Olive Downs Coking Coal Project

Environmental Impact Statement

Technical Study Report

Geomorphology

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Final

July 2018

FLUVIAL SYSTEMS

Olive Downs Coking Coal Project

Geomorphology

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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)	Sediment deposited distant from its source after transport by flowing water, as in a riverbed, floodplain, delta, or alluvial fan.
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.
Composition (of riparian vegetation)	Represented by 3 structural classes - tree (woody and >3 m high) shrub (woody) and ground vegetation.
Cover (of riparian vegetation)	Foliar projective cover of the ground.
Cumulative impacts	Combination of individual effects of the same kind due to multiple actions from various sources over time.
Discharge	A release of water from a particular source.
Drainage	Natural or artificial means for the interception and removal of surface or subsurface water.
Ecology	The study of the relationship between living things and the environment.
Ecosystem	As defined in the *Environment Protection and Biodiversity Conservation Act 1999*, an ecosystem is a 'dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit.'
Environment	As defined within the *Environmental Planning & Assessment Act, 1979*, all aspects of the surroundings of humans, whether affecting any human as an individual or in his or her social groupings.
Ephemeral	Existing for a short duration of time.
Fault	Break in the continuity of a coal seam or rock strata.
Filamentous algae	Colonies of microscopic plants growing in water that link together to form threads or mesh-like filaments; lacking roots, their growth and reproduction are dependent on the amount of nutrients in the water.
Fluvial	Of or found in a river.
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)

Term	Definition
Grid (in GIS)	An array of rectangular or square cells, with a numerical attribute value for the cell stored in its centroid; often refers to elevation but can describe any attribute (see also Raster).
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)
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.
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.
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 Spur Hill Underground Coking Coal Project.
Raster (in GIS)	A spatial data model that defines space as an array of equally sized cells arranged in rows and columns, and composed of single or multiple bands (see also Grid).
Regolith	The material that is found between unweathered bedrock and the ground surface, including weathered bedrock, deposits and soil.
Resilience (geomorphic)	Low fragility, with only minor changes likely, regardless of the level of damaging impact (Brierley et al., 2011).
Riparian	Relating to the banks of a natural waterway.
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)
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	Power per unit length 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®)
Study Area (of Geomorphology Technical Report)	Area mapped in this report.
Surface Facilities Area	Comprises surface land containing mining and non-mining infrastructure.
Surface water	Water flowing or held in streams, rivers and other wetlands in the landscape.
Terrain analysis	The automated analysis of landforms using digital elevation data sets.
Topographic Position Index (TPI) (in Terrain analysis)	Relative elevation of cells in a landscape, used to classify landforms.
Terrain Surface Classification (TSC) (in Terrain analysis)	Classifies landforms using three taxonomic criteria: slope gradient, local convexity, and surface texture.
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).
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
AHD	Australian Height Datum
DEM	Digital Elevation Model
EIS	Environmental Impact Statement

Acronym	Expansion
GIS	Geographic Information System
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
MLA	Mining Lease Application
MRVFB	Multiresolution index of valley bottom flatness
ODK	Open Data Kit
SAGA	System for Automated Geoscientific Analyses
TSC	Terrain Surface Classification
TPI	Topographic Position Index

UNITS

Symbol	Unit
ha	Hectare
km	Kilometre
Km^2	Kilometres squared
m	Metre
m^2	Metres squared, or square metres
m^3	Metres cubed, or cubic metres
mm	Millimetre

Executive Summary

This report documented the geomorphological character of the Olive Downs Coking Coal Project Study Area using repeatable field and desktop methods. Characterisation of the geomorphology of the Study Area was approached at the landscape and stream reach/point scales. Streams were classified according to Strahler Stream Order and geomorphic type, and geomorphic features of the streams were measured in the field at the reach/point-scale.

The field data were collected from 54 sites within the period 13 to 16 June 2017. In general, the measurements were made using standard techniques from the literature. The intention was to capture morphological variability at the habitat scale. The field survey involved walking or using an All Terrain Vehicle (ATV) to access the streams at representative locations and following a sampling protocol. A comprehensive set of variables was measured at sites in the field. Most of the observations involved recording presence/absence or measuring a quantity. Some variables were quantified using a subjective visual estimation method. These variables included the relative strength of the channel form, channel connectivity to floodplain, bed material calibre, and vegetation cover and continuity.

Terrain analysis, the automated analysis of landforms using digital elevation data sets, was undertaken using a Light Detection and Ranging (LiDAR) derived Digital Elevation Model (DEM). This objective of this analysis was to classify landforms. Field and desktop data were used to classify streams according to geomorphic type, and geomorphic condition.

The streams of the Study Area comprised the Order 6 sand-bed Isaac River, other large sand-bed streams in North, One Mile, Boomerang and Phillips creeks, the smaller Order 3 sand-bed Ripstone creek, plus some small shallow streams with vegetated mud bed. Of the small western tributaries streams, a portion of Western Tributary A passes through Mining Lease Application (MLA) 700032. The catchment is large enough to generate sufficient runoff to form a defined channel, as designated by a blue line, so consideration would need to be given to diversion of the flow from this small stream channel around the pit to Isaac River.

The catchments and channels of One Mile Creek, Boomerang Creek, and Phillips Creek do not pass through the MLAs, so they would not be directly impacted by open cut mining activity, although there is potential for the floodplain areas of the lower reaches of Boomerang and Phillips creeks to be impacted by altered flood hydraulics of the Isaac River. On the other hand, a large area of Ripstone Creek catchment is upstream of MLA 700033, and the creek channel then passes into and through this domain on its way to joining Boomerang Creek, just upstream of its junction with Isaac River. Open cut mining would likely directly impact a portion of lower Ripstone Creek catchment, so part of this channel require diversion around the pit. Creek diversion design and monitoring was outside the scope of this report, and was done as part of the flood study investigation.

The surface geology of the Study Area comprised extensive undifferentiated sandy sediments and soils and Quaternary alluvium within river corridors. This suggests that sand bed rivers and streams would be naturally occurring in this region, and not necessarily the result of accelerated sediment delivery caused by land use change, although this process could have increased the rate of sand delivery to channels above background levels.

The majority of the wider Study Area has moderately stable surface soils. Erodible non-cohesive soils and dispersive soils occur in fragmented patches, with more concentrated areas of erodible soils occurring in Ripstone Creek catchment just upstream of the core Study Area, and in the corridor of Isaac River just upstream of the core Study Area. The terrain within the MLAs was less than 10 degrees, except for moderately steep slopes forming the banks of Ripstone Creek. The channels of the major watercourses Isaac River, lower Phillips Creek and lower North Creek had almost continuous very steep banks, while lower Boomerang Creek channel had continuous moderately steep channel banks. Landform classification provided a reasonable separation between likely floodplain landform and surrounding valley slope landform, although the indicators were inconclusive for lower Ripstone Creek in particular.

Isaac River displayed distinctive channel narrowing in the downstream direction through the Study Area. This downstream narrowing occurred despite a significant increase in catchment area. The channel did not maintain its capacity downstream by increasing in depth or slope, suggesting that the floodplain becomes increasingly hydraulically connected to the channel in the downstream direction. The downstream slope of Isaac River is relatively constant, falling 40 m over 70 km for an average slope of 0.000587. Sinuosity of the river is 1.29. Ripstone Creek narrowed in its lower reach, as it approached its junction with Boomerang Creek. The floodplain is likely to be more hydraulically connected to the channel in the lower reach. Channel dimensions were highly variable along Ripstone Creek. The downstream slope of Ripstone Creek is relatively constant, falling 33.2 m over 26.2 km for an average slope of 0.001275. Sinuosity of the creek is 1.51.

Isaac River and North Creek, being laterally unconfined with extensive floodplain connection, belong to the Low Sinuosity Sand type. The lowland reaches of Boomerang Creek and Phillips Creek are a similar type at a smaller scale, but by virtue of their higher sinuosity are Meandering Sand type. The upper section of Ripstone Creek is partly confined with extensive floodplain connection. Downstream of this the stream is Planform Controlled Meandering Sand as the floodplain connection becomes less extensive. The lower section of Ripstone Creek is the Floodout type. Here it emerges onto the lateral zone of the Isaac River floodplain, where the channel changes from sand bed to fine-grained bed and becomes an unconfined flow path characterised by discontinuous deep pools. At the most downstream end, where Ripstone Creek starts incising to meet Boomerang Creek bed level, the channel becomes longitudinally continuous and more defined in cross-section form. Here the creek is best described as Meandering Fine Grained type. Western Tributary streams were sampled on lowland locations where they are situated on the Isaac River floodplain. Here, the channels are small, varying from continuous to discontinuous.

Most of the stream reaches were in a stable, close to natural geomorphic condition. Some streams were potentially impacted by factors that reduced their condition, in particular high loads of sand in the bed, but without historical data concerning condition prior to the land cover and drainage being modified for agricultural and mining use, this remains uncertain. No knickpoints or zones of major geomorphic instability were observed.

The risk of erosion of the Isaac River channel and floodplain was assessed using the method of maximum permissible bed shear stress and velocity assessment, with the hydraulic variables modelled as part of the flood study. This assessment of the most critical areas found that while there could be isolated areas subject to somewhat higher risk of scour compared to the existing situation, the overall risk of rapid and significant geomorphic change in the Isaac River due to the proposed mining activity was low.

1.0 Introduction

1.1 Characteristics of the Olive Downs Coking Coal Project

Pembroke Resources Pty Ltd (Pembroke) is progressing the design and approval for the Olive Downs Coking Coal Project (the Project). The Project is located in the Bowen Basin, Central Queensland, approximately 40 kilometres (km) southeast of Moranbah (Figure 1).

The Project is an open cut mining complex comprising five Mining Lease Applications (MLAs) that cover two mining areas that for some time have been known as Olive Downs South Domain and Willunga Domain, and associated linear infrastructure corridors (i.e. Isaac River haul road crossings, mine infrastructure areas (MIAs), coal handling and processing plant (CHPP), rail spur, water management infrastructure, electricity transmission line (ETL), and access roads) (Figure 2). The total extent of the of MLAs is approximately 26,402 hectares (ha).

The proposed mine plan will deliver up to 20 million tonnes per annum (Mtpa) of Run-Of-Mine (ROM) coal for more than 30 years. Approximately 90% of the product coal would be high quality metallurgical coal, with the remainder a thermal coal by-product. The main water demands for the Project, i.e. coal handling preparation plant (CHPP) water supply and dust suppression, would fluctuate with the rate of ROM coal feed to the CHPP and as the extent of the mining operation changes over time.

1.2 Scope and Objectives of this Technical Report

This report characterised the physical environment from a geomorphologic perspective. The scope of work for this Geomorphology Technical Report included, but was not limited to:

- Existing background data collection to provide a baseline of pre-mining geomorphic condition
- Field data collection within the Study Area, including, but not limited to:
  - fluvial features, including, but not limited to, incision, aggradation, 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 and related attributes, including, but not limited to:
  - Stream Order and geomorphic type classification;
  - In-channel fluvial features; and
  - Riparian zone vegetation structure.
- Technical assessment of geomorphic-related factors, including, but not limited to:
  - existing geomorphic conditions and processes within the Study Area;
  - assessment of geomorphological condition and fragility of stream reaches within the Study Area;
  - assessment of potential impacts of the Project on geomorphic character of stream reaches in the Study Area; and
  - assessment of regional cumulative impacts on geomorphic characteristics of streams.
- Recommendations for mitigation and monitoring of geomorphic condition.

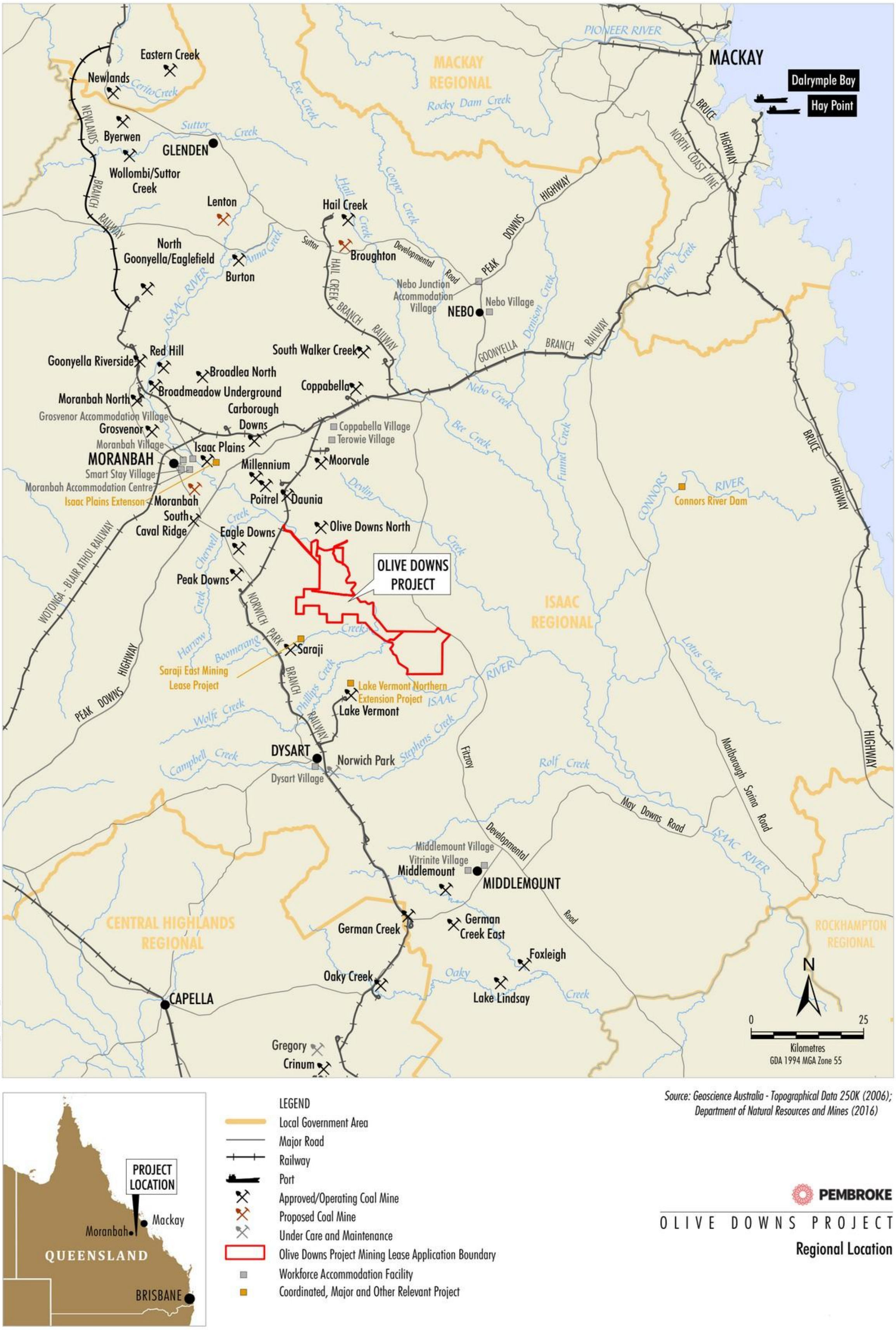

Figure 1. Olive Downs Coking Coal Project regional location. Source: Resource Strategies.

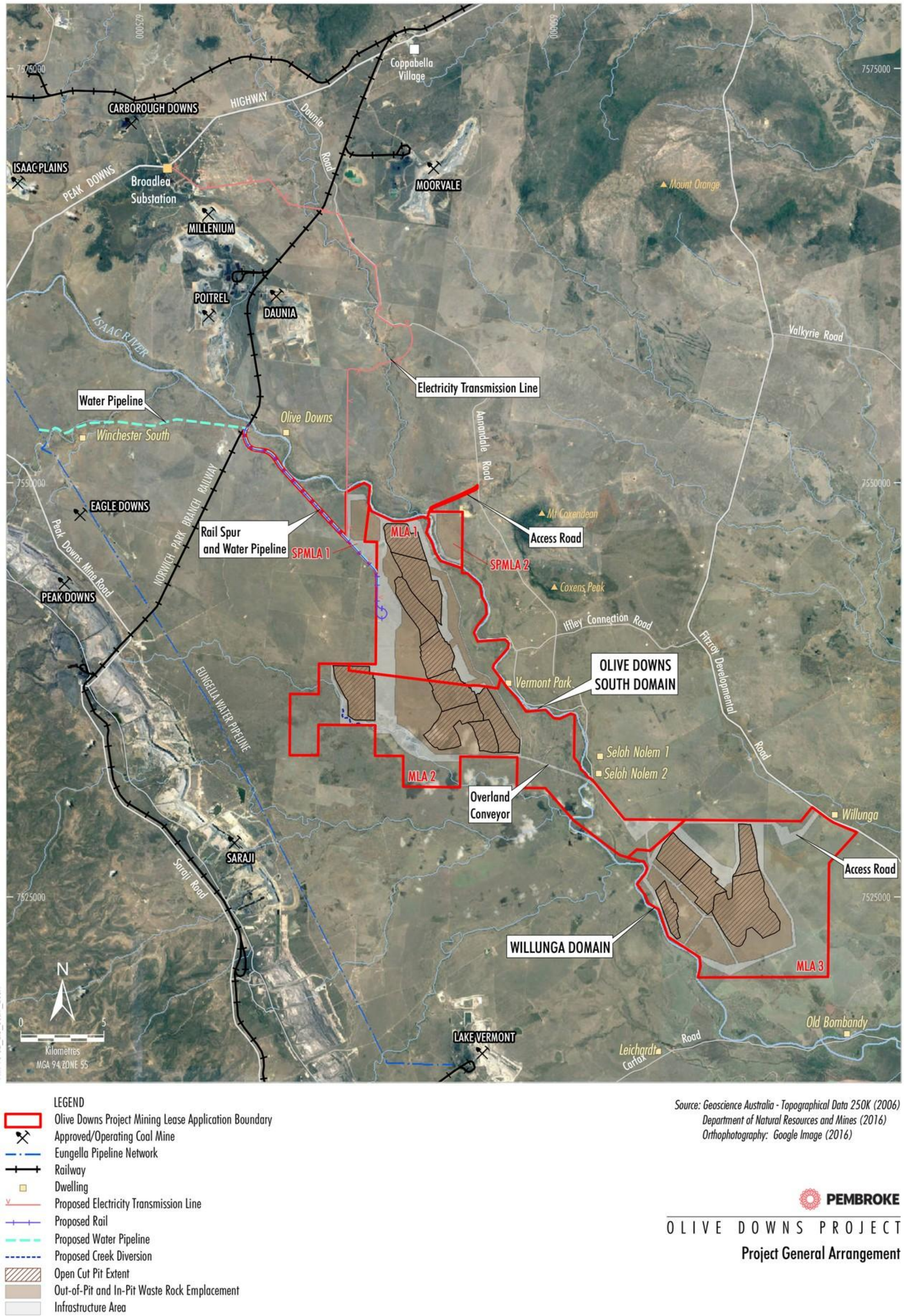

Figure 2. Olive Downs Coking Coal Project general arrangement. Source: Resource Strategies.

1.3 Relevant Policy and Legislative Requirements

This Technical Report is an input to the Project Environmental Impact Statement (EIS) and has been prepared in accordance with the terms of reference set out by the Coordinator General (Department of State Development, 2017), in keeping with the requirements of a coordinated project for which an EIS is required under section 26(1)(a) of the State Development and Public Works Organisation Act 1971 (SDPWO Act).

The requirements for an EIS under the SDPWO Act were set out in Department of State Development (2017). With respect to providing an appropriate level of detail, the general requirement is for a level of detail that is proportional to the scale of the impacts on environmental values. Additionally, all available baseline information relevant to the environmental risks of the project must be provided, including details on the quality of the information, in particular with respect to its date, reliability and uncertainty.

This Technical Report addresses part of the environmental objectives to be met under the Environmental Protection Act 1994 (EP Act) for Land, Flora and Fauna (Department of State Development, 2017, p. 16), specifically '(a)…the environmental values of land including soils, subsoils, landforms and associated flora and fauna', whereby impact prediction must address '(b) the topography, geology, geomorphology of the project sites and adjoining areas'.

There is no legislative or policy requirement regarding the methodologies to be applied in undertaking geomorphological investigations for the purpose of an EIS. The methodologies employed in this Technical Report followed current best practice.

1.4 Report structure

This report is structured as follows:

Section 1 Introduction – outlines the Project and presents the purpose of the report

Section 2 Methodology – describes the methodology employed for this Geomorphology Technical Report

Section 3 Existing environment – describes the character of the existing geomorphologic environment

Section 4 Impact assessment – describes the potential impacts to geomorphologic character of the environment resulting from the proposed Project

Section 5 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 Monitoring and Evaluation

Section 7 Conclusion

Section 8 References

2.0 Review of Some Other Geomorphic Investigations in the Fitzroy Basin

As part of an assessment of the Baralaba North Continued Operations Project, WRM Water & Environment (2014) undertook a geomorphological study of part of the Dawson River, south of the Study Area. They described the general characteristics of the stream channels and used two dimensional TUFLOW hydraulic modelling undertaken on a 20 m grid to assess the geomorphic impact of the project for low frequency, high magnitude, events in the range 1 in 20 to 1 in 1000 year average recurrence interval (ARI). The geomorphic impact was assessed in terms of the hydraulic variables velocity, within both channel and floodplain, water level, and afflux. The impact of the project on the hydraulic characteristics of these large events was small, so it was assumed that the more frequent geomorphic channel forming events would be unaffected. WRM Water & Environment (2014) also compared aerial photographs taken over the period 1961 to 2011 and observed no measureable change in stream channel alignments despite the occurrence of 5 major flood events. A separate geomorphology assessment of the area by Water Solutions compared the design guideline limits for significant erosion and geomorphological change in the 'Guideline for Watercourse Diversion – Central Queensland Mining Industry' (DERM, 2011; White et al., 2014). These guidelines are based on generic acceptable thresholds for the hydraulic variables shear stress, velocity and stream power. The thresholds take in account vegetation cover, but not the bank or bed materials, which also have a major influence on resistance to erosion and sediment transport.

The Red Hill Mining Lease is located on the upper Isaac River, upstream and north of the Study Area, approximately 20 kilometres (km) north of Moranbah and 135 km south-west of Mackay. Alluvium (2011) undertook a geomorphic assessment as part of the EIS for proposed longwall mining by BHP Billiton Mitsubishi Alliance (BMA). Alluvium (2011) described the geomorphic character, behaviour and condition of the Isaac River and tributaries within the potentially impacted area. Watercourses included in the assessment were those mapped as blue lines on Geoscience Australia digital mapping at the scale of 1:100,000. They noted that the definition of watercourse in the Water Act 2000, given as "…*a river, creek or stream in which water flows permanently or intermittently – (a) in a natural channel, whether artificially improved or not, or (b) in an artificial channel that has changed the course of the watercourse…*" could exclude discontinuous channels. However, Alluvium (2011) used aerial photography and digital terrain data to determine the flow paths of watercourses mapped as discontinuities, and then classified watercourses as unchannelised (no channel), discontinuous channel and continuous channel.

Alluvium (2011) described the Isaac River as a low to moderate sinuosity, ephemeral, sand bed stream that is largely alluvial (i.e. adjustable bed and banks) downstream of the Burton Gorge. The river was terrace-confined, with the terrace a paleo floodplain likely to have been formed during climatic conditions that produced larger discharges than the contemporary flow regime (Alluvium, 2011). The modern active floodplain is a narrow (150 – 500 m wide) band on one or both sides of the channel that is 2 – 4 m lower in elevation than the terrace (2,000 – 5,000 m wide). The narrow floodplain contains the 1 in 100 year ARI event. The riparian vegetation was described as having a reasonably continuous overstorey, minimal understorey and variable groundcover, often dense, with exotic grasses dominant.

Alluvium (2011) considered the geomorphic condition of the Isaac River to be compromised by excess sand bedload, released from the catchment at accelerated rates through changed land use. Alluvium (2011) provided no evidence to support this claim, but contrary evidence is publicly available in the journal of Ludwig Leichardt, who, upon first sighting the Isaac River on 13 February 1845, described it as having a 'very sandy' bed (Leichardt, 1846).

The G200s Project involved additional underground longwall mining in the western portion of the existing Grosvenor mining lease, located directly north and adjacent to Moranbah township on the Isaac River (Hansen Bailey, 2016). The area of the Isaac River catchment to this point was estimated to be 1,800 square kilometres (km^2). Hansen Bailey (2016) described the Isaac River as ephemeral, with naturally elevated sediment loads and extensive sediment deposition associated with wet season flows in November to April. The assessment by Hansen Bailey (2016) involved a desktop study of a high resolution topographic data to determine flow paths, supported by a field investigation. Hansen Bailey (2016) described the Isaac River as incised, inundating the floodplain only under extreme floods, and having a fairly featureless sand bed with occasional vegetated bars within the channel.

Hansen Bailey (2016) assessed geomorphic character using AusRIVAS habitat assessment methodology (Parsons et al., 2002). This Australia-wide generic approach relies largely on subjective visual assessment to quantify a range of physical stream-related variables assumed relevant to the ecological assets of the river. Establishing the relevance of variables to a particular area would require prior knowledge of the local assets and their habitat requirements and preferences. Some variables would be irrelevant, or their relevance could not be established, in which case collecting and presenting such data would be pointless. On the Isaac River main channel, Hansen Bailey (2016) chose 7 sites over a distance of about 3 km, for an average spacing of about 500 m. The description of the Isaac River near Moranbah was similar to that near Red Hill Mining Lease (Alluvium, 2011). Here it was moderately sinuous with a broad floodplain, having continuous to semi-continuous remnant riparian vegetation invaded by exotics. The channel was U-shaped with stable convex banks, covered in a mud drape, which enhanced bank stability, also noted by Alluvium (2011). Bank undercutting was apparent in locations where the mud drape had been eroded. Several small, shallow pools were present but the sand bed was largely featureless apart from extensive vegetated bars.

The Lake Vermont Northern Extension Project is a proposed open cut mine extension located on Phillips Creek, a tributary of the Isaac River, approximately 170 km southwest of Mackay and approximately 15 km northeast of Dysart (Aarc, 2016). This project is immediately west of the Willunga Domain of the Olive Downs Coking Coal Project. Field stream morphology assessments were completed at 19 sites along an approximately 15 km long reach of Phillips Creek for an average spacing of about 830 m (Aarc, 2016). The survey provided a comprehensive assessment of the landform and channel characteristics (e.g. depth, width, composition, bank stability, etc.), riparian vegetation and aquatic habitat features. Habitat quality was assessed using a modified form of the AusRIVAS habitat assessment methodology. The geomorphic variables were measured at cross-sections. Phillips Creek had a relatively flat sand bed. Riparian vegetation was dominated by River Red Gum (*Eucalyptus camaldulensis*) and River She-oak (*Casuarina cunninghamiana*), typically with an associated presence of Moreton Bay Ash (*Corymbia tessellaris*). Bank stability was rated to range from very poor to good with average side slopes of 60° on both banks. The majority of the creek was found to be of moderate condition with occasional small- to moderately-sized areas of erosion. The downstream section of the creek was considered to be of poor or very poor condition due to impacts from creek crossings and livestock access, which have resulted in significant areas of erosion. Overall, Phillips Creek was rated as having a slightly to moderately disturbed ecosystem (Aarc, 2016).

The above studies used a range of desktop and field survey methodologies to undertake geomorphic assessment. The methods used in these previous studies were considered potentially useful for the Study Area, with the exception of the AusRIVAS habitat assessment methodology, which was excluded on the basis of its generic nature and lack of focus on geomorphic processes and forms. The above studies were of fairly short stream reaches 2 to 15 km long, while the Isaac River in the Project area is over 50 km long. This scale difference suggests that for practical reasons, a wider site spacing than 500 – 800 m would be appropriate for at least some streams within the Project area (notably, the Isaac River), provided the sampling density was adequate to capture the spatial variability in geomorphic character of the streams.

3.0 Methodology

3.1 Study Area

In this Geomorphology Technical Report the core Study Area is the area bounded by the five MLA areas comprising the Olive Downs Coking Coal Project: MLAs 700032, 700033, 700034, 700035 and 700036 (Figure 2, Figure 3). With respect to sediment and surface water fluxes, the MLA areas, being situated within catchments, are not closed systems, so potential geomorphological impacts of the proposed mining are not necessarily confined within them. Also, the geomorphic character of the slopes, floodplains and channels within the MLAs is strongly conditioned by processes occurring in the upstream catchment area. Thus, the Study Area was also considered within the context of the geomorphological character of the wider area of the Project, which includes the catchments of streams that drain to and from the core Study Area (Figure 2). The areal extent of the wider area depended on the variable under consideration, but the aim was to include the area likely to significantly influence, or be significantly influenced by, geomorphic processes occurring within the core Study Area.

A number of maps in this report show geomorphologically-relevant data extending outside the Study Area. In such cases, the information located outside the Study Area was included to show the continuity of the attribute being described, and/or to illustrate the regional context of the attribute.

Some field data were collected from stream sites outside the core Study Area boundary. This data collection was either:

- unintentional because the position of MLA boundary on the stream was known in the field to within approximately ±100 m; or
- intentional because the stream under survey near the MLA boundary was perceived in the field to potentially have geomorphological relevance to assessment of baseline conditions or Project impact assessment.

3.2 Measurement scales

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

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

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

Characterisation of the fluvial geomorphological features of the Study Area was based on a combination of field survey and desktop analysis of existing data.

3.3 Data Sources

3.3.1 Primary data

A geomorphological field survey of the Project Area was undertaken by Dr Christopher Gippel of Fluvial Systems Pty Ltd over the period 13 – 16 June 2017. The field survey collected readily quantifiable data that either could not be readily obtained from remotely sensed data or was used to supplement or ground truth remotely sensed data.

3.3.2 Spatial data

The investigation relied heavily on detailed topographic data and aerial photography. Airborne Laser Scanning (ALS), also known as Light Detection and Ranging (LiDAR), data were acquired using fixed wing aircraft. The LiDAR data were supplied as three separate groups of files:

- 20 × 20 m grid of point elevations;
- 10 × 10 m grid of point elevations along stream corridors of Isaac River, Cherwill Creek, Boomerang Creek and Phillips Creek; and
- variably spaced cloud of point elevations within a 5 × 5 m grid of point elevations (nominally referred to here as a 5 × 5 m grid).

The areas covered by these three groups of survey data overlapped to a large extent (Figure 3). In general, the higher resolution data were preferred, but there was a small area (3.8 km^2) covering Isaac River 8 km upstream of the north-western extent of the Study Area where the 10 × 10 m grid data were preferred over the 5 × 5 m grid data.

The surface elevation of areas that were of interest beyond the LiDAR coverage was estimated from 3 arc-second (approximately 90 m) Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) data obtained from National Aeronautics and Space Administration (NASA) (http://www.jpl.nasa.gov/srtm). The SRTM data are affected by vegetation, and have a much poorer spatial and vertical resolution than LiDAR data.

Digital GIS layers of existing standard watercourse, road, rail, soil erodibility and underlying geology mapping of the region encompassing the Study Area were downloaded from Queensland Government Queensland Spatial Catalogue (QSpatial) (http://qldspatial.information.qld.gov.au/catalogue). Digital Atlas of Australian Soils data (1:2,000,000 scale) were downloaded from Australian Soil Resource Information System, CSIRO (http://www.asris.csiro.au/themes/Atlas.html). Australia 1:250,000 Geological Series maps, Bureau of Mineral Resources, Geology and Geophysics, Department of National Development, and Geological Survey of Queensland were downloaded as non-georeferenced images from Queensland Government Department of Natural Resources and Mines via QDEX Data (http://qdexdata.dnrm.qld.gov.au/flamingo/).

Watercourse data were from 'Watercourse lines - North East Coast drainage division - central section' published 5/05/2015, although the streamlines within the Study Area were compiled in 2009. The watercourses are connected and flow directed; a sub-type of connector flows through waterbodies to create a linear network for hydrological modelling. Features are attributed with perenniality, Strahler Stream Order, hierarchy (Major or Minor) and names where available. Features were captured or updated from the best available imagery with an attribute within the data describing the source and reliability. Data sources include Queensland ortho-photography, satellite Imagery (SPOT 5), and Geoscience Australia 1:250,000 scale watercourse lines. Features within this dataset have been progressively updated by drainage basin using imagery to 1:25,000 mapping specifications, but only 1:100,000 mapping specifications have been achieved for the Fitzroy basin. This watercourse layer is similar to digital layer 'Wetland data - version 4 - wetland lines – Queensland', which ostensibly maps the same watercourses at 1:100,000 scale. The difference is that the wetland lines depict many of the watercourses as discontinuous, and appear to be sourced directly from the Geoscience Australia 1:250,000 topographic map series. Thus, the process of updating maps to a more detailed scale resulted in fewer drainage lines being depicted as discontinuous, which is an important distinction as the Water Act 2000 defines a watercourse as being within a 'channel'. For the purposes of this Technical Report, the blue lines on the 'Watercourse lines - North East Coast drainage division - central section' were all accepted as valid and included in the investigation. LiDAR data, field inspection, and topographically-derived drainage networks generated automatically by algorithms in Geographic Information System (GIS) all suggested the presence of additional or alternative dominant drainage lines in some parts of the Study Area. This was not surprising, especially in the low gradient floodplain areas where, during flood events, it would be expected for water to take paths additional to those indicated on topographic maps. For consistency, only the streams digitally mapped as blue lines at 1:100,000 scale were included for consideration in this Technical Report.

The 'Queensland Floodplain Assessment Overlay' (QFAO) represents a floodplain area within drainage sub-basins developed for use by local governments as a potential flood hazard area. It represents an estimate of areas potentially at threat of inundation by flooding, mapped at 1:100,000 scale. The data were developed through a process of drainage sub-basin analysis utilising data sources including 10 metre contours, historical flood records, vegetation and soils mapping and satellite imagery.

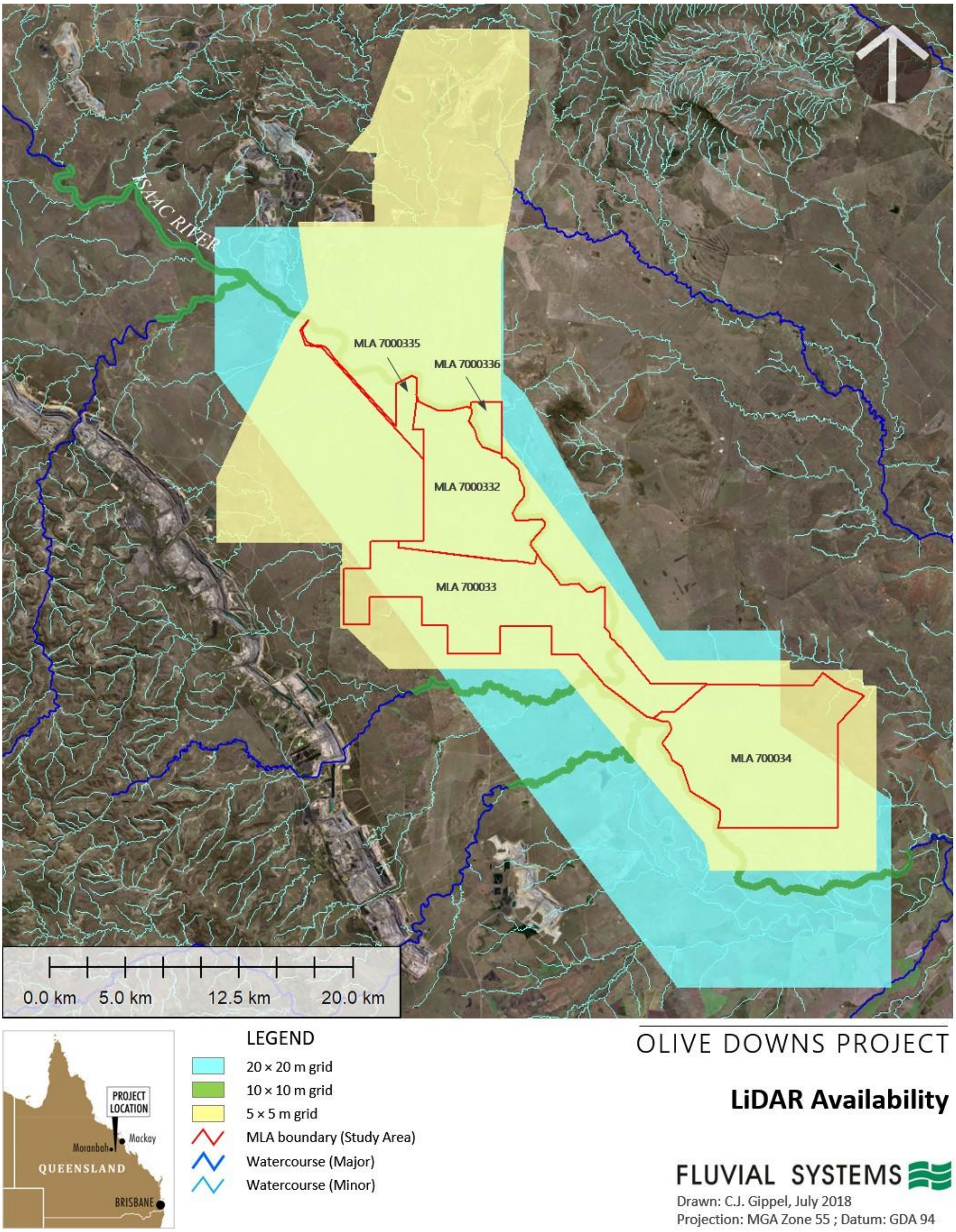

Figure 3. LiDAR data availability for the Study Area.

The Atlas of Australian Soils was compiled by H. Northcote and others of CSIRO in the 1960s to provide a consistent national description of Australia's soils. The maps were published at a scale of 1:2,000,000 but the original compilation was at scales from 1:250,000 to 1:500,000. The Digital Atlas of Australian Soils was created by the National Resource Information Centre (NRIC) in 1991 from scanned tracings of the published hardcopy maps. Mapped units in the Atlas are soil landscapes, usually comprising a number of soil types. The explanatory notes include descriptions of soils landscapes and component soils. Soil classification for the Atlas is based on the Factual Key (Northcote, 1979), which was the most widely used soil classification scheme prior to the Australian Soil Classification (Isbell, 2002). Ashton and McKenzie (2001) developed a conversion of the Atlas of Australian Soils to the Australian Soil Classification which remains unpublished but is available as a table (http://www.asris.csiro.au/themes/Atlas.html). The Australian Government Bioregional Assessment Programme, a collaboration between the Department of the Environment and Energy, the Bureau of Meteorology, CSIRO and Geoscience Australia, used the conversion table to develop the product 'Spatial Data Conversion of the Atlas of Australian Soils to the Australian Soil Classification v01', published in 2016. In this Technical Report, soils are mapped using the key soil descriptors of both systems.

Soil erodibility data were from 'Fitzroy NRM region surface soil erodibility - Central Queensland', published 24/04/2017. This raster dataset classifies surface soil erodibility on a 90 × 90 m grid at the sub-catchment scale. Soil erodibility is the susceptibility of soils to detachment and transportation by erosive agents. It is a composite expression of those soil properties that affect the behaviour of a soil and is a function of the mechanical, chemical and physical characteristics of the soil. Surface soil stability is categorised into five classes. The higher the number, the greater the erodibility:

0 = Not assessed

1 = Moderately stable surface soils

2 = Non-cohesive surface soils

3 = Dispersive surface soils

4 = Highly erodible surface soils

A related soil erodibility dataset is 'Fitzroy NRM Region soil erodibility - Central Queensland'. This dataset maps the same variable at the same spatial scale, but includes sub-classes of erodibility, to give a total of 18 classes. This greater level of data resolution would not have provided a significant improvement in information for the purpose of this geomorphological assessment.

Underlying hard rock geology was from 'Regional geology 1985 - Bowen Basin', published in 2004. The data provide an interpretation of the extent of rock units underlying regolith, soil or basalt, and the location and type of geological structures which have affected the rock units. Surface geological units, which show Quaternary material, were from Australia 1:250,000 Geological Series. The relevant maps were Clermont Sheet SF 55-11, published 1968, and Saint Lawrence Sheet SF 55-12, published 1970. These two sheets were downloaded as non-georeferenced images covering the full map extents. These images were rectified against lines of latitude and longitude, and then cropped, in GIS.

3.4 Geomorphologically-relevant variables

Two main groups of variables were of interest to geomorphological characterisation of the Study Area:

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

3.4.1 Landscape-scale variables

Landscape-scale variables provide information to help explain catchment-scale geomorphological processes, and risks associated with mining impacts; 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

3.4.2 Stream reach- and point-scale variables

Stream-reach and point-scale variables were used to characterise geomorphological processes and forms for the purpose of baseline classification of stream type, condition and fragility/resilience to disturbance. Variables were selected mainly on the basis of their relevance to stream classification, potential impacts of open-cut mining on streams, and characterisation to aid stream diversion design.

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. Streams reaches with high fragility and poor condition are rated low priority, while reaches low fragility that are in good geomorphic condition are rated the highest priority for protection.

River Styles® is a system for classifying stream geomorphic type 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).

This Geomorphology Technical Report classified the streams in the Study Area according to river type and geomorphic condition, using an approach that was consistent with River Styles®. This required collection of data concerning valley setting, stream slope, channel dimensions and shape, and bed material type.

Geomorphic condition is strongly linked to the degree of naturalness and extent of cover of riparian vegetation (Outhet and Cook, 2004; Outhet and Young, 2004a). 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. This Geomorphology Technical Report defined the riparian zone as a distance of up to 50 m from the channel edge, which is consistent with that used by Munné et al. (2003) and Raven et al. (1998), and is practical for a rapid assessment approach.

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

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[1] Meaning true grasses, of the family Poaceae (also called Gramineae).

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. Comprehensive mapping of pool and riffle morphology would require sampling and survey at a much more detailed spatial scale than that used in this investigation. Regardless, most of the streams in the Study area were sand bed and therefore lacked pool-riffle morphology. While general pool presence/absence was noted as part of the stream type classification, the field survey did not attempt to measure pool dimensions.

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

- Stream geomorphic type and condition,
- Riparian and in-channel vegetation,
- Channel slope,
- Channel dimensions, and
- Channel bed materials.

3.4.3 Sites of geomorphological significance

Geomorphological character is, for the most part, value-free in that a stream cannot be ranked in terms of importance based on their geomorphologic character alone. The main relevance of geomorphological character is the implications it has for the ecological character. 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 Queensland. No published or anecdotal evidence was found indicating the existence of sites of geomorphological significance within the Study Area.

3.5 Field survey

3.5.1 Sampling approach

The objective of the field survey was to obtain sufficient information to enable characterisation of stream type, and stream geomorphic features. Stream type classification relies partly on attributes that can only be measured in the field, and partly on attributes that can be measured from maps and terrain data.

The objective of the field survey was to sample the range of streams marked by blue lines at 1:100,000 scale by assessing short lengths of representative stream sites. Aerial photography suggested that the Isaac River and major tributaries within the Project area were of consistent geomorphic type over long distances, such that sample site spacing over the orders one to ten kilometres would be adequate.

Like most geomorphic surveys, sampling locations were not chosen randomly due to the high potential for experiencing difficulty in accessing sites. The large size of the Project area deemed foot travel impractical for most areas, and travel by light Four Wheel Drive (4WD) vehicle or All Terrain Vehicle (ATV) was mostly limited to existing tracks. Thus, the general locations of field sites was largely determined by accessibility, while the exact location was subjectively determined as representative of the general reach geomorphic character, and distant from unusual local disturbances, such as vehicle or stock crossings.

The field data were collected within the period 13 to 16 June 2017. All of the measurements, estimates and data recording were made by C.J. Gippel. Data were recorded on a GPS-equipped tablet computer using a specially designed form compiled in ODK (Open Data Kit; http://opendatakit.org/). At each observation point, two photographs were taken with the tablet device, one looking downstream and one looking upstream. Each photograph was linked to the data from the site within the ODK form. For quality assurance purposes, a second set of photographs were taken independently with a GPS-enabled camera and 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. This approach resulted in 54 sets of observations.

3.5.2 Field sampled variables

A comprehensive set of variables was measured at sites in the field (Table 1). In general, the measurements were done using standard techniques from the literature. Most of the observations involved recording presence/absence or measuring a quantity. As previously explained, the presence/absence of pools was noted, but these features were not measured. Exposed bedrock was rare, and so small relative to the scale of the river channel that it had minor impact on geomorphic process and form, so its presence was not recorded.

Table 1 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
Chanel shape variability	Strength of variability in form in cross-section and profile, and regularity of form in the downstream bed profile (3 classes each)
Bed material calibre	Presence of, and dominant, material for 7 classes (adapted from Brakensiek et al., 1979): • Mud (silt and clay) • Sand (0.06 - 2 mm) • Gravel (2 - 64 mm) • Cobble (64 - 256 mm) • Boulder (exceed 256 mm) • Exposed bedrock slab • Artificial (hard lined)
Large wood and log jams	Count of items over 20 m length of channel; large wood is ≥0.1 m diameter and ≥1 m long (Gippel, 1995); log jam is 3 or more locked pieces of large wood
Channel dimensions	Bed width, bankfull width, bankfull depth, measured using a rangefinder or tape
In-channel vegetation	Type for 6 classes - 4 macrophyte types, grass and trees - 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

Some variables were quantified using a subjective visual estimation method. These variables included the relative strength of the variability in the channel shape; floodplain size and connectivity with the channel; 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
- >5 – 25% score = 2
- >25 – 50% score = 3
- >50 – 75% score = 4
- >75% score = 5

3.5.3 Derived riparian vegetation cover index

Riparian vegetation cover index derived from the raw field-collected data. 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 on the Braun-Blanquet rank scale. 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.

$$C = \frac{3T+2S+G}{24} \qquad (1)$$

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).

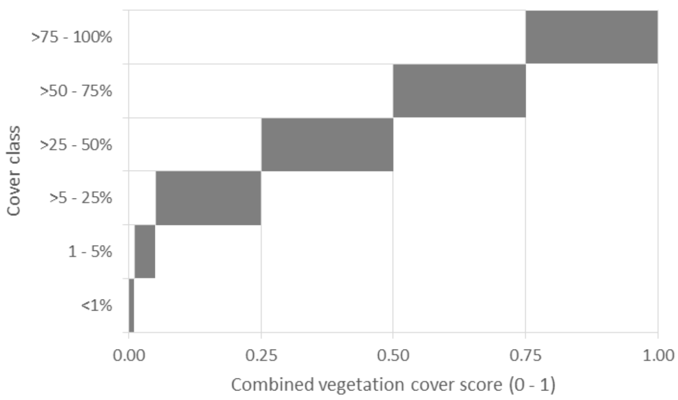

Figure 4. Scale for conversion of combined riparian vegetation cover index score to class.

3.5.4 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.

3.6 Terrain analysis

Geomorphology is concerned with both physical form and process. Process involves the dimension of time, so tends to be more difficult to measure and model than form. For this reason, geomorphologic assessments often interpret process on the basis of an analysis of physical form. Terrain analysis is concerned with the automated analysis of landforms using digital elevation data sets. The analysis involves application of algorithms within a GIS (Geographic Information System) at detailed scales over wide areas to map characteristics of interest (e.g. Gardner and Sawowsky, 1990; Wilson and Gallant, 1998; Wilson and Gallant, 2000; Lindsay, 2005; Drăguţ and Blaschke, 2006; MacMillan and Shary, 2009).

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).

3.6.1 Topography (digital elevation) definition

The topography of the Study Area was defined by a 5 × 5 m DEM derived from the supplied LiDAR data. For areas beyond the bounds of the LiDAR coverage, the DEM was extended using SRTM data. The classification of landforms is conventionally done at a coarser scale, so for this procedure a 25 × 25 m DEM was used.

3.6.2 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 was an attribute provided for all stream links in the 1:100,000 digital watercourse dataset, but it contained numerous errors, mainly with Order 1 and Order 2 stream links, a large number of which were assigned Order 0, which is invalid. These errors were corrected for all stream links within the entire Isaac River catchment upstream of Stephens Creek.

3.6.3 Sub-catchment area

Sub-catchment areas were determined for the entire Isaac River catchment upstream of Stephens Creek, which joins the river downstream of the Study Area, using the ‘Generate Watershed’ function of Global Mapper™. This function uses the standard 8-direction pour point algorithm (D-8) (Jenson and Domingue, 1988) to generate a drainage network from the DEM. Depressions in the DEM were first filled to a depth of 7 m, then drainage was generated using parameter settings of minimum stream length 500 m and minimum sub-catchment area 2 km^2. This drainage network was intended to emulate that of the 1:100,000 blue line network, but differed in some areas with respect to stream length and position. These differences were unimportant as the DEM-derived drainage network was not used in the assessment, and the associated sub-catchment areas were an acceptable representation of the areas draining to the blue line network.

3.6.4 Slope

Slope was evaluated for the entire Study Area at 5 × 5 m resolution, and also along individual stream links, by sampling the grid along the channel thalweg at a 5 m spacing.

3.6.5 Landform Classification

One determinant of stream type classification is its landscape context, which is informed by landform classification. A number of different methods have been proposed for classifying landforms based on topographic data (e.g. Schmidt and Hewitt, 2004; Iwahashi and Pike, 2007; Niculiță and Niculiță, 2011). Landform classification can provide objective assistance to stream type classification, and to delineate hydrologic and geomorphic units such as valley bottoms (also known as floodplains, or alluvium) (Gallant and Dowling, 2003). The objectivity of automatic identification of floodplain extent is an advantage over subjective methods, although manual methods that combine hydraulic, slope and soils data can produce a rational and defendable result and might be preferred in cases where high quality and high resolution data are available.

In this report three methods of landform classification, all implemented in SAGA GIS, were investigated. Methods of landform classification are very scale-dependent, being sensitive to the resolution of the DEM and the algorithm parameter settings, so reproduction of the results reported in this Technical Report requires the same input data and parameter settings to be used.

Topographic Position Index (TPI) was proposed by Guisan et al. (1999) and elaborated by Weiss (2001). The algorithm calculates the difference between a cell elevation value and the average elevation of the neighbourhood around that cell to classify landforms belonging to a total of up to 10 classes. Positive values mean the cell is higher than its surroundings while negative values mean it is lower. The degree to which it is higher or lower, plus the slope of the cell, can be used to classify the cell into slope position. If it is significantly higher than the surrounding neighbourhood, then it is likely to be at or near the top of a hill or ridge. Significantly low values suggest the cell is at or near the bottom of a valley. TPI values near zero could mean either a flat area or a mid-slope area, so the cell slope can be used to distinguish the two (Jenness, 2006). An example application of TPI to landform classification in the Carpathian Mountains, Slovakia can be found in Barka et al. (2011).

Terrain Surface Classification (TSC) was proposed by Iwahashi and Pike (2007). The TSC algorithm uses elevation, slope, convexity and surface texture to classify landforms belonging to a total of up to 16 classes

The TPI and TSC are global landform classification systems devised for universal application to any terrain. Within a small area of moderate gradient and elevation range such as the Study Area, only a subset of the maximum possible landform classes would be expected to be present.

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 or 100 times the tangent of the slope angle. 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. It is calculated as the ratio of the number of points of lower elevation to the total number of points in the surrounding region. Low values indicate the point is low in the local landscape since most of the surrounding points are higher. The MRVBF algorithm was developed using 25 m resolution DEMs. According to Gallant and Dowling (2003), 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 for 25 m DEMs; flatter and larger valley bottoms are represented by values from 1.5 to 2.5, 2.5 to 3.5, and so on. Thus, there is no absolute threshold of MRVBF that unequivocally identifies a valley bottom, or floodplain, for all situations.

3.7 Stream geomorphic type and condition

3.7.1 Stream geomorphic type classification

The geomorphic stream type classification used here borrowed from, and is consistent with, the River Styles® framework (Brierley and Fryirs, 2000; Brierley and Fryirs, 2005; Brierley and Fryirs, 2006; Fryirs and Brierley, 2006). The River Styles® classification is based on valley setting (whether confined partly-confined or unconfined), 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 criterion 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.

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 Order 3 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, cutoff channels, backswamps, wetlands and floodplains. The streams classed Major in the 1:100,000 Watercourse layer suit this classification system but small-scale Minor streams can be difficult to categorise using this system.

Stream type classification in the Study Area was done on the basis of field-collected data, aerial photography and terrain data for surveyed stream links. The subjective nature of classifying stream reaches into geomorphic types (or River Styles®) means that the procedure is uncertain and unlikely to be highly repeatable.

3.7.2 Stream geomorphic condition classification

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

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

Geomorphic condition relates primarily to the connections and linkages with the floodplain, reaches up and downstream and more importantly, assesses the effect of human disturbance on the current evolutionary stage (Cook and Schneider, 2006). For use in River Styles® assessments, Outhet and Cook (2004) classified geomorphic condition in according to three categories, with each having a number of identifying characteristics (Table 2).

Table 2 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. • Patchy effective vegetation coverage relative to the reference reaches (allowing some localised accelerated erosion).
Poor condition Stream exhibits one or more of these characteristics	• Abnormal or accelerated geomorphic instability (reaches are prone to accelerated and/or inappropriate patterns or rates of planform change and/or bank and bed erosion). • Excessively high volumes of coarse bedload which blanket the bed, reducing flow diversity. • Absent or geomorphically ineffective coverage by vegetation relative to the reference reaches (allowing most locations to have accelerated rates of erosion) or the reach is weed infested.

3.8 Impact assessment

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

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

- Removal of a stream channel and its catchment
- Removal of part of a stream, requiring diversion of the stream around the pit
- Hydrological change in the distribution of stream flows
- Hydraulic change, whereby alteration of the channel or floodplain morphology causes a change in bed shear stress, velocity and water depth, which in turn could alter sediment transport, and bed and bank erosion processes.

These potential agents of change could bring about a number of generic geomorphic responses (Table 3) that would constitute an environmental impact with possible implications for environmental values. Some of these risks were assessed directly or indirectly by other relevant technical specialists (see other technical specialists reports for details).

Table 3 Potential generic geomorphic responses to open cut mining-related causes.

Potential geomorphic response (event type)	Mining-related risks (see below for explanation)
1. Change in stream type, irreversible over management time scales (< 100 years)	1, 2
2. Change of alignment of channel	2
3. Simplification of channel morphology and habitat-scale hydraulics	2
4. Increase in sediment accumulation in channel bed	4, 5
5. Increase in sediment scouring in channel bed	3, 5
6. Increase in rate, or change in location, of bank erosion	5
7. Increase in rate of floodplain scour	3
8. Increase in cover (density) of vegetation on channel bed (baseflow shift from high depth of water to shallow depth)	4, 6
9. Decrease in cover (density) of vegetation on channel bed (baseflow shift from shallow depth of water to dry, or from shallow to deep)	4, 5, 6

Open cut mining related causes:

1. Removal of part or all of a stream channel and its catchment due to excavation of pit
2. Stream diversion construction to replace removed stream channel
3. Loss of active floodplain area due to excavation of pit
4. Decrease in stream flow due to artificially reduced catchment area
5. Increase in stream flow due to artificially increased catchment area
6. Management of natural surface water inflows and outflows from the mine site

The flood study undertaken by Hatch (2018) assessed the impacts of hydrological change in the distribution of stream flows, and management of natural surface water inflows and outflows from the mine site. In particular, Hatch (2018) addressed the design, and assessment of the impact, of the proposed diversion of Ripstone Creek. These potential risks are not further considered in this report. The main focus of geomorphic impact assessment in this Geomorphology Technical Report was on the potential for hydraulic change, whereby alteration of the Isaac River floodplain morphology could cause a change in bed shear stress, velocity and water depth, which in turn could alter sediment transport, and bed and bank erosion processes.

3.8.2 Method of maximum permissible velocity

Chow (1981, p. 164) noted that:

> "*The behavior of flow in an erodible channel is influenced by so many physical factors and by field conditions so complex and uncertain that precise design of such channels at the present stage of knowledge is beyond the realm of theory*."

Since that time there have been developments in the level of sophistication of river channel modelling capacity, but there have been no major advancements in relevant theory. The methodology used in this assessment is the traditional one, as described in Chow (1981, pp. 164-191) and other popular channel hydraulics texts. The two methods that have been most commonly applied to this type of problem are the:

- method of permissible velocity, and
- method of bed shear stress (also known as tractive force)

It is important to realize that while these approaches have been applied extensively in the river engineering industry throughout the world for decades, like all empirically based approaches, they remain subject to uncertainty.

The maximum permissible velocity (U_{max}) is the greatest mean channel velocity (U) that will not cause erosion of the channel body. A channel is stable when:

$$U < U_{max}$$

Chow (1981, p. 165) noted that maximum permissible velocity is "*very uncertain and variable*". When other conditions are the same, a deeper channel will convey water at a higher mean velocity than a shallow one. This is because the scouring is related to bottom velocities, which for the same mean velocity, are higher in the shallow channel. Tables of maximum permissible velocity appear in many channel design, engineering and hydraulics publications (e.g. Chang, 1988), and they are all based on values for canals given by Fortier and Scoby (1926), and from the USSR (Anon, 1936), although some agencies have adjusted these standard values on the basis of local empirical knowledge (e.g. Stallings, 1999) (Table 4).

Chow (1981) did not define what was meant by "*water transporting fine suspended solids*", but it would appear from Ritzema (1994, p. 769) that this refers only to very high concentrations of suspended solids, in the order of >20,000 mg/L, while the term 'clear water' essential means water with concentrations of suspended solids <1,000 mg/L. 'Clear water' would apply in nearly all situations in Australia.

The values given in Table 4 assume a bare channel surface (i.e. no grass or other lining or vegetation). Vegetation failure usually occurs at much higher levels of flow intensity than for soil (Fischenich, 2001) (Table 5, Table 6). The values given in Table 5 and Table 6 are average values for channels, and assume a reasonable depth of flow. In shallow flow situations, as would generally occur on floodplains, it is reasonable to assume that surfaces covered with sod forming grass would generally tolerate velocities of up to 2 m/s.

Flows with long durations often have a more significant effect on erosion than short-lived flows of higher magnitude (Fischenich and Allen, 2000, p. 2-23). Fischenich (2001, p. 6) recommended application of a factor of safety to U_{max} "*when flow duration exceeds a couple of hours*". Graphs are provided in Fischenich (2001) for factoring according to event duration (Figure 5). The duration of flood events naturally varies, although in general the higher the magnitude, the longer is the duration. The relationships imply that the maximum permissible velocity could be very low if the curves asymptote to zero velocity. Of course, the suggestion of a zero maximum permissible velocity is a contradiction in terms, but this raises the idea that there is no such thing as a maximum permissible velocity below which erosion does not occur (Chow, 1981, p. 166).

Anon (1936) gave correction factors for U_{max} for channels greater than 1 m deep (factor >1), and less than 1 m deep (factor <1). A factor of 0.8 would apply to flow 0.25 m deep, 0.9 would apply to flow 0.5 m deep, 1.1 would apply to flow 1.5 m deep, and 1.2 would apply to flow 2.5 m deep. The maximum factor plotted on the graph is 1.3, which would apply to flow 4 m deep. Extrapolation using a power function suggests a correction factor of 1.4 for flow 6 m deep, 1.5 for flow 8.5 m deep, and 1.6 for flow 12 m deep.

Tabulated values of U_{max} are for straight channels, and for sinuous channels U_{max} should be reduced. Lane (1955) recommended reductions in U_{max} of 5% for slightly sinuous channels, 13% for moderately sinuous channels, and 22% for very sinuous channels.

Table 4. Maximum permissible velocities for channels formed in a range of materials. Assumes a flow depth of 1 metre. Note: no vegetative cover.

Bed material (USDA soil description)	Maximum permissible velocity (m/s)		
	Clear water[3]	Water transporting fine suspended solids[3]	Values used in Virginia (USA)[4]
Ordinary firm loam[1]	0.8	1.1	0.9
Stiff clay, very colloidal[2]	1.1	1.5	1.0
Alluvial silts, colloidal	1.1	1.5	-
Alluvial silts, non-colloidal	0.6	1.1	-
Sandy loam, non-colloidal	0.5	0.8	-
Fine gravel	0.8	1.5	-

1. Plastic clay soil; mixture of clay, sand, and/or gravel, with minimum fines (silt and clay) content of 36% (Stallings, 1999).

2. Moderately to highly plastic clay; mixtures of clay, sand, and/or gravel, with minimum clay content of 36% (Stallings, 1999).

3. Fortier and Scoby (1926) – see Chow (1981, p. 165). The term 'clear water' essentially means water with concentrations of suspended solids <1,000 mg/L (Ritzema, 1994).

4. Stallings (1999).

Table 5. Maximum permissible velocities for channels with slopes of 0 – 5% in easily eroded soils lined with grass (assume average, uniform stands of each type of cover). Source: Adapted from Chow (1981, p. 185), using data from the U.S. Soil Conservation Service.

Cover	Maximum permissible velocity (m/s)
Sod forming grass: *Cynodon dactylon* (Bermuda grass)	1.8
Sod forming grass: *Bouteloua dactyloides* (Buffalo grass), *Poa pratensis* (Kentucky bluegrass), *Bromus inermis* (smooth broome), *Bouteloua gracilis* (blue grama)	1.5
Grass mixture	1.2
Bunch grass: *Lespedeza cuneate* (Chinese bushclover or Sericea lespedeza), *Eragrostis curvula* (African, or weeping love grass), *Bothriochloa ischaemum* (yellow bluestem), *Pueraria lobata* (kudzu), *Medicago sativa* (alfalfa or lucerne), Digitaria (crabgrass)	0.8
Annuals	0.8

Table 6. Maximum permissible velocities for channels lined with grass. Source: Fischenich (2001) using data from various sources.

Cover	Maximum permissible velocity (m/s)
Class A turf	1.8 – 2.4
Class B turf	1.2 – 2.1
Class C turf	1.1
Long native grasses (U.S.A.)	1.2 – 1.8
Short native grasses (U.S.A.)	0.9 – 1.2

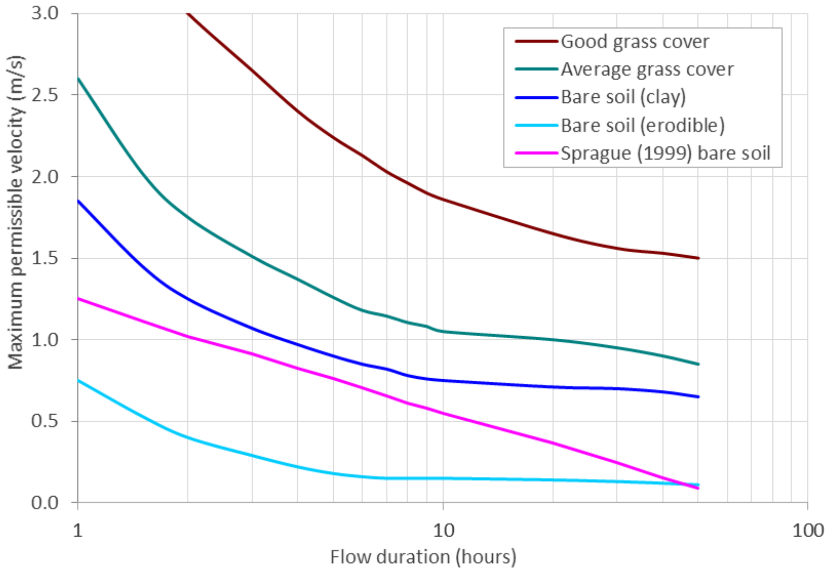

Figure 5. Erosion limits as a function of flow duration. Based on a plots from Fischenich (2001, p. 6) and Sprague (1999).

3.8.3 Method of maximum permissible bed shear stress

Mean bed shear stress (N/m^2) (τ) is:

$$\tau = \rho g R S$$

where,

R = hydraulic radius of the channel, equal to A/P where A is the cross-sectional area of the flow, and P is the length of the wetted perimeter; in a spatial flood model R of a cell can be represented by water depth at the cell (m).

S = the energy slope of the water; in a spatial flood model S can be approximated by the water surface slope at the cell (m/m).

ρ = the density of the water (usually assumed to be 1,000 kg/m^3)

g = the acceleration due to gravity (9.8 m/s^2)

Maximum permissible shear stress (τ_{max}) is the maximum unit shear stress (τ) that will not cause serious erosion of the channel.

A channel is stable when:

$$\tau < \tau_{max}$$

Tables of maximum permissible shear stress appear in many channel design, engineering and hydraulics publications (e.g. Chow, 1981; Chang, 1988), and they are all based on values given by the U.S. Bureau of Reclamation (Lane, 1952; Carter, 1953) (Table 7).

When soil is covered by vegetation its resistance to scour is considerably enhanced (Table 8 and Table 9). A critical shear stress in the range 100 – 200 N/m^2 is a reasonable guide to the shear stress required to remove typical native or pasture grass cover found on floodplains and hence initiate stripping of the floodplain surface.

Tabulated values of maximum permissible shear stress are for straight channels, and for sinuous channels the maximum permissible shear stress should be reduced. Lane (1955) recommended reductions of 10% for slightly sinuous channels, 25% for moderately sinuous channels, and 40% for very sinuous channels.

It should be noted that unit bed shear stress is not uniformly distributed along the wetted perimeter. Computed values of shear stress based on average cross-section conditions may be adjusted to account for local variability and instantaneous values higher than mean (Fischenich, 2001). A number of procedures exist for this purpose. Most commonly applied are empirical methods based upon channel form and irregularity. According to Chow (1981, p. 170), for trapezoidal channels, the maximum shear stress on the sides of a channel is close to $0.76\ \tau$. Fischenich (2001) recommended that for straight channels, the local maximum shear stress can be assumed to be $1.5\ \tau$.

Table 7. Maximum permissible bed shear stress for channels formed in fine-grained material. Note: no vegetative cover.

Bed material (USDA soil description)	Maximum permissible shear stress (N/m^2)	
	Clear water[3]	Water transporting fine suspended solids[3]
Ordinary firm loam[1]	3.6	7.2
Stiff clay, very colloidal[2]	12.5	22.0
Alluvial silts, colloidal	12.5	22.0
Alluvial silts, non-colloidal	2.3	7.2
Sandy loam, non-colloidal	1.8	3.6
Fine gravel	3.6	15.3

1. Plastic clay soil; mixture of clay, sand, and/or gravel, with minimum fines (silt and clay) content of 36% (Stallings, 1999).

2. Moderately to highly plastic clay; mixtures of clay, sand, and/or gravel, with minimum clay content of 36% (Stallings, 1999).

3. Chow (1981, p. 165). The term 'clear water' essentially means water with concentrations of suspended solids <1,000 mg/L (Ritzema, 1994).

Table 8. Maximum permissible shear stress for channels lined with grass. Source: Fischenich (2001) using data from various sources.

Cover	Maximum permissible shear stress (N/m^2)
Class A turf	177
Class B turf	101
Class C turf	48
Long native grasses (U.S.A.)	57 – 81
Short native grasses (U.S.A.)	34 – 45

Temporal variations in bed shear stress occur in turbulent flows, and these can be 10 – 20% higher than the mean value. Fischenich (2001) suggested that computed bed shear stress values be adjusted by factor of 1.15.

Bed shear stress is higher in sinuous reaches than in straight reaches. Simple 1-D hydraulic modeling such as HEC-RAS does not usually account for this, so Fischenich (2001) suggested an adjustment be made to the computed bed shear stress values, to calculate the maximum shear stress on the bend (τ_{bend}) as a function of the planform characteristics:

$$\tau_{bend} = 2.65\tau(R_c/W)^{-0.5}$$

where R_c is the radius of curvature and W is the top width of the channel. When assessing channel stability, the computed shear stress values do not need to be adjusted for sinuosity in this way if a sinuosity correction factor is applied to the maximum permissible shear stress value, as described previously (i.e. either approach can be applied to a case, but not both).

Table 9. Summary table of threshold shear stress for erosion of vegetated surfaces from various studies. Source: modified from Blackham (2006).

Vegetation type	Erosion threshold (N/m^2)
Aquatic (swampy) vegetation (Prosser and Slade, 1994)	105
Tussock and sedge (Prosser and Slade, 1994)	240
Disturbed tussock and sedge (Prosser and Slade, 1994)	180
Bunch grass† 20 - 25 cm high (Prosser et al., 1995)	184
Bunch grass† 2 - 4 cm high (Prosser et al., 1995)	104
Bunch grass† (Hudson, 1971)	80 – 170*
Bunch grass† [Ree, 1949 in (Reid, 1989)]	80 – 90*
Cynodon dactylon (Bermuda grass) (Hudson, 1971)	110 – 200*
Cynodon dactylon (Bermuda grass) [Ree, 1949 in (Reid, 1989)]	120 – 180*
Bouteloua dactyloides (Buffalo grass), *Poa pratensis* (Kentucky bluegrass) (Hudson, 1971)	110 – 200*
Bouteloua dactyloides (Buffalo grass [Ree, 1949 in (Reid, 1989)]	110 – 180*

† Any of various grasses of many genera that grow in tufts or clumps rather than forming a sod or mat.

* These ranges summarise data for a variety of soil types/hillslopes. See Reid (1989) and Hudson (1971) for more details.

3.8.4 Australian Coal Association Research Program (ACARP) design criteria for stream diversion design in the Bowen Basin

ACARP guidelines for diversion design were based on the findings of a series of research projects conducted between 1999 and 2002 on performance of existing diversions (White et al., 2014). One of the elements of the ACARP guidelines often used for diversion design is a table of hydraulic criteria. The criteria form part of the Department of Natural Resources and Mines (2014) guidelines for diversions.

The table of hydraulic design criteria in DNRM (2014, p. 33) is reproduced here (Table 10). The reference cited for the critical hydraulic values provided by DNRM (2014) was Hardie and Lucas (2002).

A similar table of criteria was provided in SKM (2009). Parsons Brinkerhoff (2010) and Kellogg Brown & Root (2013) (Table 11), quoting the source as Hardie and Lucas (2002) [also referred to as ACARP (2002)] and/or Vernon (2008) [also referred to as DERM (2008) and a later version as DERM (2011)]. The table differs from that provided by DNRM (2014) (Table 10) in values for stream power and bed shear stress for the 50 year ARI flood.

A third table of criteria was provided by White et al. (2014), also citing Hardie and Lucas (2002) as the source. This table was referred to by White et al. (2014) as "*(…ACARP design criteria)…adopted by Queensland regulators in 2002*". In this case, differing sets of criteria were provided for the three different stream types incised, limited capacity and partly bedrock controlled (Table 12). While 'incised' and 'partially bedrock controlled' have conventional meanings with respect to geomorphic stream type, White et al. (2014) did not define the meaning of 'limited capacity'. 'Capacity' could refer to sediment transport or discharge, or both, and the term 'limited' is relative. The criteria values suggest 'limited capacity' refers to channels on the lower end of the energy spectrum and relatively small in size relative to their flood discharge magnitudes, but they could also be of an expected size with high roughness.

Table 10. Guideline values for average stream powers, velocity and shear stresses for streams within the Bowen Basin. Source: DNRM (2014, p. 33).

Flood scenario	Stream power (W/m^2)	Velocity (m/s)	Bed shear stress (N/m^2)
2 year ARI (no vegetation)	<35	<1.0	<40
2 year ARI (vegetated)	<60	<1.5	<40
50 year ARI	<150	<2.5	<50

Table 11. Guideline values for average stream powers, velocity and shear stresses for streams within the Bowen Basin. Source: Vernon (2008).

Flood scenario	Stream power (W/m^2)	Velocity (m/s)	Bed shear stress (N/m^2)
2 year ARI (no vegetation)	<35	<1.0	<40
2 year ARI (vegetated)	<60	<1.5	<40
50 year ARI	<220	<2.5	<80

Table 12. Typical values for dependent variables identified for sample stream reaches; ACARP design criteria adopted by Queensland Government in 2002. Source: White et al. (2014).

Stream type/ Flood scenario	Stream power (W/m^2)	Velocity (m/s)	Bed shear stress (N/m^2)
Incised			
2 year ARI	20 - 60	1.0 – 1.5	<40
50 year ARI	50 - 150	1.5 – 2.5	<100
Limited capacity			
2 year ARI	<60	0.5 – 1.1	<40
50 year ARI	<100	0.9 – 1.5	<50
Bedrock controlled			
2 year ARI	50 - 100	1.3 – 1.8	<55
50 year ARI	100 - 350	2.0 – 3.0	<120

The ACARP guidelines are similar to the criteria recommended by the maximum permissible velocity method. The maximum permissible velocity for a stable unvegetated channel ranges from 0.5 – 1.1 m/s depending on soil type, and 0.8 – 2.4 m/s for vegetated surfaces, although lower values would be appropriate for long duration floods. ACARP guidelines recommended maximum velocities for the 2 year ARI event of 1.0 m/s for unvegeted channels and 1.5 m/s for vegetated surfaces. ACARP recommended a higher tolerable velocity of 2.5 m/s for the 50 year ARI event, whether vegetated or not. Allowing a higher limit of velocity for the larger 50 year ARI flood, even though its longer duration would present a higher risk of channel erosion, was presumably related to the infrequent occurrence of such events. Either the impacts of these large events were not observed in the investigations used to formulate the criteria, or a risk approach was taken, whereby the higher consequence of a 50 year ARI flood was traded for its lower likelihood.

The maximum permissible bed shear stress for a stable unvegetated channel ranges from 2 – 13 N/m^2 depending on soil type, and 30 - 240 N/m^2 for vegetated surfaces, although lower values would be appropriate for long duration floods. ACARP guidelines recommended maximum bed shear stress of 40 N/m^2 for the 2 year ARI event and 50 or 80 N/m^2 for the 50 year ARI event, and these limits apply to both vegetated and unvegetated channels. It seems inconsistent to specify the same thresholds for bed shear stress for vegetated and unvegetated channels when it is well established in the literature that vegetation cover markedly increases resistance to scour and sediment transport.

3.8.5 Erosion risk criteria for bed shear stress and velocity for the Isaac River in the Study Area

Floodplain soils and bank sediments of the Isaac River are sandy loams. Unvegetated ‘Sandy loam, non-colloidal’ has maximum permissible velocity of 0.5 m/s (Table 4). Correction for slight sinuosity using the method of Lane (1955) requires reduction by 5%, to give a maximum permissible velocity of 0.48 m/s. This threshold would fall to around 0.2 m/s for flood durations exceeding 5 hours. Well-vegetated floodplain surfaces should be expected to tolerate velocities of at least 2 m/s without initiation of scour. This would apply for flood durations of 2 – 7 hours.

‘Sandy loam, non-colloidal’ has maximum permissible shear stress of 1.8 N/m^2 (Table 7). Correction for slight sinuosity using the method of Lane (1955) requires reduction by 10%, to give a maximum permissible shear stress of 1.6 N/m^2. Well-vegetated floodplain surfaces should be expected to tolerate shear stresses of 100 N/m^2 to 200 N/m^2 without initiation of scour.

Based on information from the literature and local soil type, values of maximum permissible velocity and bed shear stress were assigned to risk categories for initiation of fluvial scour of floodplain soils in the Study Area (Table 13). The maximum permissible velocity and bed shear stress methods, like the ACARP guidelines, specify thresholds of hydraulic criteria that should be interpreted as mean velocities within a defined cross-sectional area, either on a floodplain or within a channel. Higher values would be tolerable for brief periods, or in parts of the cross-section. These thresholds should not be interpreted to mean that there is a single value of velocity or bed shear stress below which a channel is morphologically absolutely stable. These thresholds implicitly integrate what would conventionally be considered categories of risk of scour over management time scales.

Table 13. Risk categories of maximum permissible velocity and bed shear stress for initiation of fluvial scour of river bank and floodplain soils in the Isaac River in the Study Area. These hydraulic criteria are mean cross-sectional values.

Risk of initiation of scour	Bank and floodplain (well-vegetated)		Bank and floodplain (exposed soil)	
	Shear stress (N/m^2)	Velocity (m/s)	Shear stress (N/m^2)	Velocity (m/s)
Low	< 100	< 2.0	< 1.6	< 0.48
Moderate	101 – 200	2.1 – 4.0	1.7 – 4.0	0.48 – 1.0
High	> 200	> 4.0	> 4.0	> 1.0

4.0 Existing environment

4.1 Landscape-scale characteristics

4.1.1 Catchment topography

The Study Area lies within the Isaac River catchment down to its junction with Stephens Creek, a total area of approximately 6,407 km^2 (Figure 6). Within this catchment, land surface elevation ranges from 131 m to 697 mAHD. The Study Area lies within the lowland topographic zone of the catchment, with an elevation range of 150 m to 208 mAHD.

4.1.2 Drainage system

The Isaac River is an Order 6 watercourse at its junction with Stephens Creek, another Order 6 watercourse, below which it is an Order 7 watercourse (Figure 8). Isaac River catchment has a high stream density in the northern and western headwater areas. The lowland zone, in which the Study Area is situated, has a low stream density. Of the main streams in this area, in their lower reaches, Boomerang Creek is Order 5, Phillips Creek and North Creek are Order 4 and Ripstone Creek is Order 3 (Figure 8).

4.1.3 Sub-catchment division

The DEM-derived catchment boundaries and associated areas (Figure 8) are approximate, as they were determined from a composite DEM with three different native resolutions, including a coarse SRTM DEM. Catchment boundaries were more uncertain in the low gradient downstream floodplain zones of catchments. The current boundaries of the headwater catchments of One Mile and Boomerang creeks were uncertain due to landform modifications and possible drainage diversion associated with open cut mining. This uncertainty does not materially affect the interpretations or results of this Technical Report.

North Creek joins the Isaac River just downstream of the upstream boundary of the Study Area (Figure 8). North Creek does not flow through MLA 700032 so would not be directly impacted by open cut mining activity, although there is potential for the floodplain of its lower reaches to be impacted by altered flood hydraulics of the Isaac River, and mine-related infrastructure could cross the lower reaches of this creek.

Downstream of North Creek, four small tributaries drain to the Isaac River from the east. Due to uncertain drainage divides, three of these were combined to form Eastern Tributaries A, while the other was labelled Eastern Tributary B (Figure 8). Eastern Tributary B is located almost entirely within MLA 700033 or MLA 700034. In the long term, around half of this catchment would ultimately be excised from the natural drainage system and be subsumed by the open cut mining area (Figure 9). On the other side of the river, the area of westward-draining tributary catchment is much larger. This area includes three small tributary areas, here labelled Western Tributaries A, B and C, the main tributary Boomerang Creek, with its tributaries Ripstone Creek and One Mile Creek, plus Phillips Creek (Figure 8).

Of the western tributaries streams, a portion of Western Tributary A passes through MLA 700032 or MLA 700035 (Figure 9). The catchment is large enough to generate sufficient runoff to form a defined channel, as designated by a blue line, so consideration would need to be given to diversion of the flow from this small stream channel around the pit to Isaac River. A large proportion of Western Tributary B is located within MLA 700032 or MLA 700033 (Figure 9). The majority of the catchment would ultimately be excised from the natural drainage system and be subsumed by the open cut mining area. Almost the entire area of Western Tributary C is located within MLA 700033 (Figure 9). This tributary might not be subject to direct impact of open cut mining but could be subject to indirect impacts.

The catchments and channels of One Mile Creek, Boomerang Creek, and Phillips Creek do not pass through the MLAs, so they would not be directly impacted by open cut mining activity, although there is potential for the floodplain areas of the lower reaches of Boomerang and Phillips creeks to be impacted by altered flood hydraulics of the Isaac River. On the other hand, a large area of Ripstone Creek catchment is upstream of MLA 700033, and the creek channel then passes into and through this MLA on its way to joining Boomerang Creek, just upstream of its junction with Isaac River (Figure 8). Open cut mining would likely directly impact a portion of lower Ripstone Creek catchment (Figure 9), so consideration would need to be given to diversion of the flow from this stream channel around the pit.

Downstream of Phillips Creek catchment, a lowland area labelled Southwestern Tributaries drains eastwards to the right side of Isaac River, entering the river downstream of MLA 700034 (Figure 8). Also in this downstream area, on the left side of the river, three small tributaries, here labelled Southern Tributaries A, B and C, drain in a roughly southeast direction, partially within MLA 700034, joining Isaac River downstream of the MLA 700034 (Figure 8). Open cut mining will impact Southern Tributaries A and B by excising parts of their catchment areas (Figure 9).

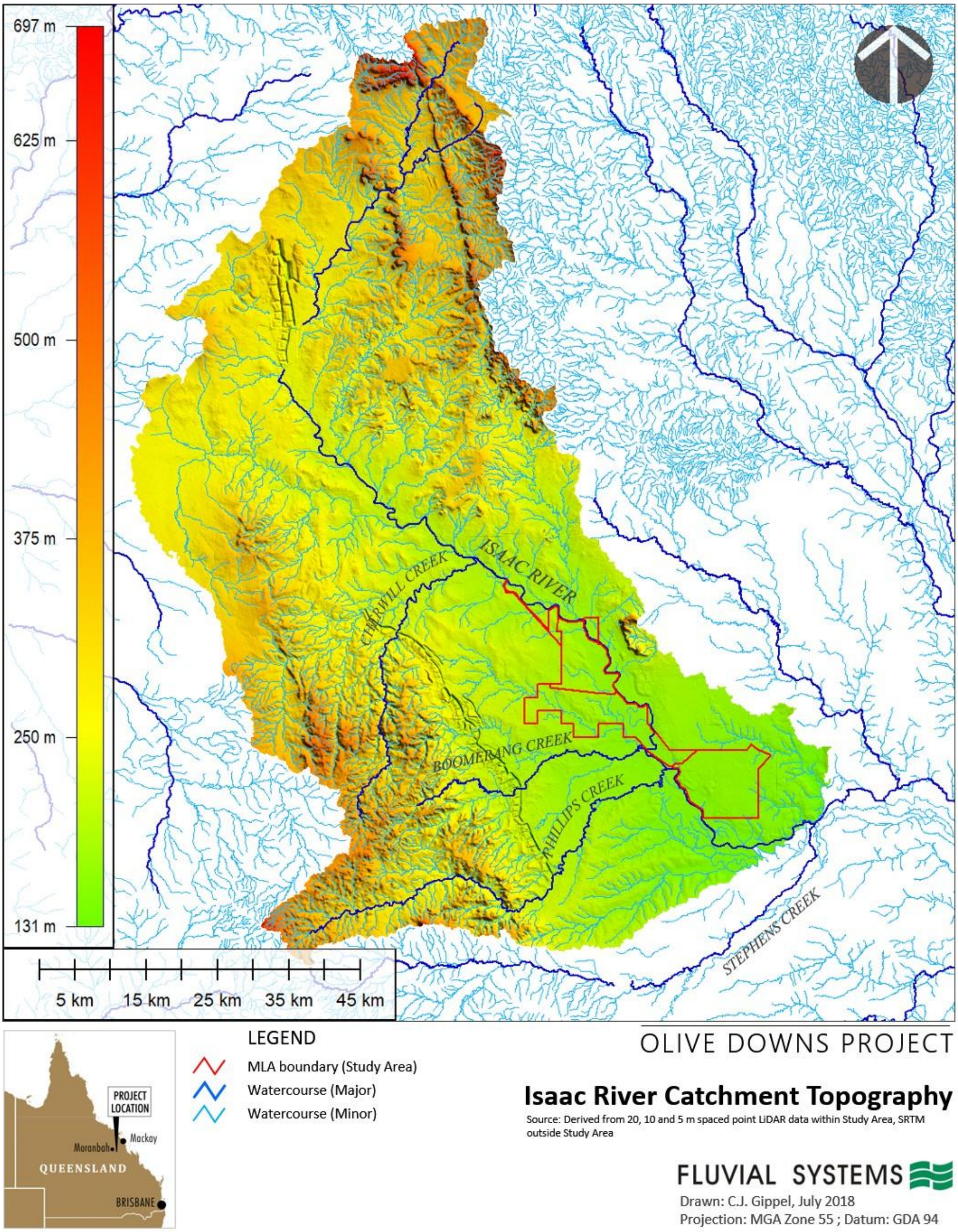

Figure 6. Isaac River regional topography.

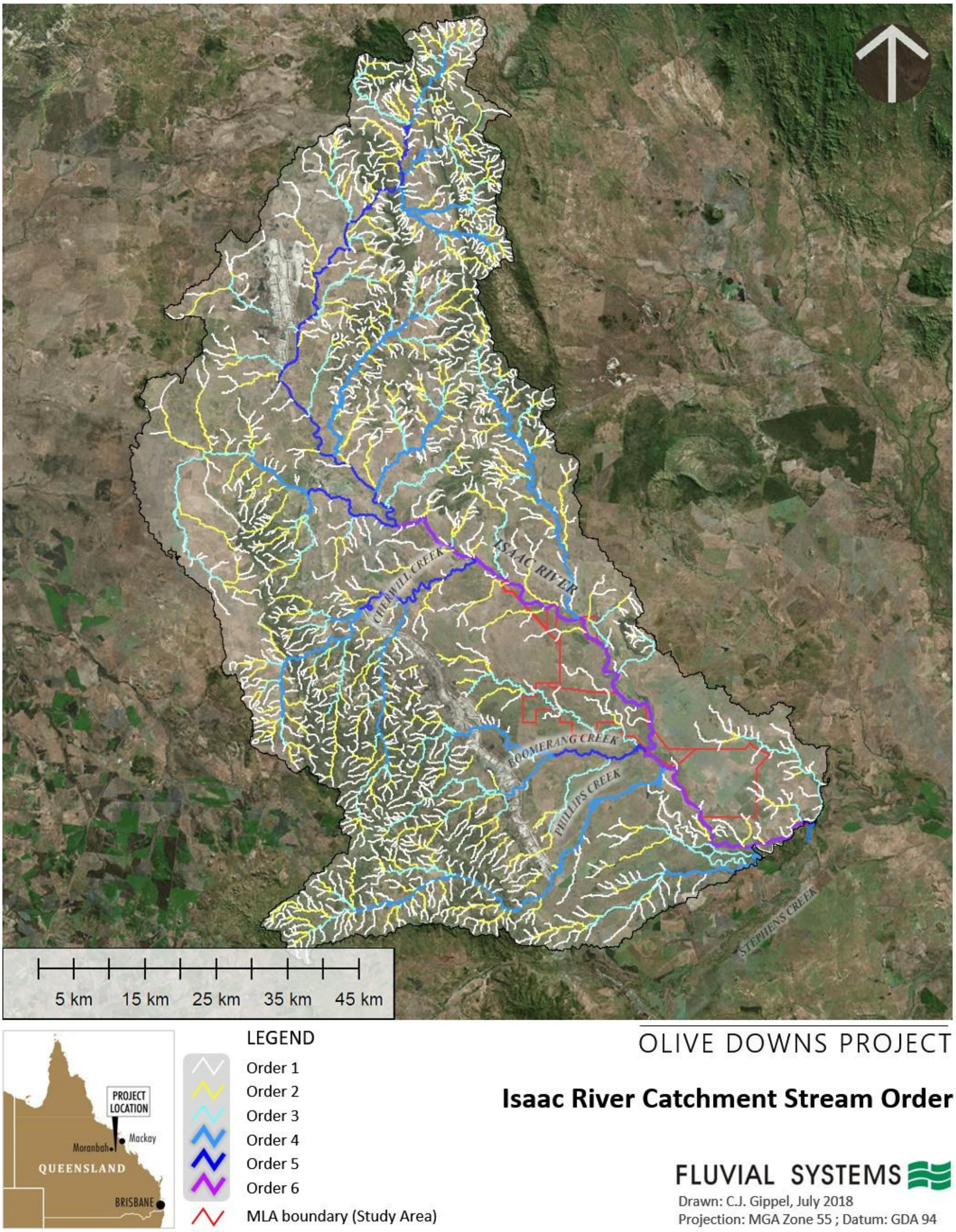

Figure 7. Isaac River catchment drainage system Stream Order.

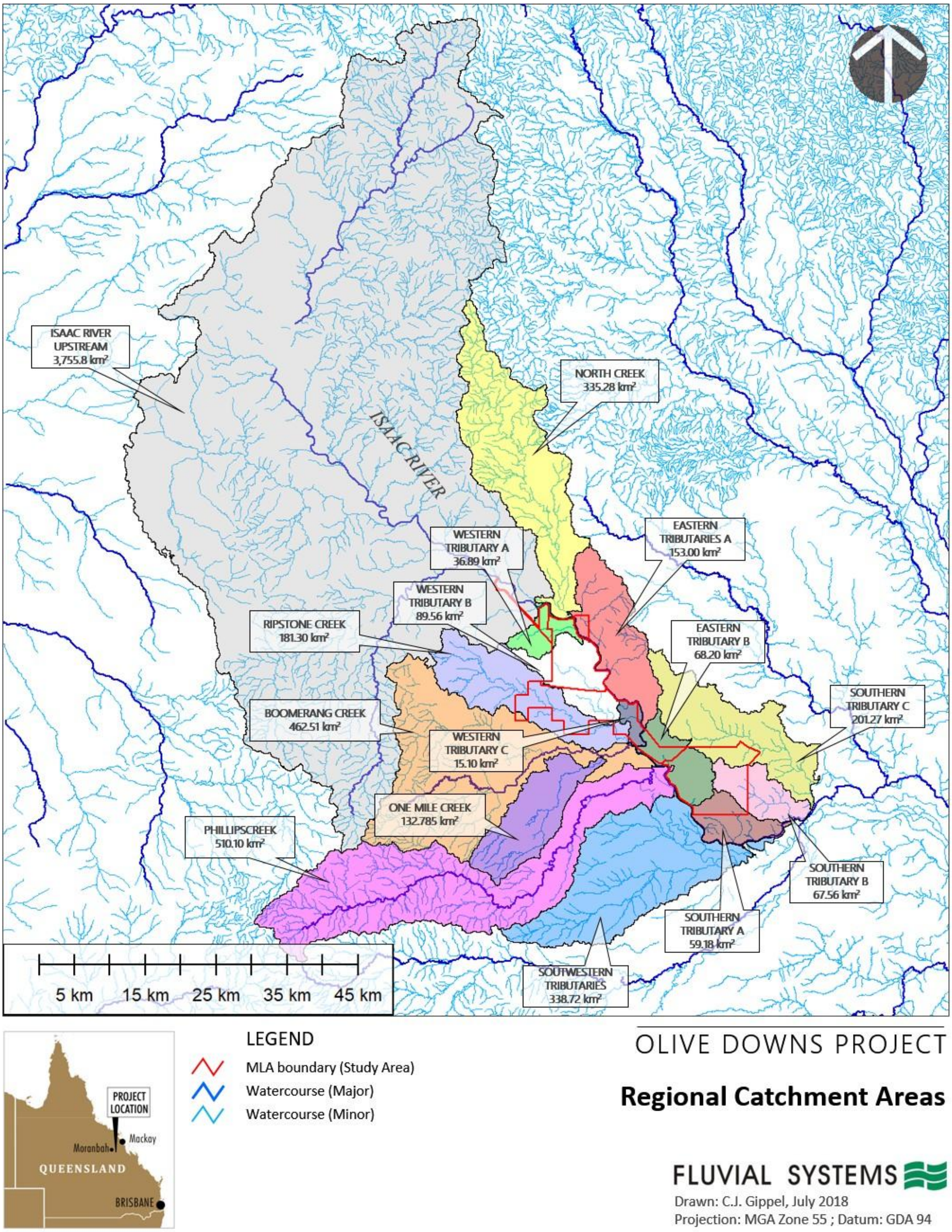

Figure 8. Isaac River regional catchments.

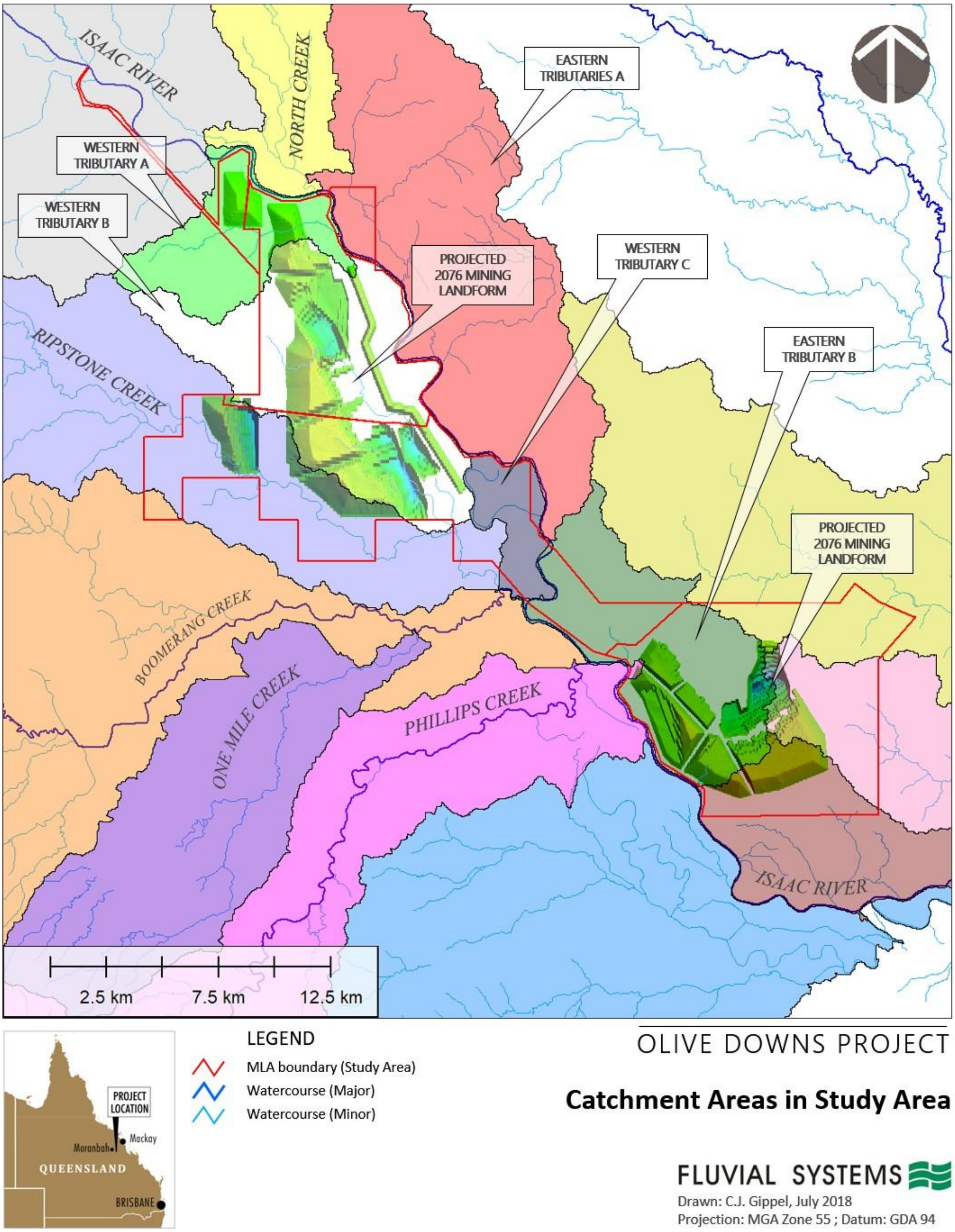

Figure 9. Isaac River catchments in the vicinity of the Study Area. Mining landforms at 2076 are indicative of maximum extent of modification only.

4.1.4 Geological classification

The sediments and volcanics of the Bowen Basin were deposited over most of the area during Permian times (Wright, 1968). Marine and non-marine sequences are represented. Thick terrestrial deposits (mainly shale and sandstone) were laid down during the Triassic. Subsequently a period of orogeny occurred during which the Bowen Basin rocks were folded, faulted, and intruded to varying degrees throughout the area. After the orogeny, the whole area except the Surat Basin in the south was exposed to erosion during Jurassic and Cretaceous times. Igneous activity occurred first with the intrusion of basaltic and andesitic material, and subsequently with the intrusion mainly of granite and diorite associated with extensive faulting, commonly aligned north-north-west and north-east. Erosion continued throughout most of the area in the Cretaceous (Wright, 1968). The geology of the wider Study Area is represented by rocks of the Early-Late Permian, Early-Mid Triassic and Early Cretaceous Periods (Figure 10).

The Australia 1:250,000 Geological Series depict surface geological units, which in the Study Area comprised extensive undifferentiated sandy sediments and soils and Quaternary alluvium within river corridors (Figure 11). This suggests that sand bed rivers and streams would be naturally occurring in this region, and not necessarily the result of accelerated sediment delivery caused by land use change, although this process could have increased the rate of sand delivery to channels above background levels.

4.1.5 Soil classification

The main Australian Soil Classification soil type along the Isaac River corridor is Chromosol, also know in the Australian Soil Atlas classification as Brown and Black Duplex Soils (Figure 12). Soils on the slopes are mainly either Sodosols (Yellow Duplex) or Vertosols (Cracking Clays). There are patches of Kandosol (Massive Earths), and an area of Tenosol (Sands) associated with a patch of Triassic Carborough Sandstone (Clematis Group) (Figure 12).

The majority of the wider Study Area has moderately stable surface soils (Figure 13). Erodible non-cohesive soils and dispersive soils occur in fragmented patches, with more concentrated areas of erodible soils occurring in Ripstone Creek catchment just upstream of the core Study Area, and in the corridor of Isaac River just upstream of the core Study Area (Figure 13).

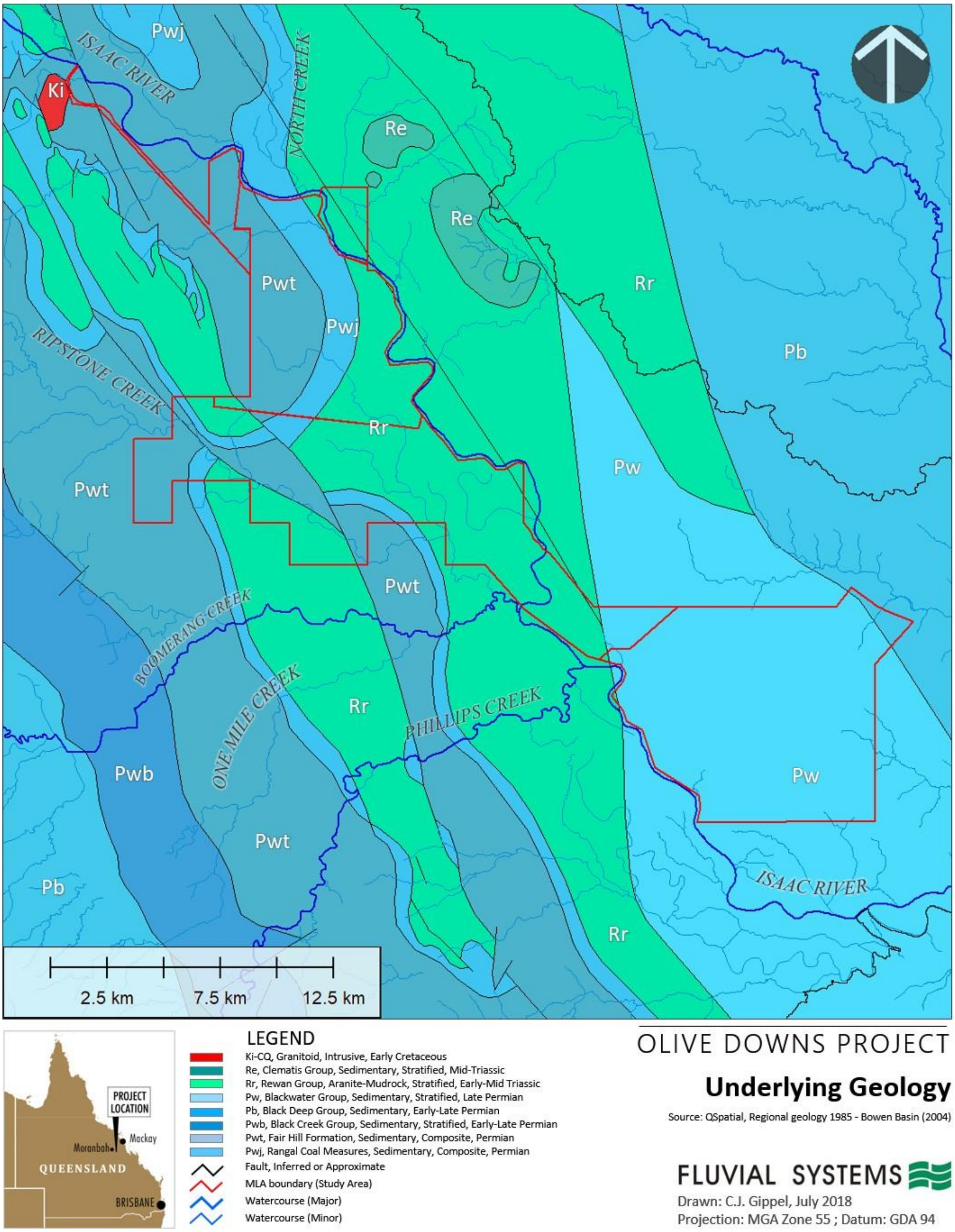

Figure 10. Underlying geology of the Study Area. The mapping does not show the distribution of Quaternary sediments overlying hard rock.

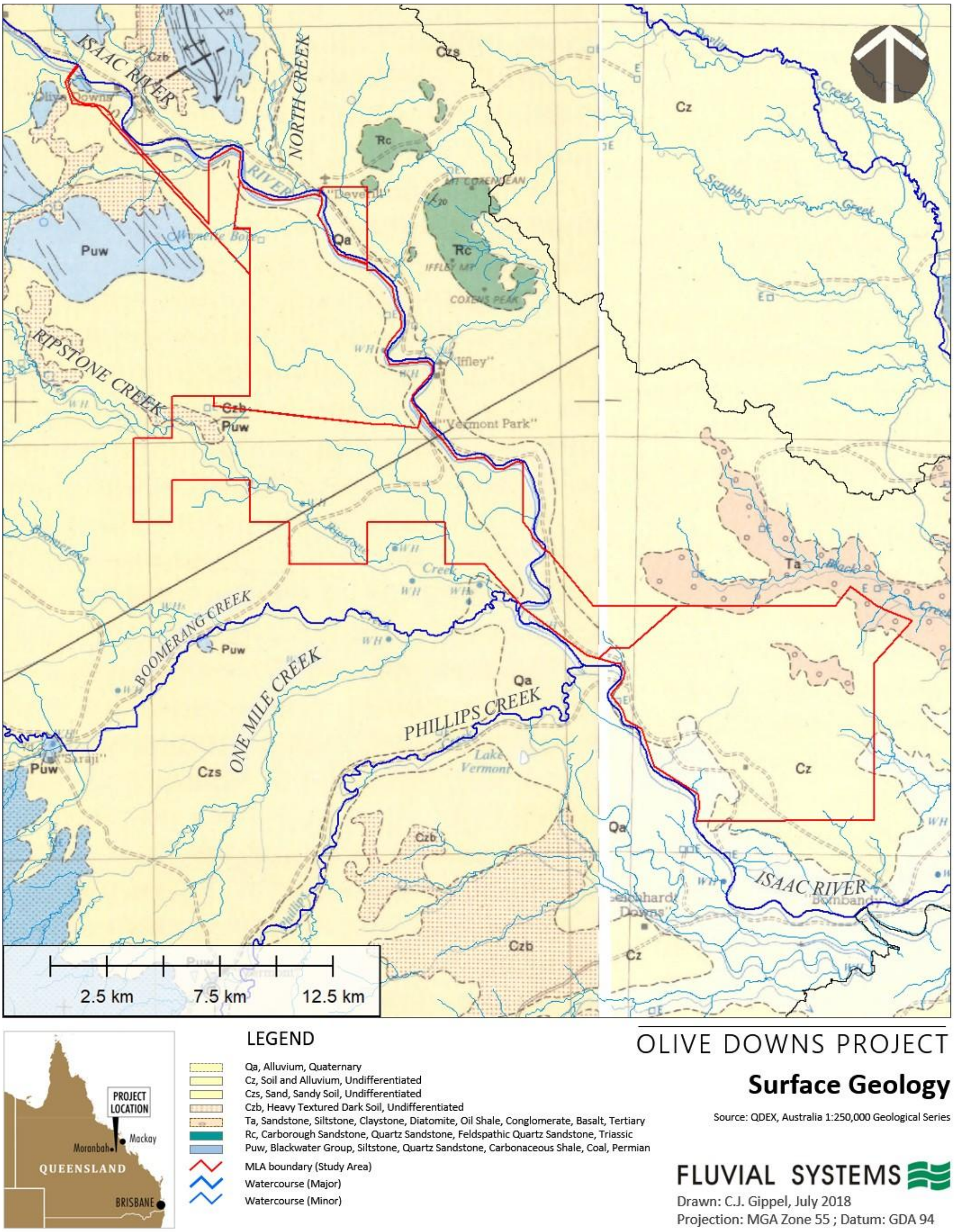

Figure 11. Surface geology of the Study Area. Scanned non-georeferenced source images were rectified and cropped in GIS.

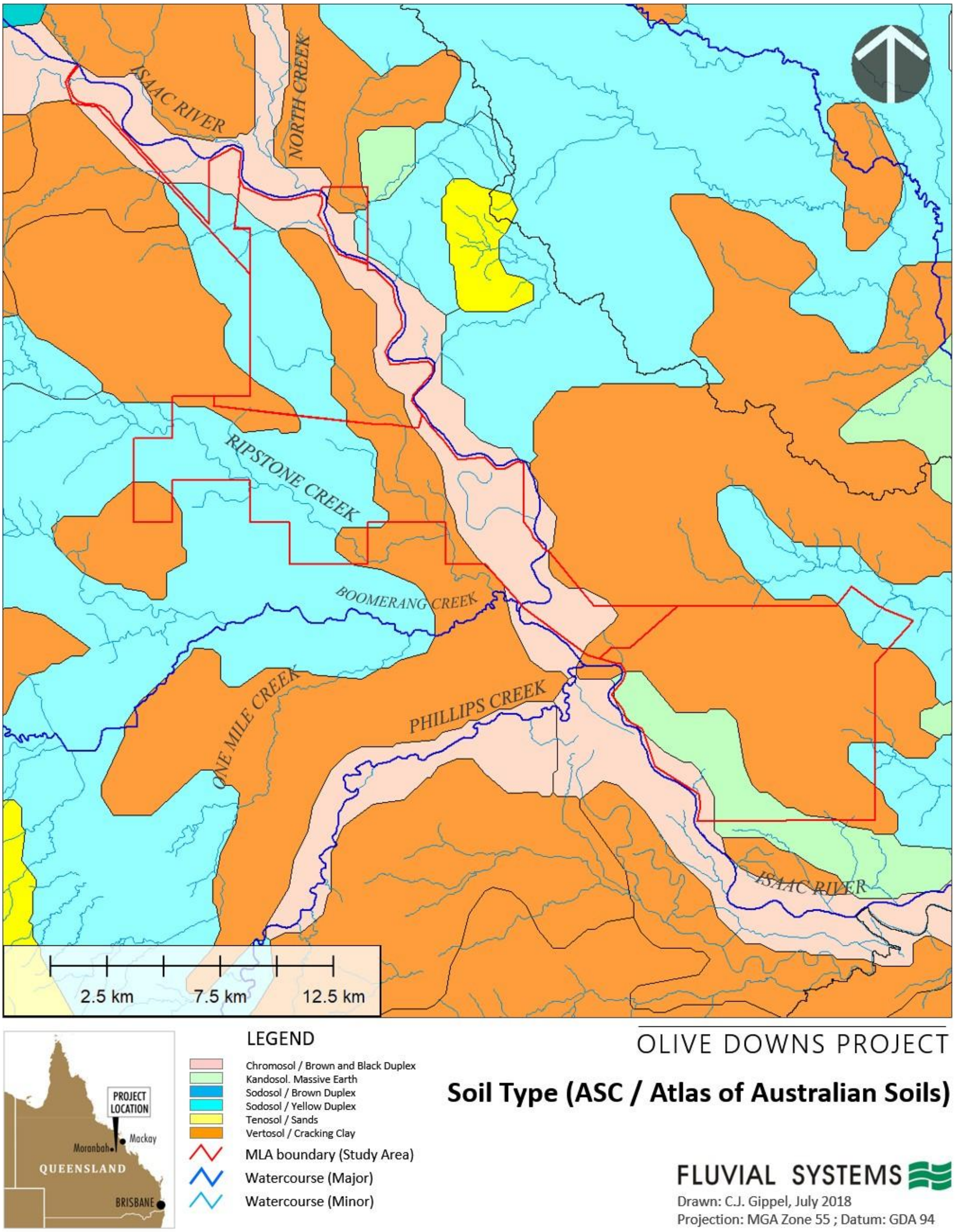

Figure 12. Soil Types in the Study Area.

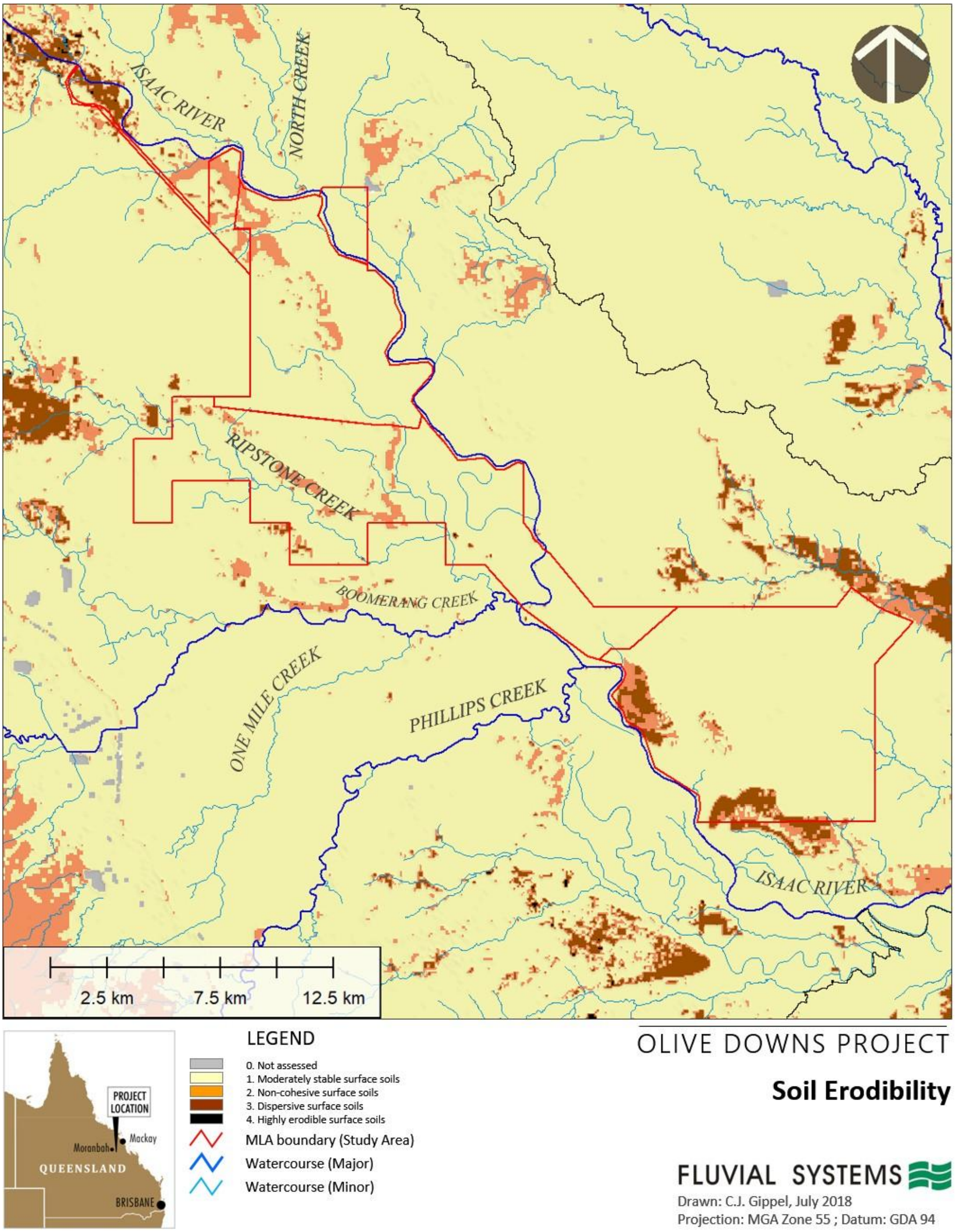

Figure 13. Soil Erodibility in the Study Area.

4.1.6 Land slope

The terrain within the MLAs was less than 10 degrees, except for moderately steep slopes forming the banks of Ripstone Creek (Figure 14). Over the plains of the wider Study Area, slopes were gentle, with steeper slopes associated with isolated hills and open cut mines to the south west. The channels of the major watercourses Isaac River, lower Phillips Creek and lower North Creek had almost continuous very steep banks, while lower Boomerang Creek channel had continuous moderately steep channel banks.

4.1.7 Landform classification

The main objective of landform classification was to identify the degree of confinement of the watercourses which mainly requires separation of floodplains from valley slopes.

Application of the Topographic Position Index (TPI) with default parameter values classified the Study Area into only two of ten possible landform classes - Plains and Open Slopes. This class resolution was too coarse to identify floodplains. The Terrain Surface Classification (TSC) classified the Study Area into four of sixteen possible landform classes. These four classes belonged to terrain series IV, coarse texture and low convexivity (Figure 15). Thus, the landform classes identified by TSC in the wider Study Area were distinguished only by slope. The 25 × 25 m spatial resolution was too coarse to identify the smaller channels, but TSC distinguished the Isaac River channel from its surrounding floodplain, although not as well as slope mapped at 5 × 5 m spatial resolution (Figure 14). The Queensland Floodplain Assessment Overlay (QFAO) represents an estimate of areas potentially at threat of inundation by flooding, mapped at 1:100,000 scale. When compared with the boundary of QFAO, the TSC agreed with the boundary between floodplain and valley side slopes along the larger watercourses, although some valleys with low slopes were classified in the same group as floodplain land (Figure 15).

Within the terrain of the wider Study Area, the MRVBF was generally a poor distinguisher of floodplain land (Figure 16). Within the overall gently sloping terrain of the wider Study Area, when compared with the boundary of QFAO, MRVBF index values that normally indicate floodplain land suggested a much wider floodplain extent (Figure 15).

Landform classification provided a reasonable separation between likely floodplain landform and surrounding valley slope landform, although the indicators were inconclusive for lower Ripstone Creek in particular. Although the QFAO suggested that Ripstone Creek had no floodplain, the TSC and MRVBF indicated that it flowed through a floodplain corridor. QFAO was devised principally as an indicator of flood hazard from the perspective of risk to people, agriculture and infrastructure, rather than as a model of floodplain morphology, so some smaller floodplains with low intensity land use might not have been mapped as having significant flood risk.

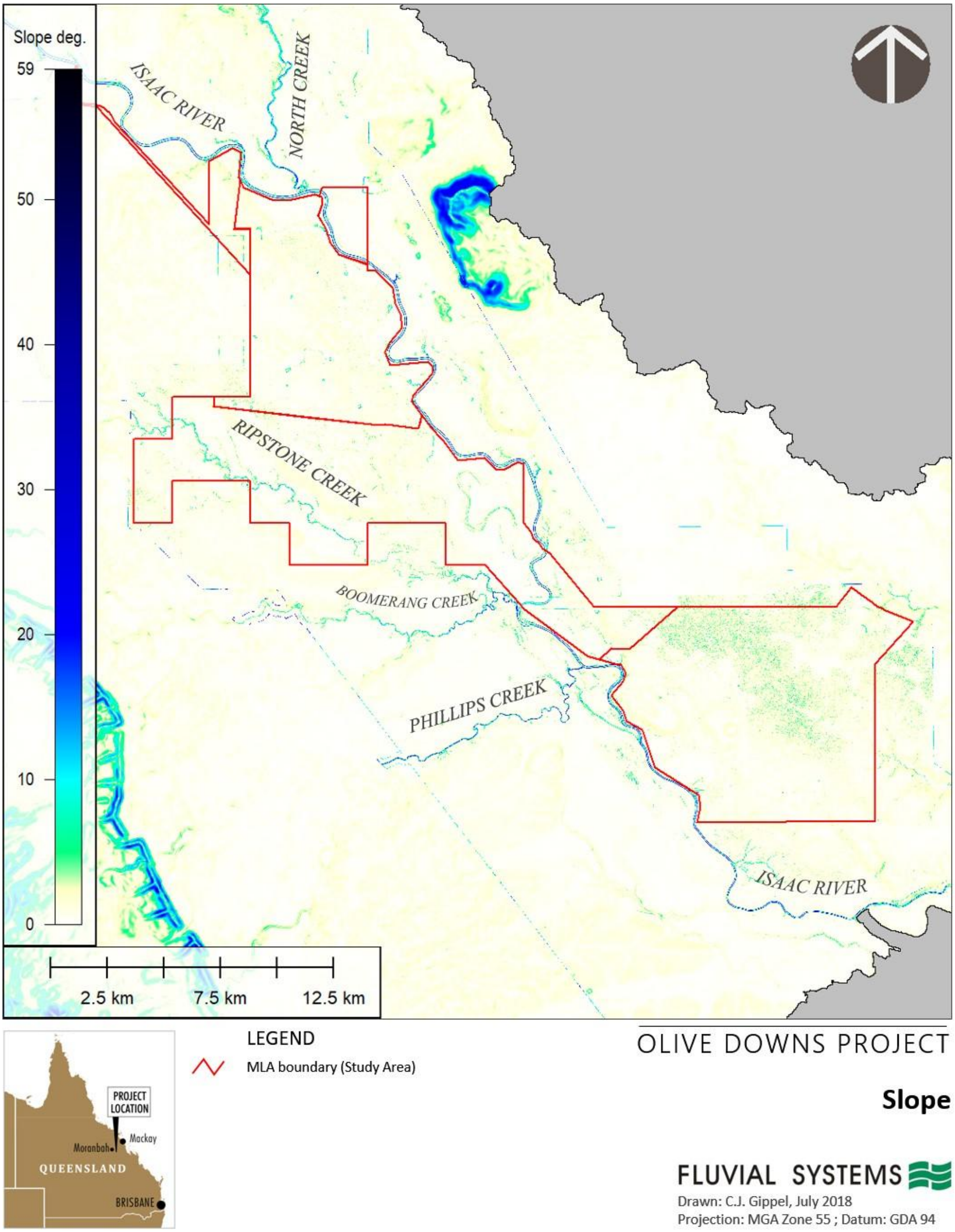

Figure 14. Land slope over the wider Study Area within the Isaac River catchment at 5 × 5 m resolution DEM. Linear discontinuities are artefacts of boundaries of LiDAR data sets.

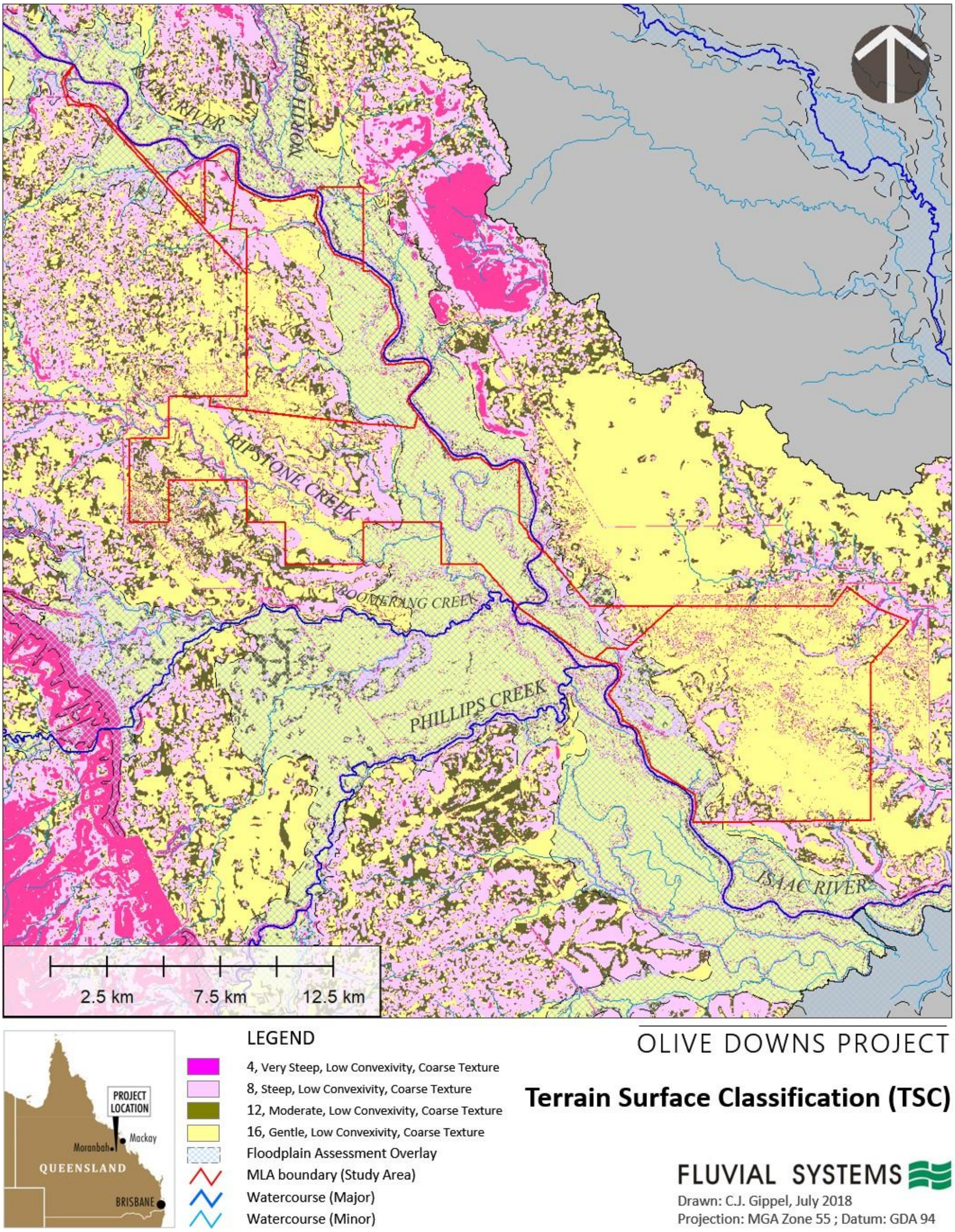

Figure 15. Terrain Surface Classification over the wider Study Area at 25 × 25 m resolution DEM, compared with Queensland Floodplain Assessment Overlay (QFAO).

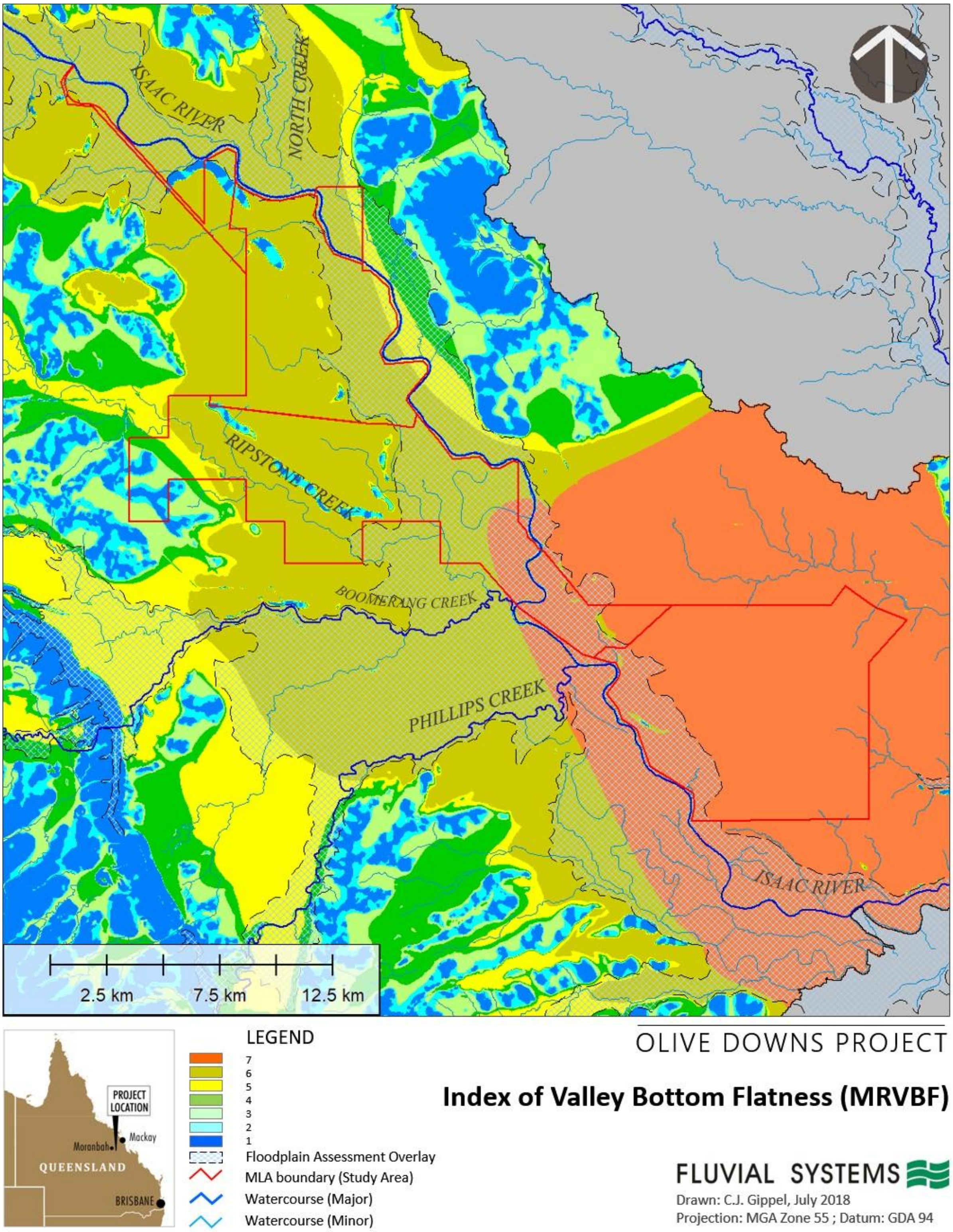

Figure 16. Multispectral index of valley bottom flatness (MRVBF) classification over the wider Study Area at 25 × 25 m resolution DEM, compared with Queensland Floodplain Assessment Overlay (QFAO).

4.2 Stream reach- and point-scale characteristics

4.2.1 Sampled sites

A total of 54 sites were sampled in the field. This comprised 25 sites on Isaac River and 17 sites on Ripstone Creek (Figure 17). Western Tributaries A, B and C were small and were sampled at one or two locations, while only the lower reaches of North, Boomerang and Phillips creeks were sampled as these were outside the core Study Area and not subject to direct impacts of mining (Figure 17).

4.2.2 Isaac River site characteristics

The geomorphic character of Isaac River was relatively constant throughout the Study Area. It was a large sand-bed river, wider in the upstream reaches (Figure 18) than in the lower reaches (Figure 19) of the Study Area, with occasional vegetated (treed) islands (Figure 20) (Table 14). The bed morphology was relatively homogeneous, being fairly flat, with shallow pools (<1 m deep) and low amplitude bar forms (Figure 18, Figure 19). The bed was composed primarily of quartz and feldspathic sand-sized material, but there was a small quantity of mud, gravel and cobbles present in places (Table 14). The banks were steep (Figure 18, Figure 19, Figure 20) and, despite being composed of erodible clayey, silty, sand (Figure 21), the general absence of bare slumped bank faces suggested they were relatively resistant to fluvial erosion. This is likely explained by almost complete coverage by vegetation, in particular thick dense grass (Figure 18, Figure 19). Large wood was not present through the upstream half of the surveyed reach, and was present at low density on the lower half of the reach (Figure 19, Table 14). The riparian vegetation structure had good tree coverage in most places, and where tree cover was low, the extensive shrub and ground cover provided for an overall riparian vegetation cover index value that was medium or high at all locations (Table 15).

4.2.3 Ripstone Creek site characteristics

The geomorphic character of Ripstone Creek was relatively unchanged through the majority of the Study Area, where it had a well-defined channel of variable width and depth, and sand bed (Figure 22, Table 16). The sand-bed of the creek was relatively thick, but had significant variation in form due to the common presence of trees and large wood in the bed which would create hydraulic resistance and turbulence under high flow conditions (Figure 22). The bed material was primarily of quartz and feldspathic sand, but there was a small quantity of surface mud present, and one site with a small quantity of gravel present. In the lower reaches of Ripstone Creek the channel became less well-defined and the dominant bed material changed from sand to mud (Figure 23, Table 16). Further downstream, where the creek approached its junction with Boomerang Creek, the channel again became well defined (Figure 24). Large wood was present in a relatively high density over the upper reaches (Figure 22, Table 16) but was not common in the lower reaches (Figure 23, Table 16). The riparian vegetation structure had variable tree cover. Where tree cover was low, the extensive shrub and ground cover provided for an overall riparian vegetation cover index value that was medium or high at most sites, but some sites with low ground cover had low overall riparian vegetation cover index values (Table 17).

4.2.4 North, Boomerang and Phillips creeks site characteristics

North (Figure 25), Boomerang (Figure 26) and Phillips (Figure 27) creeks were similar in geomorphic character. These creeks were similar in character to Isaac River, but at a smaller scale (Table 18, Table 19).

4.2.5 Western Tributaries site characteristics

Western Tributaries A and B were small scale streams, with channel form alternating between ill-defined, weakly defined or well-defined (Table 18). Western Tributary A was ill-defined over most of its course, but became well-defined as it incised into the Isaac River floodplain as it neared its junction with the river (Figure 28). Western Tributary B Site 1 had a larger catchment area than at Site 2 on a small tributary. At Site 1 the stream comprised a series of well-defined pools strung along an otherwise ill-defined drainage line, while Site 2 had ill-defined morphology and lacked pools (Figure 29). Western Tributaries A and B were low gradient, with areas of ponded water and moist bed material that encouraged the growth of emergent macrophytes and grass in the bed (Table 19). Trees were not common in the riparian zones and there was very little large wood in the channels (Table 18, Table 19).

Western Tributary C, although 80 m wide at bankfull level (Figure 30, Table 19), drained a small catchment area located entirely on the floodplain of Isaac River. This watercourse, being a largely in-filled former course of the Isaac River, was a floodplain lagoon rather than a creek.

4.2.6 Isaac River and Ripstone Creek downstream patterns of channel morphology

Isaac River displayed distinctive channel narrowing in the downstream direction through the Study Area (Figure 31). Over a distance of about 70 km the bed width narrowed from ~50 – 70 m to ~20 – 40 m, and the bankfull channel width narrowed from ~100 – 120 m to ~40 – 60 m (compare Figure 18 and Figure 19). This downstream narrowing occurred despite a significant increase in catchment area. The channel did not maintain its capacity downstream by increasing in depth or slope (Figure 31), suggesting that the floodplain becomes increasingly hydraulically connected to the channel in the downstream direction. Thus, events that just inundate the floodplain of the lower area will be contained within the channel in the upper area. The observed bed width of the Isaac River in the upper part of the Study Area is comparable with the observations made by Hardie et al. (1994) approximately 65 km upstream, near the Isaac River Diversion, adjacent to Goonyellah Riverside Coal Mine. Here, the low flow sand bed was 40 m wide, and including low benches, the bed was 60 – 85 m wide.

The downstream slope of Isaac River through the Study Area was relatively constant, falling 40 m over 70 km (Figure 31) for an average slope of 0.000587. Sinuosity of the river in the Study Area was 1.29.

Ripstone Creek narrowed in its lower reaches (Figure 31) (compare Figure 22 and Figure 23). This suggests that the floodplain is likely to be more hydraulically connected to the channel in the lower reaches, although it becomes less connected in the lowest reach where it incices into the floodplain towards its junction with Billabong Creek (Figure 24). Channel dimensions were highly variable along Ripstone Creek (Figure 31).

The downstream slope of Ripstone Creek was relatively constant, falling 33.2 m over 26.2 km (Figure 31) for an average slope of 0.001275. Sinuosity of the creek in the Study Area was 1.51.

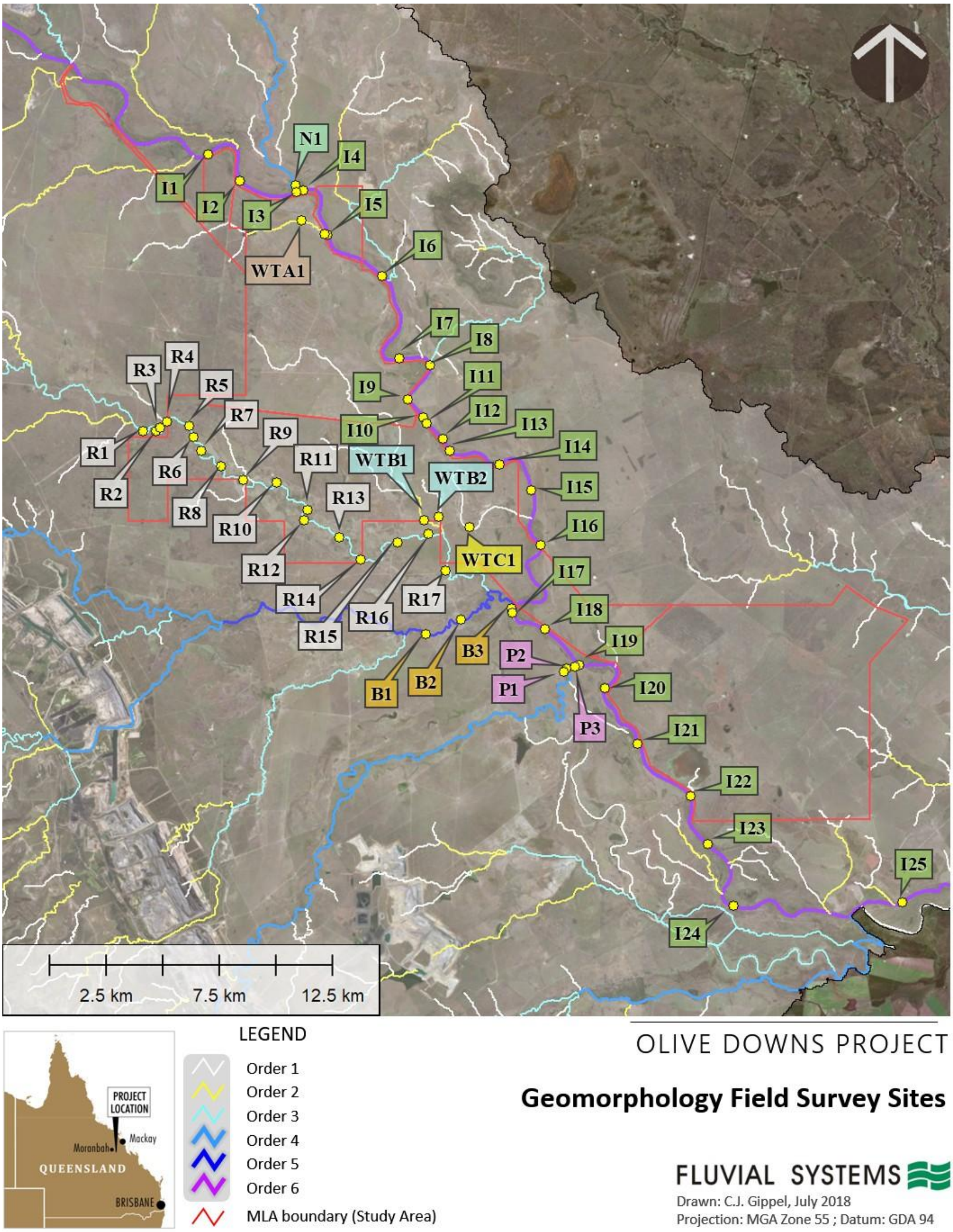

Figure 17. Geomorphology survey sample sites. Data were recorded at 54 observation points.

Figure 18. Isaac River, typical cross-section and bed morphology at two sites in the upper reaches of the Study Area.

Figure 19. Isaac River, typical cross-section and bed morphology at two sites in the lower reaches of the Study Area.

Figure 20. Isaac River, example of mid-channel vegetated island.

Figure 21. Isaac River, exposed clayey, silty, sand bank material at a cutting.

Figure 22. Typical sites on upper Ripstone Creek.

Figure 23. Two sites on lower Ripstone Creek.

Figure 24. The lowest surveyed site on Ripstone Creek.

Figure 25. Lower reach of North Creek near its junction with the Isaac River.

Figure 26. Most upstream surveyed site on Billabong Creek.

Figure 27. Most upstream surveyed site on Phillips Creek.

Figure 28. Western Tributary A upper (top) and lower (bottom) sites.

Figure 29. Western Tributary B sites.

Figure 30. Western Tributary C, an in-filled former course of the Isaac River.

Table 14. Field data collected for Isaac River sites, location, channel form, bed material and large wood.

Site	Stream	Latitude	Longitude	Longitudinal continuity	X-sec definition	Valley setting	Bed material (present)	Bed material (dominant)	Large wood (pc./100 m)
I1	Isaac	-22.152535	148.335229	continuous	strong	Unconfined/extensive	mud, sand, gravel, cobble	sand	0
I2	Isaac	-22.163178	148.348664	continuous	strong	Unconfined/extensive	mud, sand, gravel, cobble	sand	0
I3	Isaac	-22.167631	148.372991	continuous	strong	Unconfined/extensive	mud, sand, gravel	sand	0
I4	Isaac	-22.166787	148.375641	continuous	strong	Unconfined/extensive	mud, sand, gravel	sand	0
I5	Isaac	-22.184475	148.386137	continuous	strong	Unconfined/extensive	mud, sand, gravel, cobble	sand	0
I6	Isaac	-22.200938	148.409569	continuous	strong	Unconfined/extensive	mud, sand, gravel, cobble	sand	0
I7	Isaac	-22.233849	148.416858	continuous	strong	Unconfined/extensive	mud, sand, gravel, cobble	sand	0
I8	Isaac	-22.236367	148.429919	continuous	strong	Unconfined/extensive	mud, sand, gravel	sand	0
I9	Isaac	-22.250082	148.420538	continuous	strong	Unconfined/extensive	mud, sand, gravel	sand	0
I10	Isaac	-22.257293	148.426937	continuous	strong	Unconfined/extensive	mud, sand, gravel	sand	0
I11	Isaac	-22.259448	148.428361	continuous	strong	Unconfined/extensive	mud, sand, gravel	sand	0
I12	Isaac	-22.265757	148.435273	continuous	strong	Unconfined/extensive	mud, sand	sand	0
I13	Isaac	-22.270476	148.438502	continuous	strong	Unconfined/extensive	sand	sand	0
I14	Isaac	-22.276003	148.459647	continuous	strong	Unconfined/extensive	mud, sand, gravel	sand	15
I15	Isaac	-22.286015	148.473186	continuous	strong	Unconfined/extensive	sand, gravel	sand	0
I16	Isaac	-22.307938	148.477057	continuous	strong	Unconfined/extensive	sand, gravel	sand	0
I17	Isaac	-22.334933	148.465202	continuous	strong	Unconfined/extensive	sand, gravel, cobble	sand	5
I18	Isaac	-22.341437	148.478818	continuous	strong	Unconfined/extensive	sand, gravel	sand	10
I19	Isaac	-22.355557	148.493482	continuous	strong	Unconfined/extensive	mud, sand, gravel, cobble	sand	15
I20	Isaac	-22.36489	148.504561	continuous	strong	Unconfined/extensive	sand, gravel, cobble	sand	30
I21	Isaac	-22.386966	148.518524	continuous	strong	Unconfined/extensive	mud, sand, gravel, cobble	sand	40
I22	Isaac	-22.407842	148.541101	continuous	strong	Unconfined/extensive	mud, sand, gravel, cobble	sand	30
I23	Isaac	-22.426896	148.548448	continuous	strong	Unconfined/extensive	sand, gravel	sand	10
I24	Isaac	-22.451345	148.559295	continuous	strong	Unconfined/extensive	sand, gravel	sand	35
I25	Isaac	-22.450023	148.631573	continuous	strong	Unconfined/extensive	sand, gravel	sand	25

Table 15. Field data collected for Isaac River sites, channel dimensions, instream bed vegetation structure, riparian vegetation structure. Point slope is DEM-derived and uncertain.

Site	Bed width (m)	Bankfull width (m)	Bankfull depth (m)	Slope (Deg.)	Slope (%)	Instream bed vegetation presence	Macrophyte bed cover	Tree/grass bed vegetation cover	Riparian buffer width	Riparian buffer continuity	Riparian tree cover	Riparian vegetation cover index
I1	64.4	124.3	6.6	0.15	0.0027	-	-	-	>50 m	continuous	25 - 50%	50 - 75%
I2	57	119.0	8.4	0.49	0.0086	-	-	-	>50 m	continuous	25 - 50%	50 - 75%
I3	59.2	100.7	7.1	0.92	0.0160	-	-	-	>50 m	continuous	25 - 50%	75 - 100%
I4	62	117.0	6.7	0.64	0.0111	-	-	-	>50 m	continuous	50 - 75%	75 - 100%
I5	56.7	103.8	8.1	0.68	0.0118	-	-	-	>50 m	continuous	25 - 50%	50 - 75%
I6	53.9	103.0	7.9	1.31	0.0229	-	-	-	>50 m	continuous	25 - 50%	50 - 75%
I7	60.5	103.0	8.2	0.36	0.0064	-	-	-	>50 m	continuous	50 - 75%	50 - 75%
I8	65.5	99.3	7.0	3.52	0.0615	-	-	-	>50 m	continuous	25 - 50%	50 - 75%
I9	72.3	117.0	7.8	14.88	0.2657	-	-	-	>50 m	continuous	5 - 25%	50 - 75%
I10	54.2	97.5	7.8	0.58	0.0102	-	-	-	>50 m	continuous	25 - 50%	50 - 75%
I11	60.4	95.2	9.0	0.62	0.0108	-	-	-	>50 m	continuous	50 - 75%	75 - 100%
I12	52.8	91.0	8.1	0.58	0.0102	-	-	-	>50 m	continuous	25 - 50%	75 - 100%
I13	58	96.0	7.6	5.09	0.0890	-	-	-	>50 m	continuous	50 - 75%	50 - 75%
I14	42.6	60.0	9.5	10.80	0.1907	-	-	-	>50 m	continuous	50 - 75%	75 - 100%
I15	55.4	118.0	5.0	0.16	0.0028	-	-	-	>50 m	continuous	50 - 75%	75 - 100%
I16	79.4	120.0	6.9	3.79	0.0663	-	-	-	>50 m	continuous	25 - 50%	75 - 100%
I17	38.1	88.0	7.0	0.37	0.0065	-	-	-	>50 m	continuous	25 - 50%	75 - 100%
I18	49.3	81.4	9.6	0.87	0.0152	-	-	-	>50 m	continuous	50 - 75%	50 - 75%
I19	48.3	82.3	7.8	0.50	0.0088	-	-	-	>50 m	continuous	75 - 100%	50 - 75%
I20	55	98.9	8.9	0.81	0.0142	-	-	-	>50 m	continuous	50 - 75%	75 - 100%
I21	43.7	102.1	9.0	0.94	0.0165	-	-	-	>50 m	continuous	25 - 50%	75 - 100%
I22	50.3	101.7	8.4	1.07	0.0187	trees	-	5 – 25%	>50 m	continuous	5 - 25%	50 - 75%
I23	39.1	64.2	8.0	17.47	0.3147	-	-	-	>50 m	continuous	25 - 50%	50 - 75%
I24	40.5	57.8	7.9	8.65	0.1522	-	-	-	>50 m	continuous	25 - 50%	75 - 100%
I25	24.7	45.3	4.7	17.25	0.3106	-	-	-	>50 m	continuous	75 - 100%	75 - 100%

Table 16. Field data collected for Ripstone Creek sites, location, channel form, bed material and large wood.

Site	Stream	Latitude	Longitude	Longitudinal continuity	X-sec definition	Valley setting	Bed material (present)	Bed material (dominant)	Large wood (pc./100 m)
R1	Ripstone	-22.262582	148.307157	yes	strong	Partly confined/extensive	sand, gravel	sand	115
R2	Ripstone	-22.262584	148.3127	yes	strong	Partly confined/extensive	mud, sand, gravel	sand	40
R3	Ripstone	-22.26124	148.314612	yes	strong	Partly confined/extensive	mud, sand, gravel	sand	90
R4	Ripstone	-22.258962	148.317627	yes	strong	Partly confined/extensive	mud, sand, gravel	sand	30
R5	Ripstone	-22.260721	148.327215	yes	strong	Partly confined/extensive	mud, sand, gravel	sand	25
R6	Ripstone	-22.265167	148.328755	yes	strong	Partly confined/extensive	mud, sand, gravel	sand	50
R7	Ripstone	-22.270566	148.332018	yes	strong	Partly confined/extensive	mud, sand, gravel	sand	60
R8	Ripstone	-22.276691	148.340494	yes	strong	Partly confined/pockets	mud, sand, gravel	sand	100
R9	Ripstone	-22.282125	148.350223	yes	strong	Partly confined/moderate	mud, sand	sand	80
R10	Ripstone	-22.283262	148.364268	yes	strong	Partly confined/moderate	mud, sand	sand	40
R11	Ripstone	-22.29406	148.377682	yes	strong	Partly confined/moderate	mud, sand	sand	30
R12	Ripstone	-22.297994	148.376194	yes	strong	Partly confined/moderate	mud, sand	sand	35
R13	Ripstone	-22.30502	148.391279	yes	strong	Partly confined/moderate	mud, sand	sand	10
R14	Ripstone	-22.313771	148.400203	yes	strong	Partly confined/moderate	sand, gravel	sand	30
R15	Ripstone	-22.30699	148.416048	yes	strong	Unconfined/extensive	mud, sand	mud	10
R16	Ripstone	-22.303465	148.429072	no	ill-defined	Unconfined/extensive	mud	mud	0
R17	Ripstone	-22.318171	148.436574	yes	strong	Partly confined/extensive	mud, sand	mud	60

Table 17. Field data collected for Ripstone Creek sites, channel dimensions, instream bed vegetation structure, riparian vegetation structure. Point slope is DEM-derived and uncertain.

Site	Bed width (m)	Bankfull width (m)	Bankfull depth (m)	Slope (Deg.)	Slope (%)	Instream bed vegetation presence	Macrophyte bed cover	Tree/grass bed vegetation cover	Riparian buffer width	Riparian buffer continuity	Riparian tree cover	Riparian vegetation cover index
R1	21	41.4	2.7	3.35	0.0586	trees	-	25 – 50%	>50 m	continuous	5 - 25%	25 - 50%
R2	8.3	16.4	3	9.12	0.1605	-	-	-	>50 m	continuous	50 - 75%	50 - 75%
R3	11.8	20.1	3.3	2.52	0.0439	trees	-	25 – 50%	>50 m	continuous	25 - 50%	50 - 75%
R4	9	21.3	3.6	10.68	0.1885	trees	-	25 – 50%	>50 m	continuous	25 - 50%	50 - 75%
R5	10.5	16.9	3.1	5.75	0.1007	-	-	-	>50 m	continuous	5 - 25%	50 - 75%
R6	12.3	42.9	1.5	1.88	0.0328	trees	-	25 – 50%	>50 m	continuous	5 - 25%	25 - 50%
R7	9.8	18.2	2.9	2.73	0.0477	trees	-	25 – 50%	>50 m	continuous	25 - 50%	50 - 75%
R8	6	12.2	1.9	9.18	0.1616	-	-	-	>50 m	continuous	5 - 25%	50 - 75%
R9	8	22.4	2.3	3.94	0.0689	trees	-	5 – 25%	>50 m	continuous	25 - 50%	50 - 75%
R10	7.6	37	4.2	3.57	0.0623	-	-	-	>50 m	continuous	25 - 50%	50 - 75%
R11	12.2	21.2	3.1	4.31	0.0753	trees	-	5 – 25%	>50 m	continuous	25 - 50%	25 - 50%
R12	9.6	21	3.6	15.45	0.2765	trees	-	5 – 25%	>50 m	continuous	50 - 75%	50 - 75%
R13	20	38.6	3.3	9.3	0.1637	-	-	-	>50 m	continuous	5 - 25%	50 - 75%
R14	5.6	10	1.4	4.44	0.0776	grass, trees	-	5 – 25%	>50 m	continuous	5 - 25%	50 - 75%
R15	1.5	3.5	0.5	1.86	0.0325	grass, trees	-	5 – 25%	>50 m	continuous	25 - 50%	25 - 50%
R16	5.3	7.6	0.4	1.28	0.0224	grass	-	>75%	>50 m	continuous	<1%	25 - 50%
R17	2.3	11.4	2.4	2.59	0.0453	grass	-	5 – 25%	>50 m	continuous	5 - 25%	50 - 75%

Table 18. Field data collected for Boomerang, Phillips and North creeks and Western Tributary sites, location, channel form, bed material and large wood.

Site	Stream	Latitude	Longitude	Longitudinal continuity	X-sec definition	Valley setting	Bed material (present)	Bed material (dominant)	Large wood (pc./100 m)
B1	Boomerang	-22.343259	148.428256	yes	strong	Unconfined/extensive	sand	sand	0
B2	Boomerang	-22.337741	148.443155	yes	strong	Unconfined/extensive	sand	sand	20
B3	Boomerang	-22.333304	148.464829	yes	strong	Unconfined/extensive	mud, sand	sand	25
P1	Phillips	-22.358194	148.486999	yes	strong	Unconfined/extensive	mud, sand, gravel	sand	10
P2	Phillips	-22.356918	148.488135	yes	strong	Unconfined/extensive	mud, sand	sand	5
P3	Phillips	-22.356186	148.491885	yes	strong	Unconfined/extensive	mud, sand	sand	10
N1	North	-22.164845	148.372613	yes	strong	Unconfined/extensive	mud, sand	sand	0
WTA1	West Trib. A	-22.178767	148.375134	no	ill-defined	Unconfined/extensive	mud, sand	mud	5
WTA2	West Trib. A	-22.184259	148.384871	yes	strong	Unconfined/extensive	mud, sand	sand	10
WTB1	West Trib. B	-22.298037	148.427400	no	strong	Unconfined/extensive	mud	mud	0
WTB2	West Trib. B	-22.296651	148.433633	no	ill-defined	Partly confined/moderate	mud	mud	0
WTC1	West Trib. C	-22.300933	148.446696	yes	weak	Partly confined/extensive	mud	mud	60

Table 19. Field data collected for Boomerang, Phillips and North creeks and Western Tributary sites, channel dimensions, instream bed vegetation structure, riparian vegetation structure. Point slope is DEM-derived and uncertain.

Site	Bed width (m)	Bankfull width (m)	Bankfull depth (m)	Slope (Deg.)	Slope (%)	Instream bed vegetation presence	Macrophyte bed cover	Tree/grass bed vegetation cover	Riparian buffer width	Riparian buffer continuity	Riparian tree cover	Riparian vegetation cover index
B1	7.5	44	4.5	10.43	0.1842	-	-	-	>50 m	continuous	50 - 75%	50 - 75%
B2	6.7	43	5.1	9.19	0.1618	-	-	-	>50 m	continuous	5 - 25%	25 - 50%
B3	9.2	45.7	7.6	5.99	0.1049	-	-	-	>50 m	continuous	50 - 75%	50 - 75%
P1	9.2	35	7	8.14	0.143	-	-	-	>50 m	continuous	75 - 100%	50 - 75%
P2	11.7	42.4	7	7.22	0.1267	-	-	-	>50 m	continuous	75 - 100%	50 - 75%
P3	9.3	32.6	8.5	11.52	0.2037	-	-	-	>50 m	continuous	50 - 75%	75 - 100%
N1	10.5	17	3.4	7.69	0.135	-	-	-	>50 m	continuous	50 - 75%	75 - 100%
WTA1	na	na	na	0.86	0.015	emergent macrophytes, grass	5 – 25%	>75%	>50 m	continuous	1 - 5%	50 - 75%
WTA2	2.5	31	6.2	13.76	0.2448	grass	-	<1%	>50 m	continuous	50 - 75%	50 - 75%
WTB1	8	10.7	1.2	1.31	0.0228	emergent macrophytes	25 – 50%	-	>50 m	continuous	<1%	25 - 50%
WTB2	11	40	0.4	0.56	0.0098	grass	-	>75%	>50 m	continuous	<1%	25 - 50%
WTC1	18.6	80	1.5	1.36	0.0238	emergent macrophytes, trees	50 – 75%	5 – 25%	>50 m	continuous	5 - 25%	25 - 50%

Figure 31. Downstream pattern of field-measured channel width and depth, and DEM-derived elevation of Isaac River and Ripstone Creek in the Study Area. Elevation is along 1:100,000 watercourse lines at 5 m intervals from 5 × 5 m DEM. Substantial islands were present at two sites labelled ‘part’ on Isaac River. Data refer to the main channel only.

4.2.7 Stream geomorphic type

Stream geomorphic type (equivalent to River Styles®) (Figure 32) was determined for the watercourses in the Study Area using the field gathered data and terrain analysis. Descriptions of the typical geomorphic units associated with the types were taken from River Styles® literature, and the streams in the Study Area did not necessarily possess all of these characteristics. The fragility ratings for each type were also taken from River Styles® literature.

Isaac River (Figure 18, Figure 19, Figure 20) and North Creek (Figure 25), being laterally unconfined with extensive floodplain connection, belong to the Low Sinuosity Sand type. The lowland reaches of Boomerang Creek (Figure 26) and Phillips Creek (Figure 27) are a similar type at a smaller scale, but by virtue of their higher sinuosity are Meandering Sand type.

The upper section of Ripstone Creek, from R1 to R7, is partly confined with extensive floodplain connection. Downstream of R7 to R14 the floodplain connection is less extensive. This upper part of Ripstone Creek down to R14 (Figure 22) is Planform Controlled Meandering Sand. The lower section of Ripstone Creek from R15 to R16 emerges from a confined valley and fans out over the lateral zone of the Isaac River floodplain (Figure 33). The mapped 1:100,000 blue line in this area should not be interpreted as a major flow path, as flood flow is likely to spread widely over this area. Here, the observed channel changed from sand bed to fine-grained bed and became an unconfined flow path characterised by discontinuous deep pools (Figure 23). At the local scale the creek had characteristics of chain-of-ponds geomorphic stream type, but it did not fit the usual upland valley setting, or lowland setting confined by a palaeochannel. Thus, it was more accurately classified as Floodout type (Figure 33). At the most downstream section from R17, where Ripstone Creek starts incising to meet Boomerang Creek bed level, the channel becomes longitudinally continuous and more defined in cross-section form (Figure 24). Here the creek was classified as Meandering Fine Grained type.

Western Tributary streams were sampled on lowland locations where they are proximal to or on the Isaac River floodplain. Here, the channels are small, varying from continuous to discontinuous. Western Tributary A, at WTA1 and further upstream (Figure 28), is an ill-defined Low Sinuosity Fine Grained stream draining low relief terrain. Further downstream, the channel starts incising towards the Isaac River (Figure 28). In this section the sandy bed material means WTA was classified as Low Sinuosity Sand type.

Site WTB1 is on a drainage line that has a much bigger catchment than at the site WTB2 on a small ill-defined Low Sinuosity Fine Grained tributary drainage line. The channel at WTB1 is better defined, also formed in mud, with a sequence of pools linked by short shallow well-vegetated sections (Figure 29), also of Low Sinuosity Fine Grained type.

Western Tributary C is a cutoff meander loop on the margin of the Isaac River floodplain (Figure 30, Figure 33). It is infilled with sediment and of a smaller scale than the current Isaac River channel. As such, it was not classified as belonging to a geomorphic stream type, rather, it was considered a geomorphic unit of the Isaac River.

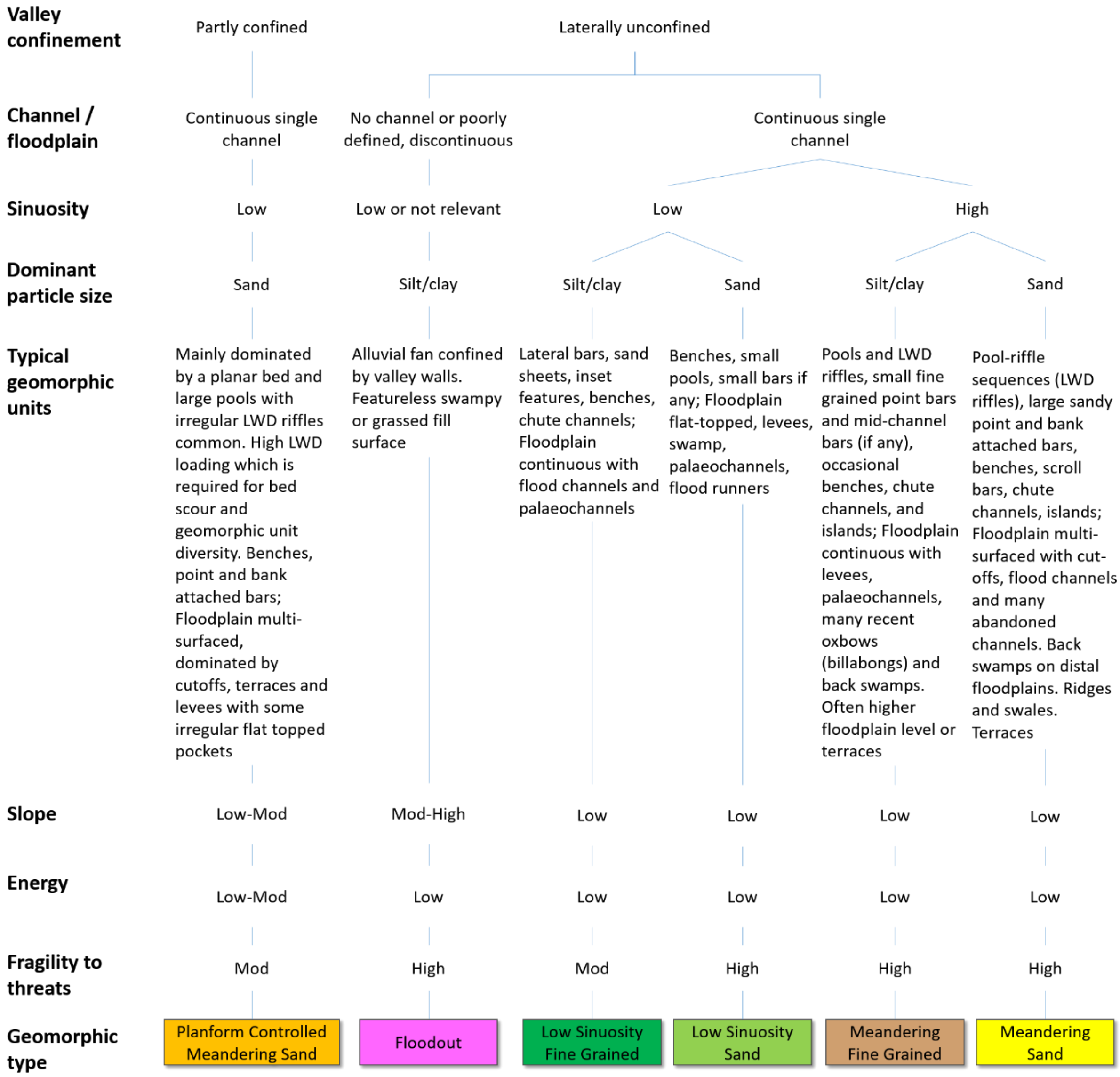

Figure 32. Stream geomorphic types identified within the Study Area. The geomorphic types and class attribute descriptions are borrowed from River Styles® framework.

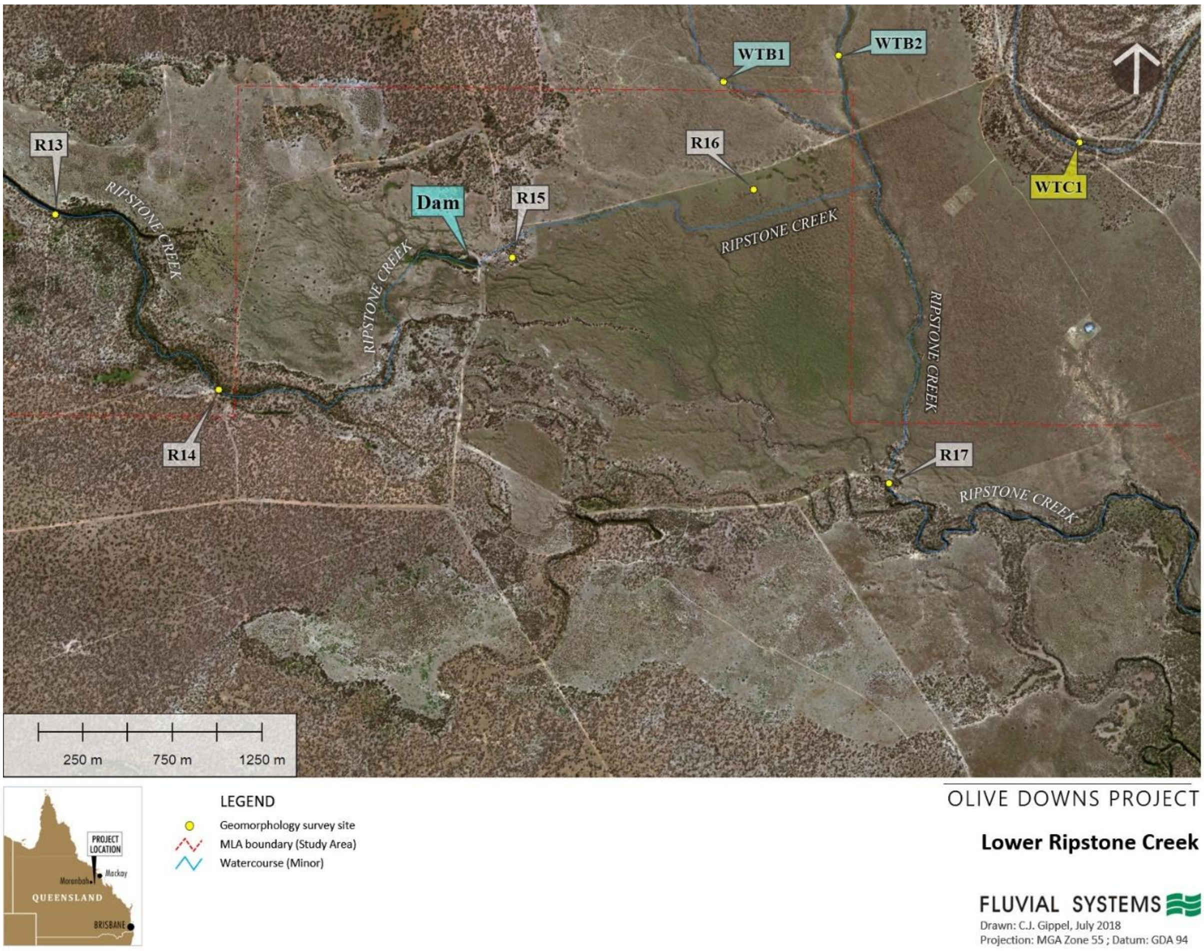

Figure 33. Lower Ripstone Creek, showing surveyed sites and 1:100,000 watercourse blue lines.

4.2.8 Stream geomorphic condition

Stream geomorphic condition was determined for the field survey sites within the Study Area using a number of stream type-independent criteria (Table 2). All of the sites fitted within the description of Good geomorphic condition. It should be noted that assessing whether a stream has geomorphic character different to its expected character is highly subjective and uncertain, unless data or evidence is available to indicate the expected character (i.e. either the undisturbed character from a time prior to pastoral settlement, or a character naturally adjusted to the current hydrological and sediment regime). The level of bank erosion observed was within what would be expected for an undisturbed or lightly disturbed stream, and longitudinal discontinuities, known as knickpoints, were not observed. Riparian vegetation cover was continuous and structurally sound at nearly all sites, although exotic species were present.

One of the descriptors of Poor geomorphic condition used by Outhet and Cook (2004) is 'Excessively high volumes of coarse bedload which blanket the bed, reducing flow diversity'. While this was a universal characteristic of all of the larger streams (Order 3 and higher) of the Study Area, no evidence was uncovered to suggest that this was unnatural. This challenges the claim by Alluvium (2011) that the sand bed of the Isaac River was evidence of geomorphic degradation due to altered catchment land use. The sub-surface geology of the wider Study Area is dominated by sandstone, and the surface geology is almost entirely sandy deposits or sandy soils. No gullies were observed in the Study Area that would indicate land degradation of the scale that would be required to modify a river system from pool-riffle gravel-cobble bed to amorphous sand sheet.

Information about the geomorphic condition of the Isaac River prior to European settlement can be gleaned from the journal of explorer Ludwig Leichardt on his 1844/45 expedition through the area on his way to Port Essington (Leichardt, 1846). The following paragraph details Leichardt's impression upon sighting the Isaac River for the first time on 13 Feb 1845:

> "*Feb. 13. — The morning was very cloudy. I continued my course to the northward, and, coming to a watercourse, followed it down in the hopes of finding water: it led us to the broad deep channel of a river, but now entirely dry. The bed was very sandy, with reeds and an abundance of small Casuarinas. Large flooded-gums and Casuarinas grew at intervals along its banks, and fine openly timbered flats extended on both sides towards belts of scrub. The river came from the north and north-west, skirting some fine ranges, which were about three miles from its left bank. As the river promised to be one of some importance I called it the "Isaacs," in acknowledgment of the kind support we received from F. Isaacs, Esq. of Darling Downs*."

Leichardt did not provide exact coordinates for the location where his party first came upon the Isaac River, but the journal entries around that time allow an approximation to be made. His camp at the time was to the west on Hughes Creek, an upper tributary of Boomerang Creek. Leichardt referred to Boomerang Creek as Hughes Creek all the way to its junction with the Isaac River. On 14 Feb a member of the party found a lagoon "…*on the left bank of the Isaacs, at a short half-mile from its junction with Hughs's Creek*". On 15 Feb Leichardt's party "…*travelled down to the above-mentioned lagoon, which was about ten miles east by north from our camp; its latitude, was by calculation, about 22 degrees 20 or 21* [minutes]*; for several circumstances had prevented me from taking observations*". This location places Leichardt on a currently existing lagoon on the western bank of the Isaac River, between latitudes 22° 20' 27" and 22° 20' 49", 1 km south of the junction of Billabong Creek and Isaac River. That same day, Leichardt "…*set out with Mr. Gilbert and Brown to examine the country around the range which I had observed some days before and named "Coxen's Peak and Range*". Coxen's Peak, 4.2 km NE of Iffley Station on the Isaac River, retains the same name today.

On the side trip to Coxens Peak and Range, Leichardt observed:

> "*The whole extent of country between the range and the coast, seemed to be of sandstone, either horizontally stratified, or dipping off the range; with the exception of some local disturbances, where basalt had broken through it. Those isolated ranges, such as Coxen's Range — the abruptness of which seemed to indicate igneous origin — were entirely of sandstone. The various Porphyries, and Diorites, and Granitic, and Sienitic rocks, which characterize large districts along the eastern coast of Australia, were missing; not a pebble, except of sandstone, was found in the numerous creeks and watercourses. Pieces of silicified wood were frequent in the bed of the Isaacs*".

Thus, Leichardt was fascinated by the ubiquitous presence of sandstone in the area, and, unlike the east coast rivers he was familiar with, the lack of material other than sand in the creek beds. During the field investigation undertaken for this Geomorphology Technical Report silicified wood was observed within occasional small outcrops of sedimentary rock at the base of the banks of the Isaac River (Figure 34), and isolated surface accumulations of gravel and cobble usually contained pieces of silicified wood.

After exploring Coxen's Range, Leichhardt returned westward to the Isaac River. On the way back to the camp at the lagoon, which they reached on 17 Feb, they noted a waterhole dug into the river bed and fortified by branches by Aborigines at latitude 22° 11', which places them just downstream of the junction of North Creek. On 21 Feb they decamped from the lagoon and headed upstream. The next day they sighted a flock of cockatoos at a point "…*About eight miles north-west from the junction of North Creek with the river*".

Leichardt's journal from 13 to 21 Feb 1845 clearly places him on the Isaac River within the Study area, between Billabong Creek junction and North Creek junction. His description of the river is similar to how it would currently be described, except for Leichardt's expected observation of more abundant, and perhaps more diverse, riparian flora and fauna.

It appears that following the publication of Leichardt's report of his expedition (Leichardt, 1846), pastoralists were quick to settle the Dawson, McKenzie and Isaac river area (Frere, 1945). This development occurred prior to Queensland being declared a separate state in 1859. The only readily available historical photograph of the Isaac River is from 1878, probably around 30 years after settlement, which shows a bullock wagon loaded with goods having just crossed the bed of the river (Figure 35). The National Library of Australia gives the location of this photograph as 22.22732°S,148.393929°E, which is not on the river, but 3.8 km WNW of Iffley Station, so the given location is approximate. Flowing water obscures the bed of the river in the photograph, but the channel morphology and riparian vegetation appear similar to the condition of the river when it was inspected in the field.

Despite evidence that the Isaac River and tributaries naturally have sand beds, it is possible, but not demonstrable, that land surface disturbance due to pastoral and mining activity has accelerated transport of sand from the land surface to the stream channel network and resulted in greater than expected volumes of sand in the bed.

Figure 34. Isaac River, localised outcrop of bedrock containing pieces of silicified wood. Lower photograph is close-up view of centre of scene of upper photograph.

Figure 35. Bullock team pulling a wagon full of goods, Isaac River, ca. 1878. Source: Trove, National Library of Australia, URL http://trove.nla.gov.au/version/167821903 (accessed 4 December, 2017).

5.0 Impact assessment – Isaac River

5.1 Hydraulic data

A 2-D hydraulic model was developed by Hatch (2018) to simulate the hydraulic characteristics of a number of flood scenarios at the Olive Downs Coking Coal Project site for the existing and developed case. Mapped and tabulated model output data were provided of hydraulic variables for 2 yr, 10 yr, and 50 yr ARI events. The data indicated that the 2 yr event was in-channel through the Project area. The 10 yr event broke out of the banks in some areas through Olive Downs South, while there were sections where a wide elevated levee remained above flood level. For the base case and the developed case, the 50 yr ARI flood fully inundated the channel and floodplain. The model confirmed the field observation of a significant downstream contraction in channel size, despite increasing tributary contributions.

On the basis of the flooding behaviour, and identified areas with the highest potential for accelerated scour or deposition associated with the development, 6 cross-sections and 3 long-profiles (Figure 36) were selected for assessment of geomorphic risk. Data were provided along all transects at 11 – 15 m intervals for the variables:

- Ground level
- Water level
- Velocity
- Stream power
- Bed shear stress

For each variable, the data for each transect represented the maximum value of the variable at the point on the transect.

Bed material transport was not evaluated here, but it is sufficient to note that the sand in the bed of the Isaac River will be mobile over a wide range of discharges. The bed is likely to be sufficiently mobile in moderate to large floods that sand will be mixed in the flow and available for deposition on the banks and floodplain surface in areas with low velocity, or as the flood recedes.

5.2 Results

The velocity and bed shear stress data for each cross-section and long profile were plotted with water surface and ground elevations (Figure 37, Figure 38, Figure 39, Figure 40, Figure 41, Figure 42, Figure 43, Figure 44, and Figure 45). For completeness, stream power was also plotted, even though this variable was not assessed using stability criteria. Modelled hydraulic conditions along the long profiles were highly variable, as the profile alignments crossed variable terrain at various distances from the river bank and within the river channel. While the long profile data complemented the cross-section data, specific reference to results from the long profiles was not necessary in order to describe the major predicted changes in channel and floodplain hydraulics due to the proposed development. Thus, this results section focuses on the cross-sections.

The data file for Cross-section 6, existing case, 50 yr ARI event, had missing velocity data (Figure 42).

Under both existing and developed cases, under the 2, 10 and 50 yr ARI events, the Isaac River channel had mean cross-section bed shear stress less than 100 N/m^2, although most individual values in the central channel area were close to, and a few exceeded,100 N/m^2. The channel bed is bare sand, so it would be mobile under these shear stresses. The geomorphological field investigation observed the banks to be generally well-vegetated and stable, with occasional areas on the outside of bends showing evidence of scour. This is part of the normal process of channel migration and adjustment.

Under existing conditions, the floodplain was not inundated under the 2 yr ARI flood event. Under the 10 and 50 yr ARI events, most areas of the floodplain had mean bed shear stress <10 N/m^2, with some areas in flood channels of 20 – 40 N/m^2. Cross-section 2 had a wide area on the left floodplain with bed shear stress approaching 50 N/m^2. The data suggest that under existing conditions, the floodplain is dominantly a depositional environment.

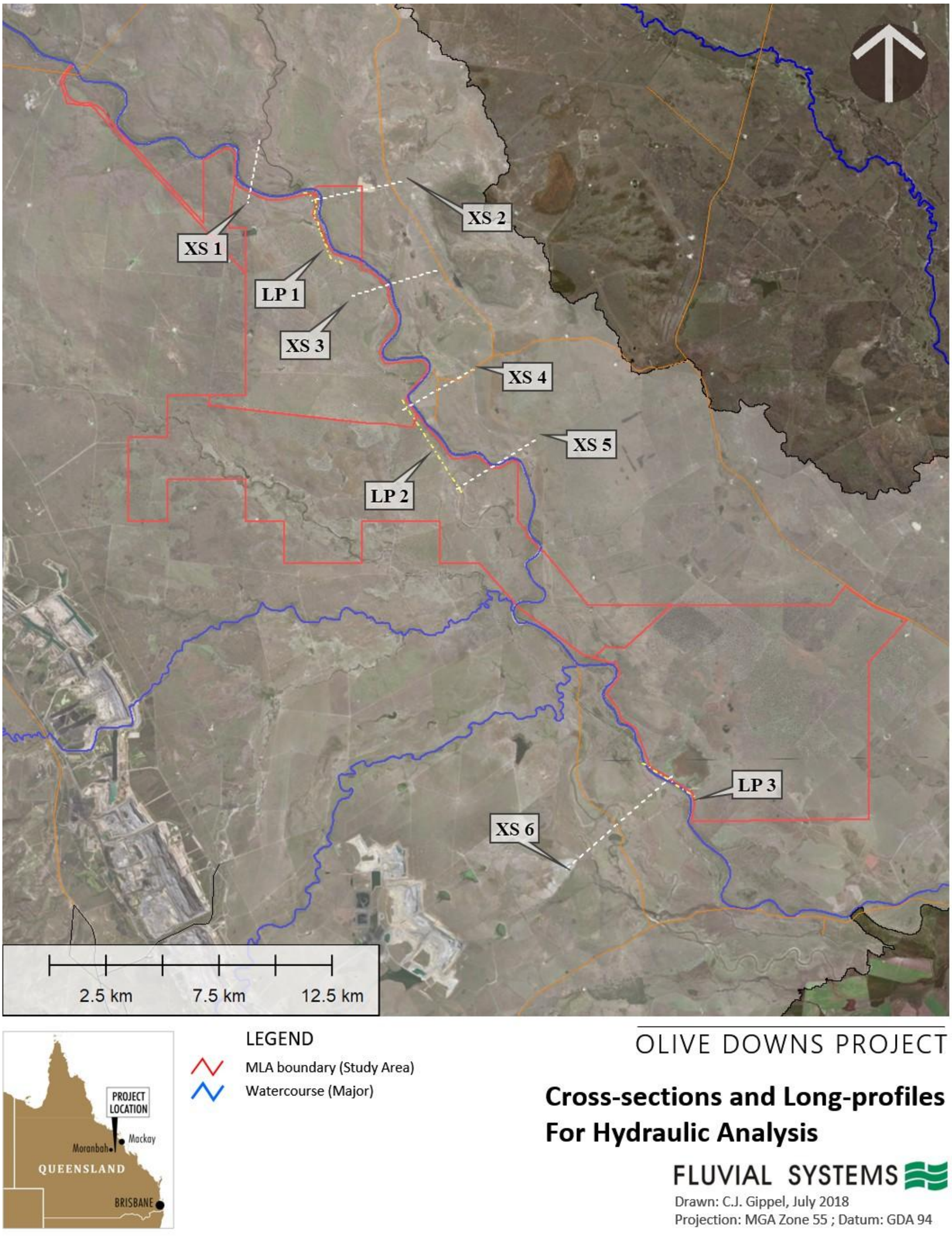

Figure 36. Locations of cross-sections and long-profiles evaluated in this preliminary assessment.

Under the developed case, a 50 yr ARI event would cause inundation of a left-bank terrace at Cross-section 2; this area would not be inundated under existing conditions. However, the bed shear stress on this terrace would be low, with most areas having less than 10 N/m^2, and all areas less than 20 N/m^2. In comparison, under existing conditions the bed shear stress on the left floodplain mostly exceeded 10 N/m^2 and reached up to 50 N/m^2 (this area of floodplain would be removed from the flow path under the developed case). A similar situation is represented by Cross-section 5, where the right bank floodplain was not inundated by the 50 yr ARI event under existing conditions, but would experience widespread inundation under the developed case. However, under the 50 yr ARI event for the developed case, the bed shear stress on the floodplain would be relatively low, with most areas having less than 20 N/m^2, and all areas less than 30 N/m^2.

A proposed embankment at Cross-section 4 would elevate bed shear stress through confinement of the flow. Bed shear stress on the areas of the floodplain impacted by confinement due to development would reach a maximum of 30 N/m^2 for the 50 yr ARI flood scenario. The maximum permissible shear stress method suggests that the floodplain surfaces most impacted by development, represented by Cross-sections 2, 4 and 5, if maintained with complete and dense vegetation cover, should remain at a low risk of fluvial scour. If the vegetative cover is weakened by drought or grazing pressure, the risk of scour would increase markedly.

Comparisons of modelled velocity with maximum permissible velocity threshold of 2 m/s were similar to the comparisons between modelled bed shear stress and maximum permissible bed shear stress. The main areas of significant risk were Cross-sections 2, 4 and 5 under the 50 yr ARI flood scenario. At Cross-section 2, velocity increased on the banks and reached 1 m/s on the confined floodplain surface. At Cross-section 4, velocity increased by a factor of two on the right-bank confined floodplain surface, although velocity did not exceed 2 m/s. Similarly, the velocity did not exceed 1.5 m/s on the area of right bank floodplain of Cross-section 5 inundated under the 50 yr ARI flood scenario.

Overall, the impact of the development on hydraulic variables would be small enough that a rapid catastrophic geomorphic response would not be expected. However, the channel will slowly adjust to the altered hydraulic conditions through minor changes in bed and floodplain levels or channel widths. The greatest risk to rapid catastrophic geomorphic change is loss of structural integrity and coverage of the channel bank and floodplain vegetation.

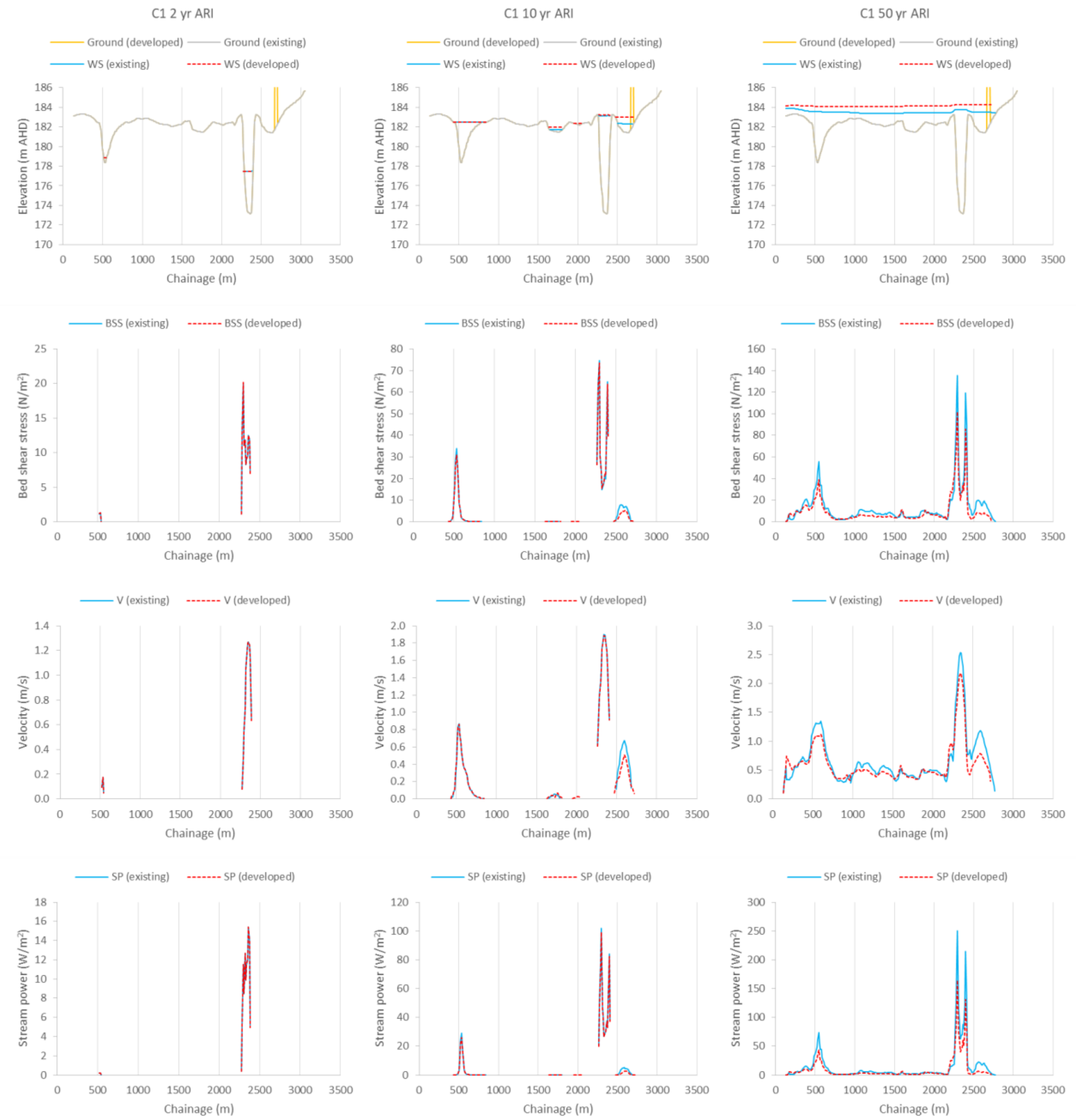

Figure 37. Cross-section 1 hydraulic character for 2 year, 10 year and 50 year ARI events. Note that Y-axis scales vary between flow scenarios.

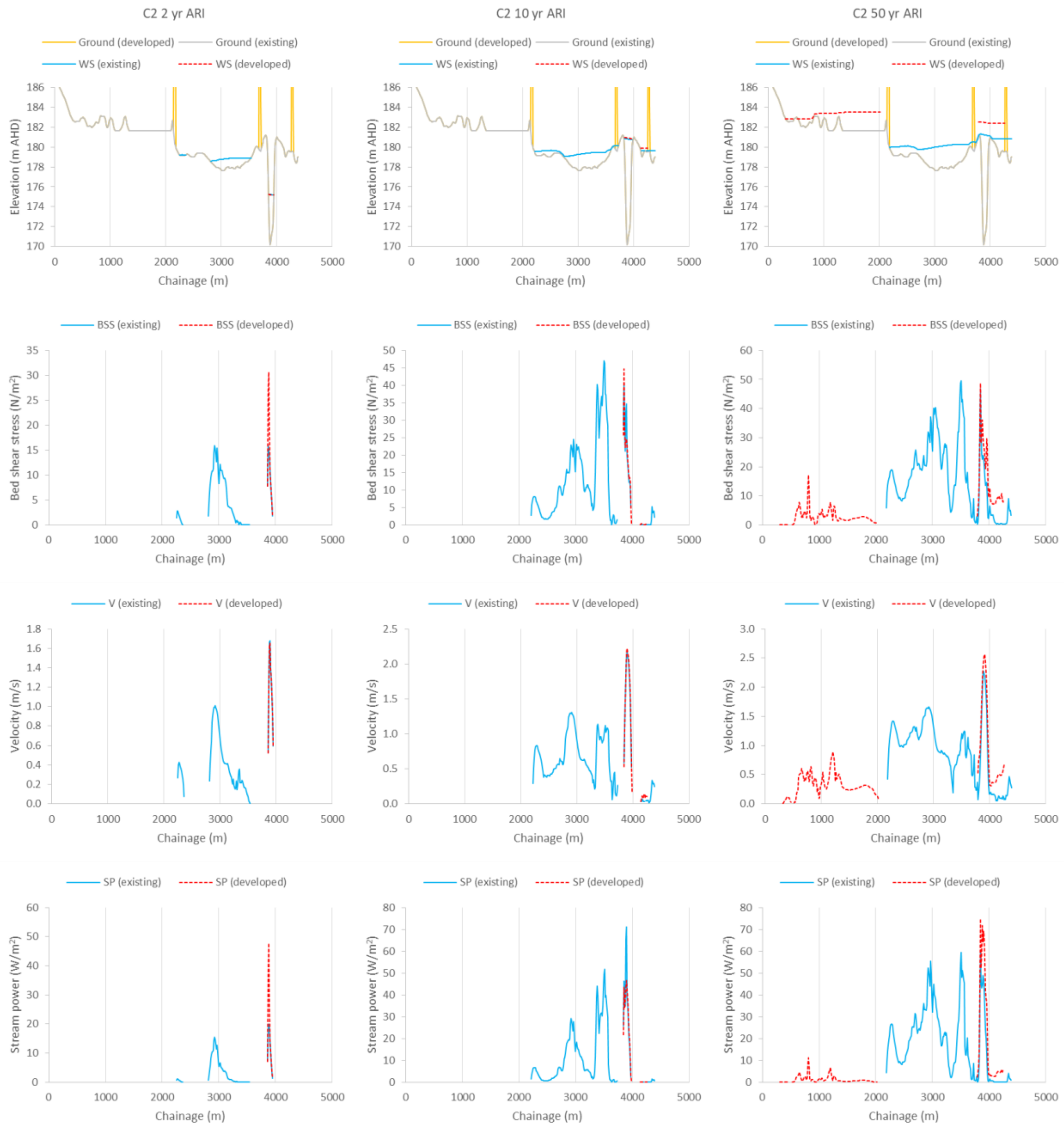

Figure 38. Cross-section 2 hydraulic character for 2 year, 10 year and 50 year ARI events. Note that Y-axis scales vary between flow scenarios.

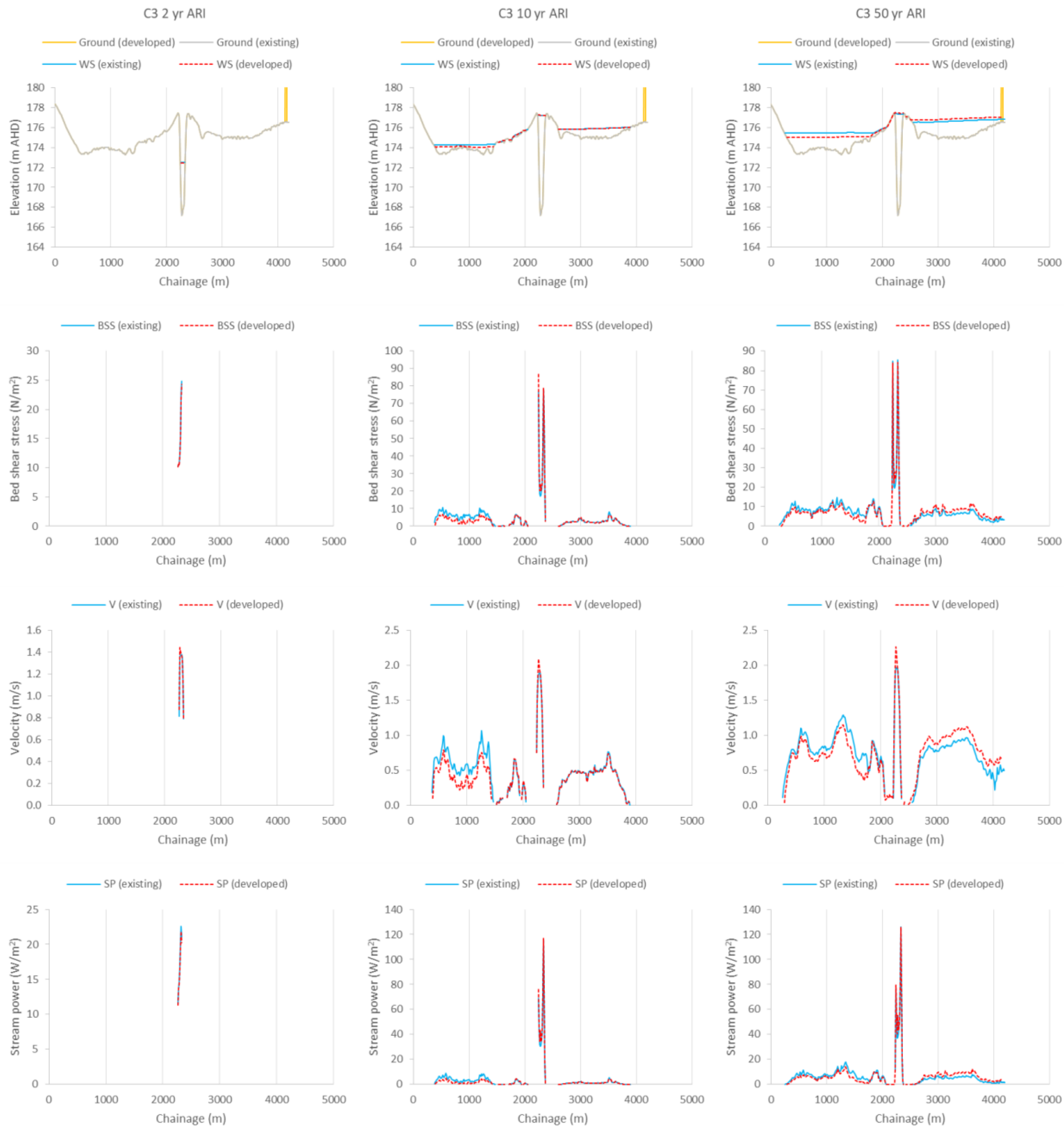

Figure 39. Cross-section 3 hydraulic character for 2 year, 10 year and 50 year ARI events. Note that Y-axis scales vary between flow scenarios.

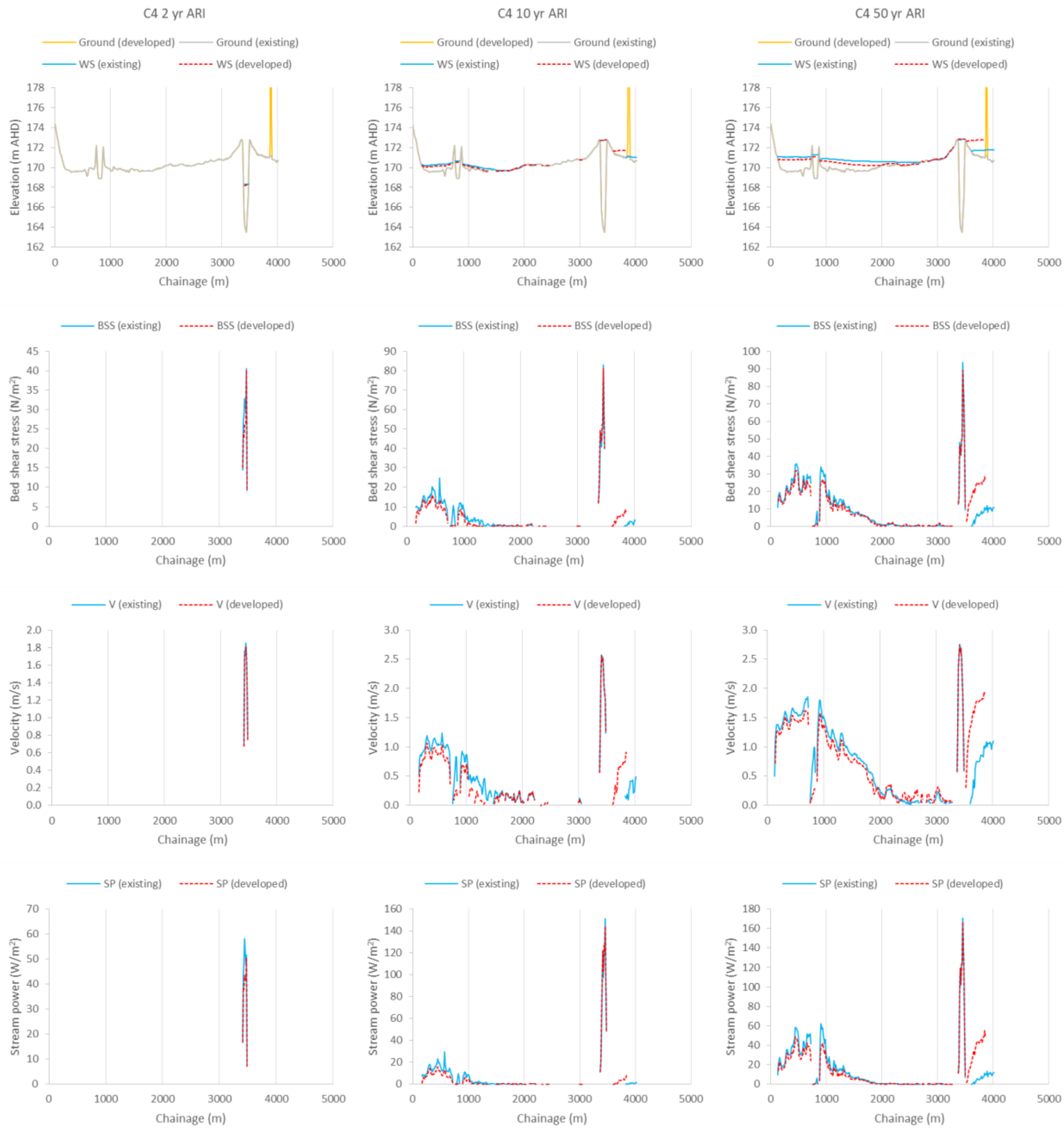

Figure 40. Cross-section 4 hydraulic character for 2 year, 10 year and 50 year ARI events. Note that Y-axis scales vary between flow scenarios.

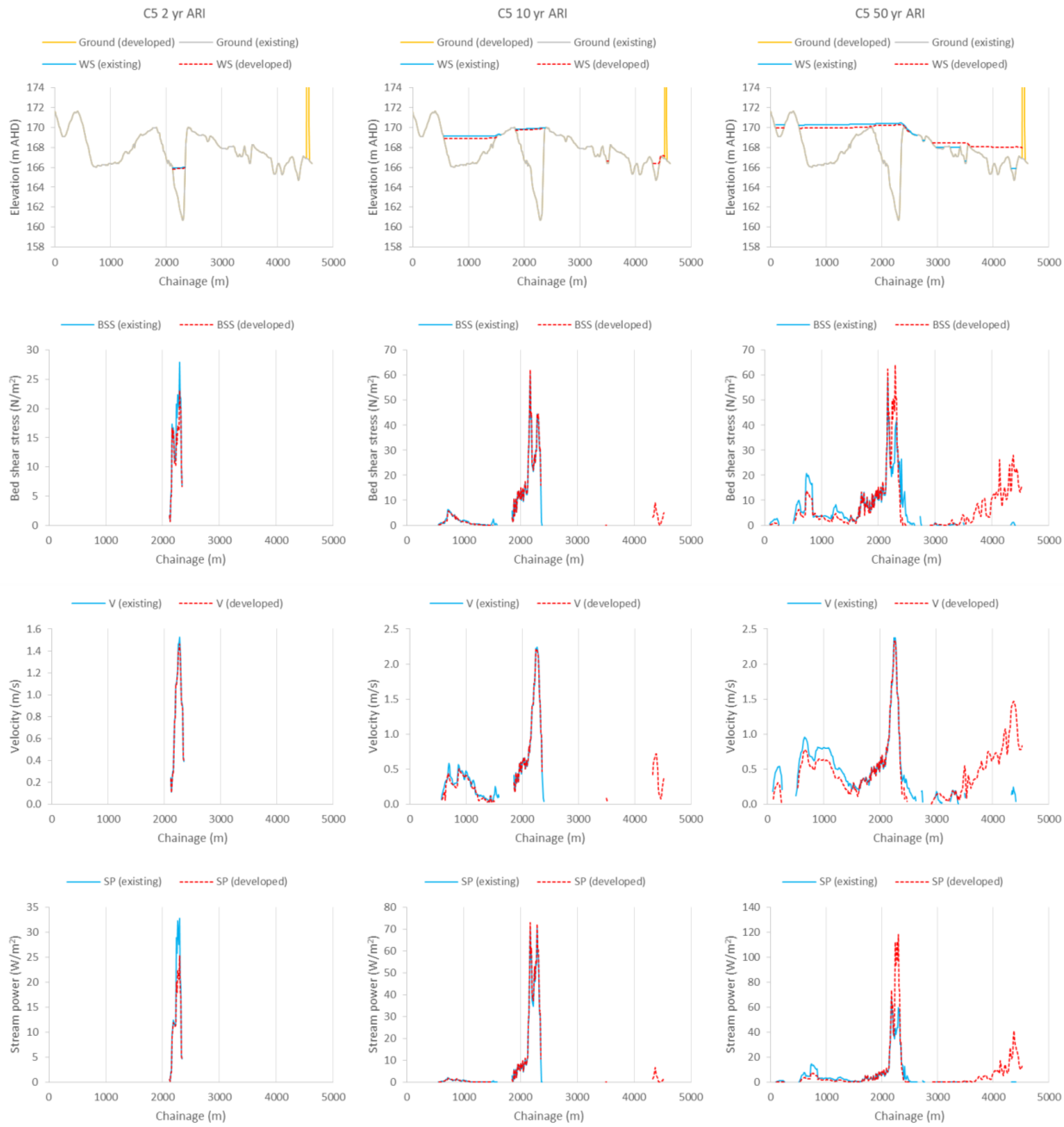

Figure 41. Cross-section 5 hydraulic character for 2 year, 10 year and 50 year ARI events. Note that Y-axis scales vary between flow scenarios.

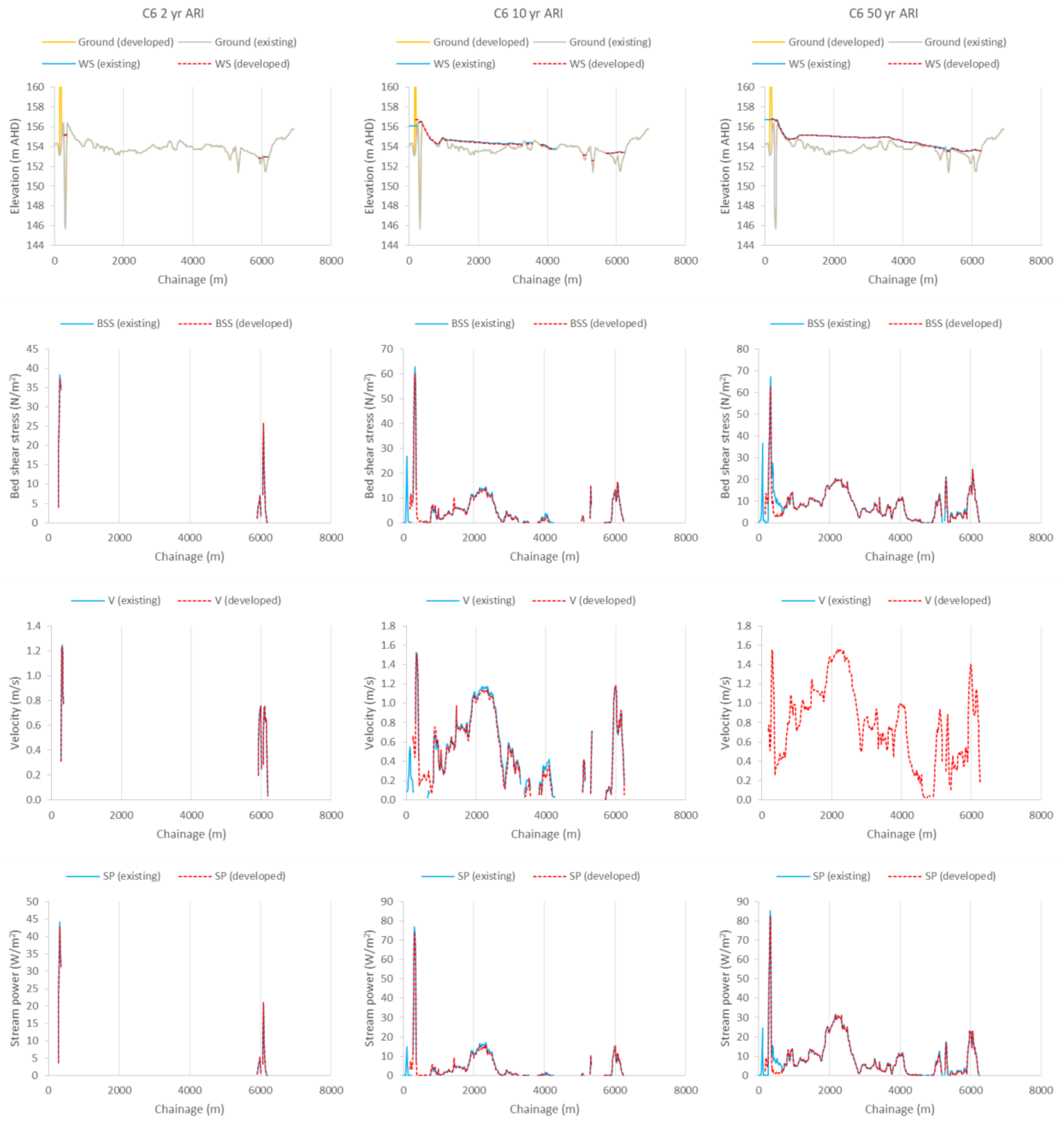

Figure 42. Cross-section 6 hydraulic character for 2 year, 10 year and 50 year ARI events. Note that Y-axis scales vary between flow scenarios. Note that velocity data are missing for existing scenario 50 year ARI event.

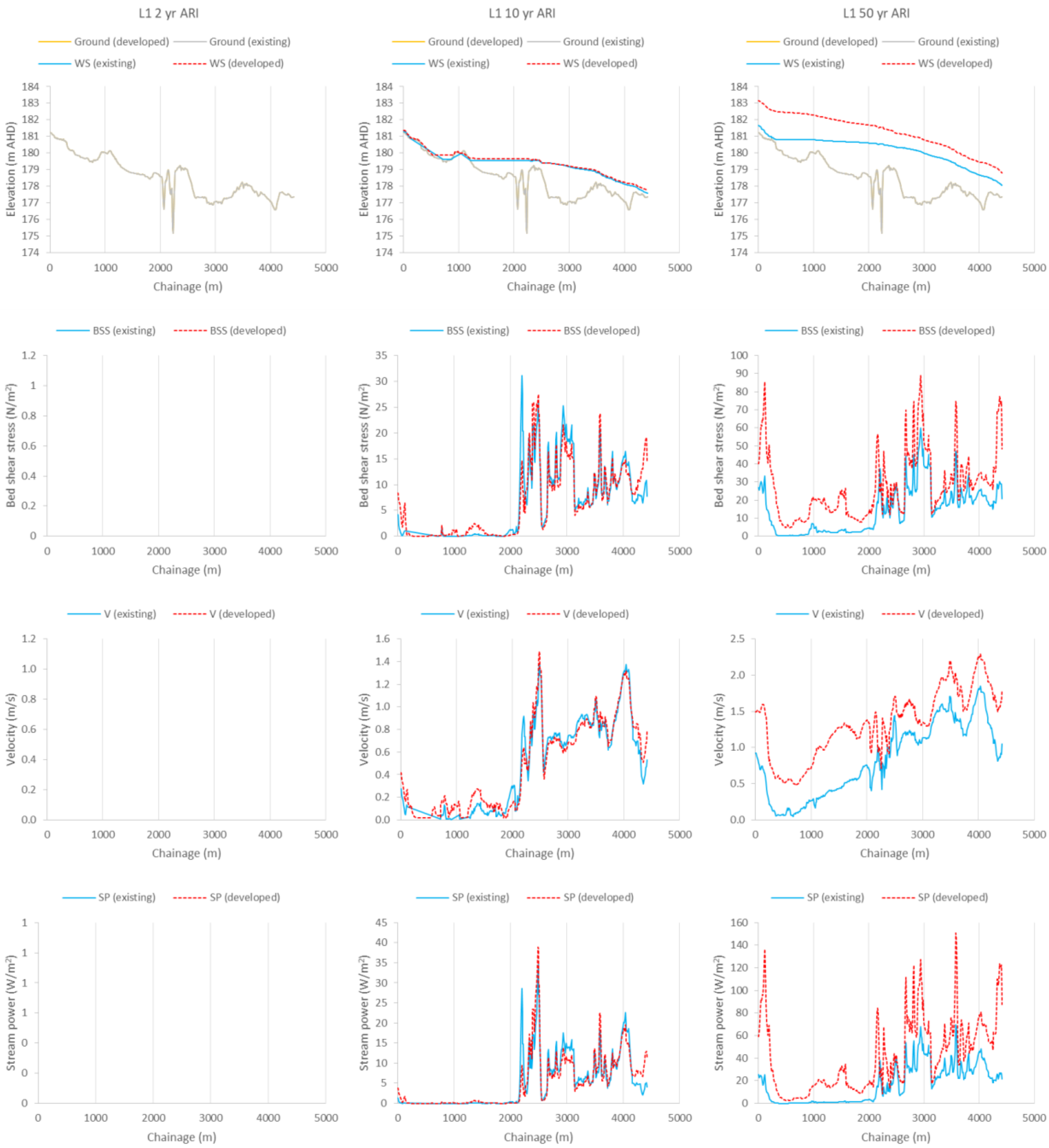

Figure 43. Long-profile 1 hydraulic character for 2 year, 10 year and 50 year ARI events. Note that Y-axis scales vary between flow scenarios.

Figure 44. Long-profile 2 hydraulic character for 2 year, 10 year and 50 year ARI events. Note that Y-axis scales vary between flow scenarios.

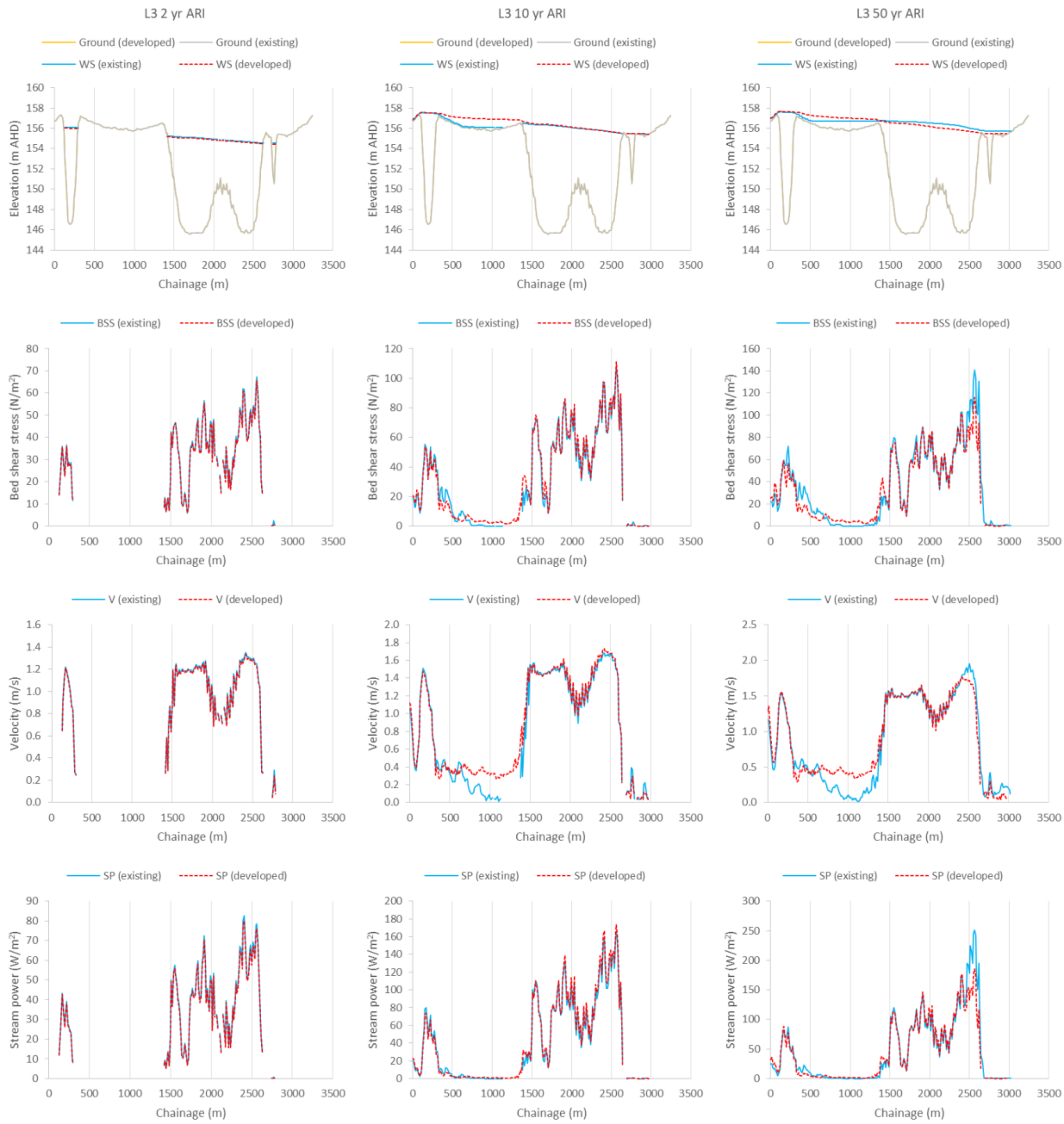

Figure 45. Long-profile 3 hydraulic character for 2 year, 10 year and 50 year ARI events. Note that Y-axis scales vary between flow scenarios.

6.0 Monitoring and Mitigation

6.1 Monitoring

Geomorphic monitoring should be undertaken using objective, scientifically sound methods, following a BACI (Before/After/Control/Intervention) design. The foundation of the recommended approach is topographic survey of Isaac River channel and floodplain, repeated every year for 3 years, and then either every five years, or after every flood event exceeding the 5 yr ARI event. This should be done using LiDAR technology, flown when the river flow is very low. It will be necessary to identify control reaches that are also monitored, preferably upstream of the mine, The monitoring principle is to characterise the degree of change at the control reaches of Isaac River and use this to set the tolerance for change in the intervention reach of the Isaac River through the Mining Lease Areas. After each survey, a monitoring report is to be prepared that uses scientific methods to evaluate the data, including statistical analysis to test for significance of differences across a range of geomorphic variables derived from the survey data.

Methods that use subjective visual assessments of geomorphic variables (e.g. erosion severity, or geomorphic condition score sheets) are not recommended, as in general, they are not founded on a sound basis of geomorphic theory, do not utilise a scientifically valid sampling strategy, observations are not repeatable within acceptable tolerances, and the data are not open to rigorous statistical testing.

6.2 Mitigation

Mitigation is to eliminate or reduce the frequency, magnitude, or severity of exposure to risks, or to minimise the potential impact of a threat. This can be achieved through vegetation management, maintaining complete vegetation cover over bank and floodplain surfaces. Mitigation measures would be triggered by unexpectedly large change in channel morphology identified through monitoring. The most appropriate response would need to be assessed at the time.

7.0 Conclusion

Repeatable field and desktop methods were used to characterise geomorphological attributes of of the Olive Downs Coking Coal Project Study Area. Most of the stream reaches were in a stable, close to natural geomorphic condition. Some streams were potentially impacted by factors that reduced their condition, in particular high loads of sand in the bed, but without historical data concerning condition prior to the land cover and drainage being modified for agricultural and mining use, this remains uncertain. No knickpoints or zones of major geomorphic instability were observed.

Most of the stream reaches were in a stable, close to natural geomorphic condition. Some streams were potentially impacted by factors that reduced their condition, in particular high loads of sand in the bed, but without historical data concerning condition prior to the land cover and drainage being modified for agricultural and mining use, this remains uncertain. No knickpoints or zones of major geomorphic instability were observed.

The risk of erosion of the Isaac River channel and floodplain was assessed using the method of maximum permissible bed shear stress and velocity assessment, with the hydraulic variables modelled as part of the flood study. This assessment of the most critical areas found that while there could be isolated areas subject to somewhat higher risk of scour compared to the existing situation, the overall risk of rapid and significant geomorphic change in the Isaac River due to the proposed mining activity was low.

Geomorphic monitoring should include topographic survey of Isaac River channel and floodplain, repeated every year for 3 years, and then either every five years, or after every flood event exceeding the 5 yr ARI event. This should be done using LiDAR technology, flown when the flow is very low. A Before-After, Control-Intervention monitoring design should be used, with tolerable limits of change in the intervention reaches set by the observed degree of change in control reaches.

Mitigation measures would be triggered by unexpectedly large change in channel morphology identified through monitoring. The most appropriate response would need to be assessed at the time.

8.0 References

Aarc 2016. Lake Vermont Northern Extension, Aquatic Ecology and Stream Morphology Assessment. Austral Asian Resource Consultants, Lake Vermont Resources Pty Ltd, April.

Abernethy, B. and Rutherfurd, I.D. 2000. The effect of riparian tree roots on the mass-stability of riverbanks. Earth Surf. Process. Landforms 25: 921-937.

Alluvium 2011. Red Hill Mining Lease EIS, Geomorphic assessment of proposed longwall mining on Isaac River and its tributaries. Alluvium Consulting, BHP Billiton Mitsubishi Alliance, December.

Anon. 1936. The maximum permissible velocity in open channels. Gidrotekhnicheskoie Stroitel'stvo (Hydrotechnical Construction), Moscow, May, No. 5: 5-7.

Ashton, L.J. and McKenzie, N.J. 2001. Conversion of the Atlas of Australian Soils to the Australian Soil Classification, CSIRO Land and Water (unpublished).

Barka, I Vladovič, J and Máliš, F. 2011. Landform classification and its application in predictive mapping of soil and forest units. In Růžička, J. and Pešková, K. (eds) Proceedings, GIS Ostrava 24-26 January 2011, VSB - Technical University of Ostrava, Czech Republic. URL: http://gis.vsb.cz/GIS_Ostrava/GIS_Ova_2011/sbornik/index.html (accessed 23 June 2013).

Blackham, D. 2006. The relationship between flow and stream channel vegetation. Unpublished PhD thesis. The School of Anthropology, Geography & Environmental Studies (SAGES), The University of Melbourne, Parkville.

Blackham, D. 2006. The relationship between flow and stream channel vegetation. Unpublished PhD thesis. The School of Anthropology, Geography and Environmental Studies (SAGES), The University of Melbourne, Parkville.

Böhner, J., Blaschke, T. and Montanarella, L. (eds.) 2008. SAGA – Seconds Out. Hamburger Beiträge zur Physischen Geographie und Landschaftsökologie, Vol.19, 113pp.

Böhner, J., McCloy, K.R., Strobl, J. (eds) 2006. SAGA – Analysis and Modelling Applications. Göttinger Geographische Abhandlungen, Vol.115, 130pp.

Bond, N.R., Lake, P.S. an Arthington, A.H. 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. Hydrobiologia 600: 3-16.

Brakensiek, D.L., Osborn, H.B., and Rawls, W.J. (eds) 1979. Field manual for research in agricultural hydrology. United States Department of Agriculture, Agricultural Handbook Number 224, USDA, Washington, DC.

Brierley, G.J. and Fryirs, K.A. 2000. River Styles, a geomorphic approach to catchment characterisation: Implications for river rehabilitation in Bega Catchment, NSW, Australia. Environmental Management 25(6): 661–679.

Brierley, G.J. and Fryirs, K.A. 2002. The River Styles® Framework: the Short Course Conceptual Book. Book given to participants in the course. Macquarie University, North Ryde.

Brierley, G.J. and Fryirs, K.A. 2006. The River Styles® Framework. http://www.riverstyles.com/ (accessed 1 July 2011).

Brierley, G.J. and Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Styles® Framework. Blackwell Publishing, Cornwall.

Brierley, G.J. and Fryirs, K.A., Cook, N., Outhet, D., Raine, A., Parsons, L. and Healey, M. 2011. Geomorphology in action: Linking policy with on-the-ground actions through applications of the River Styles framework. Applied Geography 31: 1132-1143.

Brierley, G.J. and Wheaton, J. 2013. The River Styles framework: Three Day Professional Shortcourse, School of Environment, The University of Auckland, 8-10 October. URL: http://etal.usu.edu/Workshops/RiverStyles/2013/RS 2 Stage 1 (Character and Behaviour).pdf

Brierley, G.J., Fryirs, K.A., Outhet, D. and Massey, C. 2002. Application of the River Styles framework as a basis for river management in New South Wales, Australia. Applied Geography 22: 91-122.

Carter, A.C. 1953. Critical tractive forces on channel side slopes. U.S. Bureau of Reclamation, Hydraulic Laboratory Report No. Hyd-366 (supersedes Hyd-295), February.

Causton, D.R. 1988. An Introduction to Vegetation Analysis. Unwin Hyman. London.

Chambers, P.A., Prepas, E.E., Hamilton, H.R. and Bothwell, M.L. Current velocity and its effect on aquatic macrophytes in flowing waters. Ecological Applications 1: 249-257.

Chang, H.H. 1988. Fluvial Processes in River Engineering, John Wiley and Sons, New York.

Chow, V.T. 1981. Open-Channel Hydraulics. McGraw Hill International Book Company. Tokyo, Japan.

Cimmery, V. 2007-2010. SAGA User Guide, updated for SAGA version 2.0.5.

Cook, N. and Schneider, G. 2006. River Styles® in the Hunter catchment. NSW Government, Department of Natural Resources.

Department of Natural Resources and Mines 2014. Guideline: Works that interfere with water in a watercourse—watercourse diversions. State of Queensland, September.

Department of State Development 2017. Terms of reference for an environmental impact statement: Olive Downs Project. State of Queensland, Department of State Development, Brisbane, June.

DERM 2011. Department of Environment and Resource Management, Watercourse Diversions – Central Queensland Mining Industry, Central West Region, Queensland.

Drăguţ, L. and Blaschke, T. 2006. Automated classification of landform elements using object-based image analysis. Geomorphology 81: 330-344.

Fischenich, C.J. 2001. Stability Thresholds for Stream Restoration Materials. EMRRP Technical Notes Collection (ERDC TNEMRRP-SR-29), U.S. Army Engineer Research and Development Center, Vicksburg, MS.URL: https://www.marincounty.org/depts/cu/~/media/files/departments/pw/mcstoppp/residents/fischenichstabilitythresholds.pdf (accessed 17 April 2018).

Fischenich, C.J. and Allen, H. 2000. Stream management. Water Operations Technical Support Program Special Report ERDC/EL SRW-00-1, Vicksburg, MS. URL: https://www.engr.colostate.edu/~pierre/ce_old/classes/ce717/Manuals/Fischenich/Fischenich%20Allen%202000.pdf (accessed 17 April 2018).

Fortier, S. and Scobey, F.C. 1926. Permissible canal velocities. Transactions, American Society of Civil Engineers 89: 940-956.

Franklin, P., Dunbar, M. and Whitehead, P. 2008. Flow controls on lowland river macrophytes: A review. Science of the Total Environment 400: 369-378.

Frere, B. 1945. Pastoral settlement follows Leichardt's exploration. Townsville Daily Bulletin, Thursday, August 2. URL: http://trove.nla.gov.au/newspaper/article/62856382?downloadScope=page (accessed 4 December 2017).

Frissell, C. A.; Liss, W. J.; Warren, C. E.; Hurley, M. D. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10(2): 199-214.

Fryirs, K.A. 2003. Guiding principles of assessing the geomorphic condition of rivers: application of a framework in Bega catchment, South Coast, NSW, Australia. Catena 53:17-52.

Fryirs, K.A. and Brierley, G.J. 2005. Practical application of the River Styles® framework as a tool for catchment-wide river management: a case study from Bega catchment, New South Wales. Macquarie University. URL: http://www.riverstyles.com/ebook.php (accessed 15 Jan 2015).

Fryirs, K.A. and Brierley, G.J. 2006. Linking geomorphic character, behaviour and condition to fluvial biodiversity: implications for river management. Aquatic Conservation: Marine and Freshwater Ecosystems 16: 267–288.

Fryirs, K.A. and Brierley, G.J. 2010. Antecedent controls on river character and behaviour in partly-confined valley settings: upper Hunter catchment, NSW, Australia. Geomorphology 117: 106-120.

Gallant, J.C. and Dowling, T.I. 2003. A multi-resolution index of valley bottom flatness for mapping depositional areas. Water Resources Research 39(1):1347-1359, doi:10.1029/2002WR001426.

Gardner, T.W., Sawowsky, K.S. and Day, R.L. 1990. Automated extraction of geomorphometric properties from digital elevation data. Z. Geomorphol. 80, 57–68.

Gippel, C.J. 1995. Environmental hydraulics of large woody debris in streams and rivers. Journal of Environmental Engineering 121: 388-395.

Gippel, C.J., Finlayson, B.L. and O'Neill, I.C. 1996. Distribution and hydraulic significance of large woody debris in a lowland Australian River. Hydrobiologia 318(3): 179-194.

Greening Australia 2007. Cumbungi – friend or foe? You asked for it…Hot topics in native vegetation management. Number 02, June, pp. 1-6. URL: http://www.greeningaustralia.org.au/uploads/Our%20Services%20-%20Toolkit%20pdfs/YAFI_No2_Cumbungi.pdf (accessed 6 July 2013).

Groeneveld, D.P. and French, R.H. 1995. Hydrodynamic control of an emergent aquatic plant (*scirpus acutus*) in open channels. Water Resources Bulletin 31: 505-514.

Guisan, A., Weiss, S.B., Weiss, A.D. (1999): GLM versus CCA spatial modeling of plant species distribution. Plant Ecology 143: 107-122.

Guscio, F.J., Bartley, T.R. and Beck, A.N. 1965. Water resources problems generated by obnoxious plants. Proceedings of the American Society of Civil Engineers, Journal of the Waterways and Harbours Division 10: 47-60.

Hansen Bailey 2016. G200s Project, Baseline Geomorphology Report. Anglo Coal (Grosvenor) Pty Ltd. Brisbane, September.

Hardie, R and Lucas, R. 2002. Bowen Basin River Diversions Design and Rehabilitation Criteria. Project C9068 Report for Australian Coal Association Research Program (ACARP). Fisher Stewart Ltd, July.

Hardie, R., Tilleard, J and Erskine, W. 1994. Stream morphology and hydraulics of the Isaac River Diversion. In Water Down Under '94, 21-25 November, Adelaide. 22nd Hydrology and Water Resources Symposium, Institution of Engineers, Australia, Barton, ACT, pp. 379-383.

Hatch 2018. Olive Downs Project EIS - Flood Assessment. Draft Report. Olive Downs Project. Pembroke Resources, April.

Horvath, T.G. 2004. Retention of particulate matter by macrophytes in a first-order stream. Aquatic Botany 78: 27-36.

Hudson, N. 1971. Soil Conservation, Cornell University Press, Ithaca.

Hudson, N. 1971. Soil Conservation, Cornell University Press, Ithaca.

Isbell, R.F. 2002. The Australian Soil Classification. Revised Edition. CSIRO Publishing, Melbourne.

Iwahashi, J. and Pike, R.J. 2007. Automated classifications of topography from DEMs by an unsupervised nested-means algorithm and a three-part geometric signature. Geomorphology, 86: 409–440.

Jenness, J. 2006. Topographic Position Index (TPI) v. 1.2. Jenness Enterprises, Flagstaff, AZ. URL: http://www.jennessent.com/downloads/tpi_documentation_online.pdf (accessed 26/11/2017).

Jenson, S.K. and Domingue, J. O. 1988. Extracting topographic structure from digital elevation model data for geographic information system analysis, Photogramm. Eng. Rem. S., 54(11): 1593–1600.

Lane, E.W. 1952. Progress report on results of studies on design of stable channels. U.S. Bureau of Reclamation, Hydraulic Laboratory Report No. Hyd-352, June. URL: https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/HYD/HYD-352.pdf (accessed 17 April 2018).

Lane, E.W. 1955. Design of stable channels. Transactions, American Society of Civil Engineers 120: 1234-1260.

Leichardt, L. 1846. Journal of an overland expedition in Australia, from Moreton Bay to Port Essington, a distance of upwards of 3000 miles, during the years 1844–1845. Sydney, September. Web edition published by eBooks@Adelaide, The University of Adelaide Library, University of Adelaide. URL: https://ebooks.adelaide.edu.au/l/leichhardt/ludwig/l52j/complete.html (accessed 26/11/2017).

MacMillan, R.A. and Shary, P.A. 2009. Landforms and landform elements in geomophometry. In Hengl, T. and Reuter, H.I. (eds) Geomorphometry: Concepts, Software and Applications. Developments in Soil Science Vol 33, Elsevier, Amsterdam, pp. 227 – 255.

Madsen, J.D., Chambers, P.A., James, W.F., Koch, E.W. and Westlake, D.F. 2001. The interaction between water movement, sediment dynamics and submersed macrophytes. Hydrobiologia 444: 71-84.

Munné, A., Prat, N., Solà, C, Bonada, N. and Rieradevall, M. 2003. A simple field method for assessing the ecological quality of riparian habitat in rivers and streams: QBR index. Aquatic Conserv: Mar. Freshw. Ecosyst. 13: 147–163.

Niculiță, I.C. and Niculiță, M. 2011. Methods for natural land mapping units delineation for agricultural land evaluation. Lucrări ştiinţifice, seria Agronomie 54(1): 44-49.

Northcote, K.H. 1978. Soils and Landuse. In Atlas of Australian Resources, Division of National Mapping, Canberra.

Northcote, K.H. 1979. A Factual Key for the Recognition of Australian Soils. 4th Ed., Rellim Technical Publishers, Glenside, SA.

O'Hare, J.M., O'Hare, M.T., Gurnell, A.M., Scarlett, P.M., Liffen, T. and McDonald, C. Influence of an ecosystem engineer, the emergent macrophyte *Sparganium erectum*, on seed trapping in lowland rivers and consequences for landform colonisation. Freshwater Biology 57(1): 104-115.

Outhet, D. and Cook, N. 2004. Definitions of geomorphic condition categories for streams. Unpublished internal draft paper for use throughout NSW by the Department of Infrastructure, Planning and Natural Resources.

Outhet, D. and Young, C. 2004a. Using reference reaches to suggest causes of poor river geomorphic condition. In Rutherfurd, I. (ed.), Proceedings 4th Australian Stream Management Conference, Launceston, Tasmania, 20-22 Oct., pp. 470-476.

Outhet, D. and Young, C. 2004b. River Style Geomorphic Fragility. Unpublished internal draft paper for use throughout NSW by the Department of Infrastructure, Planning and Natural Resources.

Parsons, M., Thoms, M. and Norris, R. 2002. Australian River Assessment System: AusRivAS Physical Assessment Protocol. Monitoring River Health Initiative Technical Report Number 22. Cooperative Research Centre for Freshwater Ecology, University of Canberra. Environment Australia, Canberra. URL: http://ausrivas.ewater.com.au/index.php/protocolphysical (accessed 6 July 2013).

Prosser, I.P. and Slade, C.J. 1994. Gully formation and the role of valley-floor vegetation, southeastern Australia. Geology 22: 1127-1130.

Prosser, I.P. and Slade, C.J. 1994. Gully formation and the role of valley-floor vegetation, southeastern Australia. Geology 22: 1127-1130.

Prosser, I.P., Dietrich, W.E. and Stevenson, J. 1995. Flow resistance and sediment transport by concentrated overland flow in a grassland valley. Geomorphology 13: 71-86.

Rai, R. and Shrivastva, B.K. 2012. Effect of grass on soil reinforcement and shear strength. Proceedings of the ICE - Ground Improvement 165(3): 127-130.

Raven, P.J., Holmes, N.T.H., Dawson F.H. and Everard, M. 1998. Quality assessment using River Habitat Survey data. Aquatic Conserv: Mar. Freshw. Ecosyst. 8: 477-499.

Ree, W.O. and Palmer, V.J. 1949. Flow of water in channels protected by vegetative linings. U.S. Soil Conservation Service Technical Bulletin, 967.

Reid, L.M. 1989. Erosion of Grassed Hillslopes, University of Washington, Washington.

Reid, L.M. 1989. Erosion of Grassed Hillslopes, University of Washington, Washington.

Riis, T and Biggs, B.J.F. 2003. Retention of particulate matter by macrophytes in a first-order stream. Limnology and Oceanography 48(4): 1488-1497.

Ritzema, H.P. (Ed.) 1994. Drainage Principles and Applications. ILRI Publication 16, Second Edition. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Schmidt, J. and Hewitt, A., 2004. Fuzzy land element classification from DTMs based on geometry and terrain position, Geoderma 121:243-256.

Shih, S.F. and Rahi, G.S. 1982. Seasonal variations of Manning's roughness coefficient in a subtropical marsh. Transactions of the ASAE 25(1): 116-120.

Sprague, C.J. 1999. Green engineering: Design Principles and applications using rolled erosion control products. CE News, March, pp. 76-81.

Stallings, S.L. 1999. Roadside ditch design and erosion control on Virginia Highways. Masters of Science in Civil Engineering Thesis (unpublished), Faculty of the Virginia Polytechnic Institute and State University, Blacksburg, Virginia, September. URL: https://vtechworks.lib.vt.edu/bitstream/handle/10919/35094/sheila.pdf;sequence=1 (accessed 17 April 2018).

Tengbeh, G.T. 1983. The effect of grass roots on shear strength variations with moisture content. Soil Technology 6(3): 287-295.

Vernon, C. 2008. Central West Water Management and Use Regional Guideline: Watercourse Diversions – Central Queensland Mining Industry (Version 4.0), Department of Environment and Resource Management, Queensland Government.

Weiss, A. D., 2001, Topographic Positions and Landforms Analysis (Conference Poster). ESRI International User Conference. San Diego, California, July 9-13.

White, K., Hardie, R., Lucas, R., Merritt, J. and Kirsch, B. 2014. The evolution of watercourse diversion design in central; Queensland coal mines. In Vietz, G; Rutherfurd, I.D, and Hughes, R. (editors), Proceedings of the 7th Australian Stream Management Conference. Townsville, Queensland, Pages 238-248.

White, K., Hardie, R., Lucas, R., Merritt, J. and Kirsch, B. 2014. The evolution of watercourse diversion design in central Queensland coal mines. In Vietz, G; Rutherfurd, I.D, and Hughes, R. (eds), Proceedings of the 7th Australian Stream Management Conference. Townsville, Queensland, pp. 238-248.

Wikum, D.A. and Shanholtzer, G.F. 1978. Application of the Braun-Blanquet cover-abundance scale for vegetation analysis in land development studies. Environmental Management 2: 323-329.

Wilson, J.P. and Gallant, J.C. 1998. Terrain-based approaches to environmental resource evaluation. In: Lane, S., Richards, K., Chandler, J. (Eds.), Landform Monitoring, Modelling and Analysis. Wiley, Chichester, pp. 219–240.

Wilson, J.P. and Gallant, J.C. 2000. Terrain Analysis: Principles and Application. John Wiley & Sons, New York.

Wright, W.R. 1968. Part V. Geology of the Dawson-Fitzroy Area. IN Perry, R.A. (comp.) Lands of the Dawson-Fitzroy Area, Queensland, CSIRO, Melbourne, pp. 105-116. URL: http://www.publish.csiro.au/cr/pdf/LRS21 (accessed 26/11/2017).

WRM Water & Environment 2014. Baralaba North Continued Operations Project, Geomorphology Study. Cockatoo Coal Ltd. Spring Hill, August.

Young, C. and Outhet, D. 2004. Geomorphic reference reaches – field manual. Scientific and Technical Operating Procedures. Document a0018, Issue 1. NSW Department of Infrastructure, Planning & Natural Resources, October.

Zierholz, C., Prosser, I.P., Fogarty, P.J. and Rustomji, P. 2001. In-stream wetlands and their significance for channel filling and the catchment sediment budget, Jugiong Creek, New South Wales. Geomorphology 38: 221-235.