MALABAR COAL

MAXWELL PROJECT

APPENDIX D

Geomorphology Assessment

Maxwell Project

Environmental Impact Statement

Technical Study Report

Geomorphology Assessment

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Final

June 2019

FLUVIAL SYSTEMS

Maxwell Project

Geomorphology Assessment

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GLOSSARY OF TERMS

Term	Definition
Aggrade	Persistent deposition of sediment on the bed of stream channel. Opposite to Scour.
Alluvium (alluvial)	Unconsolidated, clastic material subaerially deposited by running water, including gravel, sand, silt, clay, and various mixtures of these (USDA Natural Resources Conservation Service, 2018).
Bed shear stress (also Shear stress)	The force of moving water against the bed of the channel, calculated as a function of the product of slope and water flow depth. Used to indicate the likelihood that surface particles will be eroded or vegetative cover scoured.
Catchment	The area from which a surface watercourse or a groundwater system derives its water.
Colluvium (colluvial)	Unconsolidated, unsorted earth material being transported or deposited on side slopes and/or at the base of slopes by mass movement (e.g., direct gravitational action) and by local, unconcentrated runoff (USDA Natural Resources Conservation Service, 2018).
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 (exposed leaf) projective cover of the ground.
Curvature (of landform)	A measure of the surface roundness of an area. It can be divided into plan (horizontal) curvature and profile (vertical) curvature (Wilson and Gallant, 2000).
Cumulative impacts	Combination of individual effects of the same kind due to multiple actions from various sources over time.
Depression	A landform element that stands below all, or almost all, points in the adjacent terrain. A ‘closed depression’ stands below all such points; an ‘open depression’ extends at the same elevation, or lower, beyond the locality where it is observed. Many depressions are concave upwards and their margins should be drawn at the limit of observed curvature. National Committee on Soil and Terrain (2009, p. 20).
Discharge	A release of water from a particular source.
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 and 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 (flow of a river)	Existing for a short duration of time during and after storm events. In the binary intermittent/perennial hydrological classification, ephemeral flow is a sub-class of intermittent flow.
Fault	Break in the continuity of a coal seam or rock strata.

Term	Definition
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.
Floodplain	The nearly level plain that borders a stream and is subject to inundation under flood-stage conditions unless protected artificially. It is usually a constructional landform built of sediment deposited during overflow and lateral migration of the streams (USDA Natural Resources Conservation Service, 2018).
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.
Global Mapper™	A GIS application, especially suited to terrain analysis (see also Terrain analysis).
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.
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
Intermittent (flow of a river)	Non-perennial flow in the binary intermittent/perennial hydrological classification.
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.
Knickpoint	A local steep fall in channel bed elevation.
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 a broad front or long face.
Macrophyte	An aquatic plant that grows in or near water.
Multiresolution index of valley bottom flatness (MrVBF)	An algorithm to assist in the objective separation of floodplains from their surrounding hillslopes using slope and elevation percentile.
Panel	The mining block that has previously been extracted or is currently being extracted.
Perennial (flow of a river)	Permanently flowing year round.
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.
Proposed development	Underground coal mining and associated activities within the Study Area. Referred to as the Maxwell Project.
Regolith	The material that is found between unweathered bedrock and the ground surface, including weathered bedrock, deposits and soil.
Resilience (geomorphic)	Geomorphic property of a stream, having 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.
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 slab	A long and wide exposure of solid bedrock on the bed for a distance at least three times the width of the channel.
Runoff	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.

Term	Definition
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.
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 Watercourse and Waterway).
Stream link	Lengths of stream between two nodes, where a node is the beginning of a First 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 Power Index (SPI)	Unitless index of stream power (see also Stream power) used to identify potential for erosion due to concentrated surface runoff, based on upslope contributing area per unit contour length and land surface slope.
Stream power	Power per unit width of a stream reach dependent on the product of stream discharge and slope.
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 water	Water flowing or held in streams, rivers and other wetlands in the landscape.
Terrain analysis	The automated analysis of landforms using digital elevation data sets.
Topographic Wetness Index (TWI) (in Terrain analysis)	Identifies areas of flow convergence, which are likely to retain moisture, and be the main runoff producing zones of catchments, based on upslope contributing area and local surface slope.
Tributary	A river or stream flowing into a larger river or lake.
Vector (in GIS)	A coordinate-based data model that represents geographic features as points, lines, and polygons (see Polygon).
Water table	The surface of saturation in an unconfined aquifer at which the pressure of the water is equal to that of the atmosphere.
Watercourse	Any flowing stream of water, whether natural or artificially regulated (not necessarily permanent) (see also Stream and Waterway).
Waterway	Any flowing stream of water, whether natural or artificially regulated (not necessarily permanent) (see also Stream and Watercourse).

ACRONYMS

Acronym	Expansion
A	Authorisation
AgTEM	Agricultural Transient Electromagnetic System
AHD	Australian Height Datum
ARI	Average Recurrence Interval
BSAL	Biophysical Strategic Agricultural Land
CDI	Catchment Disturbance Index
CHPP	Coal Handling and Preparation Plant
CL	Coal Lease
DinSAR	Differential Interferometric Synthetic Aperture Radar
DEM	Digital Elevation Model
EIS	Environmental Impact Statement
EL	Exploration Licence
GIS	Geographic Information System
GPS	Global Positioning System
HS	Hydrological Stress
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
LiDAR	Light Detection and Ranging
ML	Mining Lease
MrRTF	Multiresolution Index of Ridge Top Flatness Index
MrVBF	Multiresolution Index of Valley Bottom Flatness
MSEC	Mine Subsidence Engineering Consultants
NSW	New South Wales
ODK	Open Data Kit

Acronym	Expansion
OEH	Office of Environment and Heritage
RBCI	River Biodiversity Condition Index
RCI	River Condition Index
RMZ	Risk Management Zone
ROM	Run-of-mine
RSC	River Styles® Geomorphic
RUSLE	Revised Universal Soil Loss Equation
RVC	Riparian Vegetation Cover
SAGA	System for Automated Geoscientific Analyses
SEARs	Secretary’s Environmental Assessment Requirements
SPI	Stream Power Index
TWI	Topographical Wetness Index
WSP	Water Sharing Plan

UNITS

Symbol	Unit
ha	Hectare
kg	Kilogram
km	Kilometre
km^2	Kilometres squared, or square kilometres
m	Metre
m^2	Metres squared, or square metres
m^3	Metres cubed, or cubic metres
mm	Millimetre
s	Second
W	Watt

Executive Summary

Geomorphology is concerned with the forms that make up the earth's surface and the processes that create those forms. This report documents a study that characterised the geomorphic forms and processes in the Maxwell Project Study Area. The study used a range of methods, including walking the majority of the drainage lines over 10 days, making measurements and observations about the channels and vegetation and taking photographs at 472 locations. The data and information collected in the field together with existing information about geology, soils, ground elevation and slope were used to make an assessment of the geomorphic condition of the streams and how they might be affected by mining subsidence.

Landforms of the Study Area were analysed using very detailed information on the ground elevation, available every half metre over the entire Study Area. This data was collected using a LiDAR (Light Detection and Ranging) sensor mounted in a plane. This information, combined with the field data, was used to classify streams according to geomorphic type, and geomorphic condition. Streams of different type behave differently if disturbed by subsidence, so classification helps to predict the impact of subsidence, and how likely the streams are to recover from disturbance.

The streams comprised six natural geomorphic types, with the majority being Headwater type. Headwater streams are geomorphologically resilient, so mining would not be expected to present a significant risk to changing their character. If they are impacted, the streams would be expected to recover their character quickly. Most of the streams were currently in poor geomorphic condition due to knickpoints and poor riparian vegetation as a result of historic land management practices. Knickpoints are sharp drops in the bed of the stream or drainage line. Most of them were less than one metre high, but some were more than two metres high.

Knickpoints were very common, with 300 of them mapped and measured in the Study Area. Control of these existing knickpoints would involve changes to past agricultural and land management practices, such as reducing stock numbers, fencing waterways, and replanting riparian zones.

The risks to geomorphic stream form and process associated with subsidence were assessed using a method that focused on the location of the stream course, depressions on drainage lines, and stream power. Stream power is related to slope and flow rate of the streams and is a good predictor of the capacity of a stream to erode its bed and banks. Modelling was undertaken to predict how subsidence might affect the course of the streams. There were very few places where streams were predicted to change course but these were highlighted as areas to watch during monitoring. Subsidence was predicted to increase the extent and depth of depressions on drainage lines. Depressions in channels would act as coarse sediment traps, and increased pooling of water in depressions following storm events would increase the persistence of hydrologic refugia. An increased capacity of the catchment to trap sediment would help offset the historically higher-than-natural rates of sediment generation in the catchment due to cleared and grazed hillslopes, and gullying.

Repeating the geomorphic survey every five years plus an annual visual inspection would provide information to enable management of adverse impacts. Knickpoint formation and stream channel alignment change would be managed by regular monitoring to detect change. Places where significant change occurs would be professionally assessed and then repaired using appropriate works as deemed necessary.

In addition to the above work, the extent of alluvium was mapped for the Hunter River, Saddlers Creek, lower Saltwater Creek, and smaller streams. The mapping considered existing information sources and analysis of landforms. The investigation found that mining subsidence would not affect alluvium of the Hunter River, Saddlers Creek or Saltwater Creek. Two small tributaries of Saddlers Creek have formed alluvial fans where they join Saddlers Creek. These fans are fairly thin deposits of fine-grained alluvium. It is highly unlikely that the alluvial deposits contained an exploitable groundwater resource.

1.0 Introduction

1.1 Maxwell Project

Maxwell Ventures (Management) Pty Ltd, a wholly owned subsidiary of Malabar Coal Limited (Malabar), is seeking consent to develop an underground coal mining operation, referred to as the Maxwell Project (the Project).

The Project is in the Upper Hunter Valley of New South Wales (NSW), east-southeast of Denman and south southwest of Muswellbrook (Figure 1).

Underground mining is proposed within Exploration Licence (EL) 5460, which was acquired by Malabar in February 2018. Malabar also acquired existing infrastructure within Coal Lease (CL) 229, Mining Lease (ML) 1531 and CL 395, known as the "Maxwell Infrastructure". The Project would include the use of the substantial existing Maxwell Infrastructure, along with the development of some new infrastructure.

This assessment forms part of an Environmental Impact Statement (EIS) which has been prepared to accompany a Development Application for the Project in accordance with Part 4 of the NSW *Environmental Planning and Assessment Act 1979*.

This section introduces the Project, the proposed development, and the purpose and content of this report.

1.1.1 Overview

The Project would involve an underground mining operation that would produce high quality coals over a period of approximately 26 years. At least 75% of coal produced by the Project would be capable of being used in the making of steel (coking coals). The balance would be export thermal coals suitable for the new generation High Efficiency, Low Emissions power generators.

The Project underground mining area is located entirely within EL 5460. The Project would include the following activities (Figure 2):

- underground bord and pillar mining with partial pillar extraction in the Whynot Seam,
- underground longwall extraction in the Woodlands Hill Seam, Arrowfield Seam and Bowfield Seam,
- development and use of mine access drifts and underground roadways and shafts to access and service the underground mining areas,
- development and use of a mine entry and associated infrastructure, services and facilities that support underground mining and coal handling activities and provide for personnel and materials access to the underground mine,
- establishment of a site access road from Thomas Mitchell Drive to the underground mine entry,
- establishment of power transmission infrastructure, including power lines and substations,
- establishment of infrastructure associated with mine ventilation and gas management,
- use of the existing water management systems,
- progressive development of dams, sumps, pumps, pipelines, water storages, water treatment and other water management infrastructure,
- production of run-of-mine (ROM) coal,
- construction and use of a covered overland conveyor system to transport coal from the underground mine entry area to the existing coal handling and preparation plant (CHPP) at the Maxwell Infrastructure for processing,
- transportation of early ROM coal via internal roads from the mine entry area to the existing CHPP,
- handling and processing of coal and loading of coal onto trains at the existing Maxwell Infrastructure,
- transport of product coal via the existing Antiene Rail Spur and Main Northern Railway to market or to the Port of Newcastle for export, or via the covered overland conveyor to the Bayswater and/or Liddell Power Stations,

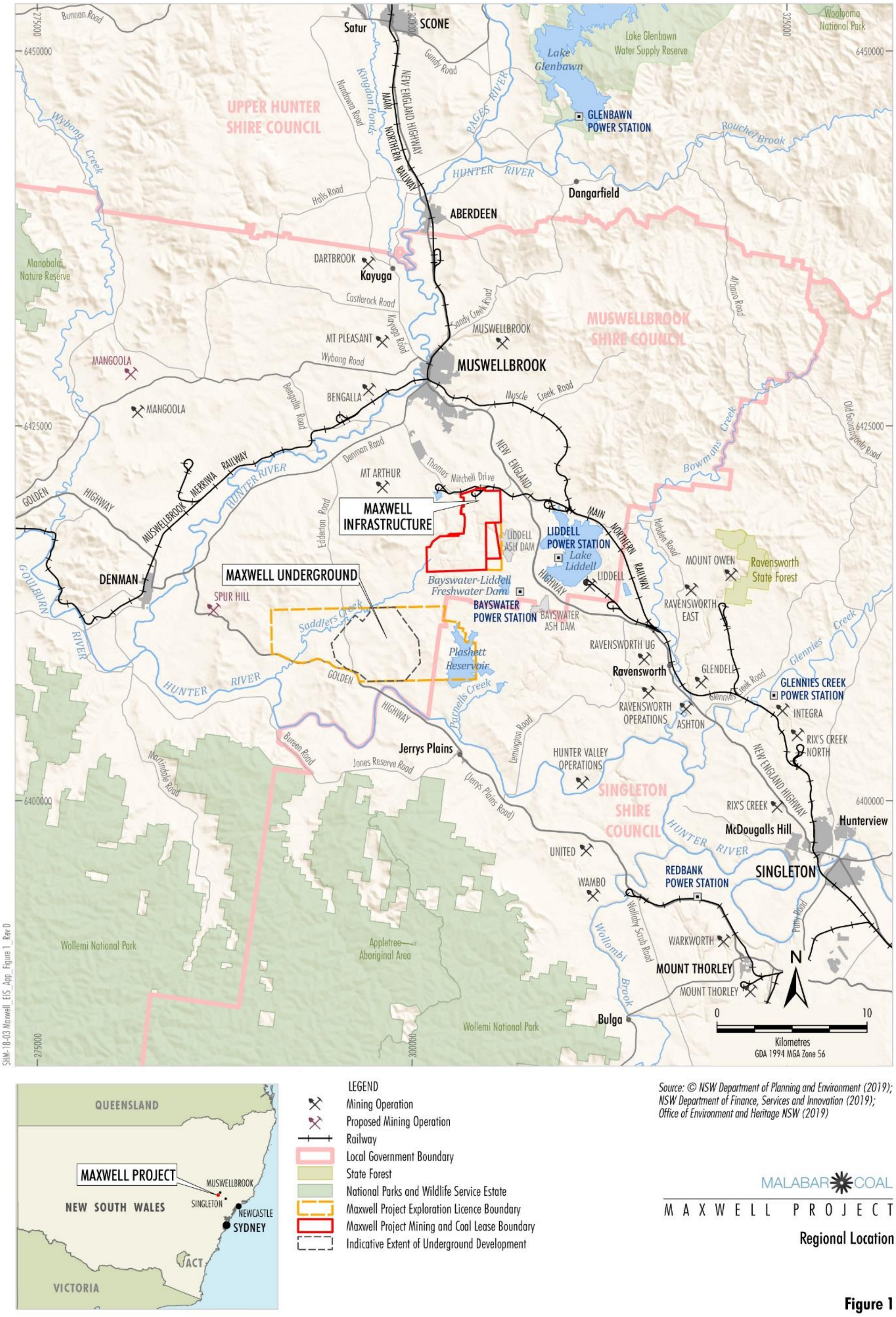

Figure 1. Maxwell Project regional location. Source: Malabar (2018).

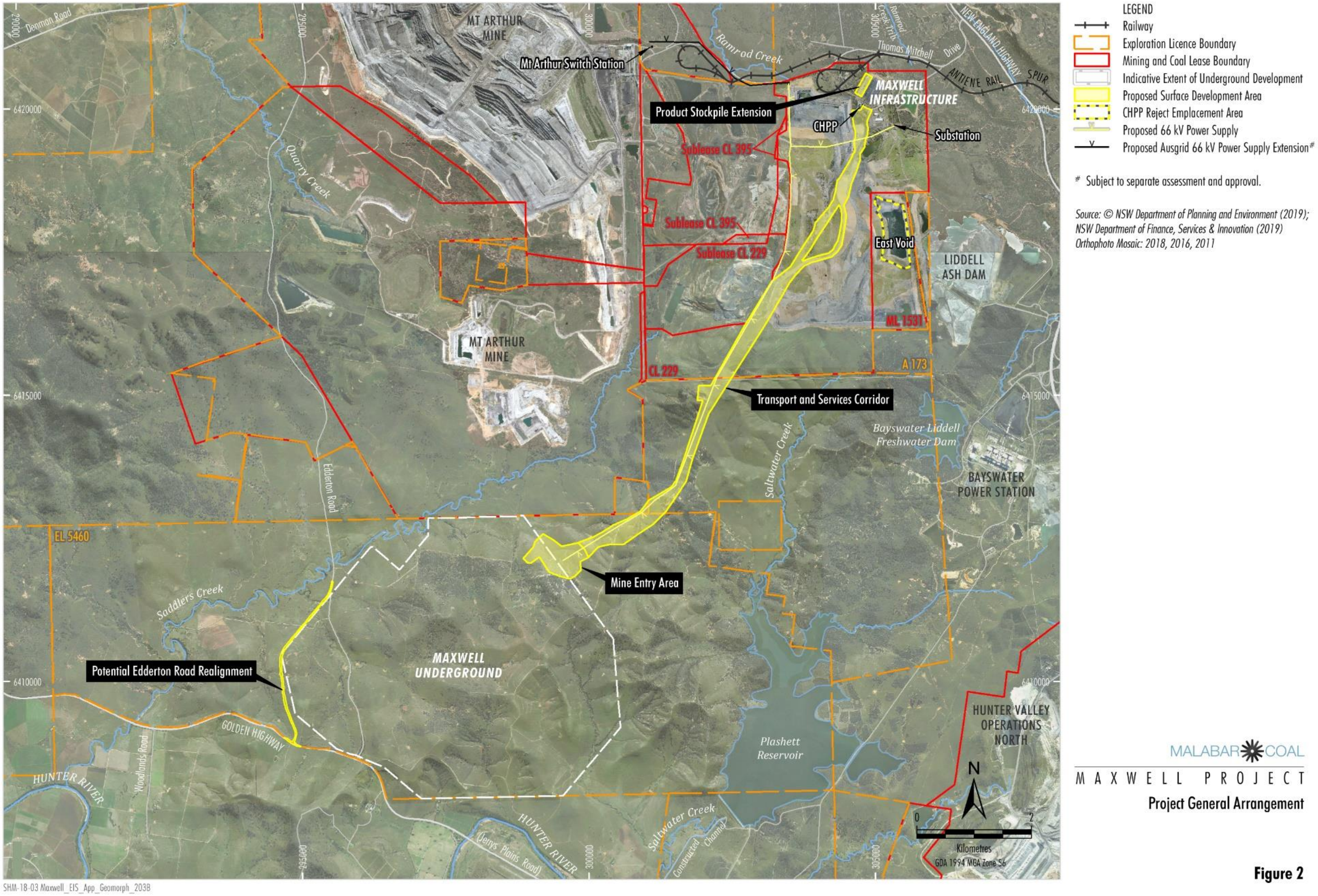

Figure 2. Maxwell Project general arrangement. Source: Malabar (2018).

- emplacement of coarse rejects and tailings and brine within existing voids in CL 229 and ML 1531,
- continued use of existing facilities and services at the Maxwell Infrastructure, with upgrades to coal handling infrastructure along with other minor upgrades,
- monitoring, rehabilitation and remediation of subsidence and other mining effects,
- management of subsidence impacts on Edderton Road,
- rehabilitation activities within CL 229, ML 1531 and CL 395, including the rehabilitation of reject and tailings emplacement areas,
- exploration activities within EL 5460 and Authorisation (A) 173, and
- other associated minor infrastructure, plant, equipment and activities.

An indicative Project general arrangement showing the underground mining area and key infrastructure is provided on Figure 2.

1.2 Proposed operations relevant to this Geomorphology Technical Report

This Geomorphology Technical Report (this Report) is mainly concerned with describing the geomorphological character of the area associated with EL 5460 that is potentially subject to subsidence from underground mining, and assessing the potential impact of subsidence on geomorphological character of the area (Figure 2).

In this Report, subsidence impacts and mitigation measures were considered for all mining stages, within the Maxwell Underground area (Figure 2). This area includes bord and pillar mining with partial pillar extraction in the Whynot Seam and underground longwall extraction in the Woodlands Hill Seam, Arrowfield Seam and Bowfield Seam.

1.3 Purpose of this Report

This Report characterises the physical environment, from a geomorphologic perspective, including areas of alluvial material. Consideration of risk and impact assessment of some geomorphologic-related aspects of the environment was incorporated within the assessments by other relevant technical specialists (refer to other technical specialists reports for details).

1.3.1 Secretary's Environmental Assessment Requirements

The EIS for the development must comply with the requirements of Schedule 2 of the *Environmental Planning and Assessment Regulation 2000*, which requires the potential environmental effects of a proposal to be properly assessed and considered in the decision-making process.

In preparing this Report, the revised Secretary's Environmental Assessment Requirements (SEARs) issued for the Project (SSD 18_9526) on 17 January 2019 have been addressed. The key matters raised by the Secretary for consideration in this Geomorphology Technical Report and where this report addresses the SEARs are outlined in Table 1. The SEARs included an attachment of correspondence from agencies' relevant to the SEARs. Table 2 outlines the key matters raised by agencies in that correspondence for consideration in this Geomorphology Technical Report and where this report addresses these matters.

In addition, the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) has provided advice on the Project. The key matters raised by the IESC for consideration in this Geomorphology Technical Report and where this report addresses the matters are outlined in Table 3.

Table 1 Secretary's Environmental Assessment Requirements (SEARs) for SSD 18_9526 applicable to this Geomorphology Technical Report. This table includes only the relevant sections and sub-sections of the SEARs.

Key SEARs relevant for geomorphological assessment	Location of requirement	Section in this report where addressed
A description of the existing environment likely to be affected by the development, using sufficient baseline data	SEARs (p. 1)	Section 3 Existing environment
An assessment of the likely impacts for all stages of the development, including any cumulative impacts, taking into consideration any relevant legislation, environmental planning instruments, guidelines, policies, plans and industry codes of practice.	SEARs (p. 1-2)	Section 4 Impact assessment
Subsidence - including … an assessment of the likely conventional and non-conventional subsidence effects and impacts of the development, and the potential consequences of these effects and impacts on the natural and built environment (including Edderton Road), paying particular attention to those features that are considered to have significant economic, social, cultural or environmental value	SEARs (p. 3)	Section 4 Impact assessment
Rehabilitation and Final Landform[1] - a description of final landform design objectives, having regard to achieving a natural landform that is safe, stable, non-polluting, fit for the nominated post-mining land use and sympathetic with surrounding landforms	SEARs (p. 4)	Section 5 Monitoring and mitigation
Water - an assessment of the likely impacts of the development on watercourses, riparian land…	SEARs (p. 5)	Section 4 Impact assessment
A description of the measures that would be implemented to avoid, minimise, mitigate and/or offset the likely impacts of the development, and an assessment of: • whether these measures are consistent with industry best practice, and represent the full range of reasonable and feasible mitigation measures that could be implemented; • the likely effectiveness of these measures; and • whether contingency plans would be necessary to manage any residual risks	SEARs (p. 2)	Section 5 Monitoring and mitigation
A description of the measures that would be implemented to monitor and report on the environmental performance of the development	SEARs (p. 3)	Section 5 Monitoring and mitigation

[1] "Final Landform" was interpreted to mean the post-subsidence landform and any intentional modifications made to that landform.

Table 2 Agencies' correspondence to Secretary's Environmental Assessment Requirements applicable to this Geomorphology Technical Report. This table includes only the relevant sections and sub-sections of the requirements.

Key requirements of agencies' correspondence relevant for geomorphological assessment	Location of requirement	Section in this report where addressed
Water and soils 9. The EIS must map the following features relevant to water and soils including: b. Rivers, streams, wetlands… 10. The EIS must describe background conditions for any water resource likely to be affected by the development including: a. Existing surface and groundwater	NSW Office of Environment & Heritage	Section 3 Existing environment
The EIS must assess the impacts of the development on hydrology, including: b. Effects to downstream rivers, wetlands, estuaries, marine waters and floodplain areas d. Impacts to natural processes and functions within rivers[2], wetlands, estuaries and floodplains that affect river system and landscape health such as nutrient flow, aquatic connectivity, and access to habitat for spawning and refuge (e.g. river benches).	NSW Office of Environment & Heritage	Section 4 Impact assessment
3. Soils and Land Degradation – The Project site is identified within the most highly degraded catchment in the Hunter Valley out of 139 catchments by the 'Soil Conservation Erosion Survey' prepared by K.A. Emery[3]. Council acknowledges that this Survey was completed in the 1980's [sic], however, it maintains that it provides a good base point for some of the soil and land degradation issues that will need to be considered and addressed. Council understands that there are erosion issues in the area, degrading gullies, soil fertility, pH, salinity and structural issues away for [sic] the alluvial flat areas. Detailed assessment of the soils and geology[4] will need to be included in the EIS to support establish [sic] mechanisms for erosion and sediment control, informs the sites [sic] management and intended rehabilitation strategies.	Muswellbrook Shire Council	Section 3 Existing environment Section 4 Impact assessment Section 5 Monitoring and mitigation
Assessment of impacts on surface and ground water sources (both quality and quantity), related infrastructure, adjacent licensed water users, basic landholder rights, watercourses, riparian land, and groundwater dependent ecosystems, and measures proposed to reduce and mitigate these impacts.	NSW Department of Industry Crown Lands and Water Division	Section 4 Impact assessment Section 5 Monitoring and mitigation

[2] Geomorphic processes were assumed to be included within the subject of "Hydrology"
[3] Emery K.A. 1985. Hunter River Catchment Soil Erosion. Soil Conservation Service of New South Wales. Sydney.
[4] "soils and geology" was interpreted to be inclusive of geomorphology.

Table 3 IESC advice applicable to this Geomorphology Technical Report. This table includes only the relevant sections and sub-sections of the requirements.

Key requirements of EIS advice relevant for geomorphological assessment	Section in this report where addressed
26. Subsidence mitigation measures are to be detailed within a subsidence management plan and implemented following impact identification through site-specific monitoring. At this stage the identified potential mitigation measures for subsidence-induced surface cracking include ripping, re-grading or in-filling of large to medium surface cracks, re-grading and erosion controls in surface drainage lines and repairing or reinstating damaged groundwater bores. However, the IESC would expect to see more detail on the specific monitoring, management and mitigation measures included within a full environmental assessment. Detailed, long-term and peer-reviewed case studies on successful use of these measures at equivalent locations are essential. Studies should be provided on the relative impacts from grading surface water drainage channels versus letting them "self-heal" after subsidence.	Section 5 Monitoring and mitigation
37. A surface water assessment is needed which: a. uses a risk-based approach to identify key surface water systems with the potential to be impacted (e.g. through subsidence fracturing, ponding or erosion), especially how this may alter the duration of periods of low and zero flow in Saddlers Creek and potentially impact on instream biota; … e. informs appropriate mitigation strategies (e.g. timing and methods for re-establishing drainage lines to minimise erosion and vegetation damage).	Section 4 Impact assessment[5] Section 5 Monitoring and mitigation

1.3.2 Geomorphology Technical Report objectives

The scope of work for this Report included, but was not limited to:

- Collation and review of existing background data to provide a baseline of pre-mining geomorphic condition
- Field data collection within the Field Survey Study Area, including, but not limited to fluvial features, such as, incision, knickpoints, pools, bedrock features, hydraulic controls, riffles, bed material, dimensions and profiles, riparian zones and alluvium.
- 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, and
    - fluvial features.
- Technical assessment of geomorphic-related factors, including, but not limited to:
    - existing geomorphic conditions and processes, and
    - potential subsidence related impacts
- Recommendations for mitigation and monitoring

[5] Potential impacts on flow duration are assessed separately by WRM Water & Environment Pty Ltd.

1.4 Legislation, policy, criteria and/or guidelines

The guidelines that possibly relate to this Report are:

- A Rehabilitation Manual for Australian Streams (Rutherfurd et al., 2000); and
- Suggestions made by Hancock (2001) on requirements for pre-mining assessments in the Hunter Valley.

A Rehabilitation Manual for Australian Streams (Rutherfurd et al., 2000) is relevant only to planning and implementing monitoring and mitigation activities.

Hancock (2001) made recommendations for pre-mining assessments in the Hunter Valley. This document was prepared some time ago, but many of the principles remain current. The advice in Hancock (2001) was essentially followed in this report, with some modifications due to technological improvements in methodologies.

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 in Schedule 4 of the *Biodiversity Conservation Act 2016*[6]. 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. Consequently, this assessment focused on characterising physical aspects of the environment that were known to contribute to aquatic and riparian habitat value.

1.5 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 this 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	Monitoring and mitigation - 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
Section 7	References

[6] See URL: https://www.legislation.nsw.gov.au/#/view/act/2016/63/sch4

2.0 Methodology

2.1 Approach

The approach taken here covered, as a minimum, the components recommended by Hancock (2001) for assessing streams subject to mining impacts in the Hunter Valley. Hancock (2001) distinguished between Schedule 1 (First and Second Order streams), Schedule 2 (Third Order and higher) and Schedule 3 (known to be associated with mapped vulnerable alluvial groundwater sources) streams.

Hancock (2001) suggested that assessments on Schedule 1 streams include:

- Mapping of the affected area
- Locating stable control points (i.e. bedrock outcrops)
- Determining flows which would cause erosion or incision
- Developing a process of remediation of incision due to mining
- Establishment of a photographic record to compare with post-mining condition

Assessments on Schedule 2 streams should include the items recommended for Schedule 1 streams, plus:

- Seam and geology information overlying the working area
- Survey chain along the affected stream from the nearest control downstream to the next stable upstream control point
- Written and photographic records of vegetation communities along the river corridor
- Survey of alluvial groundwater zones adjacent or connected to the stream
- Assessment of connectivity to the stream from alluvium

Assessments on Schedule 3 streams should include the items recommended for Schedule 1 and Schedule 2 streams, plus:

- Detailed flooding analysis, including flood peaks and energy ratings for a range of flood situations up to and beyond a 1:100 year Average Recurrence Interval (ARI) flood event
- Detailed assessment of recharge/discharge of alluvial groundwaters
- Detailed assessment of the existing level of connectivity between the hard rock boundary to the alluvium and post-mining connectivity

The above recommendations for Schedule 3 streams relate to hydrogeology and flood hydraulics, and are not within the scope of this fluvial geomorphology assessment. Hydrogeology was within the scope of the Groundwater Assessment, and flood hydraulics was within the scope of the Surface Water Assessment.

The availability of detailed LiDAR data combined with walking the majority of the streams meant that the suggestions made by Hancock (2001) for Schedule 2 streams regarding topographic and vegetation variables could also be applied to Schedule 1 streams. Hancock's (2001) list of items to include in the assessment was regarded as the minimum requirement; a number of additional items were included in the mapping, for example knickpoints, bed sediment particle size, stream geomorphic type, rock fractures and large wood density. Also included was assessment of the risk of change in stream channel alignment and depressions on drainage lines.

2.2 Study Areas

This Report assesses geomorphological attributes, processes and potential mining impacts at four Study Areas (Figure 2):

1. EL5460 Study Area – the land within EL 5460 (55.8km^2).
2. Mining Study Area – the smaller area (21.34 km^2) within EL 5460 Study Area where underground workings are proposed. This area, provided as a digital polygon by Resource Strategies, contains land that is directly above underground mining activities and would be subject to direct subsidence effects, which is the main impact mechanism relevant to this Report.

3. Field Survey Study Area – Geomorphic processes were assessed within spatial units defined by catchments, so the Mining Study Area was modified in area to cover the catchments of streams draining to and from, or adjacent to, the Mining Study Area. This “Field Survey Study Area” included all the streams surveyed in the field.
4. Catchment Study Area – the wider area (89.89 km^2), which includes the catchments of streams that drain into and out of EL5460 Study Area. This includes catchments of Saddlers Creek, the western tributary of Saltwater Creek and three small streams draining southwards, directly to the Hunter River. Excluded was the area of Saltwater Creek catchment that drained east and southeast, away from the Mining Study Area, towards Plashett Reservoir.

The collection of field data was restricted to Malabar-owned land, within EL5460 Study Area. This was not a constraint on the investigation, as this boundary contained all land potentially impacted by subsidence.

The Hunter River, situated south of the Maxwell Project, is a large perennial watercourse with regulated flow and a wide floodplain under agricultural land use that includes irrigation. Although the Hunter River and its floodplain is wholly outside EL5460 and the underground mining area, nonetheless the river was included in the characterisation of the distribution of alluvium, which was conducted at the regional scale.

2.3 Measurement scales

Characterisation of the geomorphology of the Study Areas 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 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 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 geomorphological features was based on a combination of field survey and desktop analysis of existing data, including LiDAR and aerial photography data.

2.4 Geomorphologically-relevant variables

This Report was not concerned with subsidence directly, but with the potential impacts and consequences of subsidence for the geomorphological character of the environment. Variables of interest to geomorphological characterisation were considered within four categories:

- Landscape-scale variables
- Stream reach- and point-scale variables
- Alluvium
- Sites of special significance

Alluvium was considered separately, as it is relevant to mining impact assessment at the landscape and reach scales.

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. This characterisation was undertaken at the scale of the Mining Study Area, extended slightly to include the catchments of streams that drained into or out of the Mining Study Area, plus some stream reaches in close proximity to the boundary of the Mining Study Area.

The variables included in the methodology 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; Sidle et al., 2000; Hancock, 2001; Blodgett and Kuipers, 2002; Waddington and Kay, 2003; Kay et al., 2006; Jankowski, 2007; Jankowski and Knights, 2010; Krogh, 2007; Machowski et al., 2016; Parsons Brinkerhoff, 2007; NSW Department of Planning, 2008; Hebblewhite, 2009; Morrison et al., 2018), 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). The determination of stream fragility is based on the adjustment potential of three main characteristics of each geomorphic category. These include the adjustment potential of each category’s channel attributes (geometry, size and connection to floodplain), planform (lateral stability, number of channels and sinuosity) and bed character (bedform and bed materials) (Cook and Schneider, 2006). Different stream types have characteristic levels of fragility. Stream types with “Low fragility” are resilient or “unbreakable”, those with “Medium fragility” have local adjustment potential, and those with “High fragility” have significant adjustment potential (Cook and Schneider, 2006). Following on from this, the conservation and rehabilitation priority of stream reaches can be determined on the basis of geomorphic fragility and condition. For example, stream reaches with high fragility and poor condition are rated low priority, while reaches with low fragility that are in good geomorphic condition are rated the highest priority for protection.

This Report classified the streams in the Field Survey Study Area according to river type and geomorphic condition, using an approach that was consistent with the standard River Styles® methodology used in NSW. 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). A map of RCI for the Hunter River basin in Healey et al. (2012, p. 29) indicates “moderate” condition over the land of the Study Areas, but this map was produced at a coarse-scale and shows no detail for individual streams within the Catchment Study Area. The RCI is a multi-metric index comprising River Styles® Geomorphic Condition (RSC), Catchment Disturbance Index (CDI), Hydrological Stress (HS), River Biodiversity Condition Index (RBCI) and Riparian Vegetation Cover (RVC), or fewer indicators depending on data availability (Healey et al., 2012, p. 13, 28). Of these indicators, only geomorphic condition and riparian vegetation cover condition are relevant to this Report as the other indicators are within the domain of other specialist’s reports. 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 the inclusion, in geomorphologic assessments, of 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 methodology used for this 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).

The beds of ephemeral headwater streams are often vegetated with grasses[7] 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 et al., 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 as a variable in the methodology used for this 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[8] 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 methodology used for this 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 some of those within the Study Areas, 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 can impact stream bed elevation through creation of, or accelerated headward migration of, knickpoints. Knickpoints are a local steep fall in channel bed elevation and are a common, natural feature of streams (Cook and Schneider, 2006, pp. 46-47). 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 the methodology used for this Report classified knickpoints 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 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. Mining-related subsidence can potentially impact stream bank lateral position due to: (i) lowering of the nearby land surface to a level below that of the existing stream (in which case the stream changes course), or (ii) increased erosive power associated with an increase in runoff from an expanded catchment area.

The surface geology of the region where the Project is situated includes claystone, siltstone, sandstone, and conglomerate, as well as folds and faults (Glen and Beckett, 1993). Thus, some creeks beds would be expected to be formed in exposed bedrock. Bedrock in channels can manifest as flat to gently sloping slabs of rock exposed along a bedding plane, and elevated bars of rock crossing the channel. Exposed rock can be associated

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

with pools, either by forming a low permeability bed surface, or by acting as the hydraulic control that backs up water in the pool. It would be expected to find natural joints in exposed bedrock of the stream beds. These joints are mostly very old in geological terms, and relate to previous episodes of deformation and relief of stress.

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 in the majority of streams in the Field Survey Study Area, which are relatively steep, with narrow or little alluvium present. As rock bars are potentially at risk of mining-induced fracturing, so too are the pools that the rock bars impound. Thus, the methodology used for this Report included observations of pool presence, dimensions, and the type of hydraulic control.

Based on the above considerations, the SEARs and the scope of works, reach- and point-scale variable groups included in the methodology used for this Report were:

- Stream geomorphic type and condition
- Riparian and in-channel vegetation
- In-channel bedrock features
- In-channel pools
- Channel slope
- Channel dimensions
- Channel bed materials
- Knickpoints
- Characteristics of fractures (or naturally occurring joints) in channel bedrock

2.4.3 Alluvium

A glossary of landform and geologic terms collated by USDA Natural Resources Conservation Service (2018) provides standard definitions, consistent with other sources. It defines “alluvium” as:

> “*Unconsolidated, clastic material subaerially deposited by running water, including gravel, sand, silt, clay, and various mixtures of these*”.

A “floodplain” is defined as:

> “*The nearly level plain that borders a stream and is subject to inundation under flood-stage conditions unless protected artificially. It is usually a constructional landform built of sediment deposited during overflow and lateral migration of the streams*”.

Hillslopes bordering floodplains could be formed of weathered parent rock, or “colluvium” defined as:

> “*Unconsolidated, unsorted earth material being transported or deposited on side slopes and/or at the base of slopes by mass movement (e.g., direct gravitational action) and by local, unconcentrated runoff*”.

Thus, alluvium is fine-grained eroded soil material that has been transported far from its source and deposited by a stream in a valley floor. Alluvium is found in the bed of most creeks and rivers that transport bed material. Floodplains can be found even on relatively confined upland creeks in the form of discontinuous pockets (Johnston and Brierley, 2006). On large rivers, alluvium manifests as massive stratified layers that fill the dish-shaped area in the valley bottom scoured into the bedrock by fluvial action of migrating streams over a long time period [mainly over the Holocene epoch (12 thousand years BP) within the Quaternary period (2.6 million years BP)]. Floodplain surfaces are relatively flat, although the presence of significant levees result in a transverse slope away from the channel. Alluvium can be present in the form of active modern floodplains (flooded under the current flow regime; often defined by the limit of the 100 year ARI flood) or inactive terraces (not flooded or very infrequently flooded under the current flow regime).

Alluvium is of interest in mining impact assessments because floodplains can act as aquifers that hold groundwater. Groundwater is a major resource for irrigation, town, stock and domestic uses in the Hunter River catchment (Department of Water and Energy, 2009). The potential of a floodplain deposit to contain a significant aquifer is a function of the size of the river and its perenniality, and the size of the floodplain and the texture (grain size distribution) of the sediment. Floodplains on large perennial rivers with coarse and gravel layers would provide a more reliable and ready source of groundwater than a floodplain pocket on a small upland stream or comprising low permeability silt and clay. Groundwater bores are usually situated on large lowland floodplains, but these major aquifers could be partially fed by smaller aquifers associated with the floodplains of tributary streams.

To summarise the definitions, floodplains are always composed of alluvium, but alluvium does not always contain aquifers that are an exploitable source of groundwater. In this Report, “alluvium” is meant in the geomorphic sense, and should not be interpreted to mean “alluvial aquifer”.

Manfreda et al. (2011, 2014) and Clubb et al. (2017) grouped methods of delineating floodplain landform units, equivalent to alluvium units in pedology, into two primary categories:

1. Hydraulic and hydrologic methods that map observed or modelled inundation extent for floods of given average recurrence interval, often 100 year.
2. Topographic (geomorphic) metrics or indices extracted from digital terrain models, known as terrain analysis.

A third category of method is:

3. Soil survey, sampling and classification, perhaps in association with aerial photographic interpretation. Survey methodologies include digging pits or taking cores, or geophysical, such as electrical resistivity.

Vegetation mapping could provide data to assist floodplain delineation, but defining floodplain physical boundaries is not usually a primary objective of vegetation mapping studies. Rather, given the mosaic of terrestrial and aquatic species typically found on naturally vegetated floodplains, the first mapping step is often to define the area of interest with a topographic index (e.g. Cunningham et al., 2013). The low gradient topography of floodplains combined with relatively fertile soil and proximity to a water source makes alluvial units attractive for cropping, such that in agricultural areas, it might be possible to map floodplain boundaries on the basis of historical and current land use.

The objectivity of automatic identification of floodplain extent from digital terrain data is an advantage over subjective methods, although an approach that combines hydraulic, slope and soils data could produce a rational and defendable result, and might be preferred in cases where high quality and high resolution data are available.

By definition, floodplains are formed from alluvium, so it follows that conclusive identification of a floodplain landform means that a body of alluvium has been identified. This is evident without additional information from soil sampling and laboratory analysis, or geophysical survey. However, these methods could assist definition of the alluvium boundary in situations where geomorphic methods produce an equivocal floodplain boundary. Geophysical survey and shallow transect drilling have been completed in the vicinity of Saddlers Creek and the Hunter River, and the outcomes of this work have been considered (see later Sections 3.4.2 and 3.4.3).

2.4.4 Sites of special 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. 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. No published or anecdotal evidence was found indicating the existence of sites of geomorphological significance within the Study Areas considered in this Report.

2.5 Primary field data

A geomorphological field survey of the Study Areas was undertaken by Dr Christopher Gippel of Fluvial Systems Pty Ltd in 10 days over the period 25 July to 8 August 2018. The field survey was done on foot, and sampled readily measurable data from streams within the Study Areas.

2.6 Available spatial data

2.6.1 Elevation and aerial photography

The investigation relied heavily on detailed topographic data and aerial photography. Resource Strategies provided a 0.5 × 0.5 m Digital Elevation Model (DEM) obtained by Malabar for the Project. The DEM covered the EL5640 Study Area, and also included a small area to the northeast and another small area to the south where the Hunter River is in close proximity to EL5640. The DEM was based on a LiDAR survey from July 2018. A comparison of data with control point elevations undertaken by the data supplier found a Root Mean Square Error (RMSE) value of 1 σ = 0.02 m and 95 percent confidence interval of CI95 = 0.04 m.

The wider region, including the Mining Study Area and the Catchment Study Area, is covered by a 2 × 2 m DEM produced by NSW Spatial Services, Department of Finance, Services and Innovation, available from ELVIS - Elevation and Depth - Foundation Spatial Data, Version 0.1.1.0 (http://elevation.fsdf.org.au/). In this area, the DEM was derived from LiDAR data collected from flights over the period November 2017 to March 2018. The DEM was produced using the Triangular Irregular Network (TIN) method of averaging ground heights to formulate a regular grid. This data set contains a ground surface model in grid format derived from Spatial Services Category 2 (Classification Level 3) LiDAR from an ALS80 (SN8250) sensor. The model is not hydrologically enforced. The data used to create the DEM has an accuracy of 0.3 m (95% Confidence Interval) vertical and 0.8 m (95% Confidence Interval) horizontal.

A comparison of the NSW Spatial Services DEM and the Maxwell Project DEM over a 2 × 2 km test area, centred on 32.43801355°S 150.86199431°E, indicated a topographically-dependent difference in the data. Elevation in the test area ranged from 96 to 231 m Australian Height Datum (AHD). Subtracting the Maxwell Project test area DEM (re-sized from 0.5 m to 2 m grid) from the 2 m NSW Spatial Services test area DEM, the difference ranged from -1.30 m to 2.55 m, with an average difference of 0.067 m. Compared to the Maxwell Project data, the NSW Spatial Services data tended to be higher in elevation on west facing slopes and lower in elevation on east facing slopes, with the differences directly proportional to slope. The differences were greater on steep west facing slopes (mostly less than +0.5 m) than on steep east facing slopes (mostly less than 0.1 m). The differences between the DEMs were between -0.5 and +0.5 m over 98.5% of the test area, with 1.5% of the area exceeding 0.5 m positive difference and 0.0006% of the area exceeding 0.5 m negative difference. This comparison suggests that the two DEMs are sufficiently similar that they can be used interchangeably without elevation adjustments, especially for computations on floodplains, where slopes are not high and elevations of the two DEMS are virtually identical.

Digital aerial photography of the region containing the areas of interest was accessed online from World Imagery. The available photography for this area was at 0.5 × 0.5 m pixel resolution, flown on 22/11/2015.

2.6.2 Hydrology

The drainage network was represented by National Surface Hydrology Lines (Regional) downloaded from Australian Government (https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search?node=srv#/metadata/83107). The dataset is a collaborative effort by Geoscience Australia and state governments. Geoscience Australia manages a data aggregation from multiple jurisdictional sources. The scale of the data ranges from 1:25,000 to 1: 250,000 across the continent. Geoscience Australia aggregates the data into a National Model and forms the surface water components of the Foundation Spatial Data Framework. In the area covered by the Project, these lines correspond to the hydrolines (“blue lines”) on the 1:25,000 topographic map sheet. The downloaded data are the same as the NSW Government Department of Finance, Services and Innovation NSW Foundation Spatial Data Framework - Water - NSW Hydro Line (https://data.nsw.gov.au/data/dataset/nsw-foundation-spatial-data-framework-water-nsw-hydro-line) viewable as Water Management (General) Regulation 2018 hydroline spatial data 1.0 on the NSW Government Department of Industry web mapping portal (https://trade.maps.arcgis.com/apps/webappviewer/index.html?id=07b967fd0bdc4b0099fc5be45b6d1392).

The blue lines on topographic maps, and thus the National Surface Hydrology Lines (Regional), were drawn mainly on the basis of whether a channel was visible on the aerial photographs available at the time of production, perhaps also guided by vegetation structure. Some important factors impact how well the mapped blue lines represent the existing channel network:

- The blue lines represent the channel network visible or assumed from aerial photographs; the resolution and quality of the photographs limits the scale of mapping
- Distortion inherent in the original aerial photographs makes precise transfer of the locations of the stream lines to an undistorted map difficult

- The blue lines are typically depicted as a smoothed representation of the actual stream lines
- Channels can change in size and position over time

Given these factors, the National Surface Hydrology Lines (Regional), referred to here as blue lines, were not expected to accurately represent the existing drainage lines. Nevertheless, the blue line network is the conventional standard used in impact assessments to identify streams of interest, and to classify streams by size using Strahler Stream Order. In this Report, the blue lines were used for this purpose, and also to guide the terrain analysis procedure to generate a representation of the existing drainage network that had similar drainage density to that represented by the blue lines.

2.6.3 Geology

Geology data were from Hunter Coalfield Regional Geology 1:100,000 geological map (Glen and Beckett, 1993), obtained online from NSW Planning & Environment, Resource & Geoscience (https://www.resourcesandgeoscience.nsw.gov.au/miners-and-explorers/geoscience-information/products-and-data/maps/coalfield/hunter-coalfield-regional-1100-000-geology-map). The data were consistent with the online version of Geoscience Australia Bedrock and Surficial Geology, compiled at 1:1 million scale (http://services.ga.gov.au/gis/services/GA_Surface_Geology/MapServer/WMSServer?request=GetCapabilities&service=WMS).

2.6.4 Soil Landscapes

Soil Landscapes of Central and Eastern NSW is a compilation of all 39 published soil landscape maps that cover central and eastern NSW, based on standard 1:100,000 and 1:250,000 topographic sheets. The mapping provides an inventory of soil and landscape properties of the area and identifies major soil and landscape qualities and constraints.

Soil and Land Resources of the Hunter Region is a digital dataset that upgrades 1:250,000 Soil Landscape mapping for the Singleton area providing a standardised and seamless land and soil information across the region at 1:100,000 scale. Information from previous soil and geology surveys were used. Linework was digitized at approximately 1:10,000 scale. Provisional units were established on the dominant geomorphic processes responsible for the formation of the landscape and on the geological parent material. The boundaries of these units were mapped using the interpretation of ADS40 photography, SPOT satellite imagery, DEM and radiometric imagery. Fieldwork was conducted assessing a suite of soil and landscape properties. The Soil and Land Resources dataset provides similar information to Soil Landscapes, but at a higher resolution, and using an entirely different set of unit names. Each unit is an inventory of soil and landscape information with relatively uniform land management requirements, allowing major soil and landscape qualities and constraints to be identified. Soils are described using the Australian Soil Classification and the Great Soil Groups systems. These data were obtained from the online version of Office of Environment and Heritage (2018) Soil and Land Resources of the Hunter Region, NSW Office of Environment and Heritage, Sydney (http://data.environment.nsw.gov.au/dataset/2f43ab21-7b87-4df0-8dcb-f4d704e1fed4). Descriptions of the Soil and Land Resources units (NSW Office of Environment and Heritage, 2018) were downloaded from http://www.environment.nsw.gov.au/eSpade2Webapp. The data are recent, with collection over the period 1 Jan 2012 to 1 Jan 2018.

SLR Consulting Australia Pty Ltd (2019) undertook a biophysical strategic agricultural land (BSAL) verification assessment over the Study Area using a standard protocol. BSAL is land with high quality soil and water resources capable of sustaining high levels of productivity. The 2018 study included field assessment at 30 soil survey sites, with samples from 21 of the sites also being sent for laboratory analysis. The soil classification results from the BSAL verification assessment were sufficiently consistent with the mapping of Soil and Land Resources of the Hunter Region that the latter information was considered reliable for the purposes of this geomorphology report. The Soil and Land Resources of the Hunter Region additionally included explicit assessment of extent and severity of soil degradation, which was relevant to this geomorphology report.

2.6.5 Alluvium

Four different maps of the distribution of alluvium were available that include the Study Areas considered in this Report:

1. Singleton Soil Landscape 1:250,000 (Kovak and Lawrie, 1991).
2. Soil and Land Resources of the Hunter Region 1:100,000 (Office of Environment and Heritage, 2018).

3. Hunter Coalfield Regional Geology 1:100,000 (Glen and Beckett, 1993).
4. Hunter Unregulated and Alluvial Water Sources (Department of Water and Energy, 2009).

An online version of the Singleton 1:250,000 Soil Landscape map (Kovak and Lawrie, 1991) was obtained from Office of Environment and Heritage (https://www.environment.nsw.gov.au/topics/land-and-soil/soil-data/soil-maps). Descriptions of the Soil Landscape units were downloaded from http://www.environment.nsw.gov.au/eSpade2Webapp. The relevant unit on this mapping is Hunter Soil Landscape (A-hu), described as:

> "*This soil landscape covers the floodplains of the Hunter River and its tributaries. The main soils are all formed in alluvium*", with the landform described as "*Level plains and river terraces of the Hunter River with elevations of 20 - 60 m. Slopes are 0 - 3%. The width of the plains ranges from 200 - 3200 m. Local relief is generally less than 10 m*".

On the Soil and Land Resources of the Hunter Region mapping, the relevant units are Singleton (sgw) Alluvial on the Hunter River floodplain, and Foy Brook (fyz) on Saddlers Creek and Saltwater Creek floodplains. The geological descriptions were taken from Department of Mineral Resources (2002) and Colquhoun et al. (2015).

Singleton (sgw) geology is described as:

> "*Quaternary alluvium valley deposits consisting mostly of clays and silts with minor sands and gravels*".

The sgw landform is described as:

> "*Alluvial plain of variable width. Generally 200 - 1500 m wide, the plain is up to 4000 m wide in the Singleton area. Drainage is integrated and unidirectional. The channel is slowly migrating, with prominent meandering and relict ox-bow and chute cut-off channels occurring throughout. Both high and low terraces are present. Slopes 0 - 3%, local relief <10 m and elevation 10 - 200 m*".

The soils on terraces and plains of sgw include Prairie Soils and Chernozems, Red Earths and Brown Earths, Black Earths, Red Podzolic Soils and Red Soloths, and on recent sediments and channels the soils are:

> "…*deep (100 - <150 cm), imperfectly to well-drained Stratic Rudosols (Alluvial Soils)*".

Foy Brook (fyz) geology is described as:

> "*Quaternary alluvial sand, silt and clay derived from Permian sediments of the Banxton Formation, Wittingham Coal Measures and Carboniferous sediments and felsic volcanics of the Isismurra Formation and Native Dog Member*".

The fyz landform is described as:

> "*Level to gently undulating, narrow to moderately broad (100 - 500 m) plains, terraced plains and open depressions forming the inset modern floodplains and terraces in bedrock-incised valleys. Slopes 0 - 3%, local relief <10 m and elevation 30 - 330 m. Elements include terraces, narrow incised floodplains, fluvial channels and occasional prior channels, point bars, ox-bows and small intermittent swampy depressions*."

The soils of fyz include Brown Earths and Alluvial Soils on floodplains, and Brown Earths on terraces. Rounded alluvial gravels and stones are common within some profiles.

The reports accompanying the Soil And Land Resource of the Hunter Region includes a note that they describe reconnaissance soil landscape information mapped at 1:100,000 scale which does not negate the need for site assessment at a scale suitable to the land use or development under consideration.

The relevant unit on the Hunter Coalfield Regional Geology 1:100,000 map (Glen and Beckett, 1993) is Quaternary alluvium (Qa), described on the legend as:

> "*Silt, sand, gravel*" [occurring as] "*Point bar, levee, overbank; includes some relict Tertiary alluvial terrace deposits*".

A digital version of the Plan Map of Hunter Unregulated and Alluvial Water Sources (Department of Water and Energy, 2009) was supplied by Resource Strategies. The alluvial water source type is “Coastal Alluvial Upriver”, named “Hunter River Alluvium”. Alluvium on the Hunter River belongs to Upstream Glennies Creek Management Zone of the Water Sharing Plan (WSP), and alluvium on Saddlers Creek and Saltwater Creek belong to the Jerrys Management Zone of the WSP. Shallow upriver alluvial aquifers are characterised by:

> “…*coarse materials and relatively short travel times between surface and ground. These aquifers are considered to be highly connected to their parent streams*.”

The water sharing rules for the upriver alluvial aquifers are covered in the Hunter Unregulated and Alluvial Water Sharing Plan (Department of Water and Energy, 2009).

2.6.6 Streambank erosion and gullying

A survey of erosion in the Hunter valley was undertaken by Emery (1985). This survey found the Catchment Study Area was within the most degraded catchment in the Hunter Valley. Consistent with this survey, but more recent, and available in in digital form, is the spatial layer Erosion Gully and Streambank – Landform and Condition Dataset downloaded from State Government of NSW, Office of Environment and Heritage (OEH) (https://datasets.seed.nsw.gov.au/dataset/erosion-gully-and-streambank-landform-and-condition-dataset206b0).

Gully and streambank erosion were mapped as linear features, classified according to severity and depth (Taylor, 2011) (Table 4). The metadata indicate that mapping was carried out on 1:25,000 scale topographic maps from 1:25,000 scale aerial photography. Linear features less than 100 m in length were not represented. The estimated positional accuracy of the linework is between 12.5 m and up to 75 m. Linework was based on aerial photograph interpretation (photographs dated between 1991 - 1993) by staff with training in natural resource assessment.

Table 4 Streambank and gully erosion type, severity and depth classes, mapped by OEH. Source: Taylor (2011).

Erosion type class	Erosion severity class	Description of severity class	Erosion depth class
Gully	Minor	Isolated discontinuous linear gullies, confined to primary or minor drainage lines	< 1.5 m 1.5 – 3.0 m 3.0 – 6 m >6 m
Gully	Moderate	Continuous linear gullies to primary or minor drainage lines	< 1.5 m 1.5 – 3.0 m 3.0 – 6 m >6 m
Gully	Severe	Discontinuous or continuous gullies branching into minor drainage lines, or multiple >6m deep branching within primary drainage lines	< 1.5 m 1.5 – 3.0 m 3.0 – 6 m >6 m
Gully	Extreme	Discontinuous or continuous multiple branching gullies, or sub-parallel gullies in dispersible soils, frequently feature tunnels in surrounding soils and structures	< 1.5 m 1.5 – 3.0 m 3.0 – 6 m >6 m
Streambank	No severity classes	No severity classes	< 1.5 m 1.5 – 3.0 m 3.0 – 6 m >6 m

2.6.7 River Styles® classification

In NSW, the commonly used standard for classifying stream geomorphic type is River Styles®, which is a system 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). Cook and Schneider (2006) classified and mapped River Styles®, geomorphic condition, and recovery potential, of streams in the Hunter River basin.

In the upper catchment areas of the Hunter River basin, the mapping of Cook and Schneider (2006) was done at a relatively small-scale. The mapped streams were generally limited to those Fourth Strahler Order or higher, but in the Catchment Study Area defined in this Report, some Fourth Order stream reaches were not mapped, yet some stream reaches as low in Order as Second Order were mapped. The map of River Styles® in Cook and Schneider (2006, p. 27) includes the Hunter River, Saddlers Creek, and selected tributaries of Saddlers Creek, but the majority of the blue lines on the National Surface Hydrology Lines (Regional) were not included.

The existing River Styles® data from the Catchment Study Area complemented and informed the work undertaken for this Report to assess geomorphic type, condition, and recovery potential of streams within the Field Survey Study Area.

2.7 Field survey

2.7.1 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 Field Survey Study Area, the relatively small size of the instream 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 streams and regularly following a sampling protocol. The objective was to sample the range of streams marked by the blue line network by walking lengths of representative streams in their entirety (Figure 3). It was unnecessary to walk every mapped stream in the Field Survey Study Area, mainly because some small streams were similar to nearby streams that were walked and could be characterised from the data sampled from those streams.

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 50 to 300 metres apart (depending on stream size and heterogeneity).

The field data were collected over 10 days within the period 25 July to 8 August 2018. All of the measurements, estimates and data recording were made by C.J. Gippel. The entire month of July was dry, with zero rainfall recorded at Bureau of Meteorology station Muswellbrook (Lindisfarne) (61168). On 6 August 3 mm was recorded, and on 7 August 7 mm was recorded. Due to rain on 6 August, the survey was halted at 11:30 AM, and no observations were made on the following day. The rain of 6 and 7 August did not generate significant surface runoff, with all stream beds dry on 8 August.

Data were recorded on a Global Positioning System (GPS)-equipped Panasonic Toughpad FZ-A2 tablet using a specially designed form compiled in Open Data Kit (ODK) (http://opendatakit.org/). The accuracy of the location data was improved by using an external Holux Bluetooth GPS receiver as a mock location provider to the tablet. Location was also recorded independently using a Garmin etrex 10, set to record a tracklog, as well as manually entered waypoints at the sampled sites. 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. A duplicate set of photographs were taken using a GPS-equipped Ricoh camera. This approach resulted in 472 sets of observations (Figure 3).

One stream on the north-eastern boundary of the Mining Study Area, and one just outside the south-western boundary, were included in the field survey (Figure 3). This was a conservative measure, as the extent of subsidence due to the Project was not known at the time of the field survey. Subsequent modelling indicated that these two streams would not be impacted by mining, so the data collected at the 62 sites from those two streams were not utilised in this Report.

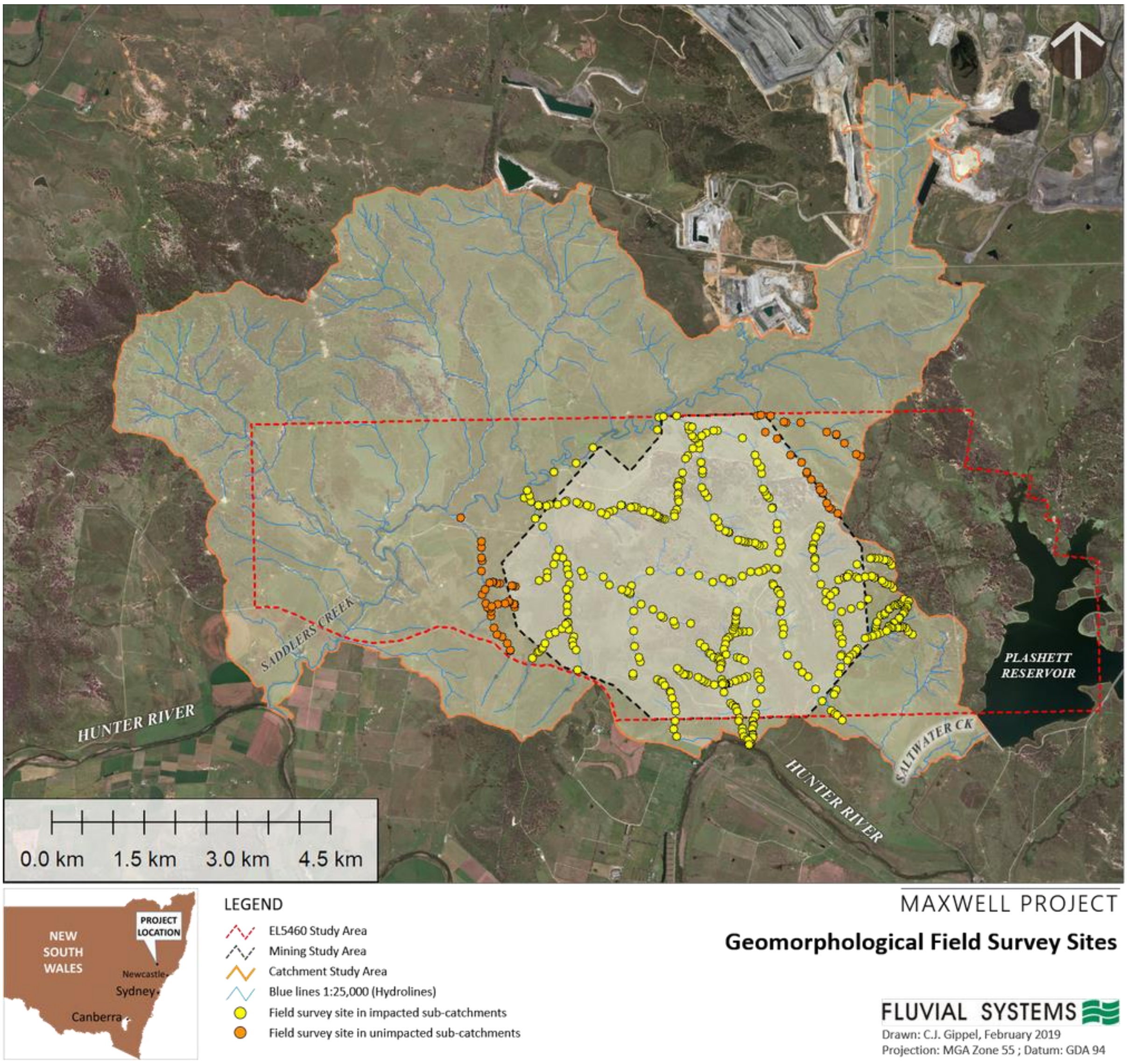

Figure 3. Coverage of the geomorphologic survey conducted over the period 25 July to 8 August 2018. Data were recorded at a total of 472 observation points. Coverage included the area subject to risk of direct subsidence impact, plus nearby streams.

2.7.2 Field sampled variables

A comprehensive set of variables was measured at sites in the field (Table 5). At some sites only a sub-set of the variables was measured. This applied to sites with a knickpoint that were close to a site where all variables had been surveyed and the general character of the stream was not appreciably different, other than the presence of the knickpoint. Collection of another set of comprehensive data would not have improved the characterisation of the reach. In general, the measurements were done using standard techniques from the literature. Most of the observations involved recording presence/absence or measuring a quantity. Ferruginous colloids and seeps were of potential interest, but were not observed anywhere in the surveyed streams.

The survey focused on 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.

Pools were not a typical feature of the majority of the surveyed stream reaches, either because of steep gradient and/or lack of bed depth variability. Some low gradient reaches set in broad depositional zones had scour holes present that could possibly fill with water during stormflow events and then act as refugia. Where present, these potential pools were numerous, and irregular in shape, dimensions, position and frequency. Rather than attempting to measure their dimensions, in all but a few exceptional cases, pools were simply noted as a typical feature of the stream type.

Significant knickpoints were deemed to be higher than 0.2 m. This threshold was applicable to most of the streams in the surveyed area. All knickpoints were classified 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. The presence of minor bedrock features was also noted when recording bed material size. Joints in bed material were identified and counted along a transect with a minimum length of 1 m and extending for the maximum practical length of exposed rock.

Some variables were quantified using a subjective visual estimation method. These variables included the magnitude and regularity of 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 relatively short 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

Table 5 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	Magnitude 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 a 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 times the channel width), or other (presence noted in bed material calibre)
Count of joints visible in bedrock	Count of joints 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
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 × 5 m plots (6 Braun-Blanquet classes)
Other observations	Any feature not otherwise covered and considered potentially relevant to geomorphologic characterisation or geomorphologic condition

2.7.3 Derived field variables

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

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

Bedrock joint density (F) was calculated as the count of joints (N) divided by the length of rock over which they were counted (L_R):

$$F = 10\left(\frac{N}{L_R}\right) \quad (1)$$

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:

$$V_P = 0.7W_P \cdot 0.7D_P \cdot L_P \quad (2)$$

At each sampling site, the cover abundances of riparian trees, T, shrubs, S, and ground cover, G, were rapidly estimated at plots approximately 5 × 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.

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

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. The index scores were converted to combined cover classes equivalent to the classes used to collect the original data (Figure 4).

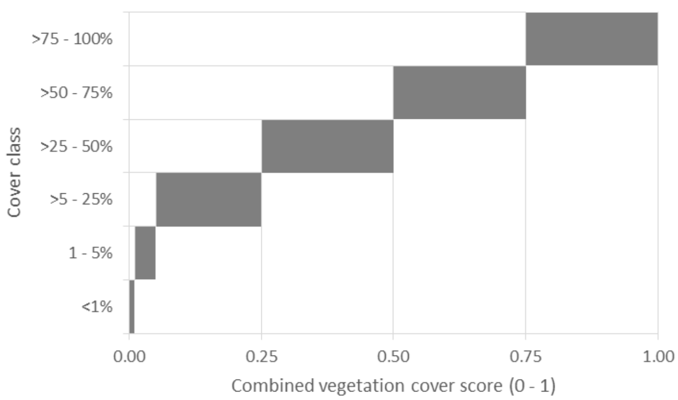

Figure 4. Scale for conversion of combined riparian vegetation cover index score to class.

2.7.4 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.

2.8 Drainage network and terrain indexes

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 et al., 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 techniques were adopted in the methodology used for this Report.

Terrain analysis was undertaken using two different GIS applications: Global Mapper™ V15.2.5 25 June 2014 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).

2.8.1 Topography (digital elevation) definition

The topography was defined by a 0.5 × 0.5 m DEM (0.5 m DEM) that covered EL5640 and a 2 × 2 m DEM (2 m DEM) that covered the wider region.

For the purpose of computing the drainage network, mapping subsidence, and calculating topographic indices, the original DEM grids were resized using Global Mapper™ to produce a 1 m DEM, 5 m DEM and 25 m DEM.

2.8.2 Strahler Stream Order

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. Stream Order is specific to the scale and method used to define the drainage network. The Stream Order of a river will be higher the larger the map scale (i.e. the more detailed the map), as more headwater streams will be counted. In NSW, the convention of measuring Stream Order from 1:25,000 Department of Lands topographic sheets has been replaced by measurement from the equivalent digital hydrolines. In this Report, Stream Order was measured from the National Surface Hydrology Lines (Regional) digital hydroline layer. Although the digital hydroline layer was produced fairly recently, it was primarily based on the existing mapped blue lines, some of which originated from 1976. Some adjustments were made to the drainage network to reflect major changes in drainage due to open cut mining in the catchment that had occurred since 1976.

2.8.3 Definition of the stream network

2.8.3.1 Conventional classification of streams by importance

The guideline “Management of stream/aquifer systems in coal mining developments” by DIPNR (2005) set out principles for considering impacts on streams associated with new or altered mining developments. The guideline took into account the *Water Act 1912* and *River and Foreshores Improvement Act 1948*, which were the relevant Acts prior to the relevant provision of the *Water Management Act 2000* coming into force. Hancock (2001) and DIPNR (2005) classified streams into three groups using the criteria Strahler Order, permanence and whether or not the stream was conventionally regarded as “major”. Schedule 1 streams as “*comprise first and second order watercourses and are usually intermittent*” (if permanent they are Schedule 2); Schedule 2 streams “*comprise primarily third order and higher streams, which drain into primary catchment river systems*”; Schedule 3 streams “*comprise major rivers and connected alluvial groundwaters*”. This guideline emphasised the importance of the geomorphic character of streams, in particular, stability and geomorphic units (such as pools, riffles, woody debris, sediment fans). The main concerns for Schedule 1 streams were considered to be bed fracturing and erosion; Schedule 2 streams were described as dynamic and complex systems, potentially with unpredictable geomorphic behaviour, and; the importance of the floodplain was emphasised for Schedule 3 streams.

Under clause 3 of the *Water Management (General) Regulation 2018*[9] a “minor stream” is defined as any stream or part of a stream that is specified in the hydroline spatial data[10], that is identified as a First or Second Order stream as determined in accordance with the Strahler system, and that does not maintain a permanent flow of water (being a visible flow that occurs on a continuous basis, or would so occur if there were no artificial abstractions of water or obstruction of flows upstream). “Minor streams” also include those stream which are not specified in the hydroline spatial data.

The above classifications are, by convention, generally adopted in mining development impact assessments to define the watercourses of main interest. This explains the usual assumption in such assessments that streams of Third Order and higher have greater importance than First and Second Order streams. The basis of the assumption is that permanence of water flow is more significant than ephemeral or intermittent flow, and Third Order streams will generally flow more often than First and Second Order streams. Importance could relate to some aspect/s of ecosystem values, aesthetic values, or reliability of water supply for consumptive use, or in the case of DIPNR (2005), the more dynamic and complex geomorphic character of Third and higher Order streams.

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 (Hebblewhite, 2009). 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 streams of Strahler Third Order and higher, significant cliff lines and valley infill swamps. The usual procedure is to define the RMZ by drawing a 400 m wide buffer around the important feature (Hebblewhite, 2009).

Valley infill swamps and cliffs were not found within the Field Survey Study Area. Streams of Third Order and higher were found within and nearby the Mining Study Area, and following the convention of mining impact assessment, in this Report they were regarded as more important than smaller streams. This Report assessed in detail the entire catchments of the Third Order and higher streams within and near the Mining Study Area, so it was unnecessary to draw formal RMZ boundaries around them.

2.8.3.2 Stream network 1: Published blue line network

The blue line network mapped on 1:25,000 Department of Lands topographic maps was represented by the National Surface Hydrology Lines (Regional) digital layer. It was found that in a number of places the blue line network did not correctly follow the alignment and location of channels identified in the field or apparent from the LiDAR data.

One reason for mismatches between the blue line and observed current stream positions was contour drains that diverted runoff to farm dams. Historical aerial photographs suggest that in 1958 there was limited development of contour drains and farm dams in the Mining Study Area; by 1982 the development of farm dams and contour drains had reached a level similar to existing conditions. The existing gully networks were present in the 1958 photograph, although some gullies might have expanded or contracted to a relatively minor extent over time. A second reason for altered drainage over time was mining activity in part of the headwaters of the Catchment Study Area at Mt Arthur Mine and Drayton Mine.

Although most of the blue lines follow existing drainage lines, their smoothed representation means that they do not consistently trace the lowest elevation down the valleys. Thus, a long profile generated in GIS from a blue line overlaying LiDAR data would not faithfully represent the channel thalweg.

The problem of inaccuracies in the published blue line network was overcome by re-defining the existing drainage network using terrain analysis.

2.8.3.3 Stream network 2: Unedited automatically DEM-generated network in the Field Survey Study Area

Given the inadequacies of the blue line network, a revised drainage network was automatically generated in the Field Survey Study Area using Global Mapper™ GIS. The new drainage network was generated by flow accumulation using the standard 8-direction pour point algorithm (D-8) (Jenson and Domingue, 1988). The drainage network was evaluated at two resolutions, 1 × 1 m and 5 × 5 m grid. In both cases the model parameters were a fixed minimum threshold catchment area of 0.03 km^2 for initiation of a channel, a fixed minimum channel

[9] See URL https://www.legislation.nsw.gov.au/#/view/regulation/2018/480/part1/sec3
[10] See URL https://www.industry.nsw.gov.au/water/licensing-trade/hydroline-spatial-data

length of 100 m, and maximum depression fill depth of 10 m. The procedure of filling depressions prior to calculating flow accumulation prevents discontinuities in the longitudinal connectivity of drainage lines at significant pools, where the flow accumulation procedure would encounter a downslope as it progresses up the catchment. At filled depressions, drainage lines project straight from the downstream to the upstream side of the depression, so pools are represented by straight lines that do not necessarily pass over the deepest point of the pool. Prior to drainage network generation, culverts at key locations identified from field observations and aerial photography were manually inserted into the DEM so that flow would correctly pass under roads and tracks.

The drainage network generation algorithm was expected to be sensitive to spatial resolution of the DEM, with the 1 m and 5 m DEMs expected to produce similar overall networks but differing in their details. The 5 m DEM would be expected to produce fewer stream lines and straighter stream lines than the 1 m DEM, but both of these automatically generated drainage networks would represent the distribution of stream channels more accurately than the blue line network.

The GIS drainage analysis procedure generated a network of drainage lines that in some sub-catchments was similar in density to that of the mapped blue line network and in other places it had higher density. While streamlines of the DEM-generated drainage network were drawn as a function of the upstream catchment area and ground elevation, cartographers would have used different criteria to map the blue lines on the 1:25,000 topographic sheet, or digital hydrolines. Thus, some streamlines that appeared on the DEM-generated network did not appear as hydrolines; this applied mainly to First Order streams. The automatically-generated drainage network was edited by removing additional streams to produce an emulation of the blue line (i.e. hydroline) network.

Unedited DEM-generated networks were generated from 1 m and 5 m DEMs for two cases:

- existing topography, and
- impacted topography under fully-developed mining.

The existing topography was represented by the 1 × 1 m grid resolution LiDAR data, and the impacted topography was modelled at 1 × 1 m grid resolution by Mine Subsidence Engineering Consultants (MSEC) (MSEC, 2019). These DEM-generated stream networks were used to assess the potential impacts of subsidence on alignments of drainage lines. For this purpose of isolating the impact of subsidence, it was important to compare networks generated objectively using identical criteria.

The impacted case used the modelled final subsided surface elevation grid, which is the predicted depth of subsidence subtracted from the existing surface elevation grid. This grid preserves the existing channel network, while in reality, as the landform subsides over time, the channel position and morphology would gradually adjust. It was not feasible to model the process of geomorphic channel evolution through slow adjustment to progressive mining subsidence, so the impacted network should be regarded as indicative, but likely to identify areas with high risk of channel directional change.

2.8.3.4 Delineation of sub-catchments in the Field Survey Study Area

Of the streams in the Catchment Study Area, only Saddlers Creek and Saltwater Creek are named on the 1:25,000 topographic sheet. Eight catchments within the Field Survey Study Area were defined by the drainage network generation procedure and labelled. The streams of Second Order or higher were labelled according to their catchment and stream order. Two catchments had no streams of Second Order or higher.

2.8.4 Slope

Landform slope and slope aspect were evaluated at 5 m and 25 m grid resolutions.

Slope along individual stream vectors was determined by sampling the 0.5 m DEM at 1 m spacing. A spacing of 1 m was preferable to 0.5 m for the purpose of confirming knickpoint locations and heights.

2.8.5 Topographic indices for alluvium definition

2.8.5.1 Slope and slope aspect

Low slope is indicative of alluvial landforms. Děd (2013) suggested a universal upper slope threshold of 4% to define floodplains, on the grounds that rivers with gradient above 4% usually do not form floodplains. While absolute slope could be a useful criterion for delineating floodplains, the threshold would be site specific and require local calibration. Soil Landscape maps describe the Hunter River floodplain near the Maxwell Project as having slopes less than 3%. A slope of 3% would be expected as a local maximum value for a floodplain landform and could also be within the normal slope range of colluvial landforms. A lower slope threshold would separate floodplains from low gradient plains and slopes with less ambiguity. In this Report, a threshold of 2% was used as a condition for identifying floodplain landforms.

Where floodplains and similarly low-gradient colluvial or erosional slopes both occur in a landscape, slope aspect could potentially complement an absolute slope threshold to distinguish these landforms. In cross-section, floodplain morphology is typically flat or slightly down-sloping away from the channel levee, and in long-section, the slope is downstream in the direction of the valley and channel. In contrast, colluvial landform elements formed from downslope movement of sediment from hills and interfluves have slope aspect that is roughly perpendicular to the downstream alignment of the alluvial floodplain they border. At tributary junctions, slope aspect discontinuity might assist definition of the boundary of the tributary floodplain from the floodplain of the main river it joins.

2.8.5.2 Topographic wetness index (TWI)

A topographic metric that has been used to delineate floodplains is the Topographic Wetness Index (TWI), ∅, (Beven and Kirkby, 1979; Quinn et al., 1995; Beven, 1997; Wilson and Gallant, 2000):

$$\emptyset = ln\left(\frac{A_s}{\tan\beta}\right) \quad (4)$$

where,

A_s = Local upslope area draining through a certain point per unit contour length (m^2)

β = Local land surface slope (radians)

The contributing area term reflects the tendency of water to accumulate at certain areas within a catchment, and the slope term represents the transfer of water downslope by gravity. High values of the topographic index represent areas which are likely to saturate first, as they have a large contributing area compared to the local slope.

Manfreda et al. (2011) suggested a modification to the index by changing the weighting on the area term:

$$\emptyset = ln\left(\frac{A^n}{\tan\beta}\right) \quad (5)$$

Manfreda et al. (2011, 2014) proposed that as high values of TWI were well correlated with areas in catchments where water tends to accumulate (e.g. Sørensen et al., 2006), then it is likely that this is also indicative of areas most exposed to flood inundation (e.g. Pourali et al., 2014).

Böhner et al. (2002) developed the SAGA Wetness Index (SAGA TWI), similar to the TWI, but based on a modified catchment area calculation. The default is to use the square root of catchment area, or $n = 0.5$ in the modified formula of Manfreda et al. (2011) (Eq'n 5). This modification is claimed to predict a more realistic high soil wetness than the TWI for grid cells situated in valley floors with a small vertical distance to a channel (Böhner et al., 2002). There are no universal threshold values of TWI or SAGA TWI that separate floodplains from surrounding landforms; practical threshold values need to be determined on a site specific basis. Glover and Gallant (2009) mapped soils by applying a threshold MrVBF (see below) value of 2.7 to separate Erosional uplands and Alluvial plains, and a threshold TWI value of 6.2 to sub-divide Erosional uplands into Higher and steeper erosional uplands and Lower erosional uplands.

As with other topographic indices, TWI is sensitive to grid cell size. Higher resolution DEMs tend to give smaller specific upstream area, spatial variation in the TWI value decreases with increasing grid size, and cell by cell comparison indicates poor correlation between TWI values computed from coarse grids (50 and 100 m DEMs) and a 25 m DEM (Ruhoff et al., 2011). A 25 m DEM is appropriate for catchment scale mapping, but a finer resolution DEM would be required to accurately map the boundaries of alluvium units with TWI. For the purpose of delineating buffers that limit the proximity of developments from the boundary of alluvium, a 5 m DEM would be appropriate.

The SAGA TWI is not intended to identify small-scale landform features, so Eq'n 5 was implemented in SAGA GIS using a 25 × 25 m elevation grid.

2.8.5.3 Multiresolution Index of Valley Bottom Flatness (MrVBF)

The Multiresolution Index of Valley Bottom Flatness (MrVBF) was proposed by Gallant and Dowling (2003), mainly as a tool to assist in the objective separation of floodplains from their surrounding hillslopes. The algorithm uses the two terrain attributes slope and elevation percentile. Slope is computed as a percentage and elevation percentile is a ranking of the elevation of a grid point with respect to the surrounding cells in a circular region of user-specified radius. The index of elevation is calculated as the ratio of the number of points of lower elevation to the total number of points in the surrounding region, with low values indicating a point is low in the local landscape, as most of the surrounding points are higher. The MrVBF algorithm was developed assuming a 25 m resolution DEM, but Gallant and Dowling (2003) included instructions, and gave an example, for its application at other resolutions, which simply requires an appropriate adjustment to the initial slope threshold parameter, and application of an offset to the calculated value of MrVBF. According to Gallant and Dowling (2003), assuming a 25 m DEM, values of MrVBF less than 0.5 are not valley bottom areas; values from 0.5 to 1.5 are considered to be the steepest and smallest resolvable valley bottoms; and increasingly flatter and larger valley bottoms are represented by values from 1.5 to 2.5, 2.5 to 3.5, and so on. CSIRO (2018) provided information to assist interpretation of MrVBF values, also tabulated by Brooks et al. (2014, p. 23) (Table 6).

Table 6 Interpretation of MrVBF values in terms of landforms, when calculated from a 25 m grid. Source: modified from CSIRO (2018) and Brooks et al. (2014, p. 23). Note: not every value of MrVBF had an accompanying landform interpretation.

MrVBF Value	Threshold slope		Resolution (approximate)	Landform Interpretation
	Percent	Degrees		
0	32	17.7	30 m	Erosional
1	16	9.1	30 m	Small hillside deposit
2	8	4.6	30 m	Narrow valley floor
3	4	2.3	90 m	
4	2	1.1	270 m	Valley floor
5	1	0.57	800 m	Extensive valley floor
6	0.5	0.29	2.4 km	
7	0.25	0.14	7.2 km	Depositional basin
8	0.125	0.07	22 km	
9	0.0625	0.04	66 km	Extensive depositional basin

Stein (2006) developed a landform index combining MrVBF and the companion Multiresolution Index of Ridge Top Flatness Index (MrRTF) (Gallant and Dowling, 2003) and applied it across Australia, computed from the national 9-sec (250 m) DEM. The valley bottom landform corresponded to where the difference in MrVBF and MrRTF exceeded 2. On most floodplains, MrRTF would be close to zero, so essentially, floodplain landforms would be delineated by MrVBF greater than 2 (assuming no offset was applied). This threshold was appropriate to the 9-sec DEM. When computed from a 3-sec (70 m) DEM, Brooks et al. (2014) adjusted the threshold to 3 (equivalent to applying an offset of -1 MrVBF values), for valley bottoms at least 90 m wide. This is consistent with Gallant and Dowling's (2003) recommended offset of +2 to MrVBF values when using a 9-sec DEM, and +1 when using a 75 m DEM, compared to a 25 m DEM (no offset).

Glover and Gallant (2009) applied MrVBF to produce a soil map of the Honeysuckle Creek catchment, a small catchment draining the Strathbogie Ranges, near Violet Town, Victoria. Alluvial (floodplain) soils were delineated by a threshold MrVBF value of 2.7 computed from a 25 m DEM. Alluvial soils were further divided into active alluvial deposits (inundated by a flood with average recurrence interval of 50 years or less) with surface slope >0.5% (0.3°) and inactive (relict) alluvial deposits with surface slope <0.5% (0.3°). Lymburner (2005) divided the landscape of the Nogoa and Comet sub-catchments of the Fitzroy River basin, Queensland into two broad categories: Slopes (with slope >2%) and Plains (with slopes <2%). A MrVBF threshold value of 2.5 was used to identify slopes and plains computed from a 90 m DEM.

Most applications of MrVBF reported in the literature have been conducted at the catchment scale using DEMs of 25 m resolution or coarser. A 25 m DEM is appropriate for mapping the extent of floodplain units at the catchment scale, but a finer resolution DEM would be required to accurately map the boundaries of these alluvium units with MrVBF. For the purpose of delineating buffers that limit the proximity of developments from the boundary of alluvium, a 5 m DEM would be a reasonable compromise between spatial resolution and computing time. According to the information in Gallant and Dowling (2003), when using a 5 m DEM, the appropriate initial slope threshold is 44°, and the MrVBF values should be offset by -1.46 to achieve 25 m DEM calculation equivalence. MrVBF was implemented in SAGA GIS using the 5 m and 25 m elevation grids.

The literature, and the author's previous experience with application of MrVBF for the purpose of delineating floodplain (alluvial) landforms, suggests that a suitable threshold value of MrVBF to delineate a significant deposit of alluvium would be in the range 2.7 to 3.0.

2.8.5.4 Landform curvature

Local landform surface curvature is a measure of the surface roundness of an area. It can be divided into plan (horizontal) curvature and profile (vertical) curvature (Wilson and Gallant, 2000). Curvature is used in terrain analysis to classify landforms (Figure 5). Profile curvature is useful for defining the boundaries of linear river features bank toe, bank top, and floodplain extent (valley toe), with curvature of these features usually within the range -0.06 to 0.06. Floodplain surface lateral boundaries correspond with the position where relatively flat alluvium abuts the valley hillslope, colluvial slope or alluvial fan (Figure 6). The curvature at the intersection of hillslopes and floodplains is concave linear (Figure 5), marked by strong curvature (< -0.04) where the hillslope is steeply sloping and has simple geometry with linear or convex curvature. The position of the hillslope-floodplain intersection is equivocal where the hillslope is gently sloping with weak concave curvature, as would occur in association with alluvial fans and colluvial deposits (Figure 6). Where alluvial terraces are present (Figure 6), the boundary of each would be delineated by strong negative curvature. Strong negative curvature is also associated with the concave boundaries of bank toes. The valley-side bank toe would define the floodplain boundary in situations where the river channel abuts the valley wall, as channels flow within the body of alluvial material that comprises the floodplain (Figure 6).

While MrVBF is well-suited to defining the extent of relatively flat floodplain units at the valley scale, the algorithm results in smoothed polygon boundaries. Also, when MrVBF is used with a fine-scale DEM in an effort to enhance the resolution of polygon boundaries, the algorithm can fail to include the channel as part of the floodplain unit. This is not ideal in situations where accuracy of the position of the floodplain boundary is important. In this case, MrVBF boundaries can be refined on the basis of defining linear features with high negative profile curvature.

Profile curvature was implemented in SAGA GIS using the method of Haralick (1983) for the 5 m elevation grid. Potential floodplain boundaries were identified by converting cells in the expected locations with curvatures ≤ - 0.04 to polygons, and then manually removing polygons that were clearly not floodplain boundaries, judged on the basis of landform position. Finally, MrVBF and curvature polygons were merged using the Coverage area (concave hull) feature creation option in Global Mapper™, applied with the lowest degree of smoothing. The boundary of this polygon was considered the best estimate of the geomorphic floodplain boundary.

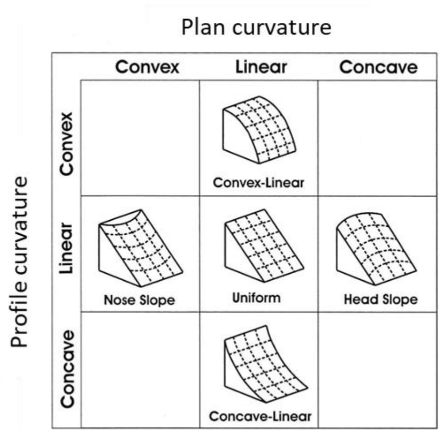

Figure 5. Types of profile and plan curvature used to classify landforms. Adapted from Rieke-Zappa and Nearing (2005).

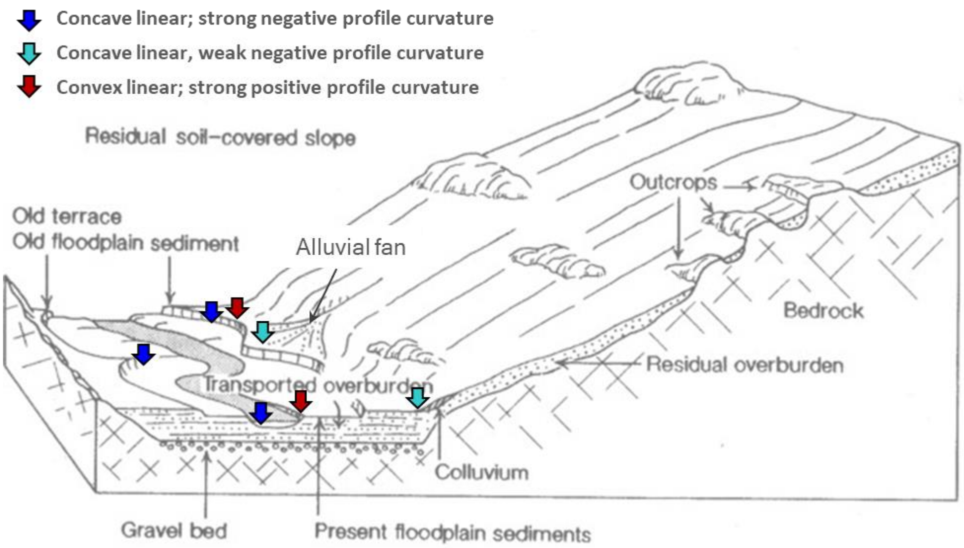

Figure 6. Typical profile curvature of linear river boundaries. Adapted from Salminen et al. (1998).

2.8.6 Estimated channel stream power

Stream power (Bagnold, 1966) is an important variable used in connection with quantitative channel stability assessment and is used in river classification. A commonly used indicator of stream power is cross-sectional stream power (Ω), which is the power per unit length of a reach (Gartner, 2016). Cross-sectional stream power (watts per metre [W/m]) was defined by Bagnold (1966) as:

$$\Omega = \rho g Q S \qquad (6)$$

where,

ρ = the specific weight of the water (usually assumed to be 987 kilograms per metre cubed [kg/m^3])

g = the acceleration due to gravity (9.8 metres per second squared [m/s^2])

Q = water discharge (cubic metres per second [m^3/s])

S = the energy slope of the stream (usually approximated by either the water slope or the channel bed slope) measured as metre fall per metre length

Bagnold (1966) also defined the "mean available power supply to the column of fluid over unit bed area", also known as is specific stream power (ω) (watts per metre squared [W/m^2]):

$$\omega = \frac{\Omega}{W} \qquad (7)$$

where,

W = the width of the flow (metre [m])

This is perhaps the most commonly used measure of energy expenditure in stream channels. In essence, specific stream power is the rate of energy expenditure per unit area of the channel bed (Gartner, 2016). Specific stream power can also be estimated at a site within a channel using the formula (equivalent to Eq'n 7):

$$\omega = \rho g R S V \qquad (8)$$

where,

R = hydraulic radius of the channel (metres [m]), equal to A/P where A is the cross-sectional area of the flow, and P is the length of the wetted perimeter

V = mean depth-averaged flow velocity (metres per second [m/s])

Stream power has been demonstrated to show a distinctive downstream pattern, peaking in the mid-catchment zone, with explainable discontinuities also possible (Knighton, 1999; Lawler, 1992; Lawler, 1995; Lecce, 1997; McEwen, 1994; Fonstad, 2003; Reinfelds et al., 2004; Jain et al., 2006). The upper-mid catchment zone of higher stream power would logically correspond with Schumm's (1977) sediment transport zone. In general, greater sediment storage occurs in the headwaters and lower valleys where stream power is low, whereas little sediment is stored in mid-basin reaches where stream power is high (Lecce, 1997).

Nanson and Croke (1992) defined three main classes of floodplain on the basis of specific stream power (energy):

- High energy, non-cohesive (>300 W/m^2)
- Medium energy, non-cohesive (10 – 300 W/m^2)
- Low energy, cohesive (<10 W/m^2)

River Styles® suggests the Styles can be distinguished as falling into one of three classes of stream energy regime (stream power), but does not provide a quantitative definition of these classes. The three energy classes of Nanson and Croke (1992) could be used to define the three energy regime classes (low, moderate and high) used in River Styles®.

Employing Eq'n 8 at a catchment scale would require detailed channel geometry and hydraulic data. However, Eq'ns 6 and 7 can be used to estimate specific stream power at sites throughout a catchment provided data are available at each site for discharge index, channel width and slope.

The area-discharge proxy works well for many small to mid-sized watersheds (Gartner, 2016). It has the form:

$$Q = aA^b \qquad (9)$$

where,

Q = a discharge index considered important to sediment transport or channel formation

A = catchment area

a = empirically derived coefficient

b = empirically derived exponent

In an analysis of 1659 gaging stations across the U.S., Finlayson and Montgomery (2003) found that drainage area (measured in km^2) explained 61% of the variation in mean annual maximum discharge (measured in m^3/s) with a = 0.92 and b = 0.7. Using data from stream gauges in the upper Hunter River catchment, NSW, Jain et al. (2006), assuming that the 2-year Average Recurrence Interval (ARI) event (Q_2 in m^3/s) suitably represented the energy distribution within the channel, developed an equation to predict discharge from catchment area (in km^2) for the purpose of calculating stream power:

$$Q_2 = 1.21A^{0.72} \qquad (10)$$

Eq'n 10 was adopted to estimate discharge at any point in the Field Survey Study Area. Catchment area was determined using Global Mapper™ GIS to calculate flow accumulation for a 5 m grid using the standard 8-direction pour point algorithm. Catchment area was extracted at vertices on the automatically generated drainage lines, and area was converted to discharge index value using Eq'n 10.

Downstream hydraulic geometry relationships suggest that at bankfull flow level, channel width is related to discharge raised to the power of 0.5 (Leopold and Maddock, 1953), even though there is considerable variation across rivers worldwide (Park, 1977). For the Bellinger River, Reinfelds et al. (2004) used an exponent of 0.7 in the relationship between catchment area and channel width.

In this Report, channel bankfull width was measured in the field at 192 locations, 25 of which were outside the Field Survey Study Area, leaving 167 data points. The geographic location of each observation was shifted to the closest point on the automatically-generated drainage network. This involved a shift of less than 5 metres in each case. The catchment area (measured in km^2) at each point was related to observed channel width (measured in metres) by the empirical equation:

$$W = 6.11A^{0.207} \qquad (11)$$

Eq'n 11, derived using data from the Field Survey Study Area, has a smaller exponent than is usually reported for area-width relationships, but most published studies use data from larger catchments.

Slope in Eq'n 6 is the energy slope of the stream, which is approximated by channel bed slope. However, the downstream pattern of channel bed slope is much more variable than energy slope, and has positive and negative slopes. The problem of negative slopes was managed by measuring slope from the depression-filled DEM. The variability of slope was reduced by using the 7-point moving average of slope. Vertex-spacing was variable, so the distance over which slope was averaged varied over a range of about 30 – 50 m. In general, points were more closely spaced on steep, variable headwater reaches, and more widely spaced on lowland reaches, which naturally scaled the averaging distance to stream size. The averaging distance was short enough that steps due to significant knickpoints were retained in the profile, although they were muted. The resulting smoothed bed slope would have been a reasonable representation of the energy slope of the 2-year ARI flow event, except for long depression-filled sections with zero slope (which resulted in zero stream power), which in reality would have a low slope.

The modelled channel stream power data were plotted along the automatically generated profiles of the main stream flow paths, from their outlet to their point of initiation in the headwaters, for both the existing and impacted cases. The predicted stream lengths, and descriptive statistics of slope and stream power data were compared between the two cases.

The methodology used in this Report to estimate channel stream power relied on modelled discharge, channel width and energy slope, which introduced unavoidable uncertainty in the estimated absolute values of stream power. Consideration of the likely range of errors in the input data suggests that the stream power estimates would be correct to order of magnitude.

2.8.7 Hillslope Stream Power Index (SPI)

Stream Power Index (SPI), calculated as the product of specific catchment area (the upslope contributing area per unit contour length) and local land surface slope has been suggested for use in identifying potential for erosion due to concentrated surface runoff on hillslopes (Moore et al., 1991; Moore et al., 1993; Wilson and Gallant, 2000). The equation for SPI is:

$$SPI = A_c \tan\beta \qquad (12)$$

Some authors suggest log transformation of SPI values to make highly skewed distributions approach a normal distribution, mainly to improve data visualisation. In this Report, the formula was implemented in its original form (Eq'n 8).

There are no published reference values of SPI to enable interpretation of the absolute value of SPI in terms of risk of slope instability. Rather, SPI was used to indicate relative risk of capacity to mobilise and transport sediment on hillslopes.

SPI was evaluated using the standard module in SAGA GIS using the 5 m elevation grid. The additional detail of the 1 m grid provided no benefit for the purpose of geomorphic characterisation.

SPI was also used as an indicator of the risk of subsidence impacting the relative geomorphic stability of hillslopes. This was done by subtracting the SPI 5 m grid computed for the modelled impacted (subsided) surface from the SPI 5 m grid computed for the LiDAR-derived existing surface:

$$\Delta \mathrm{SPI}_{I-E} = \mathrm{SPI}_I - \mathrm{SPI}_E \qquad (13)$$

where,

SPI_I = Stream Power Index value computed for a cell on the modelled impacted surface grid

SPI_E = Stream Power Index value computed for a cell on the existing surface grid

The index of Δ stream power impact ($\Delta\mathrm{SPI}_{I-E}$) was computed across all grid cells. In places where subsidence was predicted to cause a drainage line to take a new course, $\Delta\mathrm{SPI}_{I-E}$ would be high along the new course. On a drainage line with unchanged alignment after subsidence, positive $\Delta\mathrm{SPI}_{I-E}$ could be associated with increased slope or increased specific catchment area. On a drainage line with unchanged alignment after subsidence, negative $\Delta\mathrm{SPI}_{I-E}$ could be associated with decreased slope or decreased specific catchment area. Low positive or negative values of $\Delta\mathrm{SPI}_{I-E}$ would be associated with increased geomorphic stability. On the assumption that the main concern is increased risk of hillslope instability, the focus of the impact assessment was on large positive values of $\Delta\mathrm{SPI}_{I-E}$.

2.8.8 Depressions on drainage lines

A depression is a landform element that stands below all, or almost all, points in the adjacent terrain (National Committee on Soil and Terrain, 2009, p. 20). A 'closed depression' stands below all such points; an 'open depression' extends at the same elevation, or lower, beyond the locality where it is observed (National Committee on Soil and Terrain, 2009, p. 20). Farm dams are an example of closed depressions. Stream channels are an example of open depressions, as in cross-section they are concave elements with elevation lower than the adjacent terrain, but in long-section they slope downwards. At the local-scale, stream channels can contain closed depressions, which are often referred to as pools, especially when they are observed to contain water. The term 'pool' or 'pooling' is usually applied in the context of describing hydraulics or habitat (i.e. a relatively deep and quiescent water body), but in the geomorphic context, pool is synonymous with closed depression, i.e. a closed depression has potential to impound and retain water for some length of time, but could be referred to as a pool even if it is observed to be dry. In this Report, the term 'depression' is used to mean 'closed depression' and has the same meaning as 'pool', whether wet or dry.

Depressions were mapped automatically at the 1 × 1 m grid scale over the Catchment Study Area using Global Mapper™ GIS. Depressions were filled automatically, and the resulting DEM saved, for both existing and subsided surface DEMs as a precursor to flow accumulation and drainage definition computations. For both existing and subsided cases, the original DEM was subtracted from the depression-filled DEM, with positive differences representing closed depressions. This procedure generated considerable 'noise', manifested as isolated areas of negative difference (high points), and numerous areas with very small depression depth. This noise was filtered by accepting only positive differences greater than 0.05 m, which is slightly greater than the 0.04 m 95 percent confidence interval of the LiDAR data from which the DEM was generated. Following removal of noise, the depression cells were converted to polygons and a second filter was then applied. This filter retained only those polygons intersected by, or within 1 m of, the auto-generated drainage lines, or in the case of the large channels, within the bed. Farm dams, if identified as depressions, were also retained, whether or not they fell on an auto-generated drainage line. Finally, the difference in depression extent between the existing and subsided landforms was mapped by subtracting the two filtered depression DEMs.

2.9 Stream geomorphic type and condition

2.9.1 Stream geomorphic type classification

The geomorphic stream type classification used here is 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. The classification is largely subjective, based on a mix of topographic map and aerial photograph interpretation, supported by limited field inspection. Some quasi-objective criteria are used. One example is the separation of rivers into low sinuosity and meandering by the threshold of 1.3 for stream length divided by valley length, measured over a distance of "*at least 20 times the average width of the channel*" (Brierley and Fryirs, 2002). Although ostensibly objective, the sinuosity value is sensitive to the distance over which it is measured, which is determined by channel width – an attribute that can be highly variable and difficult to characterise, especially from remotely sensed data. Sinuosity of meandering channels also depends on how accurately drainage lines are drawn, as accurate, high resolution lines that follow the channel would be longer than smoothed lines, yet the valley length would be the same in both cases.

The River Styles® framework was designed to cover all Australian stream types, and it is normally applied over the basin or regional scale, with most mapped streams being Third Order or higher. Across regions or basins a range of different Styles would be expected. Most of the Styles apply to partly-confined and unconfined (i.e. alluvial/lowland) valley settings where streams are relatively large and feature many distinctive units such as levees, pools and riffles, bars, islands, benches, cut-off channels, backswamps, wetlands and floodplains. In contrast, the streams in the Field Survey Study Area were relatively small-scale, most being First and Second Order, and lacked these features.

Stream type classification in the Field Survey Study Area was done on the basis of field-collected data, aerial photography and terrain data for surveyed stream links. It should be noted that classifying stream reaches into geomorphic types (or River Styles®) is a subjective procedure that was difficult to apply in the Field Survey Study Area because: (i) the streams were small with spatially variable morphology, and (ii) the scale of mapping that was achievable from the high density quantitative field data and high resolution LiDAR data was more detailed than is normal for River Styles® surveys. The low resolution elevation data, aerial photography and low density field observations normally used in River Styles® surveys limits differentiation of Styles to reach lengths of several kilometres (e.g. Brierley et al., 2002), while the data from the Field Survey Study Area potentially allowed stream type to be differentiated over distances of 100 m or shorter. The exemplar streams of the various Styles in the River Styles® literature are mostly an order of magnitude larger than those in the Field Survey Study Area, and classification problems arose when short reaches of stream were observed in the field to have characteristics of more than one Style. The approach taken here was to generalise to a scale that would typically be applied in basin-scale River Styles® surveys.

2.9.2 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 according to three categories, with each having a number of identifying characteristics (Table 7). These are subjective criteria that are not easy to interpret, even for an expert geomorphologist. For this 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 7). However, three objective criteria were added to the Poor category to describe absence of vegetation, or an artificial and incongruous steam (Table 7). These criteria mean that the artificial stream type Contour drain rated Poor. Also, points where the stream was formed by a culvert, was crossed by a track, passed through a dam, or was formed by artificial bed stability control works (not using natural design principles), were rated Poor. The field collected data were assessed against the criteria in Table 7 to assign a geomorphic condition value (Good, Moderate or Poor) to each surveyed site.

Table 7 Categories of stream geomorphic condition defined by Outhet and Cook (2004). The term "Style" is equivalent to the term "stream type" used in this 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, e.g. *Active knickpoint >1 m high.* • Patchy effective vegetation coverage relative to the reference reaches (allowing some localised accelerated erosion). *Riparian tree cover in category 0 (<1%) or 1 (1 – 5%) and riparian vegetation cover index >0.25 and <0.5 (25 – 50%).*
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), e.g. *Active knickpoint >2 m high.* • 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. *Riparian tree cover in category 0 (<1%) or 1 (1 – 5%) and riparian vegetation cover index <0.25 (<25%).* • *Artificial and incongruous stream (or point on a stream), not designed to mimic the natural stream geomorphic type for that location.*

2.10 Impact assessment

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

Commonwealth of Australia (2015), primarily citing Lucas et al. (2009), noted that the nature and scale of potential geomorphological impacts of subsidence on a river reach or broader catchment area are complex, but listed the main impacts as:

- Cracking of rock bars or fracturing of alluvial strata altering the permeability of a stream bed, which could lead to reductions in stream flow
- Lowering of channel bed and changes to channel grade, which could potentially alter channel hydraulics and patterns of sediment erosion, transportation, and deposition
- Upstream or downstream deepening of stream beds following subsidence may lead to incision and destabilisation of incoming tributaries, resulting in increased sediment loads to waterways

- Slumping and erosion of channel banks may arise from cracking alluvial banks. Lowering channel beds can also affect channel bank stability

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

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

These potential agents of change could bring about a number of generic geomorphic responses (Table 8) that would constitute an environmental impact with possible implications for environmental values. This Report evaluated these risks qualitatively or semi-quantitatively, except for change in channel alignment, and increase in extent and depth of depressions in channels, which were predicted using quantitative methods. Some of these risks were also assessed directly or indirectly by other relevant technical specialists (see other technical specialists reports for details).

Table 8 Potential generic 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
2. Change of alignment of channel	3, 4, 5, 6
3. Migration of soft knickpoint upstream at faster than natural rate	3
4. Increase in extent and depth of depressions in channels	7
5. Increase of coarse and fine sediment supply to channel	3, 6
6. Increase in suspended sediment load of streams	3, 6
7. Increase of sediment accumulation in channel	4, 5
8. Increase of sediment scouring in channel	3, 6
9. Increase in cover (area, density and type) of vegetation on channel bed (baseflow shift from high depth of water to shallow depth)	2, 5, 7
10. Change in cover (area, density and type) of vegetation on channel bed (baseflow shift from shallow depth of water to dry, or from shallow to deep)	5, 6, 7

Mining related causes:

1. Local fracturing of rock bars that act as hydraulic controls on pools.
2. Local fracturing of bedrock in the bed.
3. Local increase in slope of channel bed.
4. Local decrease in slope of channel bed.
5. Decrease in stream flow (due to reduced catchment area or extensive fracturing).
6. Increase in stream flow (due to increased catchment area).
7. Uneven pattern of subsidence corresponding to arrangement of goafs and chain pillars.

3.0 Existing environment

3.1 Landscape-scale characteristics

3.1.1 Land elevation and slope

Land elevations within the Mining Study Area ranged from 97 to 249 m AHD (Australian Height Datum) (Figure 7). Computed on the 5 m DEM, land slopes within the Mining Study Area ranged from 0° to 47°, and average slope was 7° (Figure 8).

3.1.2 Published geology

The Study Areas lie within the Hunter Coalfield. The coal bearing rocks are Permian in age. Overlying rocks are a small area of Jurassic basalt (Jv), and Quaternary silt sand and gravel (Qa) in the base of Saddlers Creek and Saltwater Creek valleys (Figure 9). The majority of the Study Areas are in the Permian, Singleton Supergroup, Wittingham Coal Measures, Jerrys Plains subgroup (Pswj), which comprises coal seams claystones, tuff, siltstone, sandstone and conglomerate (Figure 9) (Glen and Beckett, 1993). The Mining Study Area includes a small area of Newcastle Coal Measures (formerly known as Wollombi Coal Measures) (Psl), which comprises coal seams claystones (tuffaceous), siltstone, sandstone and conglomerate (Figure 9) (Glen and Beckett, 1993).

3.1.3 Published soil landscapes

Soil and Land Resource units (Figure 10) have greater variability than the geology. The alluvium of Saddlers Creek (fyz) is mapped significantly smaller in extent than the equivalent unit (Qa) on the Hunter Coalfield Geology map (Figure 9). The north-western side of Saddlers Creek catchment has a different soil character than the south-eastern side, where the Mining Study Area is situated. The transferral Donalds Gully unit (dnz) surrounds the alluvium (fyz) and extends into the valleys of the tributaries of Saddlers Creek, comprising footslopes, drainage plains and alluvial fans (Figure 10). Geologically, dnz comprises alluvium and colluvium derived from the Permian Wittingham Coal Measure derived from moderately to strongly weathered, quartzose and lithic sandstone, polymictic conglomerate, mudstone, calcareous shale, coal and basalt. Moderately deep to deep (50 - <150 cm), imperfectly to poorly drained Brown, Yellow and Grey Sodosols and Natric Kurosols (Solodic Soils and Soloths) dominate slopes and drainage plains. While minor sheet erosion is extensive, occurrence of moderate sheet and gully erosion is rare (NSW Office of Environment and Heritage, 2018).

The majority of the Mining Study Area is situated within the erosional Cressfield Road (cfz) and Cressfield Road variant a (cfza) soil landscapes (Figure 10). Soils are often complex and controlled by landscape position and lithology. Moderate sheet, topsoil and occasionally subsoil erosion is widespread, especially in disturbed areas or with high stocking rates. Drainage lines and lower slopes exhibit past and present minor to moderate gully erosion. A relatively small area of erosional Howick (hkx) unit, associated with the Jurassic basalt (Jv) is present in the southeast area of the Mining Study Area (Figure 10). The landform is rolling hills, with rock outcrop present on upper slopes. Shallow to moderately deep (25 - <100 cm), well drained Black Dermosols (Chernozems and Prairie Soils) appear to dominate crests and hillslopes with shallow to moderately deep (25 - <100 cm), moderately well drained Brown Vertosols (Brown Clay) also common. The notes associated with Howick Soil and Land Resource (NSW Office of Environment and Heritage, 2018) reported that appreciable land degradation was not observed, which the notes explained means it was “unlikely to be found”. This should be interpreted with caution, as the notes also stated that “the distribution of soils within the soil landscape is not fully understood because of limited access” (NSW Office of Environment and Heritage, 2018).

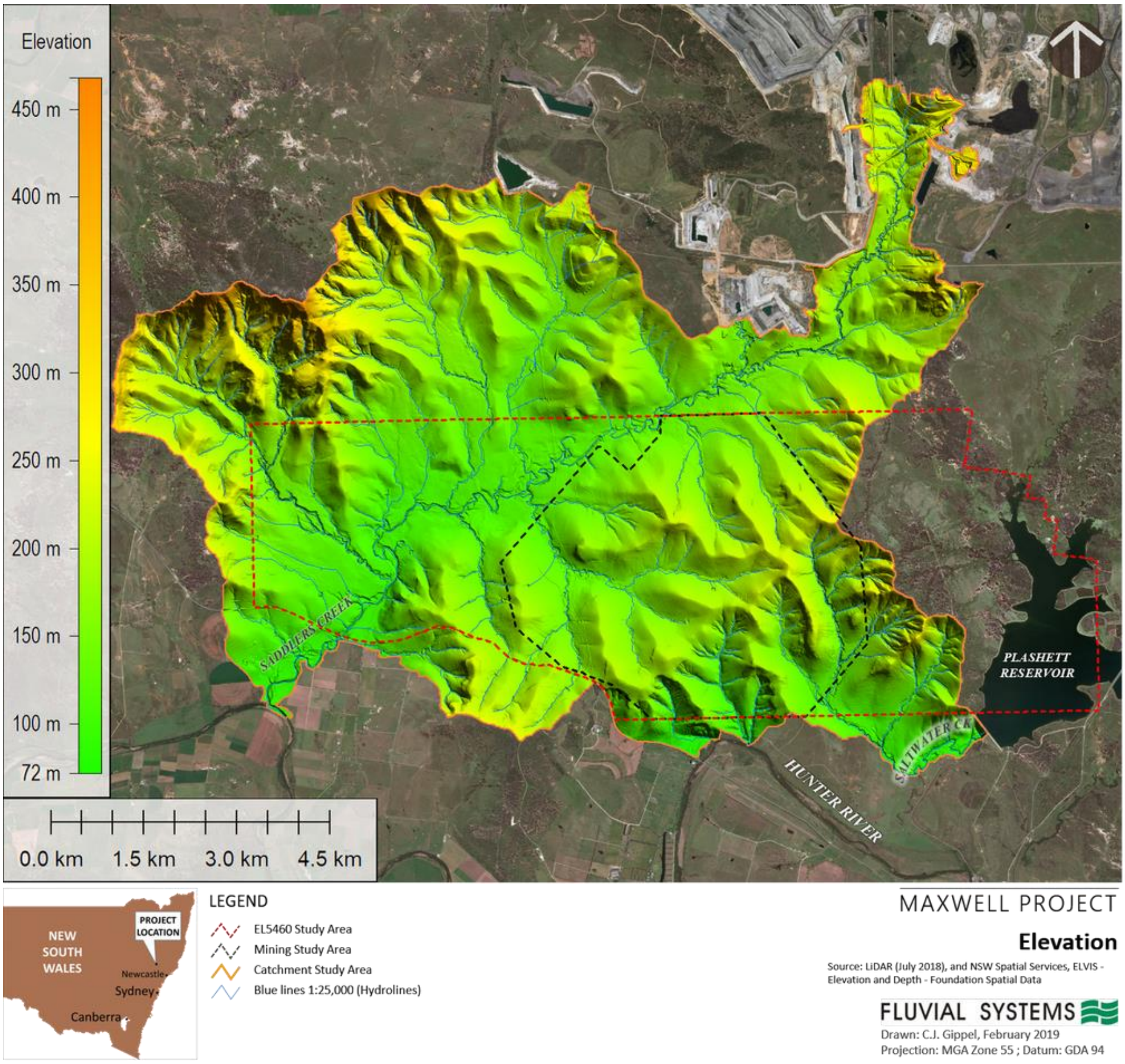

Figure 7. Land elevation of the Study Areas.

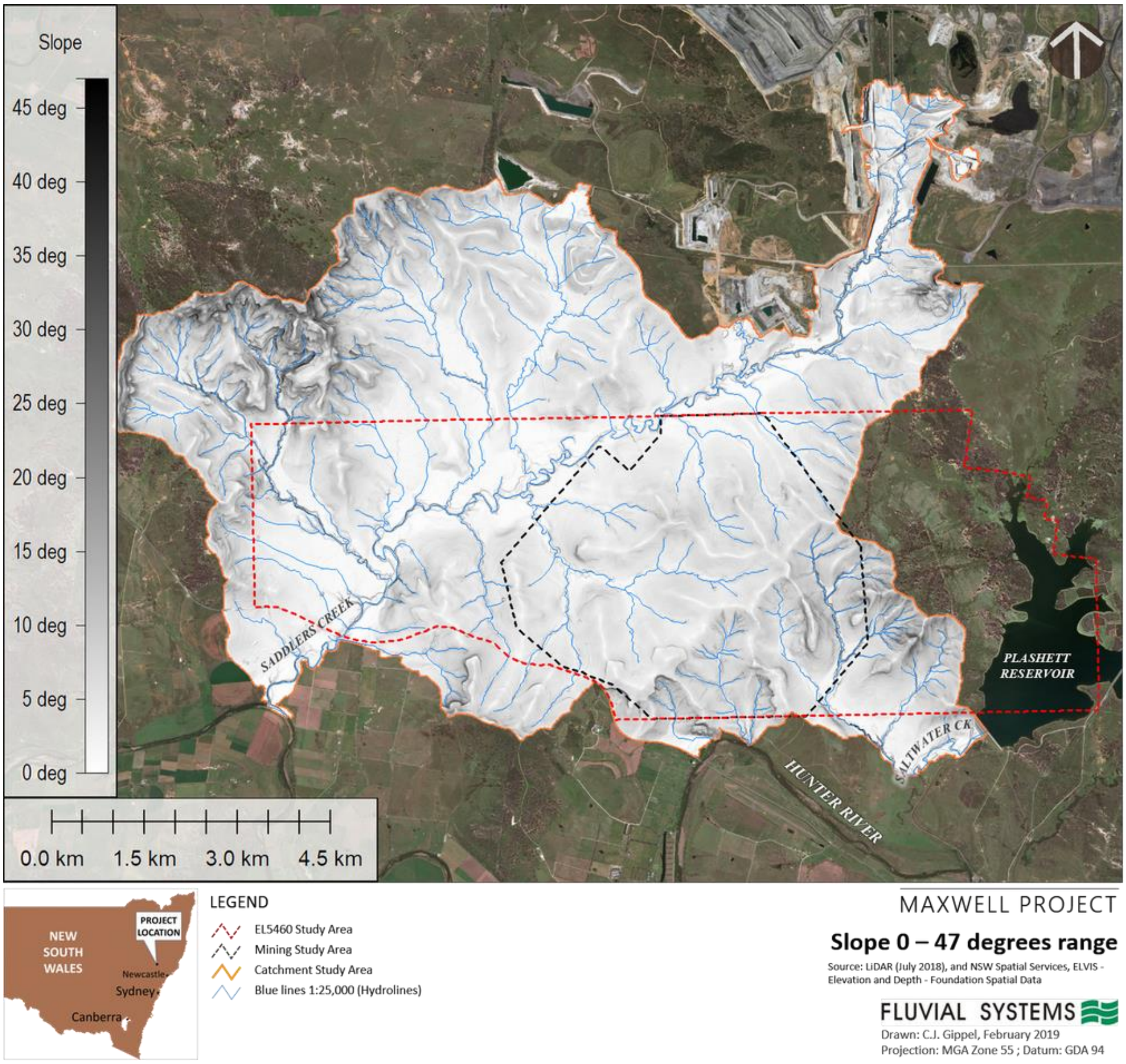

Figure 8. Land slope of the Study Areas on 5 m DEM. Maximum slope in Mining Study Area is 47º.

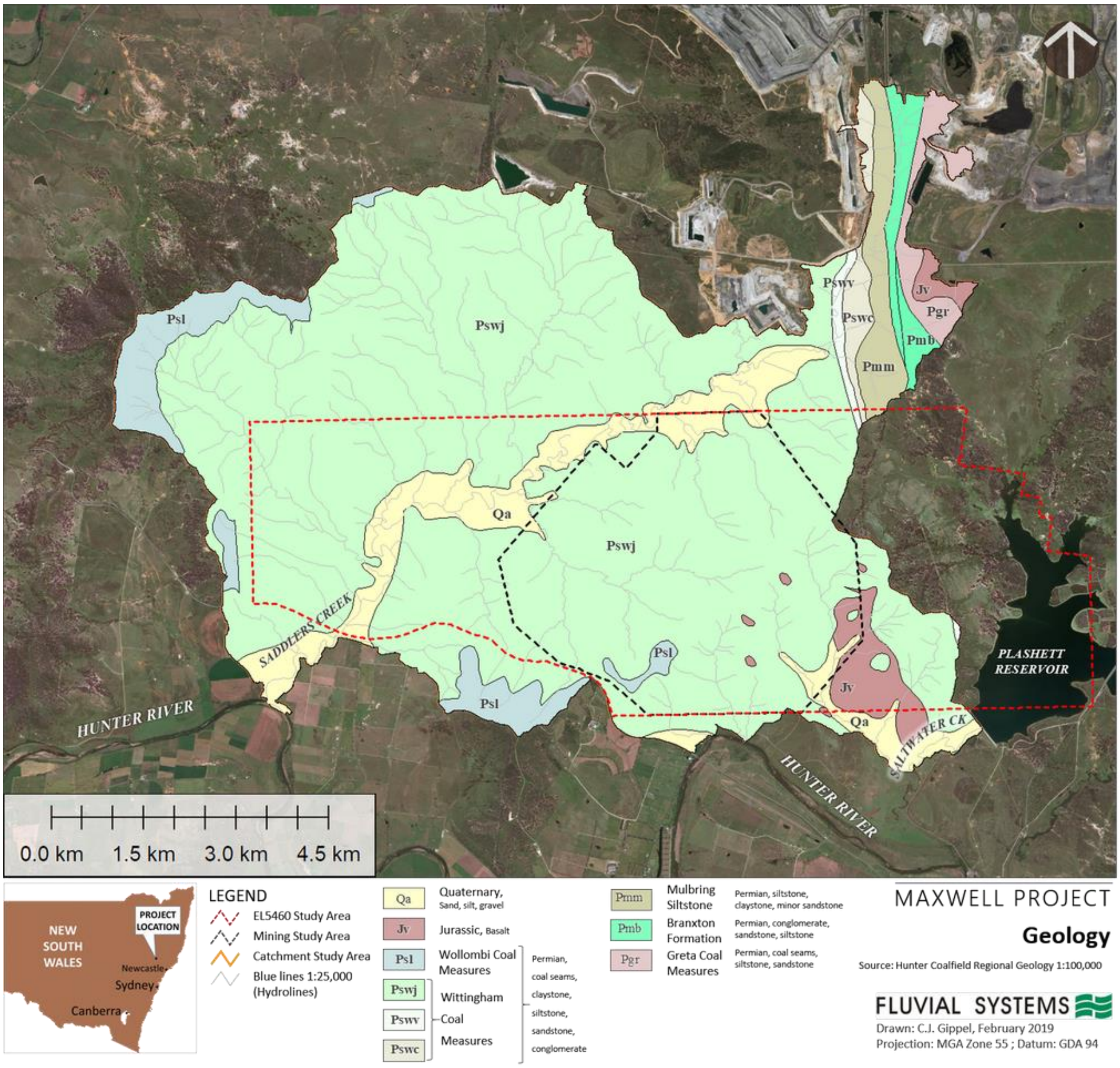

Figure 9. Geology of the Catchment Study Area.

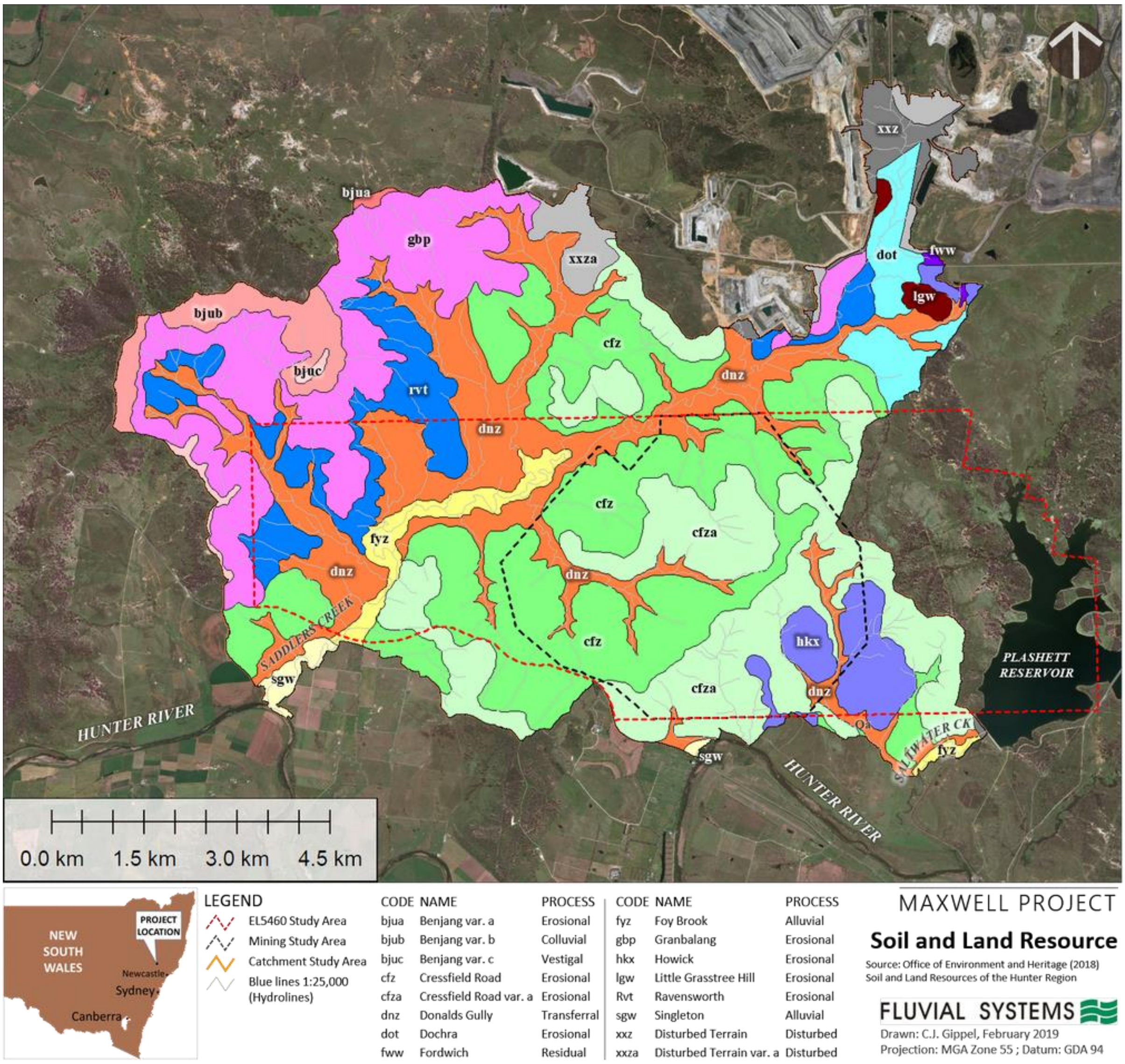

Figure 10. Soil and Land Resource of the Catchment Study Area.

3.1.4 Hillslope Stream Power Index (SPI)

SPI was computed at 5 m grid resolution across the Field Survey Study Area (Figure 11) using the methodology outlined in Section 2.8.7. SPI ranged in value up to 33, but the vast majority of values were less than 10. High stream power was characteristic of hillslopes located in the south-eastern part of the Field Survey Study Area, in particular associated with the Cressfield Road variant a (cfza) Soil and Land Resource unit (Figure 10), and, as expected, steep slopes (Figure 8). Not surprisingly, the most extensive and deepest gullies occurred in the valleys with the highest stream power (see later in this Report, Section 3.2.2).

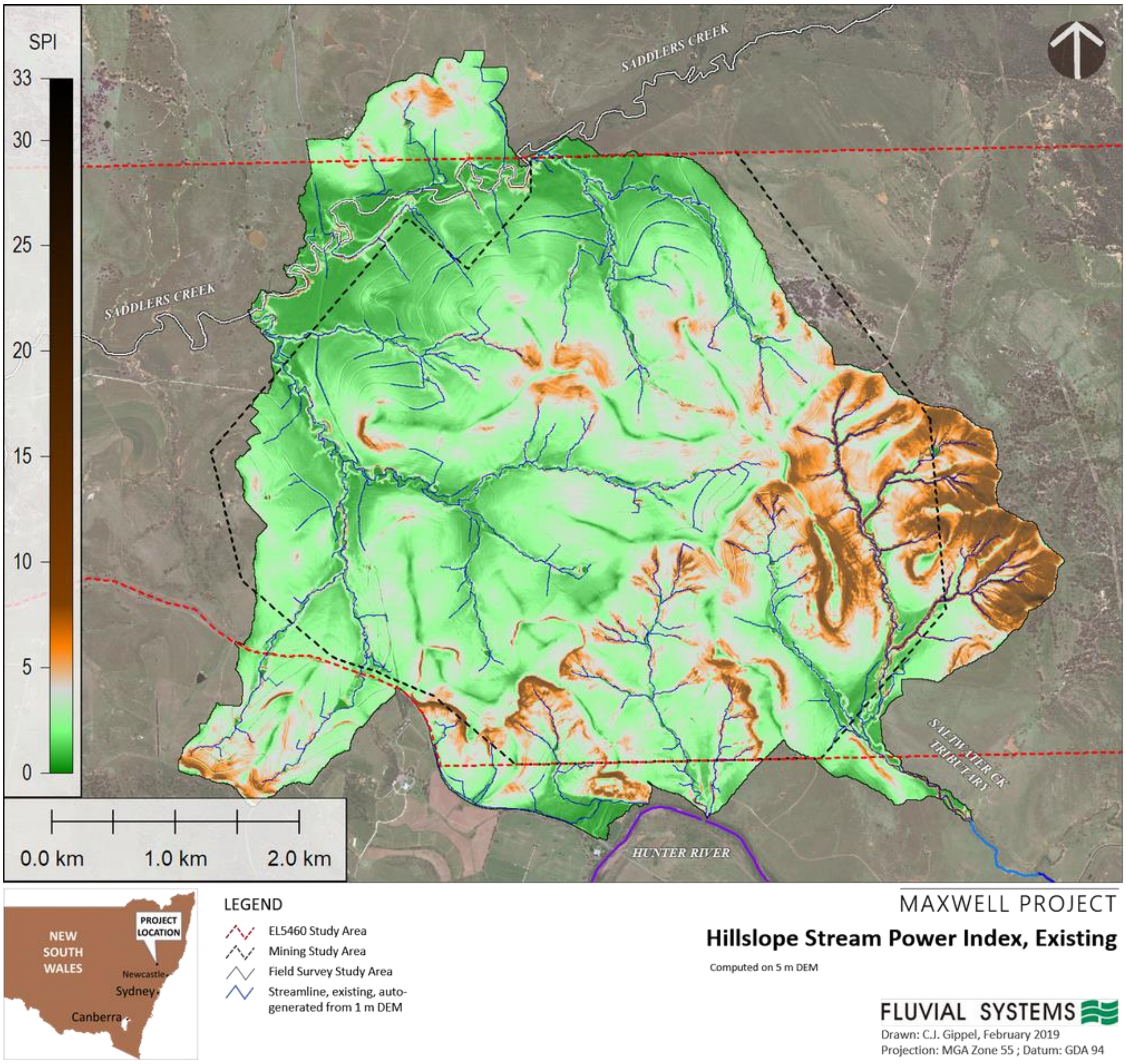

Figure 11. Distribution of hillslope Stream Power Index (SPI) calculated over the Field Survey Study Area for the existing case.

3.2 Stream network characteristics

3.2.1 Strahler Stream Order of published blue line network of the Catchment Study Area

Strahler Stream Order of the 1:25,000 blue line network of the Catchment Study Area assigned Saddlers and Saltwater creeks Stream Order 5 in their lower reaches (Figure 12). Part of the upper catchment of Saddlers Creek was excised by mining after the blue line network was mapped. This did not change the ultimate Stream Order of the creek, but it meant that its transition from Third Order to Fourth Order happened further down the catchment.

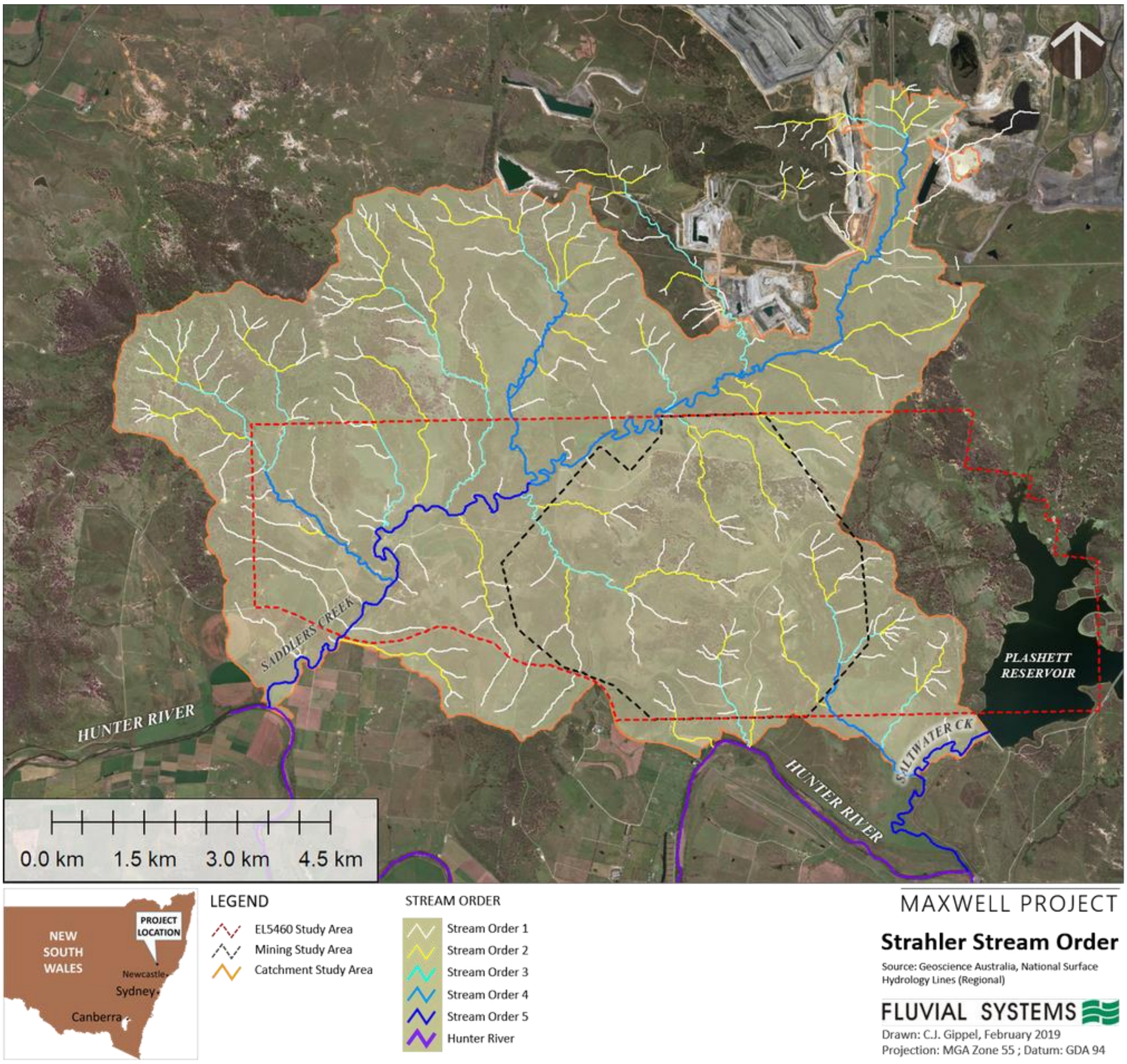

Figure 12. Strahler Stream Order of the 1:25,000 topographic sheet blue line network of the Catchment Study Area. Parts of the headwater catchment of Saddlers Creek were excised by mining after the blue line network was mapped.

3.2.2 Published streambank and gully erosion in the Catchment Study Area

Gullying was mapped as widespread throughout the catchments of Saddlers and Saltwater creeks, and streambank erosion was mapped on much of Saddlers Creek by the OEH Landform and Condition Dataset (Figure 13). There was an error in the datum used for the supplied erosion and gully spatial data that caused the streamlines to be offset relative to the hydrolines. Although this error could not be resolved, it did not affect the interpretation of the data or conclusions reached. In the Catchment Study Area, 52% of the total hydroline length was affected by erosion to some extent, and in the Mining Study Area, 69% of the total hydroline length was affected by erosion. Of this erosion, 51.7% was in the Moderate gully erosion category, 18.3% was in the Severe gully erosion category, and there were no instances of Extreme gully erosion (Figure 14).

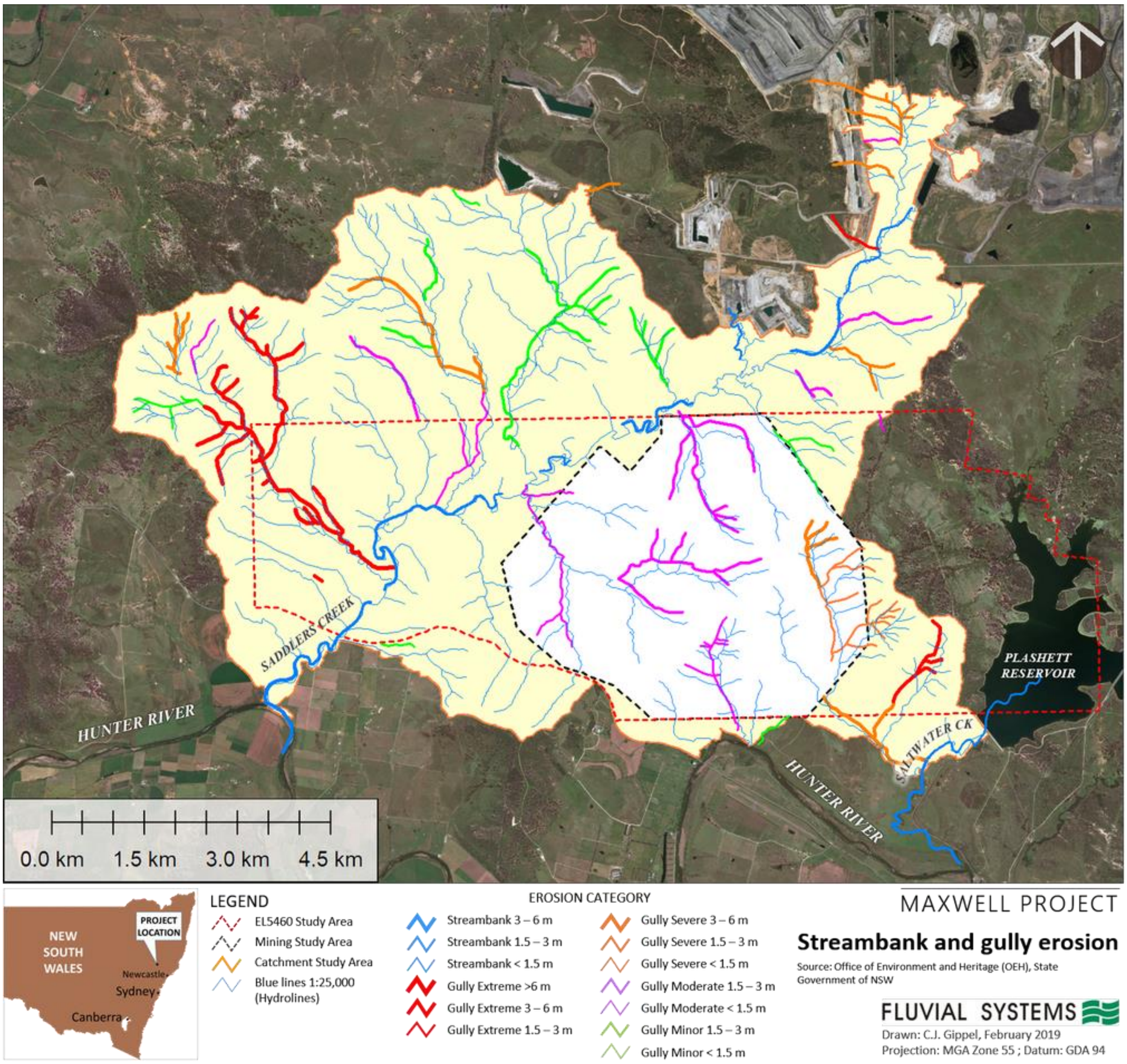

Figure 13. Streambank and gully erosion mapped in the Catchment Study Area. There was an error in the datum used for the supplied erosion and gully spatial data that caused the streamlines to be offset relative to the hydrolines.

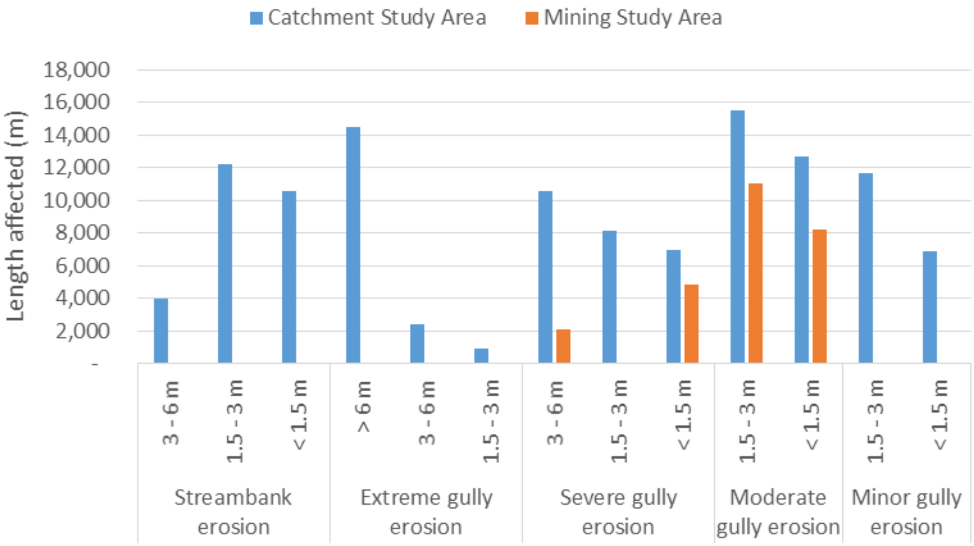

Figure 14. Distribution of streambank and gully erosion in the Catchment Study Area.

3.2.3 Published River Styles® geomorphic categories, condition and recovery potential for the Catchment Study Area

River Styles® mapping of the Hunter River Basin by Cook and Schneider (2006) included the Catchment Study Area. However, their mapping was limited to the Hunter River, Saddlers Creek, and three northern tributaries of Saddlers Creek. The upper tributary they mapped no longer flows to Saddlers Creek due to mining activity.

The Hunter River was classified as *Planform controlled low sinuosity, with sand bed* for a short distance downstream of the junction with Saddlers Creek, then changing to gravel bed (Figure 15). Saddlers Creek was classified as *Meandering, entrenched gravel bed* in the lower reach where it cuts through the Hunter River floodplain. Most of Saddlers Creek was *Planform controlled, low sinuosity gravel bed*, changing to *Floodplain pockets, gravel bed* upstream of the Mining Study Area. The tributaries of Saddlers Creek were classified *Floodplain pockets, gravel bed* in their upper reaches, and two of three were *Cut and fill* in their lower reaches. The other (uppermost) tributary was classified *Planform controlled, low sinuosity gravel bed* in its lower reaches (Figure 15).

Cook and Schneider (2006) rated geomorphic condition of the streams in the Catchment Study Area almost universally Poor. Only two reaches of upper Saddlers Creek were rated Moderate (Figure 16).

According to the mapping by Cook and Schneider (2006), the geomorphic recovery potential of streams in the Catchment Study Area was variable, with Saddlers Creek adjacent to the Mining Study Area being Moderate, and Low further downstream (Figure 17). The recovery potential of the upper reaches of Saddlers Creek tributaries was High in one short headwater section, Moderate along the majority of the upper stream lengths, Low in the lower reaches of one tributary and Strategic in the lower reaches of another (Figure 17). Strategic applies to specific locations of rapid change in condition from Good to Moderate or to Poor, where the appropriate action is to control the agent of disturbance. In this case, the disturbance was gully knickpoint progression, which would require bed control structures and revegetation. Low recovery potential applies to stream reaches with ongoing degradation, poor riparian vegetation, low large wood density, and excess sediment supply. Recovery requires extensive management actions involving revegetation, large wood reintroduction and bed control works. Moderate recovery potential applies to reaches in moderate to poor condition with excess sediment supply, but which have potential to recover at a low to moderate rate. Recovery actions should focus on improving condition of the reaches upstream (Cook and Schneider, 2006).

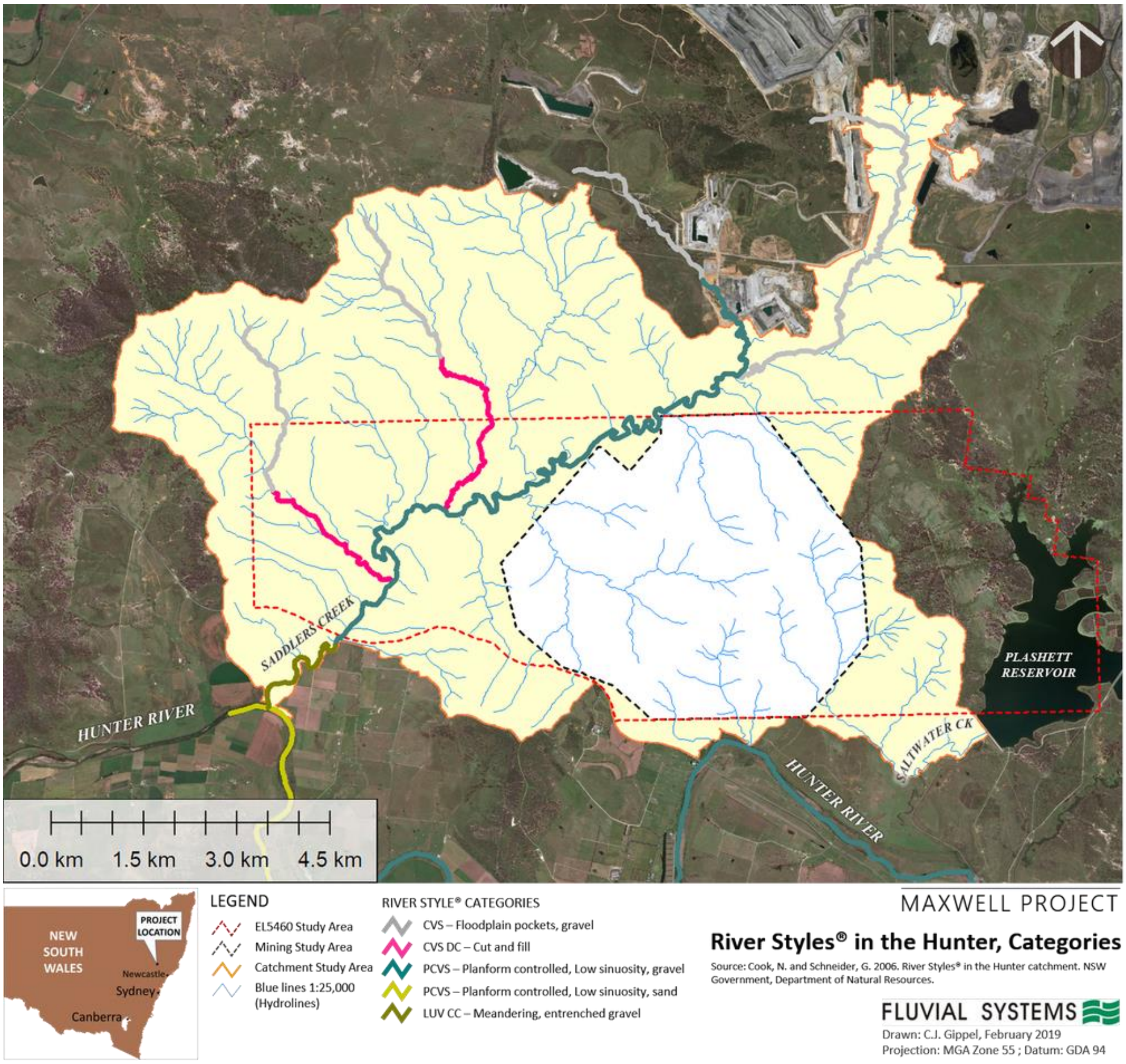

Figure 15. River Styles® geomorphic categories mapped in the Catchment Study Area by Cook and Schneider (2006).

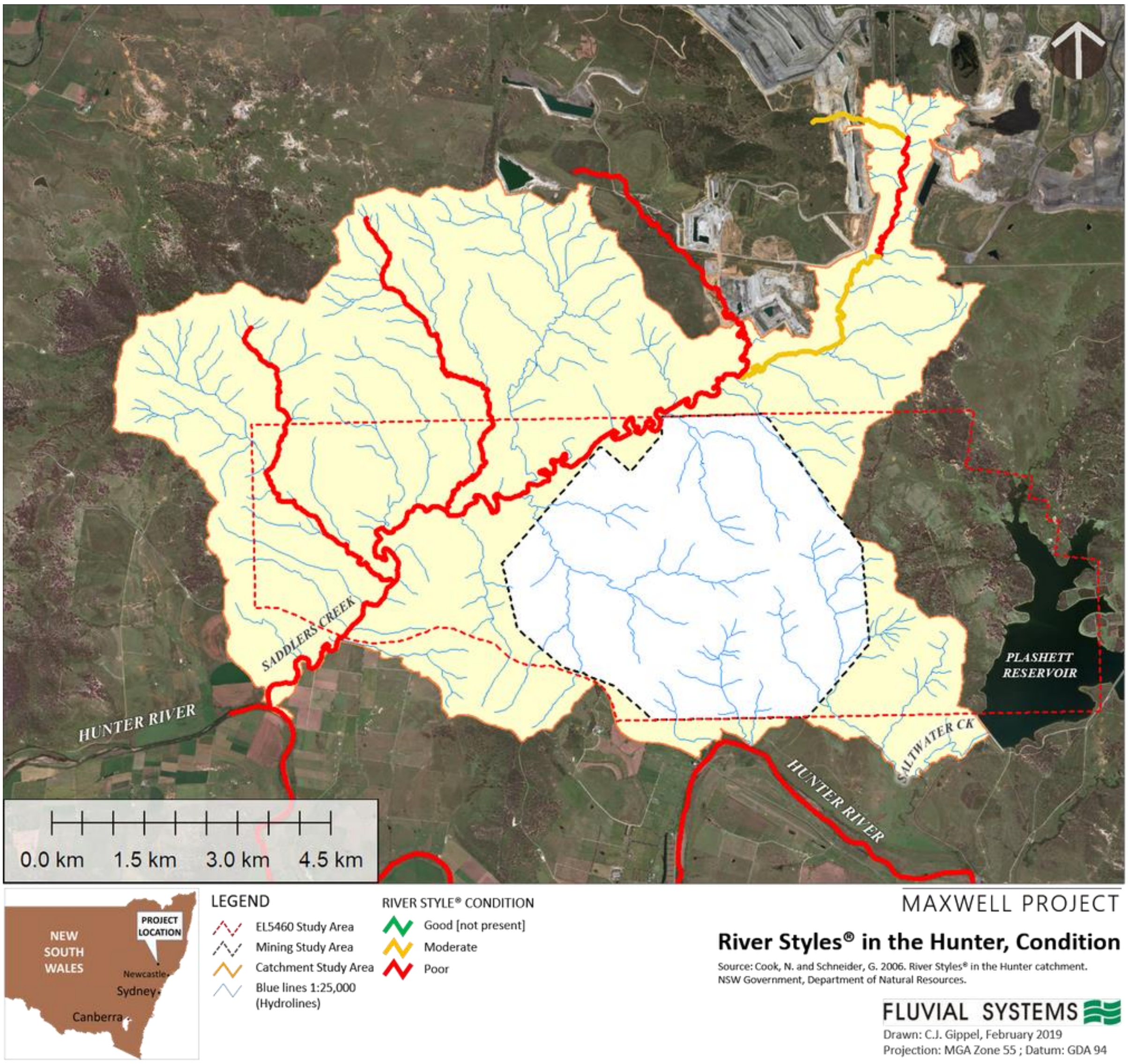

Figure 16. River Styles® geomorphic condition mapped in the Catchment Study Area by Cook and Schneider (2006).

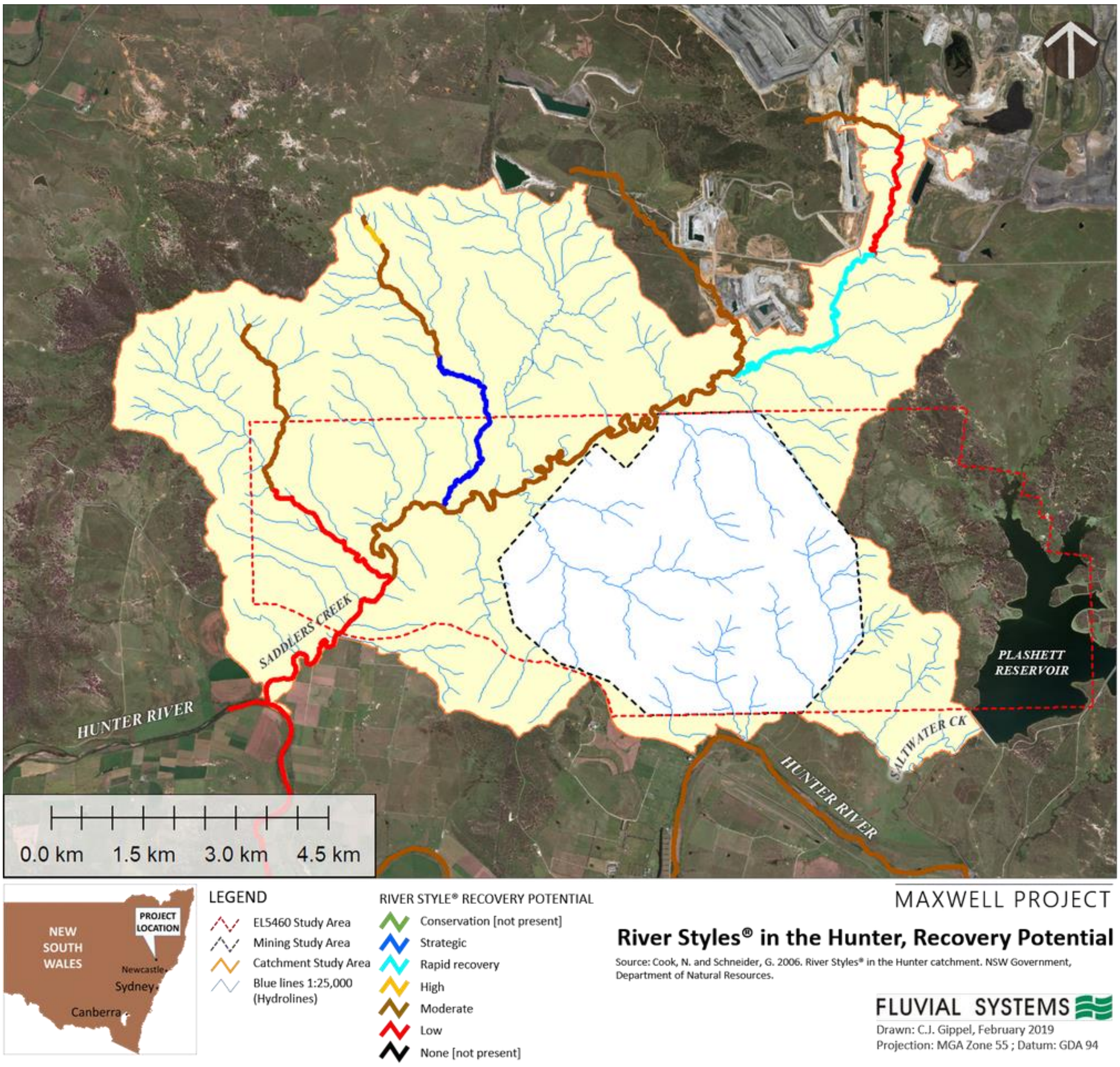

Figure 17. River Styles® geomorphic recovery potential mapped in the Catchment Study Area by Cook and Schneider (2006).

3.2.4 Catchments and emulated blue line network of the Field Survey Study Area

The Mining Study Area was associated with 8 catchments, four of which (C, D, E and F) are small tributaries of the Hunter River, one (G) drains to the Hunter River floodplain, two (A and B) drain to Saddlers Creek, and one (H) is the local catchment of the reach of Saddlers Creek between catchments A and B (Figure 18). Of these, Catchment A was by far the largest (Table 9). For identification purposes, labels were applied to streams of Second Order or higher according to their catchment and Stream Order. Those First Order streams surveyed in the field were also labelled.

The automatically-generated drainage network intended to emulate the published blue line network (Figure 18) was a more accurate representation of the existing distribution of stream channels than that indicated by the 1:25,000 topographic sheet and its digital equivalent (Figure 12). Consistent with the published blue line network, within the Field Survey Study Area, five Third Order streams, and one Fourth Order stream were mapped (Figure 18). Adjacent to the northern boundary of the Mining Study Area, Saddlers Creek is a Fourth Order stream.

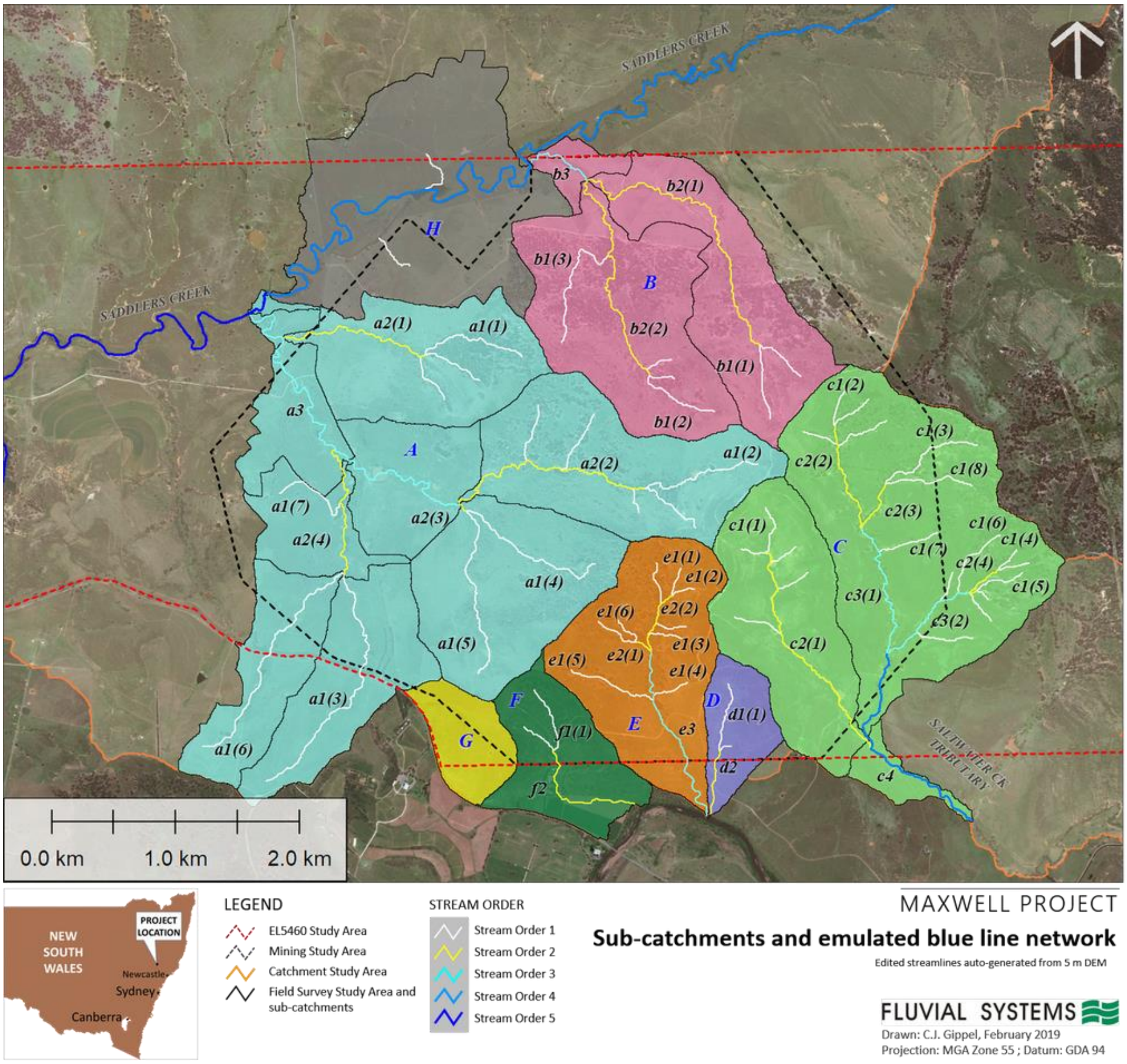

Figure 18. Catchments and sub-catchments forming the Field Survey Study Area. Also shown are labels for selected streams forming the automatically-generated emulated blue line network.

Table 9 Total area of sub-catchments forming the Field Survey Study Area.

Catchment	Total catchment area (ha)
A	1023.6
B	395.0
C	578.4
D	52.2
E	195.2
F	101.9
G	52.8
H	313.4

3.2.5 Modelled channel stream power

The downstream pattern of channel stream power was highly variable for all streams (Figure 19, Figure 20, Figure 21, Figure 22, Figure 23 and Figure 24). The high frequency fluctuations reflected the high density of knickpoints in the bed profiles, and some exceptional peaks occurred at track crossing and culverts.

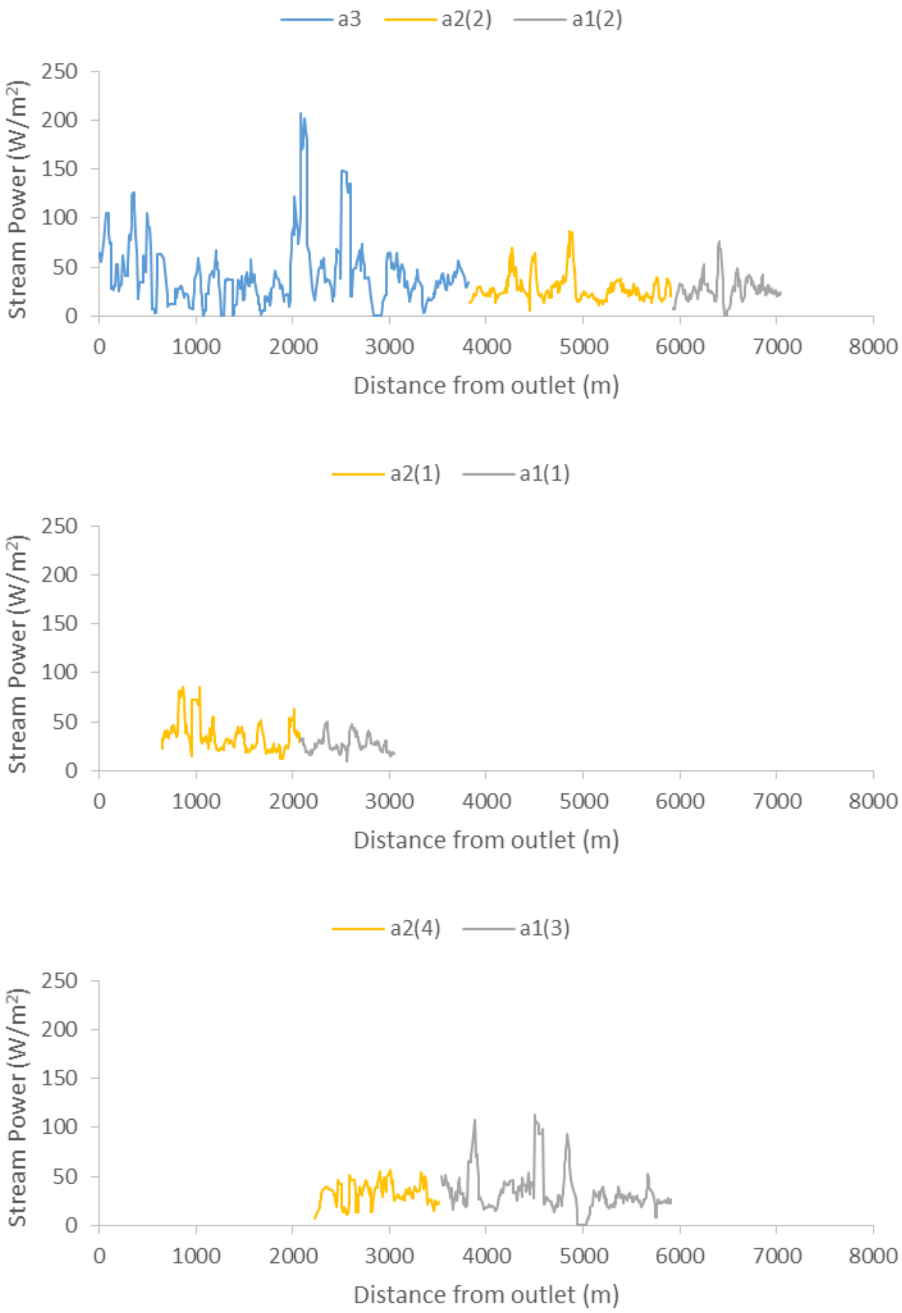

Figure 19. Existing downstream pattern of modelled stream power of stream network of Catchment A.

Few values (3.9% of total) of stream power were less than 10 W/m^2, which equates to Nanson and Croke's (1992) low energy range. Only 7 of a total of 4,155 modelled values (0.17% of total) were greater than 300 W/m^2, which equates to Nanson and Croke's (1992) high energy range. The remaining 96% of the values fell within the range 10 – 300 W/m^2, which equates to Nanson and Croke's (1992) medium energy range. Overall, the streams would be regarded as medium energy between knickpoints, and medium, and occasionally high, energy at knickpoints.

Stream power tended to be highest in the lower reaches of catchment networks, although First and Second Order streams had a similar range of stream power. Catchment C had the most extensive and deepest gullying (Figure 14) and high hillslope Stream Power Index (Figure 11), but this channel network did not have exceptional channel stream power (Figure 21).

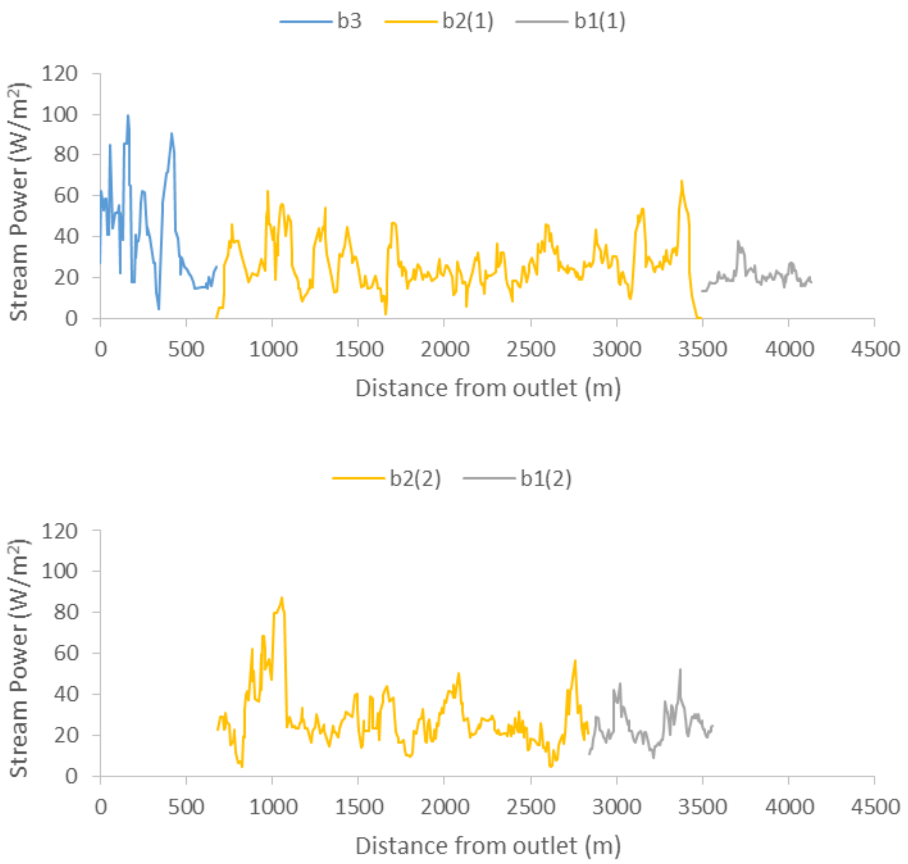

Figure 20. Existing downstream pattern of modelled stream power of stream network of Catchment B.

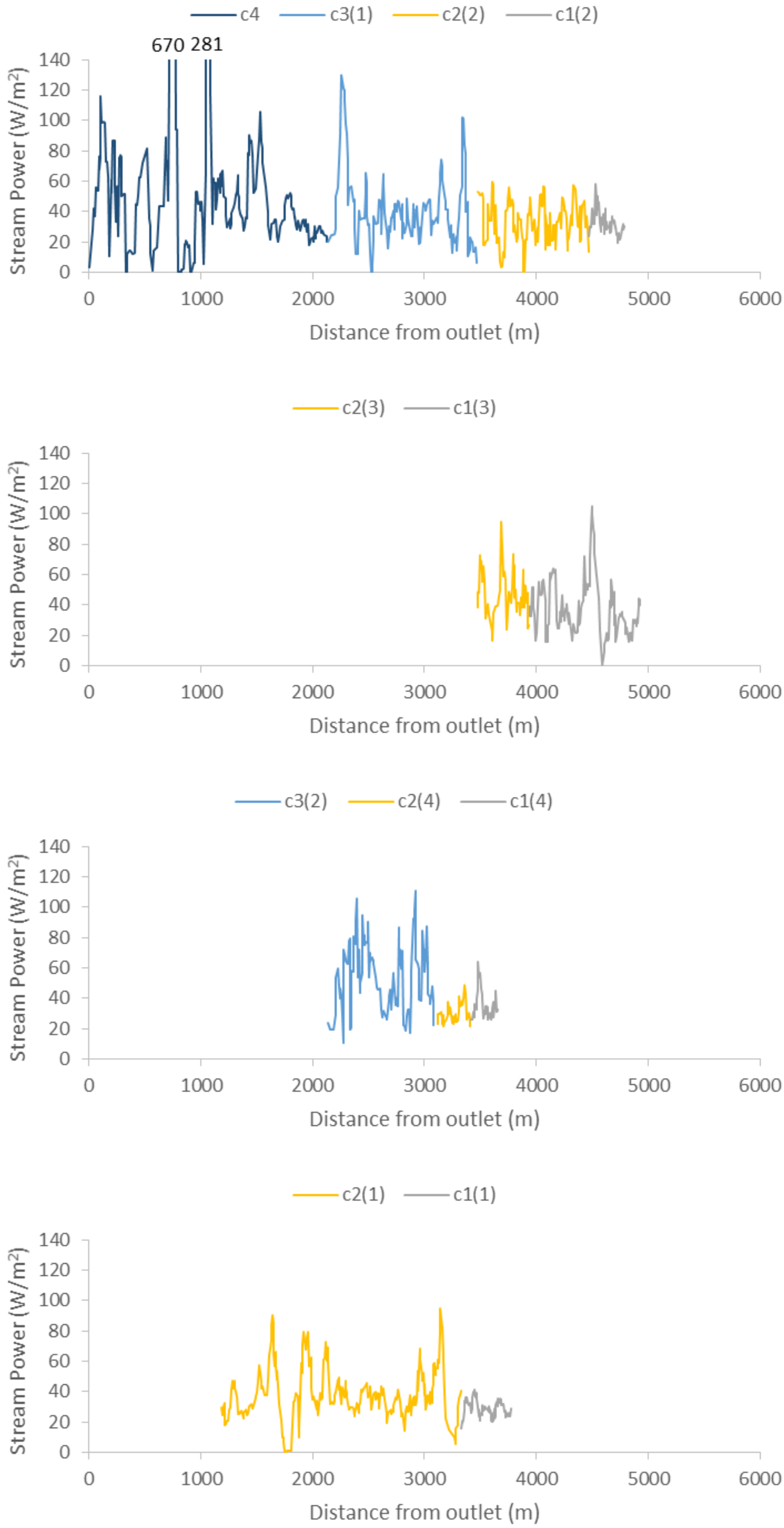

Figure 21. Existing downstream pattern of modelled stream power of stream network of Catchment C.

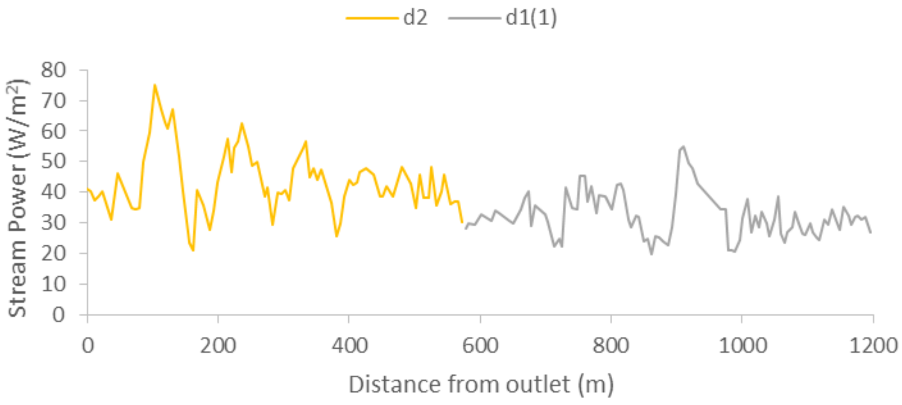

Figure 22. Existing downstream pattern of modelled stream power of stream network of Catchment D.

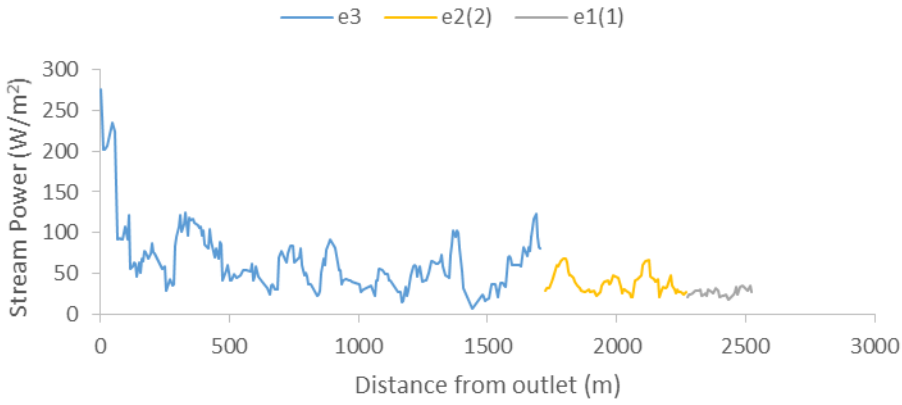

Figure 23. Existing downstream pattern of modelled stream power of stream network of Catchment E.

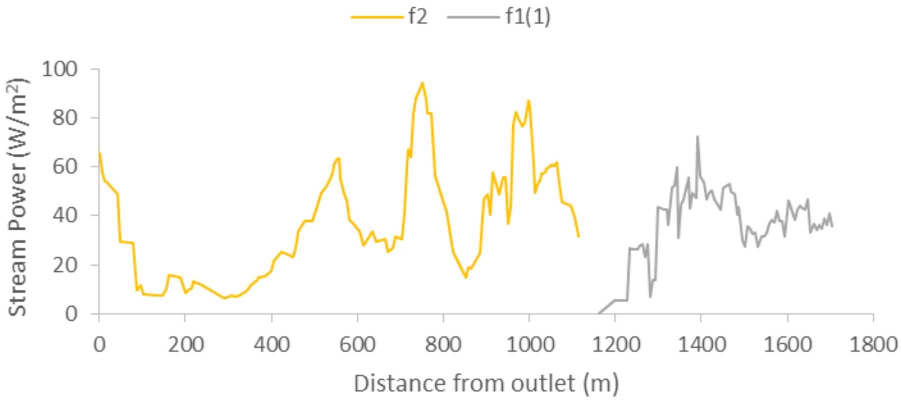

Figure 24. Existing downstream pattern of modelled stream power of stream network of Catchment F.

3.2.6 Depressions on drainage lines

The distribution of depressions on drainage lines was computed at 1 m grid resolution across the Field Survey Study Area (Figure 25) using the methodology outlined in Section 2.8.8. Depressions were common in streams of Second Order and higher. The largest depressions were formed by farm dams. The largest dam was on Saddlers Creek. There was a broad association with high frequency of depressions and extent of gullying (Section 2.6.6). Gullied reaches tended to have a high frequency of knickpoints (see later in this Report, Section 3.3.2). A short length of scoured bed was commonly observed in the field immediately downstream of these knickpoints, with the excavated coarse sediment deposited a short distance downstream, forming a closed depression.

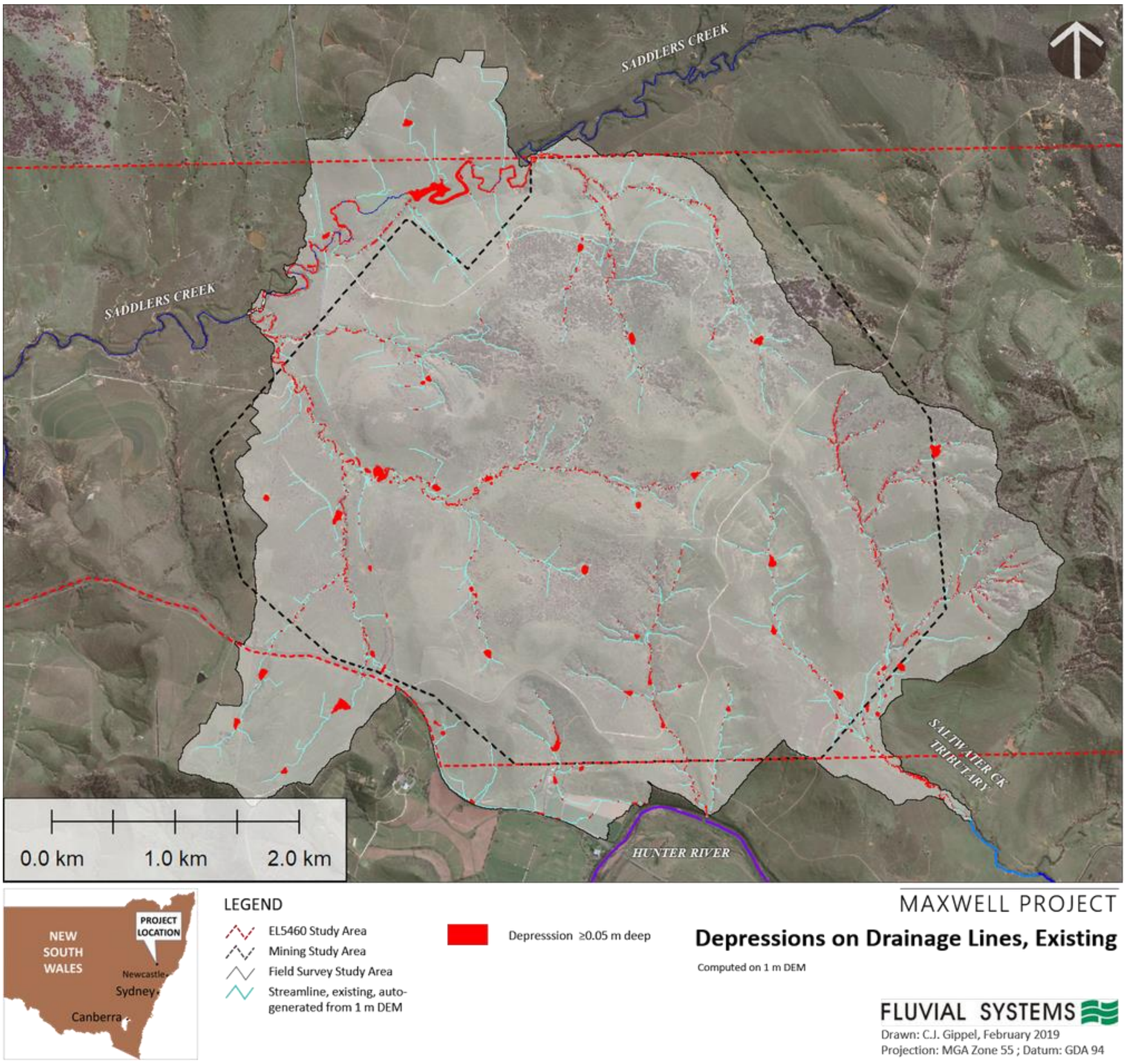

Figure 25. Distribution of depressions on drainage lines calculated over the Field Survey Study Area for the existing case.

3.3 Stream reach- and point-scale characteristics

3.3.1 Channel bed materials

A wide range of channel bed materials was observed over the Study Areas, but silt/clay/organic (mud) was overwhelmingly the dominant bed material across streams of all Orders (Figure 26). Mud was the dominant bed material in 74% of the 198 sampled sites. Although gravel- and sand-sized materials were found at a significant number of sites, the total volume of this material was small. The assessment was of surface material only, so it is possible that coarser sediment was present underneath the generally fine surface material.

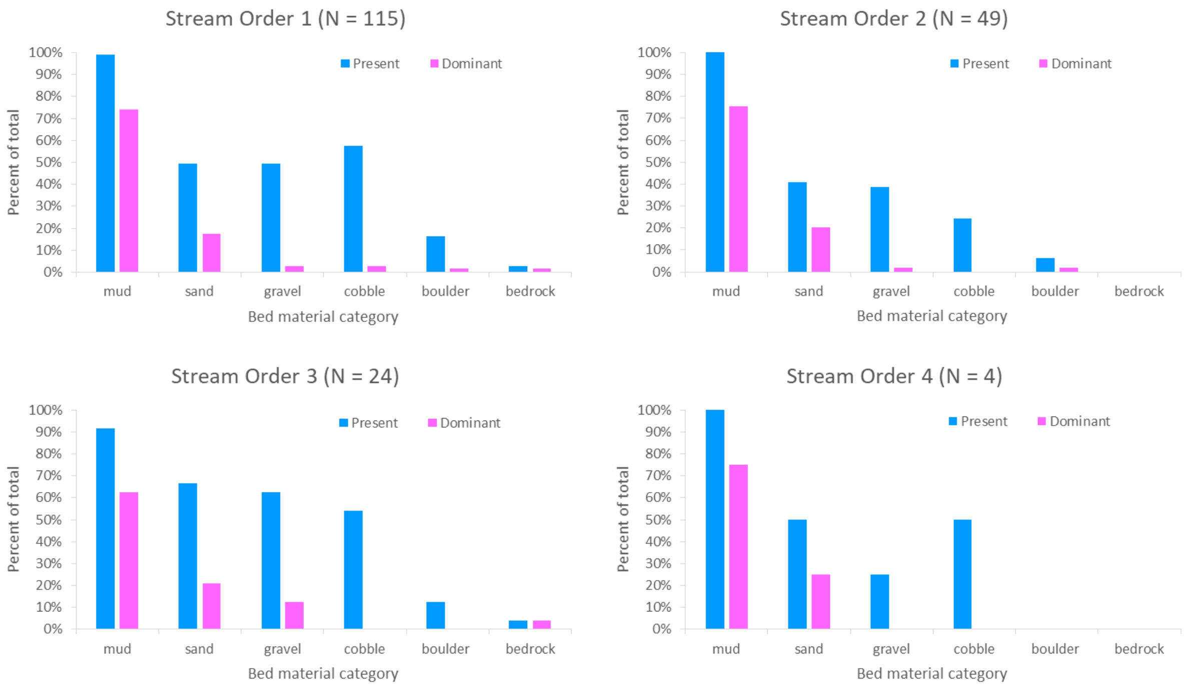

Figure 26. Distribution by Stream Order of stream bed material size class found at sites sampled within the Field Survey Study Area.

3.3.2 Knickpoints

Knickpoints were commonly observed in streams within the Field Survey Study Area, with 43 hard knickpoints and 257 soft knickpoints observed (Figure 27). While it was the intention of the survey to record every knickpoint encountered while walking the streams, the fact that a knickpoint was observed at more than half of the sites is indicative of how ubiquitous they were. Hard rock knickpoints were found mostly on headwater streams, particularly the basalt area of Catchment C [sub-catchment c3(2)] and the lower reach of catchments C, D and E. Knickpoints in unconsolidated material had a wide spatial distribution. In general, hard knickpoints were higher than soft knickpoints. Few knickpoints were higher than 2 m, and the distribution of knickpoint height was independent of Stream Order (Figure 28).

The geomorphic significance of knickpoints in most of the streams of the Field Survey Study Area is highlighted by the high percentage of the fall in elevation of the streams that was contributed by knickpoints (Figure 29).

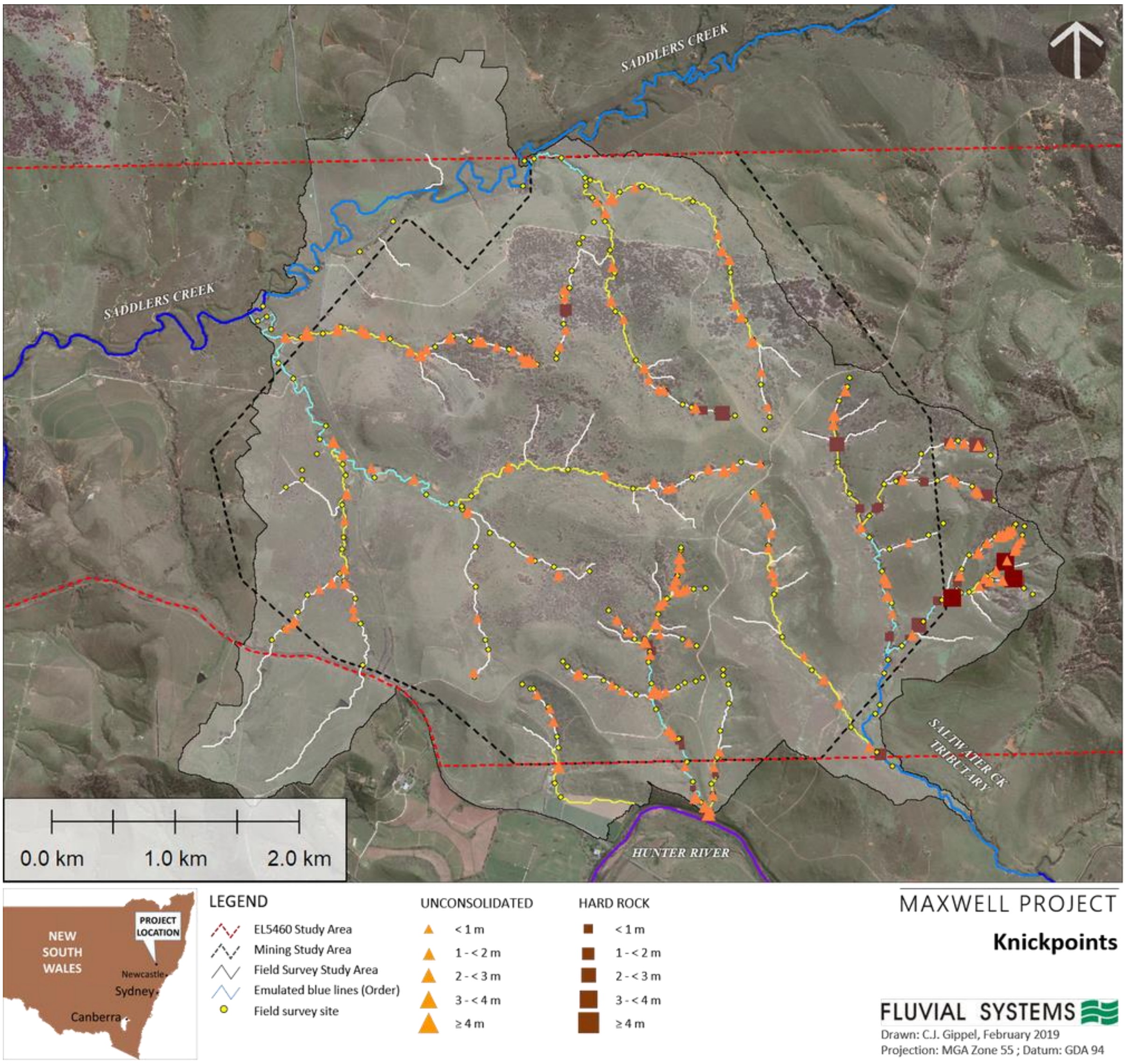

Figure 27. Distribution of knickpoints on streams within the Field Survey Study Area. Combined height is given for sites with up to three closely spaced knickpoints.

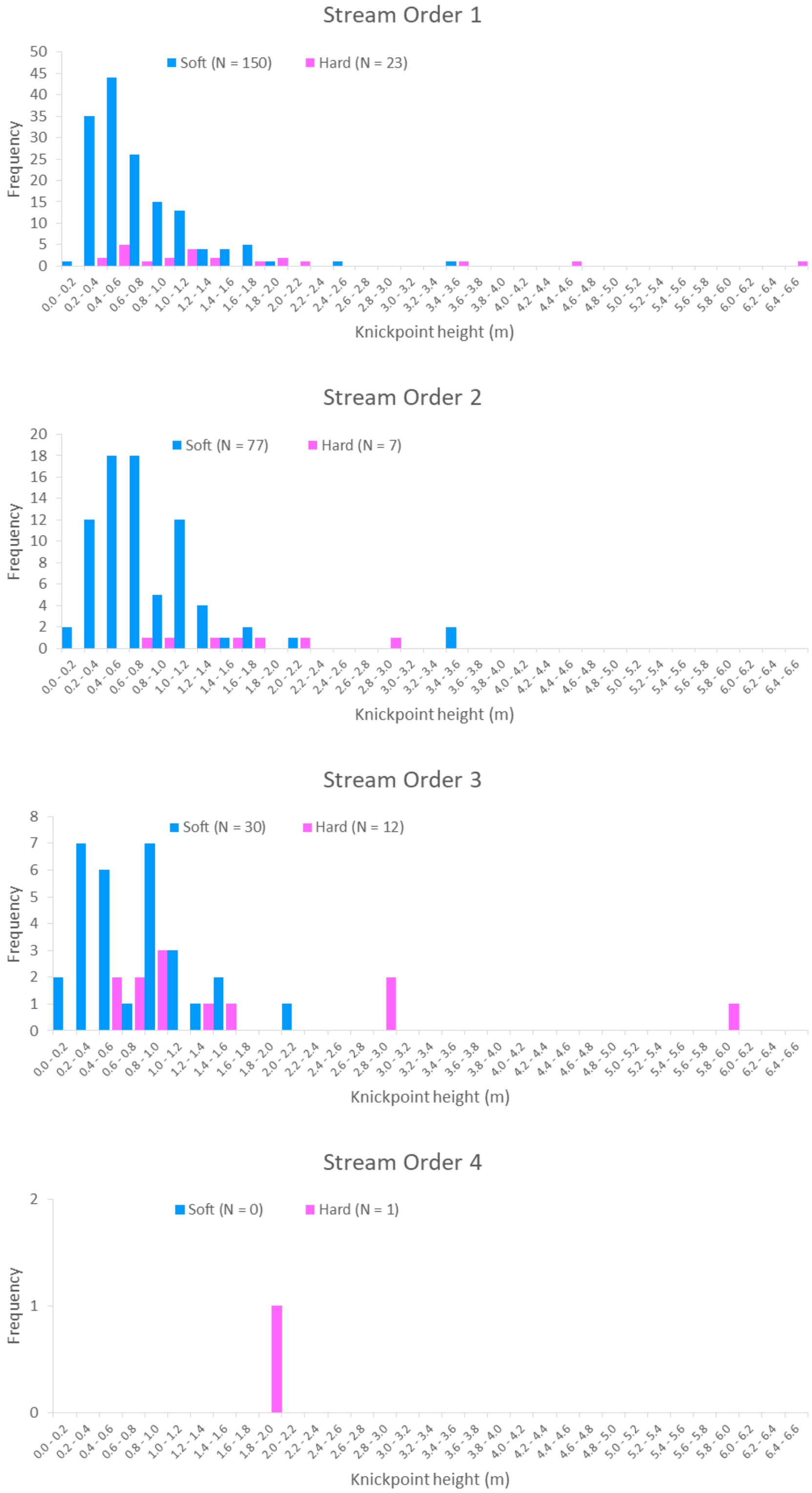

Figure 28. Histograms of height of soft (unconsolidated sediment) and hard (rock or boulder) knickpoints by Stream Order observed in streams within the Field Survey Study Area.

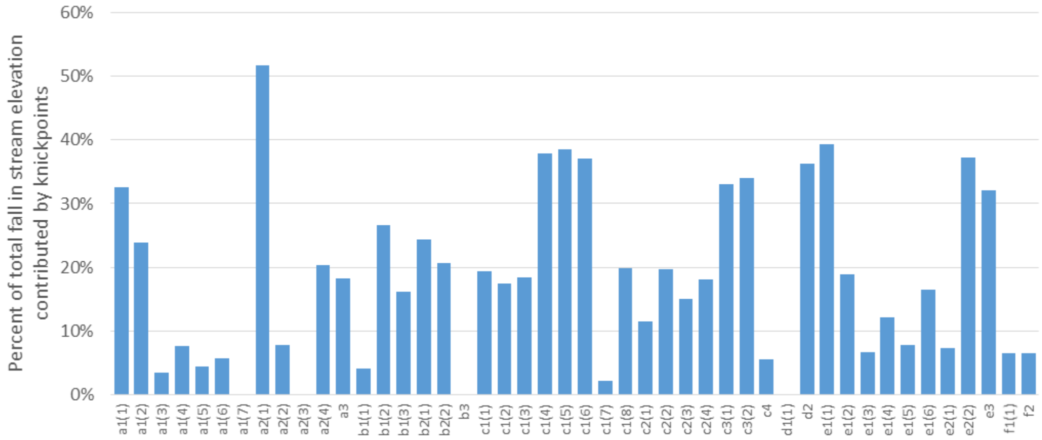

Figure 29. Percent of total fall in stream elevation contributed by knickpoints in observed streams within the Field Survey Study Area.

3.3.3 In-channel bedrock features and joint density

Exposed bedrock features were not common in the Field Survey Study Area, with only 10 significant rock slabs observed (Figure 30, Figure 31) and some hard rock knickpoints (Figure 27). Of the sites with bedrock beds, only four were within the proposed boundary of underground workings. Six of the bedrock outcrops were observed in headwater streams and the other four were in the lower reaches of streams in catchments E and F, where the streams cut down to meet the level of the Hunter River (Figure 30).

The exposed bedrock was naturally jointed with a high variability of joint spacing. The spacing ranged from an average of 17 joints per metre to 1 joint every 2 metres. The observed cracks were ancient and tight, and would not cause significant loss of water from creeks. Any future cracks in bedrock caused by subsidence would be readily distinguishable from these natural joints.

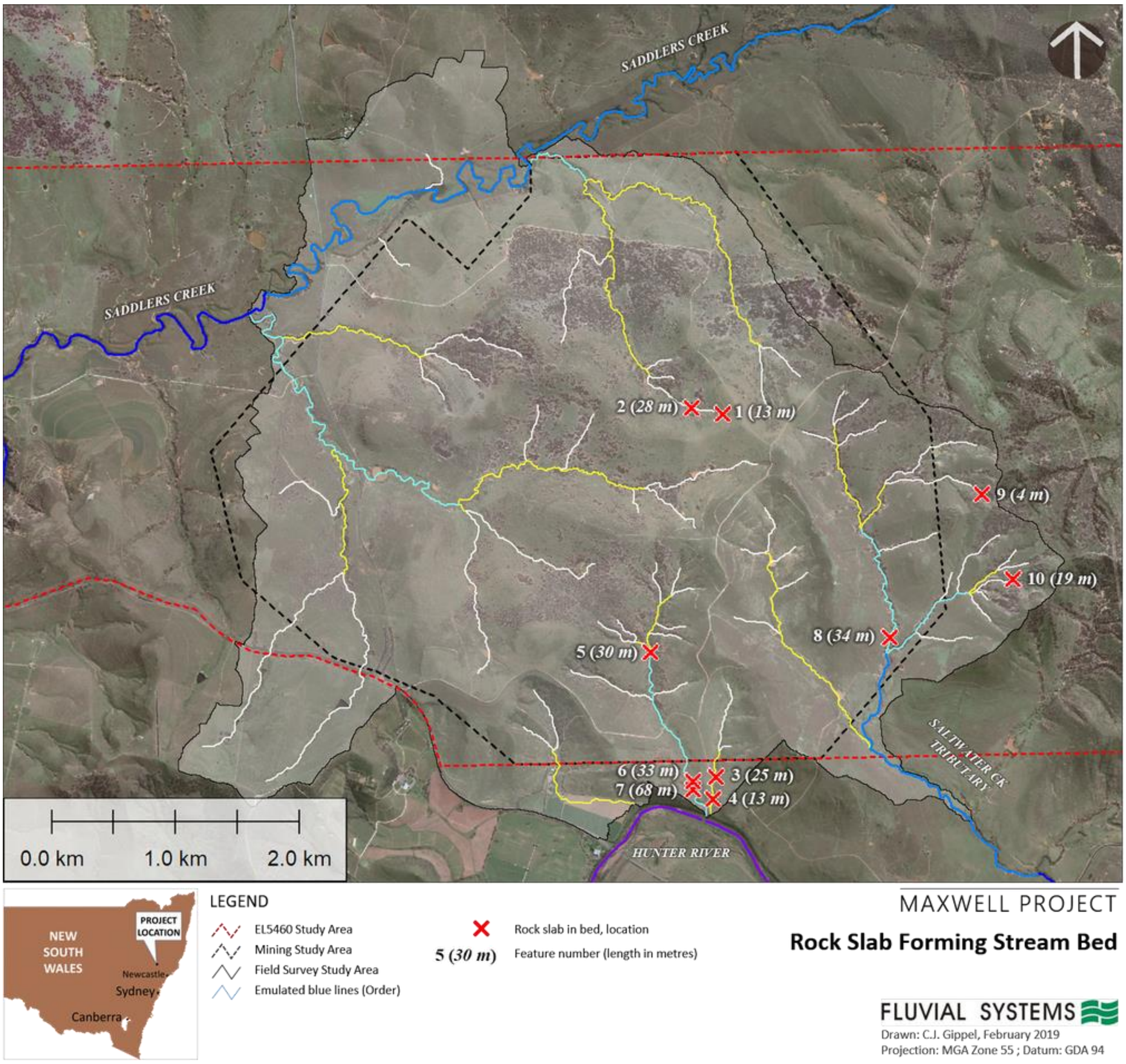

Figure 30. Distribution of significant bedrock features for sites sampled on channel beds within the Field Survey Study Area.

Figure 31. Images of the 10 sites where the bed was observed to be formed in bedrock.

3.3.4 In-channel pools

Only two pools were measured in the field, although many other smaller pools were present (see Section 3.2.6). The two measured pools contained water and both were on the lower reaches of the Third Order stream of Catchment A (stream a3), where emergent macrophytes were also present (see later Section 3.3.6). One pool (32.426153°S, 150.833118°E) was 68 m long and the other (32.414424°S, 150.819939°E) was 16 m long. The lower reaches of stream a3 had variable bed morphology, and other depressions in the bed were identified as pools.

The lower reach of stream c2(1), where the gradient decreased as it approached lowland stream c4, and the lower reach of stream a2(1), where the gradient decreased as it approached lowland stream a3, had broad, flat beds infilled with vegetated sediment. Unusually, these broad beds were characterised by numerous, relatively deep scour holes, not necessarily linked by channels. The morphology had the appearance of chain-of-ponds, but at a small scale, and situated within a channel rather than within a valley fill.

3.3.5 Riparian zone vegetation 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 Field Survey Study Area, riparian tree cover was very low - moderate at most sites (Figure 32). It was observed that a moderate level of tree cover was within the natural range of undisturbed sites, i.e. forested headwater areas did not have dense tree cover >75% (Figure 32). Riparian vegetation cover index was uniformly in the low - moderate range over the surveyed sites, mainly because of low to moderate grass cover on the hillslopes due to the prevailing dry climatic conditions.

Figure 32. Distribution by Stream Order of stream riparian cover indexes found at sites sampled within the Field Survey Study Area.

3.3.6 Instream vegetation cover and large wood frequency

Extensive grass cover on the bed of a low flow channel is usually indicative of a low energy or headwater environment where the bed shear stress (product of slope and water flow depth) 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. This geomorphological survey classified grass on the bed as distinct from macrophytes.

There were few observations of emergent macrophytes, limited to a few low gradient sites on Saddlers Creek, stream a3, and stream a2(4). These sites were also unusual in having damp or saturated bed sediments (Figure 33). Grass cover on the low flow channel bed was fairly common. Coverage was variable, but although coverage was at least moderate in many places, the grass was mostly dry and short (Figure 33). The fairly high degree of grass cover on the bed was indicative of intermittency of the flow regime.

Large wood was either present at relatively low frequency, or was non-existent (Figure 34). The streams of catchment C were the only ones that consistently had large wood present, but the frequency of wood was relatively low, such that it would not have played a major role in stabilising bed sediment.

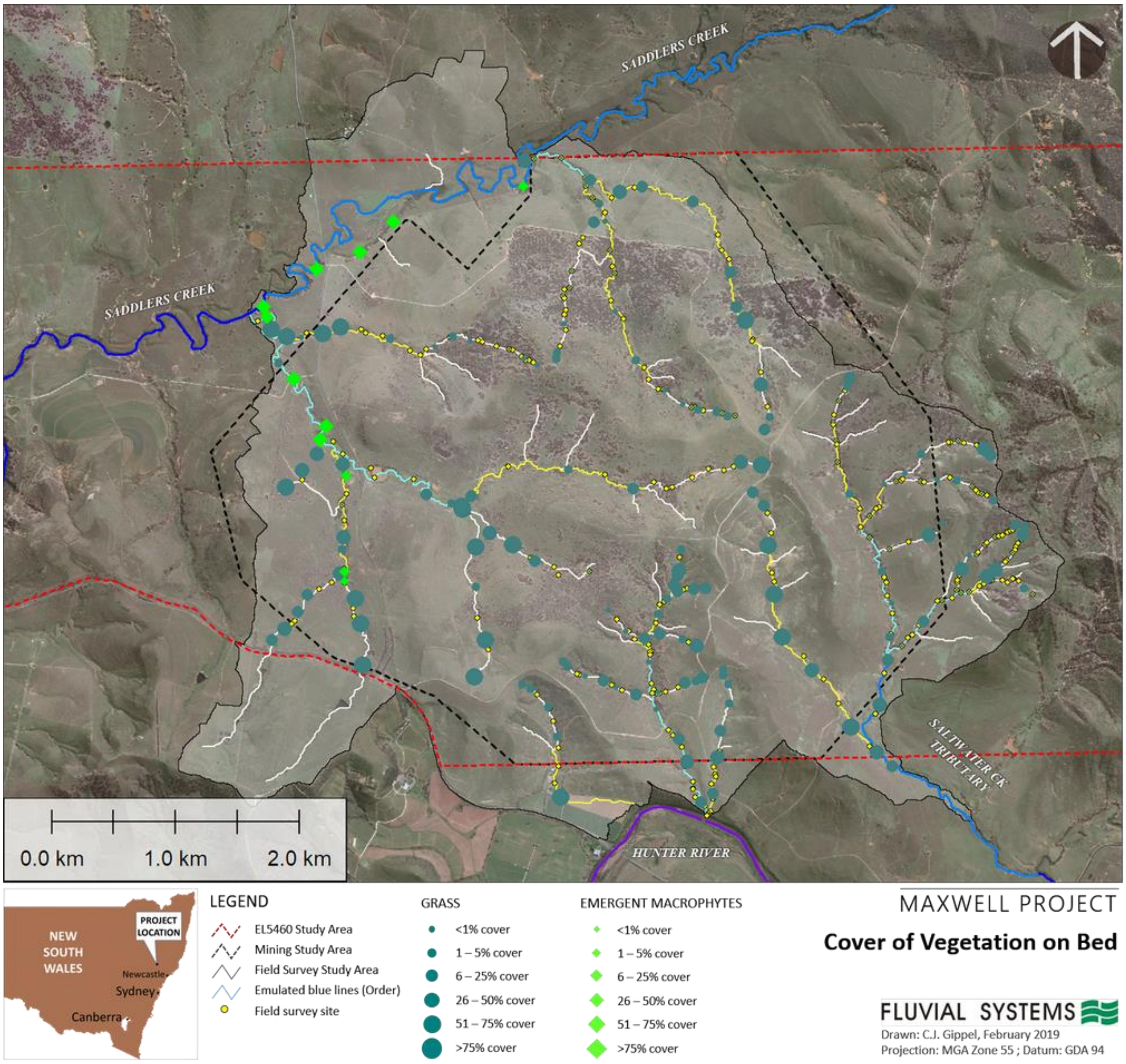

Figure 33. Distribution of vegetation cover on the bed of the low flow channel for sites sampled on streams within the Field Survey Study Area.

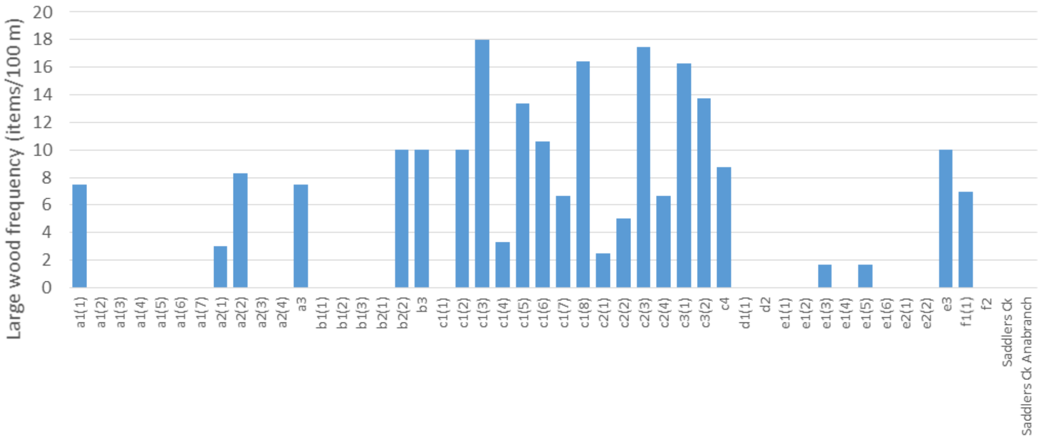

Figure 34. Distribution of large wood frequency in observed streams within the Field Survey Study Area.

3.3.7 Stream morphological attributes

Channel dimensions were measured at 198 sites within the Field Survey Study Area (Figure 35). The mean and standard deviation of the measurements for each stream indicated variable morphology, but overall, the streams were relatively small, with most having bed width less than 5 m, channel bankfull widths less than 10 m, and depths less than 0.6 m.

Stream slope was strongly related to Stream Order (Figure 35). The First and Second Order streams in catchments C, D and E in particular were steep, with a fall of 5 to 9 m every 100 m. Streams in catchments C, D and E were noticeably steeper than those in catchments A and B (Figure 35).

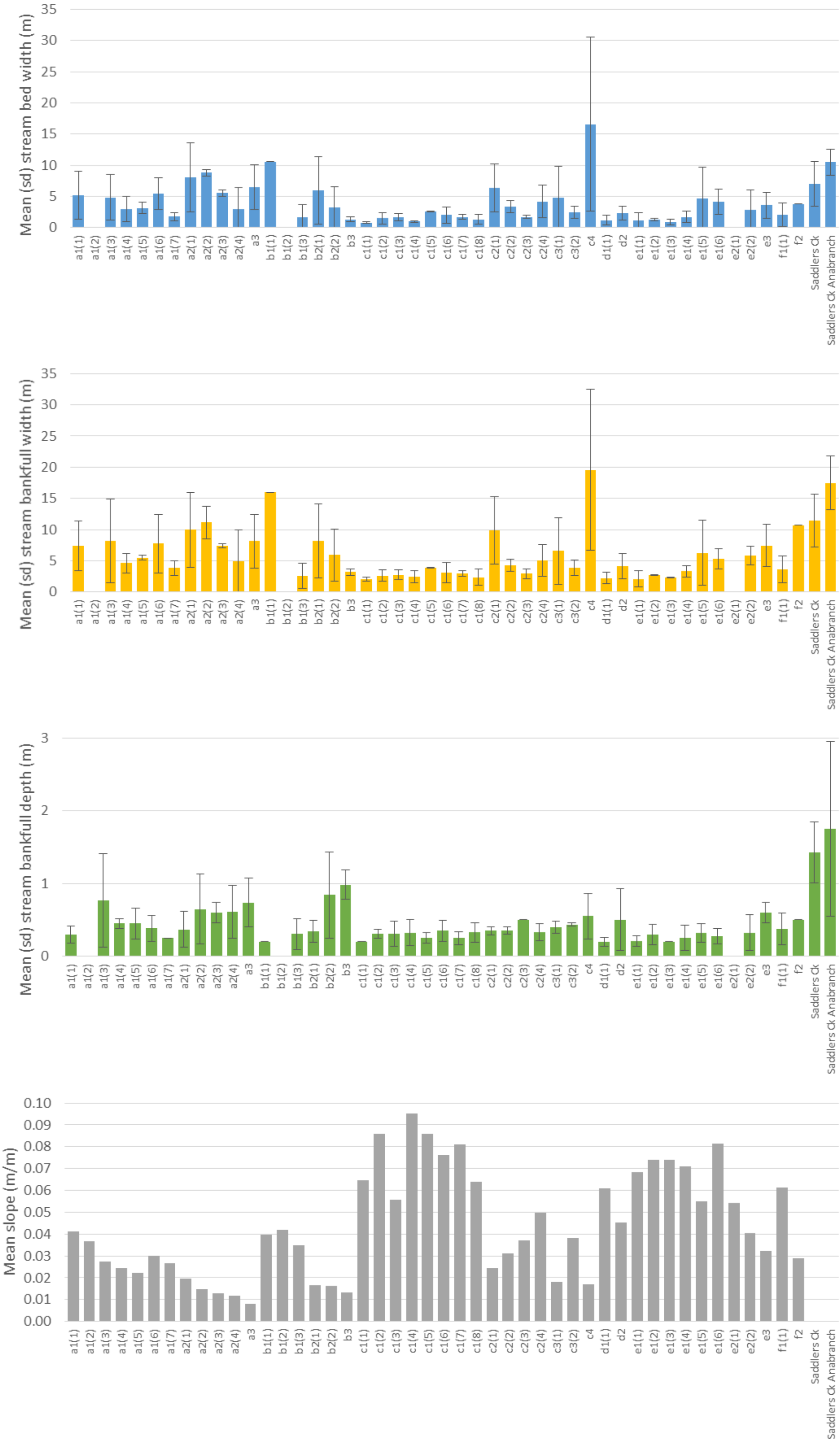

Figure 35. Distribution of morphological attributes of observed streams within the Field Survey Study Area.

3.3.8 Stream geomorphic type

The River Styles® of streams in the Hunter River basin were classified by Cook and Schneider (2006). In the upper catchment areas of the Hunter River basin, which includes the Catchment Study Area, this study was done at a relatively small-scale and, apart from Saddlers Creek, did not include streams from the Field Survey Study Area (Figure 15).

Stream geomorphic type (equivalent to River Styles®) was determined for all streams within the Study Area (Figure 36). This was done by classifying the stream at each location in the order of (i) valley confined, partly confined or unconfined, (ii) channel continuous or discontinuous, (iii) sinuosity low or meandering, (iv) dominant particle size silt/clay, sand, gravel/cobble, boulder/rock, (v) slope low, moderate or high, (vi) energy (stream power) low, moderate or high, and (v) characteristic channel geomorphic units.

Most sites were in a confined valley setting. One exception was the unconfined former course of lower b1(3), marked as a blue line on the 1:25,000 map and digital hydrolines but which had long been diverted eastward by an upstream farm dam. Saddlers Creek and Saddlers Creek anabranch sites were partly-confined. These streams had an associated floodplain, but in the surveyed area the channels abutted the valley wall on the south-eastern bank (i.e. the side closest to the Mining Study area boundary). Thus, the floodplain of Saddlers Creek was mostly to the north and north-west, and did not extend towards the Mining Study Area. Otherwise, streams a3, a2(2), a2(3), a2(4), b3, b2(1), b2(2), c2(1), and c4 flowed within fairly narrowly confined valleys, but they had developed narrow floodplains in the base of the valleys, so were classified partly-confined. Of these, streams a3 and b3 flowed into Saddlers Creek. In the vicinity of their junctions, these streams flowed within alluvial structures that had the planform shape, and downstream slope, characteristic of low-gradient alluvial fans. Lower f2 was a special case of partly-confined that flowed on the Hunter River floodplain.

The channels were all classified continuous, although ill-defined or weakly defined cross-sectional shape was observed at a small number of sites. This was considered a localised, rather than a reach-scale feature, so it did not influence the stream geomorphic type classification. For classification purposes, sinuosity is relevant only to unconfined or partly-confined streams. River Styles® classification separates rivers into low sinuosity and meandering by the threshold of 1.3 for stream length divided by valley length. Using the auto-generated stream lines, streams a3, a2(2), Saddlers Creek and Saddlers Creek Anabranch were meandering. However, the standard practice for River Styles® classification is to define streams using 1:25,000 maps, and by this definition, only streams a3 and Saddlers Creek were meandering (Table 10). Note that the meandering sinuosity of Saddlers Creek means that Cook and Schneider (2006) mis-classified this stream as ‘low sinuosity’ (Figure 15).

Dominant particle size was determined for all surveyed points, with the majority being fine-grained (Figure 26). Sand/gravel/cobble/boulder dominance was found at 3/8 sites on b1(2), 4/7 sites on b1(3), 6/8 sites on b2(2), 4/6 sites on a1(1), 1 site on a2(4), 1/8 on a3, 2/4 sites on c1(2), 3/3 sites on c1(5), 5/8 sites on c1(6), 1/3 on c1(7), 5/7 site on c1(8), 3/3 on c2(2), 1/2 on c2(2), 1/3 site on c2(4), 3/4 sites on c3(1), 4/4 sites on c3(2), and 1/4 site on c4, 1/5 on d1(1). Of these observations, gravel or cobble was dominant at only 10 scattered sites, and boulder was dominant at only 6 scattered sites. Note that the observed fine-grained bed of Saddlers Creek means that Cook and Schneider (2006) mis-classified this stream as ‘gravel’ (Figure 15).

River Styles® uses slope and energy as attributes to discriminate stream type, but does not provide criteria for classifying them as low, moderate or high. The lack of criteria in the literature suggests that in the standard River Styles® methodology, these attributes are subjectively defined, specific to each assessment. If energy is interpreted using channel stream power classes: low <10 W/m^2, medium 10 – 300 W/m^2, and high >300 W/m^2 (Nanson and Croke, 1992), then modelled average stream power data suggests that all streams in the Field Survey Study Area fall into the ‘medium’ energy class. The same problem besets slope as an attribute to discriminate geomorphic type. Applying the standards typically applied in River Styles® assessments, where ‘steep’ is >0.01 m/m, all streams in the Field Survey Study Area were ‘steep’, except a3, which was ‘moderate’. Due to the problem of lack of objective criteria, slope and energy were of marginal value in distinguishing stream types.

Table 10 Sinuosity of partly-confined streams within Field Survey Study Area.

Stream	Sinuosity	
	1:25,000 blue line	Auto-generated 5 m grid
a2(2)	1.13	1.30
a2(3)	1.04	1.18
a2(4)	1.15	1.29
a3	1.34	1.61
b2(1)	1.08	1.24
b2(2)	1.14	1.27
b3	1.07	1.21
c2(1)	1.12	1.17
c4	1.14	1.19
Saddlers Ck (Order 4)	1.99	2.12
Saddlers Ck Anabranch	1.25	1.36

Cook and Schneider (2006) classified upper catchment reaches of tributary streams in Saddlers Creek catchment as *Floodplain pockets, gravel*. Streams fitting the description of *Floodplain pockets* were observed among the streams surveyed for this Report, but they had fine-grained beds, so a new type termed *Floodplain pockets, fine-grained* was applied.

Cook and Schneider (2006) classified the lower catchment reaches of tributary streams in Saddlers Creek catchment as *Cut and fill*. This type belongs to discontinuous streams, which were not observed among the streams surveyed for this Report, but streams in catchment C otherwise fitted this description, so were interpreted as the incised phase of *Cut and fill* type.

In this Report, the upper confined reaches of tributary streams were classified as *Headwater*. The lower partly-confined reaches were classified as either; (i) *Planform controlled, low sinuosity, fine-grained*, or (ii) *Planform controlled, low sinuosity, coarse-grained*, or (iii) (in the case of a3), *Planform controlled, meandering, fine-grained*.

Cook and Schneider (2006) mis-classified Saddlers Creek as *Planform controlled, low sinuosity, gravel*. It was neither low sinuosity, nor gravel. In this Report, Saddlers Creek was classified *Planform controlled, meandering, fine-grained*. Saddlers Creek Anabranch is a reach of Saddlers Creek that has been diverted by an upstream dam. The low flow now flows to the north of the Anabranch, but a deep channel has yet to form here. The Anabranch would still transfer floodwaters. The Anabranch was classified *Planform controlled, low sinuosity, fine-grained*. One First Order stream was classified as artificial type *Contour drain*, as the original stream course was diverted by a contour drain.

3.3.9 Stream geomorphic condition

The geomorphic condition and recovery potential of river reaches in the Hunter River basin were assessed by Cook and Schneider (2006). Their mapping included some streams in the Saddlers Creek catchment, but not the tributaries under consideration in the Mining Study Area (Figure 3). The geomorphic condition of the streams in the vicinity of the Field Survey Study Area, including Saddlers Creek, was rated by Cook and Schneider (2006, p. 48) as “poor” in most cases (Figure 16).

The streams surveyed for this Report were rated “poor” geomorphic condition, mainly because of poor riparian tree cover, ubiquitous knickpoints, and as a result, either incision or excess sediment on the bed. Saddlers Creek did not have knickpoints, and it had tree cover on one side, so it was rated moderate condition.

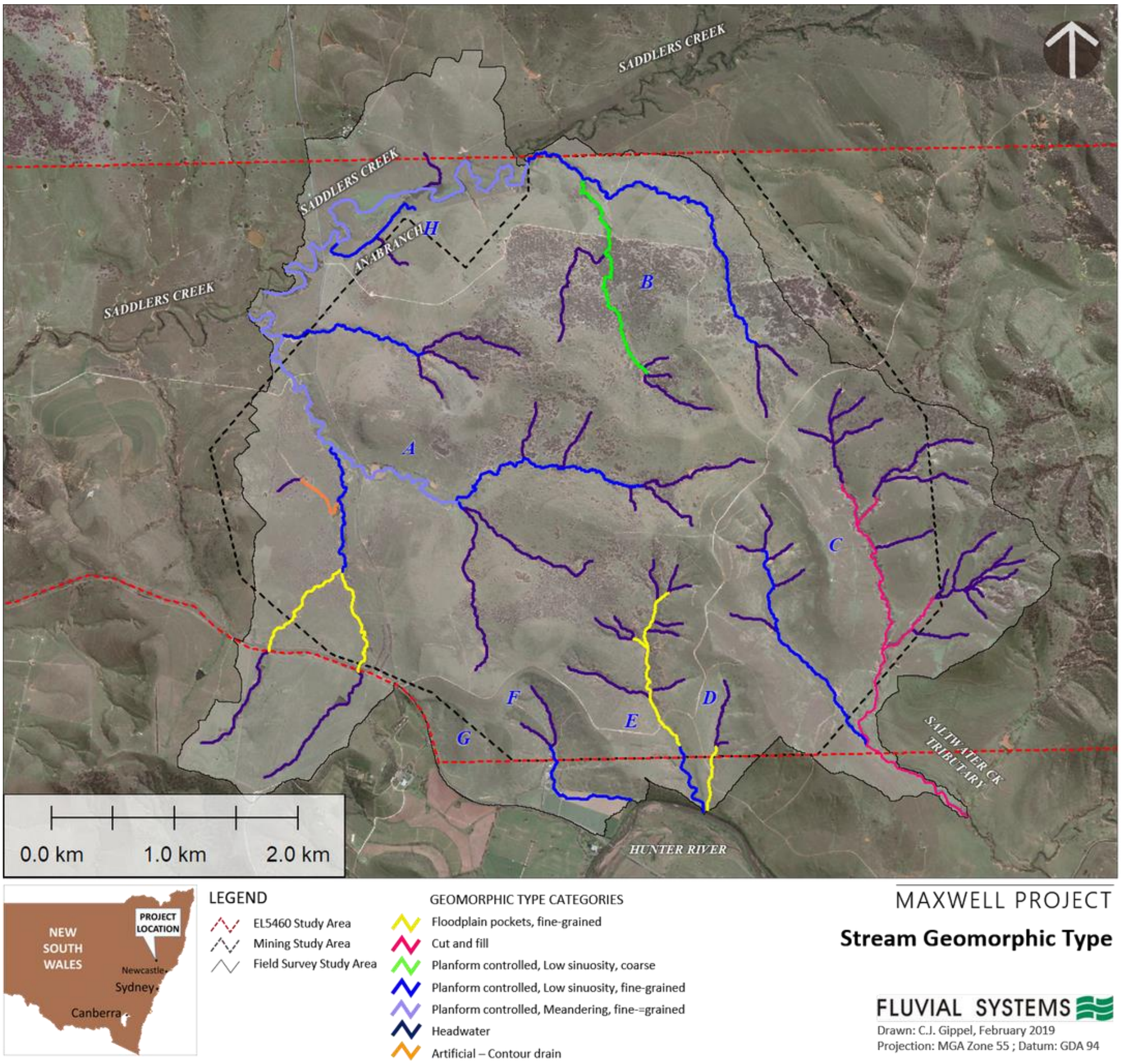

Figure 36. Auto-generated emulation of the mapped blue line stream network (1:25,000 topographic sheet) classified by geomorphic stream type.

3.4 Boundaries of Alluvium

3.4.1 Published maps of alluvium units

The boundaries of the four versions of mapped alluvium units in the region of the Study Areas do not coincide (Figure 37). This is not unique to the Study Areas; the mapping of alluvium is inconsistent across the Upper Hunter region. The Soil Landscapes of Central and Eastern NSW is mapped at the coarsest scale of 1:250,000, with some of the boundaries extending significant distances into surrounding hillslope areas. This map does not indicate the presence of alluvium in the lower valleys of Saddlers and Saltwater creeks.

The boundary of Quaternary alluvium mapped on the Hunter Coalfield Regional Geology 1:100,000 geological map extends into surrounding hillslopes in places (Figure 37). This map suggests an extensive presence of alluvium in the lower and middle valleys of Saddlers and Saltwater creeks.

The Soil and Land Resources of the Hunter Region map has more carefully drawn alluvium boundaries that follow the margins of low-slope land bordering rivers and creeks. On the Hunter River downstream of the Goulburn River, the Soil and Land Resources of the Hunter Region map indicates generally narrower alluvium extent than the Hunter Coalfield Regional Geology map. The extent of alluvium mapped in Saddlers Creek, and particularly, Saltwater Creek, is much smaller on the Soil and Land Resources of the Hunter Region map compared to the Hunter Coalfield Regional Geology map (Figure 37).

The fourth published version of alluvium extent is provided by the Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources (WSP) (Department of Water and Energy, 2009) map of Hunter River Alluvium. This map indicates alluvium extending into Saddlers Creek, but the edges do not follow the topography of the floodplain. This is also true for the bend of the Hunter River near the boundary of EL5460, where the boundary extends up the adjacent valley wall, reaching elevations 30 – 60 m higher than the floodplain (Figure 37).

The four published maps of alluvium have inconsistencies and apparent inaccuracies in their boundaries. The Soil Landscapes of Central and Eastern NSW and WSP maps appear to be the least accurate of the four maps and do not provide a sound basis for establishing development buffers. The Soil and Land Resources of the Hunter Region map appears to be the most accurate of the four maps with respect to correspondence of alluvium with river and creek channels and associated low-slope floodplain landforms. The Hunter Coalfield Regional Geology map has some isolated alluvium boundaries that are clearly inaccurate, but the much greater extent of alluvium mapped in Saddlers and Saltwater creeks compared to the Soil and Land Resources of the Hunter Region map is equivocal, and requires further investigation.

3.4.2 AgTEM geophysical survey of Study Area (2018)

Allen (2018) undertook an Electrical Resistivity Tomographic Imaging survey using Agricultural Transient Electromagnetic System (AgTEM) of parts of the Study Areas near Saddlers Creek and the Hunter River. As expected, this survey identified alluvium on the Hunter River floodplain, the boundary of which coincided with mapped alluvium boundaries (Figure 37) (with the exception of the inaccurate WSP map). Adjacent to Saddlers Creek, Allen (2018) described the zone that exists above weathered rock 'ambiguous', being either weathered rock (eluvium or colluvium) or alluvium, and drew some suggested boundaries (Figure 37).

Allen (2018) differentiated between 'unconsolidated' alluvium, a permeable deposit of sand and gravel that could contain exploitable groundwater resource, and 'consolidated' alluvium, a deposit of silt and clay with low permeability, and little prospect for containing extractable groundwater. The AgTEM methodology distinguishes these materials through their contrasting electrical resistivity. Aquifers in unconsolidated alluvium have high resistivity, while clay material is electrically conductive. The unconsolidated alluvium boundaries drawn by Allen (2018) on Saddlers Creek do not match any of the published maps of alluvium (Figure 37), nor do they follow the surface topography. This result is not a contradiction, because, with the possible exception of the Hunter Unregulated and Alluvial Water Sources, the maps depict extent of all alluvial soil (i.e. floodplains), whether clay or gravel, not limited to coarse-grained sub-surface material that might contain alluvial aquifers.

3.4.3 Borehole drilling (2018)

On 24th and 25th of September 2018, ENRS (2018) supervised test drilling at 11 sites across 3 transects to investigate the extent and nature of unconsolidated alluvial and colluvial deposits adjacent to the Maxwell Project. The northern transect extended from Saddlers Creek about 300 m southwards along the western side of tributary b3 (Figure 37). The western transect extended from Saddlers Creek about 800 m southwards along the western side of tributary a3 (Figure 37). The southern transect was on the Hunter River floodplain (Figure 37). The results were consistent with the results of the AgTEM survey. ENRS (2018) found clay in the upper layer of all drill holes on the northern and western transects. The clay was of variable thickness but at least 1 m thick and up to 5 m thick closer to Saddlers Creek. ENRS (2018) did not refer to clay as alluvium, even if it was on a floodplain unit, because their main interest was unconsolidated coarser sand and gravel alluvial material that was associated with groundwater. Groundwater was encountered at a depth of 8 m at the bores closest to Saddlers Creek at both the northern and western transects.

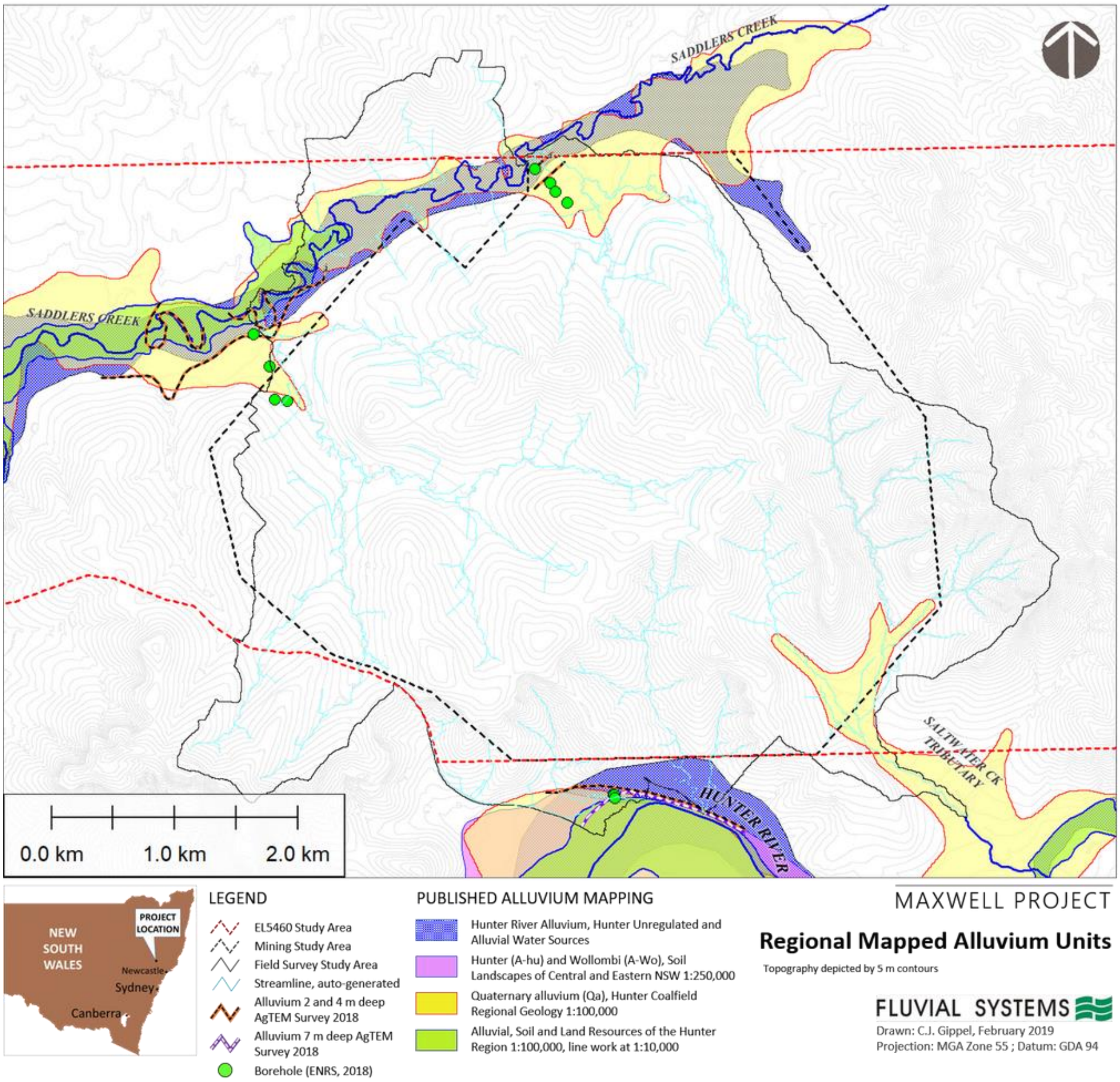

Figure 37. Four versions of mapped alluvium units in the region centred on the Field Survey Study Area. Also shown are boundaries of unconsolidated alluvium determined by AgTEM survey in 2018, and locations of boreholes drilled by ENRS (2018).

3.4.4 Topographic floodplain indices

Slope less than 2% was computed on both 25 m and 5 m grids, with the 25 m grid producing polygons of low slope that were more contiguous, which was a more realistic representation of the broad shape of the floodplain landform. Discounting small areas of flat land on ridge crests and hilltops and artificial landforms in mined areas, the distribution of land less than 2% was similar to that mapped as alluvium by the Soil and Land Resources of the Hunter Region (Figure 38). However, land less than 2% suggested a greater extent of floodplain land in the lower valleys of Saddlers and Saltwater creeks.

Slope aspect was highly variable over the Hunter River floodplain, although aspect was generally in the downstream direction (Figure 38). Some areas of low slope land outside the boundary of the alluvium mapped by the Soil and Land Resources of the Hunter Region had aspect approximately orthogonal to the downstream aspect of the river, suggesting it belonged to the base of surrounding hillslopes rather than the floodplain landform (Figure 38).

The original TWI and SAGA TWI were computed on both 25 m and 5 m grids. The original TWI had limited capacity to identify large floodplain landforms, with the index values attributed to narrow drainage lines on low order streams similar to those attributed to broad-scale lowland floodplain areas. The SAGA TWI was better able to discriminate floodplain landforms from upslope drainage lines, even though both are wet zones. The literature lacks guidance on a threshold value of the SAGA TWI index that discriminates floodplain landforms from hillslopes and small drainage lines, so the index was visually calibrated to the distribution of land with slope <2%. The calibration suggested a threshold value of 7.4 for the index computed on the 25 m grid, and 6.2 computed on the 5 m grid. These thresholds gave approximate equivalence in the spatial distributions of the index values computed on the two DEMs, but as expected, the 5 m grid produced a more variable and more discontinuous distribution of SAGA TWI values (Figure 39).

The more accurate resolution of the SAGA TWI map based on the 5 m grid gave it an advantage over that based on the 25 m grid for the purpose of defining boundaries, but the disadvantage of the 5 m resolution map was the unrealistically discontinuous nature of the identified potential floodplain land. The SAGA TWI included some narrow drainage areas extending into small sub-catchments upslope from the main floodplains (Figure 39). These are hydrologically wet zones, and might contain narrow strips or pockets of alluvium, but would be too steep to be regarded as floodplain landforms by most geomorphic definitions.

MrVBF was computed on both 25 m (Figure 40) and 5 m (Figure 41) grids. When computing MrVBF on the 5 m grid, the appropriate adjustment was made to the initial slope threshold and an offset was applied to the calculated values. It was found that to achieve approximate 25 m grid calculation equivalence for the 5 m grid, an offset of -1.75 was required (rather than the expected offset of -1.46). The upper limit of MrVBF values normally used to identify floodplains or alluvium is 3. In the Field Survey Study Area, a threshold lower than 3 identified narrow, continuous floodplains extending significant distances into small steep valleys, when field observations and LiDAR elevation data suggested that these valleys had either no floodplains or only small isolated pockets. On the other hand, a threshold larger than 3 resulted in underestimation of the lateral extent of the Hunter River floodplain. Thus, a MrVBF value of >3 was used to identify floodplain landforms.

The spatial pattern of MrVBF > 3 computed for the 5 m grid was similar to that computed for the 25 m grid (Figure 40, Figure 41). The main differences were variable minor discrepancies along boundaries. The more accurate resolution of the map based on the 5 m grid gave it an advantage over that based on the 25 m grid for the purpose of defining boundaries, so the 5 m grid map was preferred. Compared to the alluvium mapped by Soil and Land Resources of the Hunter Region (Figure 40), MrVBF predicted a greater extent of floodplain in the lower valleys of Saddlers and Saltwater creeks, and a slightly narrower extent of floodplain on the Hunter River floodplain.

Profile curvature identified the convex and concave edges of landforms (Figure 42). Where landform convexity was sufficiently strong, the edges of the floodplains and channels were identified from the curvature data. The floodplain edge data was used to complement the MrVBF floodplain extent data (Figure 43).

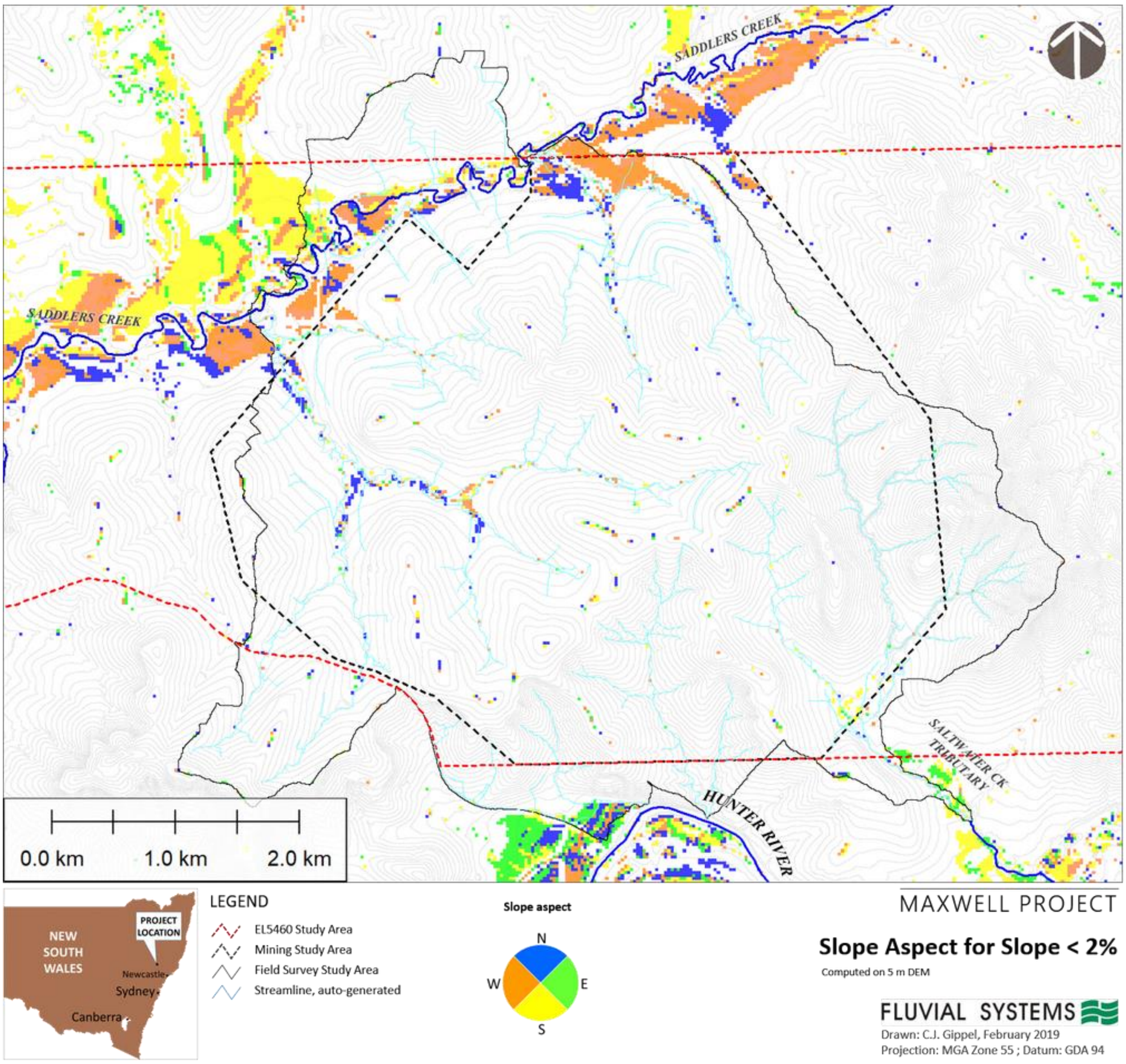

Figure 38. Slope aspect for land less than 2%, computed over the region centred on the Field Survey Study Area.

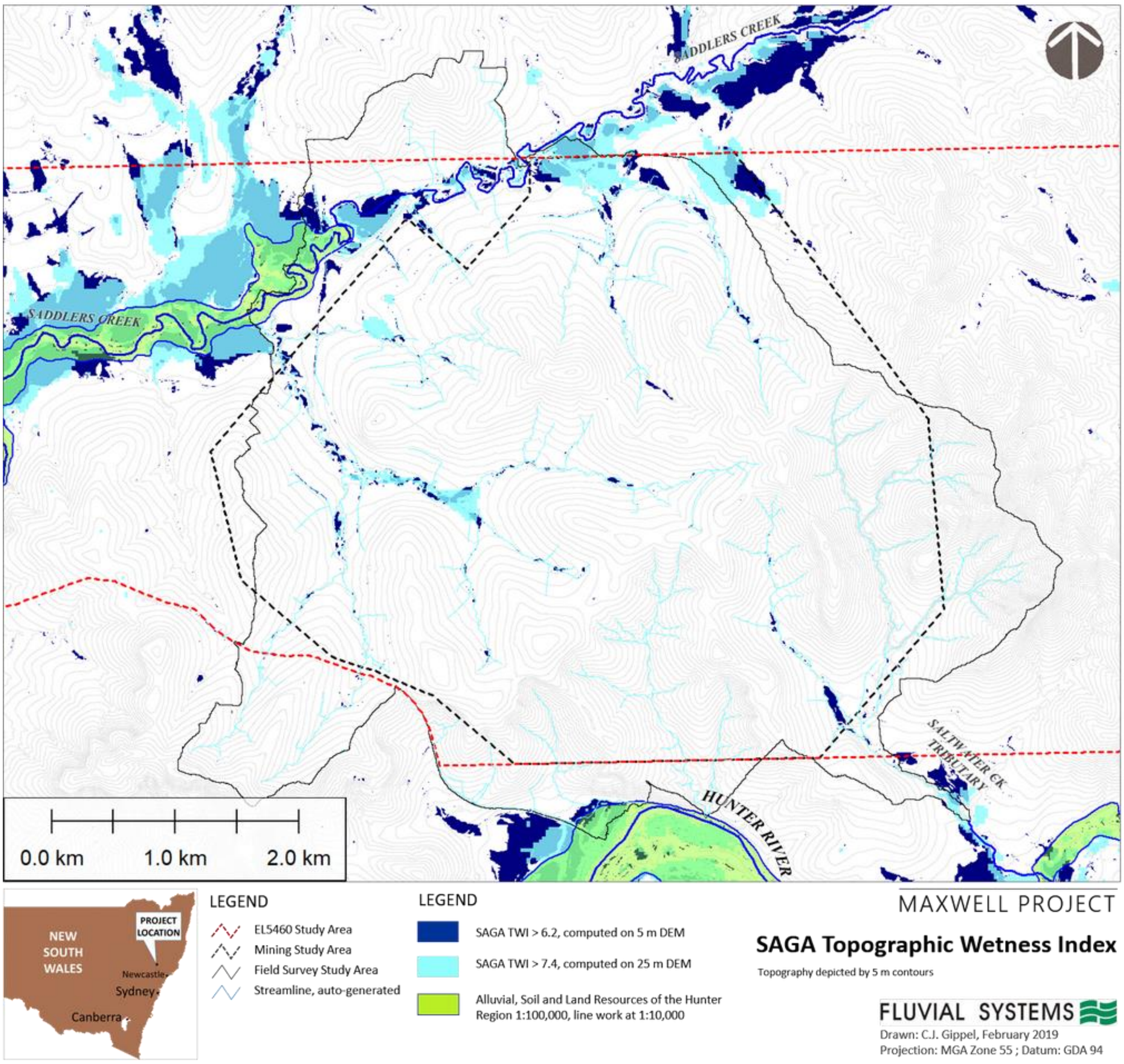

Figure 39. SAGA TWI topographic index computed over the region centred on the Field Survey Study Area.

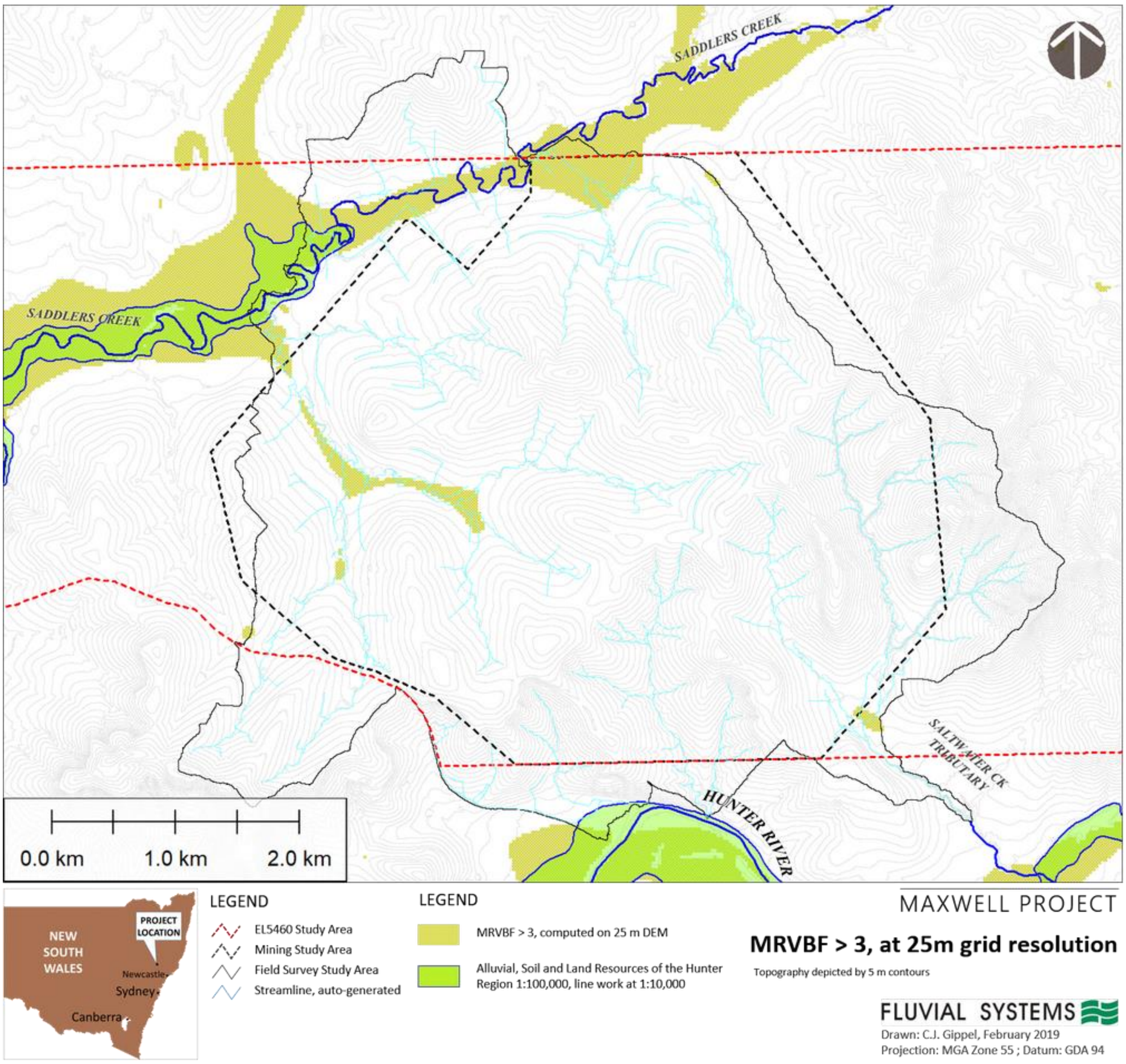

Figure 40. MrVBF topographic index computed on 25 m grid over the region centred on the Field Survey Study Area.

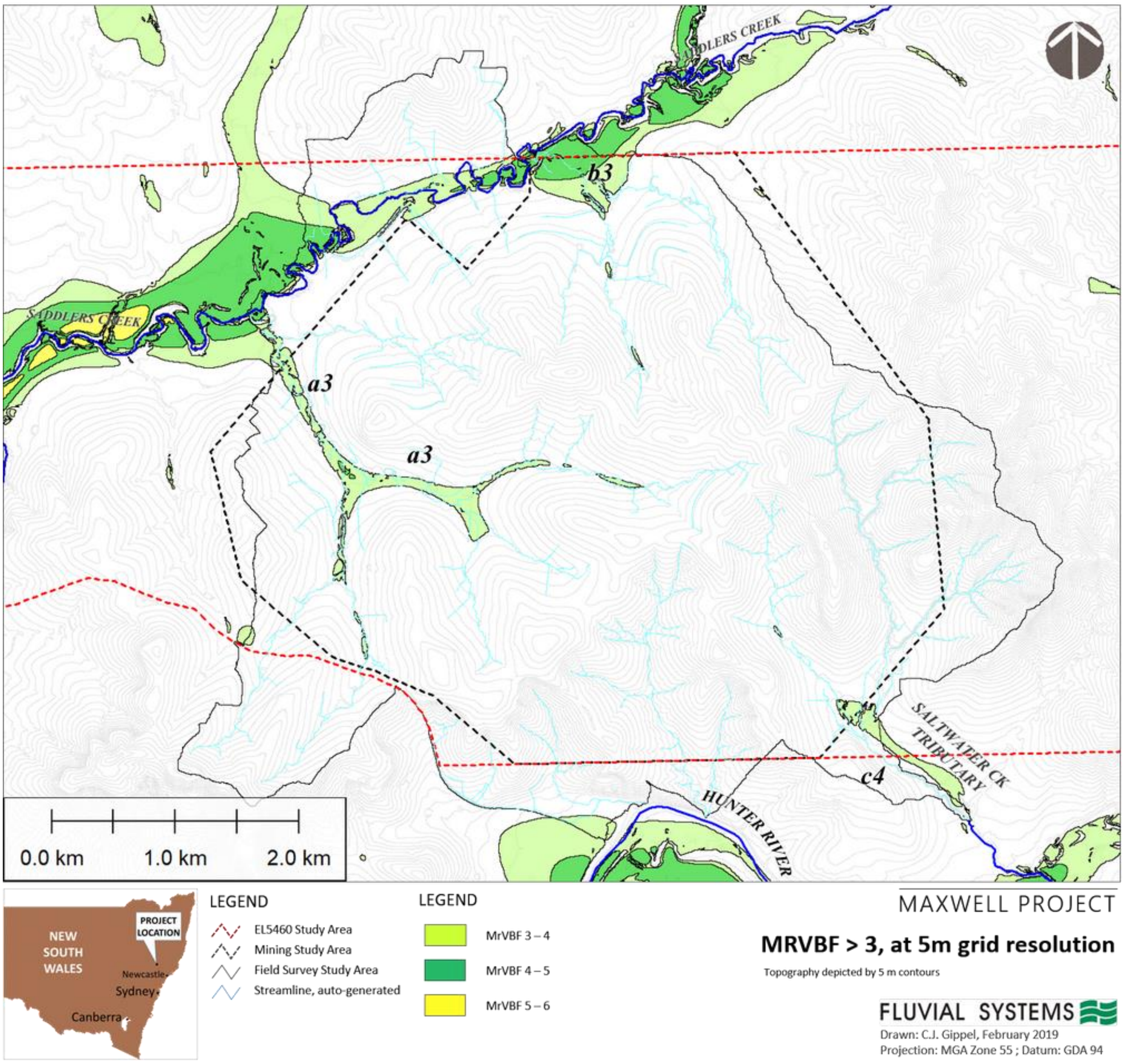

Figure 41. MrVBF topographic index computed on 5 m grid over the region centred on the Field Survey Study Area.

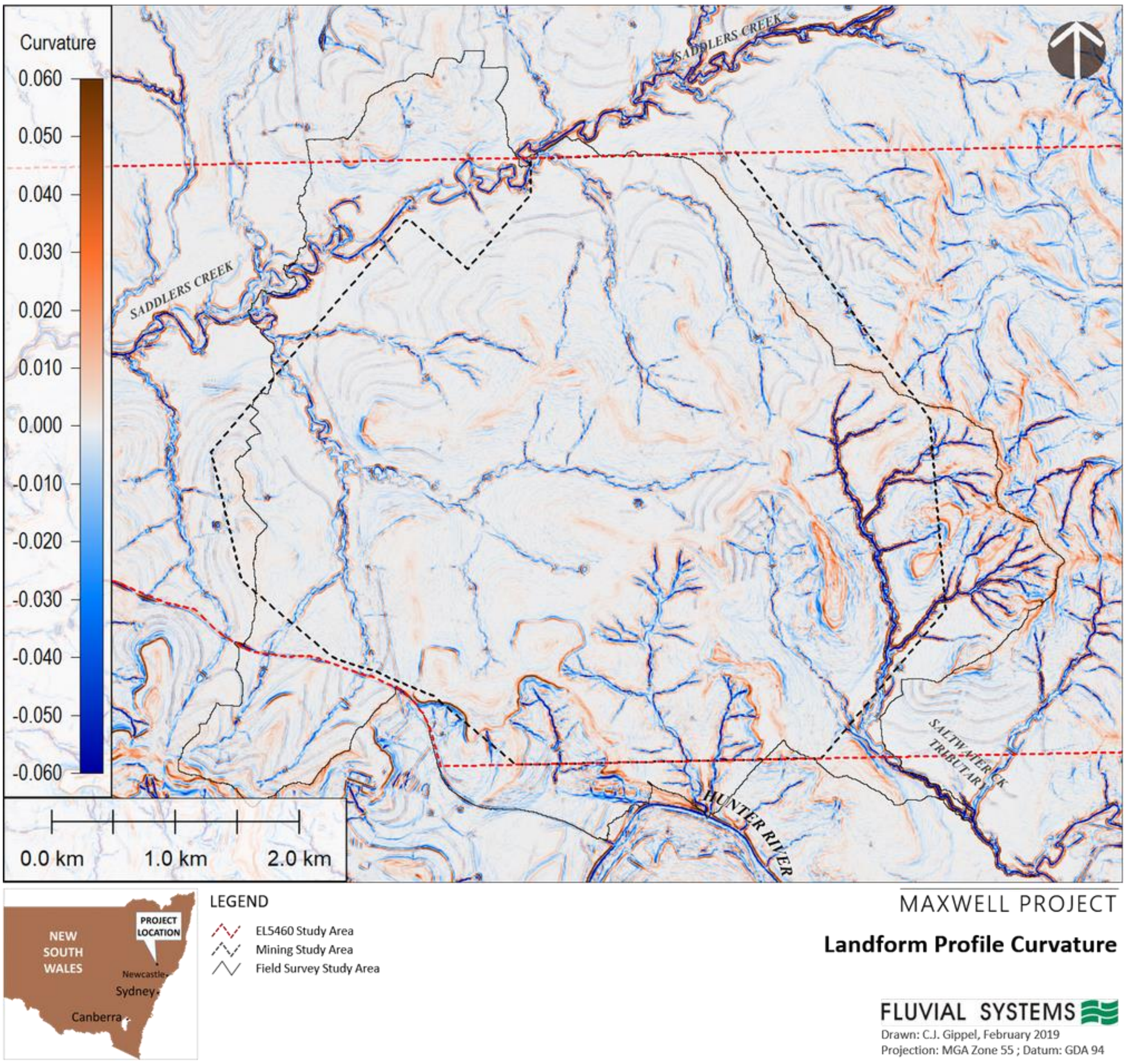

Figure 42. Landform profile curvature computed on 5 m grid over the region centred on the Field Survey Study Area.

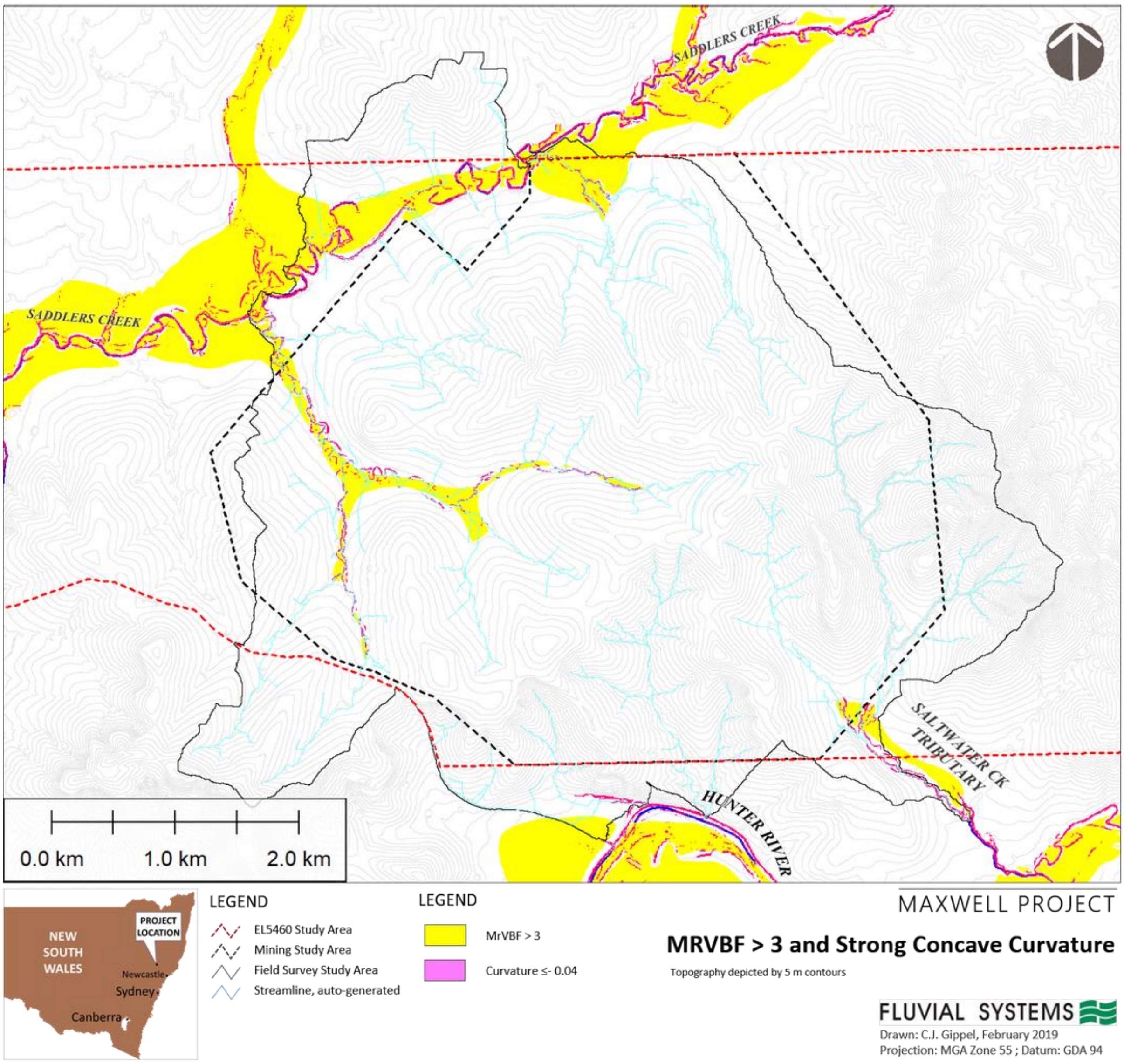

Figure 43. MrVBF floodplain index and profile curvature index of channel bank toe and floodplain edge, computed on 5 m grid over the region centred on the Field Survey Study Area.

3.4.5 Floodplain and alluvium delineation in the Field Survey Study Area

Four published maps that cover the Study Areas include alluvium boundaries, but none of them provide an ideal basis for determining mining development buffers. An alternative is to adopt a floodplain morphology boundary objectively determined by a topographic index.

Five topographic indices were computed, slope <2%, aspect of slope <2%, SAGA TWI >6.2 (for 5 m grid resolution), MrVBF >3 and landform profile curvature. Slope is an input to the other four indices, and slope aspect is useful for partitioning alluvium boundaries at tributary junctions and separating colluvial hillslopes from alluvial floodplains. SAGA TWI was originally intended as a hydrological index, while MrVBF was originally intended as a landform-shape index. MrVBF computed from the 5 m grid was preferred over that computed from the 25 m grid, as it provided higher resolution boundaries. In the Field Survey Study Area, the spatial distributions of areas of slope <2% and SAGA TWI >6.2 were less contiguous than the area defined by MrVBF >3, but the spatial extents of these three indices were remarkably similar. Thus, MrVBF >3 (5 m grid resolution) was considered the primary index of floodplain extent, but it was consistent with SAGA TWI and slope <2%.

In the Field Survey Study Area, MrVBF ranged from 3 to 6 (Figure 41), with higher values theoretically indicating thicker and wider alluvium extent (Table 6). When MrVBF was computed on a 5 m grid, channels wider than about 5 m were not classified as floodplain. For the purpose of establishing buffers from mining developments, channels should be considered part of the floodplain unit. This was achieved by incorporating floodplain areas defined by MrVBF with floodplain edges defined by profile curvature (Figure 44).

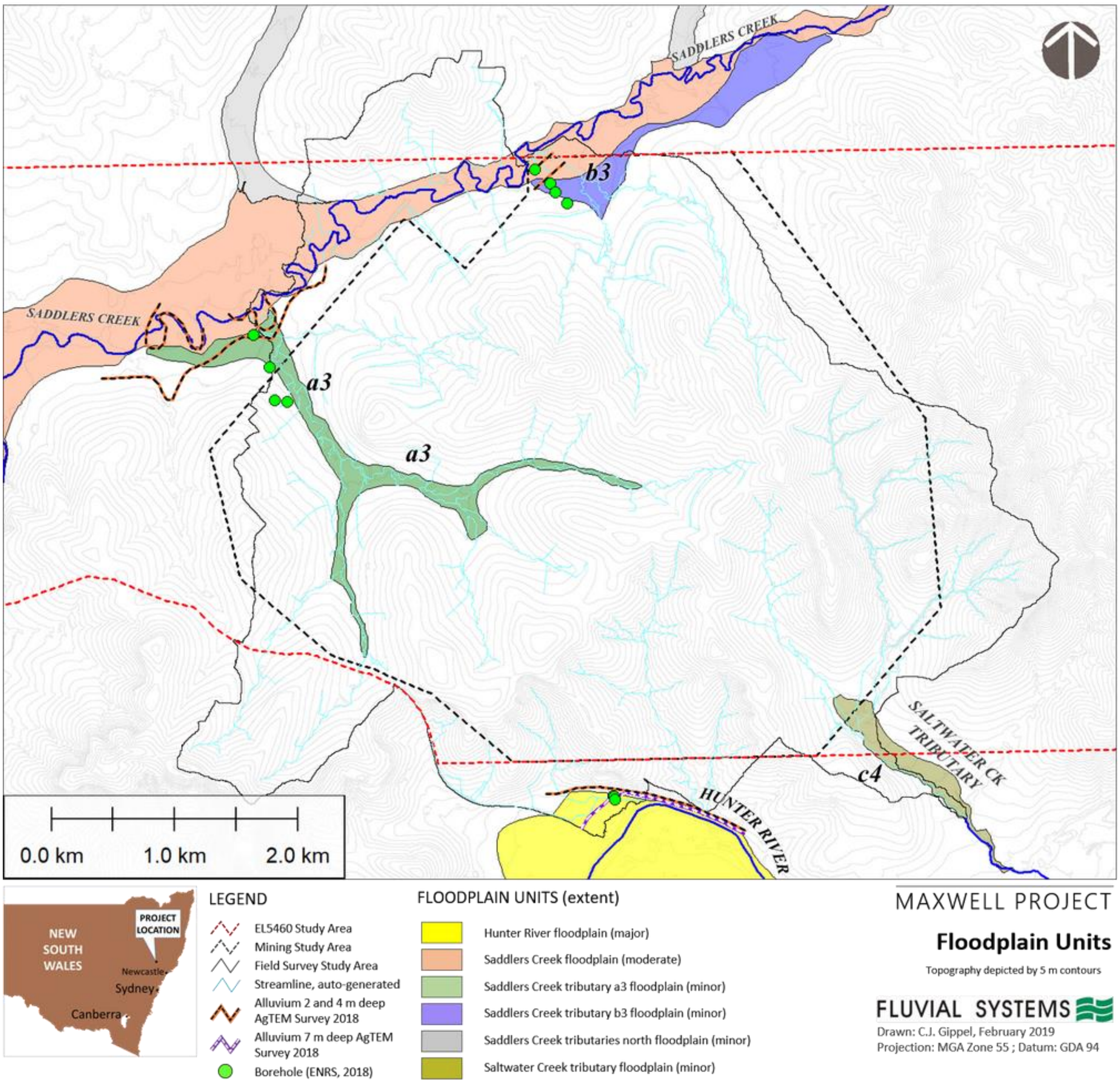

Figure 44. Floodplain units defined by merging MrVBF floodplain index and profile curvature index. The boundaries of the identified floodplain units are compared with the boundaries of unconsolidated alluvium determined by AgTEM survey in 2018, and locations of boreholes drilled by ENRS (2018).

Four main floodplain units were identified in proximity to EL5460 (Figure 41):

- Hunter River (major extent)
- Saddlers Creek (moderate extent)
- Saddlers Creek southern tributaries (a3 and b3) (minor extent)
- Saddlers Creek northern tributaries (minor extent, and distant from Mining Study Area)
- Saltwater Creek tributary (c4) (minor extent)

The Hunter River alluvium is a massive unit known to contain a significant aquifer. Near the Study Areas, the broad and flat floodplain abuts a steep valley wall. The position of this sharp surface morphological boundary was consistently defined by a range of different methods.

The geomorphological field survey was undertaken during a protracted drought, and although Saddlers Creek was not flowing, it contained some free water in shallow pools, and the bed was marshy and covered by emergent macrophytes in most places. Although Cook and Schneider (2006) classified Saddlers Creek as *Planform controlled, low sinuosity, gravel bed* (Figure 15), gravel was not observed in the bed during the field survey. This is consistent with the AgTEM geophysical survey of Allen (2018) and the drill holes of ENRS (2018), who found little evidence for extensive unconsolidated coarse alluvium with potential for containing aquifers. Thus, while Saddlers Creek has a floodplain, it appears to be composed primarily of fine-grained material and is unlikely to contain a significant exploitable groundwater resource. Also, in the vicinity of the Mining Study Area, the majority of Saddlers Creek floodplain is on the right, or northern, side of the creek. Thus, in most places the creek itself is the floodplain boundary adjacent to the Mining Study Area.

The floodplain units identified on the tributaries of Saddlers and Saltwater Creek were narrow and shallow clayey units, dry at the time of the field survey. They are likely to intermittently store water only during, and for a limited period after, significant rainfall events. Thus, they are unlikely to contain a significant exploitable groundwater resource.

4.0 Impact assessment

4.1 Potential subsidence impact on hillslope erosion risk

Hillslope erosion is relevant to this fluvial geomorphological assessment because much of the bed material in stream channels is derived from hillslopes. The yield of sediment from hillslopes is often estimated using the empirical RUSLE (Revised Universal Soil Loss Equation), which predicts the long term, average, annual soil loss from sheet and rill flow at nominated sites under specified management conditions. The variables (called factors) in the RUSLE include rainfall erosivity, soil erodibility, slope length/gradient, erosion control practice, and ground cover and management. Of these, the only factor to change under a mining subsidence (impacted) scenario would be slope length/gradient. In the RUSLE, the slope length/gradient factor is an empirically derived value selected from a lookup table of slope versus slope length. A similar, but perhaps superior, measure of this component of erosion risk is Hillslope Stream Power Index, which was assessed for the Field Survey Study Area under the existing case (Figure 11) and the impacted case (Figure 45).

Subsidence impact on hillslope erosion risk was semi-quantitatively assessed by subtracting the hillslope SPI calculated for the impacted case from that calculated for the existing case (Figure 46). The differences were mostly in the range -1.5 to 1.5. Although this represents a relatively small proportion of the range of absolute SPI values, which reached a maximum of 33, most SPI values for the existing and impacted cases were within the range 0 – 10. Thus, the impact represented about -15% to 15% change in SPI. If all other factors remain constant, this degree of change is likely to alter sediment yield from hillslopes, increasing it in some places, and decreasing it in others. Increasing risk of soil loss due to increased hillslope stream power could be offset by improving ground vegetation cover.

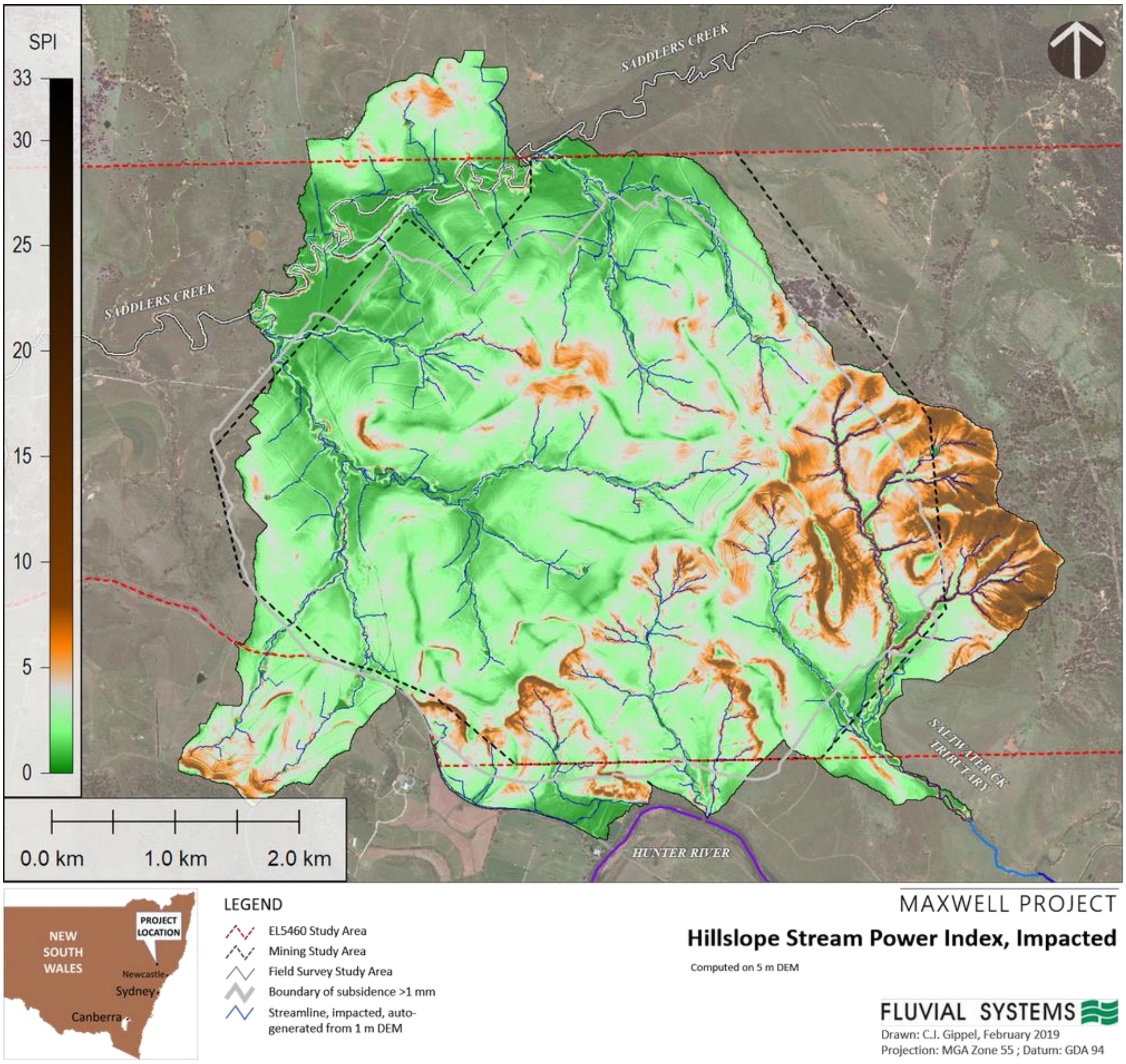

Figure 45. Distribution of hillslope Stream Power Index (SPI) calculated over the Field Survey Study Area for the impacted case.

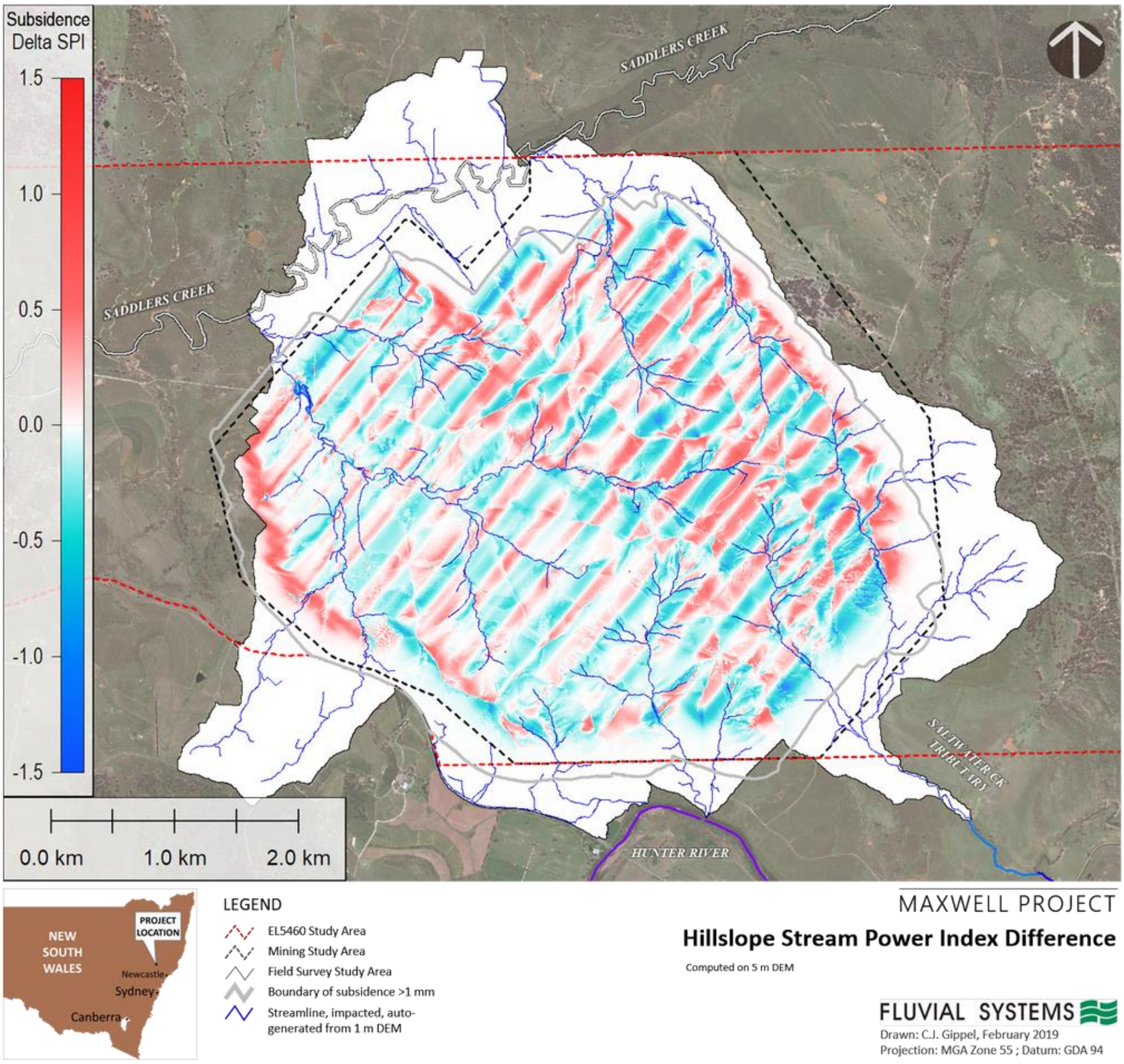

Figure 46. Hillslope Stream Power Index difference (ΔSPI) between existing and impacted cases, calculated over the Field Survey Study Area.

4.2 Potential subsidence impact on drainage

Potential subsidence movements at the surface have been estimated by MSEC (2019) using a method called the Incremental Profile Method. The Incremental Profile Method used to estimate subsidence movements for the Project was calibrated using monitoring data from elsewhere in the Hunter Coalfield and multi-seam monitoring data from the NSW coalfields (MSEC, 2019). The Incremental Profile Method has been found, in most cases, to give reasonable, if not, slightly conservative predictions of the *maximum* subsidence, tilt and curvature that would occur due to a longwall; whereas, the prediction of the conventional subsidence parameters at specific points is more difficult than the prediction of the maxima anywhere above extracted longwalls (MSEC, 2019). Variations between predicted and observed parameters at a point can occur where there is a lateral shift between the predicted and observed subsidence profiles, which can result from seam dip or variations in topography (MSEC, 2019).

Of most geomorphic interest is changes to drainage lines, where flowing water has the capacity to effect secondary changes to the landform. The changes to drainage lines could involve changes in:

- Alignment

- Slope
- Stream power
- Depressions on drainage lines

A change in alignment could come about from alteration of the catchment area of a stream, or an area of lower elevation forming adjacent to the existing channel. Directing concentrated flow to a new location could result in erosion of a new channel onto the land surface. Potential for erosion would occur if the shear stress was sufficient to overcome the critical shear stress of the land surface (related to the cohesiveness of the soil or sediment, and the resistance of the vegetative cover). Redirection of runoff along a new path would normally involve the new path linking up with an existing stream channel. The receiving stream could become wider, deeper, and/or steeper to accommodate the additional flow.

A change in local slope could trigger a knickpoint due to locally increased shear stress (product of slope and depth of flow). A change in local stream power (product of slope and discharge) could also trigger a knickpoint due to locally increased shear stress. Given that stream power is a function of slope, the geomorphic risk of change in slope is integrated in the risk associated with change in stream power.

The potential impact of subsidence on drainage alignment and stream power distribution was assessed using the unedited automatically-generated stream network. This drainage network was used because it could be objectively derived using GIS algorithms on different DEMs, representing the existing and impacted cases. While the auto-generated networks have some additional smaller streamlines present compared with the 1:25,000 blue line (hydroline) stream network, they all represent significant runoff paths, some of which may manifest as depressions rather than channels.

The potential impact of subsidence on depressions on drainage lines was assessed by modelling the distribution of depressions on drainage lines of the subsided DEM using the same method applied to the existing DEM, and then subtracting the depressions for the two cases to reveal areas where the depressions had become deeper.

Potential subsidence impacts on the stream geomorphic attributes measured in the Field Survey Study Area are difficult to predict at a fine degree of resolution. The work completed as part of this report provides an assessment of the range of likely outcomes at a broad scale, which allows for an appropriate monitoring and management system to be developed.

4.2.1 Drainage network stream alignment

Automatic generation of drainage networks is dependent on the resolution of the DEM used. This scale effect was assessed by deriving drainage networks for the existing and impacted cases using both the 1 m and 5 m grids. For 30 selected streams forming the main drainage lines, the 1 m DEM generated 24 streams that were on average 14% longer than those of the 5 m DEM (Figure 47). The other 6 streams were on average 4% shorter.

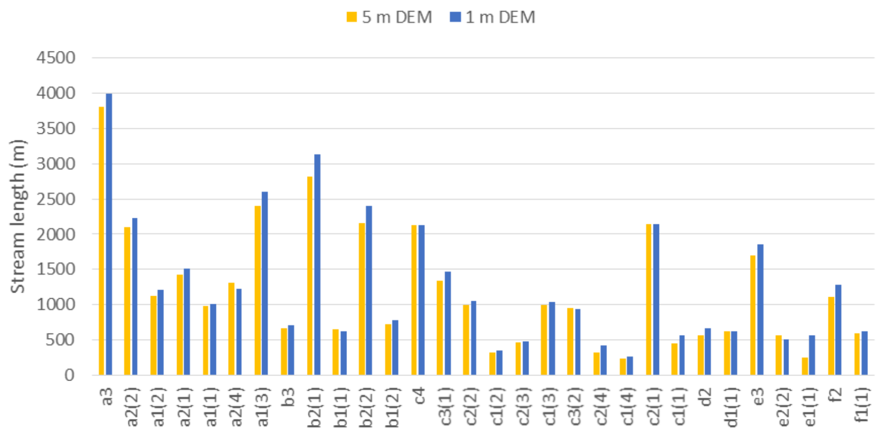

Figure 47. Length of main streams on automatically-generated drainage networks for the existing case, comparing 1 m and 5 m DEMs.

Comparing the predicted drainage networks for the existing and impacted case suggest that subsidence could lead to alteration of drainage alignments (Figure 48 and Figure 49). As expected, the 1 m and 5 m grids produced different results in detail, but the overall pattern of impact was similar for the two scales. The 1 m grid generated more streamlines than the 5 m grid, with most of the additional streamlines being contour drains. The most significant difference between the two grid resolutions was in lower catchment B. In their lower reaches, Second Order ephemeral streams b2(1) and b2(2) are narrowly separated by a low divide. The 1 m grid predicted that these two streams would retain their existing alignments, while the 5 m grid predicted that b2(2) would cut through the divide and join b2(1) higher in the catchment. This indicates that there is a reasonable likelihood that b2(1) will pirate the catchment of b2(2) in its lower reaches (Figure 49). The potential for changed stream alignment in this location is further discussed later in this Report in connection with formation of depressions on drainage lines (see later Section 4.2.4).

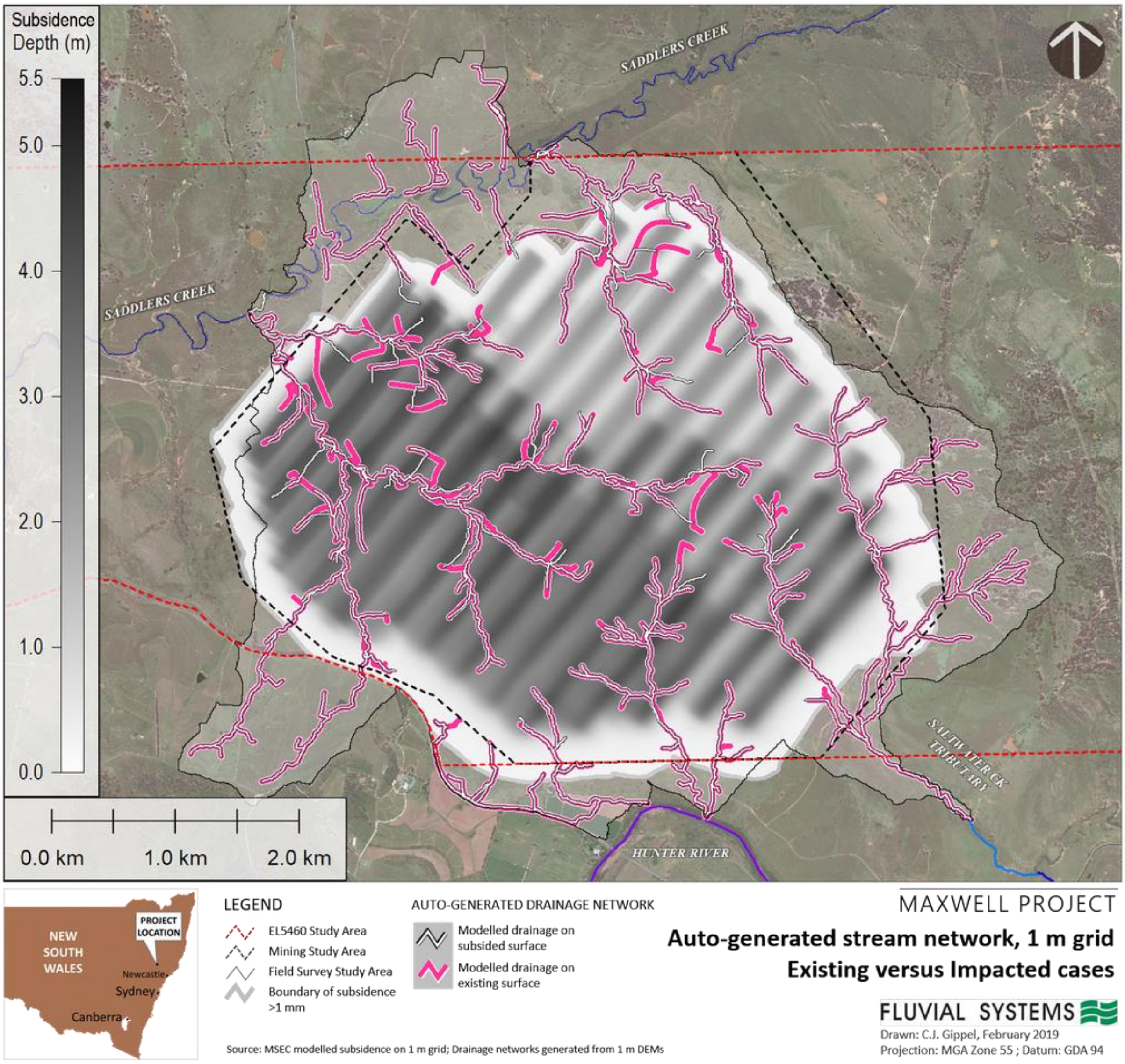

Figure 48. Automatically-generated drainage networks for existing and impacted cases, assuming no mitigation actions, for 1 m DEM.

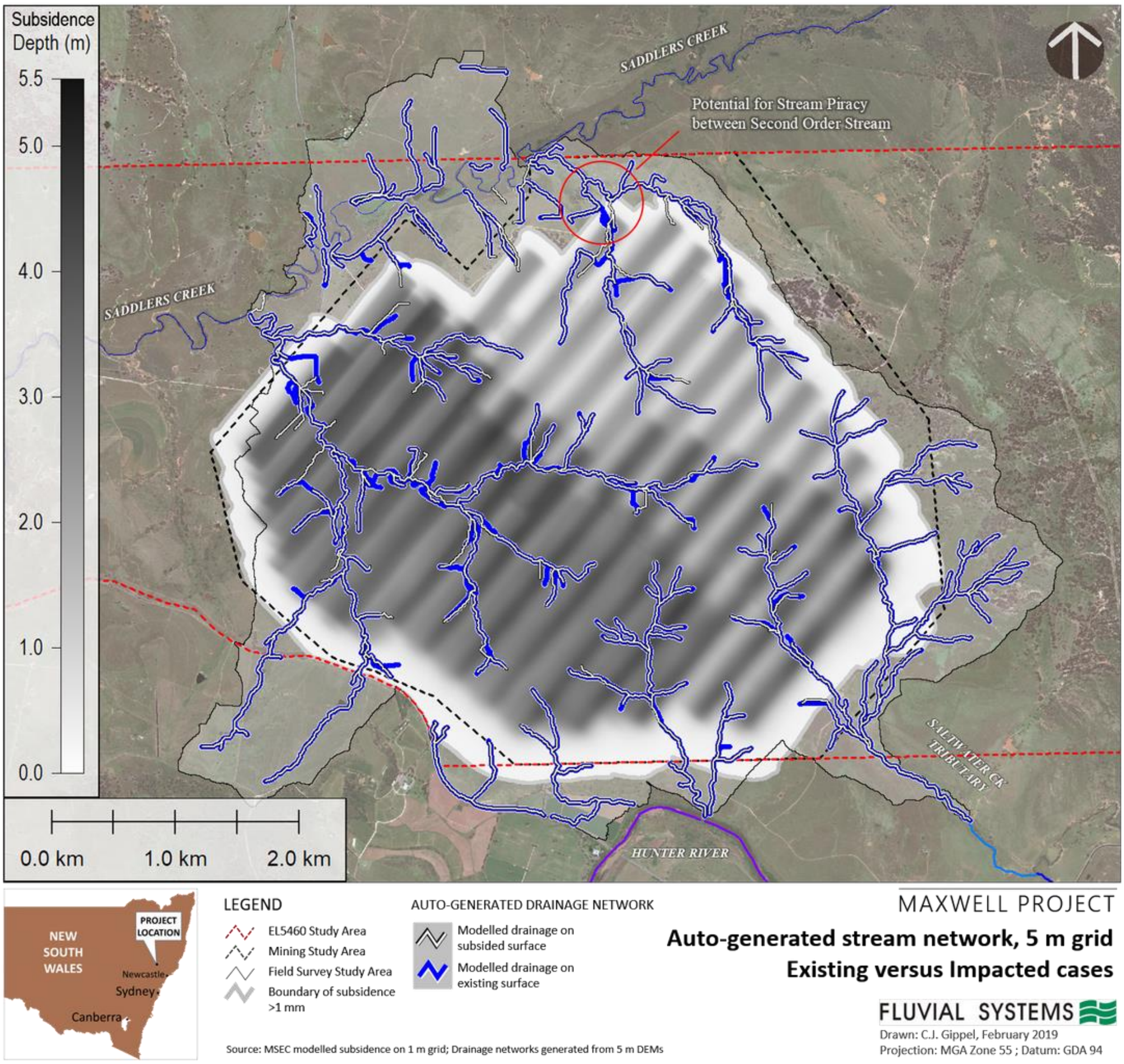

Figure 49. Automatically-generated drainage networks for existing and impacted cases, assuming no mitigation actions, for 5 m DEM.

While stream course relocation mainly affects First Order streams, at the detailed level, higher Order streams are also predicted to undergo adjustment of alignment in response to local uneven alterations in elevation (Figure 48, Figure 49). These predicted changes are based on the assumption that water will flow to the lowest point in the landscape and do not take into account variable resistance of the land surface to erosion. If the material over which the stream flows is highly adjustable, under gradual subsidence the stream might simply incise or aggrade in the same location, rather than change course. For drainage lines with small catchments, low shear stress, and lacking a well-formed channel, a change in alignment might not involve any significant change to the surface topography. In other cases, an increase in drainage area resulting from subsidence could be sufficient to scour the surface vegetation and cause incision.

4.2.2 Drainage network stream length

Comparison of the impact of subsidence on the length of individual streams was done on the basis of the 5 m grid, as this grid smoothed the variability (noise) and was closer in scale to the width of the larger stream channels, where geomorphic changes would have greater consequences.

Under the impacted case, 13 of 30 streams changed in length by more than 0.5% (Figure 50). Of these, 8 became shorter and 6 became longer. The greatest impact was on b3, which became 53% longer, which was associated with b2(1) becoming 14% shorter and b2(2) becoming 16% shorter (i.e. by b2(2) joining b3 higher in the catchment) (Figure 49). Stream d2 became 14% shorter, balanced by d1(1) becoming 12% longer (i.e. d1(1) joined d2 further down the catchment). The other notable change in length was a3, which became 12% shorter. This shortening was due to straightening of the alignment (Figure 49). Much of the shortening of a3 was due to subsidence creating longer depressions along the course of the stream, which are filled as part of the automatic drainage network generation process. The streamline generation algorithm draws the streamline as a straight line from the downstream end of the filled depression to the upstream end of the filled depression. In reality, as the land subsides over time, the stream would respond by either incising into the surface, and developing a sinuous course, or by development of an expanded depression (see further discussion of this case in later Section 4.2.4). Thus, the impacted course of a3 would not be shortened by as much as the model suggested.

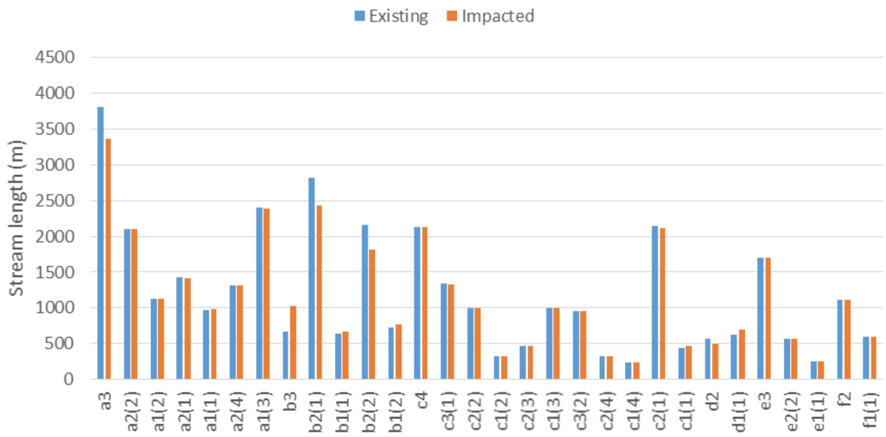

Figure 50. Length of main streams on automatically-generated (5 m DEM) drainage network for the existing and impacted cases.

4.2.3 Channel stream power

Comparison of the impact of subsidence on the stream power of individual streams was done on the basis of the 5 m grid, as this grid smoothed the variability (noise) and was closer in scale to the width of the larger stream channels, where geomorphic changes would have greater consequences. The spacing between vertices on the streams where stream power was computed was variable, so reach-mean stream power was calculated by weighting stream power at each vertex by the length of the stream segment that vertex represented. The 95th percentile of calculated stream power values was used as an index of the peak stream power values on each stream.

Under the impacted case, 13 of 30 streams had increased mean stream power (Figure 51). The largest percentage increase occurred on c2(3) (19%). The largest decrease in mean stream power was on b2(2) (-17%), f1(1) (-16%), a2(1) (-12%) and e3 (-12%).

Changes in peak stream power had a somewhat different distribution than mean stream power. Under the impacted case, 19 of 30 streams had increased 95th percentile stream power (Figure 51). The largest percentage increase occurred on a3 (55%), although large increases also occurred on c2(3) (28%), b1(2) (26%), a2(4) (24%), c2(2) (20%) and c1(2) (20%). The largest decrease in 95th percentile stream power was on f1(1) (-17%), b2(2) (-13%), d1(1) (-8%) and b1(1) (-8%).

The stream power data suggest that streams with the greatest risk of increasing channel instability due to subsidence are, in order: a3, c2(3), b1(2), a2(4), c2(2), and c1(2). These streams have intermittent flow regimes, with the First Order and Second Order streams having ephemeral flow regimes (a subclass of intermittent with very short flow duration during storm events only). Third Order streams a3 would have more persistent flow following cessation of rain events but the flow regime would be ephemeral in most years, and seasonal only in wet years with a high frequency of closely-spaced storm events.

A review of geomorphic impact-mitigation approaches is provided in Section 5.2.1 and a recommended approach to mitigation of potential Project impacts is provided in Sections 5.2.2 and 5.2.3.

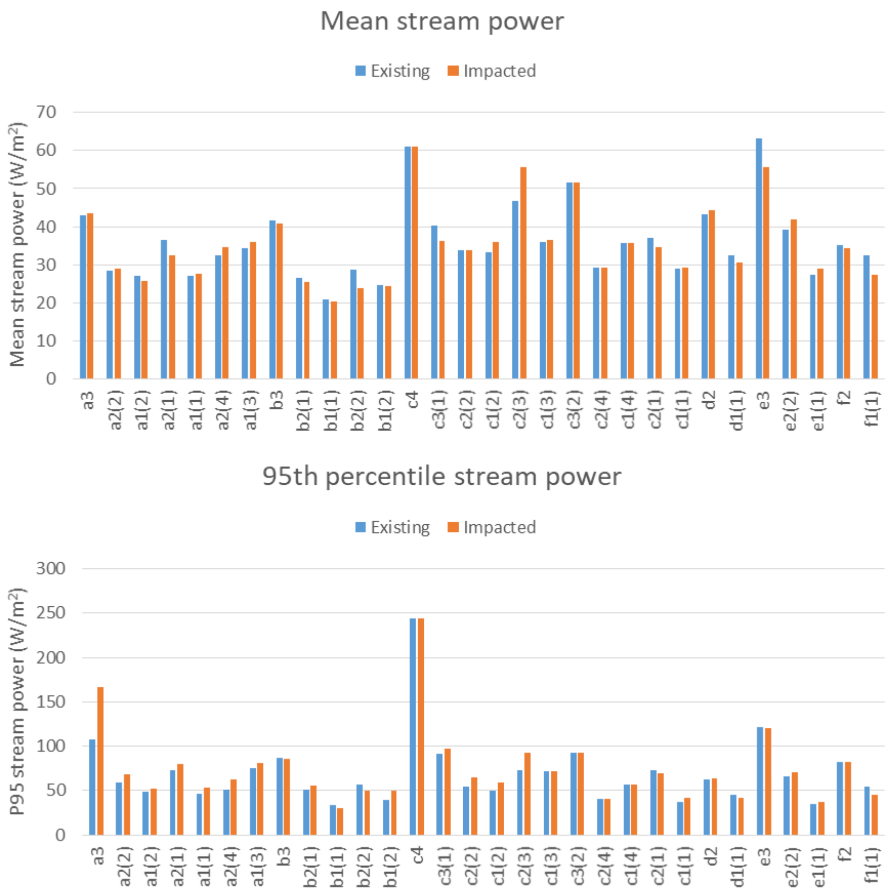

Figure 51. Mean and 95th percentile stream power of main streams on automatically-generated (5 m DEM) drainage network for the existing and impacted cases.

4.2.4 Depressions on drainage lines

The distribution of depressions on drainage lines of the impacted surface was computed at 1 m grid resolution across the Field Survey Study Area (Figure 52) using the methodology outlined in Section 2.8.8. The distribution of modelled depressions outside the area directly impacted by subsidence, was, as expected, unchanged from the existing case (Figure 25). Within the Mining Study Area, subsidence was predicted to increase the surface area of depressions in drainage lines by 45%, from 8.9 ha (existing case) to 12.9 ha (impacted case). A further 2.5 ha of the depressions present under the existing case were predicted to become deeper under the impacted case.

The distribution of the difference between the impacted and existing distributions of depressions (Figure 53) indicated that most of the difference was associated with a relatively small number of locations. The two largest increases in the extent and depth of individual depressions were predicted to occur on:

- stream a3, upstream of the junction of a2(1) (Figure 54), and
- stream b2(2), between b1(3) and b2(1) (Figure 55).

The depression on stream a3 is on a reach that has a depositional character in its existing state (Figure 54). Deepening and expansion of the depression would likely lead to an increase of the duration of ponded water in this location. The geomorphic consequence of this ponding would be a local increase in the rate of sediment deposition, but the significance of increased deposition for the overall sediment budget of this tributary and Saddlers Creek would be small. There is a culvert under the farm access road that forms the downstream boundary of the depression. Maintaining the hydraulic capacity of this culvert would help control the maximum depth of water ponded in the depression. At the present time, flow through the culvert is constrained by dense macrophytes (Figure 54).

The depression on stream b2(2) is near, and partially on, the narrow divide separating b2(1) and b2(2), where analysis of the impact of subsidence on stream alignment based on the 5 m grid suggested a risk that b2(2) could cut through the divide and join b2(1) higher in the catchment (Figure 49). These two streams are currently linked by a north-flowing, shallow flood drainage path (Figure 55). The formation of a depression in this location would not necessarily increase the risk of stream piracy. The most likely scenario would be upwards migration of the existing 3.5 m high knickpoint on stream b2(1), following the flood drainage path to join with stream b2(2). Efforts to mitigate this risk should be focused on stabilising this major knickpoint.

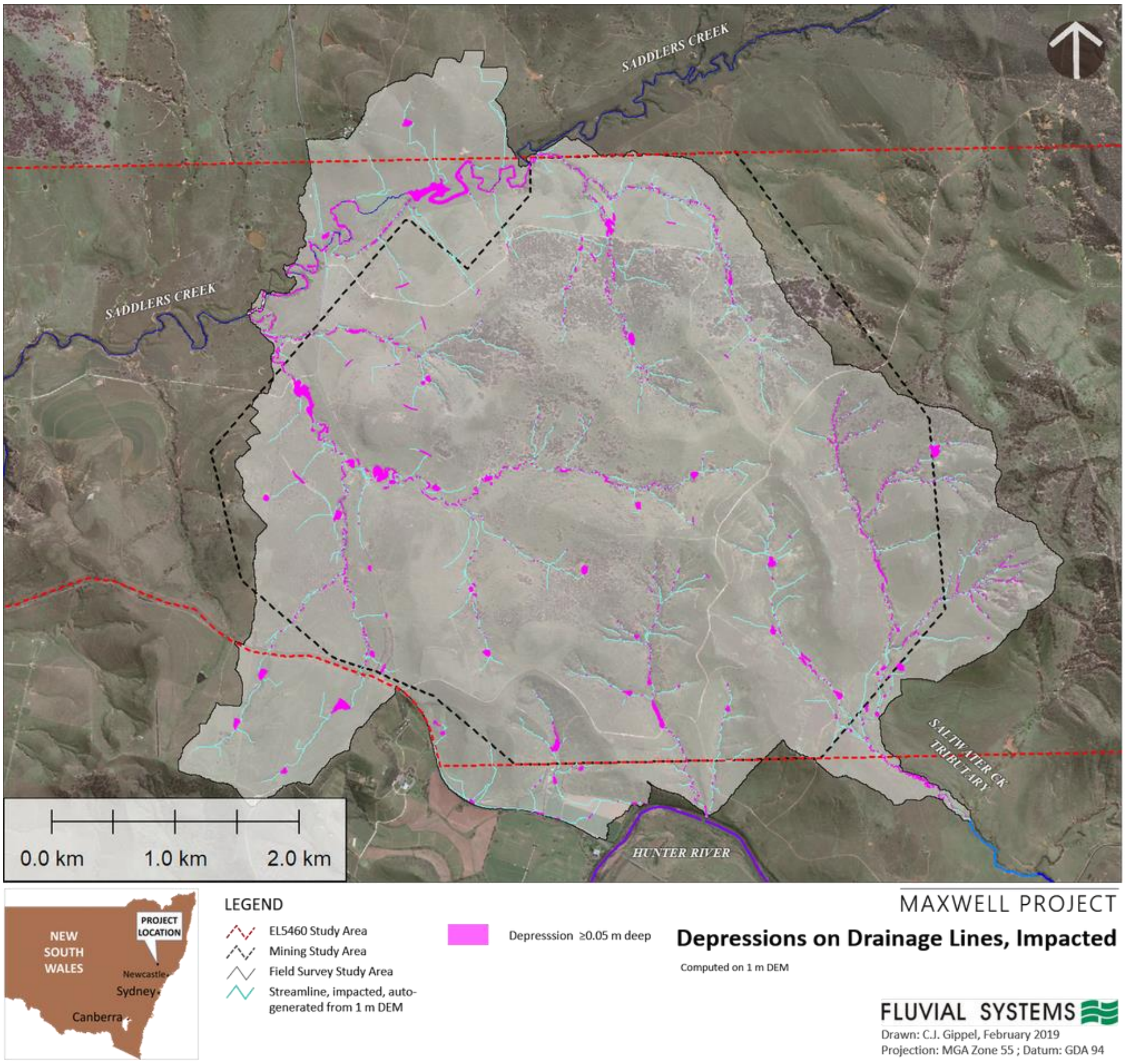

Figure 52. Distribution of depressions on drainage lines calculated over the Field Survey Study Area for the impacted case.

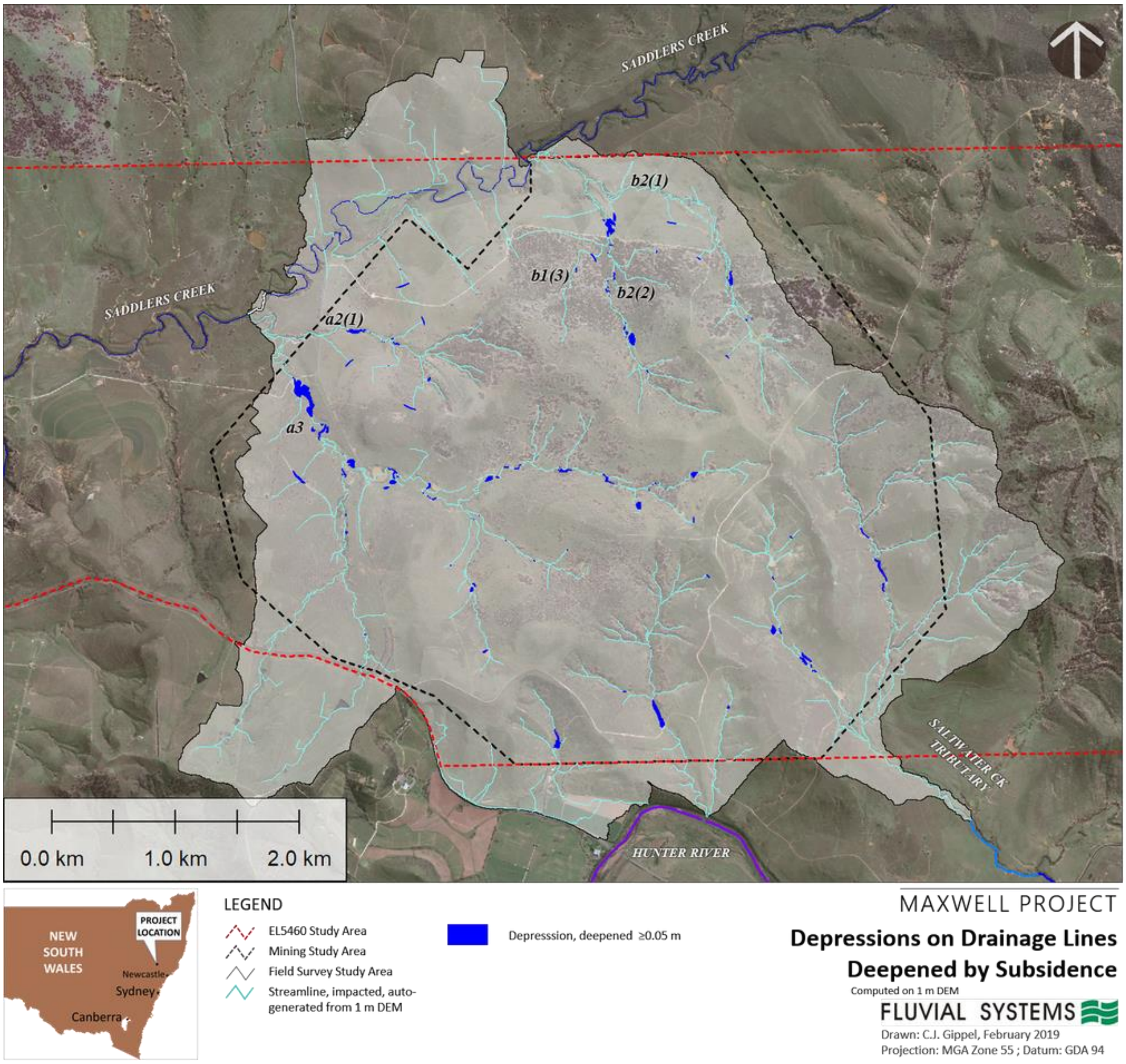

Figure 53. Distribution of depressions on drainage lines deepened by subsidence, calculated over the Field Survey Study Area.

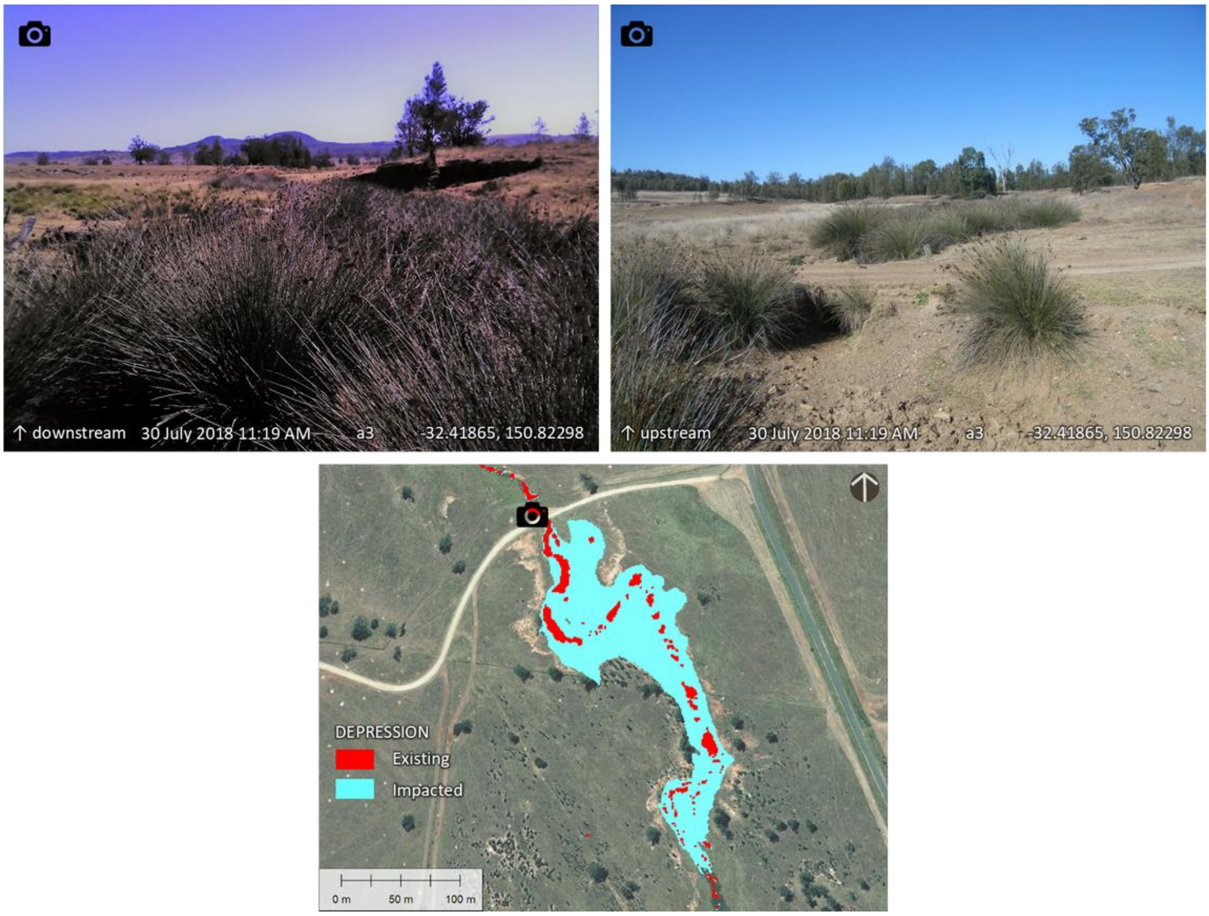

Figure 54. Detail of depression on stream a3 predicted to expand and deepen under the impacted case. Note: where impacted (rendered light blue) and existing (rendered red) depressions coincide, the impacted depressions are overlaid and obscured by the existing depressions.

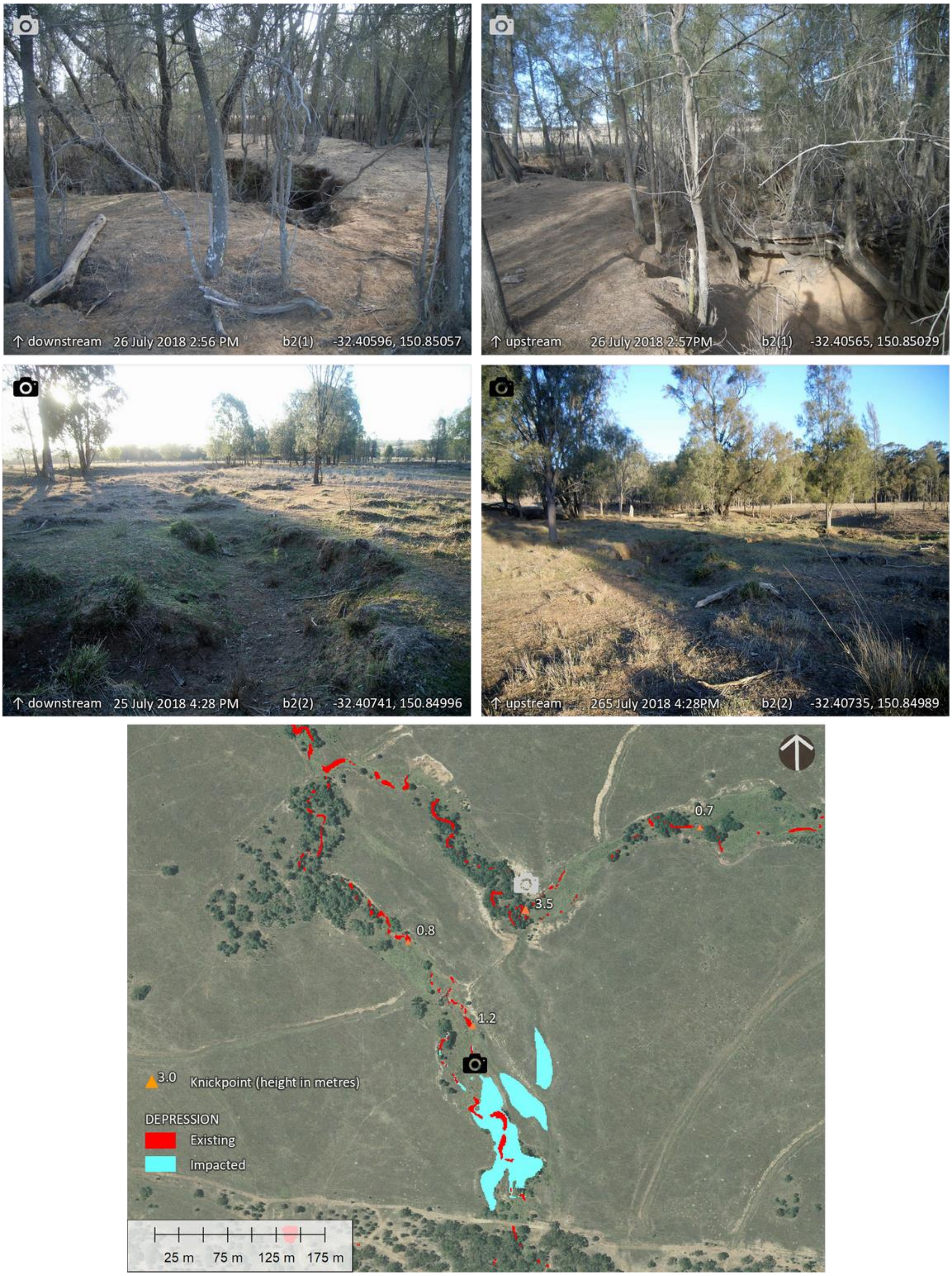

Figure 55. Detail of depressions on stream b2(2) predicted to expand and deepen under the impacted case. Note: where impacted (rendered light blue) and existing (rendered red) depressions coincide, the impacted depressions are overlaid and obscured by the existing depressions. North-flowing stream b2(2) joins west-flowing stream b2(1) 400 m downstream of the depression and the two streams are also linked by a north-flowing, shallow flood drainage path. Knickpoints are also indicated.

4.3 Qualitative assessment of risk of operational impacts

The key geomorphic risks of the Project (Table 8) were evaluated qualitatively:

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

Cook and Schneider (2006) provided descriptions of the three fragility classes low, moderate and high (Table 11). The fragility classes were associated with particular River Styles®, or types (Table 12).

On the basis of these definitions, *Headwater* streams have low risk of change in stream type, while *Planform controlled, low sinuosity, coarse* would have high risk of change (Table 12). *Contour drains* would also have high risk of changing type (to an incised stream channel) because they were formed from unconsolidated hillslope soil, and were designed to concentrate flow in a place where it was not previously concentrated. Flow in the drains themselves is shallow and low slope, but a breach would result in flow with high shear stress that could scour the hillslope. Also, the points where contour drains meet existing natural watercourses are prone to knickpoint formation due to large increases in bed slope that typically occur there (this concurrence was observed in the field). The other stream types found in the Field Survey Study Area had potential for local change of stream type (Table 12). The potential for appropriate mitigating actions to result in a stream recovering from degradation is related to the fragility of the geomorphic type and its existing condition (Cook and Schneider, 2006, pp 60-64) (Table 12).

Table 11 Description of geomorphic fragility classes (Cook and Schneider, 2006).

Fragility class	Description
Low	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
Moderate	Local adjustment potential. It may adjust over short sections within the vicinity of the threatening process. Major character changes can occur or the category or sub-category can change to another - but only when a high threshold of damaging impact is exceeded. For example, it may require a catastrophic flood, sediment slug or clearing of all vegetation from bed, banks and floodplain
High	Significant adjustment potential. Sensitive. It may alter/degrade dramatically and over long reaches. Major character changes can occur or the category or sub-category can change to another one when a low threshold of damaging impact is exceeded (e.g. clearing of bank toe vegetation alone)

Table 12 Geomorphic type and fragility for streams found within the Field Survey Study Area.

Stream type	Fragility	Adjustment potential	Condition in Field Survey Study Area	Management
Floodplain pockets, fine-grained	Moderate	Local adjustment potential	Poor	Moderate recovery potential
Cut and fill	Moderate	Local adjustment potential	Poor	Moderate recovery potential
Planform controlled, low sinuosity, coarse	High	Significant adjustment potential	Poor	Low priority
Planform controlled, low sinuosity, fine-grained	Moderate	Local adjustment potential	Poor	Moderate recovery potential
Planform controlled, meandering, fine-grained	Moderate	Local adjustment potential	Moderate	High recovery potential
Headwater	Low	Resilient (unbreakable)	Poor	Moderate recovery potential
Artificial – contour drain	High	Significant adjustment potential	Poor	Moderate recovery potential

2. Change of alignment of channel

The *Headwater* streams in the Study Areas are all confined by valleys. The likelihood of a change of alignment of this stream type due to subsidence is rare. Some First and Second Order streams in the Mining Study Area have previously changed alignment due to construction of contour banks and dams. There is a high potential for change in alignment of stream b2(1) (and receiving stream b3 if stream b2(1) changes alignment) due to subsidence, however these changes can be mitigated (see later Section 5.2). Stream a3 could change alignment by local steepening and straightening, but it is also possible that the stream would adjust to subsidence through localised incision rather than course change.

A few small headwater drainage lines on hillslopes could change course by following the SW-NE alignment of subsidence associated with the longwalls. The geomorphic consequence of this depends on whether the shear stress of the flow in the stream is sufficient to remove the surface vegetation and scour a channel. The chance of this occurring would vary with the intensity of individual storm events and the antecedent conditions that determine soil moisture and integrity of the ground cover. Regardless of this, where such a course change diverts a small stream to join the receiving stream at a location further upstream, the receiving stream will adjust to higher discharge between that point and the previous junction downstream. The adjustment could be through knickpoint formation, steepening, widening or deepening.

3. Migration of non-cohesive knickpoint upstream at faster than natural rate

Knickpoints in non-cohesive material are very common in the Mining Study Area partly due to previous and current agricultural land management practices, so ongoing knickpoint formation and migration is expected independently of subsidence. Acceleration of the rate of knickpoint migration, or creation of new knickpoints, would most likely be associated with areas where a strong gradient of subsidence, or a local increase in catchment area, occurs.

4. Increase in extent and depth of depressions in channels

The pattern of subsidence from longwall mining would increase the area of depressions in the watercourses of the Mining Study Area. Following the regular pattern of subsidence, depressions would tend to form above the goafs, with high points corresponding with the location of the chain pillars. Closed depressions would not necessarily form over every longwall crossed by a stream, with depressions that would pool water more likely to form on low gradient terrain. An increase in the area of depressions would have the effect of increasing the capacity of the channels to trap coarse sediment mobilised during storm events.

5. Increase of coarse and fine sediment supply to channel

Sediment supply to the streams in the Study Areas appear to be relatively high, evidenced by the generally high levels of accumulation of sediment in the channels. An increase in sediment supply to the channels would be expected in areas where the hillslope SPI increased significantly.

6. Increase in suspended sediment load of streams

Increase of sediment supply to channels due to increase in hillslope SPI (see point 5. above) would involve both coarse and fine-grained sediment. The fine-grained sediment would enter suspension during storm runoff events. If sediment supply increases, other things being equal, average annual suspended sediment load would increase. Suspended material would be exported from the Study Area to Saddlers Creek and other tributaries, and be transferred to the Hunter River. In the impacted streams within the Study Area, higher sediment load would be associated with an increase in average suspended sediment concentration during storm events. It is not possible to reliably predict whether peak suspended solids concentration would increase.

7. Increase of sediment accumulation in channel

The likelihood of increased sediment accumulation in channels would be related to a reduction in stream power below the sediment transport threshold. Subsidence is predicted to create zones of decreased stream slope and stream power, and increased area of depressions on drainage lines. There is a likelihood of increased sediment accumulation where subsidence significantly lessens the stream slope and stream power or creates closed depressions, and this would be enhanced if the hillslope SPI increased in the contributing catchment area.

8. 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. Subsidence is predicted to create zones of increased stream slope and stream power. There is a likelihood of increased sediment scouring of channels where subsidence significantly steepens the stream slope and stream power is high enough to mobilise sediments and scour vegetative cover.

9. Increase in cover (area, density and type) of vegetation on channel bed (baseflow shift from high depth of water to shallow depth)

The likelihood of significantly increased cover of dominantly terrestrial vegetation on channel beds due to reduced baseflow would be rare and be of little consequence. Exposed bedrock is not common in streams of the Mining Study Area, so the risk of loss of baseflow due to subsidence induced cracking of the bed would be rare. Also, the streams are mostly ephemeral, flowing for short periods of time associated with storm events and lacking persistent baseflow. The extent of bed vegetation would vary through time, being high during wet periods when it would be watered by rainfall and occasional flow events, and then contracting during extended dry periods. This general pattern will be unchanged by mining. Saddlers Creek has more persistent baseflow than the smaller streams in the Study Area, noting that Saddlers Creek would not be directly impacted by subsidence. This risk is discussed further in the Biodiversity Development Assessment Report.

10. Change in cover (area, density and type) of vegetation on channel bed (baseflow shift from shallow depth of water to dry, or from shallow to deep)

There is very low likelihood of significantly decreased cover of dominantly terrestrial vegetation on channel beds due to increased baseflow. There could be a tendency for increased extent of macrophytes on channel beds in response to the increased area and depth of depressions on drainage lines, which could lead to longer persistence of ponded water following storm events. This risk is discussed further in the Biodiversity Development Assessment Report.

5.0 Monitoring and Mitigation

5.1 Monitoring

This report provides data for the baseline geomorphic condition of streams in the Mining 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 method of establishing sampling locations where cross-sections and long profiles are re-surveyed from time to time, often recommended for monitoring streams subject to mining subsidence impact (e.g. Hancock, 2001), is not recommended here. This method of representing topography by relatively few samples of linear point data is inferior to a high resolution three-dimensional representation of the entire area impacted by subsidence derived from LiDAR. While LiDAR might not have the same level of vertical and horizontal accuracy as ground survey, this disadvantage is more than compensated by the total coverage achieved by LiDAR. A model of surface elevation change over the entire mining area on a 0.5 m grid would enable characterisation of all areas of potential concern for stream stability. Objective comparison of LiDAR-derived DEMs over the entire impacted area would be the primary basis on which mining impact on stream morphology would be measured. Approaches requiring a level of subjective interpretation, including comparison of photographs or field inspections, would provide supplementary information.

The above recommendation to base geomorphic monitoring on repeated LiDAR surveys is supported by a recent literature review of underground mining beneath catchments and water bodies undertaken by Advisian (2016) for Water NSW. This report concluded that due to insufficient knowledge of how subsidence interacts with complex topographical landforms, both LIDAR and DinSAR (Differential Interferometric Synthetic Aperture Radar) remote sensing technologies should be used to map subsidence impacts. For this application, DinSAR suffers from failure to remove vegetation and non-terrain features and is inferior to LiDAR. Also, LiDAR has been collected over the Study Area, so a benchmark data set exists.

The geomorphic response to subsidence is likely to be slow, so a frequency of five years for catchment-wide re-survey (including LiDAR survey) and reporting of stream geomorphological condition is suggested in addition to annual visual inspection. 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 field survey to confirm this assumption. It is noted that all streams would be monitored by the repeated LiDAR survey, so any areas of concern for headwater streams can be identified through this methodology.

5.2 Mitigation

5.2.1 Geomorphic impact-mitigation approaches

Mitigation is to eliminate or reduce the frequency, magnitude, or severity of exposure to risks, or to minimise the potential impact of a threat. Mitigation can be proactive or reactive.

Proactive mitigation would require reliable knowledge of where geomorphic instabilities are likely to occur, what form the instabilities would take, and what the magnitude of the impact would be. Given this knowledge, appropriate stabilisation works could be undertaken. The problem is that prediction of the exact location and extent of geomorphic impacts is uncertain, and attempts to proactively mitigate them could be costly and ineffective. The exception would be to undertake proactive surface stabilisation works that had significant additional benefits. In the Study Area, this could be revegetation of riparian zones that have been historically cleared for agriculture. However, there is no guarantee that this action would be effective in protecting stream channels from subsidence-related instability. Most stream channels in the Study Area are currently actively adjusting through knickpoint migration. Apart from the problem of distinguishing existing instability from mining-induced instability, it may take decades before revegetation of riparian zones has a significant impact on the existing state of stream channel stability.

Reactive mitigation would respond to new instabilities identified through monitoring. Whether observed new channel instabilities were related to mining or other causes could be assessed on the basis of proximity to landform changes that, in theory, would suggest the potential for such instabilities. Regardless, active knickpoints are so widespread throughout the Study Area that mining impacts are likely to be superimposed on existing instabilities, which are a legacy of decades of land degradation.

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) provided advice to this Project that "*detailed, long-term and peer-reviewed case studies on successful use of mitigation measures at equivalent locations are essential*". IESC requested that studies be provided in this assessment that address the topic of the relative impacts from grading surface water drainage channels versus letting them "self-heal" after subsidence.

In a peer-reviewed report prepared by Commonwealth of Australia (2015) on the advice of the IESC, titled "Monitoring and management of subsidence induced by longwall coal mining activity", two of the recommendations under "Areas for further research" were "*the capacity of streams affected by bedrock cracking to 'self-heal' and possible actions to accelerate this process*" and "*the effectiveness of engineering methods to reduce subsidence, including backfilling or 'stowing', and bed separation grouting*". The paucity of peer-reviewed research on these topics has not changed since this recommendation was made in 2015. Furthermore, the same report, in reference to suggested mitigation measures, including controlling bank erosion by re-grading slopes, encouraging vegetation regrowth and fencing out livestock (Dawkins, 2003), noted weaknesses identified by NSW Department of Planning (2008) that included "*lack of research and experience in applied rehabilitation techniques for these types of mining related impacts*" and "*lack of research comparing the outcomes of active remedial interventions with natural processes of remediation*". With respect to allowing cracks that form in rock beds of streams due to subsidence to self-heal, the report found "*No evaluation of the effectiveness of this method of rehabilitation is possible at present due to the lack of data and control sites*".

IESC requested provision of peer-reviewed published studies that address the topic of the relative impacts from grading surface water drainage channels versus letting them self-heal after subsidence. A brief review of the literature covering the topic of rehabilitating streams subject to geomorphic disturbance is provided. Whilst these studies are not specific to the remediation of subsidence impacts, the principles of remediation of geomorphic disturbance are still applicable to the Project. Although Commonwealth of Australia (2015) used the term 'self-heal' exclusively in the context of cracking of channels beds formed in rock, here the meaning is extended to all forms of geomorphic impact. In the stream restoration literature, allowing a stream to 'self-heal' is also referred to as passive restoration, while undertaking intervention is referred to as active restoration, or assisted restoration.

The idea that, in some cases, streams that have undergone disturbance to geomorphic form and/or process are best left to self-heal is not inconsistent with the prioritisation system set out by Rutherfurd et al. (2001) for rehabilitation of Australian streams. In this system, reaches are ranked according to rarity (rare – common), condition (good – bad), trajectory (deteriorating – improving), proximity to good reaches and ease of rehabilitation (easy – hard), and then placed within one of eight priority categories. Setting priorities for action is driven by consideration of how much natural biodiversity (or some other measure of stream health) will result from the expenditure of resources on attempting to correct the problem. Under this philosophy, rehabilitation of the most impaired reaches would be low priority. It is considered more efficient to achieve stream health outcomes by protecting reaches that are currently in good condition with relatively little effort, than to spend a large quantity of resources trying to rehabilitate reaches that are already damaged. Also, Rutherfurd et al. (2001) considered it usually more efficient to stop a stream deteriorating than to try to correct the problem at a later time when the problem has worsened. Streams possessing low-value ecological assets, highly impaired, but on an improving trajectory, would be the lowest priority for rehabilitation intervention works, and would be candidates for self-healing. An example might be headwater streams in the Study Area, mostly in poor condition due to degraded riparian vegetation, and characterised by numerous low knickpoints, with most of the scoured material deposited a short distance downstream (i.e. rapid self-healing in the downstream direction).

The approach of Rutherfurd et al. (2001) has similarities with the River Styles® concept of prioritising rehabilitation on the basis of geomorphic 'fragility'. Stream types with 'Low fragility' are resilient or 'unbreakable', those with 'Medium fragility' have local adjustment potential, and those with 'High fragility' have significant adjustment potential (Cook and Schneider, 2006). Following on from this, the conservation and rehabilitation priority of stream reaches can be determined on the basis of geomorphic fragility and condition. For example, stream reaches with high fragility and poor condition are rated low priority, while reaches with low fragility that are in good geomorphic condition are rated the highest priority for protection. On the basis of these definitions, Headwater streams, on which knickpoints were prolific in the Study Area, have low fragility and have low risk of change in stream type, making them low priority for rehabilitation intervention works.

Askey-Doran (1999) viewed stream rehabilitation interventions as a means to overcome system thresholds by either reinstating dynamic processes (process-driven thresholds) or overcoming gross changes to the physical environment or to the range of species available (component-driven thresholds). They defined three classes of rehabilitation intervention:

- Unassisted regeneration threshold - the system cannot self-heal without some intervention, but it is still resilient and can return to its pre-existing state with a “kick-start”;
- Assisted regeneration threshold – organisms or substrate critical for recovery are depleted and need to be restored in order to return to a pre-existing state; and
- Reconstruction threshold – component-driven thresholds have been crossed and recovery of the pre-existing system is not possible, so creation of a new state is the only option.

Considering the frameworks of Rutherfurd et al. (2001), Cook and Schneider (2006) and Askey-Doran (1999), it is apparent that any comparison of the outcomes of active remedial interventions with those of passive remediation would need to consider the context and setting of the rehabilitation.

Although application of the principles of Rutherfurd et al. (2001), Cook and Schneider (2006) or Askey-Doran (1999) might rate knickpoints in the Study Area low priority for intervention with structural works, knickpoints are not always treated passively. Brierley et al. (2002) considered that knickpoints on discontinuous alluvial channels should be proactively managed out of concern for excessive sediment supply to downstream river reaches or retreat of the knickpoints into upstream remnant swamps. Thus, in two of the three reaches Brierley et al. (2002) investigated they recommended installation of a rock or concrete flume on a retreating knickpoint, while in the third reach, they recommended treatment of a retreating knickpoint with a log weir, fencing and revegetation.

In the USA, vegetation has been used with conditional success to control bank erosion (Shields et al., 1995a) and gully erosion (Shields et al., 2005), and stone weirs have also been used in some situations to control channel incision (Shields et al., 1995b). Pederson et al. (2006) investigated the problem of gully erosion threatening high-value cultural sites in Grand Canyon National Park, Arizona. They found that the first-order controls on gully extent and location of knickpoints were slope and contributing catchment area (i.e. the same as the Stream Power Index used in this report, Eq’n 12). In the Grand Canyon study, erosion-control structures (ECS) reduced erosion compared to control sites. Wooden checkdams were found to be preferable to rock lining, but maintenance of wooden structures was essential, as damaged structures could exacerbate erosion. In Europe, bioengineering techniques of erosion control have a long tradition (Evette et al., 2009), and more recently, large wood has become popular in stream restoration (Kail et al., 2007). 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 trialled in rivers and streams in the Hunter Valley and northern NSW. A comprehensive description of various methods of stream channel stabilisation, and geomorphic/ecologic restoration interventions, was provided in Chapter 9 of Gordon et al. (2004). That chapter also reviewed global literature that evaluated the success or otherwise of rehabilitation projects. Overall, reviews of the performance of stream rehabilitation projects demonstrate that hard engineering, soft engineering, and passive approaches all have achieved mixed success, with geomorphic context, and how objectives were framed, being important determinants of measurable success.

There are few studies in the literature that have evaluated the effectiveness of restoration of streams impacted by mining subsidence. Subsidence from longwall mining can impact streams by creating a series of deep pools that trap sediment, reduce habitat diversity, and impair macroinvertebrate and fish communities (Nuttle et al., 2017). A method used in parts of the USA to mitigate this impact is known as ‘gate cutting’, whereby the unsubsided ‘gates’ between longwalls that act as small dams in the streams are excavated to re-establish the stream grade. Gate cutting is usually accompanied by procedures that stabilize the channel, restore substrates, and enhance in-stream and riparian habitat (Nuttle et al., 2017). The detailed methods employed at each site depend on site-specific condition, agency objectives, and landowner preferences and constraints. However, the dominant activity at each site is channel excavation to restore stream grade (Nuttle, et al., 2017). The effectiveness of gate cuts in restoring streams affected by subsidence pooling was investigated by Nuttle et al. (2017) at 18 independent restoration sites located over two mines in southwestern Pennsylvania. All biological indices and substrate-related habitat indices declined following subsidence but improved following restoration. Macroinvertebrate indices and taxa richness, substrates, and riparian vegetation continued to improve with time following restoration.

Commonwealth of Australia (2015, p. 49) listed the methods used in Australia for rehabilitating channels impacted by subsidence-induced rock bed cracking and erosion. These methods included sealing rock floors with clay or injected grout; controlling bank erosion by re-grading slopes, revegetation and fencing; use of indigenous trees and shrubs; installing weirs to control knickpoint migration; and one case of strain relief slotting to protect a prominent waterhole rock bar. The effectiveness of these practices has never been scientifically evaluated, but anecdotally, Dawkins (2003) reported that they were often ineffective, or resulted in damage due to the use of heavy equipment in their construction.

5.2.2 Geomorphic impacts most likely to require mitigation

There are few peer-reviewed, published studies in the international literature concerning the impacts of subsidence on channel and drainage line morphology, and consequences for channel stability, sediment delivery and routing, and riparian habitat. Most publications on this topic from Australia have focused on dramatic cracking of sandstone stream beds in the Southern Coalfields (e.g. Waddington and Kay, 2003; Kay et al., 2006; Jankowski, 2007; Jankowski and Knights, 2010; Krogh, 2007; NSW Department of Planning, 2008; Hebblewhite, 2009; Morrison et al., 2018), but the streams of the Study Area mostly had silt-clay beds, with 10 lengths of bedrock outcrop found (one 4 m long, and the others 13 – 68 m long). One of the few studies of geomorphic impacts of subsidence published in an international peer-reviewed journal is Sidle et al. (2000). This study evaluated short-term geomorphic and hydrologic effects of subsidence induced by longwall mining under Burnout Creek, Utah.

Sidle et al. (2000) reported 0.3 – 1.5 m of subsidence had occurred near impacted reaches of the mountain stream channel within one year of longwall mining. The major channel changes that occurred in a 700 m long reach of Burnout Creek were: (1) increases in the lengths of cascades and, to a lesser extent, glides; (2) increases in the length, number and volume of pools; (3) increase in median particle diameter of bed sediment in pools; and (4) some constriction in channel cross-section morphology. Most of the changes were short-lived, with channel recovery approaching pre-mining conditions within one or two years of subsidence occurring. In another 300 m long reach, only channel constriction was observed. A control creek and non-impacted reaches of Burnout Creek experienced similar channel sedimentation and loss of pool habitat to that observed in the impacted reach of Burnout Creek. This study has limited relevance to the streams in the Study Area because of vastly different stream types. Burnout Creek had cascades, riffles, runs, glides, and pools, while these are not typical features of streams of the Study Area. However, the study of Sidle et al. (2000) does provide an example of a stream undergoing geomorphic adjustment to the impacts of subsidence without assistance from mitigation measures. This contrasts with the use of gate cutting to rapidly restore the grade of streams impacted by longwall subsidence in southwestern Pennsylvania (Nuttle et al., 2017).

The key subsidence related processes that threaten to change the geomorphic character of streams in the Mining Study Area are:

- the formation of new, or expansion/deepening of existing, depressions in channels;
- the development, and upward migration, of knickpoints, and
- alteration to the alignment of drainage lines, particularly on reaches positioned low in the catchment.

The data collected and modelling undertaken for this report suggest that the streams with the greatest risk of increasing channel instability due to subsidence are, in order: c2(3), b1(2), a2(4), c2(2), and c1(2). Also, stream b2(2) is at risk of changed alignment, potentially shortening by cutting of a new channel over a low divide and joining b2(1) higher in the catchment. This would mean the resultant stream b3 would start higher in the catchment, and this new upper reach of b3 [formerly the lower reach of b2(1)] would adjust to the increased discharge from b2(2) by increasing in depth or width (or both) or changing slope. Modelling predicted that stream a3 would shorten in length, which could imply steepening and erosion, but much of this apparent shortening was due to increased extent of depressions. The depression-filling procedure performed in GIS creates a theoretically more direct flow path from the upstream end to the downstream end of the pond, but in practice the flow would continue to follow the thalweg.

The above mentioned streams have intermittent flow regimes, with the First Order and Second Order streams having ephemeral flow regimes (a subclass of intermittent with very short flow duration during storm events only). Third Order streams a3 and b3 would have more persistent flow following cessation of rain events but the flow regime would be ephemeral in most years, and seasonal only in wet years with a high frequency of closely-spaced storm events.

5.2.3 Recommended approach to mitigation

Formation of depressions in watercourses due to subsidence would create potential for erosion or knickpoint formation on the downstream sides of the hydraulic controls (i.e., the gates, or high points corresponding to the un-subsided chain pillars), which would tend to be steeper than the average stream bed slope. Excavating the gates to reinstate an even stream grade would result in a continuous incised channel form that would increase flow confinement and potentially initiate further incision. The depressions formed from subsidence would be conducive to coarse sediment deposition, so they could provide a positive benefit in trapping sediment released from upstream degraded hillslopes and gullies. Ultimately, the depressions would fill with sediment, reforming an even stream grade. Thus, it is not recommended to adopt a policy of routine gate cutting.

It is recommended to address the risk of knickpoint formation and stream channel alignment change 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 a significant increase is observed in the rate of knickpoint development or migration, 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. 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.

It is noted that knickpoints are a ubiquitous feature of the existing environment of the Mining Study Area. Control of these existing knickpoints would involve changes to past agricultural and land management practices, such as reducing stock numbers, fencing waterways, and replanting riparian zones.

Changes to stream alignment do not necessarily need to be arrested. Forcing streams to follow their original alignment when a more hydraulically efficient path is present can be expensive and ultimately futile. In this situation, work to maintain the existing course should be undertaken only where not doing so threatens significant assets. Channel instabilities can be managed through construction of bunds to maintain runoff paths towards the original drainage line locations, or hardlining the banks and possibly beds of sections of channels that are under threat of change.

6.0 Conclusion

This report documented the geomorphological character of the Study Areas. 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 Areas can be compared.

The streams comprised six natural geomorphic types: *Headwater*; *Floodplain pockets, fine-grained*; *Cut and fill*; *Planform controlled, low sinuosity, coarse*; *Planform controlled, low sinuosity, fine-grained*; *Planform controlled, meandering, fine-grained*; and one artificial type: *Contour drain*. The majority of the streams were *Headwater*. *Headwater* streams were judged to be geomorphologically resilient because of their setting in confined 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 Headwater streams. Any changes that do occur would be expected to recover quickly because the streams are resilient even though many of them are in poor geomorphic condition (due to knickpoints and poor riparian vegetation as a result of historic land management practices). The other stream types are high or moderate fragility, so are at risk of change under disturbance due to subsidence, which would occur progressively throughout the Project life.

Knickpoints are a ubiquitous feature of the existing environment of the Mining Study Area. Control of these existing knickpoints would involve changes to past agricultural and land management practices, such as reducing stock numbers, fencing waterways, and replanting riparian zones. The existing streams generally have poor coverage and quality of riparian vegetation due to previous land clearing.

The risks to geomorphic stream form and process associated with subsidence were assessed using quantitative methods focusing on stream alignment and stream power. These data suggest that of the thirty streams within the Mining Study Area, there are eight streams with a greater risk of geomorphic change due to subsidence. These are: a3, b2(2), b3, c2(3), b1(2), a2(4), c2(2), and c1(2), all of which have intermittent, and mostly ephemeral, flow regimes. 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. A model of surface elevation change over the entire mining area on a 0.5 m grid would enable characterisation of all areas of potential concern for stream stability. Objective comparison of LiDAR-derived DEMs over the entire impacted area would be the primary basis on which mining impact on stream morphology would be measured. Approaches requiring a level of subjective interpretation, including comparison of photographs or field inspections, would provide supplementary information.

It is recommended to address the risk of knickpoint formation and stream channel alignment change 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 a significant increase is observed in the rate of knickpoint development or migration, these should be professionally assessed in order to determine the most appropriate control measure.

The extent of alluvium was mapped for the Hunter River, Saddlers Creek, lower Saltwater Creek, and smaller streams within the Mining Study Area. The mapping has considered existing information sources, and multi-resolution index of valley bottom flatness. The conclusion reached was that mining subsidence would not impinge on alluvium of the Hunter River, Saddlers Creek or Saltwater Creek. Lower stream b3 has formed an alluvial fan where it joins Saddlers Creek. This fan is within the margin of the Mining Study Area, but it is likely to be a relatively thin deposit of fine alluvium with low potential for containing an exploitable groundwater resource. Stream a3 also has formed an alluvial fan where it joins Saddlers Creek, but this feature is not within the Mining Study Area. The lower sections of Second Order and Third Order streams in catchment A (a sub-catchment of Saddlers Creek) technically flow within a body of alluvial material. However, this is likely to be a relatively thin deposit of fine alluvium, usually dry, and having low potential for containing an exploitable groundwater resource.

7.0 References

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