstream of Tufa A. Similar infestations occur on tufa deposits downstream of the road. (Photo source: SMEC 2019)**

Photo 17 **View of Tufa B looking southeast up Lobs Hole Ravine Road. Tufa B East is behind the vehicle, Tufa B West includes the cliff in the foreground. (Photo source: EMM 2019)**

Photo 18 **At Tufa B East, the main tufa exposure is several metres high and displays various structures including pillow-shaped features and discontinuous layering.**

Photo 19 **A close up of delicate tufa structures at Tufa B East, possibly formed as a result of tufa deposition on vegetation.**

Photos 20 & 21 **Part of the main tufa exposure at Tufa B West. The lower photo is a close up of the top right section of the upper photo showing a stalactitic formation.**

Photos 22 & 23 Examples of the variety of tufa forms that occur at Tufa B West.

Photo 24 **Tufa cliff just below Lobs Hole Ravine Road at Tufa B West with formations resembling branching corals. (Photo source: SMEC 2019)**

Photos 25 & 26 **Adjacent to the eastern edge of Tufa B East, pale granular tufa deposits encrust a road cut formed from dark grey Lick Hole Formation limestone, providing evidence that tufa deposition has occurred here in recent decades.**