APPENDIX H

Appendix H - Geomorphology

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Tahmoor South Project

Environmental Impact Statement

Technical Specialists Report

Geomorphology

Dr Christopher J Gippel

Final

December 2013

FLUVIAL SYSTEMS

Tahmoor South Project

Geomorphology

Prepared for:

Tahmoor Coal Tahmoor Coal

Prepared by:

Fluvial Systems Pty Ltd

PO Box 49, Stockton, NSW Australia, 2295

P: +61 2 4928 4128, F: +61 2 4928 4128; M +61 (0)404 472 114

Email: fluvialsystems@fastmail.net

ABN: 71 085 579 095

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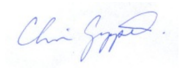
A	15-Jul-2013	Draft for Review	Chris Gippel Director Geomorphologist	
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GLOSSARY OF TERMS

Term	Definition
Acid sulfate soil	Naturally occurring soils containing pyrite (iron sulphides) which, on exposure to air, causes oxidisation and creates sulfuric acid.
Aggrade	Persistent deposition of sediment on the bed of stream channel. Opposite to Scour.
Alluvium (alluvial)	Sediment deposited distant from its source after transport by flowing water, as in a riverbed, floodplain, delta, or alluvial fan.
Catchment	The area from which a surface watercourse or a groundwater system derives its water.
Cliff	A continuous rock face, including overhangs, having a minimum length of 20 m, a minimum height of 10 m and a minimum slope of 2 to 1 (≥63.4°).
Cliff terrace	A combination of two to five minor cliffs in close proximity that result in a "stepped" surface profile, with a total minimum cliff height of 10 m and having a minimum length of 20 m.
Colluvium (colluvial)	Unconsolidated sediments deposited at the base of hillslopes through gravity or non-concentrated surface flow.
Composition (of riparian vegetation)	Represented by 3 structural classes - tree (woody and >3 m high) shrub (woody) and ground vegetation.
Cover (of riparian vegetation)	Foliar projective cover of the ground.
Culvert	A drain or covered channel that crosses under a road, railway or embankment. Usually constructed from concrete pipe or boxes.
Cumulative impacts	Combination of individual effects of the same kind due to multiple actions from various sources over time.
Discharge	A release of water from a particular source.
Dissected	A landform divided into hills and ridges.
Drainage	Natural or artificial means for the interception and removal of surface or subsurface water.
Ecology	The study of the relationship between living things and the environment.
Ecosystem	As defined in the *Environment Protection and Biodiversity Conservation Act 1999*, an ecosystem is a 'dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit.'
Environment	As defined within the *Environmental Planning & Assessment Act, 1979*, all aspects of the surroundings of humans, whether affecting any human as an individual or in his or her social groupings.
Ephemeral	Existing for a short duration of time.
EPL	Environment Protection Licence. EPLs are issued by EPA under the *Protection of the Environment Operations Act 1997*. EPLs with respect to scheduled development work or scheduled activities or non-scheduled activities may regulate all forms of pollution (including water pollution) resulting from that work or those activities. EPLs authorising or controlling an activity carried on at any premises may also regulate pollution resulting from any other activity carried on at the premises to which the licence applies.

Term	Definition
Existing Tahmoor Approved Mining Area	Shown on Figure 1. Encompasses all existing approved mining areas associated with the Tahmoor Mine, including the Surface Facilities Area.
Fault	Break in the continuity of a coal seam or rock strata.
Ferruginous colloids	Iron oxyhydroxides present in colloidal (fine particulate) form suspended in river water; an orange-red colour; water appears turbid.
Ferruginous seep	Dissolution (precipitation) of iron oxyhydroxides from iron-bearing groundwater where it emerges to the surface; also, bacteria can oxidize iron dissolved in groundwater to produce ferric oxide; an orange-red colour.
Filamentous algae	Colonies of microscopic plants growing in water that link together to form threads or mesh-like filaments; lacking roots, their growth and reproduction are dependent on the amount of nutrients in the water.
Fluvial	Of or found in a river.
Fracture	A minor break in the continuity of solid rock; could be ancient (joint), or recent (in this context, subsidence induced).
Fragility (geomorphic)	Relative ease of adjustment of bed material, channel geometry, and channel planform when subjected to degradation or certain threatening activities (Cook and Schneider, 2006) (see also Resilience).
Geology	Science of the origin, history, and structure of the earth.
Geomorphic condition (of a stream)	Relative state of stream geomorphic characteristics relative to the state that is unimpacted by human disturbance (Fryirs, 2003).
Geomorphology	The science of the structure, origin, and development of the topographical features of the earth's surface.
Gorge	A stream type, found in a rectangular or slot valley with cliffs, and located in sediment transport zones where there is very little sediment storage.
Grid (in GIS)	An array of rectangular or square cells, with a numerical attribute value for the cell stored in its centroid; often refers to elevation but can describe any attribute (see also Raster).
Groundwater	Water located within an aquifer, that is, held in the rocks and soil beneath the earth’s surface.
Gully	The deep and narrow channel form that results from incision into soil or sediment.
Habitat	The place where a species, population or ecological community lives (whether permanently, periodically or occasionally).
Headwater	A stream type found in V-shaped valleys, and located within source zones for sediment.
Hydraulic	Refers to the physical properties of flow: velocity, depth and bed shear stress.
Hydrogeology	The study of subsurface water in its geological context.
Hydrology	The study of rainfall and surface water runoff processes.
Impact	Influence or effect exerted by a project or other activity on the natural, built and community environment.
Incision	Deepening of a channel by scour (erosion) (see also Scour)

Term	Definition
Joint	A fracture in solid rock where the displacement associated with the opening of the fracture is greater than the displacement due to lateral movement in the plane of the fracture (up, down or sideways) of one side relative to the other.
Key threatening process	As defined under the *Threatened Species Conservation Act 1995*, a key threatening process is any listed process under the Act that adversely affects threatened species, populations or ecological communities, or that could cause species, populations or ecological communities that are not threatened to become threatened.
Knickpoint	A local steep fall in channel bed elevation.
Landscape character	The aggregate of built, natural and cultural aspects that make up an area and provide a sense of place. Includes all aspects of a tract of land – built, planted and natural topographical and ecological features.
Large wood	Wood fallen into streams, larger than 0.1 m diameter and more than 1 m long.
LiDAR	Light Detection and Ranging (see ACRONYMS), also known as airborne laser scanning; a remote sensing tool that is used to map ground elevation.
Long profile	A plot of elevation against distance, in this case along a stream bed.
Longwall	A system of coal mining, where the coal seam is extracted from on a broad front or long face.
Minor cliff	A continuous rock face, including overhangs, having a minimum length of 20 m, heights of 5 – 10 m and a minimum slope of 2 to 1 (≥63.4º), or; a rock face having a maximum length of 20 m, a minimum height of 10 m and a minimum slope of 2 to 1 (≥63.4º).
Panel	The mining unit that has previously been extracted or is currently being extracted.
Plateau	An elevated, comparatively level expanse of land, raised above adjoining land on at least one side.
Pollutant	Any matter that is not naturally present in the environment.
Polygon (in GIS)	A closed shape defined by a connected sequence of x,y coordinate pairs, where the first and last coordinate pair are the same and all other pairs are unique.
Pool	A deeper section of a stream that retains water.
Study Area (of Geomorphology Technical Report)	Shown on Figure 1.
Proposed development	Extension of underground coal mining and associated activities at Tahmoor Mine within the Study Area. Referred to as The Tahmoor South Project, as described in Section 4 of this EIS.
Raster (in GIS)	A spatial data model that defines space as an array of equally sized cells arranged in rows and columns, and composed of single or multiple bands (see also Grid).
Regolith	The material that is found between unweathered bedrock and the ground surface, including weathered bedrock, deposits and soil.
Resilience (geomorphic)	Low fragility, with only minor changes likely, regardless of the level of damaging impact (Brierley et al., 2011).
Riparian	Relating to the banks of a natural waterway.

Term	Definition
River Styles®	A geomorphic classification based on valley setting, level of floodplain development, bed materials and reach-scale physical features within the stream (see also Stream type)
Rock bar	A relatively narrow bar of exposed bedrock elevated above the bed level and crossing all or most of the channel.
Rock face	A rock face having a minimum length of 20 m, heights 3 – 5 m and a minimum slope of 2 to 1 (≥63.4º).
Rockfall	A relatively small landslide confined to the removal of individual and superficial rocks from a cliff face (Selby, 1982).
Rock slab	A long and wide exposure of solid bedrock on the bed for a distance at least three times the width of the channel.
Run-off	The portion of water that drains away as surface flow.
Scour	Persistent removal of sediment from the bed of a stream channel by fluvial erosion. Opposite to Aggrade.
Slope (quantified)	Also known as gradient, expressed as a ratio of integers (vertical:horizontal), the vertical gain divided by the horizontal distance (m/m), or the angle of the incline (degrees).
Soil landscape	A mapping unit that reflects soil and landscape processes.
Stockpile	Stored materials such as product coal, soil, sand, gravel and spoil/waste.
Steep slope	An area of land having a gradient between 1 in 3 (33% or 18.4º) and 2 in 1 (200% or 63.4º).
Stream	A general term that covers all morphological features, from small rivulets to large rivers, that perennially, intermittently or ephemerally convey concentrated water flow (see also Waterway).
Stream link	Lengths of stream between two nodes, where a node is the beginning of a 1st order stream, the junction of two streams, or some other locally defined boundary.
Stream order	According to the Strahler system, whereby a headwater stream is order 1, and the order increases by 1 when a stream of a given order meets one of the same order.
Stream type	A geomorphic classification based on valley setting, level of floodplain development, bed materials and reach-scale physical features within the stream, consistent with River Styles® (see also River Styles®)
Subsidence	The vertical lowering, sinking or collapse of the ground surface.
Surface Facilities Area	Comprises surface land containing mining and non-mining infrastructure.
Surface water	Water flowing or held in streams, rivers and other wetlands in the landscape.
Talus	An accumulation of rock debris at the base of a cliff, likely to have a slope between 26.6° (1 to 2) and 36.9° (4 to 3).
Terrain analysis	The automated analysis of landforms using digital elevation data sets.
Topographic Position Index (in Terrain analysis)	Relative elevation of cells in a landscape, used to classify landforms.
Tributary	A river or stream flowing into a larger river or lake.
Valley depth (in terrain analysis)	The relative elevation of a point in a valley relative to the elevation of the land above.

Term	Definition
Vector (in GIS)	A coordinate-based data model that represents geographic features as points, lines, and polygons.
Water table	The surface of saturation in an unconfined aquifer at which the pressure of the water is equal to that of the atmosphere.
Waterway	Any flowing stream of water, whether natural or artificially regulated (not necessarily permanent) (see also Stream).

ACRONYMS

Acronym	Expansion
3-D	Three Dimensional
AHD	Australian Height Datum
ASC	Australian Soil Classification
DEM	Digital Elevation Model
DGRs	Director-General's Requirements
EIS	Environmental Impact Statement
EPA	NSW Environment Protection Authority
EP&A Act	*Environmental Planning and Assessment Act 1979* (NSW)
EPL	Environment Protection Licence
GIS	Geographic Information System
GPS	Global Positioning System
LDP	Licenced Discharge Point
LiDAR	Light Detection and Ranging
ML	Mining Lease
NPA	National Parks Association
NSW	New South Wales
ODK	Open Data Kit
REA	Rejects emplacement area. Can also be called refuse emplacement area.
RMZ	Risk Management Zone
SAGA	System for Automated Geoscientific Analyses
TPI	Topographic Position Index

UNITS

Symbol	Unit
ha	Hectare
km	Kilometre
m	Metre
m^2	Metres squared
m^3	Metres cubed
mm	Millimetre
ML/d	Megalitres per day

Executive Summary

This report documented the geomorphological character of the Tahmoor South ProjectStudy Area using repeatable field and desktop methods. Risk Management Zones were identified for significant streams and major cliffs, and the risks to geomorphic stream form and process associated with changes due to subsidence were quantitatively assessed.

Characterisation of the geomorphology of the Study Area was approached at the landscape and stream reach/point scales. Streams were classified according to Strahler stream order and geomorphological type, and geomorphic features of the streams were measured in the field at the reach/point-scale.

The field data were collected by a team of 2 people in 18 days over the period 22 January to 19 February 2013. In general, the measurements were made using standard techniques from the literature. The intention was to capture morphological variability at the habitat scale. The field survey involved walking the streams and regularly following a sampling protocol. The majority of the lengths of the mainstems of the streams in the Study Area were walked in their entirety. A comprehensive set of variables was measured at sites in the field. At some sites only a sub-set of the variables was measured. Most of the observations involved recording presence/absence or measuring a quantity. For practical reasons, the survey focused on pools, knickpoints and bedrock featured that were large relative to the channel size. Some variables were quantified using a subjective visual estimation method. These variables included the relative strength of the variability in the channel shape; bed material calibre, and vegetation cover and continuity.

Terrain analysis, the automated analysis of landforms using digital elevation data sets, was undertaken using a LiDAR (Light Detection and Ranging) derived DEM (Digital Elevation Model). This analysis defined slope, valley depth, landform class, cliffs, steep slopes and potential talus slopes. Field and desktop data were used to classify streams according to geomorphic type, and geomorphic condition.

Risk Management Zones, areas where high value features are sufficiently close to proposed longwalls that they warrant careful assessment, were identified for significant streams and major cliffs.

The Study Area is located in a region characterised by generally weakly developed soils on sandstone and shale. Some of the soils are highly susceptible to erosion by concentrated water flow, but in this would be expected of weakly developed soils in steep environments. The susceptibility of the soils to water erosion is part of the natural process of delivery of sediment to streams. The streams comprise small headwater streams on relatively low gradient plateau landscapes and streams eroded into rocky gorges. The gorges are rimmed by cliffs of various lengths and heights, with densely vegetated talus slopes below the cliffs. These cliffs, and the talus slopes below them, appeared to be relatively stable.

The streams of the Study Area were of two main types – headwater and gorge. Being bedrock controlled, they are naturally resilient to geomorphic change. The majority of streams were in a stable, close to natural geomorphic condition. Some streams were impacted by factors that marginally reduced their condition. These factors included clearance of riparian trees, licenced discharges, incision, mobile knickpoints, and filamentous algae. Some streams were affected by loss of water to the subsurface over short reaches, and others were impacted by ferruginous seeps and suspended colloids. These factors do not have strong implications for geomorphic condition, but they could have relevance for ecological condition. A few isolated major culverts were judged to be in poor condition, as these were an unnatural stream type.

The proposed mining is not expected to present a significant risk to change in geomorphic character of the streams. Any changes that do occur would be expected to recover quickly because the streams are resilient and in generally good geomorphic condition (i.e. essentially natural with intact form and process). A qualitative assessment found that the overall risk of geomorphic change due to subsidence was minor. Geomorphological changes can have implications for other aspects of the environment – other relevant technical specialists should be consulted for detailed assessments of associated risks.

1.0 Introduction

1.1 Tahmoor South Project

This section provides an introduction to the Tahmoor Mine, the proposed development (the Tahmoor South Project), and the purpose and content of this report.

1.1.1 Overview

Tahmoor Coal Pty Ltd (Tahmoor Coal) Tahmoor Coal owns and operates the Tahmoor Mine, an underground coal mine approximately 80 km (kilometres) south-west of Sydney in the Southern Coalfields of NSW (Main Report Figure 1.1). Tahmoor Coal is a wholly owned entity within Glencore's coal business (Glencore Xstrata plc.) Tahmoor Coal produces up to two million tonnes per annum of product coal from its existing operations at the Tahmoor Mine, and undertakes underground mining under existing development consents, licences and the conditions of relevant mining leases.

Tahmoor Coal is seeking approval for the Tahmoor South Project (the proposed development), being the extension of underground coal mining at Tahmoor Mine, to the south and east of the existing Tahmoor Mine surface facilities area. The proposed development will continue to be accessed via the existing surface facilities at Tahmoor Mine, located between the towns of Tahmoor and Bargo.

The proposed development seeks to extend the life of underground mining at Tahmoor Mine until approximately 2040. The proposal will enable mining to be undertaken within the southern portion of Tahmoor Coal's existing lease areas and for operations and employment of the current workforce to continue for approximately a further 18 years.

The proposed development will extend mining at Tahmoor Mine within the Study Area, using longwall methods, with the continued use of ancillary infrastructure at the existing Tahmoor Mine surface facilities area. The generic Study Area is shown on Main Report Figure 1.2 and comprises an area adjacent to, and to the south of, the Existing Tahmoor Approved Mining Area. It also comprises the surface facilities area, reject emplacement area (REA), historical workings and other existing mine infrastructure.

1.1.2 Proposed development

The proposed development will use longwall mining to extract coal from the Bulli seam within the bounds of CCL 716 and CCL 747. Coal extraction of up to 4.4 million tonnes of ROM coal per annum is proposed as part of the development. Once the coal has been extracted and brought to the surface, it will be processed at Tahmoor Mine's existing Coal Handling and Preparation Plant (CHPP), and then transported via the existing rail loop, the Main Southern Railway and the Moss Vale to Unanderra Railway to Port Kembla for export to the international market.

The components of the proposed development comprise:

- Mine development including pit bottom redevelopment, vent shaft construction, pre-gas drainage and service connection;
- Longwall mining in the Central and Eastern Domains;
- Upgrades to the existing surface facilities area including:
    - upgrades to the CHPP;
    - expansion of the existing REA;
    - additional mobile plant for coal handling;
    - additions to the existing bathhouses, stores and associated access ways; and
    - upgrades to offsite service infrastructure, including electrical supply;
- Rail transport of product coal to Port Kembla;

- On-going exploration;
- Mine closure and rehabilitation; and
- Environmental management.

1.2 Proposed operations relevant to the Geomorphology Technical Report

The proposed operations include mine development, longwall mining, upgrades to surface facilities, rail transport, ongoing exploration, mine closure and rehabilitation and environmental management. This Geomorphology Technical Report is mainly concerned with the geomorphology of the natural features overlying the mine plan and proposed longwalls.

Mine development in the Tahmoor South Central Domain is proposed to start between 2016 and 2018 using continuous miners to establish roadways in preparation for longwall mining. Pre-gas drainage will also be undertaken in preparation of longwall development, and that will commence between 2021 and 2023.

Longwall mining is proposed to commence in the Eastern Domain once mining is completed in the Central Domain, in approximately 2034, depending upon geological and mining conditions, with mining competed by approximately 2040, with surface works, rehabilitation and mine closure occurring after this time. Coal will be cut from the coal face by the longwall shearer and loaded onto the armoured face conveyor (AFC) and transported to the surface facilities area via an underground conveyor. The longwall will retreat as coal is mined and the overlying rock strata (or goaf) will collapse into the void left by the coal extraction.

1.3 Purpose of the report

This report characterised the physical environment and identified Risk Management Zones from a geomorphologic perspective. Detailed risk and impact assessment of geomorphologic-related aspects of the environment was incorporated within the assessments by other relevant technical specialists, i.e. Niche for ecology, Gilbert & Associates for surface water, HydroSimulations for groundwater/hydrogeology, Niche for heritage, and MSEC for subsidence, stream slope and cliffs (see other technical specialists reports for details).

1.3.1 Director General's Requirements

The Tahmoor South Project Environmental Impact Statement has been prepared in accordance with Division 4.1, Part 4 of the *Environmental Planning and Assessment Act 1979* (EP&A Act) which ensures that the potential environmental effects of a proposal are properly assessed and considered in the decision-making process.

In preparing this Geomorphology Technical Report, the Director General's Requirements (DGRs) issued for the Tahmoor South Project (SSD 5583) on 6 November 2012 have been addressed as required by Clause 75F of the EP&A Act. The key matters raised by the Director General for consideration in the Geomorphology Technical Report and where this report addresses the DGRs is outlined in Table 1.

1.3.2 Geomorphology Technical Report objectives

The scope of work for the Geomorphology Technical Report included, but was not limited to:

- Existing background data collection to provide a baseline of pre-mining geomorphic condition
- Field data collection within the Study Area, including, but not limited to:
    - fluvial features, including, but not limited to, incision, knickpoints, pools, bedrock features, hydraulic controls, riffles, bed material), dimensions and profiles, riparian zones, iron staining, alluvium and cliffs.
- Mapping of relevant remotely sensed, field-collected, and derived geomorphic-related attributes, including, but not limited to:
    - Stream Order and River Styles® classification or equivalent methodology;
    - fluvial features.
- Technical assessment of geomorphic-related factors, including, but not limited to:
    - existing geomorphic conditions and processes;

  - identification of Significant Areas potentially impacted by mining;
  - identification of Risk Management Zones for input into mine planning.
- Recommendations for mitigation and monitoring

Table 1 Director General's Requirements applicable to the Geomorphology Technical Report.

Director Generals Requirement		Section Addressed
A detailed quantitative and qualitative assessment of the potential impacts of the development on geomorphological processes and forms that includes:	A description of the existing environment, using sufficient baseline data.	**Section 3** Existing environment
	Accurate predictions of the potential…impacts of the development, including a robust sensitivity analysis of these predictions.	**Section 4** Impact assessment
	Risk assessment of the potential environmental impacts of the development, identifying the key issues for further assessment. An assessment of the potential impacts of all stages of the development, including any cumulative impacts, taking into consideration any relevant guidelines, policies, plans and statutes. A detailed assessment of the potential impacts on landforms and topography, including cliffs, rock formations and steep slopes, particularly along Dog Trap Creek. Detailed assessment of potential impacts on the quality and quantity of existing surface and groundwater resources, including…impacts on geomorphological values of watercourses…with particular reference to Bargo River, Picton Weir, Dog Trap Creek, Cow Creek, Nepean River, Eliza Creek, and Mermaid Pools [Author's note: named on the 1:25,000 topographic mapsheet as Mermaids Pool].	**Section 4** Impact assessment
	A description of the measures that would be implemented to avoid, minimise and if necessary, offset the potential impacts of the development, including proposals for adaptive management and/or contingency plans to manage any significant risks to the environment.	**Section 5** Safeguards and management

1.4 Report structure

This report is structured as follows:

Section 1	Introduction – outlines the Project and presents the purpose of the report.
Section 2	Methodology – describes the methodology employed for the Geomorphology Technical Report.
Section 3	Existing environment – describes the character of the existing geomorphologic environment.
Section 4	Impact assessment – describes the potential impacts to geomorphologic character of the environment resulting from the proposed Project.
Section 5	Safeguards and management - provides a summary of environmental mitigation, management and monitoring responsibilities in relation to management of geomorphologic aspects of the environment for the Project.
Section 6	Conclusion.

2.0 Methodology

2.1 Measurement scales

Characterisation of the geomorphology of the Study Area was approached at two measurement scales:

1. Landscape, which covers geomorphological or geomorphologically-relevant characteristics such as landform terrain attributes and soil attributes at the regional and catchment scale.
2. Stream reach- and point-scale, which covers physical attributes of streams at the cross-section- and reach-scale (1 to 1,000 metres), plus the scale of stream type which varies from 10s to 1,000s of metres long.

An approach, based on standard methods, was devised to classify streams of the Study Area according to geomorphic type, and to measure the geomorphic features of the streams at the cross-section and reach-scale. This report provides sufficient technical information such that the methodology could be repeated in the Study Area at a later time by a third party. Also, the primary and secondary data from the work were provided in sufficient detail to allow a comparison of future geomorphological character with benchmark (current) geomorphological character.

Characterisation of the fluvial geomophological features of the Study Area was based on a combination of field survey and desktop analysis of existing data, including LiDAR flown during February 2013 and supplied by Tahmoor Coal. The field survey was undertaken by Dr Christopher Gippel of Fluvial Systems Pty Ltd over the period 22nd January to 19th February 2013.

2.2 Legislation, policy, criteria and/or guidelines

The guideline that directly relates to the Geomorphology Technical Report is:

- A Rehabilitation Manual for Australian Streams (Rutherfurd et al., 2000)

There is no legislation or policy that specifically refers to geomorphology in this context, and the above guideline is relevant only to planning and implementing monitoring and mitigation activities. Geomorphic processes and forms are connected to aquatic ecological character and processes through provision of physical habitat and influence on water quality. Thus, biodiversity and water resources legislation, policy and/or guidelines are indirectly relevant to this Geomorphology Technical Report. Of most relevance is the list of threatening processes listed on Schedule 3 of the *Threatened Species Conservation Act 1995*. This list includes “Alteration of habitat following subsidence due to longwall mining”. In this context, the emphasis is on aquatic and riparian habitat, and includes physical structure, hydrology, water quality and riparian character. So, this assessment focused on characterising physical aspects of the environment that were known to contribute to aquatic and riparian habitat value.

2.3 StudyStudy Area

The Study Area boundary considered for this Geomorphology Technical Report forms a 600 m (metre) buffer around the proposed maximum extent of longwall panels (the longwall panel layout could be refined during the planning process, but within this maximum extent), and including the majority of CCL747 (Main Report Fig 1.1). The Study Area was 7,206.8 ha (hectares) in area. This Study Area relates to potential subsidence impacts, which is the main factor relevant to the Geomorphology Technical Report. In deep valleys and gorges in the Southern Coalfield, closure and upsidence movements have been detected more than 500 m from the edges of longwalls (Kay et al., 2006), which is the main reason why the buffer distance of 600 m was a recommendation of the Southern Coalfields Inquiry .

In this report, some maps show data extending outside the Study Area. In such cases, the information located outside the Study Area was included to show the continuity of the attribute, and/or to illustrate the regional context of the attribute. Some field data were collected from areas just outside the Study Area boundary, and, although such data might be plotted on maps in this report, only data from within the Study Area was used in statistical data summaries, and to identify Geomorphologic Risk Management Zones (unless otherwise stated).

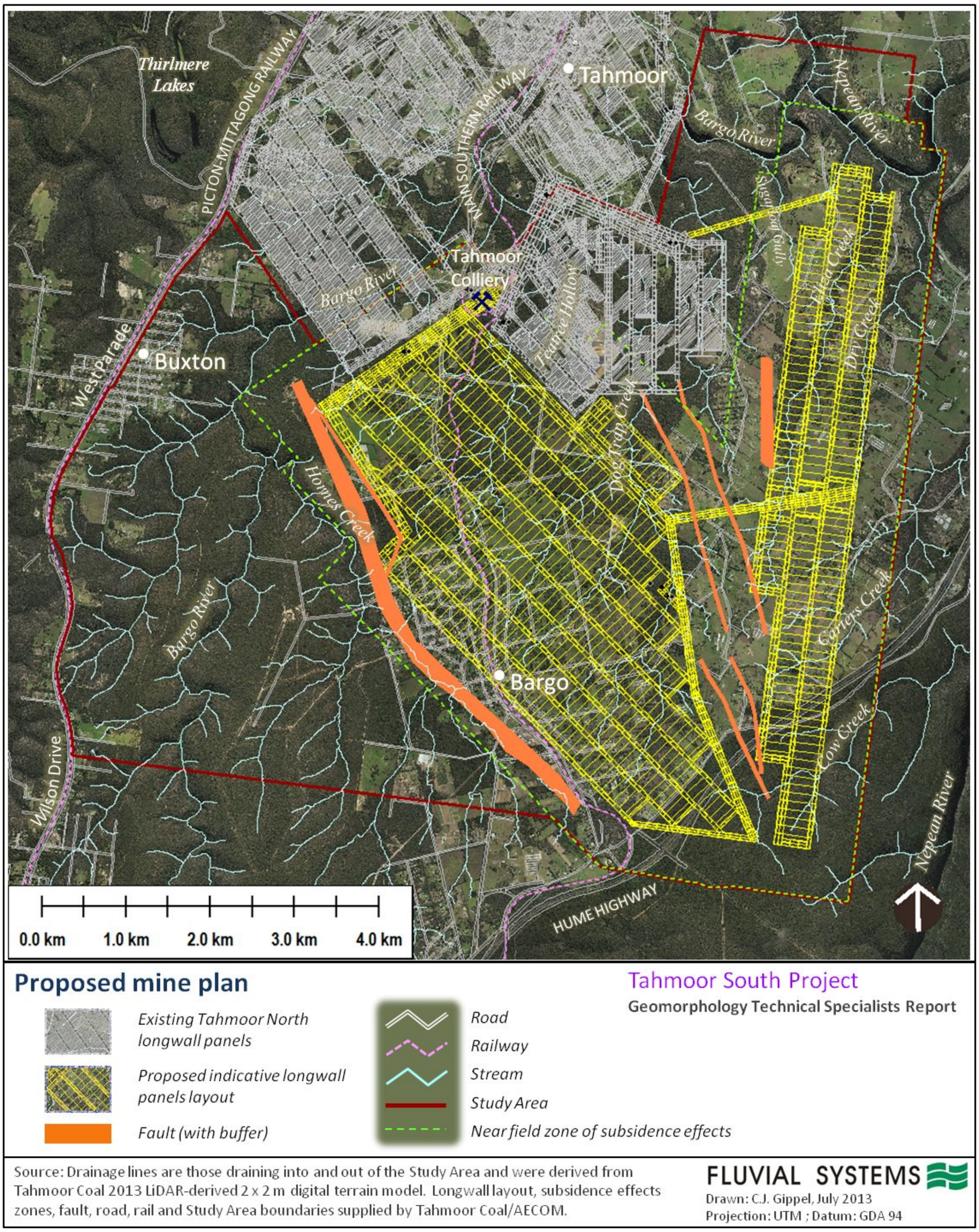

Figure 1. Proposed mine plan and existing workings, also showing Study Area considered for the Geomorphology Technical Specialists Report.

2.4 Geomorphologically-relevant variables

The Geomorphology Technical Report was not concerned with subsidence directly, but with the potential impacts and consequences of subsidence for the geomorphological character of the environment. Two main groups of variables were of interest to geomorphological characterisation of the Study Area:

- Landscape-scale variables
- Stream reach- and point-scale variables

2.4.1 Landscape-scale variables

Landscape-scale variables provide information to help explain catchment-scale geomorphological processes, and risks associated with subsidence impact; they also provide contextual information to help explain local-scale physical processes and forms. Information was compiled at the landscape-scale regarding:

- Geology
- Soils
- Topography

2.4.2 Stream reach- and point-scale variables

Stream-reach and point-scale variables were used to characterise geomorphological processes and forms that could be at risk of direct subsidence impacts. The variables were selected mainly on the basis of their relevance to well documented potential impacts of mining on streams and their valleys (Holla and Barclay, 2000; Blodgett and Kuipers, 2002; Kay et al., 2006; Parsons Brinkerhoff, 2007; NSW Department of Planning, 2008; Hebblewhite, 2009), which can be summarised as:

- Fracturing in the riverbed and rock bars
- Surface water flow diversion from the surface to the shallow sub-strata
- Increased ponding, flooding or desiccation
- Increased stream bed and bank erosion
- Changes to stream alignment
- Changes to water quality
- Impacts on terrestrial and aquatic flora and fauna
- damage to vertical or near-vertical cliff faces and overhangs, resulting in collapse and potential landslides

The sensitivity of stream geomorphic character to physical disturbance, such as mining-related subsidence, can be described in terms of stream channel fragility/resilience. Fragility is the ease of adjustment of bed material, channel geometry, and channel planform when subjected to degradation or certain threatening activities, and resilience is the property of having low fragility (Cook and Schneider, 2006; Brierley et al., 2011). Different stream types have characteristic levels of fragility. In NSW, the commonly used standard for classifying stream geomorphic type is River Styles® classification, which is based on valley setting, level of floodplain development, bed materials and reach-scale physical features within the stream (Brierley et al., 2011). The potential for physical recovery after disturbance depends on stream geomorphic condition, whereby streams in good condition (undisturbed and close to natural state) are more likely to be resilient and recover faster than those that are already degraded (Outhet and Cook, 2004; Brierley et al., 2011). The geomorphic type, condition and recovery potential of river reaches in the Hawkesbury Nepean system were assessed by New South Wales Department of Land & Water Conservation (2001). This study was done at a relatively small-scale that included the Bargo and Nepean River mainstems but not the tributaries under consideration in the Study Area (Figure 2). The Bargo and Nepean river reaches within the Study Area were mapped as having greater than 50% tree cover in the riparian zone, good river condition, and moderate (Nepean River) and high (Bargo River) geomorphic recovery potential (New South Wales Department of Land & Water Conservation, 2001; Hawkesbury Nepean Catchment Management Authority, 2007). The Geomorphology Technical Report classified the streams in the Study Area according to river type and geomorphic condition, using an approach that was consistent with the standard methods used in NSW (New South Wales). This required collection of data concerning valley setting, stream slope, channel dimensions and shape, and bed material type.

The NSW River Condition Index (RCI) is a framework for assessing river health in New South Wales (Healey et al., 2012). Two of the four indices used in the RCI were geomorphic condition and riparian vegetation cover condition. These are related, as geomorphic condition is strongly linked to the degree of naturalness and extent of cover of riparian vegetation (Outhet and Cook, 2004; Outhet and Young, 2004). These considerations justify inclusion in a geomorphologic assessment, variables that characterise riparian and in-channel vegetation and related large woody debris, both of which contribute to the structural stability of streams (Abernethy and Rutherfurd, 2000; Gippel, 1995; Gippel et al., 1996). The influence of vegetation on stream processes declines rapidly with distance from the channel edge. The Geomorphology Technical Report defined the riparian zone as a distance of up to 50 m from the channel edge, which is consistent with that used by Munné et al. (2003) and Raven et al. (1998), and is practical for a rapid assessment approach.

The beds of ephemeral headwater streams are often vegetated with grasses[1] that resist erosion by increasing the inherent shear strength of soils and sediments (Hudson 1971; Tengbeh, 1983; Reid 1989; Prosser and Slade, 1994; Zierholz et al., 2001; Rai and Shrivastva, 2012). Blackham (2006) demonstrated that hydraulic conditions (absolute shear stress and duration of shear stress) in small- to medium-sized streams are rarely sufficient to scour well-grassed surfaces. In larger streams, rooted (especially emergent) macrophytes commonly act as a hydraulic/geomorphic agent in stream channels through their resistance to erosion, ability to trap sediment, and roughness effect (Guscio, 1965; Shih and Rahi, 1982; Groeneveld and French, 1995; Riis and Biggs, 2003; Horvath, 2004; O'Hare et al., 2011). Macrophyte growth is a function of numerous factors, but water flow is known to be a prime factor (Franklin et al., 2008). The effects of flow on macrophytes are usually considered in terms of the hydrological regime (frequency of disturbance and duration of stable flow conditions) and velocity (which is associated with mechanical damage and uprooting). Long periods of stable baseflow may encourage invasion by macrophytes. Periods of low flow can also keep macrophytes in check (Franklin et al., 2008). Both the abundance and diversity of macrophytes are stimulated at low to medium velocities, with growth being restricted at higher velocities (Madsen et al., 2001). Chambers et al. (1991) reported few if any macrophytes were found in waters with velocities exceeding 1 m/s, and Greening Australia (2007) noted that Typha spp. was not found in water deeper than 2 m. Cover of in-channel vegetation was included in the Geomorphology Technical Report because of its important role in channel stability and its sensitivity to hydrological conditions, which could potentially be impacted by mining.

Low turbidity water, open riparian canopy, and stable substrates can promote excessive growth of filamentous green algae on the stream bed when these conditions occur in conjunction with an enriched supply of nutrients (Welch et al., 1988). Measurement of filamentous algae cover is included in the AusRivAS[2] physical assessment protocol for the reason that "*Excess filamentous algae growth may be indicative of nutrient enrichment*" (Parsons et al., 2002). Cover of filamentous algae was grouped with the in-channel vegetation cover category in the Geomorphology Technical Report because when present at high levels it can alter the hydraulic properties (i.e. distribution of velocity and depth) and surface properties of the bed.

The change in physical form of streams over time (morphological dynamism) can manifest in a number of ways. Alluvial streams naturally migrate laterally across their floodplain without necessarily changing in cross-sectional shape, but streams confined within bedrock valleys, like those within the Study Area, maintain a relatively stable position over the management time scale (here defined as < 100 years). In cross-section, streams can widen, narrow, deepen (scour), or shallow (aggrade). Such changes occur naturally, but could be of concern if human-related disturbance causes the rate of change, or the extent of change, to exceed the natural ranges. Mining-related subsidence is more likely to impact stream bed elevation than stream bank lateral position, with creation of, or accelerated headward migration of, knickpoints being a potential threat to channel stability. Knickpoints are a local steep fall in channel bed elevation and are a common, natural feature of streams. Stable (or fixed) knickpoints occur on river profiles due to a local control, such as a resistant lithological unit, fault, or large coarse sediment supply; unstable (or mobile) knickpoints are initiated by a downstream event that lowers the hydraulic control, with erosion propagated upstream as a headcut (Brush and Wolman, 1960; Gardner, 1983; Wolman, 1987; Bishop et al., 2005; Crosby and Whipple, 2006). It is not possible to determine geomorphic process rate in a single field survey, so for the Geomorphology Technical Report knickpoints were classified as either 'hard' (i.e. likely to be fixed) or 'soft' (i.e. likely to be mobile), on the basis that hard knickpoints were set in bedrock and/or boulders, and soft knickpoints were set in erodible bed material composed of a mix of cobble, gravel, sand, silt or clay. Under disturbance from mining-induced subsidence, or a significant increase in stream flow, existing hard

[1] Meaning true grasses, of the family Poaceae (also called Gramineae).
[2] The standard approach used in Australia for biological assessment of stream condition using macroinvertebrates.

knickpoints were assumed to be resilient to change, while existing soft knickpoints were assumed to be fragile, and there was a risk of formation of new soft knickpoints.

Streams of the Southern Coalfield area that flow through sandstone/shale geology typically have a significant proportion of their beds formed in exposed bedrock. The bedrock manifests as flat to gently sloping slabs of rock exposed along a bedding plane, and elevated bars of rock crossing the channel. Exposed rock is often associated with pools, either by forming a low permeability bed surface, or by acting as the hydraulic control that backs up water in the pool. In the Study Area, the Hawkesbury Sandstone is typically present as massive beds with widely spaced and roughly orthogonal (i.e. sub-vertical to vertical) joint sets. The spacings between major parallel joints were reported by Herbert (1983) as 3 – 10 m, while the review of Pells (1993) indicated that the Hawkesbury Sandstone in Southern Catchment Area of Sydney had joint spacing of 3 – 4 to 30 – 40 m with an average of 7 – 15 m. Thus, it would be expected to find natural fractures in the bedrock of the stream beds. These fractures are mostly very old in geological terms, and relate to previous episodes of deformation and relief of stress. Underground mining can cause compressive horizontal strain in the vicinity of streams, particularly those within deep valleys. This can manifest as a rise in the level of the base of the valley, which in the mining context is usually referred to as upsidence (Waddington and Kay, 2003; Kay et al, 2006). Similar movements can occur naturally, but it is generally understood that the process is accelerated by mining (Kay et al., 2006). Fracturing of rock in river beds and subsequent surface water flow diversion are well recognised impacts associated with mining beneath rivers (Kay et al., 2006; Total Environment Centre, 2007; NSW Department of Planning, 2008). The fractures in stream beds associated with mining have a different appearance to the geologically-old fractures (joints) in the rock. Photographs of this phenomenon in NSW Department of Planning (2008) and Total Environment Centre (2013) illustrate open fractures with fresh, sharp edges, whereas the ancient fractures associated with joints would generally be expected to appear tight, with edges weathered to the same extent as the rock itself. Geoterra (2007) and Geoterra (2011) observed cracks in the bed of Myrtle Creek up to 10 mm wide that were associated with Tahmoor Mine longwall mining. The Tahmoor South Project Geomorphology Technical Report included observations of the type of rock feature present in stream beds (i.e. massive slab, or bar), the density of fractures present on bedrock features, and noted any instances of loss of flow to the sub-surface.

The description of broad habitat zones of a stream by NSW Department of Primary Industries (2013) included pools, gravel beds (or "riffles"), snags, wetlands and riparian (riverbank) vegetation, as well as microhabitats within these zones. Pools and riffles are the two habitat elements of streams that have received the most attention from a geomorphological and ecological perspective (Frissell et al., 1986; Maddock, 1999). Pools are commonly a focus of habitat assessments because of their ecological importance, especially as a refuge when streams stop flowing (Bond et al, 2008). Riffles act as hydraulic controls on pools in alluvial streams, but they would not be expected to be common in streams in the Study Area, which are bedrock controlled. In the Study Area, pools would likely be found in association with large wood, coarse deposits of sediment and in particular, rock bars. As rock bars are potentially at risk of mining-induced fracturing, so too are the pools that the rock bars impound. Thus, the Geomorphology Technical Report included observations of pool presence, dimensions, and the type of hydraulic control.

Based on the above considerations, the DGRs and the scope of works, reach- and point-scale variable groups considered relevant to the Geomorphology Technical Report were:

- Stream geomorphic type and condition
- Riparian and in-channel vegetation (including filamentous algae)
- In-channel bedrock features
- In-channel pools
- Channel slope
- Channel dimensions
- Channel bed materials
- Knickpoints
- Characteristics of fractures in channel bedrock

2.4.3 Sites of geomorphological significance

Geomorphological character is, for the most part, value-free in that a stream cannot be ranked in terms of importance based on their geomorphologic character alone. The main relevance of geomorphological character is the implications it has for the ecological character of the environment. The exception is geomorphological sites that either represent a specific characteristic of a region, or include an outstanding, rare, or possibly unique geomorphological feature. There is no standard method for classification, or a compiled list, of geomorphologically significant sites in NSW. However, the Study Area contains two geomorphological features that, at least locally, are considered by some to have inherent significance, mainly with regard to their scenic and recreational value. These two features are:

- The Bargo Gorge (the lower 4.3 km (kilometre) of The Bargo River before its confluence with the Nepean River)
- Mermaids Pool (at the upstream end of the Bargo River Gorge)

A case for the significance of the geomorphological values of the Bargo River Gorge area was presented by NPA Macarthur (2006). The scope of the Geomorphology Technical Report did not specifically include evaluation of the inherent geomorphological significance of sites within the Study Area. However, such values were implicitly considered in the assessment, because risks that were included, such as cracking of rock bars, and rockfall, would potentially impact the scenic and recreational values of these sites.

2.5 Field survey

2.5.1 Sampling approach

The objective of the field survey was to obtain sufficient information to enable characterisation of stream type, and stream geomorphic features. Stream type classification relies partly on attributes that can only be measured in the field, and partly on attributes that can be measured from maps and terrain data. In the Study Area, the dense vegetation cover, deep gorges, and the relatively small size of the geomorphic features, meant that for most streams, their attributes could not be measured from aerial photographs or other remotely sensed imagery. This limitation necessitated a field sampling program.

The field survey involved walking the streams and regularly following a sampling protocol. The majority of the lengths of the mainstems of the streams in the Study Area were walked in their entirety (Figure 2). Situations where a stream length was not walked included:

- Access was unavailable through private property.
- A small stream that, based on aerial photography and terrain data, was similar to one or more nearby streams that were walked (the data from which enabled characterisation of similar streams).
- A large river (parts of Bargo River and the Nepean River) that was too deep to safely navigate and cross on foot, and which could be adequately characterised using aerial photography and DEM terrain data.

The approach to field survey was to walk along the streamline until a noteworthy feature was encountered. In most instances this constituted a knickpoint, a pool, a bedrock feature or a change in stream form or bed material. In the absence of noteworthy features, a standard comprehensive set of observations was made at regular intervals (at randomly located points on the streams) about 20 to 100 metres apart (depending on stream size and heterogeneity).

The field data were collected by a team of 2 people in 18 days over the period 22 January to 19 February 2013. All of the measurements and estimates were made by C.J. Gippel with the assistant recording data. Data were recorded on a GPS-equipped tablet computer using a specially designed form compiled in ODK (Open Data Kit; http://opendatakit.org/). At each observation point, two photographs were taken with the tablet device, one looking downstream and one looking upstream. Each photograph was linked to the data from the site within the ODK form. This approach resulted in observations being made at 732 sites (Figure 2). The majority of observations were made at a frequency of one set of observations every 5 to 10 minutes (including walking time).

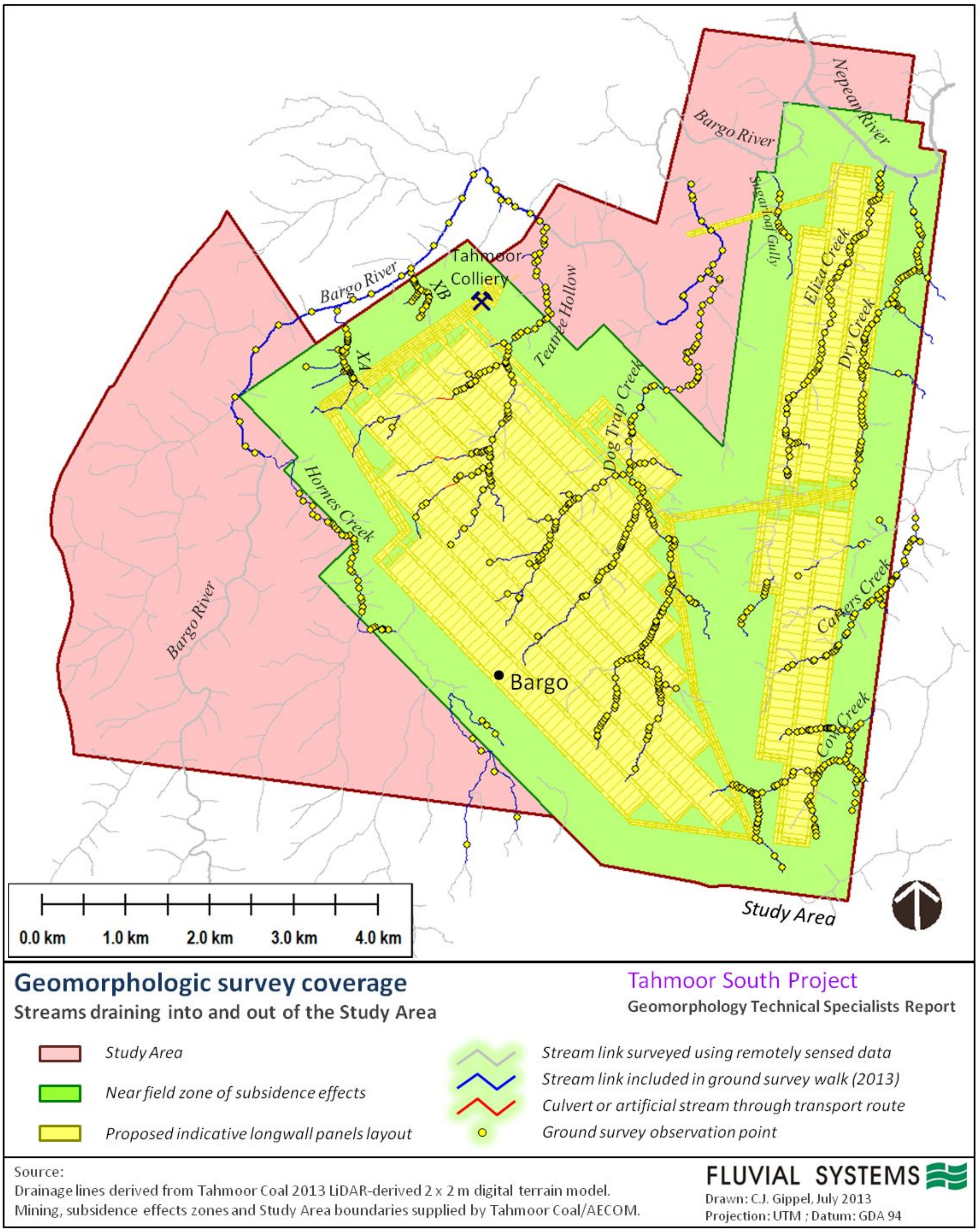

Figure 2. Coverage of the geomorphologic survey conducted over the period 22 January to 19 February 2013. Data were recorded at a total of 732 observation points. Most observation sites were located within the near field zone of potential subsidence effects.

2.5.2 Weather conditions during field survey

The field survey was undertaken during a relatively wet period, but rainfall was minimal on survey days, except late on 22 January when an intense thunderstorm occurred (Figure 3). A period of unusually heavy rainfall occurred on 27 – 29 January. At Buxton weather station (68166), the 133 mm rainfall that fell on 29 January was the highest January daily rainfall recorded since the station opened in 1967. This was a regional event, and other nearby weather stations also observed a record January daily rainfall on this day [Douglas Park (St. Marys Towers): 68200; Cawdor (Woodburn): 68122; Oakdale (Cooyong Park): 68125; Menangle Bridge (Nepean River): 68216; Menangle Bridge (Nepean River): 68216]. January and February rainfall totals were well above average across the region.

The heavy rainfall experienced early in the fieldwork period meant that for most sites, in-channel pools were full at the time of survey, which helped to facilitate their identification and measurement.

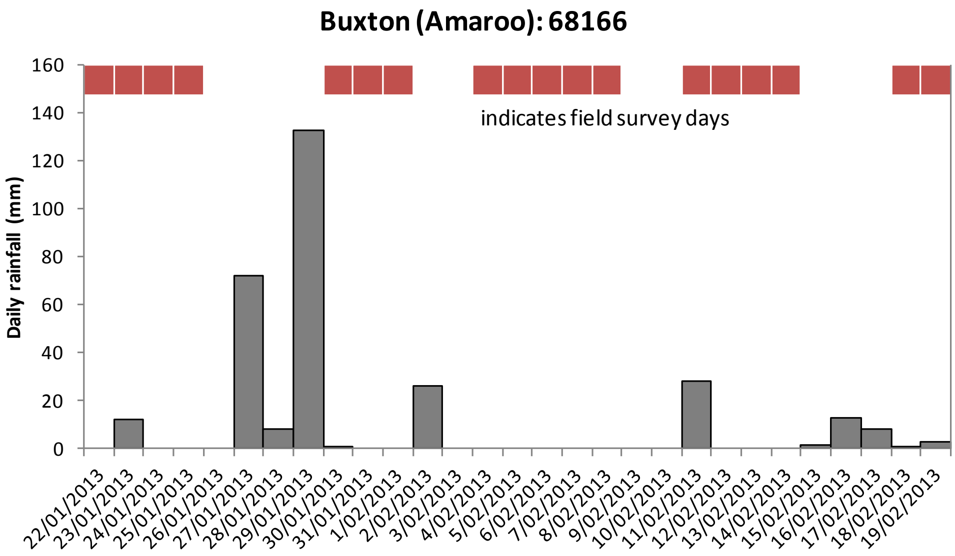

Figure 3. Rainfall at Buxton weather station, 4 km west of Tahmoor Mine, over the period when the field survey was conducted. Daily rainfall observations nominally made at 9 AM and record the total for the previous 24 hours. Source: Bureau of Meteorology (http://www.bom.gov.au).

2.5.3 Field sampled variables

A comprehensive set of variables was measured at sites in the field (Table 2). At some sites only a sub-set of the variables was measured. In general, the measurements were done using standard techniques from the literature. Most of the observations involved recording presence/absence or measuring a quantity.

The survey focused on pools, knickpoints and bedrock featured that were large relative to the channel size. The intention was to capture morphological variability at the habitat scale. There is no standard threshold for the minimum size of useful habitat, so project-specific thresholds were set.

Significant pools were at least 0.2 metres deep and longer than 4 times the average channel width in the area. This minimum size was intended to make the field survey feasible and does not relate to a minimum size required to support a particular ecological community or perform some other physical, chemical or ecological function. The streams of the Study Area contained thousands of pools smaller than those that were recorded here, but it was not feasible to include them in the survey. Pool dimensions were relative to the level of the hydraulic control (i.e. as if the pool was full of water). The depth of a pool when it is just filled to the level of the hydraulic control is known as the residual pool depth (Lisle, 1987).

Significant knickpoints were deemed to be higher than 0.2 m. This threshold was generally applicable to small streams of low and moderate gradient. In moderate- and large-sized, steep streams, especially those with boulder and bedrock beds, the amplitude of local roughness elements usually exceeded 0.2 m, so a higher threshold for identifying significant knickpoints was used. In this situation (common in the Study Area), significant knickpoints were defined as having a height at least double that of the average amplitude of local roughness elements. For practical reasons it was necessary to judge this visually. The type of knickpoint was judged as hard or soft, depending on the material forming the face of the knickpoint. Hard knickpoints were relatively fixed in position, being composed of solid rock, large broken rock, or boulders. Soft knickpoints were formed in erodible material, such as gravel, sand, silt and clay.

Significant bedrock features were identified as either rock bars, defined as a relatively narrow bar of exposed bedrock elevated above the bed level and crossing all or most of the channel, or rock slab, defined as a long and wide exposure of solid bedrock on the bed for a distance at least three times the width of the channel. A natural limitation on recording bedrock slabs was that they had to be visible, so in deep and/or turbid water, some slabs might have been missed. The presence of less significant bedrock features was also noted when recording bed material size. Fractures in bed material were identified and counted along a transect extending for the maximum practical length of exposed rock.

Some variables were quantified using a subjective visual estimation method. These variables included the relative strength of the variability in the channel shape; bed material calibre (visual estimation was regularly calibrated against measurement), and vegetation cover and continuity. While error can be expected in such estimates, it was minimised by using the same experienced observer for every estimate and conducting the fieldwork over one unbroken period of time.

Vegetation cover and continuity were estimated using the Braun-Blanquet rank scale, which provides a rapid, robust and repeatable estimate of cover abundance (Wikum and Shanholtzer, 1978). Cover refers to foliar projective cover of the ground. The Braun-Blanquet scale was the same as the original, except that the lowest class was sub-divided to provide a class (<1% cover) to describe the situation where cover was essentially absent, as used by Causton (1988):

- <1% score = 0
- 1 – 5% score = 1
- 6 – 25% score = 2
- 26 – 50% score = 3
- 51 – 75% score = 4
- >75% score = 5

2.5.4 Derived field variables

Three variables were derived from the raw field-collected data:

- Bedrock fracture density
- Pool volume
- Riparian vegetation cover index

Bedrock fracture density (F) was calculated as the count of fractures (N) divided by the length of rock over which they were counted (L_R), multiplied by 10 to convert the value to frequency per 10 m:

$$F = 10\left(\frac{N}{L_R}\right)$$

Pools were measured for their length (L_P), maximum width (W_P) and maximum depth (D_P) (as if the pool was full of water to the level of the hydraulic control). It was observed that most pools had a trapezoidal shape in cross-section and profile. The width and depth measurements were both factored by 0.7 to achieve an estimate of pool volume (V_P), reported in the unit of m^3:

$$V_P = 0.7W_P \cdot 0.7D_P \cdot L_P$$

Table 2 Field measured geomorphologically-relevant variables.

Variable	Description of variable measurement
Flow conditions	Dry or flowing at the time of survey
Channel setting	Longitudinal continuity, number of channels, and degree of valley confinement
Valley shape	Perceived relative relief, shape of valley walls, presence of cliffs (gorge or not gorge)
Chanel shape variability	Strength of variability in form in cross-section and profile, and regularity of form in the downstream bed profile (3 classes each)
Bed material calibre	Presence of, and dominant, material for 7 classes (adapted from Brakensiek et al., 1979): • Mud (silt and clay) • Sand (0.06 - 2 mm) • Gravel (2 - 64 mm) • Cobble (64 - 256 mm) • Boulder (exceed 256 mm) • Exposed bedrock slab • Artificial (hard lined)
Large wood and log jams	Count of items over 20 m length of channel; large wood is ≥0.1 m diameter and ≥1 m long (Gippel, 1995); log jam is 3 or more locked pieces of large wood
Pool dimensions	Length, maximum width and maximum depth (as if full to the level of the hydraulic control), measured using a laser rangefinder (±0.1 m accuracy)
Pool hydraulic control	Type for 5 classes - rock bar, boulders, cobble/gravel/sand, cohesive material, or artificial
Exposed bedrock feature	Type for 3 classes - rock bar in the bed (elevated and crossing all or most of the channel), rock slab in bed (exposed bedrock on the bed for at least 3 x the channel width), or other (presence noted in bed material calibre)
Count of fractures visible in bedrock	Count of fractures along a transect of variable length (depending on the observable length of exposed rock), with length measured using a rangefinder or tape
Channel dimensions	Bed width, bankfull width, bankfull depth, measured using a rangefinder or tape
Knickpoint type and dimensions	Material type for 2 classes - hard rock, or soft, erodible material - and height from top edge to elevation of downstream hydraulic control, measured using a retractable tape
Ferruginous material	Presence/absence of seeps on rock, or colloidal material suspended in stream water
In-channel vegetation	Type for 6 classes - 4 macrophyte types, grass and filamentous algae - and cover (6 Braun-Blanquet classes)
Width of riparian vegetation	Left and right, up to a maximum of 50 m, measured using rangefinder
Continuity of riparian vegetation	Left and right, downstream continuity along the riparian zone (6 Braun-Blanquet classes)
Composition and cover of riparian vegetation	Left and right, type for 3 classes - tree (woody and >3 m high) shrub (woody) and ground vegetation – and cover within 5 x 5 m plots (6 Braun-Blanquet classes)
Other observations	Any feature not otherwise covered and considered potentially relevant to geomorphologic characterisation or geomorphologic condition

At each sampling site, the cover abundances of riparian trees, T, shrubs, S, and ground cover, G, were rapidly estimated at plots approximately 5 x 5 m in size, with cover scored as an integer from 0 to 5. Vegetation cover of the left and right sides of the channel were measured separately. A cover index was devised to rate both the degree of coverage of the ground by plants, and the vegetation structure. A high degree of cover was rated higher than a low degree of cover, and trees were rated more valuable than shrubs, and shrubs rated more valuable than ground cover. The coverage rating was based on the higher geomorphic stability, habitat availability, and energy and nutrients provided by greater plant abundance. The plant structure rating was based on the different capacity of trees, shrubs and ground cover to provide these same services, as well as the additional ability of trees to provide shade. For each plot, the raw cover abundance scores for trees, shrubs and ground cover were factored and summed, and then converted to a riparian cover abundance (C) score between 0 and 1 by dividing the total by 24.

$$C = \frac{3T + 2S + G}{24}$$

An index score of at least 1.0 would be achieved if tree, shrub and ground cover were all in the 50 – 75% or >75% cover classes. A very well vegetated site might achieve a combined factored score exceeding 1.0, in which case the score would be rounded down to 1.0.

2.5.5 Descriptive statistics

The field-collected data were described using descriptive statistics, including, mean, standard deviation, median, sum and count of data, and sum of a subset of data, or count of a subset of data, as a percentage of the total. The percent of a reach comprised of pool habitat was estimated by summing the lengths of each pool and dividing by the reach length – a statistic suggested by Roper et al. (2002).

2.6 Terrain analysis

Geomorphology is concerned with both physical form and process. Process involves the dimension of time, so tends to be more difficult to measure and model than form. For this reason, geomorphologic assessments often interpret process on the basis of an analysis of physical form. Terrain analysis is concerned with the automated analysis of landforms using digital elevation data sets. The analysis involves application of algorithms within a GIS (Geographic Information System) at detailed scales over wide areas to map characteristics of interest (e.g. Gardner and Sawowsky, 1990; Wilson and Gallant, 1998; Wilson and Gallant, 2000; Lindsay, 2005; Drăguţ and Blaschke, 2006; MacMillan and Shary, 2009). Using an example from the Southern Coalfield, Palamara et al. (2006) illustrated application of terrain analysis to underground coal mine impact assessment. Similar methods were used in the Tahmoor South Project Geomorphology Technical Report.

Terrain analysis was undertaken using two different GIS applications: Global Mapper™ V14.2.2 July 2013 Build (Blue Marble Geographics), and SAGA (System for Automated Geoscientific Analyses) GIS (http://www.saga-gis.org; Institute of Geography, Section for Physical Geography, Klimacampus and University of Hamburg, Germany) (Cimmery, 2007-2010; Böhner et al., 2006; Böhner et al., 2008).

2.6.1 Topography (digital elevation) definition

The topography of the Study Area was defined by a 2013 LiDAR (Light Detection and Ranging) derived DEM (Digital Elevation Model) supplied by Tahmoor Coal. This data was supplied as a 2 x 2 m (metre) grid DEM. This was compiled from LiDAR data surveyed in two flights, one conducted in 2012 and one in 2013. There was no evidence of a seam at the boundary of the two surveys. This grid was used for all terrain analysis, except for cliff definition.

For cliff definition, a 1.5 x 1.5 m grid was required, so a new DEM was generated from the original groundstrike data. The cliff definition process also required a 2.5 x 2.5 m and a 5 x 5 m grid DEM, and these were generated from the 1.5 x 1.5 m grid DEM.

2.6.2 Definition and naming of the stream network

The stream network was defined ostensibly as those streams marked with a blue line on the 1:25,000 Topographic Map Series, covered by Bargo 9029-3N and Picton 9029-4S sheets (Land and Property Information, NSW Government). It was found that, in detail, the blue line network did not correctly follow the DEM-defined topography. Thus, a revised drainage network was generated automatically in Global Mapper™ GIS using the 2 x 2 m DEM.

The new drainage network was generated using the standard 8-direction pour point algorithm (D-8) (Jenson and Domingue, 1988). A preliminary network was generated for the catchments within which the Study Area was situated using a fixed threshold catchment area for initiation of a channel and a fixed minimum channel length. This result was compared with the blue line network on the1:25,000 topographic sheets. Then, as necessary, each sub-catchment was re-analysed using revised parameter settings so as to generate a drainage network that mimicked that of the the1:25,000 topographic sheets with respect to number and extent of streams. The main difference between the blue line network and the generated network was that a small stream emanating from a dam on Eliza Creek flowed directly to the main creek channel, whereas on the topographic sheet it is drawn joining a small adjacent tributary before entering the main creek channel. The alignment indicated on the topographic sheet contradicts the topography, so it was not retained. This had the effect of maintaining Eliza Creek as a 2nd order[3] creek all the way to where it joins the Nepean River (Figure 4), whereas the (apparently incorrect) alignment on the topographic sheet changed it to a 3rd order creek.

Ten named streams flow fully within or partially through the Study Area (Figure 4):

- Nepean River
- Bargo River
- Hornes Creek
- Teatree Hollow
- Dog Trap Creek
- Sugarloaf Gully
- Eliza Creek
- Dry Creek
- Carters Creek
- Cow Creek

For the purpose of reporting the geomorphic characteristics of all of the streams within the Study Area it was necessary to name every stream. Stream links are lengths of stream between two nodes, where a node is the beginning of a 1st order stream, the junction of two streams, or some other locally defined boundary. For the purposes of the Geomorphology Technical Report, it was not necessary to provide a unique name for every stream link, so a notation system was devised based on sub-catchment and stream order (Figure 4). The numbering of multiple streams of the same order began by assigning 1 to the most upstream stream link, and then incrementally increasing the number downstream according to the relative position that the stream joined the mainstem. Bargo River flowed out of the Study Area in two places, so an additional letter was used to name the three reaches to indicate their northern (N), central (C) and western (W) locations (Figure 4).

2.6.3 Slope

Slope was evaluated for the entire Study Area at 2 x 2 m grid resolution, and also along individual stream vectors, by sampling the grid at a 2 m spacing.

2.6.4 Valley depth

Waddington and Kay (2003) indicated that valley depth is one of the major factors controlling the magnitude of upsidence. Valley depth can be measured subjectively at points across valleys using topographic data, but the advantage of terrain analysis is that it allows valley depth to be calculated for an entire valley in a systematic and objective way. Examples of application of the valley depth algorithm can be found in Palamara et al. (2006) and Feuillet et al. (2012). In Tasmania, Kidd and Viscarra Rossel (2011) and Independent Verification Group Report (2012) both used the standard valley depth algorithm in SAGA, which calculates the elevation of a cell relative to that of cells in a widely surrounding area. For the Geomorphology Technical Report, the valley depth algorithm was evaluated in SAGA, using the default parameter values of w (0.5), t (10) and e (2).

[3] Stream order was assigned according to the Strahler system, whereby a headwater stream is order 1, and the order increases by 1 when a stream of a given order meets one of the same order.

Valley depth was measured to assist interpretation of subsidence predictions, and to assist with the identification of the gorge landform in the classification of stream types. For these purposes, only relatively deep valleys were of interest, so the minimum depth for mapping was set at 10 m.

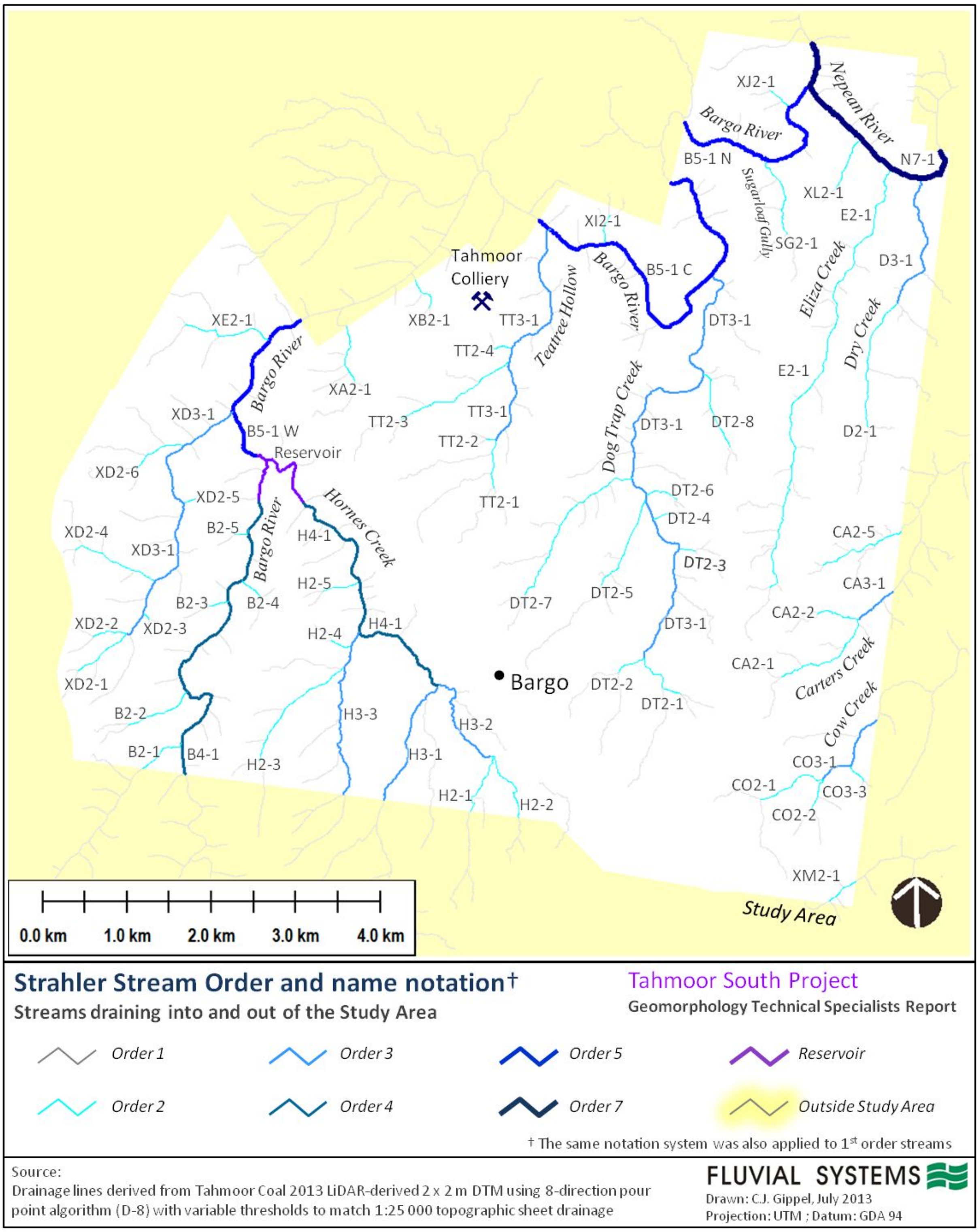

Figure 4. Strahler Stream Order of streams draining into and out of the Study Area, showing the system used to name all streams of a given order.

2.6.5 TPI (Topographic Position Index) Landform Classification

A number of different methods have been proposed for classifying landforms based on topographic data (e.g. Schmidt and Hewitt, 2004; Niculiță and Niculiță, 2011). The method used in the Geomorphology Technical Report was the Topographic Position Index (TPI), as proposed by Guisan et al. (1999) and elaborated by Weiss (2001). An example application of TPI to landform classification in the Carpathian Mountains, Slovakia can be found in Barka et al. (2011).

The TPI algorithm compares the elevation of each cell in a DEM to the mean elevation of a specified neighbourhood around that cell. Positive TPI values represent locations that are higher than the average of their surroundings, as defined by the neighbourhood (ridges). Negative TPI values represent locations that are lower than their surroundings (valleys). TPI values near zero are either flat areas (where the slope is near zero) or areas of constant slope (where the slope of the point is significantly greater than zero). In this application, the default SAGA radius settings of inner radius 100 m and outer radius of 1000 m were used.

The TPI algorithm in SAGA produces 10 landform classes:

- High ridges
- Midslope ridges
- Local ridges
- Upper slopes
- Open slopes
- Plains
- Valleys
- Upland drainages
- Midslope drainages
- Streams

2.6.6 Cliffs, steep slopes and potential talus slopes

Cliffs and steep slopes were defined on the basis of a standard definition that has been used in previous similar assessments. An additional class called ‘potential talus slopes’ (see discussion below), a sub-class of steep slopes, was also identified. The definitions, illustrated in Figure 5, are:

- Cliff: a continuous rock face, including overhangs, having a minimum length of 20 m, a minimum height of 10 m and a minimum slope of 2:1 (V:H) (200% or 63.4º).
- Steep slope: An area of land having a gradient between 1:3 (V:H) (33% or 18.4º) and 2:1 (V:H) (200% or 63.4º).
- Potential talus slope: An area of land having a gradient between 1:2 (V:H) (50% or 26.6°) and 3:4 (V:H) (75% of 36.9°).

Some previous similar assessments have included features with minimum slopes of 2:1 (V:H), but of lower height than 10 m, termed minor cliffs and rock faces. These features have heights down to 5 m and 3 m respectively. The strict definition of cliff height is the vertical distance from base to top at a local point, but a convention of previous similar assessments has been to interpret ‘height’ in the above definition to mean ‘relief’ (the difference between the maximum and minimum elevations of the entire cliff feature). In this assessment, cliffs were identified using GIS tools on the basis of LiDAR-derived 1.5 x 1.5 m grid. Each cell with a slope exceeding 63.4º (and therefore at least 3 m height) was identified. Cells touching at any corner or side were coalesced into cliff polygons. Measurement of polygon length cannot be readily automated in GIS, but polygon perimeter can be readily measured. Previous experience with linear-shaped cliff polygons suggested that perimeter factored by 0.375 gave a reasonable estimate of length. Valid cliff polygons were defined as those at least 20 m in length (perimeter at least 53.33 m), and having a relief of at least 10 m. Note that this definition includes minor cliffs and rock faces within the definition of cliff, provided these lower relief features are part of a continuous rock face that has an overall relief of at least 10 m and has an overall length of at least 20 m (i.e. the rock face does not necessarily have a local height higher than 10 m along its entire length).

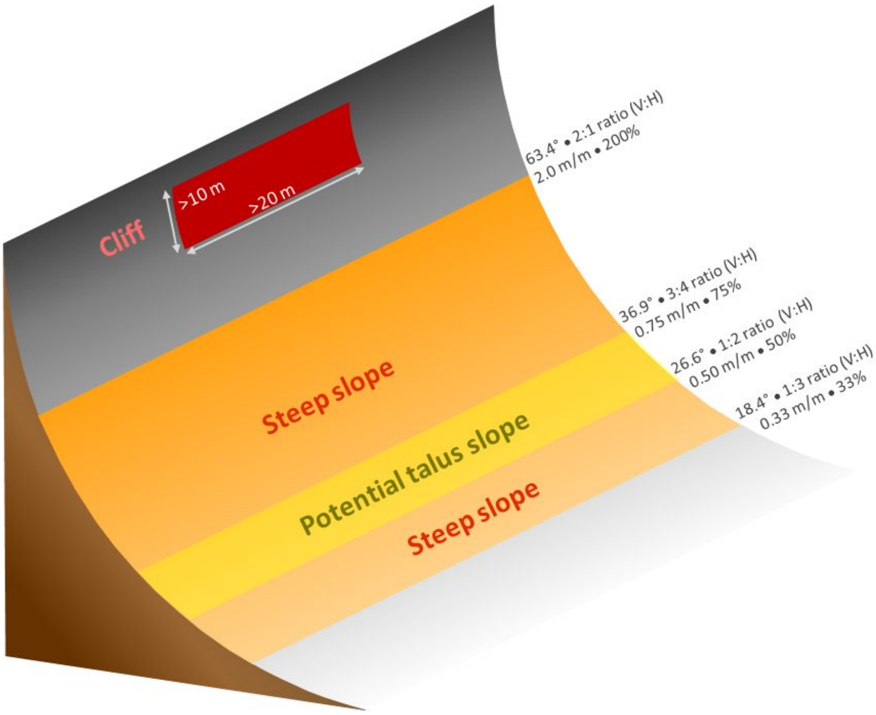

Figure 5. Illustration of cliff and slope definitions used in the Geomorphology Technical Report.

Rockfall is a relatively small landslide confined to the removal of individual and superficial rocks from a cliff face (Selby, 1982). Rockfall is evidenced by talus slope deposits (an accumulation of rock debris) at the foot of steep cliff faces, which are often in the form of a cone, or a planar surface following the base of a cliff line. A talus slope is at the angle of repose, and is therefore potentially unstable if disturbed. Rockfall starts with the detachment of rocks from bedrock slopes, which is mostly a cliff face in the case of a rockfall source area (Dorren, 2003). Once a rock is detached, its mode of movement is either falling, bouncing, rolling or sliding. Freefall occurs on slopes steeper than around 70°, bouncing at slopes between 70° and 45° and rolling at slopes between 45° and 30° (Dorren, 2003; Wichmann and Becht, 2006). The fall of rocks stops abruptly due to energy lost through collisions and friction forces that act on the rock during transport over slope surfaces (Dorren, 2003). When rockfall occurs on slopes covered with vegetation the evidence for talus cones is less distinct (Dorren, 2003; Loye et al., 2008). As rockfall initiation is strongly correlated to steep slopes, slope thresholds to identify source areas are typically in the range from 30° to 60° (Petje et al., 2005; Wichmann and Becht, 2006). Jaboyedoff (2003) reported that talus cones usually have angles of inclination in the range 27° to 37°. The talus cones investigated by Albjär et al. (1979) (from various regions) had mean slope gradients of 25° to 35°.

On the basis of the above studies, for the Geomorphological Impact Assessment, potential talus slopes were defined as between 26.6° and 36.9° (Figure 5). Land falling within this range of slopes was regarded as potential talus slope, as it is possible to find non-talus slopes (i.e. not an accumulation of rock at the base of a cliff) within this slope range in landscapes.

2.7 Stream geomorphic type and condition

2.7.1 Stream geomorphic type classification

The geomorphic stream type classification used here borrowed from, and is consistent with, the River Styles® framework (Brierley and Fryirs, 2000; Brierley and Fryirs, 2005; Brierley and Fryirs, 2006; Fryirs and Brierley, 2006). The River Styles® classification is based on valley setting, level of floodplain development, bed materials and reach-scale physical features within the stream. In the Study Area, all streams were all within confined valley settings, and therefore exhibited no floodplain development. In the River Styles® classification, all of the streams in the Study Area would be either Gorge or Headwater styles. The differentiating factor that separates these two styles is that Headwater style is found in V-shaped valleys and Gorge is found in a rectangular or slot valley with cliffs. Another key difference relates to process, with Headwater streams located within source zones for sediment while Gorges are located in sediment transport zones where there is very little sediment storage. Gorges would tend to be higher energy systems than headwater streams.

In practice, it can be difficult to distinguish between Headwater and Gorge styles and in reality there would be transition areas between these types. Also, while a non-expert could easily identify a particularly striking gorge as such (e.g. Bargo River Gorge), it is more difficult when the valley walls are not as steep, high or narrowly-spaced. Headwater streams, as they become smaller towards the head of a valley, eventually become weakly defined flow paths, lacking bed and banks. This stream type is not described in the standard River Styles® classification. In an attempt to overcome these definitional problems, and to provide a higher level of resolution to stream type classification, the Headwater and Gorge types were each sub-divided into three types (Table 3, Figure 6). These sub-types reflected the relative strength of the channel forms compared to the classic type-descriptions found in River Styles® literature. Stream type classification was done on the basis of field-collected data, aerial photography and terrain data for surveyed stream links, and on the basis of aerial photography and terrain data on unsurveyed stream links.

Table 3 Description of geomorphic stream types identified in the Study Area.

Stream type	Stream sub-type	Description
Headwater	Headwater weak	Found at the head of stream systems with small catchment areas and low valley depths; indistinct channel; low degree of variability in cross-section and profile form; bed is cohesive material and likely to be densely vegetated with ground cover; in the Study Area, found only on plateau areas
	Headwater moderate	Found in upper- and mid-catchment positions; indistinct channel with low degree of variability in cross-section but variability in profile form; variability in bed materials; can be identified in the field, but not possible to identify from remotely sensed data
	Headwater strong	Symmetrical to irregular V- or U-shape valley; highly variable form including pools and rock outcrops, bed material size tends to be mostly cobble-size and coarser, but is highly variable
Gorge	Gorge weak	Found on tributary streams; symmetrical to irregular, partial vertical slot-shape valleys; upper levels of valleys have low to high rock cliffs while the mid- and lower levels of valleys mostly have steep slopes; channel banks can be low rock cliffs; channel bed has boulders, cobbles, rock bars, rock slabs, falls, cascades and pools, and is mostly free of easily transportable sediment
	Gorge moderate	Found on mid- to large-scale river mainstems; moderately deep (< 50 m deep) and wide (generally width/depth > 3.0), symmetrical to irregular, partial vertical slot-shape valleys; side slopes of valleys have distinct rock cliffs, while the mid- and lower levels of valleys have some sections of steep slopes; channel bed has boulders, cobbles, rock bars, rock slabs, falls, cascades and pools, and is mostly free of easily transportable sediment
	Gorge strong	Found on large-scale river mainstems; deep (> 50 m deep) and narrow valley (generally width/depth < 3.0), symmetrical to irregular, mostly vertical slot-shape valleys; side slopes of valleys have high and long rock cliffs; the channel bed has boulders, cobbles, rock bars, rock slabs, falls, cascades and pools, and is mostly free of easily transportable sediment; in the Study Area, found only on the Bargo River and Nepean River mainstems

Figure 6. Examples of geomorphic stream types defined for the Geomorphology Technical Report. Note: Headwater weak type also included streams in undisturbed, forested sites.

2.7.2 Stream geomorphic condition classification

Outhet and Cook (2004) defined geomorphic condition of a reach as:

> "*the capacity of a river to perform the biophysical functions that are expected for that river type within the valley setting that it occupies*"

Geomorphic condition relates primarily to the connections and linkages with the floodplain, reaches up and downstream and more importantly, assesses the effect of human disturbance on the current evolutionary stage (Cook and Schneider, 2006). For use in River Styles® assessments, Outhet and Cook (2004) classified geomorphic condition in according to three categories, with each having a number of identifying characteristics

(Table 4). These are subjective criteria that are not easy to interpret, even for an expert geomorphologist. For the Geomorphology Technical Report, additional objective criteria were provided to help judge stream condition. These additions referred to local phenomenon, so were added to the Moderate condition categories rather than the Poor category, which applied to major instabilities and sediment aggradation over the reach scale (Table 4). However, one objective criterion was added to the Poor category to describe absence of vegetation (Table 4). The field collected data were assessed against the criteria in Table 4 to assign a geomorphic condition value (Good, Moderate or Poor) to each surveyed site.

Table 4 Categories of stream geomorphic condition defined by Outhet and Cook (2004). The term "Style" is equivalent to the term "stream type" used in the Tahmoor South Geomorphology Technical Report. Some additions were made to the descriptions to suit the Assessment (in italics).

Geomorphic condition	Description
Good condition Stream exhibits all of these characteristics	• River character and behaviour fits the natural setting, presenting a high potential for ecological diversity, similar to the pre-development intact state. • There is no general bed incision or aggradation. The reach has already recovered from major natural and human disturbances and has adjusted to the present flow regime. It has stopped evolving and has adjusted to prevailing catchment boundary conditions. • The patterns and forms of the geomorphic units are typical for the Style. • The Style is consistent with the natural setting and controls. • The reach has self-adjusting river forms and processes, allowing fast recovery from natural and human disturbance. • There is intact and effective vegetation coverage relative to the reference reaches, giving resistance to natural disturbance and accelerated erosion. • The reach has all good condition attributes without artificial controls.
Moderate condition Stream exhibits one or more of these characteristics	• Localised degradation of river character and behaviour, typically marked by modified patterns of geomorphic units. • Degraded forms of geomorphic units, as marked by, for example, inappropriate grain size distribution. *Active knickpoint >1 m high.* • Patchy effective vegetation coverage relative to the reference reaches (allowing some localised accelerated erosion). *Tree cover in category 0 or 1 and vegetation cover index >0.2 and <0.4.* • *Licenced discharges moderately alter stream bed or suspended sediment load.* • *Localised interference by fill added to channel, or failed in-channel dam.* • *Filamentous algae cover exceeding 50% of bed area.* • *Mining-induced bed fractures with surface flow loss.* • *Minor culvert through local road, or track crossing stream.*
Poor condition Stream exhibits one or more of these characteristics	• Abnormal or accelerated geomorphic instability (reaches are prone to accelerated and/or inappropriate patterns or rates of planform change and/or bank and bed erosion). • Excessively high volumes of coarse bedload which blanket the bed, reducing flow diversity. • Absent or geomorphically ineffective coverage by vegetation relative to the reference reaches (allowing most locations to have accelerated rates of erosion) or the reach is weed infested. *Tree cover in category 0 or 1 and vegetation cover index <0.2.* • *Major culvert through railway or main road*

2.8 Impact assessment

2.8.1 Risk Management Zones

NSW Department of Planning (2008, p. 112) proposed that "*identification and use of 'natural features Risk Management Zones' or RMZs*" would help mine proponents to identify features requiring detailed assessment, careful management and appropriate environmental outcomes. RMZs are considered to be of particular relevance to non-conventional subsidence effects, especially valley closure and upsidence. Thus, NSW Department of Planning (2008, p. 112) recommended that RMZs be identified for all significant environmental features which are sensitive to valley closure and upsidence, including rivers, significant streams, significant cliff lines and valley infill swamps.

In its original conception, a natural feature RMZ would define areas where features of high value came within proximity of a longwall. If the high value feature was distant from the longwall then it was not at risk and did not require special consideration in mine planning and impact assessment. However, the convention (also adopted here) has become to map buffers around all high value features and then examine where they overlap the proposed longwalls. It is the overlapping areas that require detailed attention in the assessment, and careful management and monitoring. The RMZ is an area that includes the footprint of the feature itself and the area within the 40° angle, or 400 m lateral distance, whichever is greater, on each side of the feature.

In the Study Area, the depth of cover to the Bulli seam varies from approximately 350 m in the south-western section of CCL 747 to approximately 430 m in the north-eastern section of CCL 716. Thus, the lateral distance on the surface for a 40° angle ranges from 294 to 361 m. Being less than 400 m, the appropriate RMZs for the Study Area are 400 m lateral distance from the edge of the feature.

Department of Planning (2008, p. 112) proposed that RMZs should be developed for:

- All streams of 3rd order or above, in the Strahler stream classification
- Valley infill swamps not on a 3rd or higher order stream
- Major cliff lines and overhangs not directly associated with watercourses. In the case of cliffs and gorges, the edge of the feature should be defined as the top of the cliff line when the extraction panel is approaching the cliff line from the high side of the cliff, and from the bottom of the cliff line when extraction is approaching it from the low side

Streams of 3rd order and above were determined on the basis of the stream network defined from the DEM, but according to the Strahler stream order that was identified from 1:25,000 topographic map sheets. This was because, although the DEM correctly classified Eliza Creek as a 2nd order stream, on the map sheet it is a 3rd order stream, and the DGRs specifically requested that Eliza Creek be considered (Table 1), along with other streams of 3rd order or higher.

In this assessment, valley infill swamps were not relevant, as these features were not found within the Study Area.

Major cliff lines were defined as continuous areas of rock face having a minimum slope of 2:1 (V:H), a minimum length of 20 m, a minimum local height from base to top of 3 m, and a minimum relief of 10 m over the feature.

The field survey identified and characterised various geomorphological features within streams. The significance of these (i.e. bed material calibre, large wood, pools, bedrock slabs and bars, soft knickpoints, and riparian and in-channel vegetation) to ecological and hydrological processes, and the relative risk posed by subsidence to these processes, was assessed by other relevant technical specialists (see other technical specialists reports for details).

2.8.2 Types of geomorphic response (event type) to mining related changes

There are two main mining-related agents of change that could cause an impact on geomorphological processes and forms in the Study Area:

- Subsidence
- Hydrological change (change in the distribution of stream flows)

These potential agents of change could bring about a number of geomorphic responses (Table 5) that would constitute an environmental impact with possible implications for environmental values. The Geomorphology Technical Report evaluated these risks qualitatively, with detailed assessment being done by other relevant technical specialists (see other technical specialists reports for details).

Table 5 Potential geomorphic responses to mining-related causes.

Potential geomorphic response (event type)	Mining-related causes (see below for explanation)
1. Change in stream type, irreversible over management time scales (< 100 years)	1, 2, 3, 4, 5, 6, 7
2. Change of alignment of channel	3, 4
3. Reduction of existing in-channel pool volume	1, 2, 3, 6
4. Formation of new in-channel pool, or deepening of existing pools	4, 7
5. Migration of soft knickpoint upstream at faster than natural rate	3
6. Increase of sediment supply to channel	3, 5, 7
7. Increase of sediment accumulation in channel	4, 6
8. Increase of sediment scouring in channel	3, 7
9. Increase in cover (density) of vegetation on channel bed (baseflow shift from high depth of water to shallow depth)	6
10. Decrease in cover (density) of vegetation on channel bed (baseflow shift from shallow depth of water to dry, or from shallow to deep)	6, 7
11. Increase in rockfall frequency above natural rate	5

Mining related causes:

1. Local fracturing of rock bars that act as hydraulic controls on pools.
2. Local fracturing of bedrock in the bed of pools.
3. Local increase in slope of channel bed.
4. Local decrease in slope of channel bed.
5. Partial or total face collapse of cliff, minor cliff and rock face.
6. Reduction in stream flow (due to diversion or extensive fracturing).
7. Increase in stream flow (due to diversion).

3.0 Existing environment

3.1 Landscape-scale characteristics

3.1.1 Geology and soils

The Study Area lies within the Southern Coalfield in the southern part of the Sydney Basin (NSW Department of Planning, 2008). The Study Area was included in the geological mapping of Stroud et al. (1985) (Figure 7). The majority of the proposed development is underlain by Hawkesbury Sandstone with a smaller portion underlain by Wianamatta Group. There is a small area of Jurassic volcanic geology at Coombes Sugarloaf. The shale-dominated younger Wianamatta Group lies conformably over the Hawkesbury Sandstone. Hawkesbury Sandstone mainly comprises medium to very coarse grained quartz sandstone with minor laminated mudstone and siltstone lenses.

There are several known major and minor structures (e.g. faults or fault systems) in the Study Area. The Bargo Fault and Nepean Monocline are indicated on the 1:100,000 Geological Sheet (Stroud et al., 1985) (Figure 7), and additional faults were mapped by Tahmoor Coal (see Merrick, 2012, and Figure 1).

Soil landscapes integrate soil and landform constraints into a single mapping unit (Northcote, 1978; Murphy et al., 2001). The soil landscapes occurring within the Study Area were included in the mapping of Hazelton and Tille (1990) (Figure 8). The Landscapes present are:

- Erosional soil landscapes: Gymea associated with sandstone geology, and a small area of Luddenham on the slopes of Coombes Sugarloaf associated with shale geology
- Hawkesbury colluvial soil landscape where the sandstone is steep. Colluvial slopes are dominated by areas where mass movement is the principal agent of accumulation
- Residual soil landscapes: Volcanic on the peak of Coombes Sugarloaf, Blacktown associated with shales, and Lucas Heights associated with sandstone. Residual soils are areas where soils are derived from the long term in situ weathering of parent materials
- Disturbed terrain: Tahmoor Mine

Wianamatta Shale soils (Blacktown landscape) are high in iron content and can be responsible for release of dissolved iron to stream water (MSEC, 2006). GeoTerra (2004) also noted that Lucas Heights landscape lateritic podzolic soils on crests can generate dissolved iron. Hawkesbury landscape soils have low salt store, Volcanic landscape has moderate salt store, and soils on Wianamatta Shale contain high salt stores in soils and regolith (Winkler et al., 2012).

Hazelton and Tille (1990) reported erosion hazard for the soil landscapes in the Study Area. Erosion hazard is a measure of the susceptibility of an area of land to prevailing agents of erosion and is assessed by factors such as topography, soil erodibility and land use. Erosion hazard refers to water erosion hazard, which is the likelihood of soil detachment and movement under the effects of raindrop impact, initiation of runoff, and flowing water (Morse et al., 1982). The hazard is conditioned mainly by inherent soil properties, degree of soil disturbance, slope and vegetation cover. Of main interest to the Geomorphology Technical Report is erosion hazard under concentrated flows, as this relates to risk of rill, gully and channel erosion, which are the main processes that release significant quantities of sediment to streams. The concentrated flow erosion hazard for the four soil landscapes with significant drainage lines present (and thus concentrated flow), are:

- Lucas Heights: Moderate
- Blacktown: Moderate to High
- Gymea: High to Extreme
- Hawkesbury: Extreme

Soil Types according to the ASC (Australian Soil Classification) to Order level (Isbell et al., 1997; Isbell, 2002) for the Study Area were mapped by Office of Environment and Heritage (2012). The ASC has 14 soil orders, 7 of which are present in the Study Area (Figure 9). The nature of the soil orders (CSIRO, 2013) can be briefly described as:

- Organosols: Contain organic soil material

- Rudosols: Negligible pedological organisation – rudimentary soil development
- Tenosols: Weak pedological organisation – weak soil development
- Kurosols: Strong texture contrast (pH <5.5 in B horizon) – pertaining to clay increase
- Ferrosols: Lacking strong texture contrast (high free iron in B horizon) – high iron content
- Dermosols: Lacking strong texture contrast (structured B horizon) - often with clay skins on ped faces
- Kandosols: Lacking strong texture contrast (massive B horizon) -

There is a fairly strong relationship between soil type (ASC Order) and soil landscape (compare Figure 8 and Figure 9). Lucas Heights landscape is dominantly Kurosols, Blacktown landscape is dominantly Dermosols, Hawkesbury is dominantly Rudosols, and Gymea landscape is dominantly Rudosols and Tenosols. The weakly developed tenosols and rudosols dominant in Hawkesbury and Gymea landscapes partly explains their high to extreme erosion hazard rating.

Acid sulfate soils are naturally occurring soils containing pyrite (iron sulphides) which, on exposure to air, causes oxidisation and creates sulfuric acid. Mapping by CSIRO (2012) indicates that the Study Area lies within areas designated as low probability or extremely low probability of acid sulphate soils being present, although the confidence level is very low (Figure 10).

3.1.2 Topography

Land elevations in the Study Area range from 95 to 448 m AHD (Australian Height Datum) (Figure 11); land slopes range up to 85.6° (Figure 12). The landform of the Study Area comprises three main units:

- heavily dissected, high-elevation, high slope land in the south west
- dissected, mid-elevation, undulating plateau land in the central area
- a small area of dissected, low-elevation land in the north east, downstream of the Nepean Fault (also mapped as the Bargo Fault).

3.1.3 Valley depth

Valley depth was high in the Nepean River and most of the Bargo River, regularly reaching 50 m relative height, and occasionally exceeding 100 m in the Bargo River Gorge and the Nepean River Gorge (Figure 13). The central reaches of Bargo River within the Study Area had a significantly lower valley depth. Tributary streams generally had valley depths lower than 20 m relative height. Tributaries flowing from the central plateau area had lower valley depths than those in the dissected, high-elevation land to the south west.

3.1.4 TPI Landform Classification

The dominant TPI landform class present in the Study Area was Plains, with Upper slopes and Open slopes associated with elevated patches of land within the plateau, and also on the slopes of the less-steep valleys (Figure 14). Mid-slope and Local ridge, and Valley classes were associated with deep gorges of the Bargo and Nepean rivers. The High ridge class was found on the crest of the Nepean Fault. The Upland drainage class was not found within the Study Area, but occurred just outside the Study Area.

3.1.5 Cliffs, steep slopes and potential talus slopes

Steep slopes were mostly found along the deeply dissected drainage lines, with the Bargo Fault also within this classification (Figure 15). Potential talus slopes were mostly found on mid- and lower-levels within the deeply incised gorges. This suggests that true talus landforms are present within the gorges. This was expected, as cliffs were present along the edges of much of the gorge terrain. Where cliffs were not present, either small (unclassified) cliffs were present, or it is likely that at some time in the past active cliffs were present there. Steep slopes covered 563.4 ha (7.8%) of the Study Area. Of the steep slope area, 210.9 ha (37.4%) fell within the potential talus slope class.

The terrain analysis method identified 316 major cliff features within the Study Area. These were not ground-truthed, because of the practical difficulty and safety risk that this would present. The cliff structures at the junction of Eliza Creek with the Nepean River illustrate the potential complexity of cliff morphology (Figure 16).

Cliffs were mostly located along the Bargo and Nepean rivers (Figure 17 and Figure 18). Over the entire Study Area, the combined linear distance of cliffs was approximately 26.7 km. The 3-D surface areas of these features is equivalent to the rock face surface area. Over the entire Study Area, the combined face surface areas of cliffs was

327,398 m^2. Only a relatively small number of cliffs were present in streams other than the Bargo and Nepean rivers, with those two rivers containing 83% of the cliffs (Figure 18).

There was a large variability in the lengths, surface areas and reliefs of cliffs, both within streams, and between streams (Figure 18). The 2013 and historical aerial photographs did not show evidence of recent rockfalls (evidence would be exposed loose rock forming a talus slope without vegetation). At the landscape-scale, the cliffs appear to be relatively stable, but at the local-scale, recent natural rockfalls are likely to be present.

3.2 Stream reach- and point-scale characteristics

3.2.1 Channel bed materials

A wide range of channel bed materials was observed over the Study Area (Figure 19). Mud was more prevalent in small streams on the plateau, but it was also occasionally present in the lower reaches of tributary streams. Sand, gravel, coble and bedrock were commonly found throughout the Study Area. Bed material dominance showed a spatially variable pattern (Figure 20). Mud (in headwaters), boulder and bedrock were the most common dominant bed materials.

3.2.2 In-channel bedrock features and fracture density

Exposed bedrock, in the form of rock bars and rock slabs (Figure 21), was commonly observed in streams throughout the Study Area (Figure 22). Streams with particularly frequent bedrock features in their beds were Lower Eliza Creek and creeks XA and XB. The frequency of bedrock features was also high in Dog Trap Creek, Cow Creek and Dry Creek, but less so in Carters Creek, Hornes Creek and Teatree Hollow (Figure 22). The observed frequency of bedrock features in the bed of Bargo River was an underestimate because at the time of sampling, for most of its length the water was too deep to permit observation of the bed.

Fractures were absent at 68% of sites with exposed bedrock (Figure 23). For sites where fractures were observed, the density ranged from 0.11 to 15 fractures per 10 m, with an average of 2.3 and median of 1.6 fractures per 10 m. This compares with the expected average natural joint density of Hawkesbury Sandstone of 0.17 – 3.3 joints per 10 m (Herbert, 1983; Pells, 1993). Most observed fractures were regarded as natural characteristics of the rock, appearing tight and ancient (as evidenced by even weathering across the bedrock surface) (Figure 24). A site on TT1-18, a small tributary of Teatree Hollow, had the highest recorded fracture density, but this was an observation of 3 fractures over a length of rock that was only 2 m long, so this data point could be unrepresentative. At two locations, one on each of creeks XA2-1 and XB2-1, fractures were observed in the rock beds that were of a distinctly different appearance to the others observed in the Study Area, being open and having sharp, unweathered edges (Figure 25). There was also some evidence of overriding of bedding slabs. These two creeks flow over areas that have been previously mined (Figure 23), so circumstantial evidence suggests that at least some of the observed fracturing in these creek beds was an impact of mining. The rock fracturing observed on the beds of creeks XA2-1 and XB2-1 had the appearance of those illustrated as examples of mining impact in photographs in NSW Department of Planning (2008), Total Environment Centre (2007), GeoTerra (2007) and GeoTerra (2011), but the severity of the fracturing was considerably less than illustrated in those examples. Note that the survey undertaken for the Geomorphology Technical Report was not intended as a comprehensive investigation of subsidence impacts from previous mining, so the suggestion that the observed fracturing was mining-related is tentative.

3.2.3 Knickpoints

Knickpoints were common in streams within the Study Area, with 149 hard knickpoints and 44 soft knickpoints observed (Figure 26, Figure 27). Soft knickpoints were found mainly on small, plateau streams running through both cleared and uncleared land. Hard knickpoints were found in steeper streams. Soft knickpoints ranged in height from 0.22 m to 1.4 m with an average height of 0.62 m. Hard knickpoints ranged in height from 1.4 m to 35 m with an average height of 1.7 m. The highest observed knickpoint was found at the downstream end of Eliza Creek where it joined the Nepean River Gorge. The fall in elevation from the edge of the cliff on the bed of Eliza Creek down to the edge of the bed of the Nepean River measured in the field with a rangefinder was 35 m. This height was confirmed by the LiDAR-derived DEM, although the height of the steep cliff face (i.e. the section steeper than 63.4°) was less than this, being approximately 20 m. Some high, steep drops were also observed near Mermaids Pool, and on the Cow Creek system.

3.2.4 In-channel pools

In-channel pools were common in streams within the Study Area (Figure 28). The frequency of pools was highest on Dog Trap Creek, Dry Creek and Cow Creek. Teatree Hollow had a lower frequency of pools compared to other creeks. The pools were of widely varying dimensions, with the largest observed pool being Mermaids Pool. The depth of Mermaids Pool was not measured in the field; its depth of 12 m was reported by National Parks Association Macarthur (2006).

Boulders was the most common type of hydraulic control on pools, with 47% being boulders, 33% rock bars, 12% high points of cohesive material, 8% gravel, cobble or sand bars, and 1% artificial material. The spatial distribution of hydraulic control type was variable (Figure 28).

3.2.5 Riparian vegetation width and continuity

Of the 313 sites in the Study Area where riparian vegetation was surveyed, riparian width was greater than 50 m at 91% of left bank sites and 96% of right bank sites. A total of only 3% of sites (left and right banks) had riparian widths less than 10 m. Continuity of riparian vegetation was in the >75% class at 93% of left bank sites and 94% of right bank sites. A total of only 1% of sites (left and right banks) had riparian continuity in a class lower than 50 – 75%. These data suggest that poor riparian vegetation width and continuity does not present a significant threat to the geomorphic stability of streams in the Study Area.

3.2.6 Riparian tree cover

In riparian zones, trees alone were regarded as offering better structural stability to streams than shrubs or ground cover alone, because: (i) presence of trees is usually associated with presence of shrubs and ground cover (which can add to structural stability), while presence of shrubs and ground cover is not necessarily associated with presence of trees, (ii) the presence of trees suggests a lower degree of human disturbance, and (iii) trees have more extensive root systems for increasing inherent soil stability.

In the Study Area, riparian tree cover was generally high (Figure 29). Although some small plateau streams flowing through cleared land had low riparian tree cover, the majority of sites on these streams had moderate (>25%) to high (>75%) cover. Streams within dissected valleys and gorges tended to have moderate to high riparian tree cover. In the Study Area, it was observed that a moderate level of tree cover was within the natural range of undisturbed sites.

3.2.7 Riparian vegetation cover index

The riparian cover index generally had moderate to high values over the Study Area (Figure 30). A total of 13% sites had a score in the very high range (0.8 – 1.0), 49% had a score in the high range (0.6 – 0.8), 30% of sites had a score in the moderate range (0.4 – 0.6), 8% of sites had a score in the low range (0.2 – 0.4) and no sites had a score lower than 0.3. In this environment, undisturbed sites can naturally have an index score as low as 0.5, and perhaps lower, because the abundance of exposed sandstone on the ground can limit vegetation cover. Despite this, the lowest cover index scores occurred on small plateau streams flowing through cleared land (Figure 30).

3.2.8 Grass cover on low flow channel

Extensive grass cover on the bed of a low flow channel is usually indicative of a low energy, headwater environment where the bed shear stress of high flows is inadequate to overcome the inherent resistance of the vegetation roots, and the baseflow is not deep or persistent enough to discourage grass growth. The survey classified grass as distinct from macrophytes, which were rarely observed in the Study Area. Also, the grass category did not include Lomandra spp. Lomandra spp. thrives near water but will not live with its roots in water, so it was not regarded as in-channel vegetation, despite its typically extensive colonisation of the low-level areas of some tributary gorge-type streams. There were a few exceptional instances where Lomandra spp. was observed to be growing on the low flow channel bed, in which case it was recorded as grass cover.

Grass cover on the low flow channel was found on all of the small headwater streams of the creeks in the Study Area, but it was uncommon in 2nd order streams and higher (Figure 31). Dry Creek was an exception, but Dry Creek has a small catchment area, so it is a relatively low energy stream.

3.2.9 Large wood frequency

The frequency of large wood in the streams of the Study Area had high spatial variability (Figure 32). Of 313 sites surveyed for large wood frequency, 43% had no wood present. For sites with large wood present the frequency ranged from 5 to 65 items per 100 m length of stream, with an average of 15 and a median of 10 items per 100 m length of stream. Sites with low riparian tree cover (Figure 29) tended to have low wood frequency. Although steams flowing through undisturbed forested land (e.g. Cow Creek) tended to have the highest wood frequency, it was not uncommon for sites within these areas to have no wood, or low wood frequency. Log jams were uncommon in the Study Area, being recorded at only 26 sites (8% of all sites), and all but one of these had only one log jam present (Figure 29). Overall, large wood density was so variable in the streams of the Study Area that alone it was not a reliable indicator of stream condition.

3.2.10 Stream long-profiles

Long profiles of the major streams flowing into and out of the Study Area (Figure 33) were plotted using DEM and topographic map data (Figure 34). These profiles revealed three types of profile:

• River mainstem with major profile variation	Bargo and Nepean rivers
• Tributary streams lacking a major fixed knickpoint near their junction with the river mainstem	Hornes Ck, Teatree Hollow, Dog Trap Ck
• Tributary streams with a major fixed knickpoint near their junction with the river mainstem	XD3, XE2, XA2, XB2, XH3, XI2, XC2, Sugarloaf Gully, XJ2, XM2, Cow Ck, Carters Ck, Dry Ck, Eliza Ck

The Bargo River has a major fixed knickpoint beginning just upstream of Mermaids Pool, with a zone of high slope (0.026 m/m) extending down to the junction with the Nepean River (Figure 34). The Bargo Fault lies within this zone. Above the knickpoint the river has a relatively planar profile with a slope of approximately 0.0044 m/m. The profile of the Nepean River in this area is the inverse of that of the Bargo River. From about 5 km downstream of the Nepean Dam, the river slopes steeply down to the Cordeaux River junction (0.015 m/m), and from there downstream (into the Study Area) the slope is much lower (0.0039 m/m) (Figure 34).

Hornes Creek, Teatree Hollow and Dog Trap Creek have slopes not much greater than the Bargo River, into which they flow. Where Dog Trap Creek and Tea Tee Hollow join the Bargo River, the Bargo River valley is much shallower than further upstream and downstream (Figure 13 and Figure 34).

The small unnamed tributaries of the Bargo and Nepean rivers, as well as Cow Creek, Carters Creek, Dry Creek and Eliza Creek have fairly steep slopes, in addition to a major fixed knickpoint close to where they join the main river (Figure 34). Of these, Eliza and Dry creeks have the most dramatic knickpoints, located close to the edge of the Nepean River gorge.

3.2.11 Valley shape-type

Valley shape was interpreted in the field as belonging to either low relief (without cliffs) or high relief types (possibly with cliffs). These valley types corresponded well with the distribution of steep slopes (Figure 35).

3.2.12 Stream geomorphic type

Stream geomorphic type was determined for all streams within the Study Area using a number of criteria (Table 3). Field surveyed sites were classified on the basis of observations made at each site (Figure 36). An artificial stream type was added to the classification to cover major culverts. The distribution of stream types showed a strong correspondence with the spatial distributions of elevation (Figure 11), valley depth (Figure 13), TPI Landform Class (Figure 14), steep slopes (Figure 15), dominant bed material (Figure 20), and grass cover on the low flow channel (Figure 31). These associations were used to map stream geomorphic type for all stream links in the Study Area (Figure 37).

3.2.13 Stream geomorphic condition

Stream geomorphic condition was determined for all field sites within the Study Area using a number of stream type-independent criteria (Table 4). Of the 696 surveyed sites within the Study Area, 591 (85%) were in Good geomorphic condition, and 15% were in Moderate geomorphic condition (Figure 38). Only major culverts were judged to be in Poor geomorphic condition (due to transformation to an unnatural stream type). The localised sites of moderate condition mostly related to instances of minor culverts or track crossings; low riparian vegetation cover; sites of moderate condition on Teatree Hollow related to the impact of licenced discharges to the stream; sites of moderate condition on Eliza Creek related to fill tipped into the channel and a failed dam; and sites of moderate condition on creeks XA and XB related to loss of surface flow to the subsurface in apparent association with mining-induced bed fracturing.

3.2.14 Channel dimensions and slopes of streams by geomorphic type

Channel dimensions were measured at 249 sites within the Study Area. The data indicated that gorge-type streams were larger than headwater-type streams, and strong-type streams were larger than moderate- and weak-type streams (Figure 39). However, these data suggested that there was little difference in the dimensions of Headwater strong and Gorge weak types. Although Headwater weak streams were wider than Headwater moderate streams, they were shallower. The majority of streams in the Study Area were relatively small-scale (< 5 m wide and < 0.6 m deep).

Slopes of all stream links were measured using the 2 x 2 m DEM. These data indicated a fairly wide range of slopes for all stream types, but in particular for Headwater strong type (Figure 40). Headwater strong streams were steeper than streams of other types, and they covered a much wider range of slopes.

3.2.15 2nd order streams and higher - summary of key physical characteristics

First order streams were of lower interest to the assessment of geomorphic risk compared with 2nd order streams and higher. This is because in the Study Area, compared with larger streams, 1st order streams had:

- Smaller catchments (with less flow)
- Lower energy (and hence lower capacity to mobilise and transport sediment)
- Fewer, if any, pools
- Fewer exposed bedrock features

The length and mean slope of all streams of 2nd order and higher were measured from the 2 x 2 m DEM (Table 6). Also, for these streams, the field measured data concerning pools, knickpoints and bedrock features (the features of most interest to the assessment of geomorphic risk) were summarised (Table 6). These data indicated that a high percentage of the lengths of some of these streams comprised pools, in particular the 3rd order section of Cow Creek (CO3-1), the 3rd order section Dog Trap Creek (DT3-1), and to a lesser extent the 3rd order section of Dry Creek (D3-1) and the 4th order section of Hornes Creek (H4-1) (Table 6). These streams also had a relatively high number of bedrock features present. At the coarsest level of risk assessment, these streams present the highest risk to change of geomorphic character because they have a high density of features that are potentially sensitive to subsidence impact.

3.3 Miscellaneous field observations

A number of miscellaneous observations were made in the field that had potential relevance to the Geomorphology Technical Report (Figure 41). Some of these miscellaneous observations (e.g. filamentous algae, ferruginous seeps) were not unexpected, and the data were recorded in fields that were included in the standard digital form. Others were not anticipated and were added to the data opportunistically.

3.3.1 Licenced discharges to Teatree Hollow

The Environment Protection Licence EPL1389 (EPA, 2012) includes three Licenced Discharge Points (LDPs) that flow to Teatree Hollow. Treated water from dams M1, M2, M3 and M4 discharge to Teatree Hollow via LDP1 (Figure 41) (Tahmoor Coal Tahmoor Mine, 2012). Main dam S4 is the primary discharge point for the stormwater system for the coal stockpiles and REA (Rejects Emplacement Area). Water from S4 discharges to Teatree Hollow via LDP4 (Figure 41). Stormwater from the operational shaft area is directed to Dams M5 and M6 for settling prior to discharge through LDP6 (Tahmoor Coal Tahmoor Mine, 2012).

Turbidity and TSS (total suspended solids concentration) are the main parameters of geomorphic interest because they indicate suspended sediment transport. The licenced upper limits for turbidity and TSS (total suspended solids concentration), are 150 NTU for turbidity and 30 mg/L for TSS for LDP1, and 50 mg/L for TSS for LDP4 and LDP6. The results of the monthly sampling required by the EPL are reported in Annual Environmental Management Reports. The data indicate that turbidity and TSS have always been within the licenced limits.

The geomorphology survey covered TT3-1 (Teatree Hollow 3rd order) on 6 February 2013. At the time, the discharge from LDP4 was noticeably turbid, but water quality was not measured because the necessary equipment was not being carried. At the point where LDP4 discharge water met Teatree Hollow, the water in Teatree Hollow changed from clear (bed clearly visible, even in deep pools) to turbid (bed not visible, even in shallow water) (Figure 42). Although the water quality of LDP4 discharge has always been compliant with the TSS criterion of EPL1389, this one observation of turbid water is sufficient to suggest the possibility that Teatree Hollow below LDP4 receives a higher than natural suspended sediment load, which would reduce its geomorphic condition relative to natural. It is understood that a current project will consolidate the licenced discharge points into one consolidated point at LDP1, which should lessen any impacts.

On 6 February 2013, the discharge from LDPI was not particularly turbid, but it was unnaturally coloured. The tributary stream that transfers water from LDP1 to Teatree Hollow (TT1-21) was impacted by extensive development of a dark-coloured crystalline precipitate on the stream bed. This material was also found on rock and boulders in the bed of TT3-1 (Teatree Hollow), where it persisted all the way to the junction with the Bargo River. The chemistry of the precipitate was not investigated at the time, but its thickness (several mm) and extensive coverage altered the physical character of the bed material, thereby reducing the geomorphic condition of TT1-21 and Teatree Hollow relative to natural. Subsequent testing of the precipitate indicated that it was high in concentration of iron and barium.

During May 2013, the licenced discharge points noted on EPL1389 were consolidated into one discharge point, being LDP1. A mine water treatment plant to remove heavy metals from mine waters discharged from LDP1 is currently underway as a requirement of EPL 1389 Pollution Reduction Program 22 (PRP22), with the treatment plant anticipated to be commissioned during 2014.

3.3.2 Rockfall blocking channel on Dry Creek

On upper Dry Creek (D2-1), a large rockfall was observed that had blocked the channel, causing formation of a significant pond upstream (Figure 41). At some stage the wall has been artificially enhanced to improve the functionality of the pool as a water supply dam. Although the riparian canopy is dense in this area, the pond is large enough that open water is clearly visible on the 2013 aerial photograph (Figure 45). Open water is not obvious in this area on the 1975 or 1983 aerial photograph, but is clearly apparent on the 1998 photograph (Figure 45). The cause of the rockfall is unknown, but no evidence was found to suggest that the cause was unnatural.

3.3.3 Incised gully on upper Dog Trap Creek

An isolated area of incised gully was observed on DT2-7 (Dog Trap Creek) (Figure 41). The drainage line had incised down to 1.2 m deep, with two soft knickpoints present on the main channel, one of 1.2 m height and one of 1.3 m height (Figure 46). A bank gully network had developed westward from the main creek into the surrounding hillslope for a distance of about 50 m; the main knickpoint marking the upstream extent of this gully was set in rock and was 0.9 m high. Downstream of this area, DT2-7 was characterised by a series of hard knickpoints (Figure 46). The cause of this gully is unknown.

3.3.4 Recently active knickpoint on Teatree Hollow

Many knickpoints were observed in the Study Area, with the majority being effectively fixed by hard rock. Soft knickpoints have potential to be mobile, but their status is usually difficult to deduce from casual field observation. The exception is when the field inspection is conducted immediately after a significant storm event, and bare vertical banks and freshly collapsed sods can be found. This was the case at one notable section of TT3-1 (Teatree Hollow), 160 m downstream of the point where LDP4 enters the Hollow (Figure 41, Figure 47). The deeply incised section downstream of the knickpoint extended for 130 m. As well as freshly eroded sods, that section contained a sand deposit in the bed, which was rare in the Study Area. It is not known why this particular knickpoint was noticeably active and it cannot be assumed that it was related to LDP4, because another similarly-sized soft knickpoint was observed 160 m upstream of where LDP4 enters TT3-1 (Figure 47).

3.3.5 Failed dam on Eliza Creek

An apparently failed dam was observed on E2-1 (Eliza Creek) (Figure 41, Figure 48). Directly upstream of the breach there was an extensive deposit of fine sediment, densely colonised by Typha spp. In its current state the dam does not pond water, as the breach has eroded to the level of the deposited sediment and a knickpoint is migrating upstream into this sediment. It is not known when this dam was originally built or when it failed, however, it appeared to be intact on the 1975 and 1983 aerial photographs, whereas the 1998 photograph is unclear (Figure 49).

3.3.6 Fill tipped into channel of Eliza Creek

In one location on Eliza Creek, a significant quantity of loose fill had recently been pushed down the steep and high bank from the property above (Figure 41, Figure 50). The relatively fine-grained material was of unknown origin or composition. The fill had a noticeable local impact on the creek quality. Upstream of this site the stream water was clear and the bed was clean. Downstream of this site fine sediment was deposited on the bed, and the sediment appeared to contain ferruginous material, as the water took on a red/orange hue for a short distance (Figure 50).

3.3.7 Filamentous algae

The storm event of 27 – 29 January would have temporarily flushed any filamentous algae from the beds of streams. Filamentous algae was not recorded at any site prior to 7 February, but it is also possible that the sites visited prior to that date did not characteristically have filamentous algae present. This uncertainty means that the data possibly underestimate the spatial extent of filamentous algae presence throughout streams of the Study Area. Of the sites where the cover of filamentous algae was estimated, 25% had algae present at some level. Of these sites (Figure 41) the percentage of the bed covered with filamentous algae was generally low, with 20% having < 1% cover, 27% having 1 – 5% cover, 30% having 5 – 25% cover, 9% having 25 – 50% cover and 14% having 50 – 75% cover. No sites had filamentous algae at > 75% cover. The data suggest that filamentous algae was typical of Hornes Creek, Cow Creek, creek XB, Eliza Creek and some shallow sections of Bargo River (Figure 41; Figure 51).

The cause of the algal growth was not investigated, nor were nutrient levels measured. However, each location where filamentous algae growth was found had potential sources of nutrient enrichment in upstream areas: Hornes Creek receives drainage from the town of Bargo, Bargo River receives drainage from several villages in its headwaters, the sites on creek XB were immediately downstream of a school sports oval, and Cow Creek receives runoff from the Hume Highway and an unsealed access track that runs around the northern and western edges of its catchment. Eliza Creek is perhaps a unique case because the presence of filamentous algae coincided with the presence of ferruginous colloids suspended in the water, and all observations but one were found downstream of a point where fill had been pushed into the stream from above. These two issues are reported in separate sections of this report.

3.3.8 Surface flow lost to subsurface

Loss of surface stream flow to the subsurface, either as hyporheic flow (within the bed sediments) or loss to groundwater, is usually only noticeable to the casual observer if flow ceases. This situation was observed in four locations in the Study Area (Figure 41). It is possible that this phenomenon was active to a lesser extent elsewhere (i.e. a proportion of the flow lost to the subsurface), but went unnoticed.

The loss of surface flow was measured in the field at two locations using an estimate of velocity and flow cross-sectional area. Conditions at the other two sites were unsuitable for flow gauging. The details of the points of surface flow loss are:

- XA2-1 (7/2/2013)……………………. flow ceased for 85 m…… flow rate 0.36 ML/d at point of loss, and 0.14 ML/d where it returned
- XB2-1 (7/2/2013)……………………. flow ceased for 225 m (to Bargo River)…………….. flow rate 0.22 ML/d at point of loss
- CO1-1 (Cow Creek) (18/2/2013)….. flow ceased for 17 m…… flow rate not measured
- CO2-1 (Cow Creek) (18/02/2013)… flow ceased for 20 m…… flow rate not measured

Creeks XA2-1 and XB2-1 were located over an area that had formerly been mined (Figure 23), and there were some fractures observed in the beds of these creeks that were suggestive of a mining impact. This is it possible that the loss of surface flow in creeks XA2-1 and XB2-1 was a mining impact, but this cannot be firmly established. Regardless, the existence of the sites on Cow Creek, which is located within an undisturbed catchment, suggests that temporary loss of surface flow to the subsurface can occur naturally.

3.3.9 Ferruginous seeps from rock

Ferruginous seeps in rocks close to stream channels were uncommon in the Study Area. One seep was observed on DT2-1 (Dog Trap Creek), and one on CA2-1 (Carters Creek) (Figure 41). The seep on Dog Tap Creek covered a very small area of a few square centimetres, while the seep on Carters Creek was more substantial. The seep on Carters Creek was clearly related to emergence of water to the creek that had seeped through the wall of a farm dam located immediately upstream (Figure 52). The creek water downstream of this ferruginous seep was not discoloured.

3.3.10 Ferruginous colloids suspended in stream water

The storm event of 27 – 29 January would have temporarily flushed any suspended ferruginous material from streams. The phenomenon of ferruginous colloids suspended in stream water was not recorded at any site prior to 11 February, but it is also possible that the sites visited prior to that date did not characteristically have suspended ferruginous colloids present. This uncertainty means that the data possibly underestimate the spatial extent of the presence of suspended ferruginous colloids throughout streams of the Study Area. Suspended ferruginous colloids were observed in only two streams, Sugarloaf Gully and Eliza Creek (Figure 41).

Suspended ferruginous colloids were present in the water of Sugarloaf Gully over a 310 m long reach. Both the beginning and end of the affected reach was abrupt. In this case, where the water flowed shallowly over bedrock the iron formed a precipitate, which had the appearance of a seep (Figure 53). The ferruginous material stopped at a large dam across the creek, which casts suspicion on the dam as playing a role in the release of iron to the stream. However, the water in the dam was clear (Figure 53).

Eliza Creek was affected by suspended ferruginous colloids downstream of the Pheasants Nest Road Bridge (Figure 41, Figure 54). The effect was quite marked, creating turbidity in the water and a precipitate where the water flowed shallowly over bedrock. In this area, the ferruginous colloids occurred in association with filamentous algae (Figure 54). The presence of the colloids was strong for a distance of 640 m, after which the water cleared for a distance of 455 m. The failed dam was then encountered (see above), after which the suspended ferruginous colloids reappeared for a further 310 m. Further downstream the water then cleared and remained so all the way to the junction with the Nepean River.

3.4 Summary of existing geomorphic character

3.4.1 Landscape scale characteristics

The Study Area is located in a region characterised by generally weakly developed soils on sandstone and shale. Some of the soils are highly susceptible to erosion by concentrated water flow, but in this would be expected of weakly developed soils in steep environments. The susceptibility of the soils to water erosion is part of the natural process of delivery of sediment to streams. The streams comprise small headwater streams on relatively low gradient plateau landscapes and streams eroded into rocky gorges. The gorges are rimmed by cliffs of various lengths and heights, with densely vegetated talus slopes below the cliffs. These cliffs, and the talus slopes below them, appeared to be relatively stable.

3.4.2 Stream reach- and point-scale characteristics

The streams of the Study Area were of two main types – headwater and gorge. Being bedrock controlled, they are naturally resilient to geomorphic change. The majority of streams were in a stable, close to natural geomorphic condition. Some streams were impacted by factors that marginally reduced their condition. These factors included clearance of riparian trees, licenced discharges, incision, mobile knickpoints, and filamentous algae. Some streams were affected by loss of water to the subsurface over short reaches, and others were impacted by ferruginous seeps and suspended colloids. These factors do not have strong implications for geomorphic condition, but they could have relevance for ecological condition. A few isolated major culverts were judged to be in poor condition, as these were an unnatural stream type.

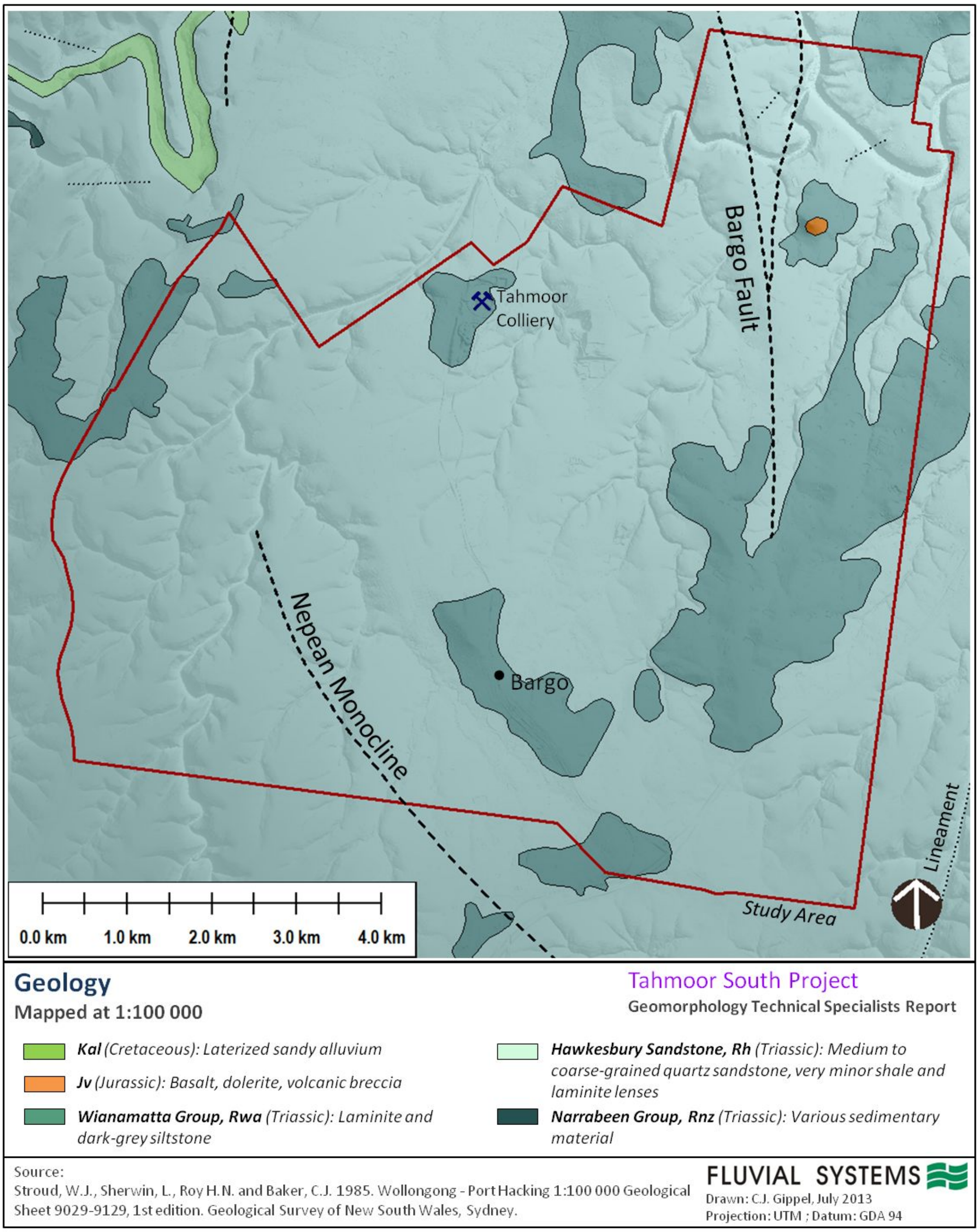

Figure 7. Geology of the Study Area.

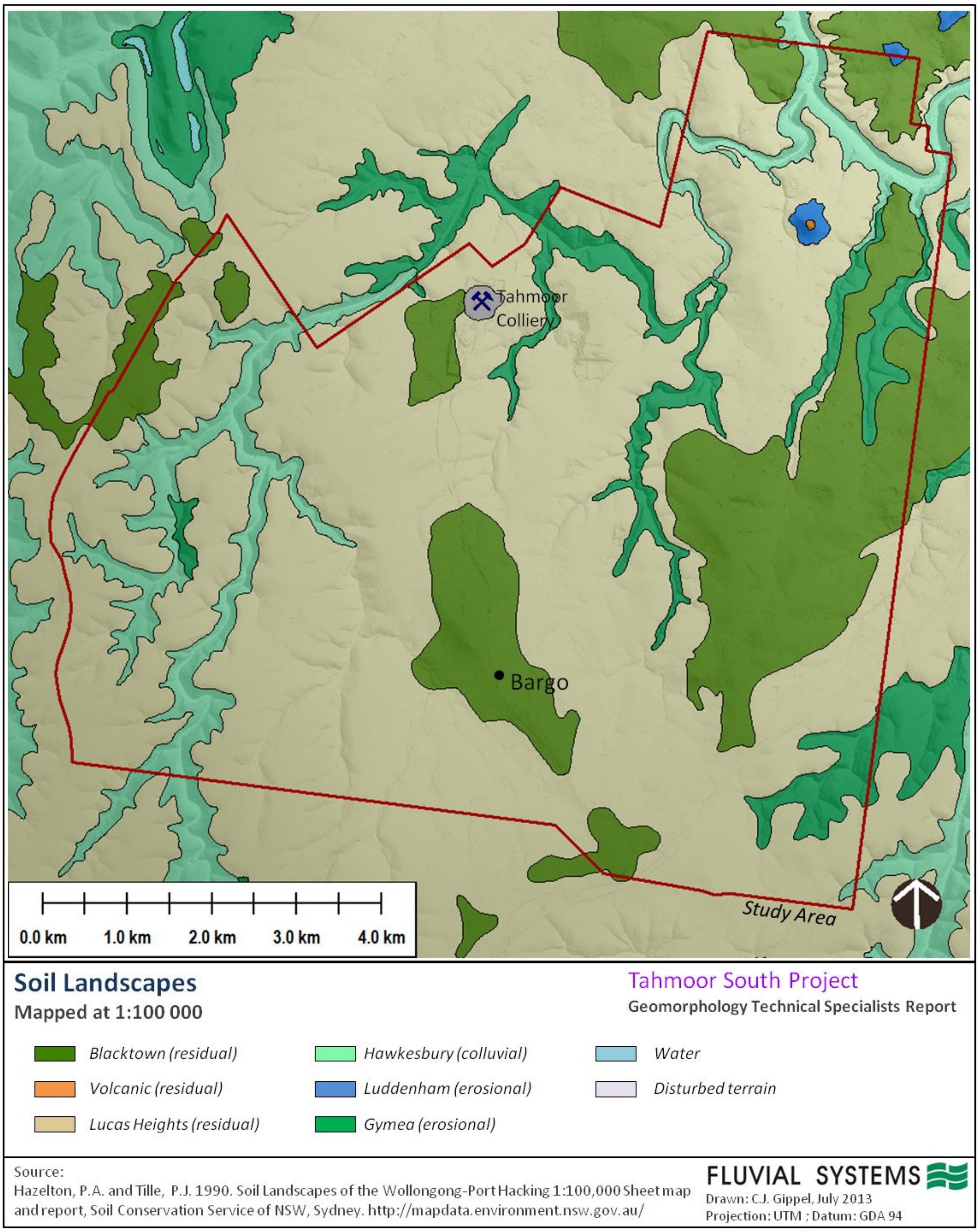

Figure 8. Soil Landscapes of the Study Area.

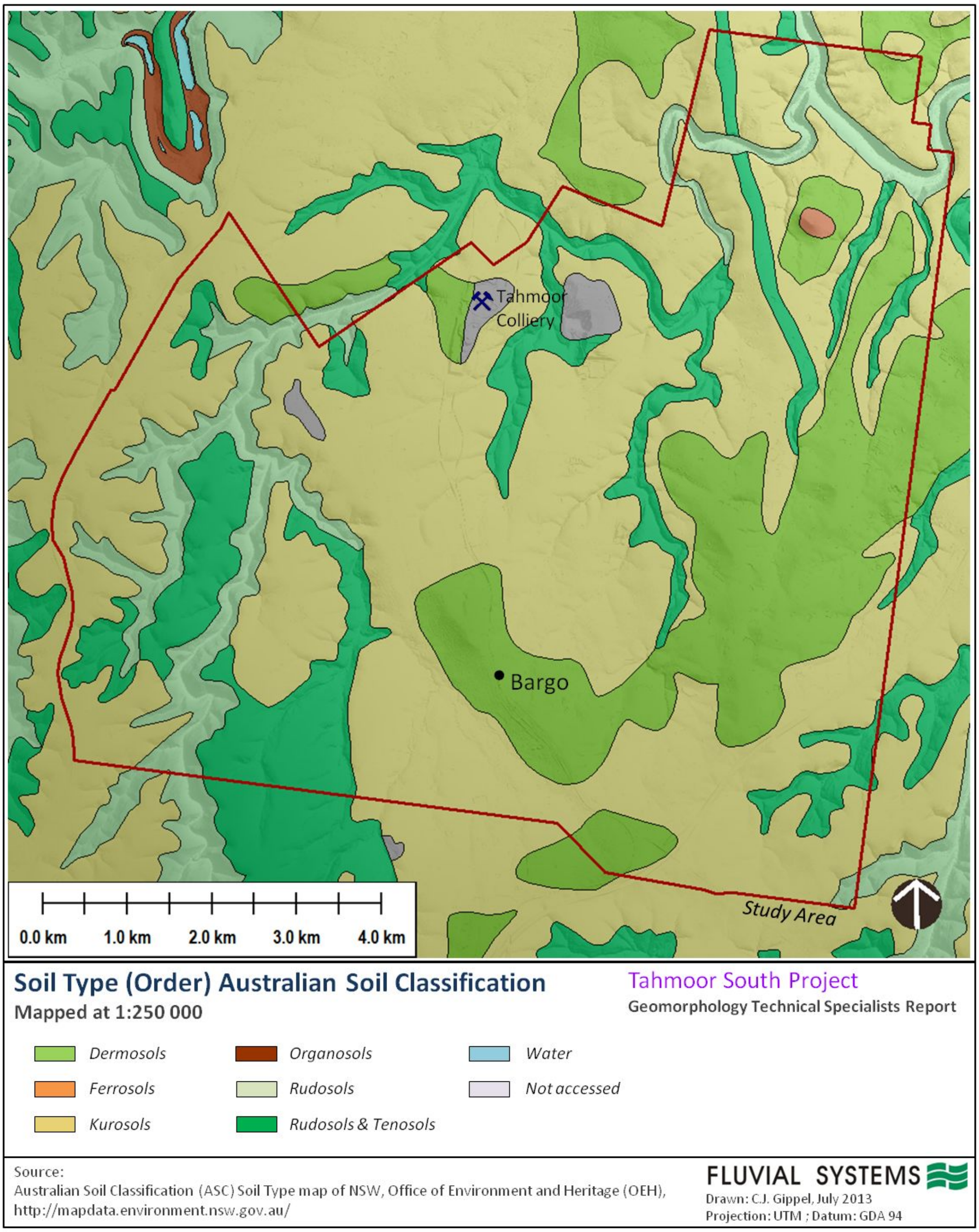

Figure 9. Soil types (Australian Soil Classification, Order) over the Study Area.

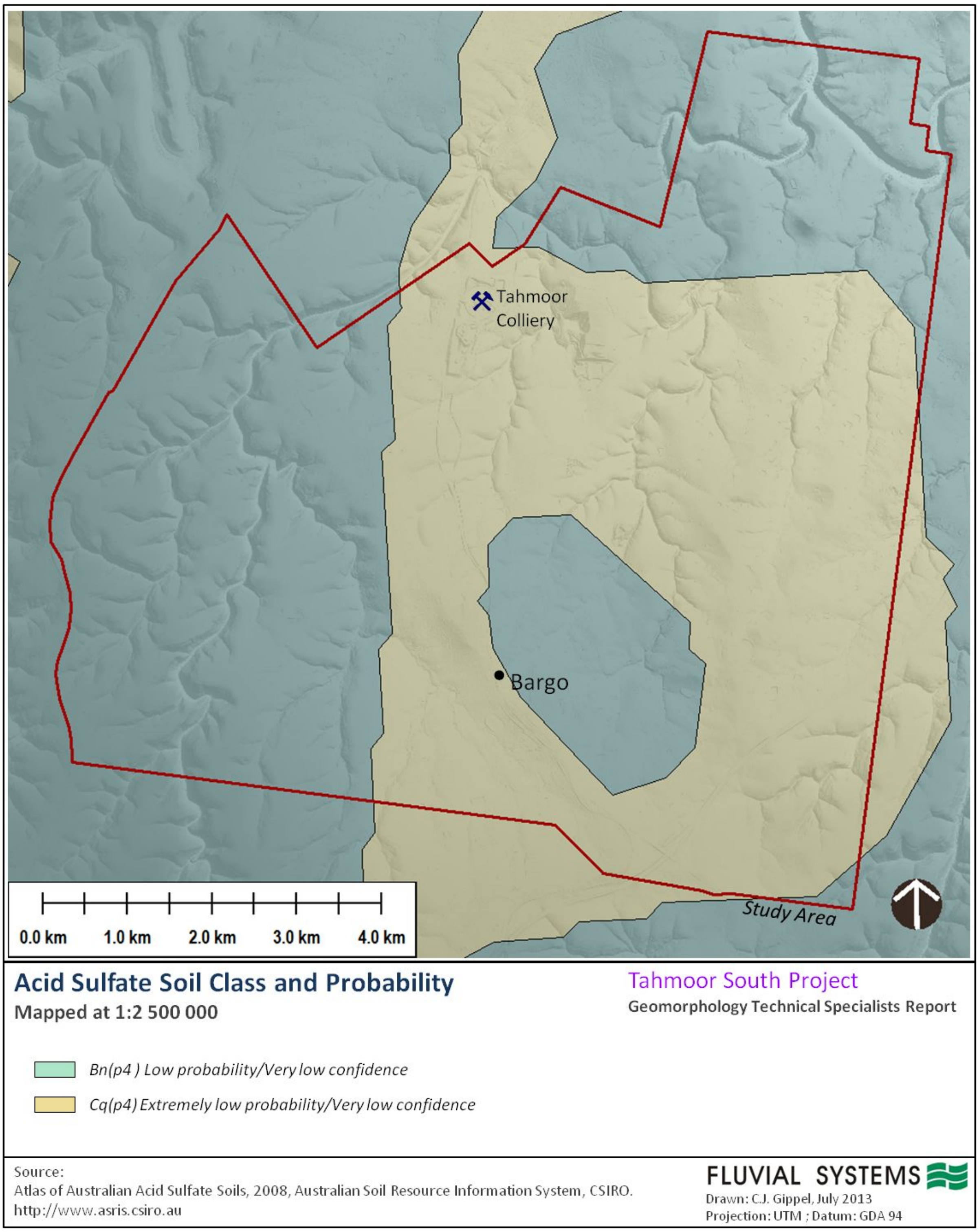

Figure 10. Acid sulphate soil class and probability of occurrence over the Study Area.

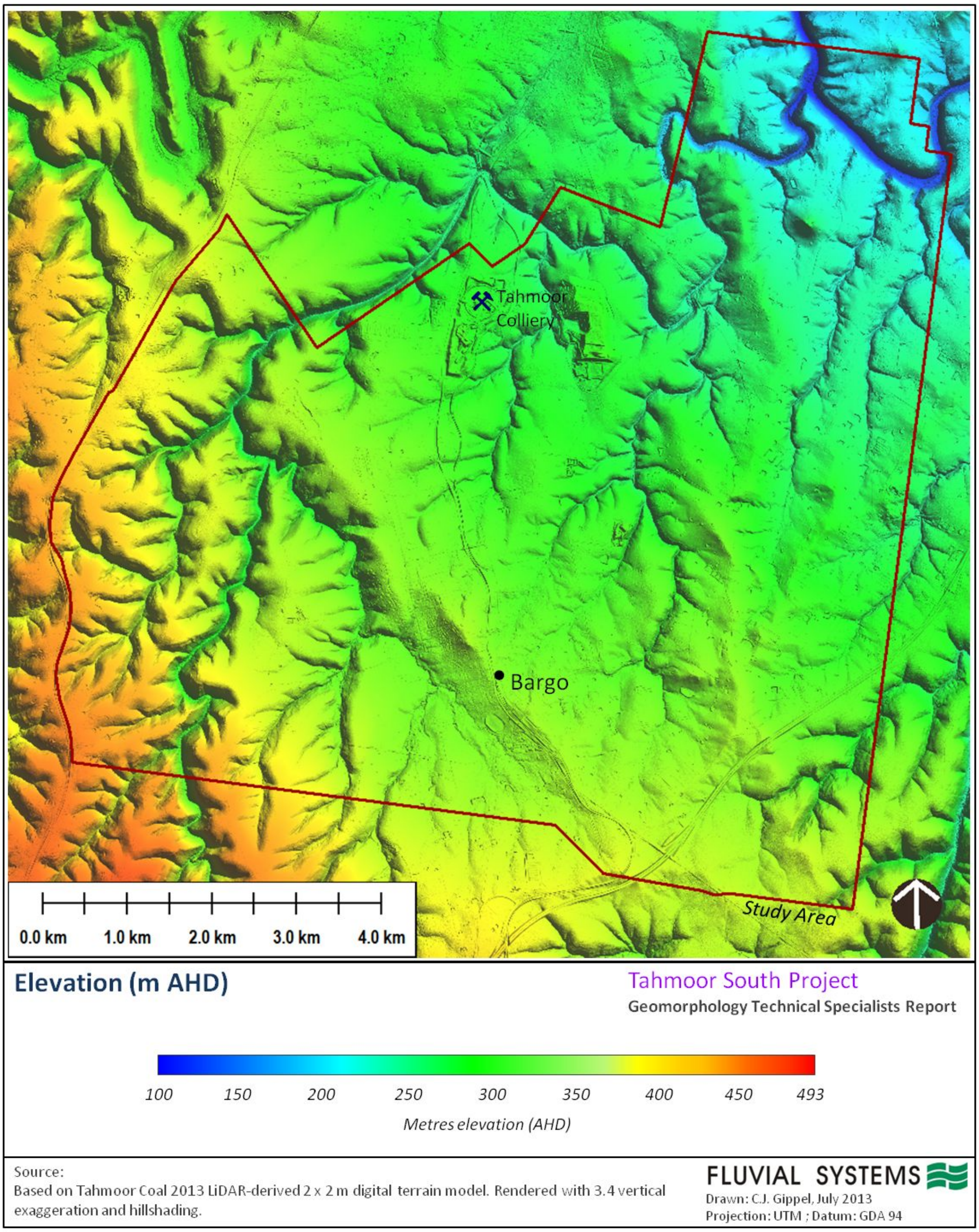

Figure 11. Land elevation over the Study Area.

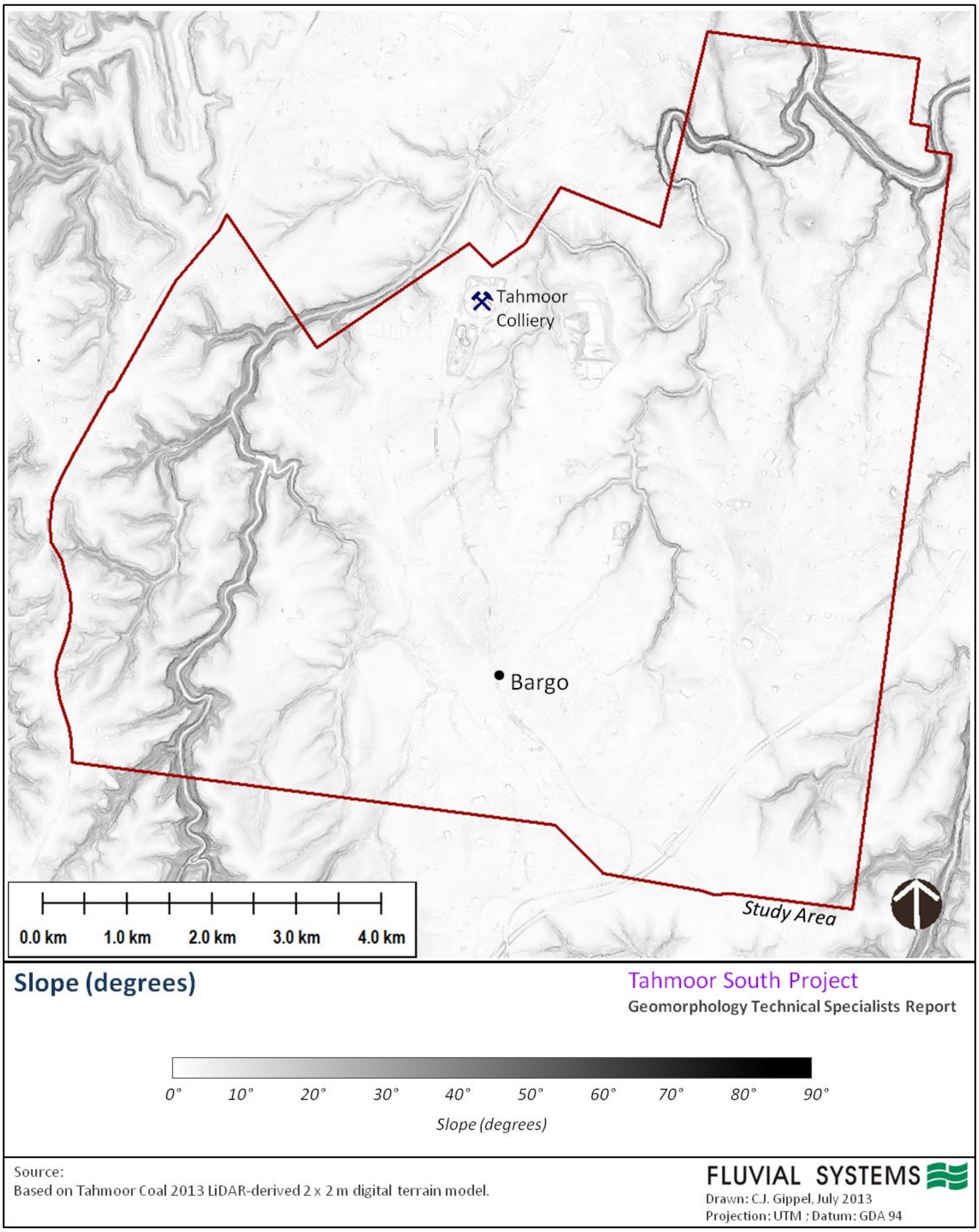

Figure 12. Land slope over the Study Area.

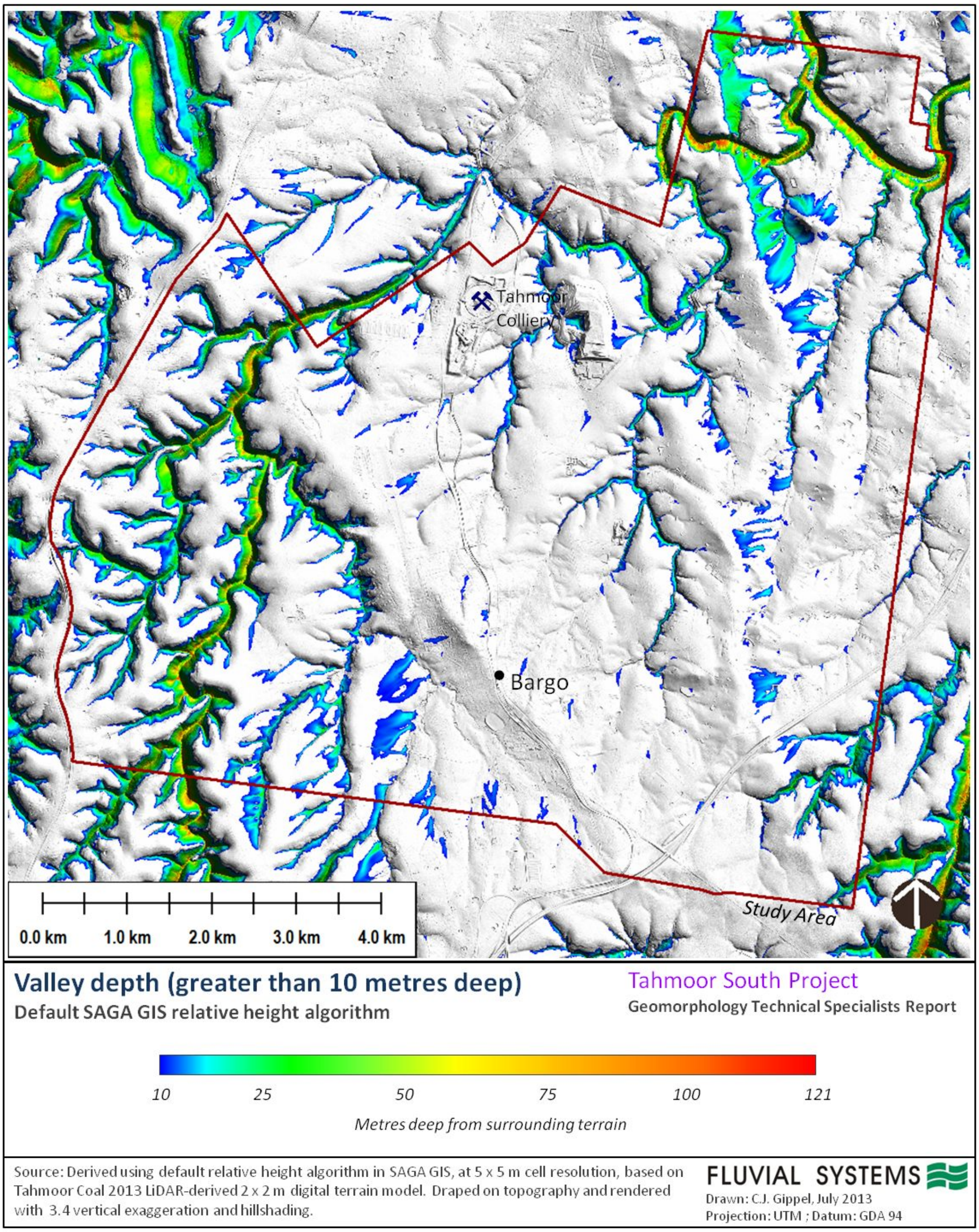

Figure 13. Valley depth greater than 10 metres over the Study Area.

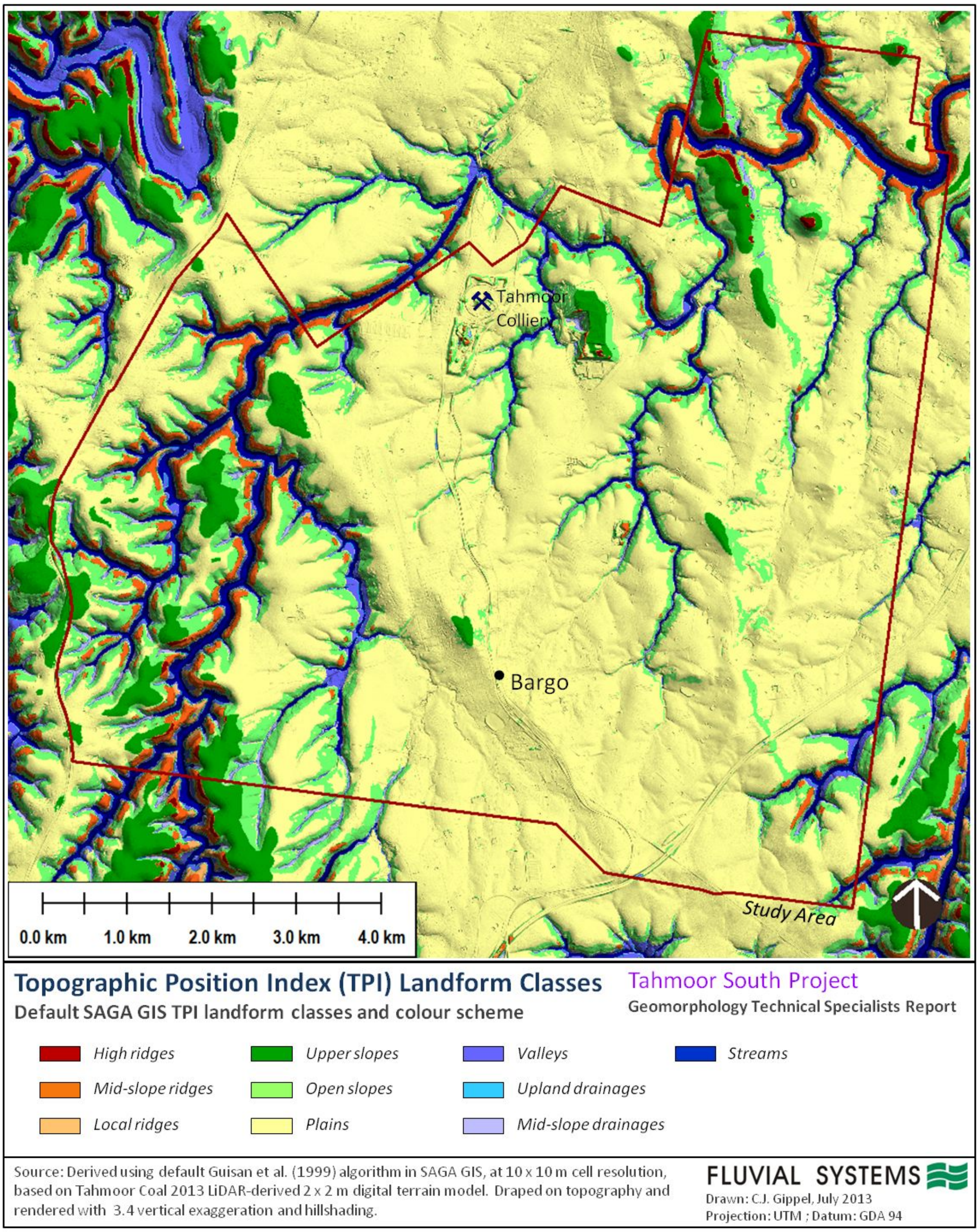

Figure 14. TPI Landform Classification over the Study Area.

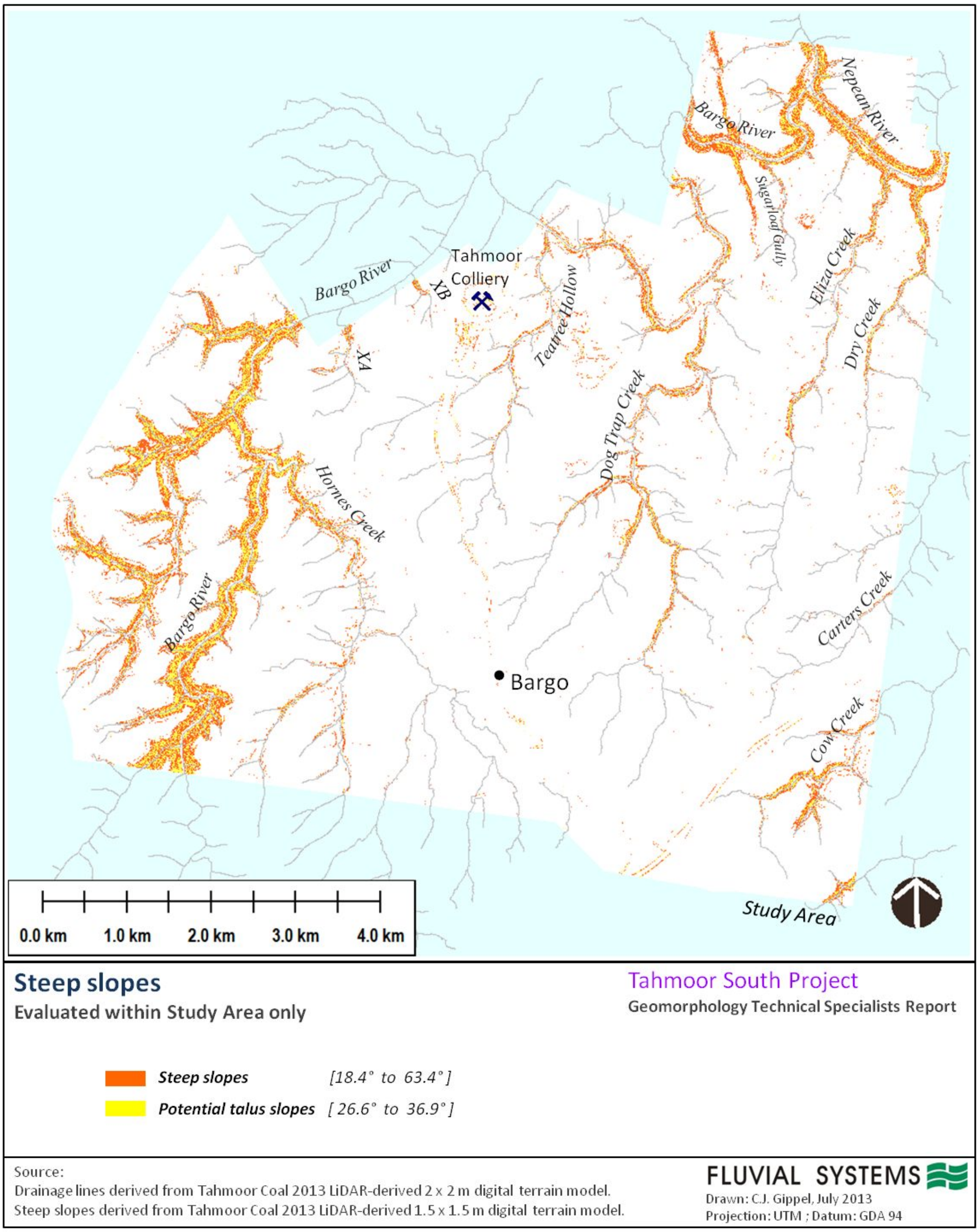

Figure 15. Steep slopes and potential talus slopes within the Study Area.

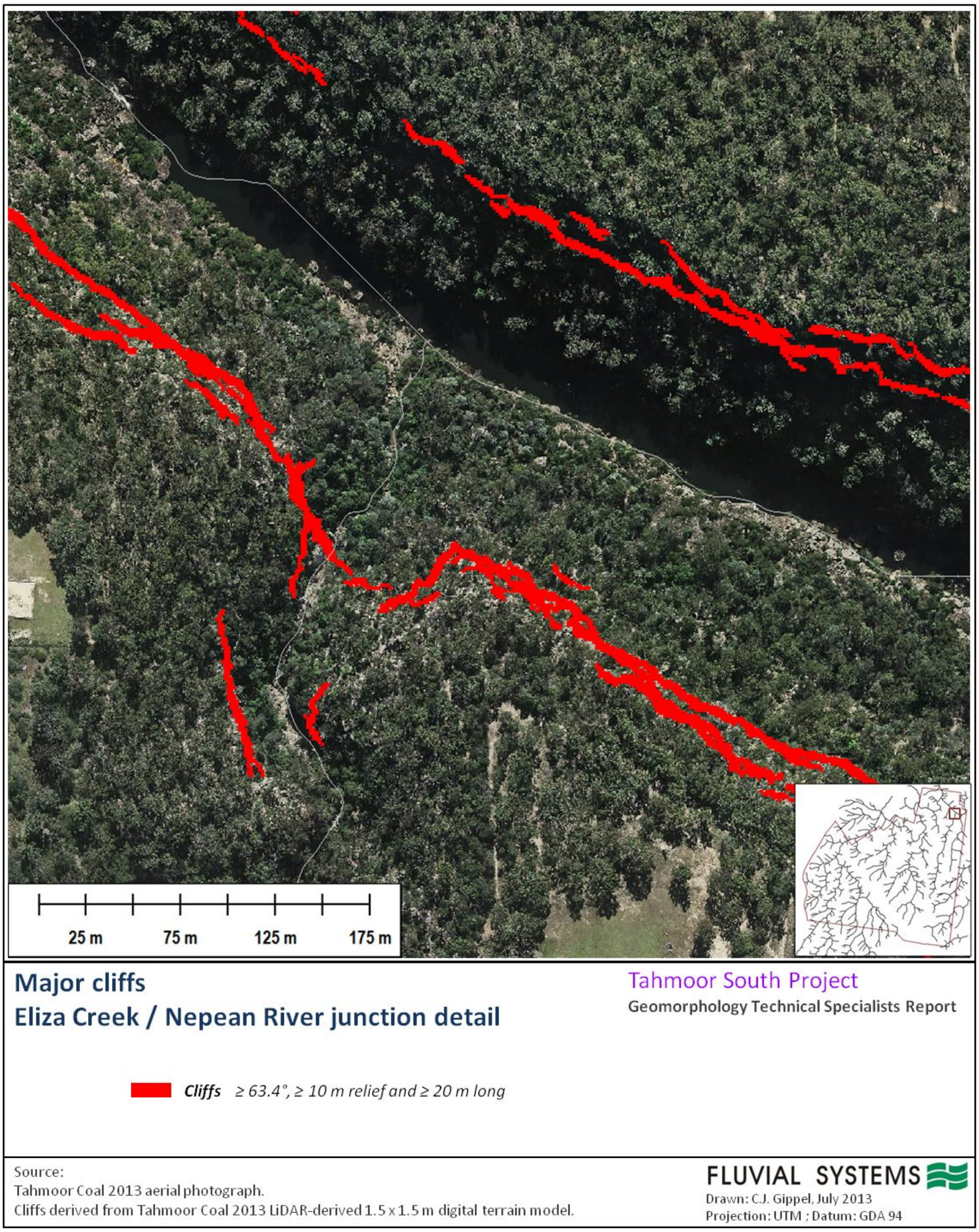

Figure 16. Detail of major cliffs at the junction of Eliza Creek with Nepean River.

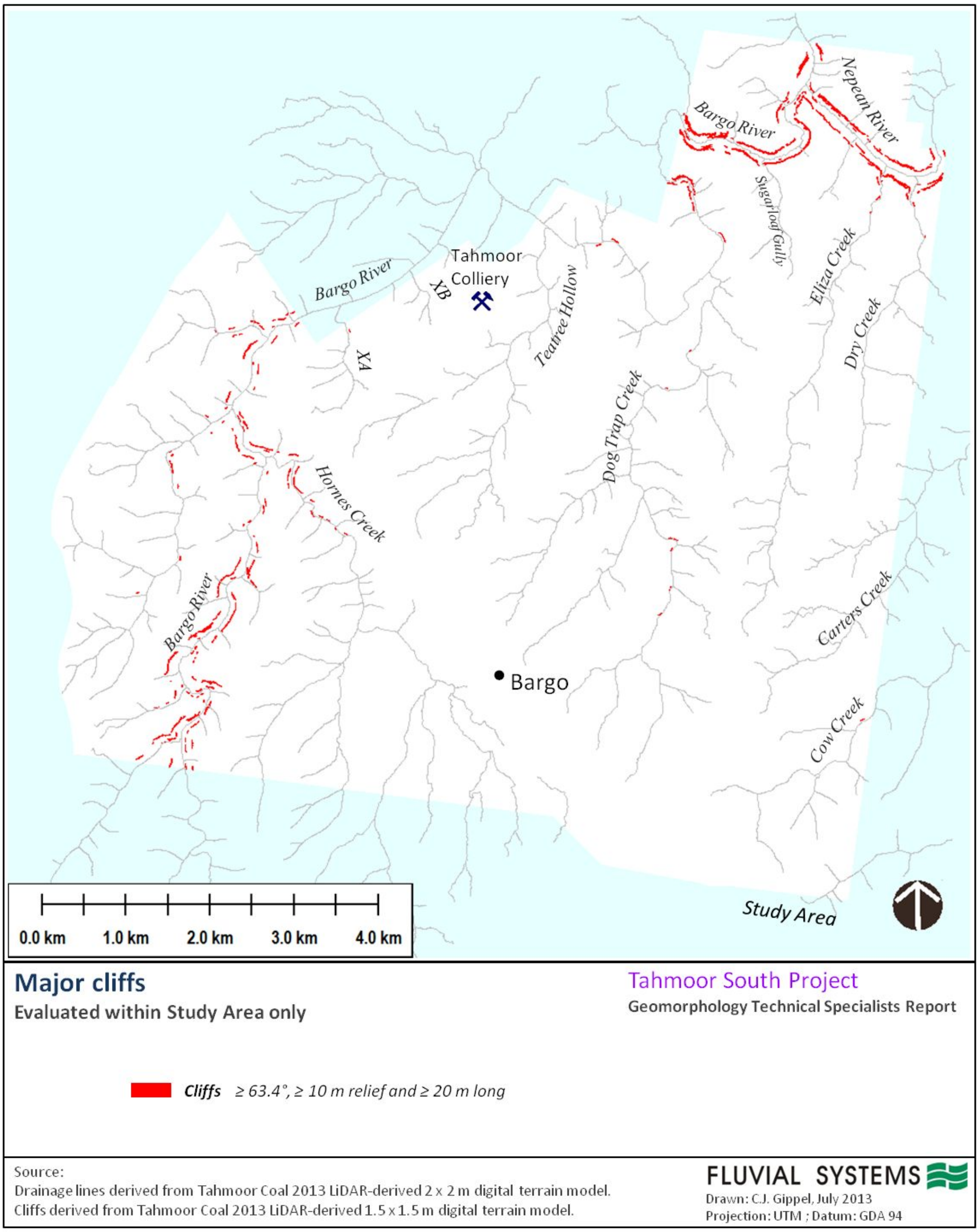

Figure 17. Major cliffs within the Study Area.

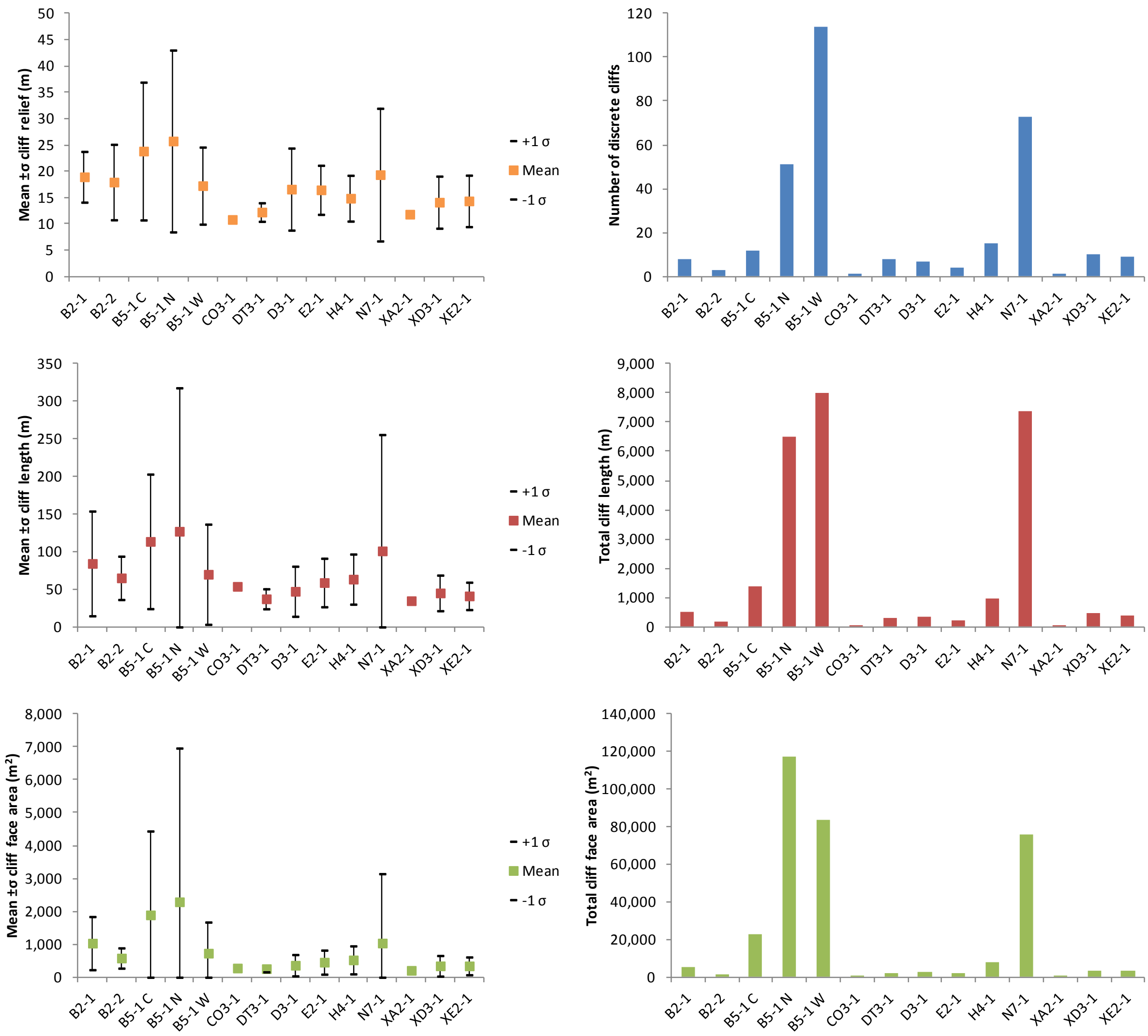

Figure 18. Descriptive statistics of attributes of major cliffs among streams of the Study Area. Streams not included had no such features.

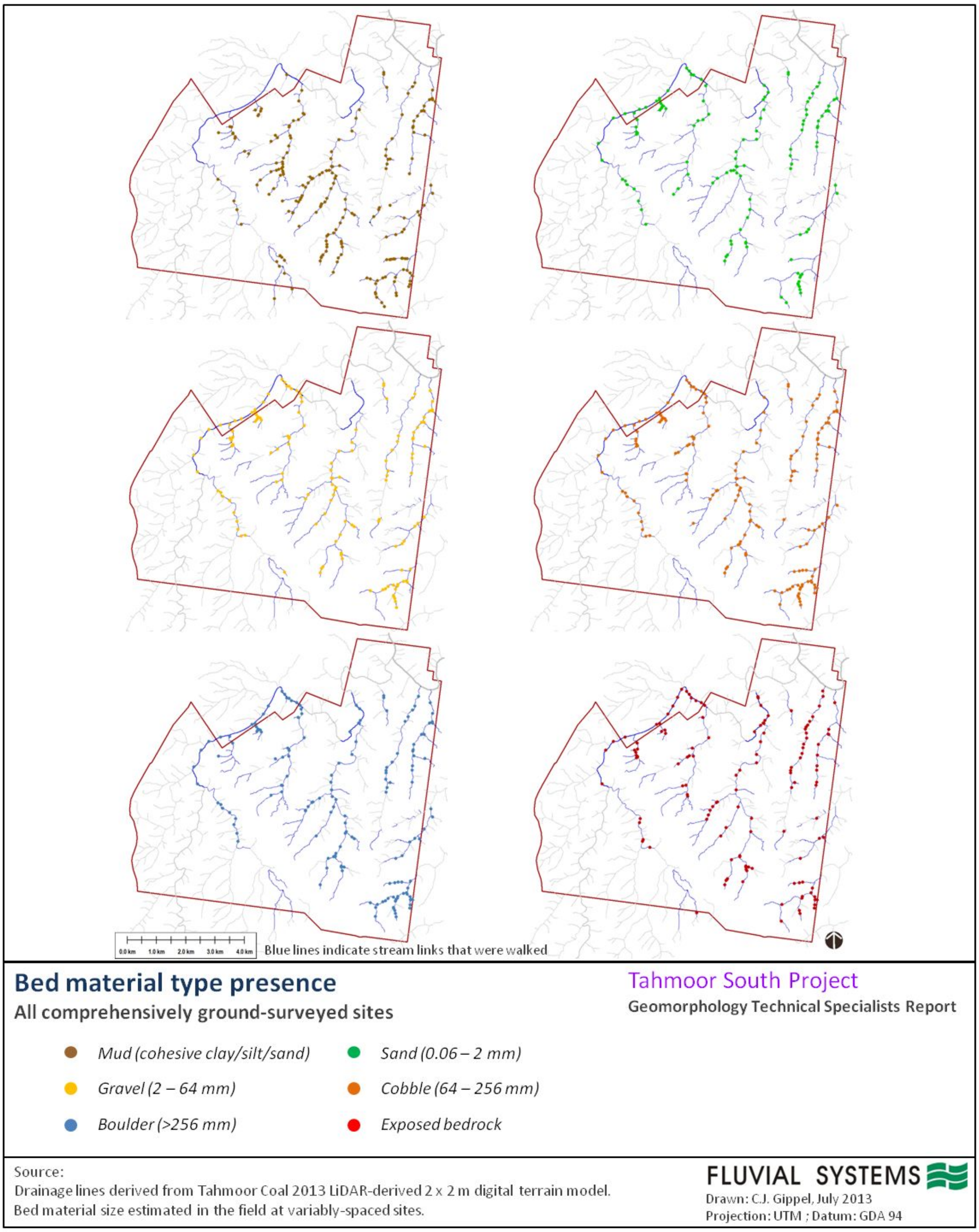

Figure 19. Distribution of bed materials found within the Study Area.

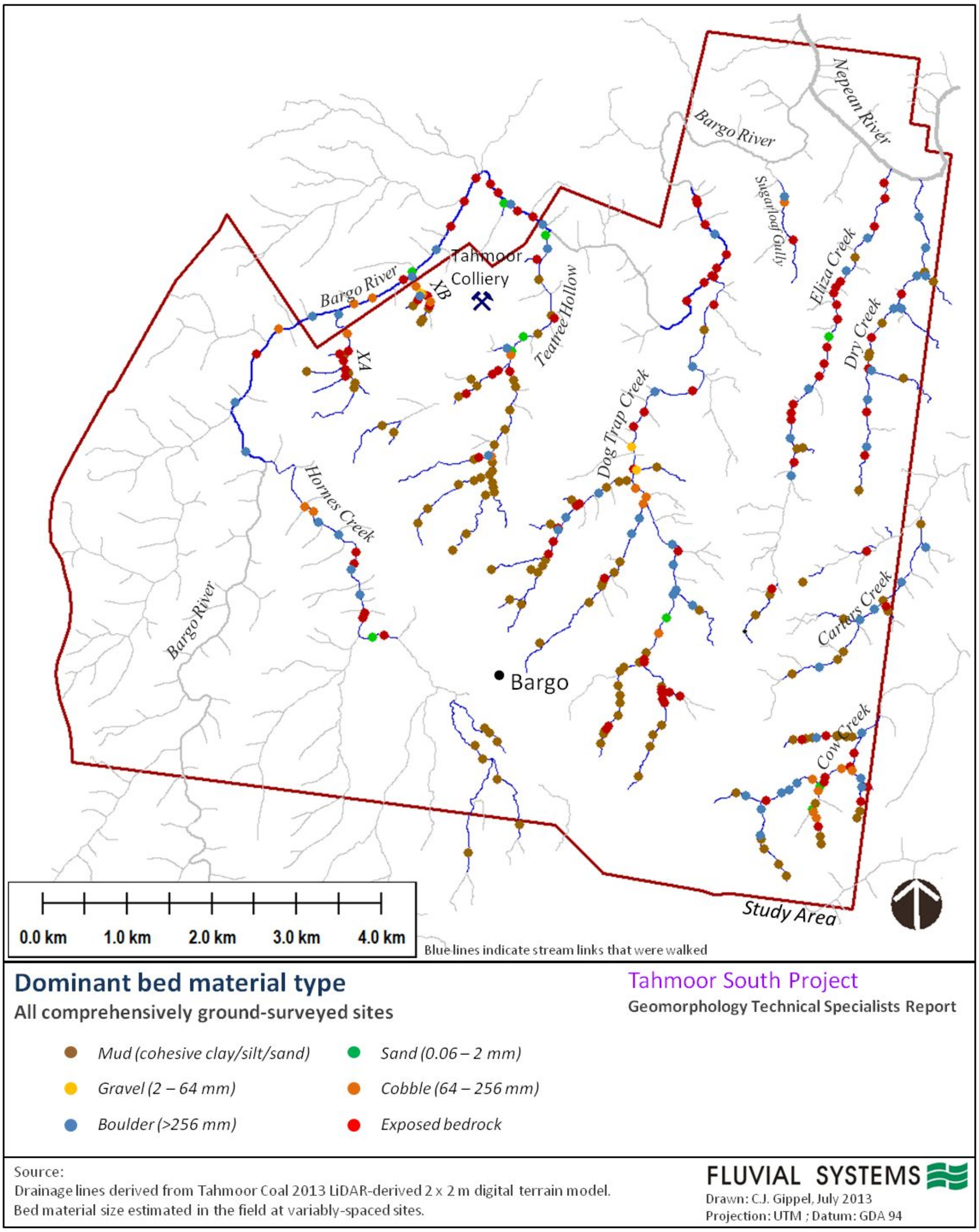

Figure 20. Distribution dominant bed materials found within the Study Area.

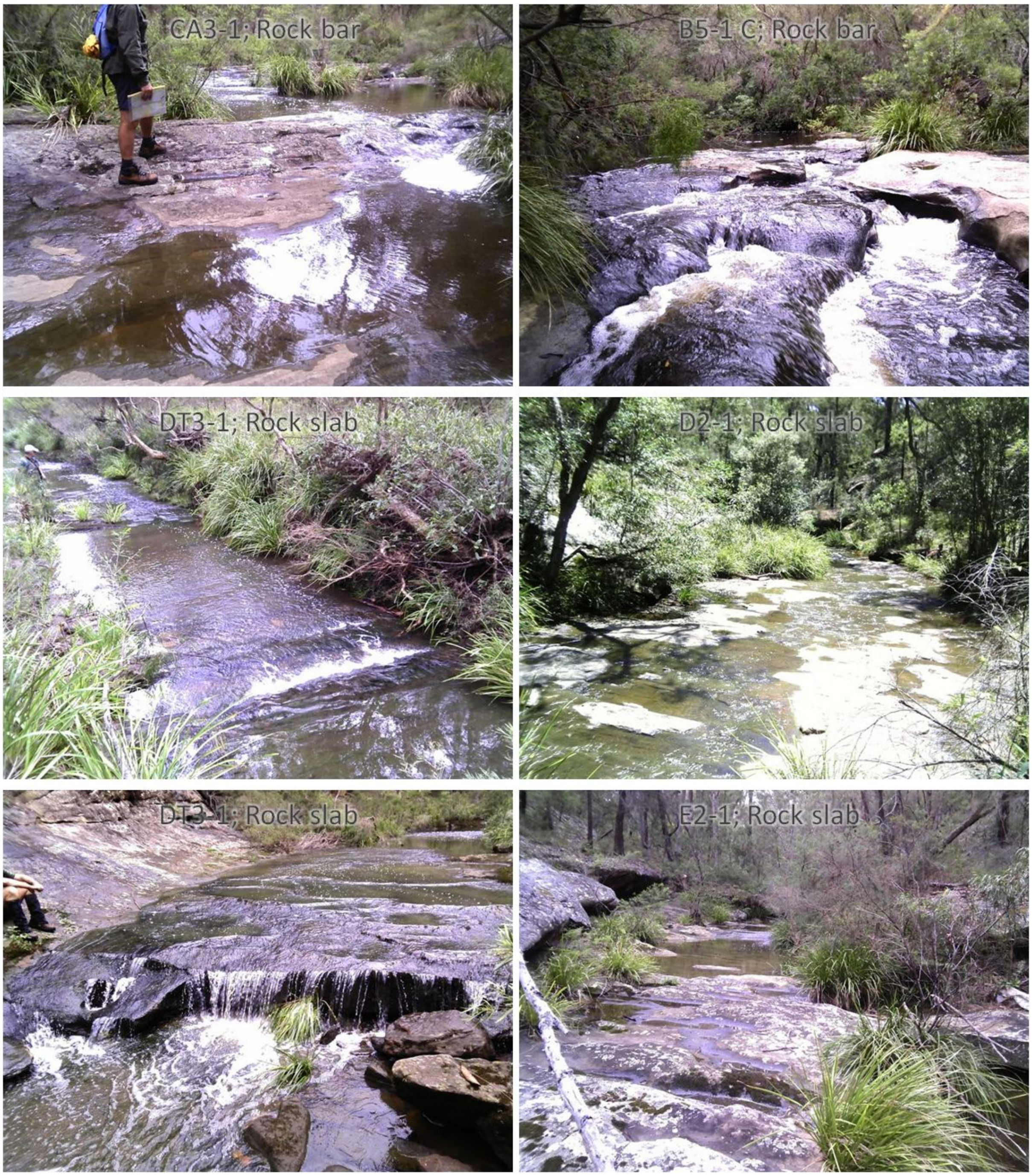

Figure 21. Examples of rock bars and rock slabs. Photography: CA3-1, 30/1/2013; B5-1 C, 12/2/1013; DT3-1, 4/2/2013; D2-1, 31/1/2013; E2-1, 11/2/2013.

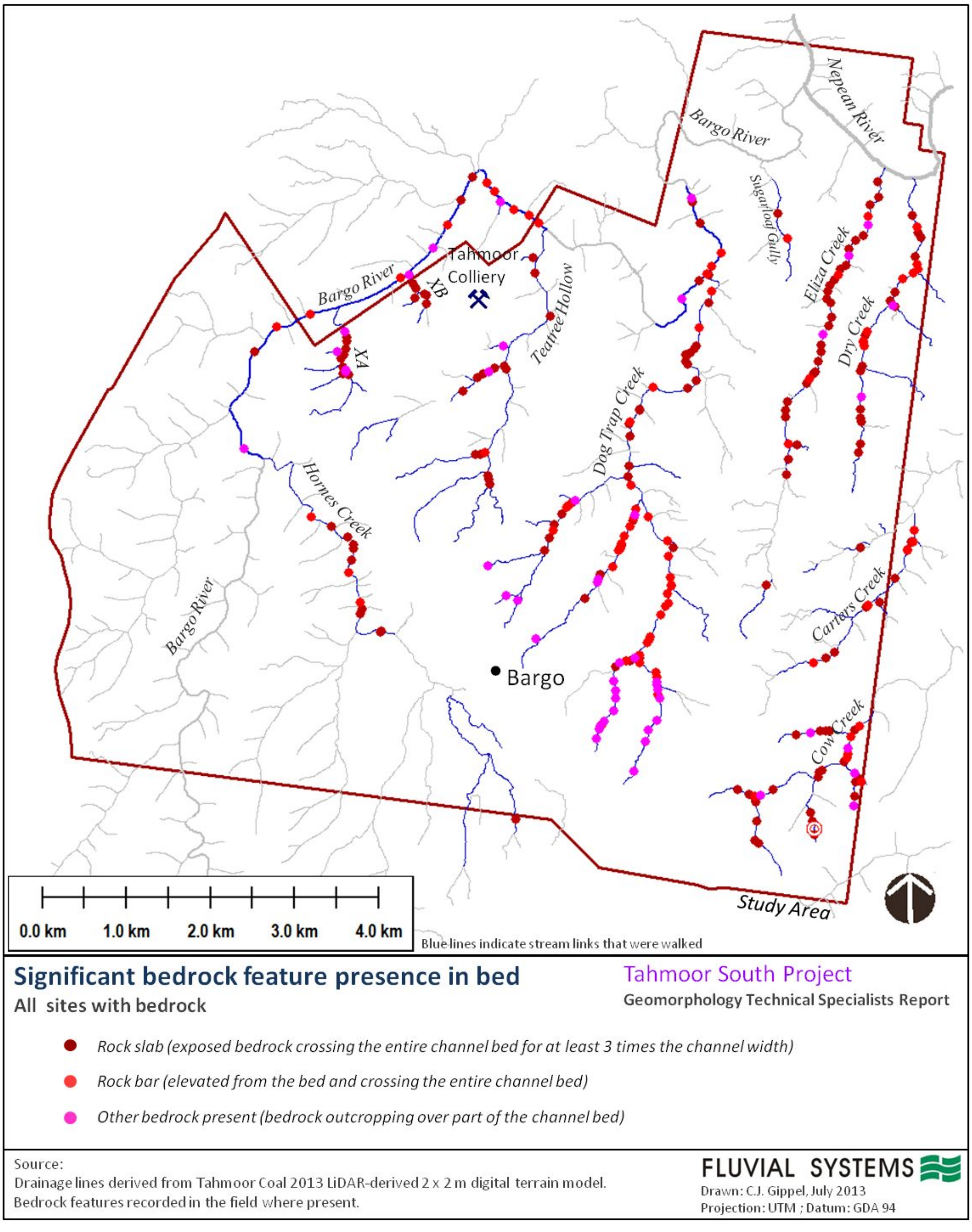

Figure 22. Distribution of significant bedrock features in channel beds within the Study Area.

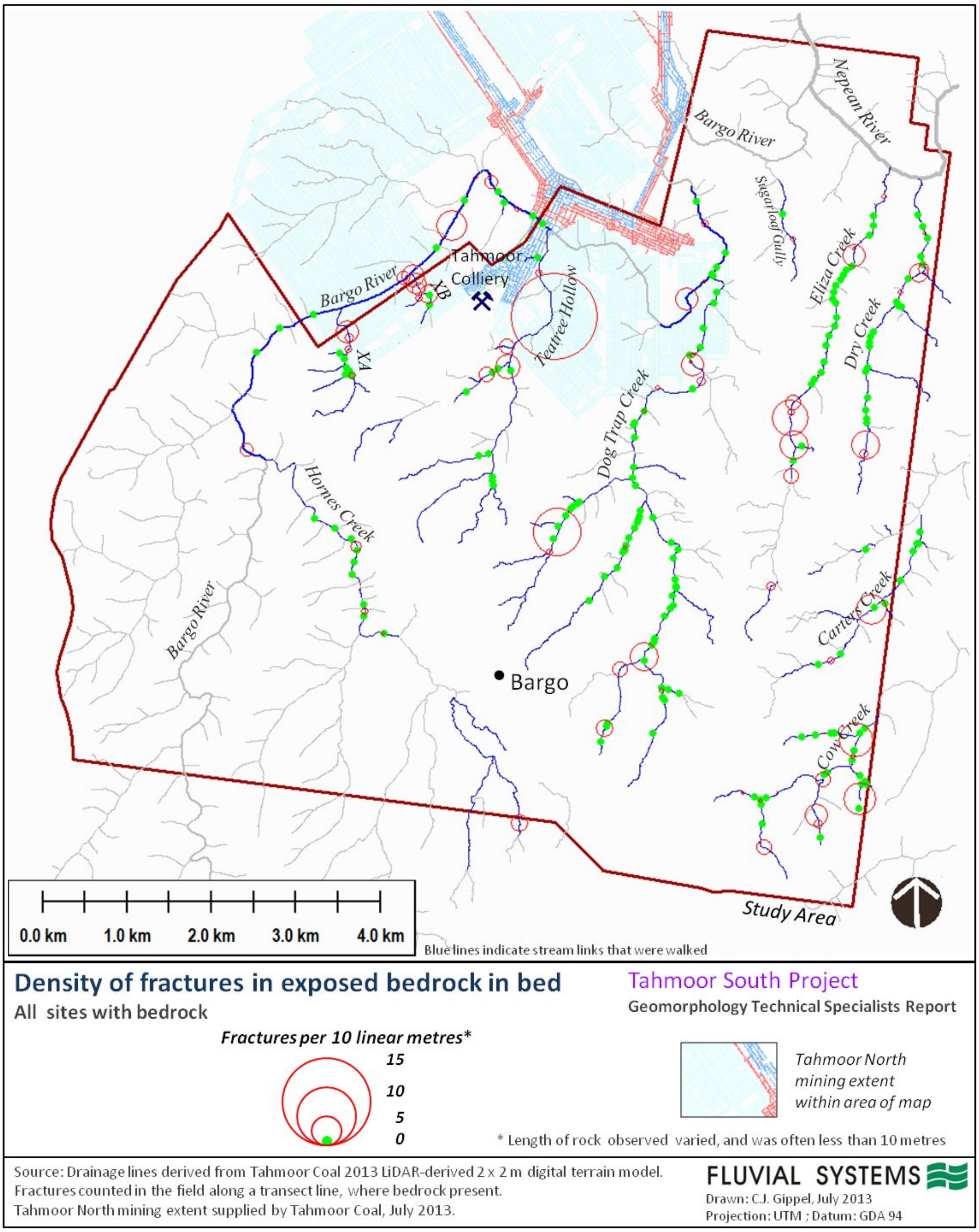

Figure 23. Distribution of density of fractures in exposed bedrock slabs within the Study Area.

Figure 24. Examples of natural fractures in exposed bedrock. Photographed on 11 February 2013 for E2-1, and 30 January 2013 for CA3-1.

Figure 25. Open fractures in exposed bedrock slabs in creeks XA2-1 and XB2-1. Photographed on 7 February 2013.

Figure 26. Examples of hard and soft knickpoints. Photography: E2-1, 13/2/2-13; DT3-1; 4/2/2103; DT1-29, 4/2/2103; TT1-4, 5/2/2013; DT1-14, 23/1/2013; E1-1, 11/2/2013; XB1-2, 7/2/2013; TT2-3, 6/2/2013.

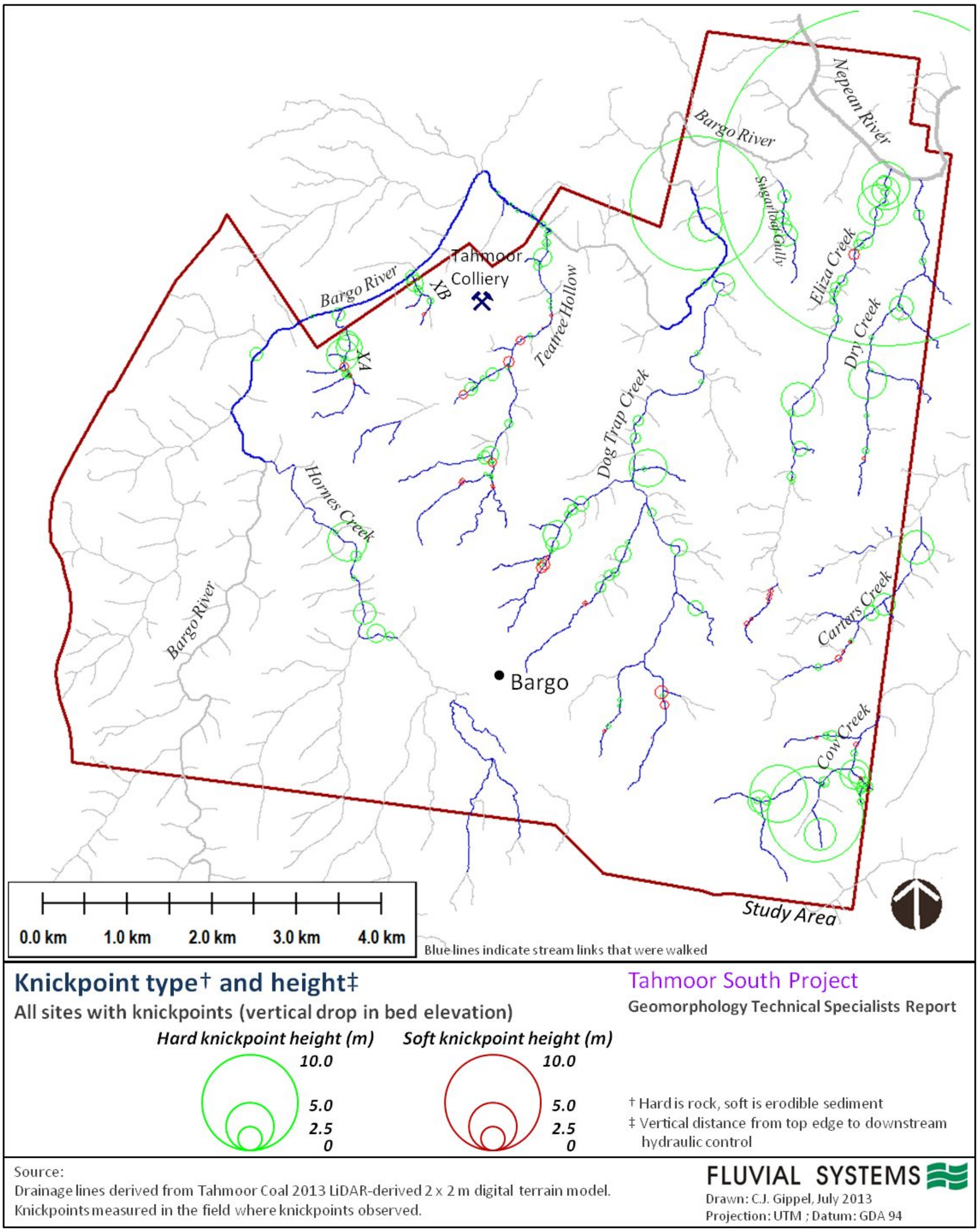

Figure 27. Distribution of knickpoints in streams within the Study Area.

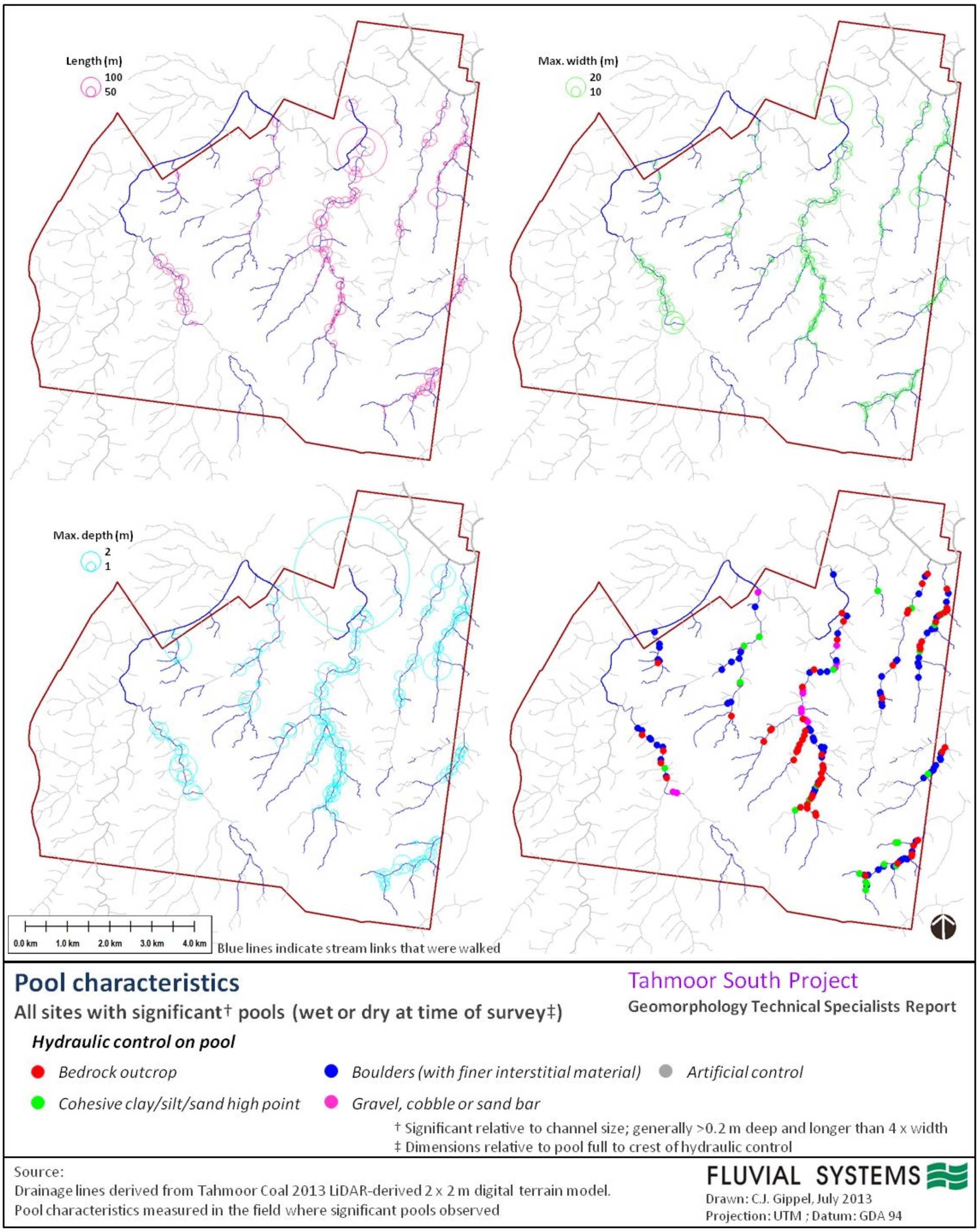

Figure 28. Distribution of in-channel pools in streams within the Study Area.

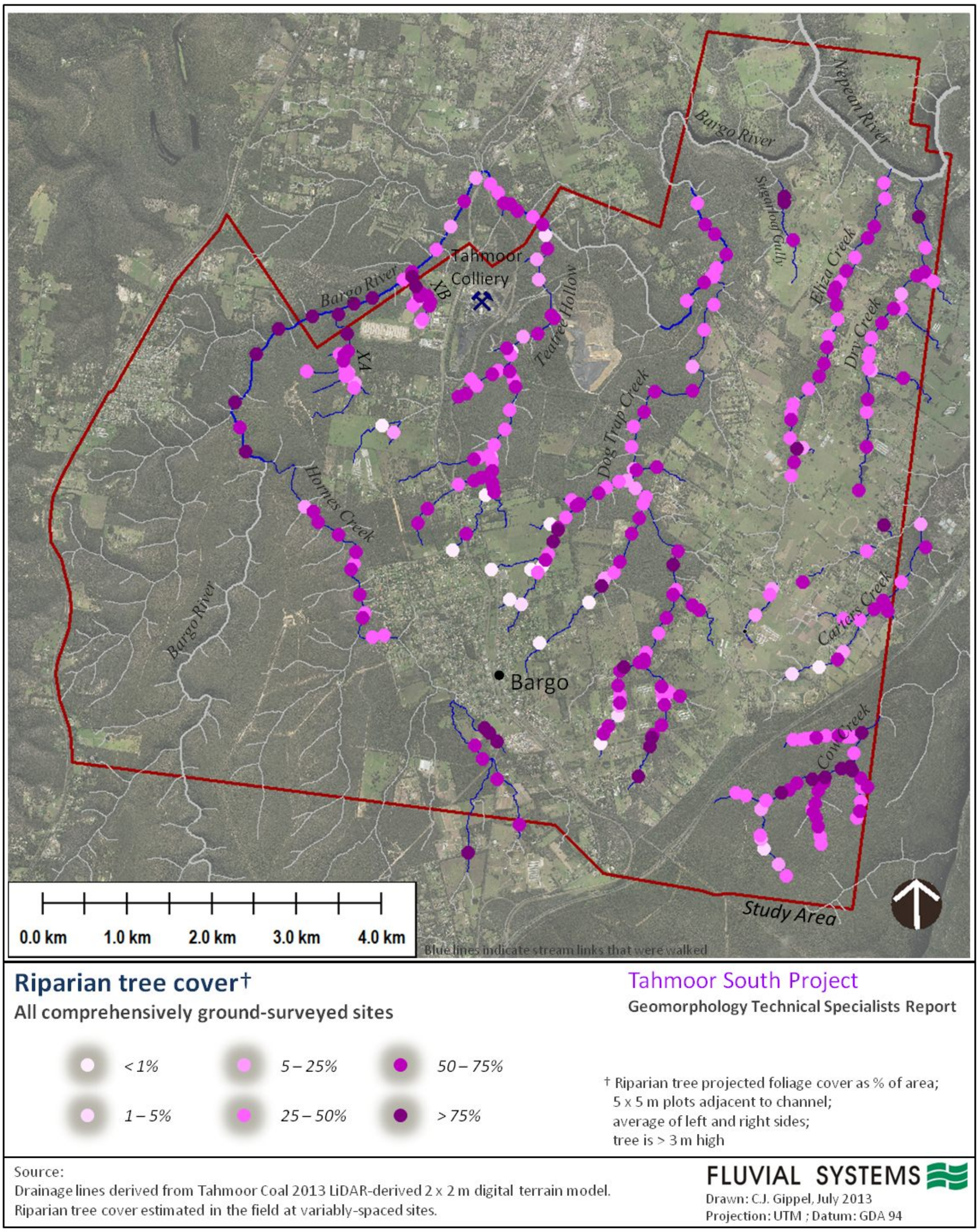

Figure 29. Distribution of riparian tree cover in streams within the Study Area.

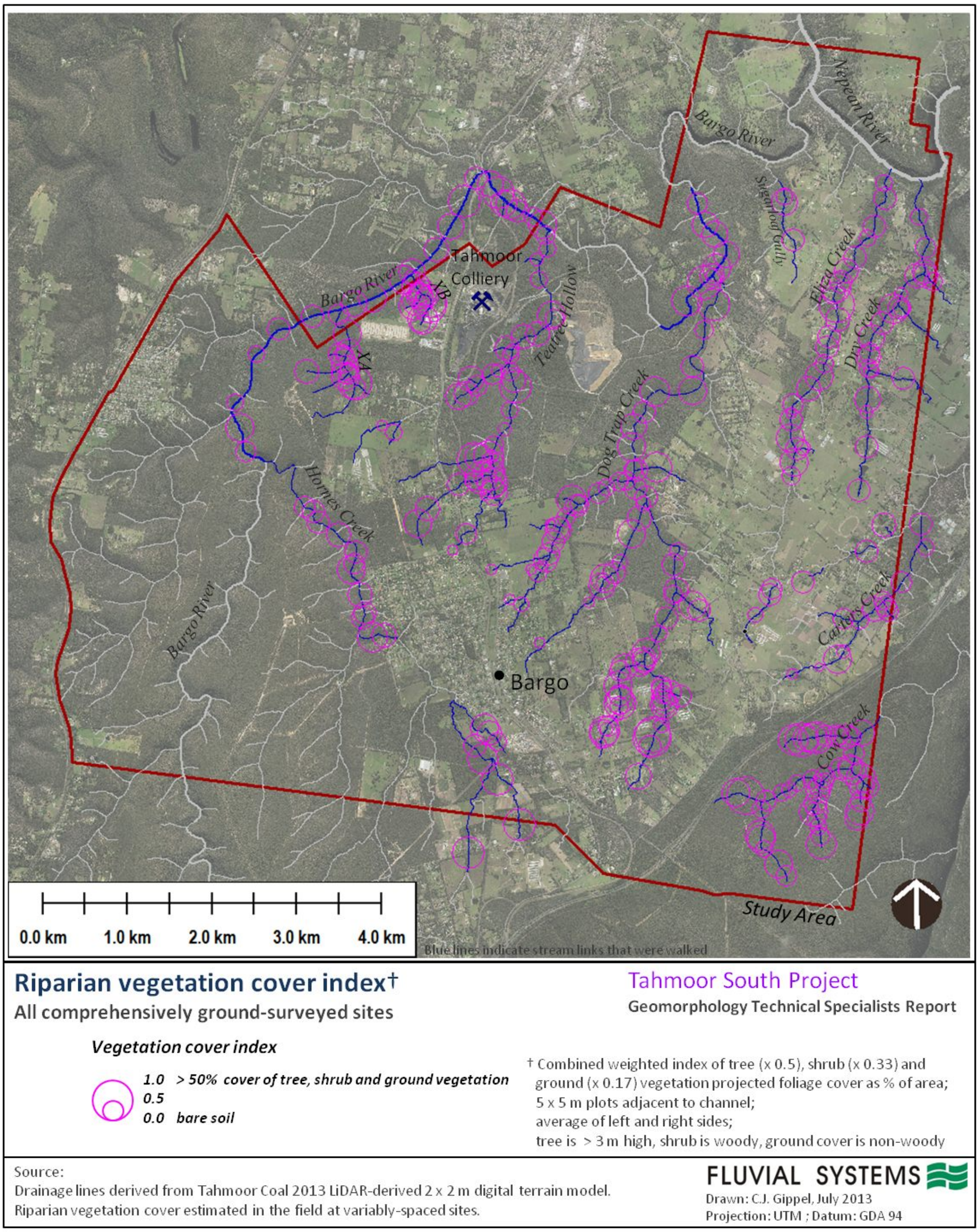

Figure 30. Distribution of riparian vegetation cover index in streams within the Study Area.

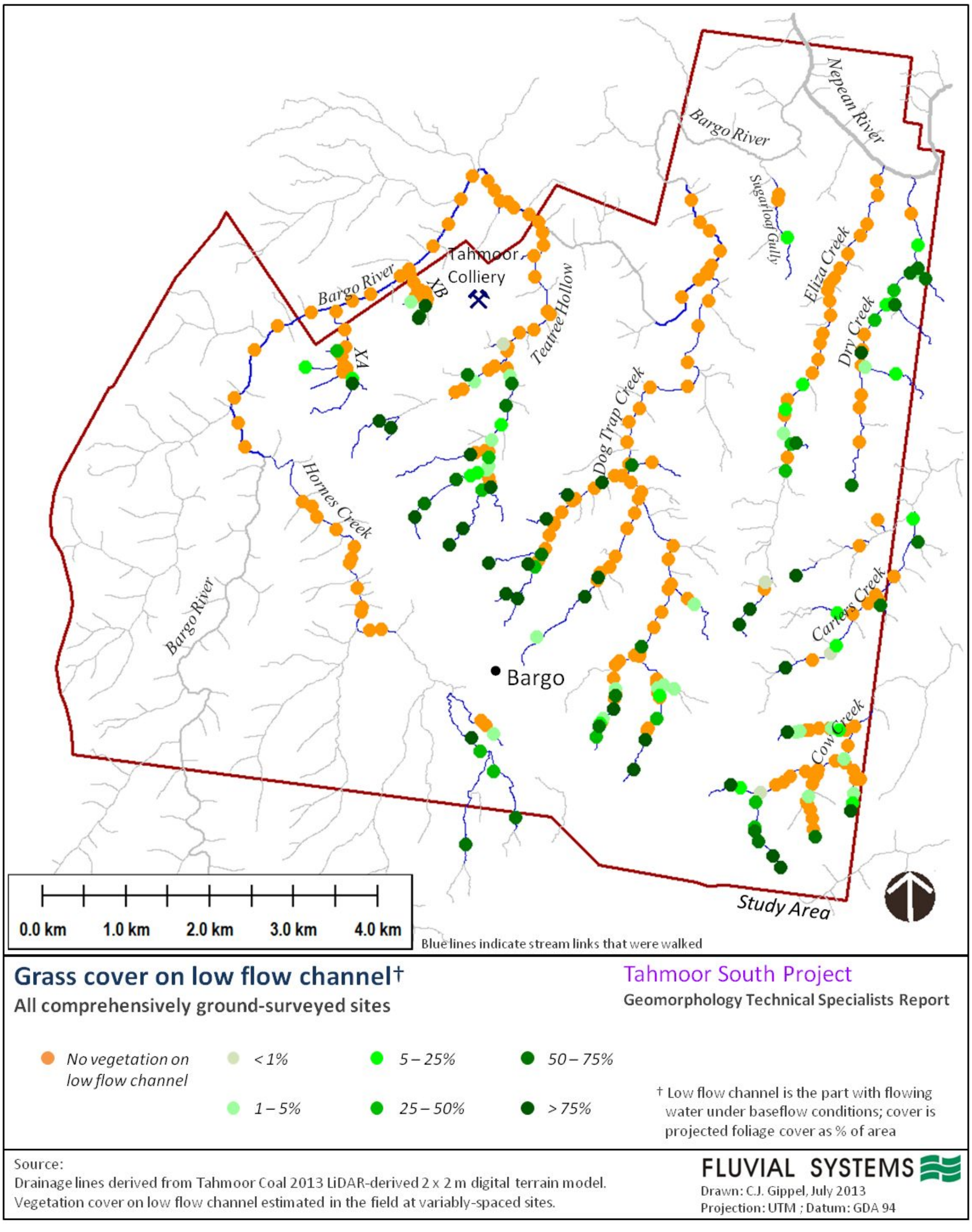

Figure 31. Distribution of grass cover on the low flow channel in streams within the Study Area.

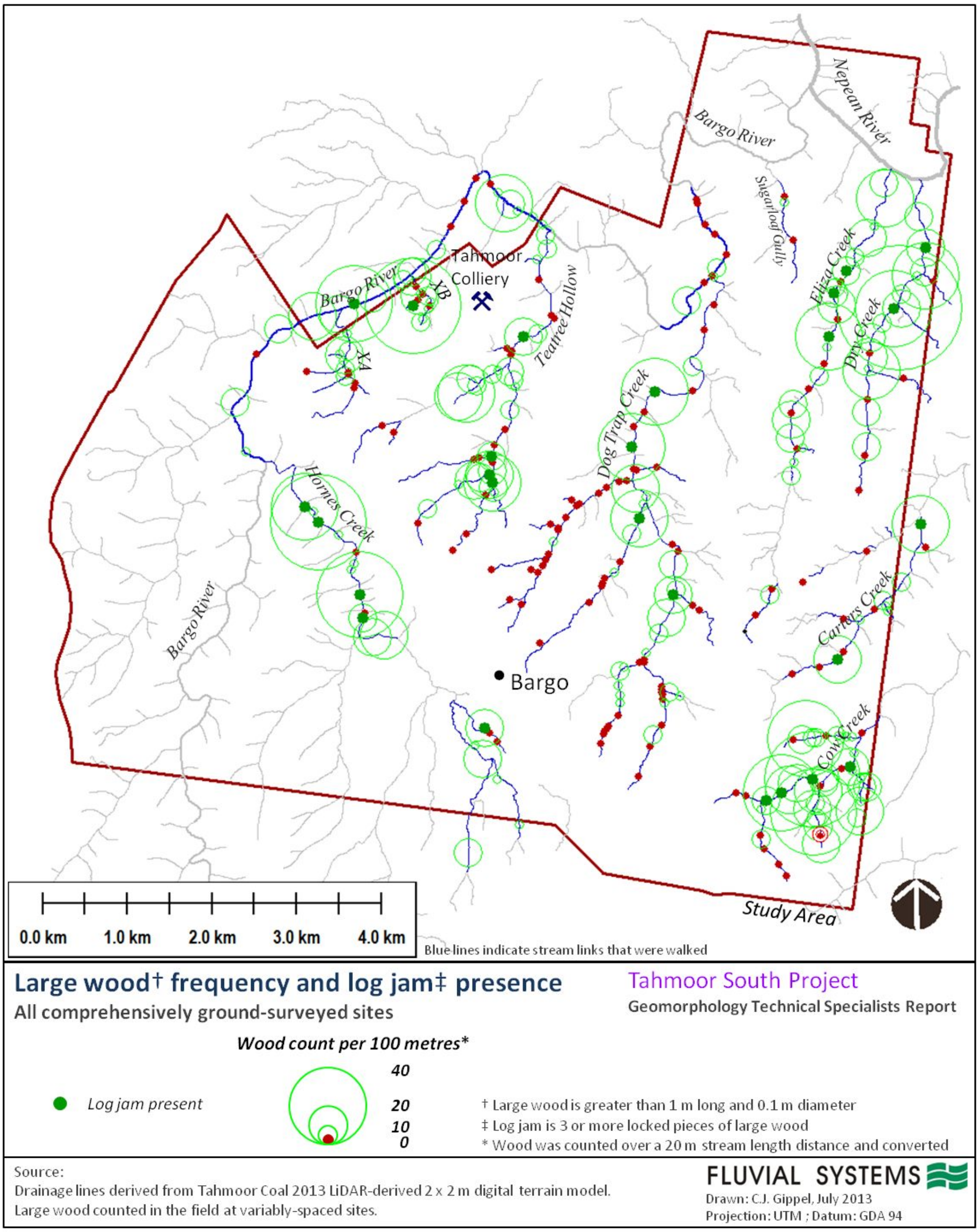

Figure 32. Distribution of large wood in streams within the Study Area.

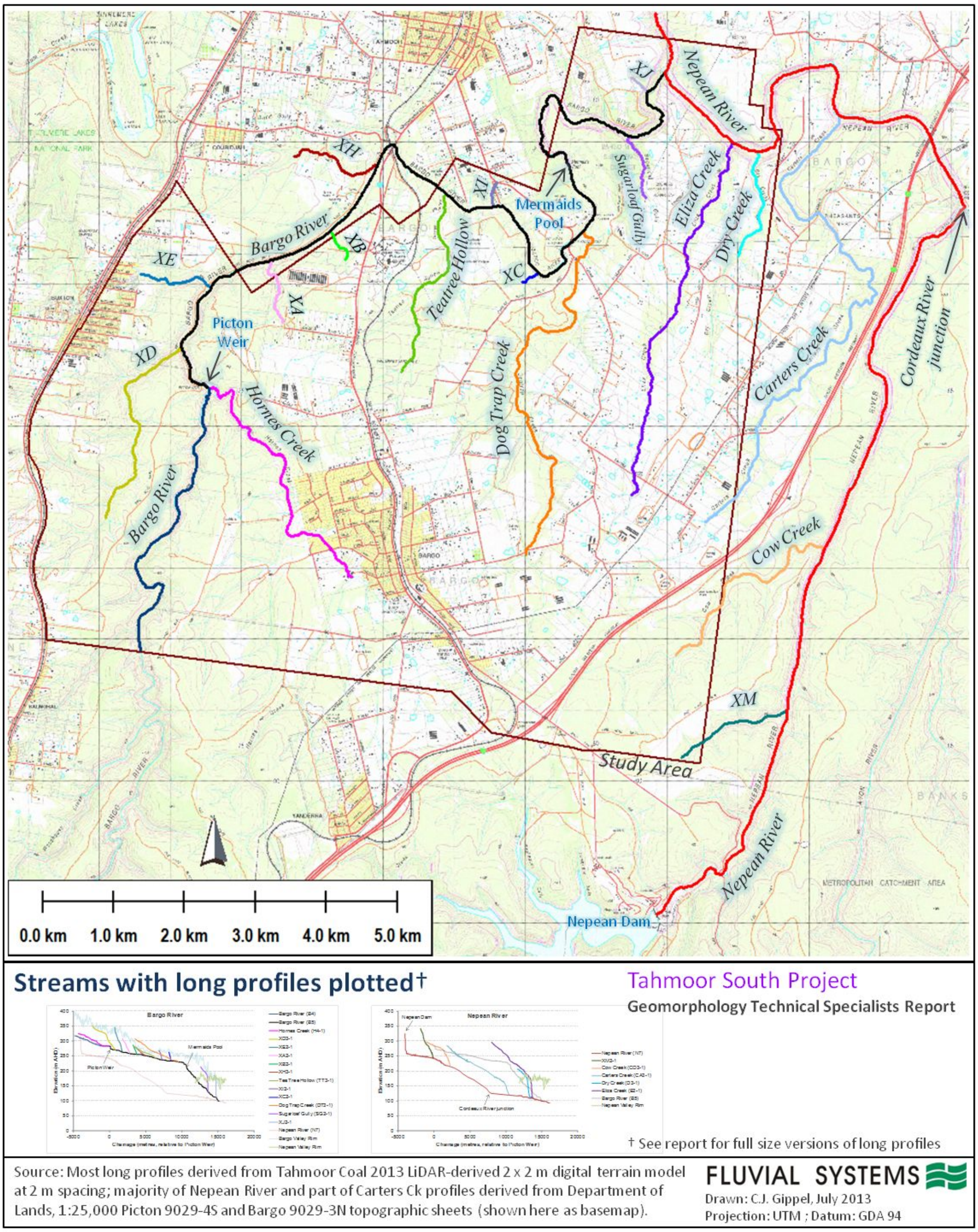

Figure 33. Streams flowing into and out of the Study Area, for which long profiles were plotted.

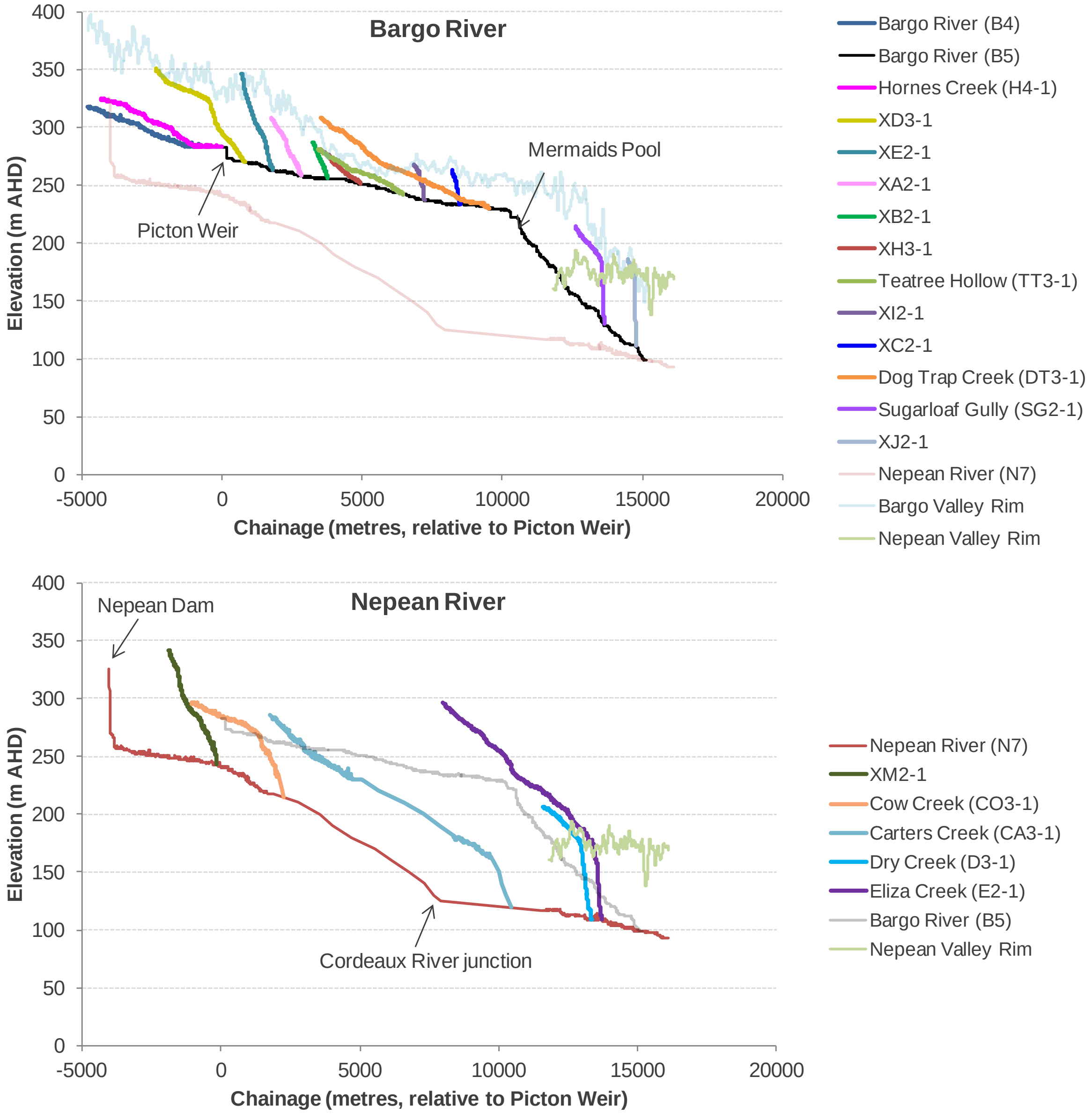

Figure 34. Long profiles of the Bargo River, Nepean River (mostly outside of the Study Area) and most of the tributary streams flowing into and out of the Study Area. Valley rim is the elevation of the thalweg of the river plus the 'valley depth' at the thalweg.

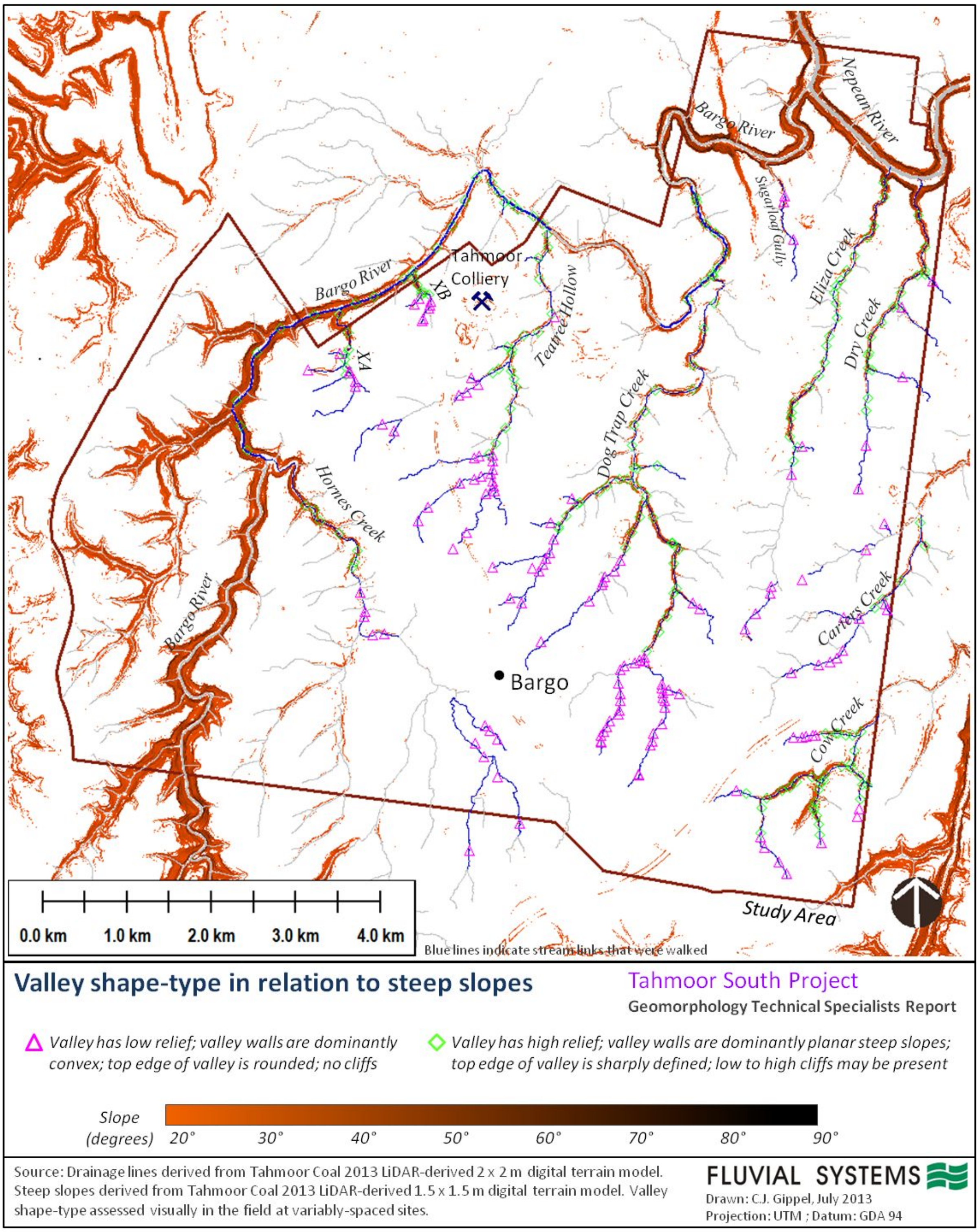

Figure 35. Valley shape-type (field observations), shown in relation to steep slopes (determined from DEM).

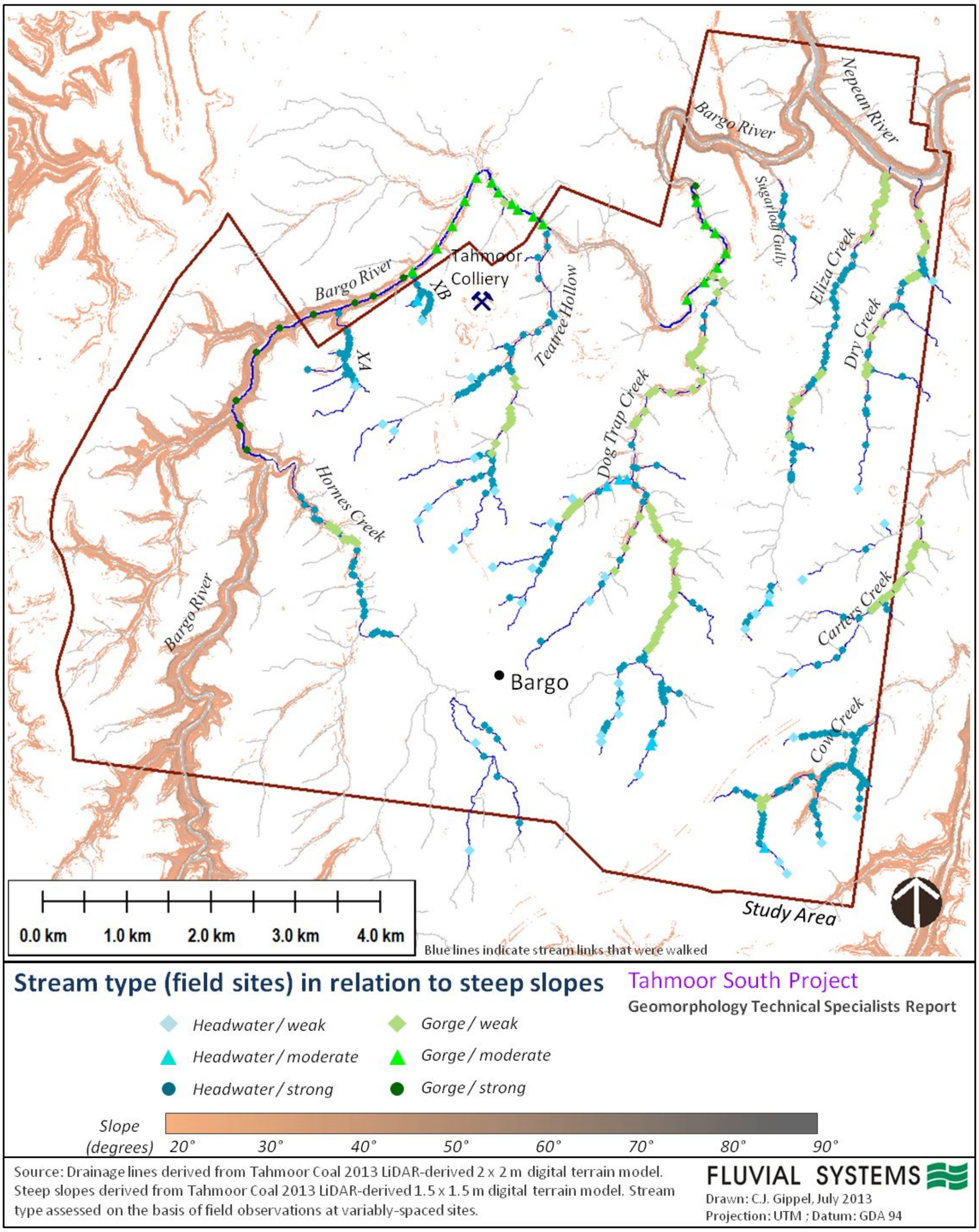

Figure 36. Stream geomorphic type at field sites, shown in relation to steep slopes (determined from DEM).

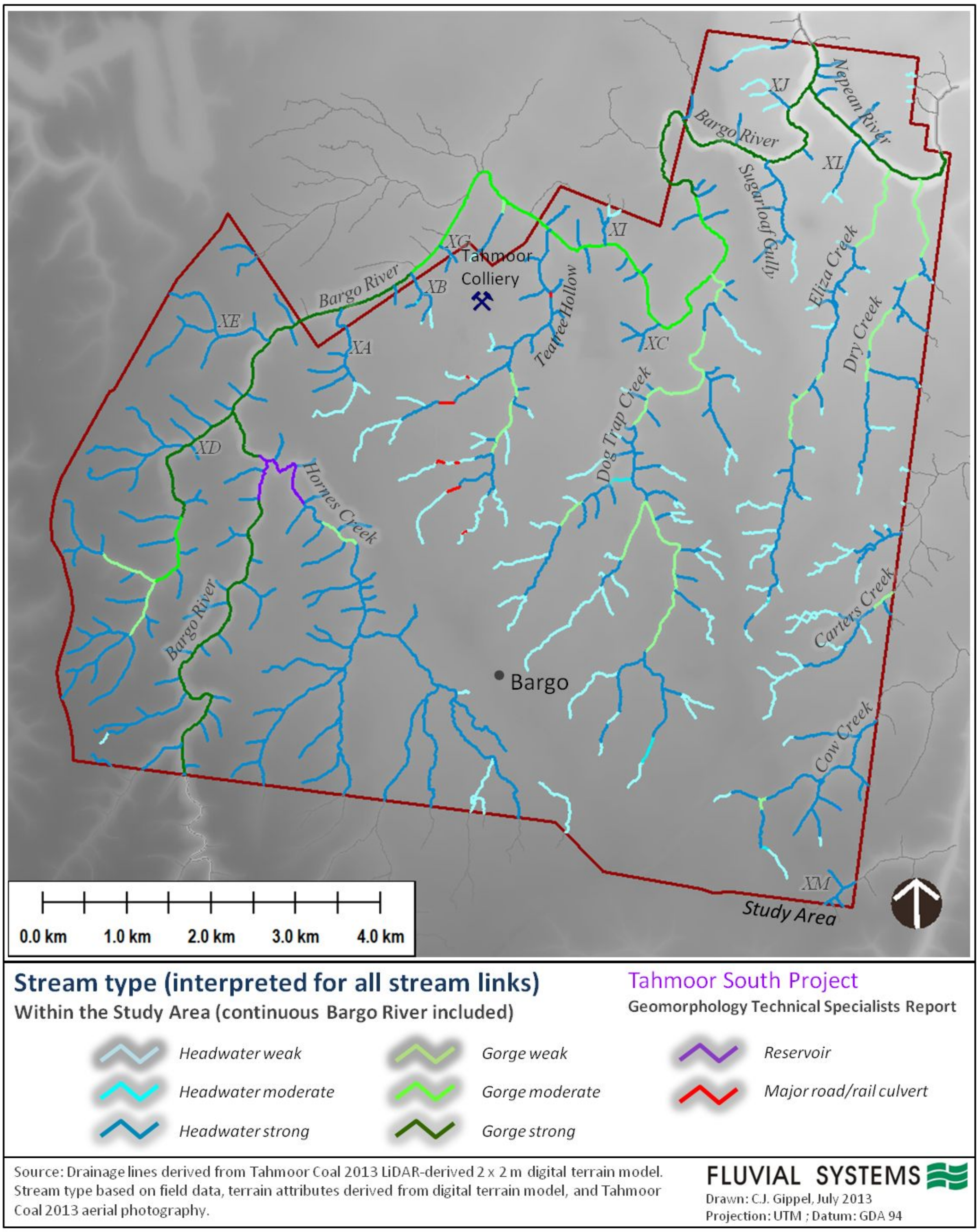

Figure 37. Stream geomorphic type for all stream links across the Study Area.

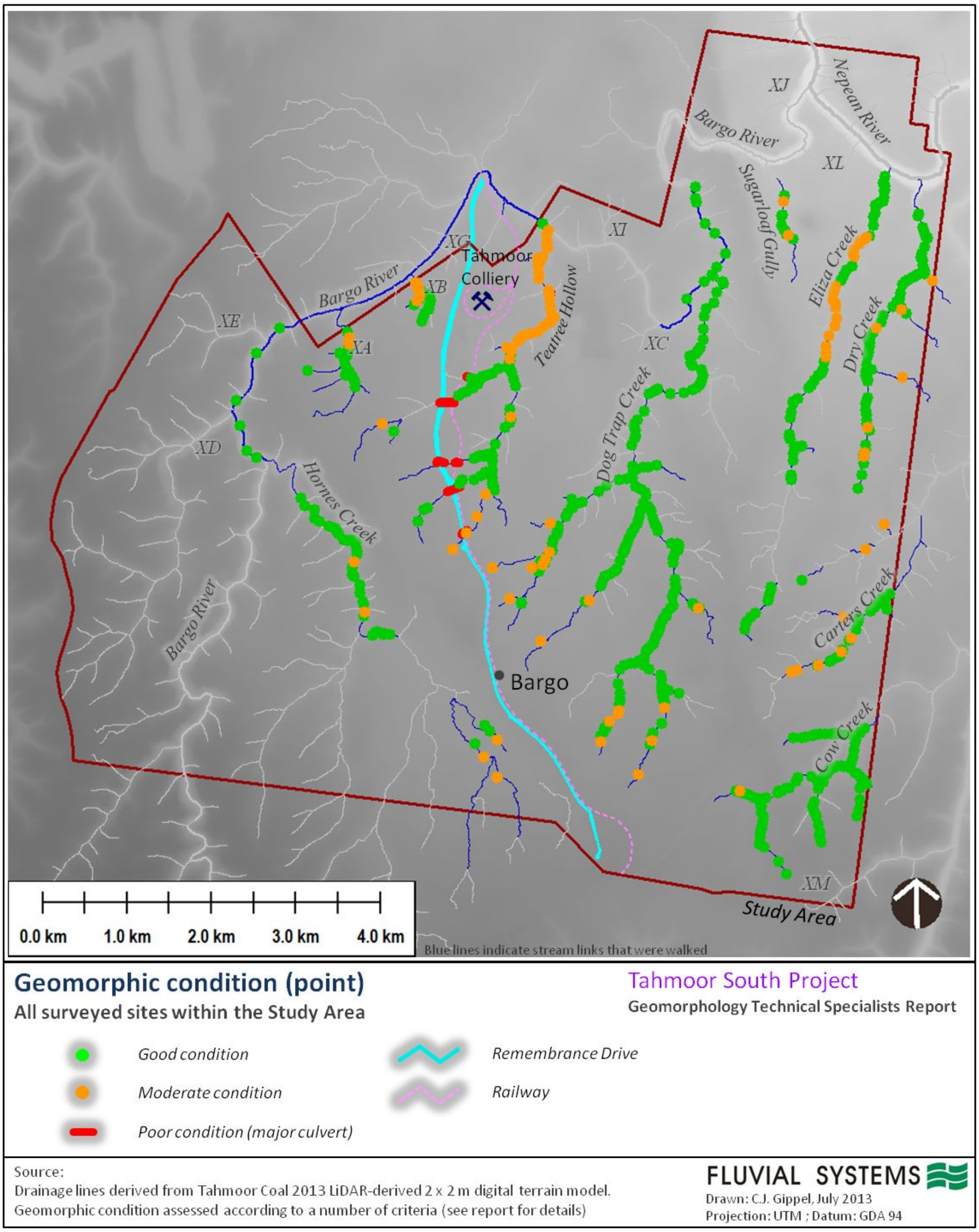

Figure 38. Stream geomorphic condition for all surveyed sites in the Study Area. The major culverts on Remembrance Drive, Main Southern Railway and Tahmoor Mine Access/Haul Road (over Teatree Hollow) were the only sites judged to be in Poor condition.

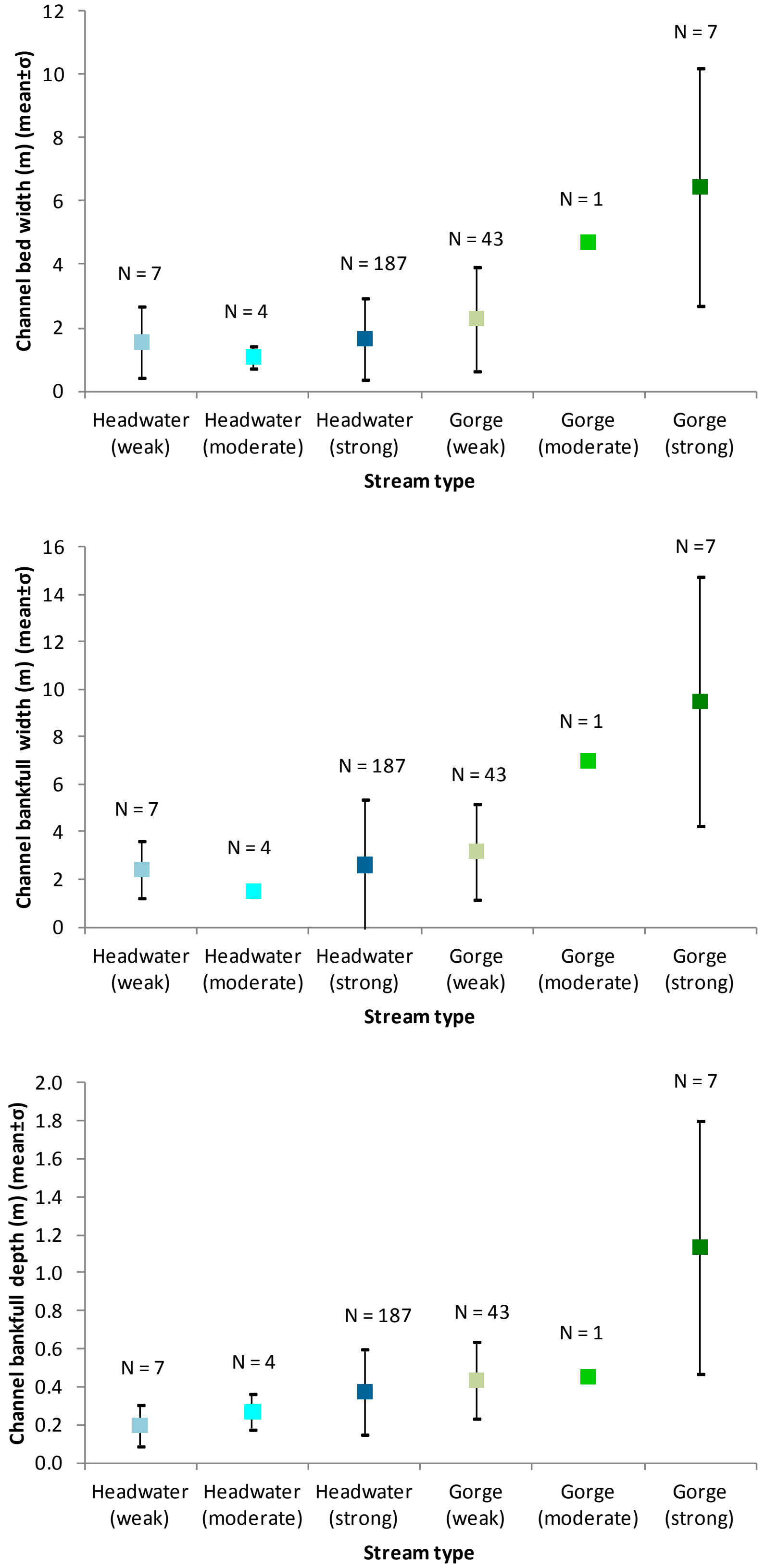

Figure 39. Channel dimensions of streams in the Study Area belonging to the six geomorphic type classes.

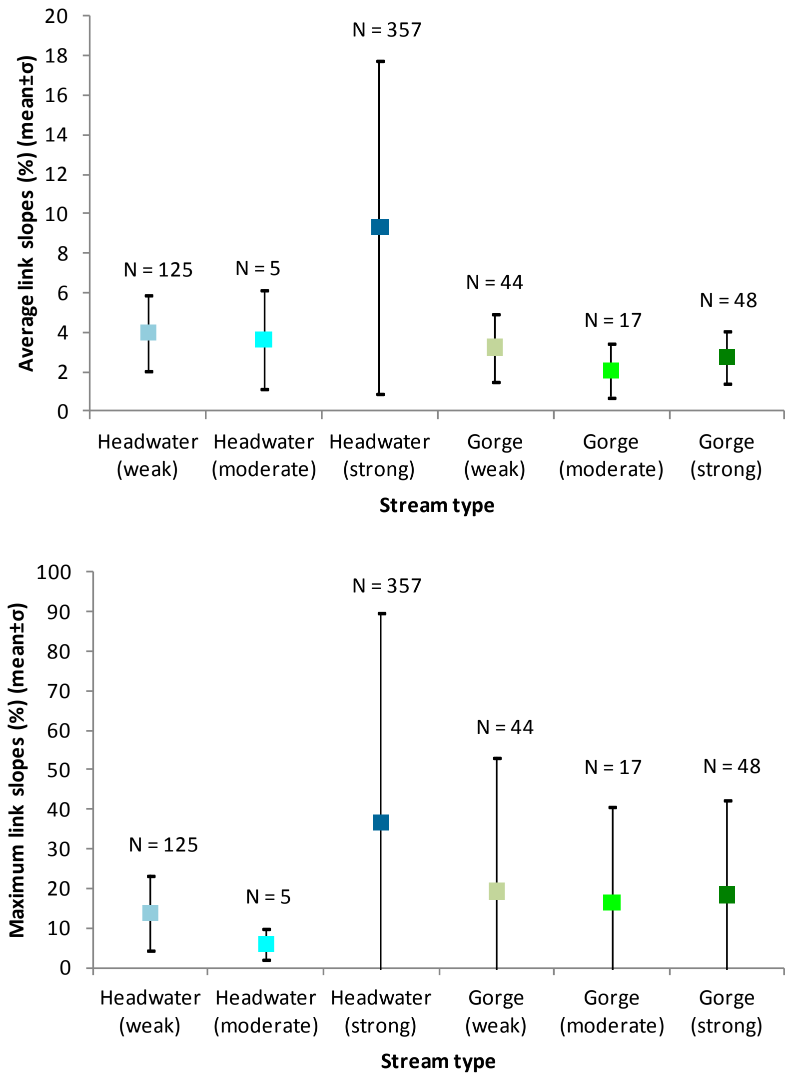

Figure 40. Distributions of slopes of channel links in the Study Area belonging to the six geomorphic type classes.

Table 6 Streams 2nd order and higher – statistical summary of slope, length, order, and characteristics of pools, soft knickpoints and bedrock features. ns = not surveyed in the field, no = not observed in the field. The single pool measured on B5-1 C was Mermaids Pool.

Stream name	Mean slope (%)	Length 3-D (m)	Strahler Order	Pools							Soft knickpoints			Bedrock features			
				Mean length (m)	Mean width (m)	Mean depth (m)	Mean volume (m^3)	Count	Total length (m)	Pools, % of stream length	Mean height (m)	Max. height (m)	Count	Rock slab count	Rock bar count	Other rock count	Total count
B2-1	6.2	615	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B2-2	12.3	860	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B2-3	23.1	239	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B2-4	15.2	295	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B2-5	20.8	206	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B4-1	2.2	4,310	4	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B5-1 C	2.1	4,895	5	67.0	40.0	12.0	15,758	1	67	-	no	no	no	1	4	no	5
B5-1 N	3.3	2,808	5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B5-1 W	2.7	2,169	5	ns	ns	ns	ns	ns	ns	ns	no	no	no	3	1	2	6
CA2-1	2.4	1,290	2	no	no	no	no	no	no	no	0.6	0.9	3	2	1	no	3
CA2-2	3.0	551	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CA2-5	3.0	1,103	2	no	no	no	no	no	no	no	no	no	no	1	no	no	1
CA3-1	2.9	551	3	19.3	6.8	1.0	64	3	58	11	no	no	no	3	4	no	7
CO2-1	4.2	876	2	20.7	7.4	1.2	100	7	145	17	no	no	no	1	1	1	3
CO2-2	4.0	407	2	no	no	no	no	no	no	no	no	no	no	1	no	no	1
CO2-3	9.4	238	2	no	no	no	no	no	no	no	0.5	0.5	1	no	no	1	1
CO3-1	2.0	1,070	3	47.7	5.4	0.9	123	11	525	49	0.8	0.8	1	4	4	1	9
D2-1	3.2	1,620	2	17.0	3.6	0.7	21	10	170	10	no	no	no	2	4	no	6
D3-1	6.2	1,774	3	30.3	5.4	0.9	82	13	394	22	no	no	no	6	5	no	11
DT2-1	2.5	713	2	20.8	4.1	0.7	35	3	62	9	no	no	no	1	3	2	6
DT2-2	2.4	371	2	12.3	3.9	0.5	13	2	25	7	no	no	no	2	1	no	3
DT2-3	10.6	182	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
DT2-4	12.1	212	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
DT2-5	3.1	1,184	2	no	no	no	no	no	no	no	no	no	no	3	9	1	13
DT2-6	8.1	416	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
DT2-7	2.4	2,121	2	no	no	no	no	no	no	no	1.0	1.3	3	5	3	1	9
DT2-8	3.8	977	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
DT3-1	2.4	6,043	3	42.9	6.7	1.1	264	56	2403	40	no	no	no	18	19	no	37
E2-1	3.8	5,772	2	32.8	6.1	1.1	101	16	525	9	0.8	1.2	2	27	4	3	34
H2-1	1.9	811	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Stream name	Mean slope (%)	Length 3-D (m)	Strahler Order	Pools							Soft knickpoints			Bedrock features			
				Mean length (m)	Mean width (m)	Mean depth (m)	Mean volume (m^3)	Count	Total length (m)	Pools, % of stream length	Mean height (m)	Max. height (m)	Count	Rock slab count	Rock bar count	Other rock count	Total count
H2-2	2.1	944	2	no	no	no	no	no	no	no	no	no	no	1	no	no	1
H2-3	3.9	1,601	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
H2-4	7.8	262	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
H2-5	7.8	455	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
H3-1	2.5	1,646	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
H3-2	1.3	1,377	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
H3-3	2.9	2,172	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
H4-1	2.7	3,354	4	49.9	10.2	1.4	351	15	749	22	no	no	no	8	3	no	11
N7-1	2.1	2,948	7	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SG2-1	8.9	1,037	2	28.0	12.5	0.7	120	1	28	3	no	no	no	1	1	no	2
TT2-1	2.6	585	2	14.0	7.1	1.4	151	2	28	5	0.6	1.1	3	3	no	no	3
TT2-2	6.7	119	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TT2-3	3.3	1547	2	no	no	no	no	no	no	no	1.2	1.2	2	4	no	2	6
TT2-4	6.6	244	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TT3-1	2.0	3,026	3	35.2	5.8	0.9	139	9	317	10	0.5	1.1	5	3	no	no	3
XA2-1	4.6	734	2	14.9	4.0	1.0	27	5	75	10	0.7	1.0	2	8	no	3	11
XB2-1	5.7	424	2	no	no	no	no	no	no	no	no	no	no	5	no	1	6
XD2-1	6.3	753	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XD2-2	8.0	417	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XD2-3	7.5	85	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XD2-4	4.0	1,083	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XD2-5	11.9	152	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XD2-6	8.6	683	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XD3-1	3.5	3,523	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XE2-1	7.6	1,138	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XI2-1	8.5	386	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XJ2-1	24.1	333	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XL2-1	15.8	681	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
XM2-1	7.3	391	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Reservoir (H4)		989	4	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Reservoir (B5)		641	4	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TOTALS		78,187						161	5,735				22	109	62	16	187

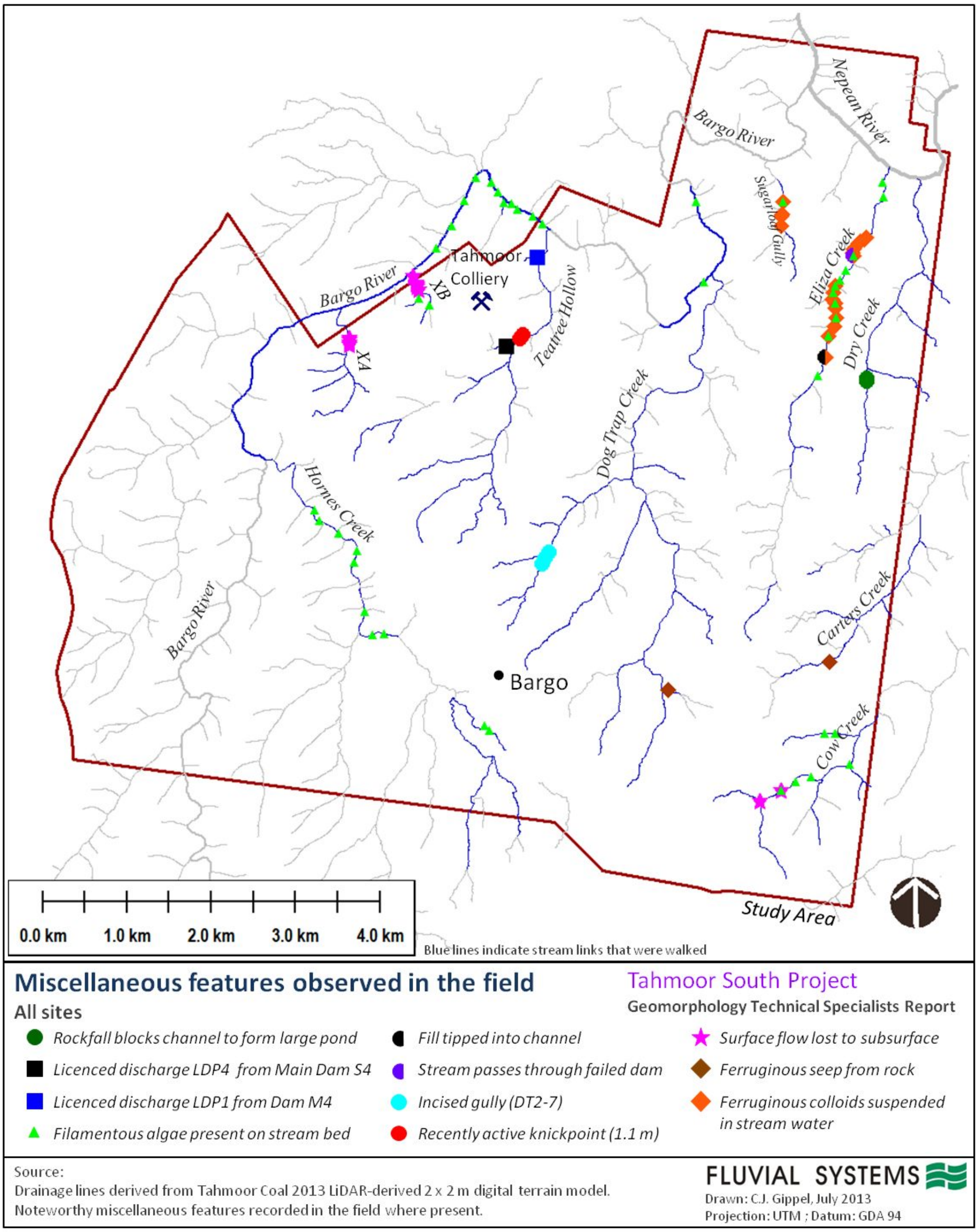

Figure 41. Miscellaneous featured observed in the field with potential relevance to the Geomorphology Technical Report.

Figure 42. TT3-1 (Teatree Hollow) in the vicinity of where turbid discharge from LDP4 was observed to enter the Hollow via TT2-4. Photographed on 6 February 2013.

Figure 43. TT1-21 in the vicinity of where it transfers discharge from LDP1 to Teatree Hollow. Exposed bedrock and boulders in the bed were covered by a layer of dark-coloured precipitate. Photographed on 6 February 2013.

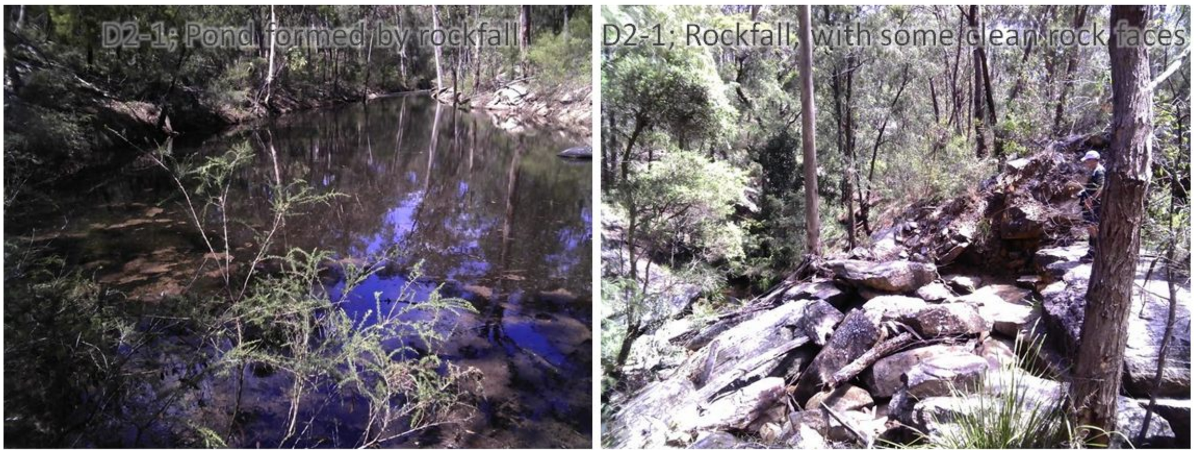

Figure 44. A pond in D2-1 (Dry Creek) created by a significant rockfall. Photographed on 31 January 2013.

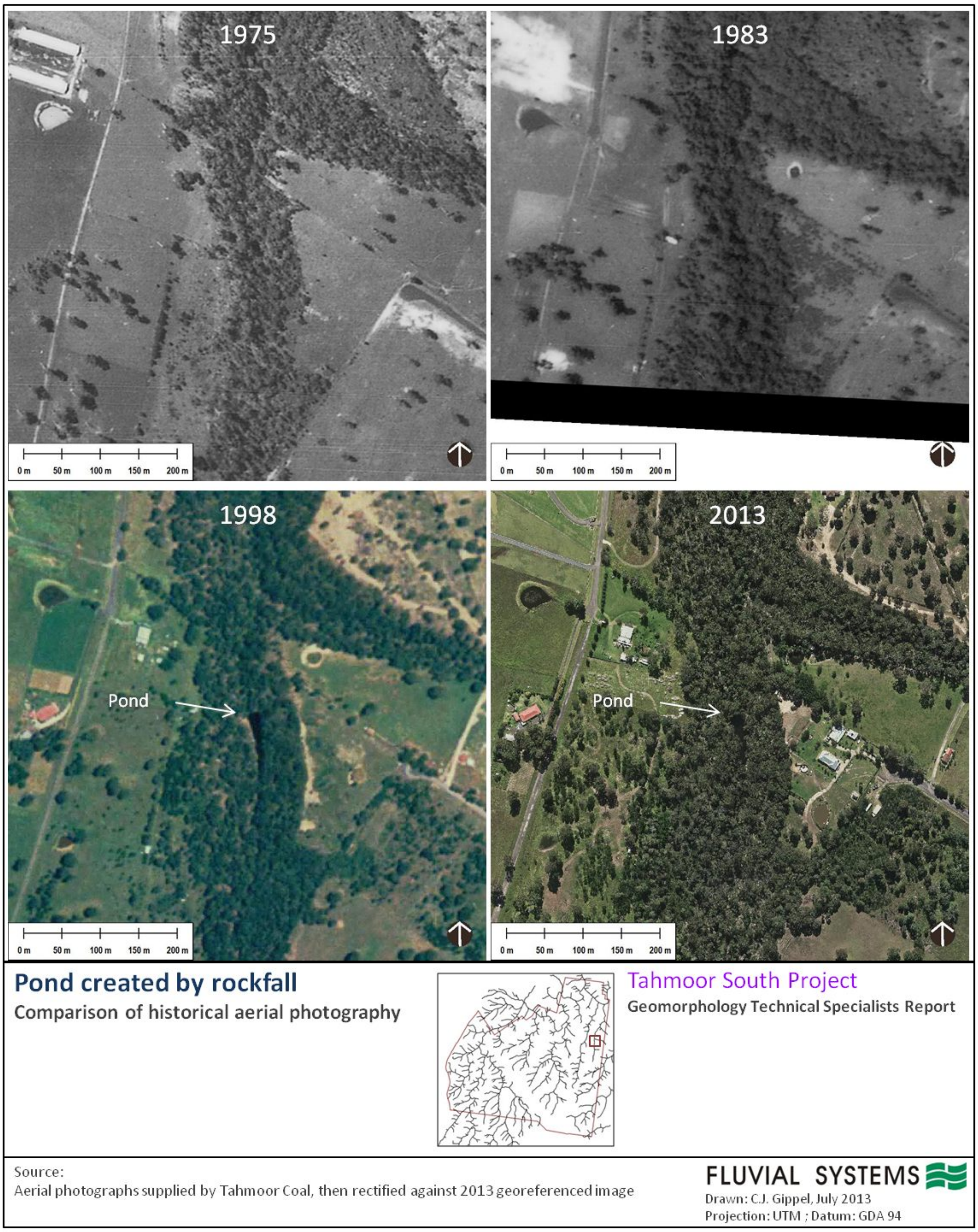

Figure 45. Site of a pond in D2-1 (Dry Creek) created by a rockfall that apparently occurred sometime between 1983 and 1998.

Figure 46. Incised gully on upstream end of DT2-7 (Dog Trap Creek). Photographed on 24 January 2013.

Figure 47. Recently active knickpoint (left) and another soft knickpoint 320 m upstream, both on TT3-1 (Teatree Gully). Photographed on 6 February 2013.

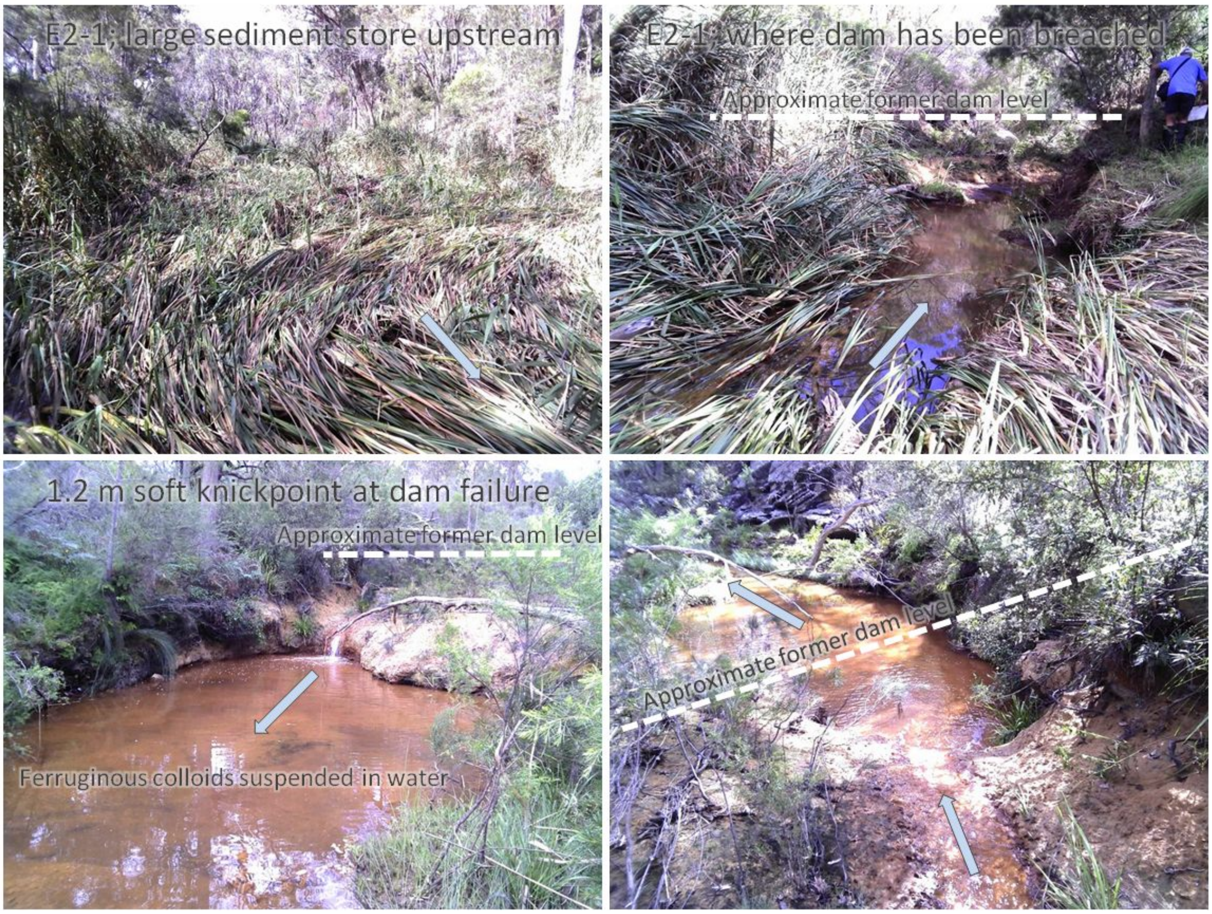

Figure 48. Failed dam on Eliza Creek. Photographed on 13 February 2013.

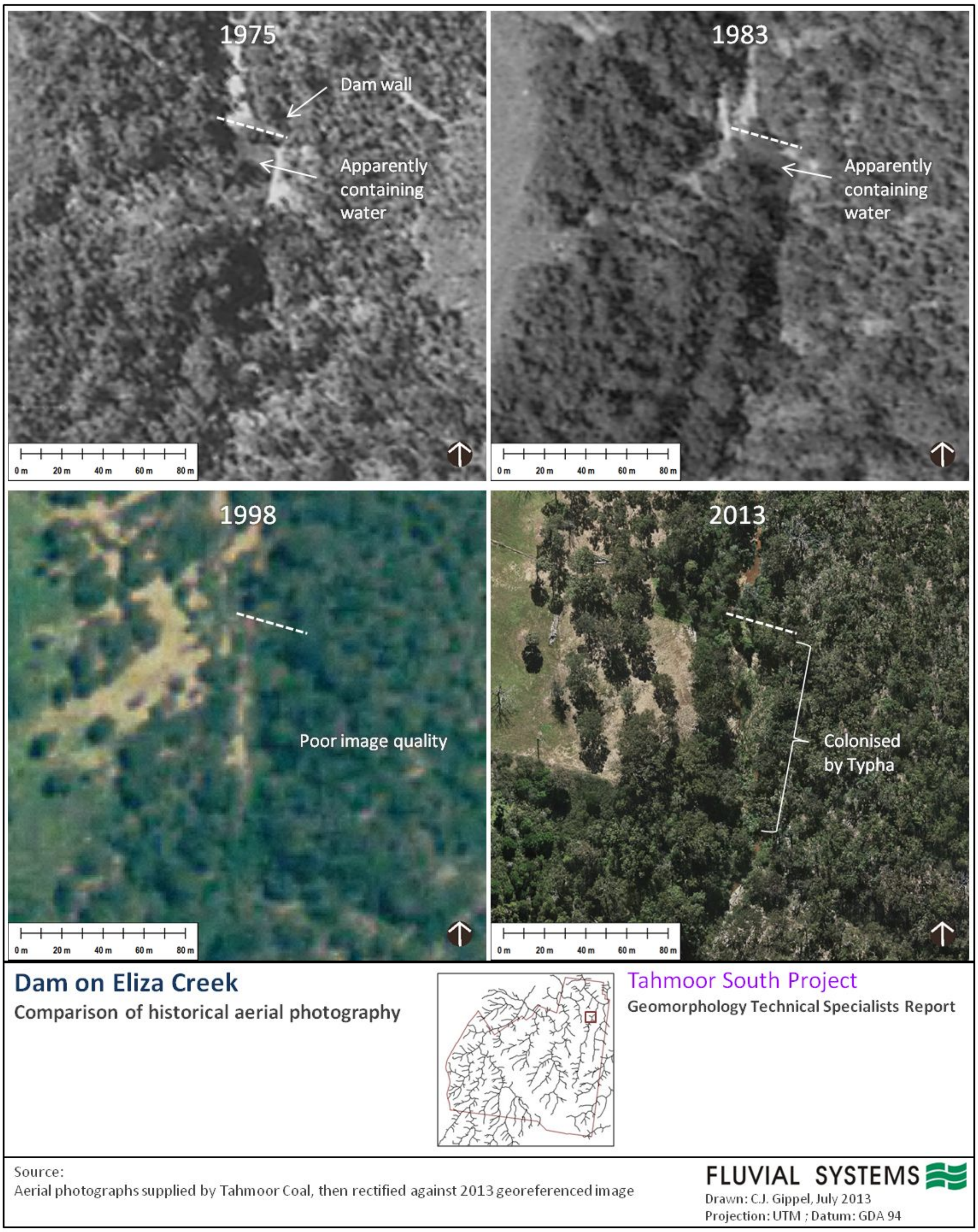

Figure 49. Historical aerial photographs of area on Eliza Creek where a failed dam was observed in February 2013.

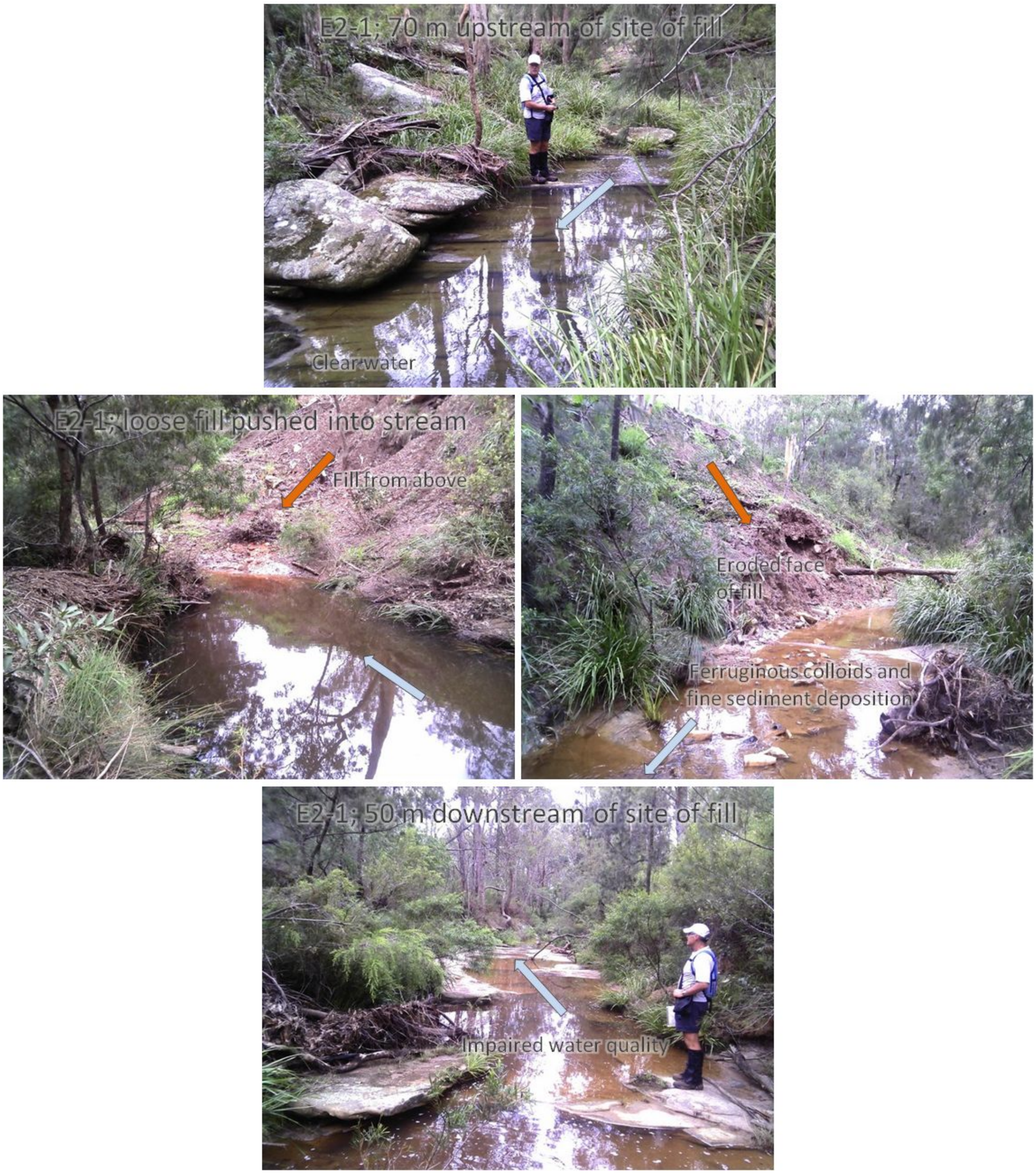

Figure 50. Site where loose fill was observed to have been tipped into Eliza Creek from above. Photographed 11 February 2013.

Figure 51. Examples of filamentous algae, observed on creek XA2-1 on 2 February 2013 and Hornes Creek (H4-1) on 8 February 2013.

Figure 52. Site where ferruginous seep was observed on Carters Creek. Photographed 30 January 2013.

Figure 53. Ferruginous colloids suspended in the water of Sugarloaf Gully over a 310 m long reach. Photographed 13 February 2013.

Figure 54. Ferruginous colloids suspended in the water, and iron precipitate on bedrock, of Eliza Creek. Photographed 13 February 2013.

4.0 Impact assessment

4.1 Risk Management Zones

High value features within the Study Area were identified as: (i) significant streams, which in the Study Area were all 3rd order streams plus Eliza Creek (a 2nd order stream, but marked as 3rd order on the 1:25,000 topographic map sheet), and (ii) major cliffs. Buffers 400 m wide were drawn around these features and although they are conventionally known as RMZs (Risk Management Zones) the actual zone of risk is where the RMZ overlaps the proposed longwalls (Figure 55). The combined risk areas are largely governed by the significant stream RMZs. The combined RMZs indicate that detailed assessment is required in upper Teatree Hollow, upper Dog Trap Creek, small areas of Carters and Cow creeks, and the entire lengths of Dry and Eliza creeks (Figure 55).

4.2 Qualitative assessment of risk of operational impacts

The following risks were evaluated qualitatively. For detailed assessment of these and associated risks, refer to reports by other relevant technical specialists.

4.2.1 Events where the risk is constant over the entire Study Area

1. Change in stream type over management time scales (< 100 years)

The only stream types occurring in the Study Area were Headwater and Gorge. Cook and Schneider (2006) defined these two types as having Low fragility, which they defined as:

> "*Resilient ('unbreakable'). Minimal or no adjustment potential. Only minor changes occur such as bedform alteration and the Style or sub-Style never changes to another one regardless of the level of damaging impact*"

Furthermore, Nanson and Young (1983) noted that streams in the Sydney Basin "…*are stable on resistant bedrock*". Thus, the likelihood of a change in stream type, either irreversible or reversible, is rare.

If such an event were to occur, it would be localised and affect Headwater rather than Gorge stream type, with Headwater changing to Cut and Fill (Cook and Schneider, 2006). Such a change would be reversible with management action, so the consequence would be minor.

2. Change of alignment of channel

The streams in the Study Area are all confined by valleys, with beds and banks controlled by bedrock or hard regolith. The likelihood of a change of alignment is rare. If such an event were to occur it would only be in small Headwater streams on the plateau, so the consequence would be minor.

4.2.2 Events where the risk varies over the Study Area

1. Reduction of existing in-channel pool volume

The likelihood of a reduction of in-channel pools depends on the extent of mining-induced fracturing of rock bars and rock slabs that form the beds of pools. There is a high probability of at least part of the bed of most pools in the Study Area would have had been formed in bedrock. Fracturing of rock bars that form the hydraulic controls of significant pools would be likely to result in pools holding water for a shorter period of the year, assuming hydrology was unaltered. The potential for fracturing to occur is assessed within the MSEC subsidence impact assessment.

2. Formation of new in-channel pool

The formation of new pools, or deepening of existing pools, would be the result of uneven or differential subsidence. The likelihood of this event occurring depends on the spatial distribution and depth of subsidence. The potential for uneven or differential subsidence is assessed within the MSEC subsidence impact assessment.

3. Migration of uncohesive knickpoint upstream at faster than natural rate

Knickpoints in uncohesive material are present in the existing environment. The survey found 44 of these in the Study Area, but there would almost certainly have been others present on unsurveyed streams. Soft knickpoints occurred in areas that were disturbed by urbanisation and agricultural development, and also in undisturbed, well vegetated streams. Acceleration of the rate of knickpoint migration, or creation of new knickpoints, would most likely be associated with small headwater streams on the plateau at the boundary of the mine, where there was a gradient of subsidence,which is assessed within the MSEC subsidence impact assessment.

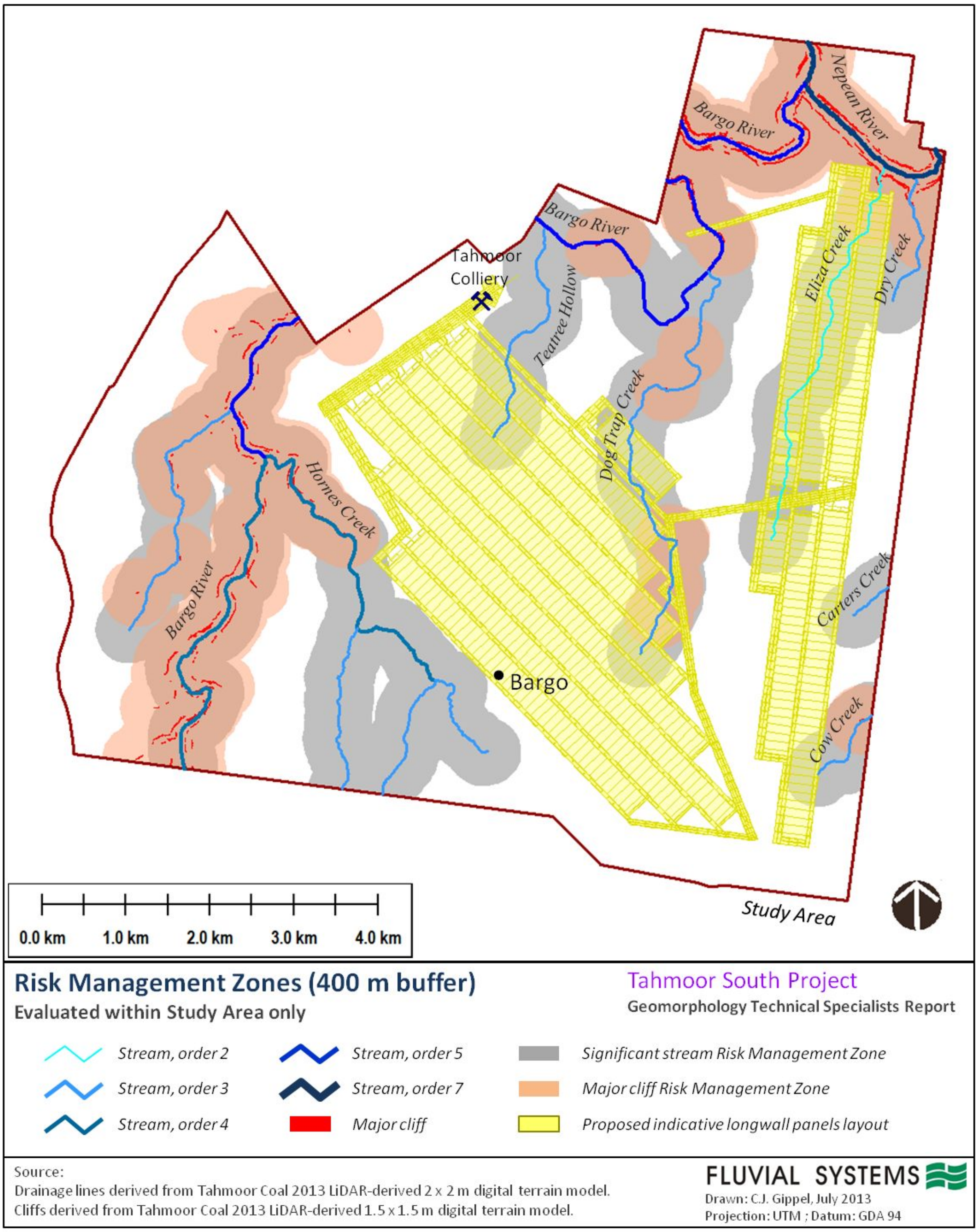

Figure 55. Risk Management Zones for significant streams and major cliffs. The area of risk is where the RMZ overlaps the proposed longwalls.

4. Increase of sediment supply to channel

Sediment supply to the streams in the Study Area seems to be low, evidenced by the generally low accumulation of sediment in the channels. Most of the headwater strong types are either free of loose sediment, or contain boulders, with lesser quantities of cobble gravel, sand and mud present. In reference to cliffs of the Sydney Basin, Nanson and Young (1983) noted that "*The escarpment naturally erodes extremely slowly*" and that "*Non-cliffed sandstone valley walls are stable*". This suggests that rockfall is rare and the talus slopes are stable, which is evidenced (and in turn, assisted) by the dense vegetation cover on the talus. An increase in sediment supply to the channels would require destabilisation of talus slopes through an increase in their slope beyond the angle of repose.

5. Increase of sediment accumulation in channel

In reference to streams of the Sydney Basin, Nanson and Young (1983) noted that "*There is very little sediment in storage in channels*", and this was confirmed by the Geomorphology Technical Report field survey. This observation is explained by the high energy conditions that would occur under storm event (high flow) conditions. The likelihood of increased sediment accumulation in channels would be related to a reduction in stream power below the sediment transport threshold. The likelihood of this would be rare.

6. Increase of sediment scouring in channel

The likelihood of an increase in the rate of sediment scouring would normally be linked to a steepening of channel slopes, and increased stream power. However, under existing conditions, sediment transport is very efficient (i.e. most of the readily transportable material is transported), and the majority of stream beds cannot scour because they are bedrock controlled, so there is limited scope for increasing sediment scour. Thus, the likelihood of increased sediment scouring of channels would be rare.

7. Increase in cover (density) of vegetation on channel bed (baseflow shift from high depth of water to shallow depth)

Macrophytes were uncommon in streams of the Study Area, explained by the rocky beds and banks, and relatively steep banks on pools, where macrophytes would normally be expected. Also, the streams are high energy, and macrophytes would be frequently disrupted, preventing establishment of large areas of plant cover. The likelihood of significantly increased cover of vegetation on channel beds due to reduced baseflow would be minor.

8. Decrease in cover (density) of vegetation on channel bed (baseflow shift from shallow depth of water to dry, or from shallow to deep)

As for a decrease in baseflow, the likelihood of significantly decreased cover of vegetation on channel beds due to increased baseflow would be minor.

9. Increase in rockfall frequency above natural rate

The likelihood of a significant increase in the rate of rockfall from cliffs and talus slopes depends on the spatial distribution and depth of subsidence.

5.0 Safeguards and management

5.1 Monitoring

Visual inspections and photographic surveys are proposed before, during, and after mining as an adjunct to the topographic survey. This program will provide some of the information required for monitoring of stream geomorphology.

In addition, permanent reference points for annual photographic recording should be established. These photographs must be assessed, and then reported on, by a professional geomorphologist.

This report provides data for the baseline geomorphic condition of streams in the Study Area. The methodology used in this report to survey geomorphic characteristics is repeatable, and as such, the geomorphological survey undertaken for this report should be repeated after mining to identify potential impacts associated with subsidence.

The geomorphic response to subsidence is likely to be slow, so a frequency of five years for catchment-wide re-survey and reporting of stream geomorphological condition is suggested in addition to monitoring for each longwall. The headwater streams identified in this report would not need to be included in the monitoring program, as the risk to geomorphic character is expected to be insignificant. However, it is suggested that a sample of 10 headwater sites (i.e. randomly distributed points on headwater streams) be included in the survey to confirm this assumption.

5.2 Safeguards and management measures

Mitigation is to eliminate or reduce the frequency, magnitude, or severity of exposure to risks, or to minimise the potential impact of a threat. The key subsidence related process that threatens the geomorphic condition of streams in the Study Area is the development, and upward migration, of knickpoints. It is recommended to address the risk of knickpoint formation through a process of adaptive management. Under this process: (i) regular monitoring would detect if and where the threat occurs, (ii) an assessment would be made to determine the potential consequences of the observed threat, and then, (iii) appropriate control works would be put in place.

If significant development of knickpoints is observed, these should be professionally assessed in order to determine the most appropriate control measure. The most commonly used, and reliable, approach to knickpoint control is rock grade control structures. Large wood structures are a potential alternative approach. Brooks et al. (2006) noted the difficulty of controlling bed degradation using wood-based strategies alone, but described some examples of this approach being successfully trialed in streams in the Hunter Valley and northern NSW. The most appropriate method for knickpoint control would need to be assessed for each knickpoint, with access to the site likely to be a significant determinant. Control of soft knickpoints within gorge-type streams will require hand labour as it would not be practical to take heavy machinery into these areas.

6.0 Conclusion

This report documented the geomorphological character of the Study Area. The report used repeatable methods which were fully described. The data described the benchmark condition from which the future geomorphic condition of the streams in the Study Area can be compared.

The streams comprised two main geomorphic types, with each main type having three sub-types that reflected the scale and landscape position of the streams. The streams were geomorphologically resilient because of the common presence of bedrock in the stream beds, and the confined setting of the valleys (i.e. no alluvial floodplains were present). Thus, mining is not expected to present a significant risk to change in geomorphic character of the streams. Any changes that do occur would be expected to recover quickly because the streams are resilient and in generally good geomorphic condition (i.e. essentially natural with intact form and process).

The risks to geomorphic stream form and process associated with subsidence were quantitatively assessed. Overall, the risk of change to geomorphic character due to subsidence was judged to be minor. For detailed assessment of these and associated risks, refer to reports by other relevant technical specialists.

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