Central Queensland Coal Project

Appendix 5d – Fluvial Geomorphology Assessment

Central Queensland Coal

CQC SEIS, Version 3

October 2020

Central Queensland Coal Project

Environmental Impact Statement

Supplementary Study Report

Fluvial Geomorphology

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Final

July 2020

FLUVIAL SYSTEMS

Central Queensland Coal Project

Fluvial Geomorphology

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GLOSSARY OF TERMS

Term	Definition
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.
Cover (of riparian vegetation)	Foliar projective cover of the ground.
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.
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)
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.

Term	Definition
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.
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	Coal mining and associated activities within the CQC Project area.
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).
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 watercourse.
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.
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).
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).
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 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®)
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.
Tributary	A river or stream flowing into a larger river or lake.

Term	Definition
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).

ACRONYMS

Acronym	Expansion
AHD	Australian Height Datum
DEM	Digital Elevation Model
EIS	Environmental Impact Statement
GIS	Geographic Information System
LiDAR	Light Detection and Ranging
ML	Mining Lease
SEIS	Supplementary Environmental Impact Statement

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
ML/d	Megalitres per day
t	Tonne

Executive Summary

This report documented the geomorphological character of the CQC Project area using repeatable methods. Characterisation of the geomorphology of the 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 at the reach/point-scale.

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 streams according to geomorphic type, and geomorphic condition.

Most of the stream reaches were in a stable, moderate geomorphic condition. Some streams were potentially impacted by factors that reduced their condition. Riparian vegetation, although present in most places, was impaired in terms of width and continuity. One migrating bend on the Styx River, just downstream of the Ogmore Bridge, outside the Project area, was identified as a significant source of sediment to the river. No knickpoints or zones of major geomorphic instability were observed on the mapped watercourses. However, the Styx River catchment contains a significant number of alluvial gullies and small tributaries incised into old alluvium. These are potentially sources of high sediment loads to the river system, and thus the Great Barrier Reef.

The main hydrologic impact during the early stages of development (up to and including P8) would be diversion of the southern catchment area via the Northern Diversion Drain to Deep Creek, just upstream of Barrack Creek junction. Under Existing conditions, the two most western sub-catchments that drain to the mine site flow in a northeast direction and discharge to Deep Creek. Under the developed scenario, the flow from these sub-catchments would be diverted to flow northwards around the western boundary of the mine to discharge to Tooloombah Creek. The redistribution of these flows would have negligible impact on the extent of flood inundation of the floodplains of Deep Creek, Tooloombah Creek and Styx River.

The risk of erosion of the watercourses was assessed over a 2.5 m grid using the method of maximum permissible bed shear stress and maximum permissible velocity, using hydraulic data provided by the two-dimensional TUFLOW flood study model. This geomorphic assessment evaluated the 10% AEP and 1% AEP flood events for the Existing and the Developed P8 scenarios. The results of the assessment based on velocity were consistent with those based on bed shear stress. This assessment found that, for Tooloombah and Deep creeks and Styx River channels and floodplains, while there could be isolated areas subject to slightly higher risk of scour under the Developed scenario compared to the Existing scenario, the overall risk of rapid and significant geomorphic change due to the proposed mining activity was negligible. However, the assessment identified some localised areas where modelled velocity and bed shear stress values were such that specific mitigation and/or monitoring actions were recommended.

Six locations were highlighted where the velocity and/or bed shear stress values associated with the Developed P8 scenario were high enough to warrant monitoring and/or mitigation.

1. The 400 m-long area where drainage from the western sub-catchments concentrates and then discharges to Tooloombah Creek.
2. Discharge channel from Dam 1 to Deep Creek.
3. Where sub-catchments upstream of the mine discharge to the Northern Diversion Drain.
4. The Northern Diversion Drain, particularly the lower 500 m.
5. At the proposed rail bridge crossing over Deep Creek.
6. An isolated location near Dam 1 wall.

Sites 1 and 3 are risk areas for gully formation. They will require maintenance of good vegetation cover and regular monitoring of stability, plus preparation of a plan to fortify them with rock rip-rap should significant incision occur. Site 4, the lower end of the Northern Diversion Drain where it discharges to Deep Creek, will require fortification with rip-rap. Site 2 is likely to require fortification with rip-rap to eliminate the risk of formation of knickpoints that could migrate towards Dam 1 embankment. This is a risk with a high consequence. Site 5, at the proposed rail bridge crossing over Deep Creek, was predicted to experience bed scour. This risk can be managed by designing the bridge crossing in accordance with civil engineering design standards. Site 6 was an isolated area about 50 × 50 m near Dam 1 wall where confinement due to the dam wall was predicted to locally increase

the water surface slope and thus the bed shear stress and velocity. Even so, provided this area remains vegetated, the risk of scour of the surface would be low.

Geomorphic monitoring should be undertaken using objective, scientifically sound methods, following a BACI (Before/After/Control/Intervention) design. Also, the monitoring should target areas where this assessment predicted the risk of geomorphic instability would be greatest. The foundation of the recommended approach to monitoring is topographic survey at targeted risk areas, repeated every year for 3 years, and then either every five years, or after every flood event exceeding the 5 yr ARI event. 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. Regular (monthly) visual inspections that involve fixed photo points and completion of standard documentation could support the less frequent survey data by potentially providing early detection of change.

Mitigation of the impacts of accelerated sediment delivery to the drainage system, and then to the Great Barrier Reef, can be achieved through vegetation management, maintaining complete vegetation cover over hillslope, river bank and floodplain surfaces. Grass provides good resistance to erosion on hillslopes and small gently sloping drainage channels, but forest, with tree, shrub and ground cover, is preferable on steep land, larger drainage channels and river banks. In general, the surface water management works should follow standard civil engineering design principles. However, this report draws particular attention to the need for fortification of the outlet from Dam 1 to Deep Creek, and the lower 500 m of the Northern Diversion Drain. This report also draws particular attention to the 400 m-long area where drainage from the western sub-catchments concentrates and then discharges to Tooloombah Creek, where sub-catchments upstream of the mine discharge to the Northern Diversion Drain, and an isolated location near Dam 1 wall, which will require maintenance of good vegetation cover in order to remain at low risk of surface scour.

The need for application of mitigation measures over the life of the mine would be triggered by unexpectedly large change in morphology identified through monitoring. The most appropriate response would need to be assessed at the time.

1.0 Introduction

1.1 Characteristics of the Central Queensland Coal Project

The Central Queensland Coal Project (the Project) will be developed and operated by Central Queensland Coal (CQC) and Fairway Coal (joint Proponents). As Central Queensland Coal is the senior proponent, Central Queensland Coal is referred to throughout this report.

The Project is located 130 km northwest of Rockhampton in the Styx Coal Basin in Central Queensland (Figure 1). The Project will involve mining a maximum combined tonnage of 10 million tonnes per annum (Mtpa) of semi-soft coking coal (SSCC) and high grade thermal coal (HGTC). The Project consists of two open cut operations. The run-of-mine (ROM) coal will ramp up to approximately 2 Mtpa during Stage 1 (2019 - 2022), where coal will be crushed, screened and washed to SSCC grade with an estimate 80% yield. Stage 2 of the Project (2023 - 2037) will include further processing of up to an additional 8 Mtpa ROM coal within another coal handling and preparation plant (CHPP) to SSCC and a HGTC plant with an estimated 95% yield. At full production, two CHPPs, one servicing Open Cut 1 and the other servicing Open Cut 2, will be in operation, with rehabilitation and mine closure activities occurring between 2036 and 2038.

Production from the Project is expected to commence in 2019 and extend for approximately 19 years until the depletion of the current reserve. The Project will be located within Mining Lease (ML) 80187 and ML 700022 which are adjacent to Mineral Development Licence (MDL) 468 and Exploration Permit for Coal (EPC) 1029, both of which are held by the Proponent.

The current version of the Supplementary Environmental Impact Statement (SEIS) is CQC (2020) Central Qld Coal Project Supplementary Impact Assessment Version 3. This supersedes CDM Smith (2017) and CDM Smith (2018a), now referred to as SEIS Version 1 and Version 2 respectively.

1.2 Scope and Objectives of this Report

This fluvial geomorphology assessment was undertaken at an advanced stage of the EIS process, with EIS, SEIS, as well as specialist assessments, already completed, and Government agency review comments received.

Government submissions from the Qld Department of Environment and Science (DES), Department of Agriculture and Fisheries (DAF) and Commonwealth Department of the Environment and Energy (DEE) were received by the Proponent on 14 June 2019, with the following items identified as relevant to the scope of this report (Table 1):

- DAF: Item 1.1.
- DES: Items 32.1, 32.39, 32.59 & 32.97.
- DEE: Items [21] & [3, 11, 21].

This fluvial geomorphology assessment will be used in conjunction with other assessments to inform and support the Government responses.

The key watercourses and drainage lines assessed in this report included:

- Tooloombah Creek;
- Deep Creek;
- Styx River; and
- other associated drainage lines within and in the immediate vicinity of the CQC Project Area.

This assessment builds upon the information available in the EIS and SEIS (CQC, 2020), and other resources, to provide a report that includes the following components:

1. **Baseline Component**: to help inform other specialist studies and provide background to address specific Government submission issues:
    a) Description of geology and sediment deposition processes in the Styx Basin, including:
        (i) (Qa) Quaternary Alluvium
        (ii) (Qpa) Pleistocene Alluvium / Cainozoic
        (iii) (Qr, Qf and Kx) Colluvium / Alluvial Fan Deposits (Holocene to Pleistocene) / Styx Coal Measures

    (iv) (Qhe/s) Estuarine Deposits (Holocene)
    (v) (Qhe/m) Estuarine Deposits
    (vi) (Ta, Td, TQr) Tertiary Sediments

b) Description of the tidal interface, normal tidal limit, peak tidal limit, and storm tide limit to support tidal/estuarine mapping.

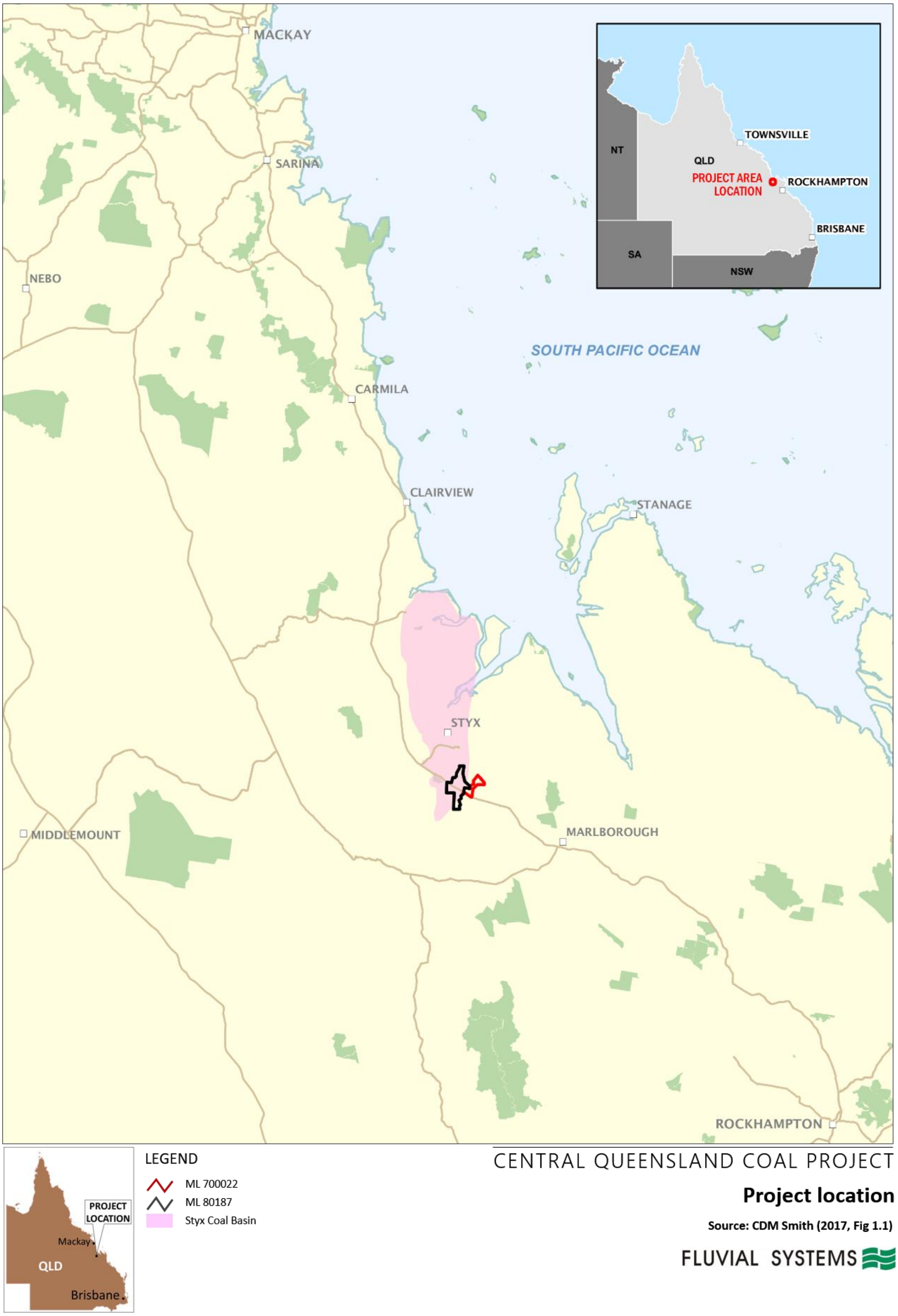
c) Description of Soil Landscapes and Sodicity based on desktop and field assessments in the SEIS (CQC, 2020) and the land suitability assessment by HESSE (2020).

d) Review of Base Case Flood Model / Assessment Results in the SEIS (CQC, 2020) and more recent two-dimensional hydraulic modelling of flood events undertaken by WRM Water & Environment (2020).

e) Following Commonwealth of Australia (2018, p. 19) Information Guidelines for Proponents Preparing Coal Seam Gas and Large Coal Mining Development Proposals, as part of the checklist of specific information needs under surface water, "*Describe the hydrological regime of all watercourses…including geomorphology, including drainage patterns, sediment regime and floodplain features*" and following Doody et al. (2019, p. 37) Information Guidelines Explanatory Note: Assessing Groundwater-Dependent Ecosystems, among the criteria to be used to assess ecosystem value "*Diversity of species, habitats, ecological processes and abiotic features such as geomorphology*". The characterisation of fluvial geomorphology of the CQC Project area includes the following:

- Fluvial geomorphological features, including, but not limited to:
    - channels, incision, aggradation, knickpoints, pools, bedrock features, hydraulic controls, riffles, bed material, dimensions and profiles, riparian zones, alluvium and gullies.
- Measured and derived geomorphic and related attributes, including, but not limited to:
    - Strahler Stream Order
    - in-channel fluvial features;
    - riparian zone vegetation structure and cover;
    - observed rate of geomorphic change; and
    - geomorphic type, condition and fragility classification

2. **Impact Assessment Component**: to help address specific Government submission issues:
    a) Discuss the potential increased risk of stream bed and bank erosion based on the identified stream geomorphic type and geomorphic features and attributes, together with the results of modelling of flood hydraulics and also considering historical rates of geomorphic change.
    b) Discuss the potential sodicity of waste rock and relevant management measures in the SEIS (CQC, 2020)
    c) Comment and compare potential sediment loads to that presented in the SEIS (CQC, 2020)
3. **Recommended Mitigation Measures and Monitoring**
    a) Recommend measures that would mitigate any identified risks of geomorphic impact.
    b) Identify target sites to monitor relevant geomorphologic processes throughout the life of the proposed project and beyond.



Source: CDM Smith (2017, Fig 1.1)

Figure 1. Central Queensland Coal Project regional location.

Table 1 Summary of government submissions considered relevant to the scope of this report.

Number	Issue	Required action	Relevance
DAF: Item 1.1	The drop in base flows to Tooloombah Creek and Deep Creek will cause the loss of permanent and ephemeral pools. This loss will reduce the fisheries resources in the vicinity of the project. It is uncertain if supplementary water inputs would be sufficient to maintain this system and if this mechanism is able to be continued until the mines impacts cease. The impacts of the reduction in base flows in the estuarine areas connected to these systems has not been quantified.	The drawdown causing the mobilisation of the groundwater-saltwater interface is of particular concern as it can potentially negatively impact large areas of brackish and freshwater fish habitats as well as the Broad Sound Declare Fish Habitat Area. This impact is likely to be expressed to the greatest extent, a decade or more post the closure of the mine. Once such a delayed impact manifests how can it be halted?	The results of this geomorphic assessment will inform the (separate) groundwater assessment
DES: 32.1	Additional information regarding GDEs and water supply is still required to address the supplementary environmental flows mitigation measure.	A longer term understanding of alluvium and Styx Coal measure overburden groundwater levels is required to understand groundwater interactions. The report indicates that this will be collected.	This assessment will inform the (separate) groundwater assessment.
DES: 32.39	Sediment and erosion. Section 9.10.2 discussed potential increases in water velocities for sections of the stream downstream of the mine site. There is a need to assess and discuss the potential increased risk of stream bed and bank erosion and potential impacts to aquatic fauna as a result of bed mobilisation. The sediment loads exported to the Great Barrier Reef (GBR) world heritage area need to be assessed and minimised and adequate monitoring is necessary. Chapter 9 does not describe potential impacts to water quality and aquatic ecosystem health from the potential increased risk of stream bed and bank erosion.	Address this issue and provide load estimation analysis especially as it relates to downstream impacts. A Receiving Environment Monitoring Program (REMP) must include a monitoring program for sediment load and particle size distribution to assess impacts from stream bed/bank erosion and sediment mobilisation. Findings from sediment monitoring must also be considered in the Water Management Plan and Erosion and Sediment Control Plan annual revision.	Erosion and sediment processes will be re-assessed. Estimation of sediment load from the site is the subject of a separate assessment.
DES: 32.59	It is not clear as to whether these are the same drainage diversions referred to in Section 11.3.3.2.	Clarify whether the diversions mentioned in Table 11 -15, under the Waste rock stockpile and Water infrastructure domains are the same drainage diversions which are mentioned in Section 11.3.3.2.	Consider geomorphic implications of drainage diversions.
DES: 32.97	The proponent has not specifically addressed the potential impacts to potential refugia and nursery areas for aquatic species in any of the chapters identified in their response. Further work is required in relation to the impacts of groundwater baseflow reduction along the reaches of affected watercourses.	Baseline and Groundwater Dependent Ecosystem (GDE) studies (including mitigation and management measures) will be a requirement in any approval… A Draft GDE Monitoring and Management Plan (GDEMMP) should be submitted for assessment by the department as part of the EIS material.	This assessment will inform the (separate) groundwater assessment
DEE: Items [21]	The Department has a low degree of confidence in the ability of the current groundwater model to adequately predict the likely direct and indirect impacts on MNES, both within the project site and downstream of the project	Based on the information in the AEIS, the Department considers the proponent has not adequately responded to submission 21 site.	This assessment will inform the (separate) groundwater assessment
DEE: Items [3, 11, 21]	Due to the Department's low confidence in the groundwater model predictions, the Department considers the AEIS does not provide an adequate assessment of potential groundwater drawdown impacts on riparian vegetation, surface water-groundwater connectivity, aquatic ecosystems (particularly waterholes), stygofauna, wetlands and surface water quality. There is the potential that the magnitude and spatial extent of groundwater drawdown has been underestimated.	Based on the information in the AEIS, the Department considers the proponent has not adequately responded to submission 3, 11 and 21 site. The relevance of this is the results of this geomorphic assessment inform the groundwater modelling.	This assessment will inform the (separate) groundwater assessment

1.3 Relevant Policy and Legislative Requirements

This report addresses part of the environmental objectives to be met under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) and Queensland Environmental Protection Act 1994 (EP Act).

This report was prepared in consideration of the checklist of specific information needs under surface water in *Information Guidelines for Proponents Preparing Coal Seam Gas and Large Coal Mining Development Proposals* (Commonwealth of Australia, 2018, p. 19), which included "*Describe the hydrological regime of all watercourses…including geomorphology, including drainage patterns, sediment regime and floodplain features*", and in consideration of criteria to be used to assess ecosystem value in *Information Guidelines Explanatory Note: Assessing Groundwater-Dependent Ecosystems* (Doody et al. (2019, p. 37), which included "*Diversity of species, habitats, ecological processes and abiotic features such as geomorphology*".

This report was prepared in consideration of government submissions from the Qld Department of Environment and Science (DES), Department of Agriculture and Fisheries (DAF) and Commonwealth Department of the Environment and Energy (DEE) received by the Proponent on 14 June 2019.

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 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 this report
Section 2	Methodology – describes the methodology used in this assessment
Section 3	Existing environment – describes the character of the existing geomorphologic environment
Section 4	Impact assessment – describes the potential impacts to geomorphologic character of the environment resulting from the proposed Project
Section 5	Monitoring and Mitigation – provides a summary of environmental mitigation, management and monitoring responsibilities in relation to management of geomorphologic aspects of the environment for the Project
Section 6	Conclusion – states the main conclusions arising from this assessment
Section 7	References – lists details of cited references

2.0 Methodology

2.1 Study Area

The area of interest of this report varied depending on the issue under assessment. At the broadest scale it included the entire catchment of the Styx River down to the estuary, while at the finest scale it included the zone within, and immediately adjacent to (i.e. potentially directly influenced by), the area covered by ML 80187 and ML 700022 where mining activities are proposed to be conducted (referred to as the CQC Project area) (Figure 2).

Where maps in this report depict geomorphologically-relevant attributes extending outside the CQC Project area, the purpose was to show the continuity of the attribute being described, and/or to illustrate the regional context of the attribute.

2.2 Measurement Scales

Characterisation of the geomorphology of the area of interest 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 of the CQC Project area at the cross-section- and reach-scale (1 to 1,000 metres), plus the scale of stream type which varies from 10s to 1,000s of metres long.

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

Characterisation of fluvial geomorphological features was based on a combination of desktop analysis of existing data and previously collected field data.

2.3 Data Sources

2.3.1 Primary data

It was not possible to undertake a field inspection of the site due to government restrictions that applied at the time of preparation of this report. This did not pose a significant limitation to this report, because: i) the methodology made use of existing spatial data layers, aerial imagery and topographic data, ii) extensive field assessment had previously been undertaken for the EIS and Supplementary EIS, iii) ground photographs previously obtained by WRM Water & Environment in connection with recent flood hydraulic modelling were made available, and iv) CQC staff obtained ground photographs taken at specific locations on request.

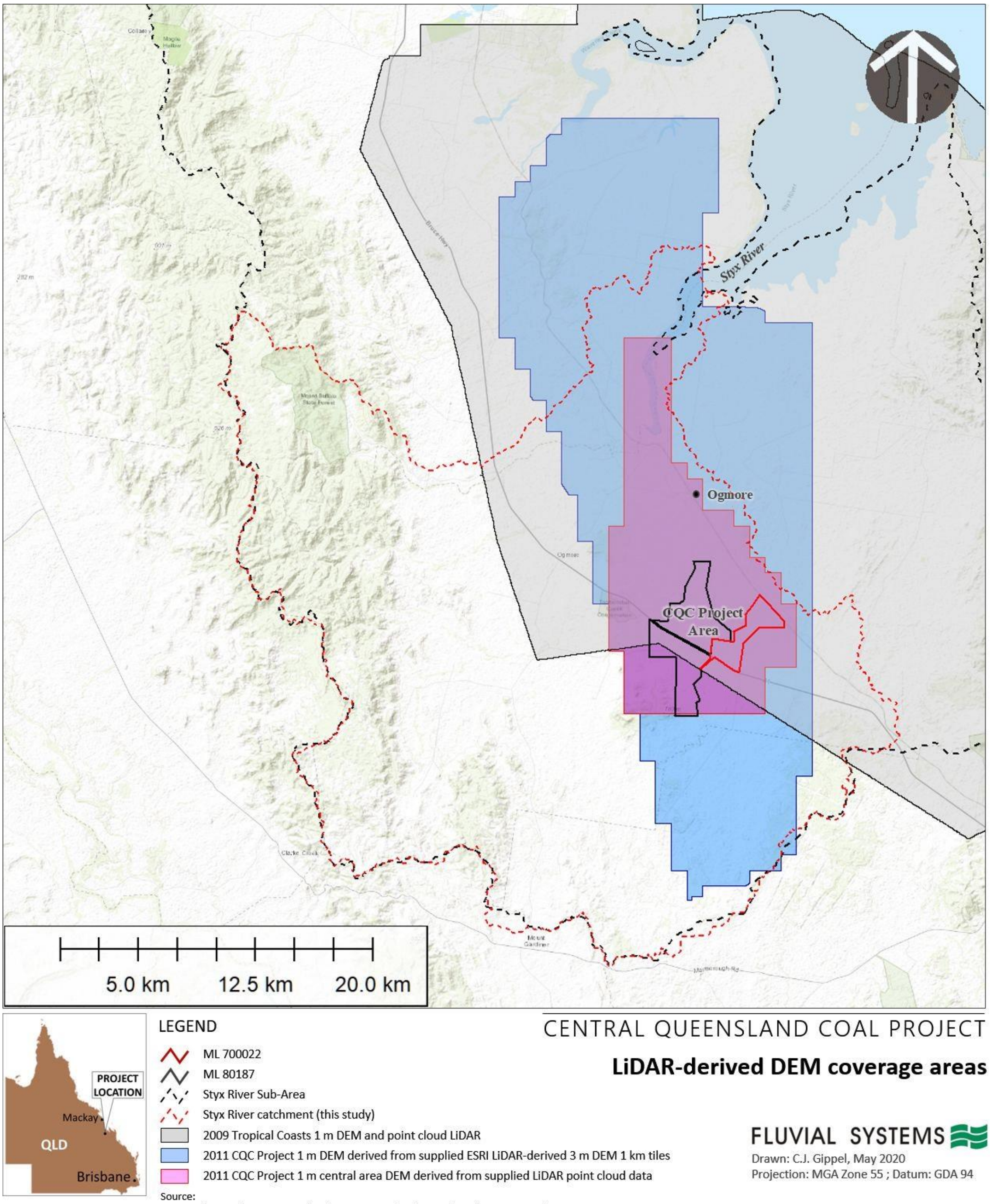
2.3.2 Elevation data

This geomorphic investigation relied on digital elevation model (DEM) data, derived from Light Detection and Ranging (LiDAR), also known as Airborne Laser Scanning (ALS), surveys flown at a range of scales and collection dates (Figure 2):

- LiDAR survey data captured in 2011 by Vekta on behalf of Yeats Consulting Engineers (Vekta, 2011), covering Exploratory Permit for Coal (EPC) 1029 on land on associated with the CQC Project, and within which ML 80187 and ML 700022 are located, available as LiDAR point clouds and 1 m and 3 m DEM tiles derived from the point cloud data,
- LiDAR survey data captured in 2009 for the Tropical Coast Project over sections of the Queensland coast from Cairns Regional Council (within the current Douglas Shire) to Rockhampton Regional Council (within the current Livingstone Shire), available as LiDAR point clouds or 1 m DEM tiles derived from the point cloud data,
- Digital Elevation Model (DEM) 5 Metre Grid of Australia (Geoscience Australia), derived from the 2009 Tropical Coast Project LiDAR in this area, and

- Digital elevation model – 25 metre – Fitzroy River catchment (Department of Natural Resources, Mines and Energy), derived from contours and drainage (scanned repromats) from AUSLIG 1:100000 mapsheets with a 20 metre contour interval for most areas.

The 5 m and 25 m products were used in this report only to depict the topography of the wider Styx River catchment, with the 2009 and 2011 products used for detailed terrain analysis.



Source:
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
World Topographic Map, Global Mapper
Styx River catchment auto-generated from 1m, 5m ELVIS DEMs, 2011 and Queensland 25m DEM
2009 Tropical Coasts 1 m DEM and point cloud LiDAR from ELVIS - Elevation and Depth - Foundation Spatial Data

Figure 2. LiDAR data availability for the area of interest. A 25 m DEM was available for the entire area.

The Tropical Coast Project data were downloaded from ELVIS – Elevation and Depth – Foundation Spatial Data, Version 0.1.1.0 (http://elevation.fsdf.org.au/). The associated metadata indicated that the data for most of the project area were collected between 28 August 2009 and 21 October 2009. Data were collected from a fixed wing aircraft at an altitude of 1340 – 2070 m, using a Leica ALS50, with average point specification of 1 point per square metre. Ground filtering algorithms were applied to the full dataset. The ground filtered dataset was then visually checked by an operator, and incorrectly classified data was corrected or the ground filtering algorithm was adjusted and then visually checked. The accuracy of the final product was quoted as +/- 0.15 m at 67% CI in the vertical, and +/- 0.3 m at 67% CI in the horizontal.

Vekta (2011) undertook a LiDAR survey over the Styx Coal Mine area, north of Rockhampton on 17 June 2011. Data were collected from a fixed wing aircraft using a Leica ALS60, with average point specification of 1 point per square metre. Laser strikes were classified into ground and non-ground points using a single algorithm across the project area. Auto-classification was followed by manual checking and editing to remove obvious errors. Related field survey was performed on 7 June 2011. The GPS base data for the processing of the airborne LiDAR data was obtained from a base station located at permanent survey mark PSM133415 situated at Ogmore. This mark was used as the datum mark for the airborne LiDAR survey and all ground survey checks. During the flight, GPS data was logged at 0.5 second epochs from the base station. This data was used in the GPS processing of the LiDAR data. Vekta surveyors also performed a number of detail surveys evenly distributed throughout the project area to validate the accuracy of the final surface model. GPS accuracies were tested across all sections and found to be within tolerance. The accuracy of the final product was quoted as +/- 0.15 m in vertical and +/- 0.45 m in horizontal (1 sigma) in areas of clear and open terrain. An independent survey of borehole locations was supplied by surveyor Dave Beatty for validation against the LiDAR data. A total of 80 points were compared, with average vertical accuracy of 0.029 m RMSE (1 sigma). Minimum and maximum differences were -0.259 and +0.547 m. The minimum and maximum difference points were investigated and no obvious explanations were apparent. The LiDAR ground surface around these points was clear open flat ground (Vekta, 2011).

2.3.3 QSpatial environmental attribute datasets

Digital spatial layers of Fitzroy drainage basin sub-area, watercourses, Queensland Floodplain Assessment Overlay, surface geology, land systems, soil erodibility, woody foliage protective cover, NDRP Storm Tide Hazard Interpolation, highest astronomical tide, and usual high spring tide, covering the area of interest were downloaded from Queensland Government Queensland Spatial Catalogue (QSpatial) (http://qldspatial.information.qld.gov.au/catalogue). All the descriptions of the data layers provided below were sourced from QSpatial metadata.

Fitzroy Drainage Basin Sub-Area was from Drainage basin sub areas – Queensland, published 1/06/2020. The dataset was captured at 1:100 000. The seaward edge of this data aligns with the Coastline and State Border - Queensland dataset. The boundary of the Styx River catchment on this layer differed in detail to that derived by this study using terrain analysis. The difference is explained by the higher resolution elevation data used in this study to delineate the Styx River catchment boundary.

Watercourse data were from ‘Watercourse lines - North East Coast drainage division - central section’ published 5/05/2015, although the streamlines within the area of interest 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. For the purposes of this 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. Topographically-derived drainage networks generated automatically by algorithms in Geographic Information System (GIS) suggested the presence of additional or alternative dominant drainage lines in some parts of the area of interest. This was not surprising as 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 report.

The layer ‘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. Initial inspection of the QFAO layer suggested that in the area of interest the extent of the floodplain overlay far exceeded the modelled 100 year ARI flood extent. Also, the floodplain extent covered wide areas not mapped as alluvial geology, so the QFAO was not used in this report as a representation of the extent of alluvium.

Geology was from ‘Detailed surface geology – Queensland’, a digital representation of the distribution or extent of geological units represented by polygons with a range of attributes including unit name, age, lithological description and an abbreviated symbol for use in labelling the polygons (Table 2). The polygons were extracted from the Rock Units Table held in Department of Natural Resources, Mines and Energy MERLIN Database. The data date from the period 2004 to 2018. The key attribute of interest to this report was age of the lithological unit.

Table 2. Key to the main surface geology lithological units mapped in the CQC Project area on layer ‘Detailed surface geology – Queensland’.

Symbol	Rock Unit Name	Age	Lithological summary
Kx	Styx Coal Measures	Early Cretaceous	Quartzose sandstone, green lithic sandstone, mudstone, conglomerate, carbonaceous shale and coal
Pb	Back Creek Group-Pb	Late Permian	Predominantly massive, cleaved mudstone and siltstone (commonly with concretions), minor lithic sandstone
Pbm	Boomer Formation	Late Permian	Lithic sandstone, siltstone, mudstone, rare conglomerate
Pc/b	Carmilla Beds/b	Earlier Permian	Altered (uralitised and carbonatised) locally amygdaloidal, aphyric basalt
Pc/s	Carmilla Beds/s	Early Permian	Siltstone and mudstone, volcanilithic sandstone and conglomerate; minor altered basalt and local rhyolitic to dacitic volcanic rocks
Qa	Qa-QLD	Quaternary Alluvial	Clay, silt, sand, gravel; flood-plain alluvium
Qf	Qf-QLD	Quaternary Alluvial	Clay, silt, sand and clayey to sandy gravel; alluvial fans, sheetwash and floodout sheets
Qhe/s	Qhe/s-YARROL/SCAG	Holocene	Sand, muddy sand, mud and minor gravel; estuarine channels and intertidal sand banks and flats
Qpa	Qpa-QLD	Pleistocene Alluvial	Clay, silt, sand, gravel; flood-plain alluvium on high terraces
Qr,Qf>Kx	Qr-QLD,Qf-QLD>Styx Coal Measures	Quaternary Colluvial	Clay, silt, sand, gravel and soil: colluvial and residual deposits
TQa	TQa-QLD	Late Tertiary – Quaternary	Locally red-brown mottled, poorly consolidated sand, silt, clay, minor gravel; high-level alluvial deposits, generally dissected, and related to present stream valleys
TQr>Kx	TQr-QLD>Styx Coal Measures	Late Tertiary – Quaternary	Clay, silt, sand, gravel and soil; colluvial and residual deposits (generally on older land surfaces)

Land systems were from ‘Land systems - land systems of the Capricornia coast - CCL3’. The boundaries of the land systems were based on the coincidence of dominant landform, soils and vegetation communities. Polygon boundaries were drawn as probabilistic interpretations of changes in soil or land type. Eleven land systems occurred in the CQC Project area (Table 3). Mapping was based on aerial photography interpretation and field traverses with site descriptions ranging from one observation to an area of 1000 hectares, to one observation to an area of 400 hectares. The area of interest was covered by Map 1 St Lawrence Marlborough Area. The data were published in printed form in 1995 based on data captured in 1992.

Table 3. Key to land systems mapped in the CQC Project area on layer 'Land systems - land systems of the Capricornia coast - CCL3'.

Land System	Agricultural Class meaning	Description
Ar - Artillery	Pasture Land - Native pastures	Bleached sandy and loamy surface, brown and grey, alkaline sodic duplex soils formed on undulating low hills, rises and fans on fine grained sedimentary rocks; Eucalypt woodland.
Bl - Blackwater	Crop Land	Brigalow plains and cracking clay soils on weathered Tertiary clay and older rocks along the central axis of the area.
Hl - Headlow	Pasture Land - Native pastures	Bleached loamy, clay loamy and silty surface, brown and grey, alkaline sodic duplex soils formed on broad, level to gently undulating alluvial plains and fans on silty and fine textured alluvium; Mixed eucalypt woodland.
Kt - Kooltandra	Pasture Land - Native pastures	Bleached clay loamy and silty surface, brown and grey, alkaline sodic duplex soils formed on undulating rises and plains on sedimentary rocks and unconsolidated sediments; Gum-topped box and rosewood woodland.
Pv - Plainview	Pasture Land - Native pastures	Black and grey, strongly sodic cracking clays or bleached loamy and clay loamy surface, brown and grey, alkaline sodic duplex soils formed on gently undulating to level plains on unconsolidated fine and medium textured sediments; Eucalypt woodland.
Rd - Rosewood	Pasture Land - Native pastures	Bleached sandy and loamy surface, brown and grey, alkaline sodic duplex soils formed on rolling low hills and rises on hard sedimentary rocks; Rosewood open forest with emergents.
So - Somerby	Pasture Land - Sown pastures, and native pasture on high fertility soils	Gilgaied plains with brigalow and cracking clay soils on weathered Tertiary clay along the central axis of the area.
Sx - Styx	Crop Land	Brown, massive, fine sandy loams formed on narrow floodplains along the Styx River and Wellington Creek; Eucalypt woodland.
Tb - Tooloomba	Pasture Land - Native pastures	Bleached sandy and loamy surface, brown and grey, alkaline sodic duplex soils formed on gently undulating rises and plains on sedimentary rocks; Eucalypt woodland.
Tl - Torilla	Pasture Land - Native pastures	Red, structured gradational clay loams and uniform clays formed on undulating rises and low hills on deeply weathered sedimentary and metamorphic rocks; Eucalypt woodland.
Ws - Woodstock	Pasture Land - Native pastures	Red, massive, gradational loams and clay loams or red, structured gradational clay loams formed on dissected low plateaus on gently dipping sedimentary rocks; Eucalypt woodland.

Surface soil erodibility data were from 'Fitzroy NRM region surface soil erodibility - Central Queensland', published 24/04/2017. This raster dataset, in this report termed 'Surface soil erodibility', 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 (Zund, 2017). Surface soil stability is categorised into 4 categories. The higher the number, the greater the erodibility (Table 4).

Table 4. Key to surface soil stability cell values on layer ‘Fitzroy NRM region surface soil erodibility - Central Queensland’. Descriptions are from Zund (2017).

Code	Category	Description
0	Not assessed	-
1	Moderately stable surface soils	Soils that are unlikely to be dispersive. These are usually well-structured and resilient to degradation
2	Non-cohesive surface soils	Sandy soils that are non-structured or only weakly so and non-cohesive. These soils are easily eroded
3	Dispersive surface soils	Erodible loamy or clayey soils that are sodic, hardsetting and likely to disperse in water
4	Highly erodible surface soils	Highly erodible clay soils that are sodic and dominated by expanding/swelling clays that disperse readily

A secondary soil erodibility dataset is ‘Fitzroy NRM Region soil erodibility - Central Queensland’. This dataset, termed here ‘Overall inherent soil erodibility’, classifies overall inherent soil erodibility on a 90 × 90 m grid. Overall inherent soil erodibility is a combination of the stability of the surface soil and the dispersibility of the subsoil (Zund, 2017). Surface soil stability and subsoil dispersibility were combined to form 17 categories. The higher the number, the greater the vulnerability to erosion (Table 5, Table 6).

Vegetation structure and coverage was from ‘Wooded extent and foliage projective cover - Queensland 2013’ Foliage Projective Cover (FPC) is the percentage of ground area occupied by the vertical projection of foliage. The methodology was described in Armston et al. (2009) and Gill et al. (2017). The FPC mapping is based on an automated decision tree classification technique applied to dry season (May to October) Landsat-5 TM, Landsat-7 ETM+ and Landsat-8 OLI imagery for the period 1988-2013. Pixels were classified as woody or not woody, their foliage projective cover was quantified, and pixels were then classed as forest or other wooded lands based on cover density. Field data from 2002 to 2014 were used to calibrate the remotely sensed data. The wooded extent product has a nominal accuracy of 85%. Image value = FPC + 100 (i.e. FPC of 5% = image value of 105). Range is 100-200 which is equivalent to 0-100% FPC.

Extent of tides for a range of average recurrence intervals (ARI) was from ‘NDRP Storm Tide Hazard Interpolation’. The purpose of the NDRP (National Disaster Resilience Program) Storm Tide Hazard Interpolation study was to map, based on a consistent methodology using data from existing studies, the ARI for a range of ocean water levels for each coastal LGA (Local Government Area). The methodology was described in GHD (2014). The tide extent surfaces were developed via inland extrapolation of coastal levels (the so-called 'bathtub' approach) and thus hydraulic gradients were not been assessed. The flood extents are considered indicative and are subject to the accuracy of the Queensland Government 10 m DEM. The levels modelled corresponded to the 20, 50 ,100, 200, 500, 1,000 and 10,000 year ARI event, plus the estimated Theoretical Maximum Storm Tide (TMST) level.

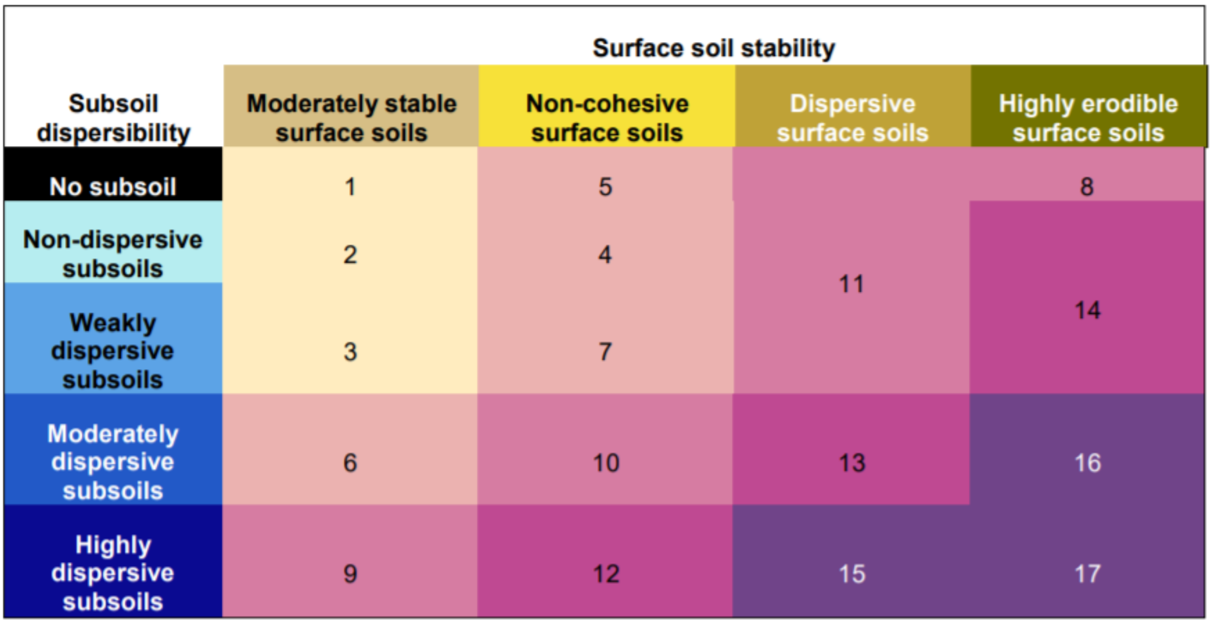
The extent of the highest astronomical tide was from ‘Highest astronomical tide – Queensland’. The highest astronomical tide line represents an approximation of the land-tidal water interface at the highest water level that can be predicted to occur under any combination of astronomical conditions. The data were derived from information obtained from Queensland tide gauges and digital elevation models generated from LiDAR surveys. The data can be considered to date to 2009, which corresponds to the date the LiDAR data were flown.

The point to which the high spring tide ordinarily flows and reflows in the Styx River, whether due to a natural cause or to an artificial barrier was identified by ‘Watercourse identification map - downstream limits – Queensland’. Version 48 was published on 1/05/2020. This point is identified to show the boundary between where water is either managed under the Water Act 2000 or under the Coastal Protection and Management Act 1995. Water services officers from the Departments of Natural Resources, Mines and Energy and the Department of Environment and Science collaboratively agree on the location of the downstream limit of a watercourse using a number of analytical and measuring techniques, including desktop analysis using aerial imagery and other map resources, and optionally a site visit.

Table 5. Key to inherent soil stability cell values on layer 'Fitzroy NRM Region soil erodibility - Central Queensland'. Expected soil characteristics are from Zund (2017).

Code	Category	Expected soil characteristics
Very low erosion vulnerability		
0	Not assessed	
1	Moderately stable surface soils over rock or sediment	Shallow loamy or clayey soils
2	Moderately stable surface soils over nondispersive subsoils	Loamy or clayey soils over non-dispersive subsoils
3	Moderately stable surface soils over weakly dispersive subsoil	Loamy or clayey soils over weakly dispersive subsoils
Low erosion vulnerability		
4	Non-cohesive surface soils over non-dispersive subsoil	Sandy massive surface soils over non-dispersive subsoils
5	Non-cohesive surface soils over rock or sediment	Shallow sandy massive soils
6	Moderately stable surface soils over moderately dispersive subsoils	Loamy or clayey soils over moderately dispersive subsoils
7	Non-cohesive surface soils over weakly dispersive subsoils	Sandy massive surface soils over weakly dispersive subsoils
Moderate erosion vulnerability		
8	Clayey soils that erode and/or slake readily over rock or sediment	Clay soils that are sodic and dominated by expanding/swelling clays that disperse readily
9	Moderately stable surface soils over highly dispersive subsoils	Loamy or clayey soils over highly dispersive clayey subsoils
10	Non-cohesive surface soils over moderately dispersive subsoils	Sandy massive surface soils over moderately dispersive subsoils
11	Weakly dispersive clayey soils	Loamy or clayey soils that are sodic throughout the profile, have hardsetting surfaces and are weakly dispersive
High erosion vulnerability		
12	Non-cohesive surface soils over highly dispersive subsoils	Sandy massive surface soils over highly dispersive subsoils
13	Dispersive clayey soils	Loamy or clayey soils that are sodic throughout the profile, have hardsetting surfaces and are moderately dispersive
14	Clayey surface soils that erode and/or slake over weakly dispersive subsoils	Clay soils that are sodic and dominated by expanding/swelling clays that have weakly dispersive sodic subsoils
Very high erosion vulnerability		
15	Dispersive clayey surface soils over highly dispersive subsoils	Loamy or clayey surface soils that are sodic and hardsetting over highly dispersive clay subsoils
16	Clayey surface soils that erode and/or slake over moderately dispersive subsoils	Clay soils that are sodic and dominated by expanding/swelling clays that have moderately dispersive sodic subsoils
17	Clayey surface soils that erode and/or slake over highly dispersive subsoils	Clay soils that are sodic and dominated by expanding/swelling clays that have highly dispersive sodic subsoils

Table 6. Overall inherent soil erodibility based on surface soil stability and subsoil dispersibility. Source: Zund (2017, Table 2).



	Surface soil stability			
Subsoil dispersibility	Moderately stable surface soils	Non-cohesive surface soils	Dispersive surface soils	Highly erodible surface soils
No subsoil	1	5	11	8
Non-dispersive subsoils	2	4		14
Weakly dispersive subsoils	3	7		
Moderately dispersive subsoils	6	10	13	16
Highly dispersive subsoils	9	12	15	17

2.3.4 Soil Map Units

HESSE (2020) undertook an agricultural land capability and soil suitability assessment in the CQC Project area. Soil profiles were described initially from reconnaissance survey auger holes to 1.5 m or refusal to develop a soil map key. This was followed by detailed soil descriptions and sampling made from test pits excavated to 2 m at selected sites that were considered central to, and typical of, each map unit. Five soil units were mapped by HESSE: Alluvial soils (gravelly and non-gravelly), Earthy Soils – Kandosols, Sodic texture-contrast duplex soils – Sodosols, and Cracking clay soils – Vertosols (Table 7).

Table 7. Soil units mapped by HESSE (2020).

Soil unit concept	Soil Order	Location and description
Alluvial Soils, Gravelly Shallow Sand, Gravel Loam	Tenosols, Rudosols	Narrow band along active river beds.
Alluvial Soils, Non-gravelly, Sandy Loam to Clay textures	Tenosols, Rudosols, Vertisols	Occurs on river flats and terraces, cleared for pasture, no rocks, no microrelief, imperfectly drained, slope <1%; Alluvial Soils with minimal profile development on Tooloomba and Deep Creek narrow floodplains
Red and Brown Gravelly Earths, Sandy Loam Topsoil over Clay Loam Subsoil	Kandosols	On higher elevation land and slopes.
Vertic Hypernatic Grey and Brown Sodosols, Gravelly Clay-loamy Clayey	Sodosols	Occurs on terraces, cleared for pasture, gravelly, crabhole gilgai microrelief, imperfectly drained, slope <1%;Sodic soils with contrasting topsoil and subsoil texture on terrace plains and undulating rises of Deep Creek
Brown and Grey Sodic Vertosols Non-gravelly Medium Clay over Medium Heavy Clay	Vertosols	Occurs on terraces, cleared for pasture, gravelly, melonhole gilgai microrelief, imperfectly drained, slope <1%; Uniform textured cracking clay soils with shrink-swell properties on terrace plains and alluvial plains of Tooloomba Creek and the Styx River

2.3.5 Aerial imagery

The current landuse and land cover was represented by imagery dated 03/12/2016, sourced online from World Imagery through Global Mapper GIS. Historical aerial imagery was sourced from QImagery (https://qimagery.information.qld.gov.au/) and Google Earth (Table 8). The QImagery data were ostensibly georeferenced, but the stated projection was incorrect. The images were loaded to Global Mapper GIS and rectified against ground control points.

Table 8. Historical aerial imagery sourced for this report.

Image Series	Date of image	Colour	Scale
Styx 1953	01-06-1953	Black and White	1:26,000
Marlborough 1975	27-06-1975	Black and White	1:30,000
Marlborough 1985	23-06-1985	Black and White	1:24,000
Marlborough 2003	8-07-2004	Colour	1:40,000
Google Earth 2018	20-09-2018	Colour	-

2.3.6 Watercourse flood hydraulic characteristics

CDM Smith (2018c) undertook a flood assessment for Tooloombah Creek, Deep Creek and the Styx River. The methodology used XP-RAFTS to model storm event hydrographs for design rainfall data. The catchment has no discharge gauge to provide calibration data but comparison between peak flows modelled by XP-RAFTS and the Regional Flood Frequency Estimation (RFFE) method for peak flows found that the two methods produced comparable results. The developed case model build involved applying the same temporal patterns and design rainfall intensities as the existing case model, but with the area covered by the open cut pit removed as a contributing area, applying a higher impervious area value to the MIA, diverting upstream flow around the pit and Waste Rock Stockpile, and applying a lower impervious value to the waste area. Hydrographs were developed to represent 9.5%AEP, 4.9%AEP, 2%AEP, 1%AEP and 0.1%AEP. Hydraulic modelling of flow in the watercourses was undertaken using MIKE21. The 2011 LiDAR data, resampled to a 10 m grid, were used to represent the topography. The downstream boundary condition did not account for tides.

WRM Water & Environment (2020) developed a 2.5 m grid TUFLOW hydraulic model of the watercourses in the CQC Project area, including Barrack Creek, Deep Creek, Tooloombah Creek and upper Styx River. The model was run for hydrographs representing 10%, 5%, 2%, 1% and 0.1% AEP peak design discharges, as well as the probable maximum flood (PMF) discharge based on design rainfall data (rainfall depths, areal reduction factors and temporal patterns) applied in accordance with ensemble event procedures in Australian Rainfall and Runoff (AR&R). The WRM Water & Environment (2020) model is more recent and higher spatial resolution than the model of CDM Smith (2018c). On this basis, it was preferred for the geomorphic assessment. Modelled hydraulic spatial data from the 10% AEP and 1% AEP events were evaluated in this report. The main variables of interest were velocity and bed shear stress (BSS).

2.4 Geomorphologically-Relevant Variables

Two main groups of variables were of interest to geomorphological characterisation:

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

2.4.1 Landscape-scale variables

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

- Topography
- Drainage network
- Geology
- Land systems
- Soils

- Vegetation
- Tidal extent

2.4.2 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, and potential impacts of open-cut mining on streams.

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 with 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 report classified the streams in the CQC Project 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 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).

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. Water present in the channels at the time of the LiDAR flights prevented mapping pools and riffles from available topographic data.

The frequency, magnitude, type and location of geomorphic change on rivers depends on the distribution of forces that act to mobilise, transport, and deposit sediments, and the distribution of characteristics of the materials that resist erosive forces and favour deposition. The characteristics of the materials that resist erosive forces can be characterised by soil type and vegetative cover, as described above. The forces acting to erode river channels and floodplains can be characterised by velocity and bed shear stress. The methodology is described in the following subsections.

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

- Stream geomorphic type and condition,
- Riparian vegetation,
- Channel slope,
- Channel dimensions,

- Channel bed materials,
- Velocity, and
- Bed shear stress.

2.4.3 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:

$$U < U_{max} \tag{1}$$

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 9).

Table 9. 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 (Bos, 1994).

4. Stallings (1999).

Chow (1981) did not define what was meant by "*water transporting fine suspended solids*", but it would appear from Bos (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 9 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 10, Table 11). The values given in Table 10 and Table 11 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.

Table 10. 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 11. 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

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 3). 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.

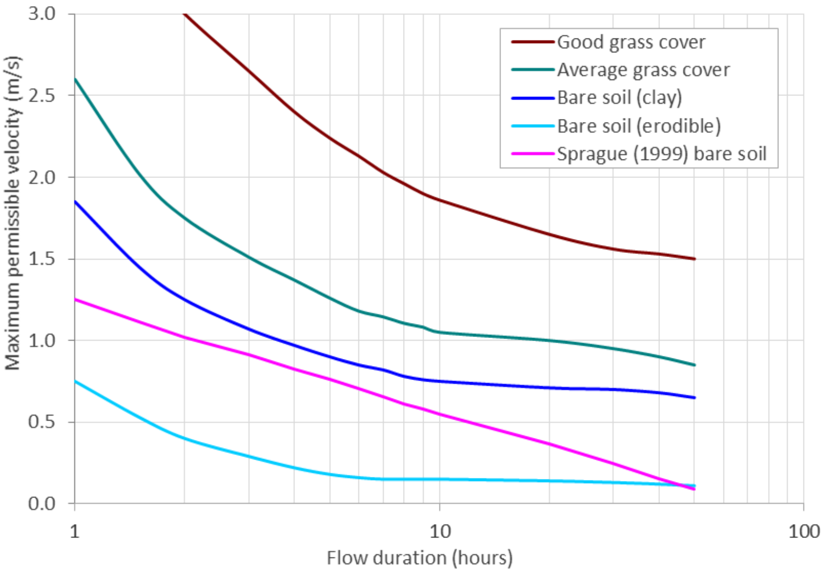


Figure 3. Erosion limits as a function of flow duration. Based on a plots from Fischenich (2001, p. 6) and Sprague (1999).

2.4.4 Method of maximum permissible bed shear stress (BSS)

In one-dimensional (cross-sectional) space, mean bed shear stress (N/m^2) (τ) is conventionally calculated as (Gordon et al., 2004, p. 163):

$$\tau = \rho g R S \qquad (2)$$

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 y (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)

In two-dimensional space, in TUFLOW hydraulic model, for each cell, bed shear stress is calculated as:

$$\tau = \frac{\rho g V^2 n^2}{y^{\frac{1}{3}}} \qquad (3)$$

where,

V = velocity of the cell (m/s).

n = Manning's roughness coefficient of the cell

y = water depth of the cell (m)

The formula used in TUFLOW (Equation 3) avoids the use of slope, presumably because the relatively high resolution cells of a 2-D grid can have significant spatial variation in slope, and have negative values (i.e. upstream sloping water surface). The Manning equation predicts velocity from roughness, hydraulic radius and slope. Equation 3 is derived by rearranging the terms of the Manning equation to predict slope from roughness, hydraulic radius and velocity. This expression is then substituted for slope in Equation 2. Assuming depth is equivalent to hydraulic radius then gives Equation 3.

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:

$$\tau < \tau_{max} \qquad (4)$$

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 12).

When soil is covered by vegetation its resistance to scour is considerably enhanced (Table 13 and Table 14). 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.

Table 12. Maximum permissible bed shear stress (BSS) 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 (Bos, 1994).

Table 13. Maximum permissible bed shear stress (BSS) 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

Table 14. Summary table of threshold bed shear stress (BSS) 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.

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 $1.5\,\tau$.

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:

$$\tau_{bend} = 2.65\tau(R_c/W)^{-0.5} \qquad (5)$$

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).

2.4.5 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 15). 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 16), 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 15) in values for stream power and bed shear stress for the 50 year ARI flood. Stream power (W/m^2) is the product of shear stress and velocity.

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 17). 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 15. Guideline values for average stream powers, velocity and bed shear stresses (BSS) 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 16. Guideline values for average stream powers, velocity and bed shear stresses (BSS) 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 17. 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 unvegetated 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.

2.4.6 Erosion risk criteria for bed shear stress and velocity for the main watercourses in the CQC Project area

The main watercourses included in the TUFLOW hydraulic model were Tooloombah Creek, Deep Creek and Barrack Creek. The alluvial floodplain soils within which these watercourses flow were described by HESSE (2020) as Alluvial Soils, Gravelly, Shallow (Tenosols, Rudosols), Sand, Gravel, Loam. On Lower Tooloombah Creek, Styx River and an area of Deep Creek, the floodplain soils were described by HESSE (2020) as Alluvial Soils, Non-gravelly (Tenosols, Rudosols, Vertisols), Sandy Loam, to Clay textures. HESSE (2020) mapped the alluvium as a narrow band that included the channels and inset benches. The high banks of the watercourses would be formed in soils of spatially variable clay, silt and sand content. Most of Deep Creek and Barrack Creek alluvium was situated within soil HESSE (2020) described as Vertic, Hypernatic, Grey and Brown Sodosols, Gravelly, Clay-loamy, Clayey texture. Lower Deep Creek, Tooloombah Creek adjacent to the CQC Project area, and Styx River alluvium was situated within soil HESSE (2020) described as Brown and Grey Sodic Vertosols, Non-gravelly, Medium Clay over Medium Heavy Clay texture. The soil types likely to be found on the floodplains, and thus the bank faces, had clay texture. For the purpose of setting velocity and shear stress thresholds it was assumed that the soils had thresholds equivalent to those of ‘Alluvial silts, colloidal’ in Table 9 and Table 12.

Unvegetated ‘Alluvial silts, colloidal’ has maximum permissible velocity of 1.1 m/s (Table 9). Correction for slight sinuosity using the method of Lane (1955) requires reduction by 5%, to give a maximum permissible velocity of 1.05 m/s. This threshold would fall to around 0.7 m/s for flood durations of 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.

Unvegetated ‘Alluvial silts, colloidal’ has maximum permissible shear stress of 12.5 N/m^2 (Table 12). Correction for slight sinuosity using the method of Lane (1955) requires reduction by 10%, to give a maximum permissible shear stress of 11.3 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 CQC Project area (Table 18). 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 18. Risk categories of maximum permissible velocity and bed shear stress (BSS) for initiation of fluvial scour of river bank and floodplain soils of the main watercourses in the CQC Project 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[1]	< 2.0[2]	< 11.3[4]	< 1.05[6]
Moderate	100 – 200[1]	2.0 – 3.0[3]	11.3 – 80[5]	1.05 – 1.25[7]
High	> 200[1]	> 3.0[3]	> 80[5]	> 1.25[7]

1. See Table 14
2. See Table 10 and Table 11
3. Assumes good grass cover and flow duration < 2 hours, see Figure 3
4. Assumes ‘Alluvial silts, colloidal’ and slight sinuosity, see Table 12
5. Assumes 50 year ARI, see Table 16
6. Assumes ‘Alluvial silts, colloidal’ and slight sinuosity, see Table 9
7. Assumes bare soil, (clay) and flow duration < 2 hours, see Figure 3

2.4.7 Geomorphic effectiveness of trees versus grass cover on river banks

When soil is covered by vegetation its resistance to scour is considerably increased, depending on the vegetation type. Most tables of maximum permissible bed shear stress or velocity for vegetated channels consider only grass, not shrubs or trees. This is because the primary use of the tables is to guide design of drainage channels, which are built to transfer water as efficiently as possible. Trees are not established on drainage channels because of their high resistance to flow. The merits of ground cover, shrubs and trees in protecting banks from erosion has been debated in the literature. It is not universally accepted that trees, as opposed to shrubs or grass, have clear superiority in imparting erosion resistance to river banks. There are published papers that demonstrate superiority of grass over trees in this regard. Also, it is not established in the literature that the level of erosion protection is directly related to the age of trees.

A study of sand-bed channels in NSW by Huang and Nanson (1997) found that streams with trees and shrubs growing on the banks, but also in the bed, were 2.2 times wider than streams with trees on the banks only, implying greater bank instability. Trimble (1997), in a study in Wisconsin, found that streams running through forest were significantly wider than those in pasture. This was confirmed by a New Zealand study by Davies-Colley (1997). However, this latter study found that width was independent of vegetation cover for catchments >3 km^2. It was postulated that as stream power increased with basin area, the protective influence of grassy vegetation became less important.

The studies that have found channels to be narrow under pasture have warned that rehabilitation of channels by re-establishment of forests on riparian zones could lead to channel instability, release of sediment stored in channel banks, and consequent deterioration in water quality. Riparian trees can shade banks, eliminating grass cover, and exposing bank surfaces to erosion. Trimble (1997) warned that restoration of forests in riparian zones may not be good public policy. This suggestion runs counter to the general recommendation of ecologists that riparian forests are preferable to grassed banks (Montgomery, 1997). The widespread narrowing of channels by conversion from forest to pasture has significantly reduced the area of habitat available in channels (Sweeney, 1993; Davies-Colley, 1997).

The process that explains channels being wider under forest is woody debris and in-channel trees deflecting flow onto the banks, which erodes them. This effect is reflected in the high roughness coefficients of channels with woody debris or in-stream growth. It is clear that in certain circumstances, the influence of in-stream and riparian trees deflecting flows and causing widening of a channel can be overridden when vegetation increases channel roughness to the extent that it reduces mean flow velocities (Huang and Nanson, 1997).

Montgomery (1997) pointed out that the contradictory findings on the topic of riparian vegetation and channel stability are due to the highly complex nature of the interaction of stream variables. He stated “This smorgasbord of influences means that simple guidelines and blanket generalizations rarely provide a sound basis for the management of rivers and streams” (p. 328). Similarly, Hession et al. (2008) reviewed the literature on riparian vegetation and channel stability, concluding that there is a high level of uncertainty surrounding the topic. It appears likely that grass cover provides good resistance to erosion in small channels but forest cover would be superior in rivers with high banks where the root systems of trees would play a role in bank stabilisation. Significant stability is also imparted to river bed material by large wood sourced from riparian forests (Gippel, 1995). These geomorphic benefits are additional to the ecological benefits provided by riparian forests relative to the limited habitat variability and ecological diversity typically associated with grass.

In a situation where riparian vegetation is being restored, the maximum permissible shear stress values recommended for grassed surfaces are appropriate over the short-term following establishment of grass cover, and the maximum permissible shear stress range for hardwood tree plantings in Fischenich (2001, their Table 2) (i.e. 20 – 120 N/m^2) is appropriate for a rehabilitated forested surface in the long-term.

2.4.8 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 CQC Project area.

2.5 Terrain Analysis

Geomorphology is concerned with both physical form and physical 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. Terrain analysis was undertaken using the GIS applications Global Mapper™ V15.2.5 25 June 2014 Build (Blue Marble Geographics).

2.5.1 Topography (digital elevation) definition

The topography of the CQC Project area was defined by a 1 × 1 m DEM derived from the supplied 2011 LiDAR point cloud data and a 1 × 1 m DEM derived from the 2009 Tropical Coasts LiDAR point cloud data. For areas beyond the bounds of the LiDAR coverage, the DEM was extended using 5 m and 25 m DEMs. While major bridges over watercourses had been removed from the LiDAR data, culverts under roads required manual editing to maintain correct drainage pathways. The process was to identify areas requiring editing by examination of aerial photography and LiDAR data, seeking physical evidence of culverts and observing where automatically generated drainage lines were hydrologically incorrect due to blockage by road embankments. A small plane at the elevation of the local drainage path was inserted into the DEM over the obstruction to simulate drainage through the culvert. A total of 46 culverts were inserted into the DEM across the Styx River catchment.

2.5.2 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. While this dataset contains errors, they mainly affect Order 1 and Order 2 stream links, a large number of which were not assigned an Order. These errors did not affect the higher Order streams that flowed through the CQC Project area.

2.5.3 Sub-catchment areas

The Styx River catchment was defined from a point in the upper-estuary (Figure 2), which excluded small streams flowing directly to coastal areas. Sub-catchments and stream lines were defined 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, then drainage was generated using parameter settings of minimum stream length 50 m and minimum sub-catchment area 10 ha. 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. In areas of the Styx River catchment not within the CQC Project area, the sub-catchments draining to the main tributaries entering the river were merged to form entire catchments.

2.5.4 Stream slope

Slope was evaluated for the main watercourses in the vicinity of the CQC Project area. Long profiles were constructed by sampling the DEM along the automatically defined channel thalwegs at a 5 m spacing. Most of these main watercourses were represented by the 1 m DEM, but parts of some of them were represented by 5 m and 25 m DEMs.

2.5.5 River bank and gully erosion rates

Erosion of the subsoil is thought to be responsible for 90% of the fine sediment load delivered to the Great Barrier Reef (Wilkinson et al., 2016). The majority of this sediment is derived from erosion along gully and stream channels. Gully erosion contributes at least 40%, stream erosion approximately 30%, and some subsoil is eroded from rilling on hillslopes (Wilkinson et al., 2016). To establish a baseline, an assessment was made of the types and rates of gully and river bank erosion occurring over the CQC Project site.

Alluvial gully erosion is likely to be a major sediment source in many large tropical rivers in northern and north eastern Australia, including the Fitzroy (Brooks et al., 2007). In the Gulf region, specific annual sediment yields up to 1,250 t/ha have been estimated for individual gullies (Brooks et al., 2007). Alluvial gully erosion is distinct from incisional features in erodible hillslope colluvium that are explained by exceedance of the critical shear stress of the soil surface. Rather, alluvial gullies are found exclusively within alluvium and can propagate entirely as a result of basal sapping (i.e. the preferential erosion of the sub-soil by dissolution weathering and positive pore pressures). Brooks et al. (2007) and Shellberg (2011) presented a typology of alluvial gully erosion in northern Australia, and developed a conceptual model of their formation and progression. The four types were Linear, Dendritic, Amphitheatre and Continuous Scarp Front (Table 19).

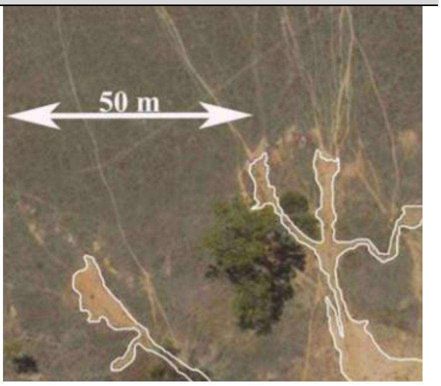
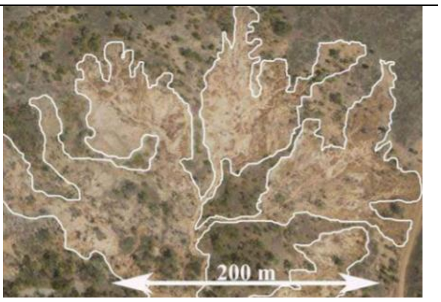
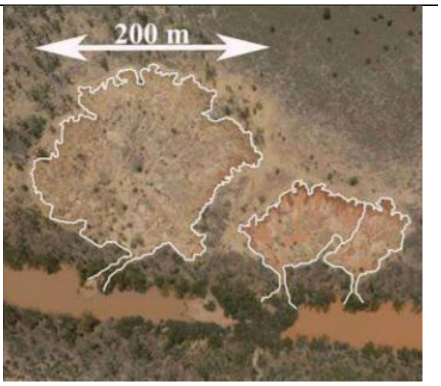
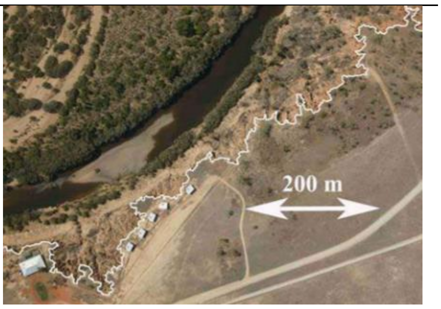
While expansion of alluvial gullies could be related to introduction of roads, it appears that alluvial gullying is an inherent feature of the landscapes where it has been observed (Brooks et al., 2007; Brooks et al., 2009). The Mitchell fluvial megafan, which drains to the Gulf of Carpentaria, is the product of at least five cycles of fan building over the Pleistocene and Holocene (Shellberg, 211). Whilst river incision into the megafan since its formation developed the relief potential for gullying, Brooks et al. (2009) found that other factors such as floodplain hydrology, soil dispersibility, and vegetation cover also influenced the distribution of gullies. Brooks et al. (2009) proposed that the mechanism of initiation of alluvial gullies was concentrated overland flow following rainfall or flooding over steep banks, but whether a gully develops or not depends on surface soil properties and vegetative cover. In the Mitchell River catchment, north east Queensland, the onset of significant gully erosion was coincident with the arrival of cattle (Shellberg et al., 2010; Shellberg et al., 2013). Evidence provided by Brooks et al. (2013) indicated that a similar increase in erosion rate accompanied settlement in the adjoining Normanby River catchment.

Trevithick et al. (2010) mapped gully density on the Fitzroy Basin (not including the Styx River catchment) on the basis of sampling 0.6 m resolution Quickbird satellite imagery. Comparison of mapping of gullies from high resolution imagery with field mapping and mapping from LiDAR-derived DEMs (Prosser, 2018) suggested that relying on imagery can lead to underestimation of gully extent due to obscuration by tree cover (Brooks et al. 2013; Tindall et al. 2014). LiDAR has been applied to gully mapping only in small proportions of regional catchments (Prosser, 2018). One example of application of LiDAR is a study by Benn (2015) of linear gullies on duplex soils at two sites within the Southern Tablelands, NSW. Benn (2015) used high resolution repeat LiDAR surveys to determine the response of the gullies to a 10 – 20 year ARI rainfall event in February-March 2012. LiDAR was captured on 1/08/2011 and 20/06/2012. LiDAR point density was close to 1 point per square metre, and vertical accuracy was 0.1 m at 67% CI. The point cloud data were converted to 1 m DEMs. Benn (2015) found that compared to historical rates of erosion, the 2011 storm event caused little morphological change, with no extension of gully headcuts at either site. The annualised rates of sediment yield from the two sites over the study period were 13.2 – 30.1 and 0.41 – 0.87 t/ha/yr (the range allowed for error). These rates of soil loss are not exceptional, and probably reflect stabilisation of the gullies since 2008 (Benn, 2015).

The availability of LiDAR over the CQC Project area from two dates, Sep-Oct 2009 and 17 June 2011, allowed an analysis of landform change associated with river bank migration and gully erosion over a relatively short period of time. A significant storm event occurred in the Fitzroy River catchment during that period of time. A flood peak of 1,209,975 ML/d was recorded on 1 January 2011 at the gauge Fitzroy River at Riverslea (130003). The flood frequency relationship for this gauge provided by SunWater (2015, p. 3-13) suggests that the December 2010 - January 2011 flood was a 37 year ARI event. A synthetic daily time series of mean discharge in the Styx River provided by WRM Water & Environment suggested that this event peaked on 27 December 2010. Flood frequency analysis suggested this was a 5 to 7 year ARI event in the Styx River.

River bank erosion rate was assessed at a site on the Styx River, just downstream of Ogmore Road bridge. Comparison of the 2009 and 2011 LiDAR data indicated that this was the only site of notable river bank migration in the vicinity of the CQC Project area. Six gully sites in the vicinity of the CQC Project area were selected for assessment of erosion rate between 2009 and 2011 LiDAR surveys. These sites were chosen to be representative of different gully types.

Table 19. Typology of alluvial gully erosion in northern Australia. Source: Shellberg (2011).

Type	Description	Example
Linear	Elongate planform morphologies without well developed secondary drainage networks. They are likely to be an incipient phase of other gully forms, which are usually preceded by rilling. They are also commonly associated with anthropogenic disturbances such as roads, stock tracks, or other linear disturbances that tend to concentrate overland flow	
Dendritic	Associated with well defined drainage networks, separated by distinct interfluves. The gully head is often indistinct, grading relatively gradually into the adjacent floodplain	
Amphitheatre	Often as wide as or wider than they are long, due to the lack of structural control on their lateral expansion. They have well developed head scarps around three-quarters of the gully perimeter, and drain into relatively narrow outlet channels on the proximal or distal sides of alluvial ridges	
Continuous scarp front	Located parallel with the main stem channel of major rivers. They develop from the coalescence of numerous amphitheatre gullies and/or from river bank erosion on meander bends. Thus they are either more mature than other forms	

Two approaches were used to assess geomorphic change at the river bank site. First, the previous positions of the bank edge were determined from interpretation of historical aerial photographs. Second, profile curvature, calculated in GIS from the 2009 and 2011 LiDAR-derived 1 m DEMs, was used to define the edge of the top of bank. Profile curvature greater than 0.1 was used to delineate the strong convex edge of the bank top. The volume of eroded bank material was calculated by subtracting 2009 elevations from 2011 elevations. This was converted to mass by multiplying by a specific gravity of 2.65. A correction was made to adjust for background difference between the 2009 and 2011 LiDAR elevations. This was done by measuring the average difference in elevation of the two LiDAR data sets over a 20 m wide strip of land unimpacted by erosion or deposition that extended around the bank erosion site. A similar procedure was applied to the gully sites to determine the change in soil mass within the defined perimeter of each gully between the dates when the 2009 and 2011 LDAR were flown. The erosion rate was annualised, assuming a period of 631 days between the surveys.

2.6 Stream Geomorphic Type and Condition

2.6.1 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 CQC Project area was done on the basis of spatial data layers, aerial imagery and ground photography. The subjective nature of classifying stream reaches into geomorphic types (or River Styles®) means that the procedure is uncertain.

2.6.2 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 20).

2.7 Impact Assessment

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

There are four main mining-related agents of change with potential to cause an impact on geomorphological processes and forms in the CQC Project 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 21) that would constitute an environmental impact with possible implications for environmental values. Some of these risks were assessed directly or indirectly for the EIS by other technical specialists.

Table 20 Categories of stream geomorphic condition defined by Outhet and Cook (2004). The term "Style" is equivalent to the term "stream type" used in this report.

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.

Table 21 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

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

2.7.2 Indicators of risk of geomorphic change

The surface water assessment undertaken by WRM Water & Environment (2020) included design of mine site water management, as well as modelling the impact of the Project on hydraulic characteristics (water depth, velocity, and bed shear stress) of flood hydrographs for the main watercourses in the vicinity of the CQC Project area. These hydraulic characteristics were of interest to this report, as they condition sediment transport, and bed and bank erosion processes.

The modelling was run for flood events covering a range of recurrence intervals for the Existing scenario and the Developed scenario Project Stage 2, Mine plan representative year 8, representing the modelled period 2026-2029 (scenario P8).

The model was run for 114 climate sequences, each referred to as a “realisation”. Each realisation was based on an 18-year sequence extracted from the historical rainfall data. The first realisation was based on rainfall data from 1889 to 1906. The second used data from 1890 to 1907 and so on. Statistical analysis of the results from all realisations provided probability distributions of key hydrologic parameters (WRM Water & Environment, 2020).

In this report, the risk of geomorphic change was indicated by comparison of Existing and Developed (P8) scenario spatial distributions of the maximum of bed shear stress and velocity for the 10% AEP and 1% AEP event hydrographs. The magnitude of the distributions, and the differences in the magnitude of the distributions between Existing and Developed (P8) scenarios were used to locate areas of potential erosion risk that were then considered for mitigation and monitoring. Erosion risk was assessed on the basis of the maximum permissible velocity and bed shear stress categories established for streams and floodplains in the Project area (Table 18).

3.0 Existing environment

3.1 Landscape-Scale Characteristics

3.1.1 Catchment topography

The CQC Project area lies within the Styx River Sub-area of the Fitzroy Drainage Division. In this report, the Styx River catchment was defined as the part of the Styx River Sub-area draining directly to the upper estuary, a total area of 1,093 km^2 (Figure 4). The Styx River catchment area defined automatically from the DEMs had a slightly different boundary to that defined by the Styx River Sub-area. Within this catchment, land surface elevation ranges up to 602 mAHD. The main area of interest, the CQC Project area, lies manly within the lowland topographic zone of the catchment, with an elevation range up to 249 mAHD (Figure 5).

3.1.2 Drainage system and sub-catchments

The Styx River is an Order 7 watercourse where it enters the estuary (Figure 6). The catchment has a high stream density in the western headwater area. The lowland zone, in which the CQC Project area is situated, has moderate to low stream density (Figure 6). Of the main streams in this catchment, in their lower reaches, Tooloombah Creek and Deep Creek are Order 6, and Barrack Creek is Order 5 (Figure 6 and Figure 7). The majority of the Styx River catchment comprises the sub-catchments of Tooloombah Creek/Mamelon Creek, Deep Creek/Barrack Creek, Montrose Creek and Granite Creek (Figure 7). In the lowland area, smaller tributaries drain directly to Styx River. The CQC Project area, situated on the interfluve between Tooloombah and Deep creeks, was drained by a system of minor creeks (Figure 8). The majority of this land drained to Deep Creek downstream of Barrack Creek junction (Figure 8).

The larger mapped watercourse lines were in general agreement with the auto-generated drainage lines, although there were differences in detail (Figure 8). On the other hand, the alignments of some Order 1 and 2 streams in the Styx River catchment differed significantly from the auto-generated drainage lines. Some of these watercourses had been captured and diverted by farm dams and other obstructions that were constructed since the time of the original mapping.

A ubiquitous feature of the Styx River drainage system is channel incision. Tooloombah Creek and Deep Creek are both incised, and downstream of their junction, Tooloombah Creek/Styx River flows through an incised belt up to approximately 1 km wide (Figure 5). All of the small tributaries draining to the main watercourses are also incised (Figure 5).

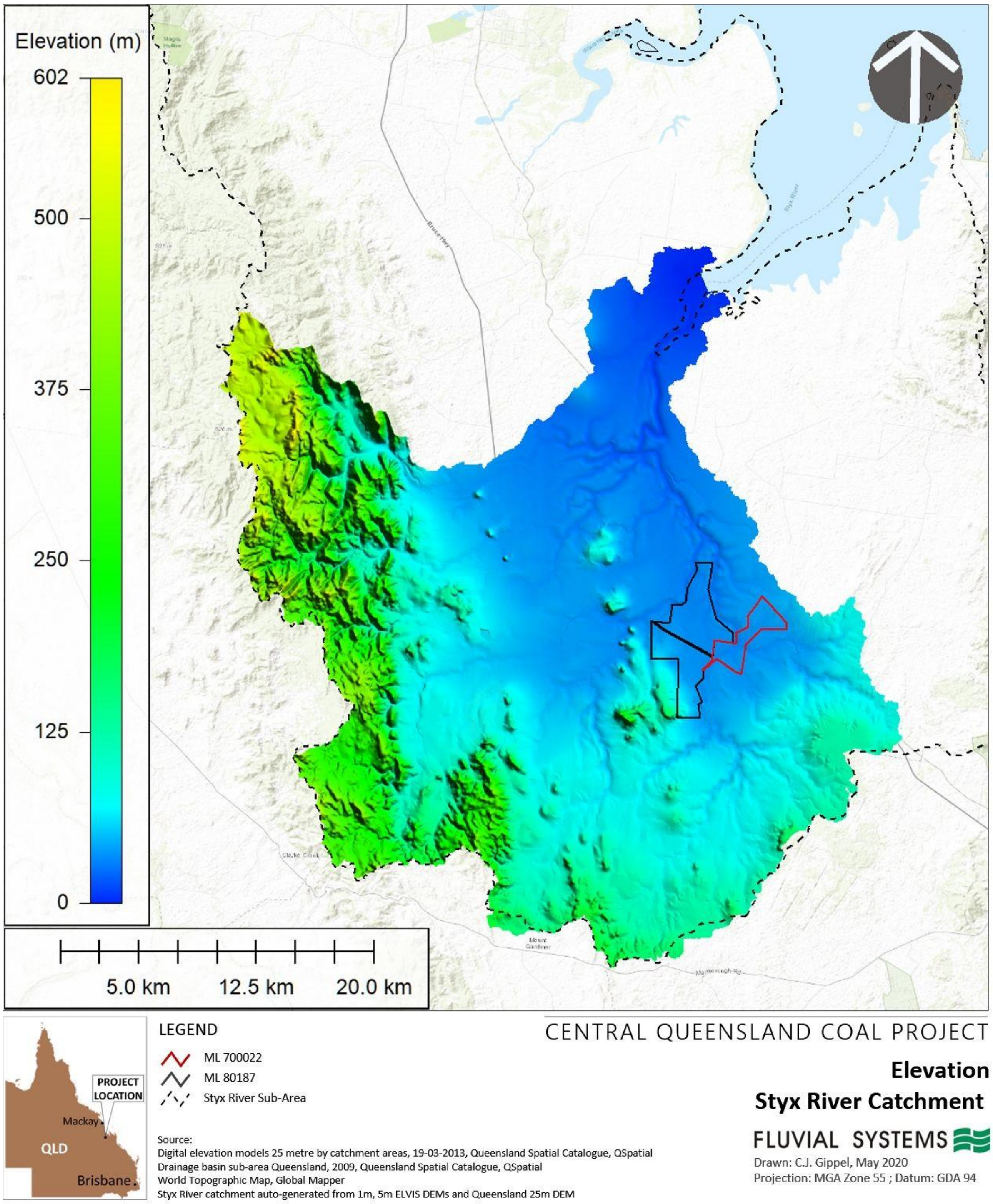
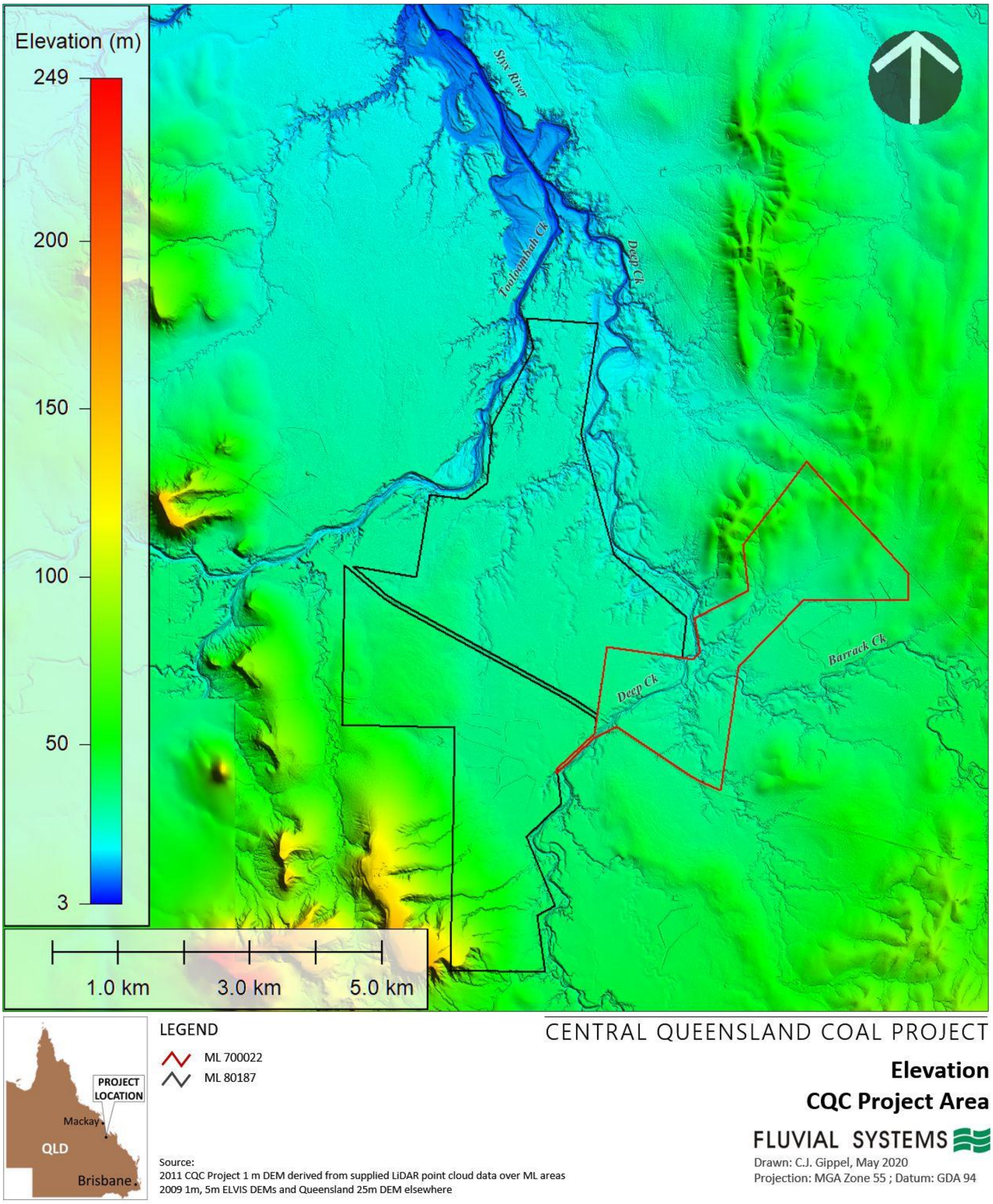


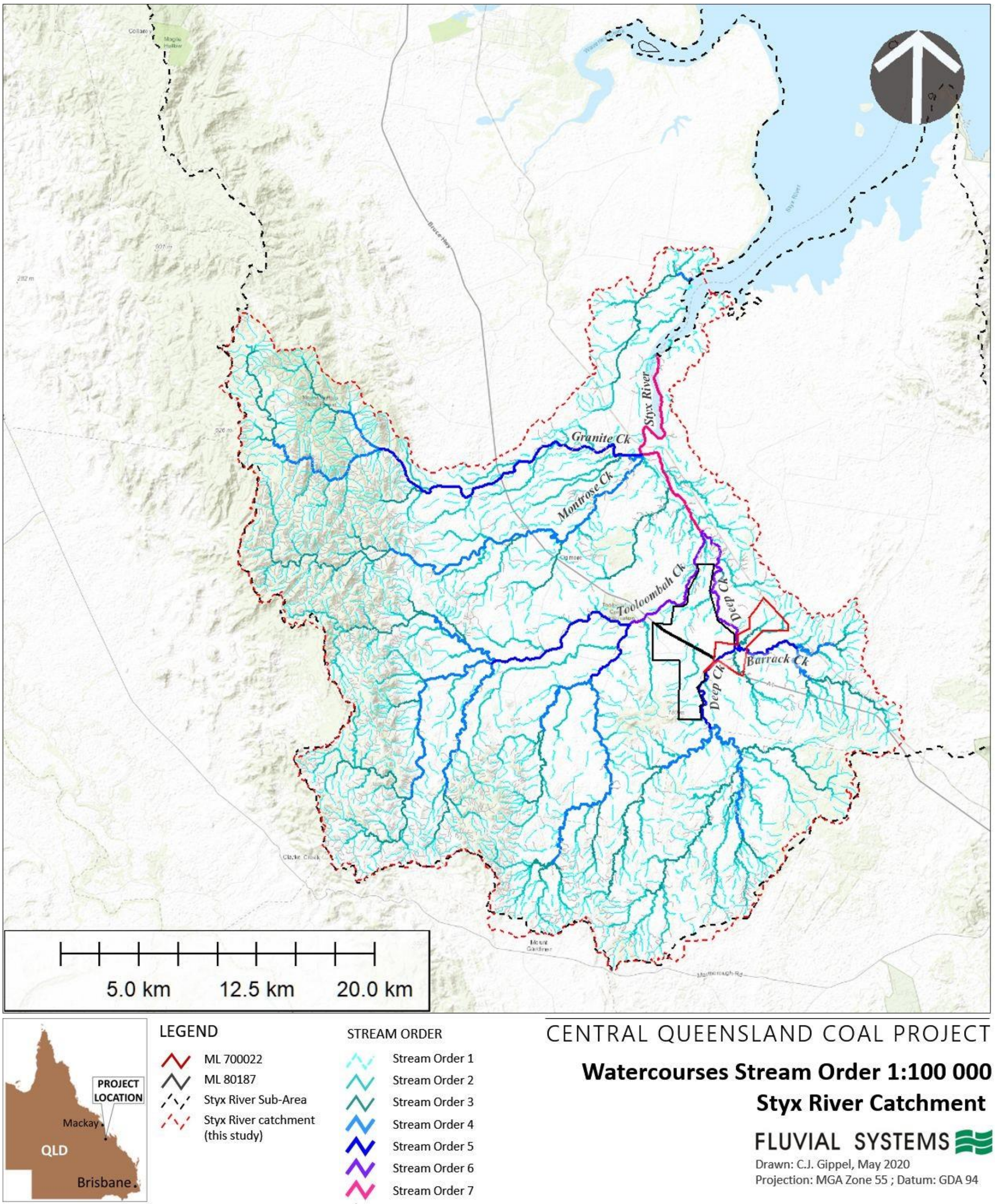
Figure 4. Styx River catchment topography.



Source:
2011 CQC Project 1 m DEM derived from supplied LiDAR point cloud data over ML areas
2009 1m, 5m ELVIS DEMs and Queensland 25m DEM elsewhere

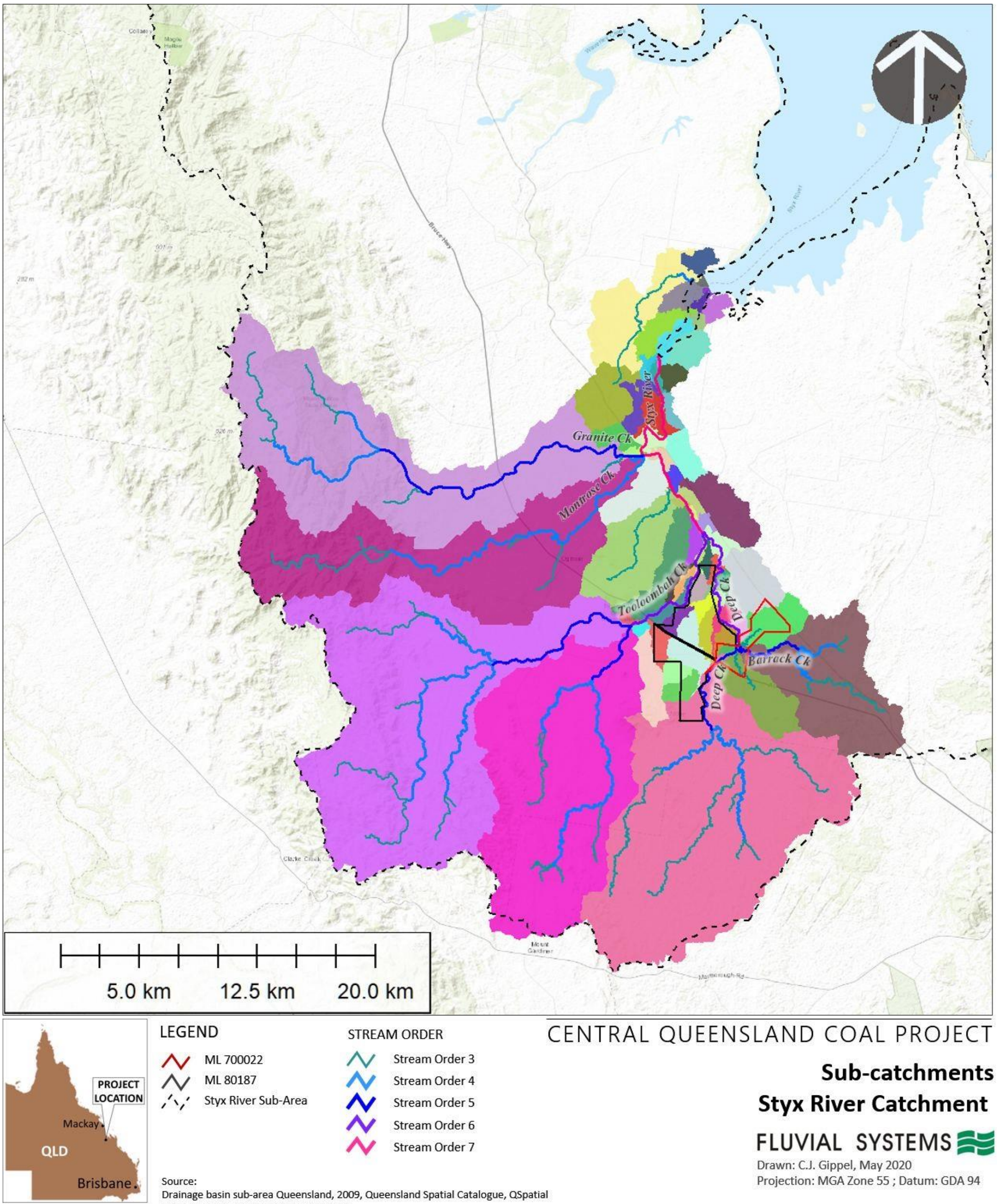
Drawn: C.J. Gippel, May 2020
Projection: MGA Zone 55 ; Datum: GDA 94

Figure 5. CQC Project area topography.



Source:
Watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019, Queensland Spatial Catalogue, QSpatial
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
World Topographic Map, Global Mapper
Styx River catchment auto-generated from 1m, 5m ELVIS DEMs and Queensland 25m DEM

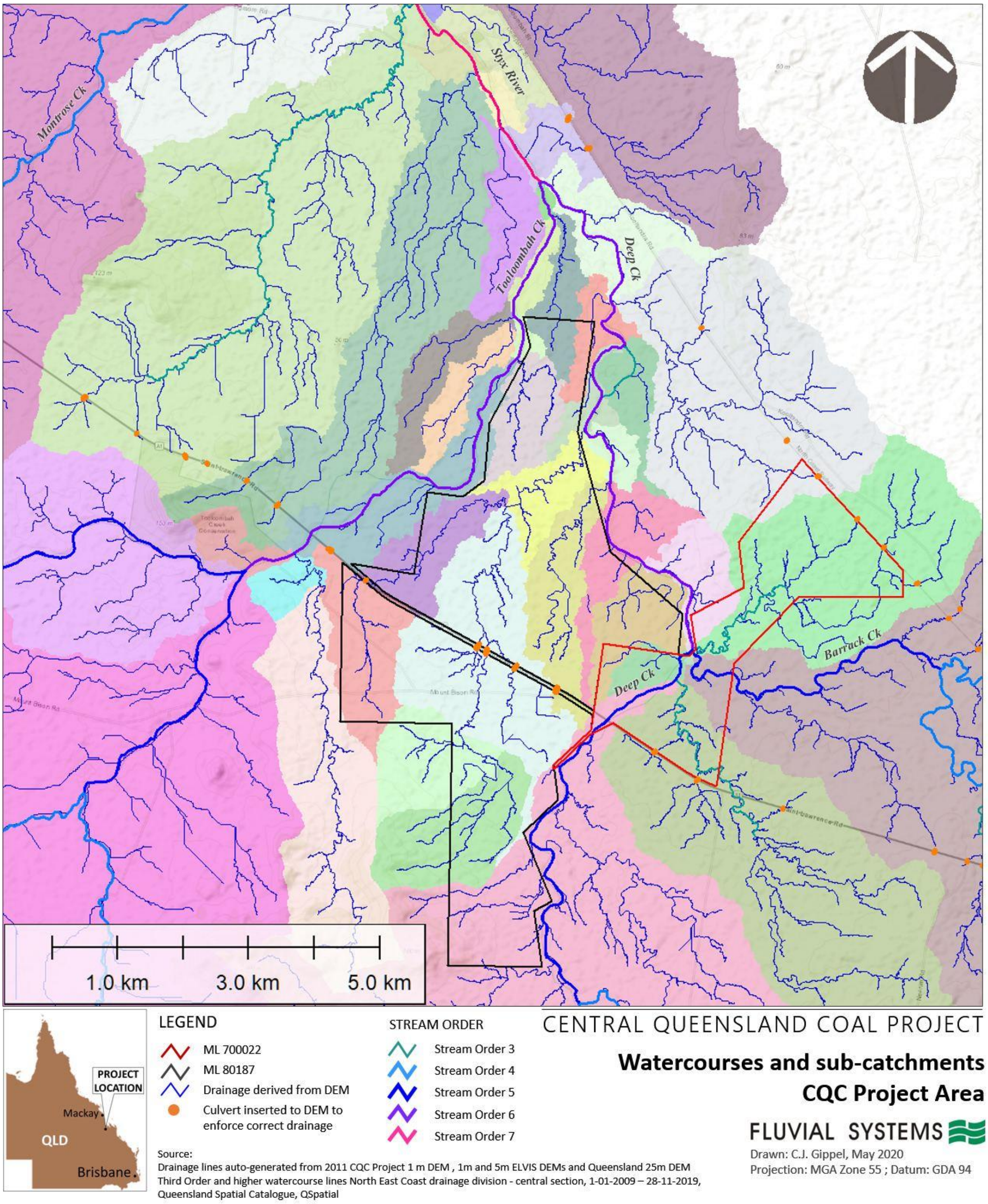
Figure 6. Styx River catchment Watercourses and Stream Order.



Drawn: C.J. Gippel, May 2020
Projection: MGA Zone 55 ; Datum: GDA 94

Source:
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
World Topographic Map, Global Mapper
Watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019, Queensland Spatial Catalogue, QSpatial
Styx River sub-catchments auto-generated from 1m, 5m ELVIS DEMs and Queensland 25m DEM

Figure 7. Styx River catchment main watercourse sub-catchments.

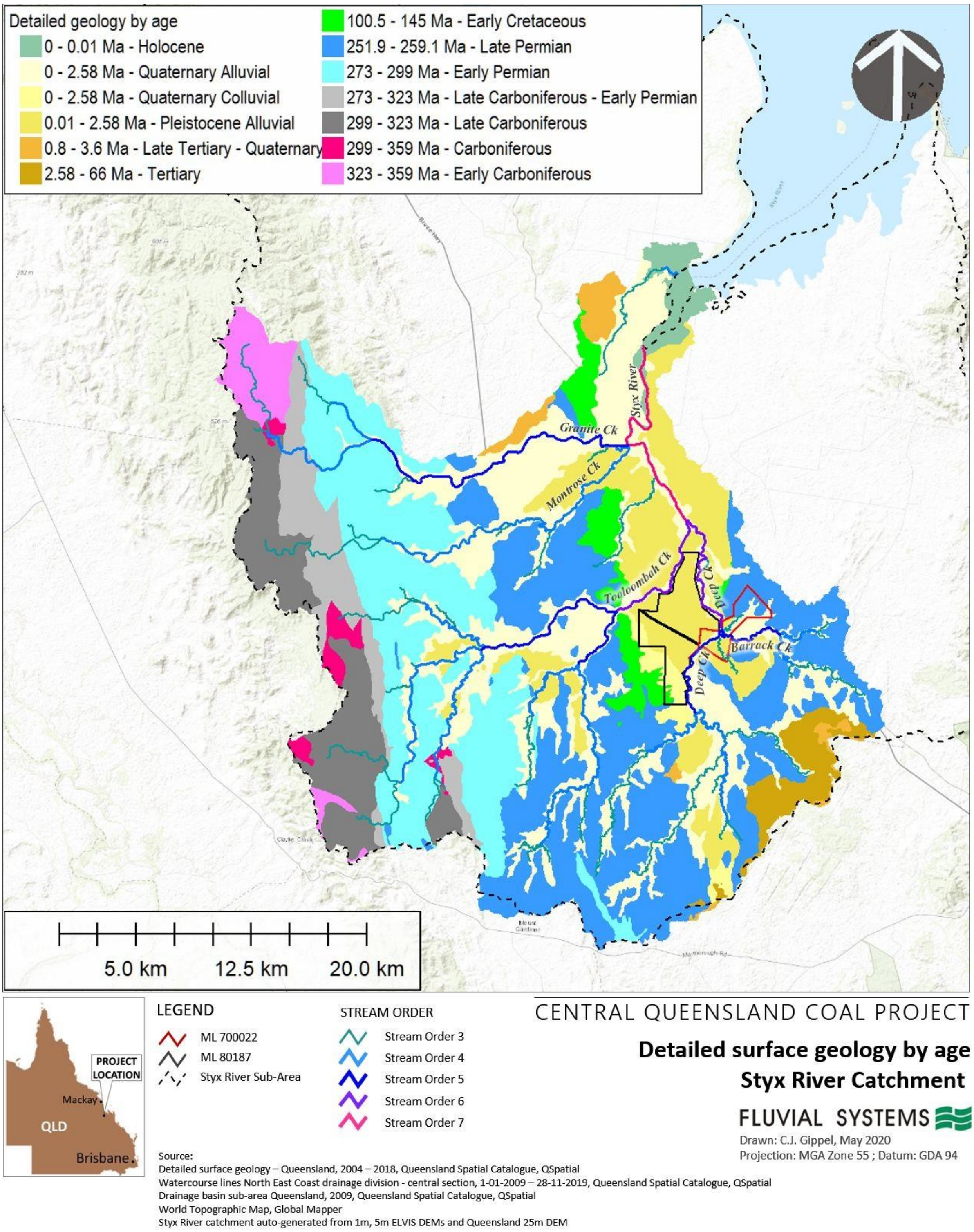


Source:
Drainage lines auto-generated from 2011 CQC Project 1 m DEM , 1m and 5m ELVIS DEMs and Queensland 25m DEM
Third Order and higher watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019,
Queensland Spatial Catalogue, QSpatial

Figure 8. CQC Project area watercourses and sub-catchments.

3.1.3 Geological classification

The geology of the Styx River catchment is characterised as Holocene sediments in the estuary, with vast areas of Quaternary alluvial deposits overlying the early Cretaceous Styx Coal Measures, the strata of which consists of quartzose, calcareous, lithic and pebbly sandstones, pebbly conglomerate, siltstone, carbonaceous shale and coal (CDM Smith, 2017; 2018). The Styx Coal Measures overly a progression of Late Carboniferous to Late Permian deposits (Figure 9). Alluvial lithological units Qpa and Qa dominate the CQC Project area (Figure 10) with Holocene Qh sediments also occurring in the estuary (Figure 11).



Source:
Detailed surface geology – Queensland, 2004 – 2018, Queensland Spatial Catalogue, QSpatial
Watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019, Queensland Spatial Catalogue, QSpatial
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
World Topographic Map, Global Mapper
Styx River catchment auto-generated from 1m, 5m ELVIS DEMs and Queensland 25m DEM

Figure 9. Detailed surface geology of the Styx River catchment by age.

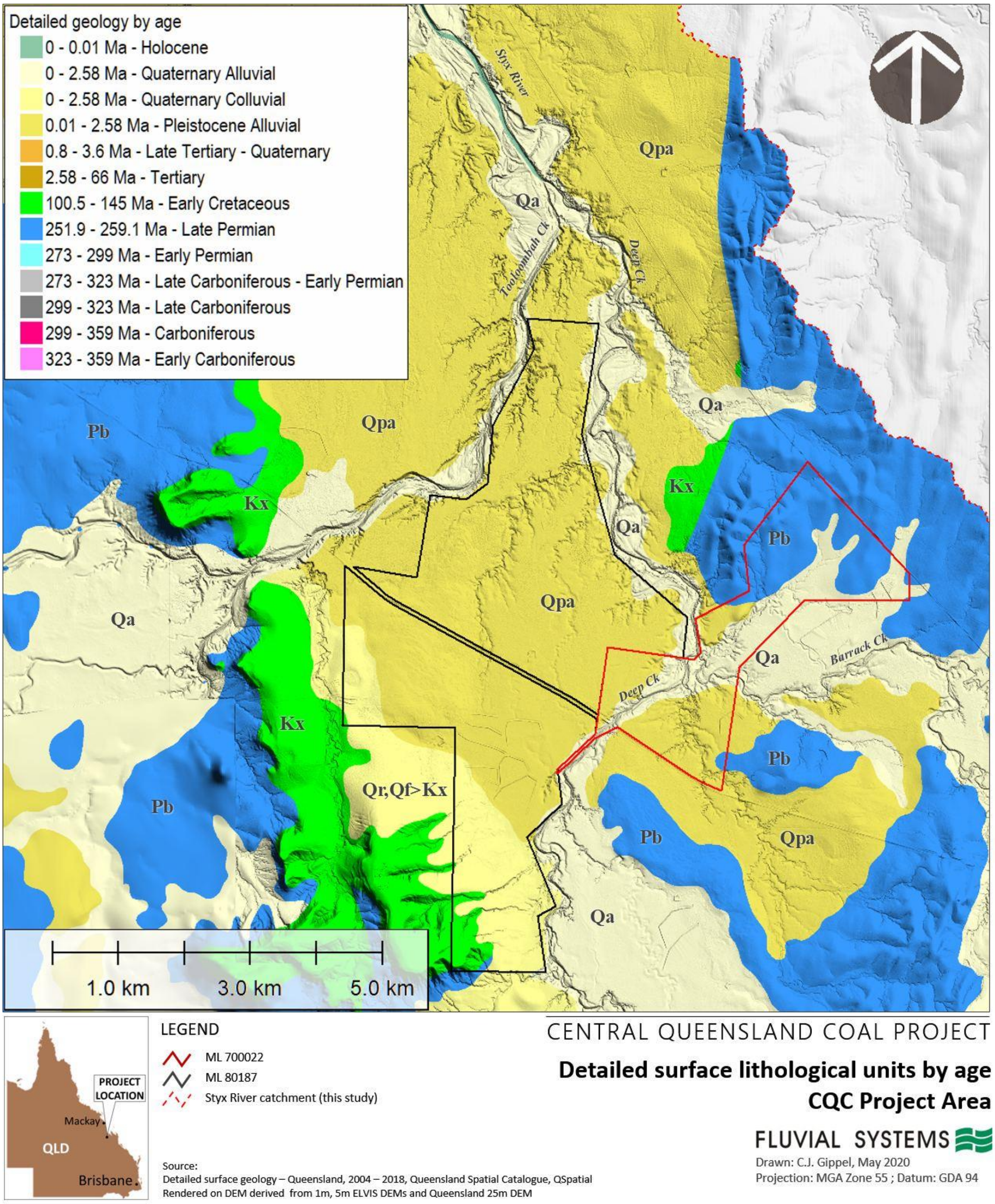
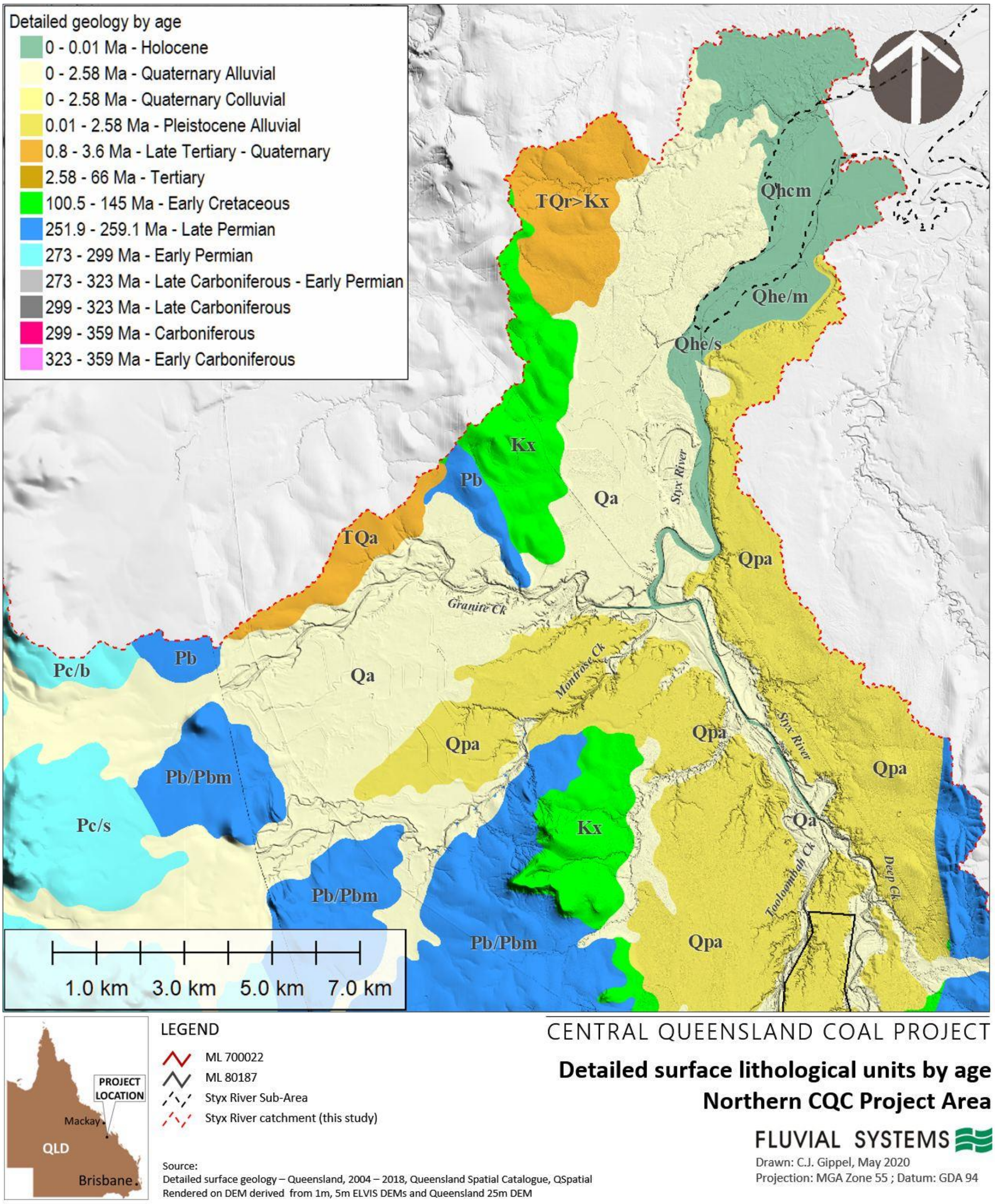


Figure 10. Detailed surface geology of the CQC Project area by age.



Source:
Detailed surface geology – Queensland, 2004 – 2018, Queensland Spatial Catalogue, QSpatial
Rendered on DEM derived from 1m, 5m ELVIS DEMs and Queensland 25m DEM

Drawn: C.J. Gippel, May 2020
Projection: MGA Zone 55 ; Datum: GDA 94

Figure 11. Detailed surface geology of the northern CQC Project area by age.

3.1.4 Geomorphology of alluvium in the Styx River valley

Alluvium is eroded material that has been transported far from its source and deposited by a stream in a valley floor. ‘Unconsolidated’ alluvium is a permeable deposit of sand and gravel that could contain alluvial aquifers, while ‘consolidated’ alluvium is a deposit of silt and clay with low permeability, and little prospect for containing alluvial aquifers. Floodplains are by definition composed of alluvium, but alluvium does not always contain aquifers with significant reserves of groundwater. In this report, ‘alluvium’ is meant in the geomorphic sense, and should not be interpreted to mean ‘alluvial aquifer’.

All of the alluvium in the Styx River valley was formed within the Quaternary Period (2.58 million years ago to the present day) of the Cainozoic Era (66 million years to the present day). The Quaternary Period comprises the Pleistocene (2.58 million years ago to 11,700 years ago) and Holocene (11,700 years to the present day) epochs.

Alluvium in the Styx River valley has been classified and mapped according to geological age in the digital layer Detailed surface geology – Queensland (Department of Natural Resources, Mines and Energy, 2019). The boundaries of Qpa (Pleistocene), Qa (undifferentiated Quaternary) and Qhe (Holocene) units were mapped at a relatively coarse scale (1:100,000, but derived from 1:250,000 map sheets and other data) (Figure 9, Figure 10 and Figure 11).

There were two main periods of Quaternary alluvial deposition in coastal streams within alluvial valleys. The first was responsible for formation of the Qpa terraces that bound the rivers of the region, while the second was responsible for formation of the Qa benches and inset floodplains that are found within the macro-channel formed in Qpa sediments.

The Upper Pleistocene sub-epoch occurred 11,700 – 130,000 years ago. During the early interglacial part of the Upper Pleistocene, 130,000 – 119,000 years ago, sea levels were 4 – 6 metres higher than present (Wilson and Taylor, 2012) (Table 22). What is now the current coast line would have been submerged, with estuarine deposits forming further inland than currently. The onset of glaciation resulted in decline of sea levels. Near the coast, rivers would have incised into previously deposited alluvium. The glacial cycle peaked 21,000 years ago, when the sea level was around 125 m lower than present (Table 22). The latter part of the glacial cycle was coincident with the development of vast alluvial plains that form the current Qpa terraces. The main depositional phase started around 30,000 years ago and ceased around 9,000 years ago (Table 22).

The Holocene Epoch occurred over the past 11,700 years. Lambeck and Nakada (1990) suggested that present sea-level was reached about 6,000 years ago, but this date has been revised to 7,700 years (Table 22). A fluvially active period occurred around the time of the Holocene Climate Optimum (HCO), 6,000 – 9,000 years ago, resulting in the relatively rapid incision of a macro-channel into Qpa sediment. Tributaries would have incised into the Qpa in response to base level lowering of the main river channels. This period of incision was followed by the second main period of alluvial deposition which involved development of Holocene-age benches and inset floodplains within the macro-channel (Table 22). Despite this being a depositional phase, knickpoints on steepened, incised tributaries might have continued to progress upstream. In estuarine areas, alluvium was reworked to produce Qhe morphology (Table 22).

On the West Normanby River at Kings Plains, located in the Wet Tropics of north Queensland, Pietsch et al. (2015) determined that the alluvial terrace was built through the Upper Pleistocene and into the Holocene, with approximately 10 m of medium to coarse sands laid down between 33,000 and 16,400 years ago, and the upper two metres dating to 8,760 years ago. At the sampled sites, the surface of the Pleistocene terrace was around 25 – 30 m above the current channel thalweg. The surfaces of inset Holocene benches were at various elevations within and between sites, mostly within the range 3.5 to 10 m above the channel thalweg (Pietsch et al., 2015).

In the Styx valley, Detailed surface geology – Queensland (Department of Natural Resources, Mines and Energy, 2019) maps Holocene-age alluvium variants Qhe/s, Qhe/m and Qhcm (Figure 11). These are all estuarine sediments. Qha is not mapped in the Styx valley. Rather, within the macro-channel, where Qha would be expected, the unit is labelled Qa (undifferentiated) with lithology described as clay, silt, sand, gravel; floodplain alluvium. Undifferentiated means that it was not possible to specify finer age divisions. Qa potentially comprises active Holocene alluvium (Qha) and Upper Pleistocene alluvium (Qpa). In the Styx valley, Detailed surface geology – Queensland (Department of Natural Resources, Mines and Energy, 2019) described the lithology of Pleistocene-age Qpa as clay, silt, sand, gravel; flood-plain alluvium on high terraces. The only lithological difference with Qa is reference to its occurrence on high terraces.

Soil developed from Pleistocene alluvium commonly has a higher degree of profile development than that developed from Holocene alluvium (Wilson and Taylor, 2012). However, these landscapes often grade into each other, making it difficult to distinguish a hard boundary for the purpose of geological mapping. In some places, the Pleistocene alluvium can be inundated by flood events from creeks draining the local uplands (Wilson and Taylor, 2012). Also, the depositional phase that built the Qpa terraces continued into the early part of the Holocene, so the upper layers of the terrace do not necessarily belong to the Pleistocene epoch. Although Holocene alluvium is found within a macro-channel, the morphology of this channel can be complex, with multiple channels dissecting through the terrace. Together, these difficulties with boundaries and classification have led to the currently active river corridor falling within a zone mapped Qa (undifferentiated).

Table 22. Quaternary history and fluvial geomorphic response.

Period	Epoch	Sub-epoch	Stage/climate	Sea level	Channel morphology
Quaternary	Holocene <11,700 years		0 – 2,000 years	Declining to present level[1]	Development of modern Qa units within the macro-channel formed in Qpa[2]. In estuarine areas, alluvium was reworked to produce Qhe morphology. Deposition and erosion cycles reworked alluvium according to sea level variation (deposition in the highstands), climatic change, periods of drought and flood dominance, plus human influence on catchment and riparian vegetation cover[3]. Gullies developed in upper tributaries, and alluvial gullies developed and expanded on main channels[4]. -
			2,000 – 3,500 years; sharp decline in precipitation and increased climatic variability 3,700 – 1900 years[5]	Within 0.5 m of present[6]; evidence for an oscillation 2,000 – 2800 years[7]	
			Highstand 4,000 – 7,000 years; wetter during HCO, then becoming drier after 5,000 years[8]	1.5 – 2.0 m higher than present[9]	
			7,700 years	Approximately the same as present[10]	
			Holocene Climate Optimum (HCO); 6,000 – 9,000 years wet, warm climate period[11]	Lower than present[12]	Incision and abandonment of Qpa terraces occurred in the Qld Wet Tropics 6,000 – 19,000 years[13] and 8,000 – 13,000 years[14]; in SEQ (Lockyer, Logan, Albert, Brisbane rivers) 7,500 – 10,800 years[15]; in Bellinger River (mid-north coast NSW) 4,500 – 10,000 years[16]; possibly rapid terrace abandonment[17]
	Pleistocene 11,700 – 2.58 M years	Upper Pleistocene 11,700 – 130,000 years	Meltwater Pulse 1A, coinciding with the Bølling warming event 14,650 years[18].	Rapid sea-level rise began	Ongoing deposition of Qpa.
			Last Glacial Maximum (LGM) 21,000 years[19]. Coincided with a period of significantly reduced rainfall in NE Australia 19,000 – 23,000 years[20].	Around 125 m lower than present	Base-level lowering led to incision of old Qpa on coastal margin[21]. Deposition of existing Qpa terraces occurred in the Qld Wet Tropics, 14,000 – 27,000 years ago[22]; Nogoa and Fitzroy 11,000 – 30,000 years ago[23]; Normanby River 8,760 – 33,000 years ago[24]
			Last inter-glacial high-stand, within the Marine Isotope Stage (MIS) 5e 119,000 – 130,000 years	Approximately 4 – 6 m higher than present[25]	Deposition of old Qpa in coastal areas.
		Middle and lower Pleistocene 130,000 – 2.58 M years	Around 50 glacial cycles[26]	Alternating lower and sometimes higher than present[27]	Erosion and deposition cycles of old Qpa

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[1] See Lewis et al. (2008).
[2] See Pietsch et al. (2015).
[3] See Leonard and Nott (2016).
[4] See Brooks et al. (2007), Brooks et al. (2009), Brooks et al. (2013),
[5] Sloss et al. (2018) cited <3,500 years for southern Gulf of Carpentaria; a date of 2,000 years was cited by Lewis et al. (2008) for eastern Australia.
[6] See Sloss et al. (2018).
[7] See Lewis et al. (2008).
[8] See Sloss et al. (2018).
[9] See Sloss et al. (2018). Lewis et al. (2008) cited a highstand range of 1.0 – 1.5 m. Dougherty et al. (2019) provided evidence to support a highstand with earliest date approx. 7,000 years, synchronous over an area that extended from the Gulf of Carpentaria to Tasmania.
[10] See Sloss et al. (2018).
[11] See Cohen and Nanson (2007). Leonard and Nott (2016) cited evidence that increased rainfall persisted from the end of the LGM (18,000 years) until 6,000 – 8,000 years. The climate was drier from 6,000 years (Cohen and Nanson, 2007).
[12] See Sloss et al. (2018).
[13] See Leonard and Nott (2016).
[14] See Hughes and Croke (2017).
[15] See Daley and Cohen (2018).
[16] See Cohen and Nanson (2008).
[17] Increased precipitation-driven terrace abandonment may have been associated with extreme events and may well have occurred rapidly (Daley and Cohen, 2018).
[18] See Brendryen et al. (2020). A range of 14,300 – 14,600 years was suggested by Lewis et al. (2013).
[19] See Williams et al. (2018) and Ulm et al. (2018). A range of 17,000 – 19,000 years according to references cited by Ludt and Rocha (2014). A range of 19,000 – 21,000 years according to Lewis et al. (2013). The lowest sea level varies within the literature, but 125 m is often cited.
[20] See Leonard and Nott (2015).
[21] See Wilson et al. (2012). Trenching of Qpa in response to lowering base-level (i.e. sea level) would apply in close proximity of the coast.
[22] See Leonard and Nott (2016), Hughes and Croke (2017),
[23] See Croke et al. (2011).
[24] See Pietsch et al.(2015), dates from 12 m exposure of a terrace 27 m above the channel of the West Normanby River at Kings Plains.
[25] See Wilson et al. (2012) and Gornitz (2007). Also, reported for tectonically-stable areas of the Southern Hemisphere, sea levels higher than present by 6.0 – 8.5 m (South Africa) (Carr et al., 2010), 7 m (southern Brazil) (Tomazelli and Dillenburg, 2007), 4 – 10 m (Western Australia) (Hearty et al. 2007, O'Leary et al., 2008), 2 – 6 m (southern Australia) (Murray-Wallace, 2002), 2 - 4 m (Eyre Peninsula) (Murray-Wallace and Belperio, 1991; Murray-Wallace et al., 2016), 1 m (Spencer Gulf) (Hails et al., 1984). See Hearty et al. (2007) for data from other areas. A probabilistic assessment by Kopp et al. (2018) found a 95% probability that global sea level peaked at least 6.6 m higher than present and 67% probability to have exceeded 8.0 m higher than present.
[26] See Woodruff (2010).
[27] See Spratt and Lisiecki (2016).

3.1.5 Land Systems

Across the Styx River catchment, although some Land Systems and surface geology lithological unit boundaries coincided, in general, Land Systems were only broadly related to geology (Figure 9 and Figure 12). Within the CQC Project area (Figure 13), Styx Land System coincided with Qa, but only when Qa was situated within Sommerby Land System. Styx Land System soils were described as brown, massive, fine sandy loams formed on narrow floodplains (Table 3). Sommerby and Blackwater are described as comprising Brigalow plains and cracking clay soils on weathered Tertiary clay (Table 3), yet these are located on Pleistocene Qpa geological units. Plainview and Tooloomba Land Systems occur over other areas of Qpa and Qa (Figure 13). These two Land Systems are similar, with both containing alkaline sodic duplex soils (Table 3).

3.1.6 Soil mapping by CDM Smith (2018b)

CDM Smith (2018b) undertook a preliminary desktop soils and landform assessment using: ASRIS 2011, which provides a general description of soils classified in accordance to the Australian Soil Classification (Isbell, 2002); the ‘Atlas of Australian Soils’ by CSIRO; Queensland Globe’s ASS distribution map which provides an indication of the likelihood of Acid Sulphate Soils (ASS) or potential ASS (PASS) being present, and; a review of site-specific soil sample records in the locality. CDM Smith (2018b) also undertook a field soil survey that included 11 soil auger sites (where detailed soil profile descriptions were made and samples were taken), 16 observation locations, and laboratory analysis.

Queensland soil maps indicate sodosols, vertosols and kandosols are the predominant soil orders within the CQC Project area. Vertosols correspond to the flatter landscape to the north, Sodosols are the most widespread soil order and correspond to the more elevated plains, while Kandosols correspond to the undulating land to the south west. CDM smith (2018b) found reasonable alignment between the soil orders mapped by desktop analyses and the soil classifications made by field investigations.

CDM Smith (2018b) reported that the CSIRO National ASS mapping described most of EPC 1029, which includes the CQC Project area, as having a low to extremely low probability of containing ASS.

3.1.7 Soil Map Units

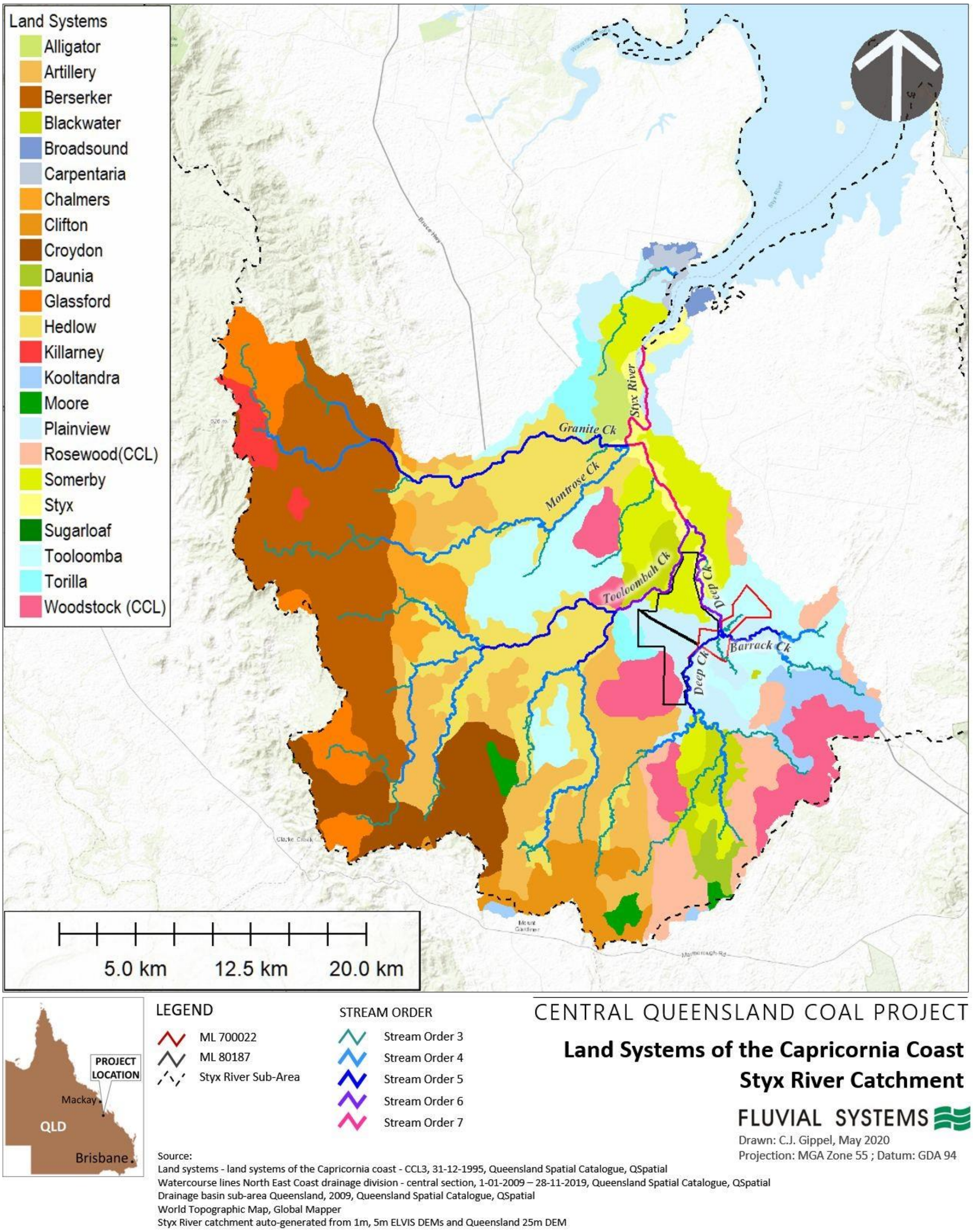
Soil Units were mapped by HESSE (2020) for the CQC Project area (Figure 14). The areas within the lease area plus a 300 m buffer were ground-truthed. Areas outside of this have lower confidence in the soil unit identification. The map of HESSE (2020) is similar to the map of CDM Smith (2018b, p. 5-35) based on ASRIS, 2011. The main differences relate to the distribution of Kandosols, which HESSE (2020) mapped in an area to the south east of the CQC Project area, in addition to the area to the south west, and HESSE (2020) including Alluvial soils.

Some of the boundaries of the Soil Units corresponded with mapped geological and Land Systems boundaries, but the coincidence was inconsistent. Shallow, gravelly alluvium occurred within the narrow geomorphically-active river beds. Non-gravelly alluvium occurred on Tooloomba Creek and Styx River terraces. Much of the CQC Project area within the mining lease boundaries is on Sodosols, described as sodic soils with contrasting topsoil and subsoil texture (Table 7).

3.1.8 Surface soil and overall inherent soil erodibility

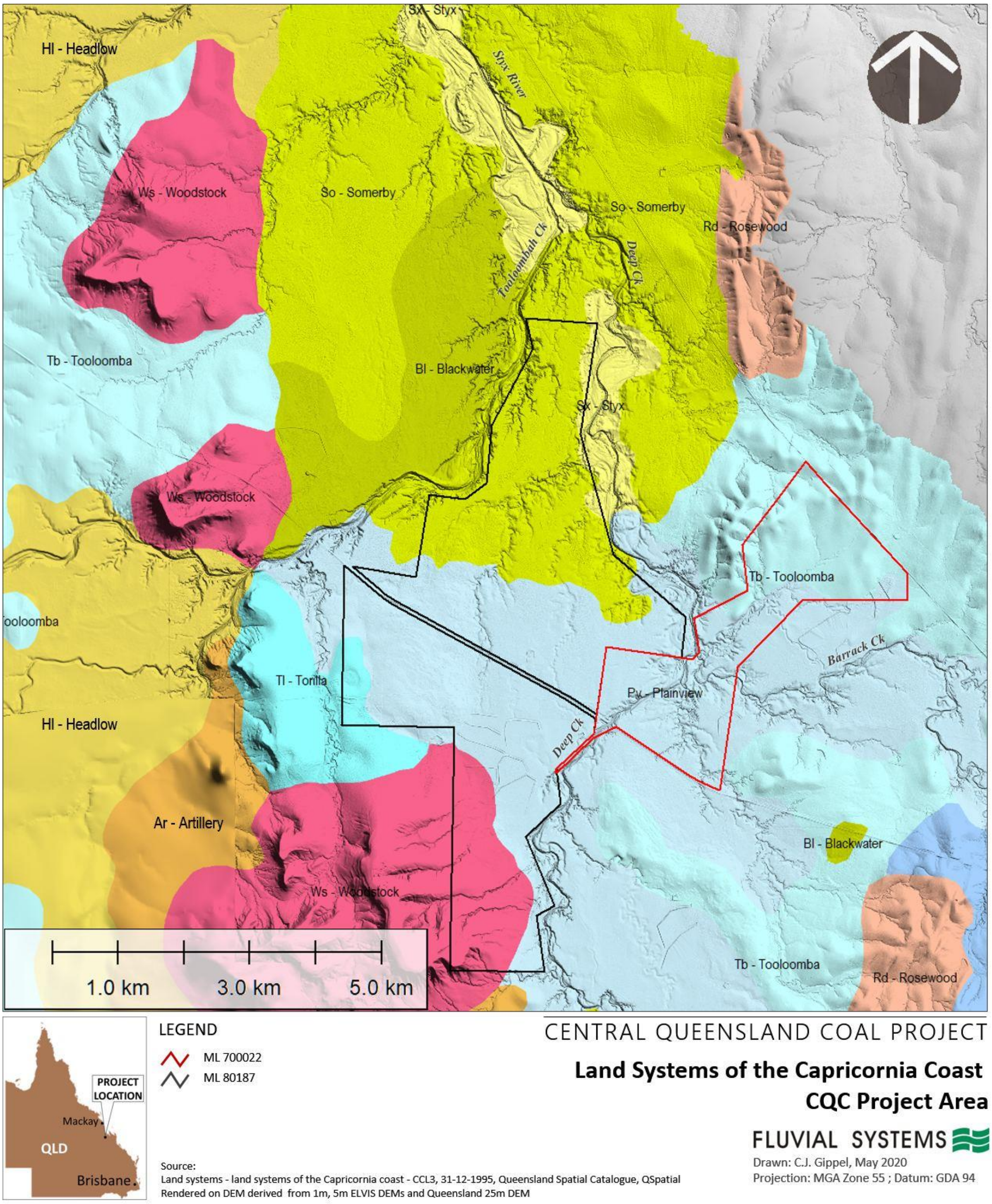
Soil erodibility is relevant to management of runoff from disturbed areas, and management of the surface condition of soils on disturbed areas. Over the Styx River catchment, soil surfaces tended to become more erodible towards the lowland area (Figure 15). Sodic, dispersible surface soils with high erodibility occurred over the majority of the CQC Project area (Figure 16). Barrack Creek in particular was located in an area of highly erodible surface soils.

The pattern of overall inherent soil erodibility was similar to that of surface soil erodibility. Overall inherent soil erodibility was stable in the headwater areas of the Styx River catchment, while in the lowland areas the soils were clayey and dispersive (Figure 17). As for surface soil erodibility, the overall inherent erodibility of soils over the CQC Project area was mapped high and very high vulnerability to erosion (Figure 18).



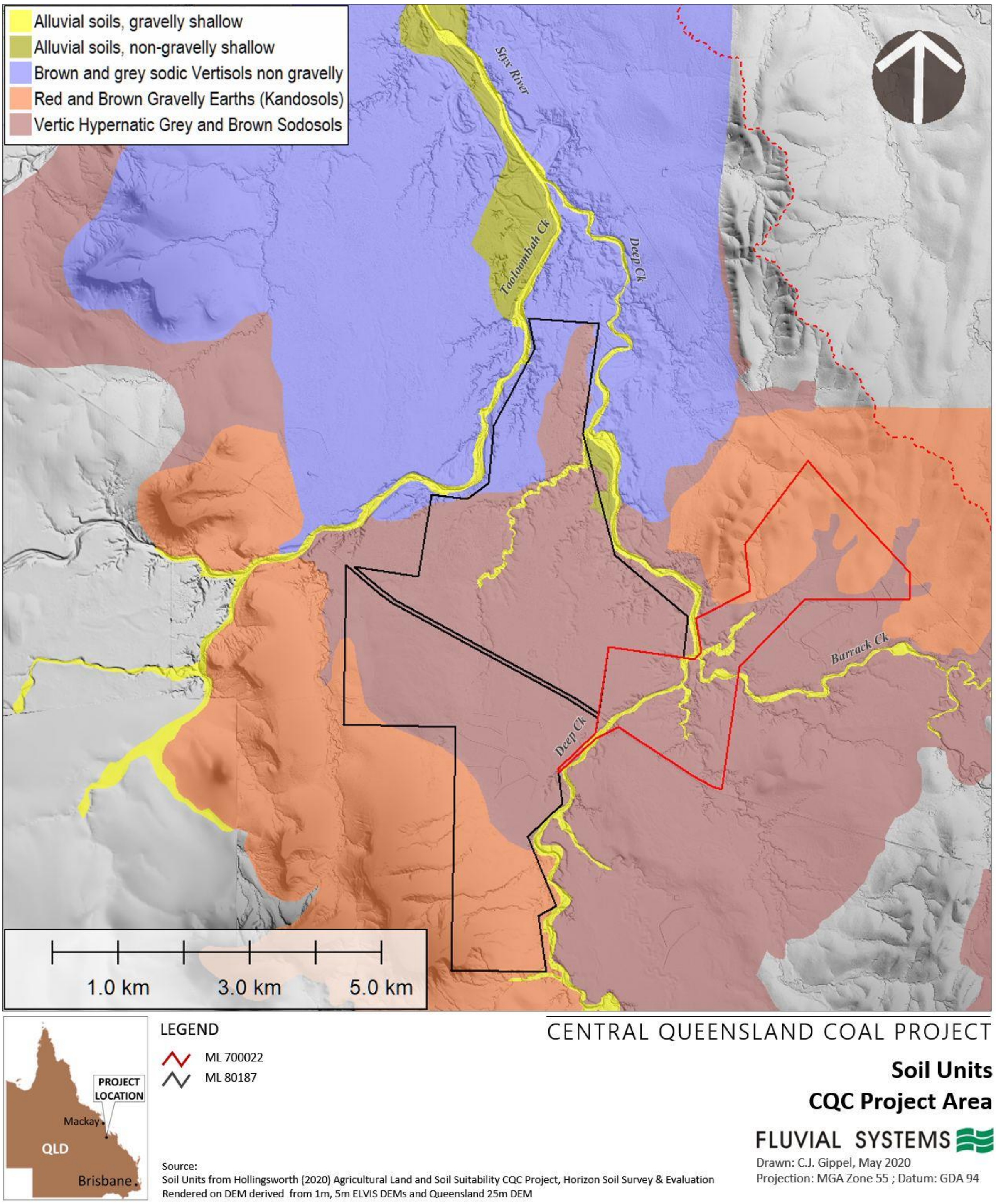
Source:
Land systems - land systems of the Capricornia coast - CCL3, 31-12-1995, Queensland Spatial Catalogue, QSpatial
Watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019, Queensland Spatial Catalogue, QSpatial
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
World Topographic Map, Global Mapper
Styx River catchment auto-generated from 1m, 5m ELVIS DEMs and Queensland 25m DEM

Figure 12. Land Systems of the Styx River catchment.



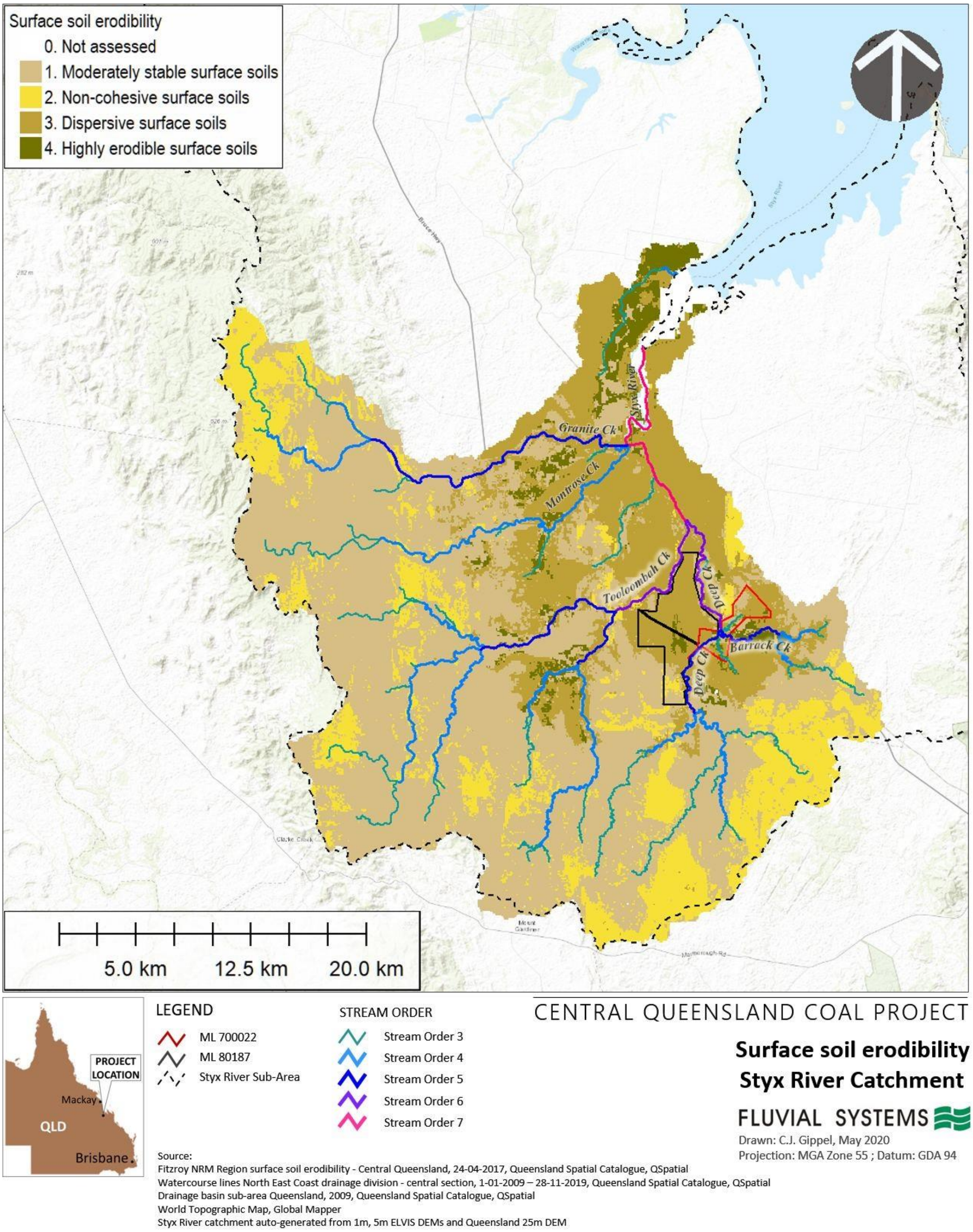
Source:
Land systems - land systems of the Capricornia coast - CCL3, 31-12-1995, Queensland Spatial Catalogue, QSpatial
Rendered on DEM derived from 1m, 5m ELVIS DEMs and Queensland 25m DEM

Figure 13. Land Systems of the CQC Project area.



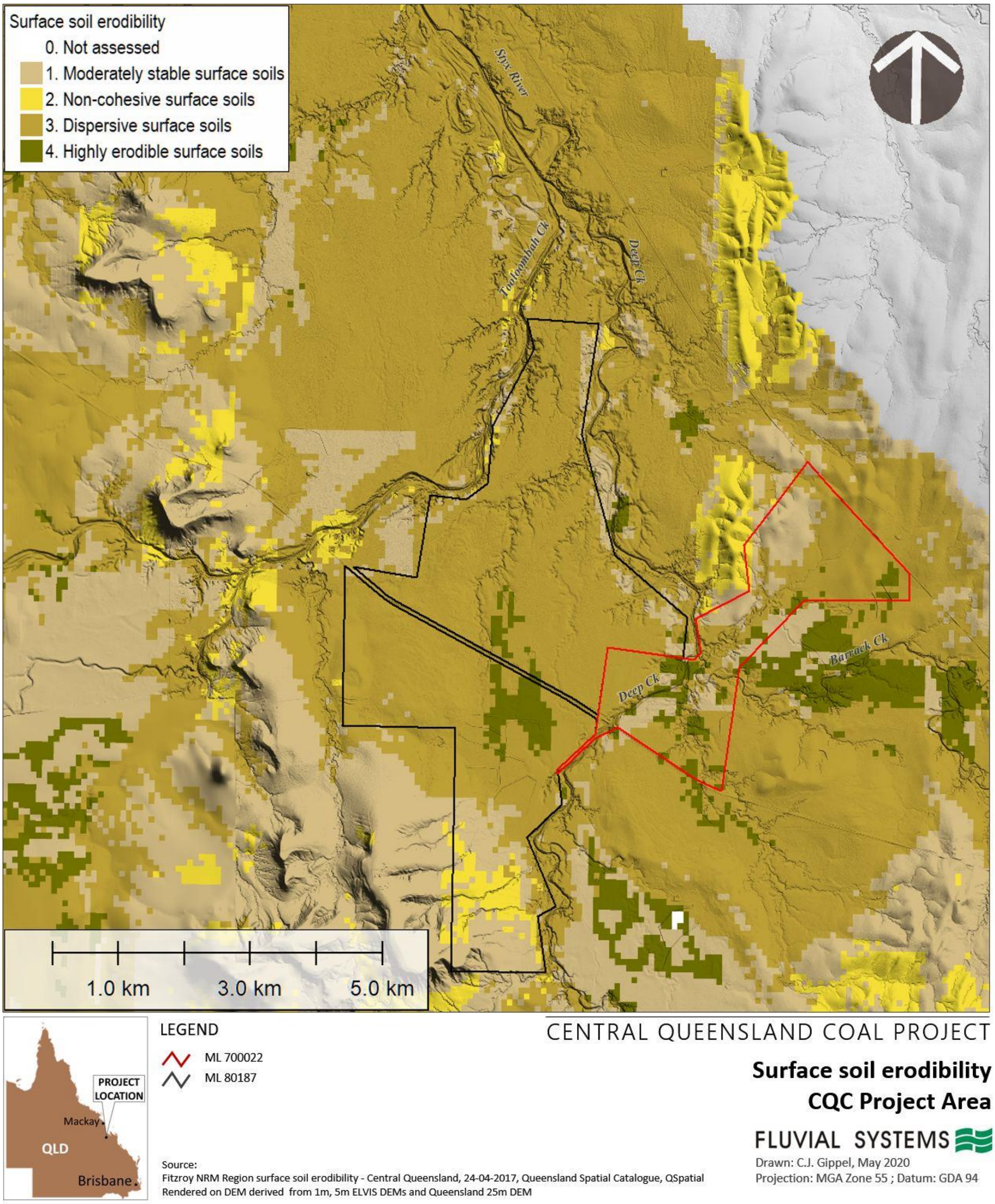
Source:
Soil Units from Hollingsworth (2020) Agricultural Land and Soil Suitability CQC Project, Horizon Soil Survey & Evaluation
Rendered on DEM derived from 1m, 5m ELVIS DEMs and Queensland 25m DEM

Figure 14. Soil Units mapped by HESSE (2020) over the CQC Project area. Note: The area inside the lease area plus a 300 m wide buffer was ground-truthed. Outside of this area the soil unit identification has lower confidence.



Source:
Fitzroy NRM Region surface soil erodibility - Central Queensland, 24-04-2017, Queensland Spatial Catalogue, QSpatial
Watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019, Queensland Spatial Catalogue, QSpatial
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
World Topographic Map, Global Mapper
Styx River catchment auto-generated from 1m, 5m ELVIS DEMs and Queensland 25m DEM

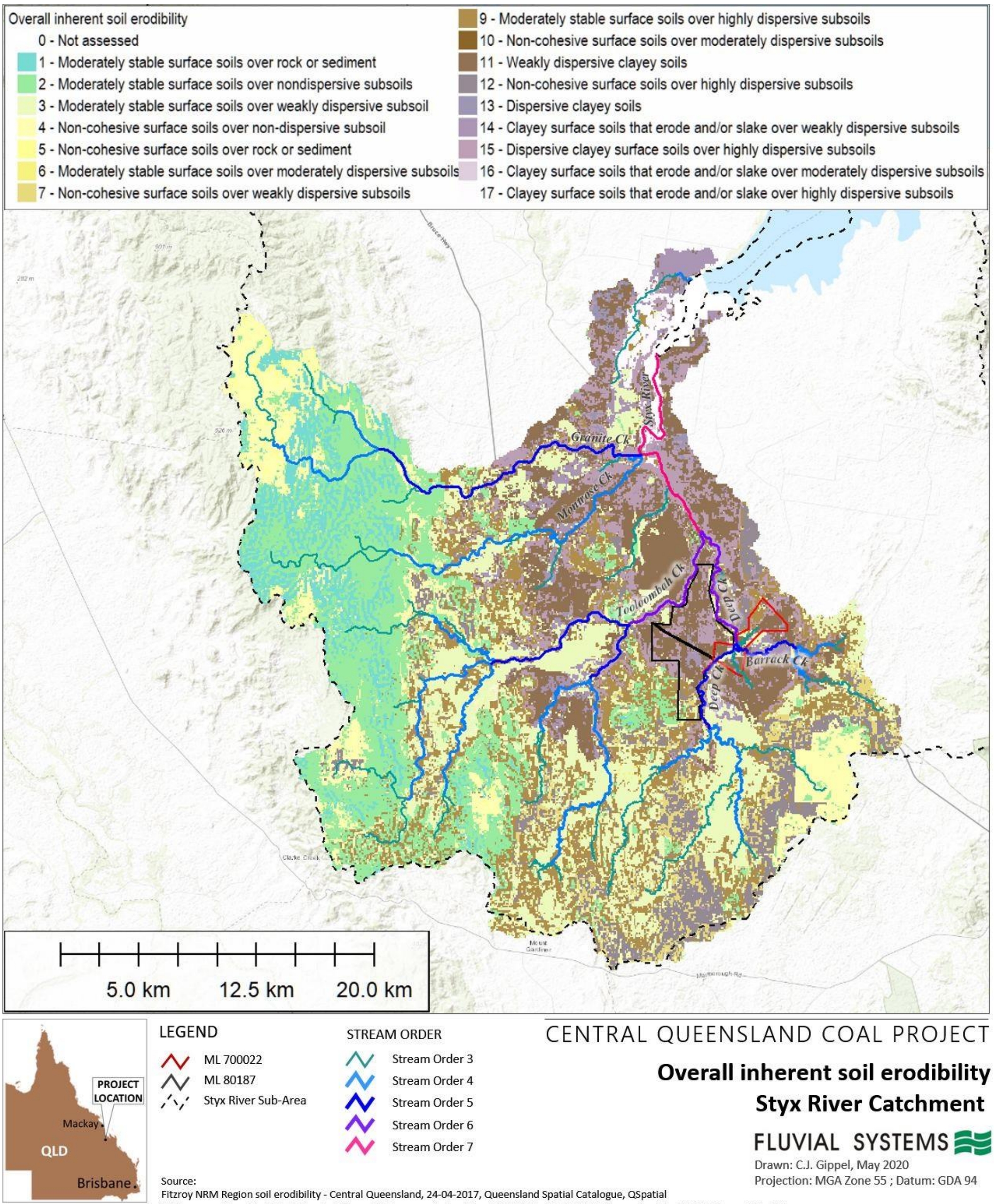
Figure 15. Surface Soil Erodibility in Styx River catchment.



Source:
Fitzroy NRM Region surface soil erodibility - Central Queensland, 24-04-2017, Queensland Spatial Catalogue, QSpatial
Rendered on DEM derived from 1m, 5m ELVIS DEMs and Queensland 25m DEM

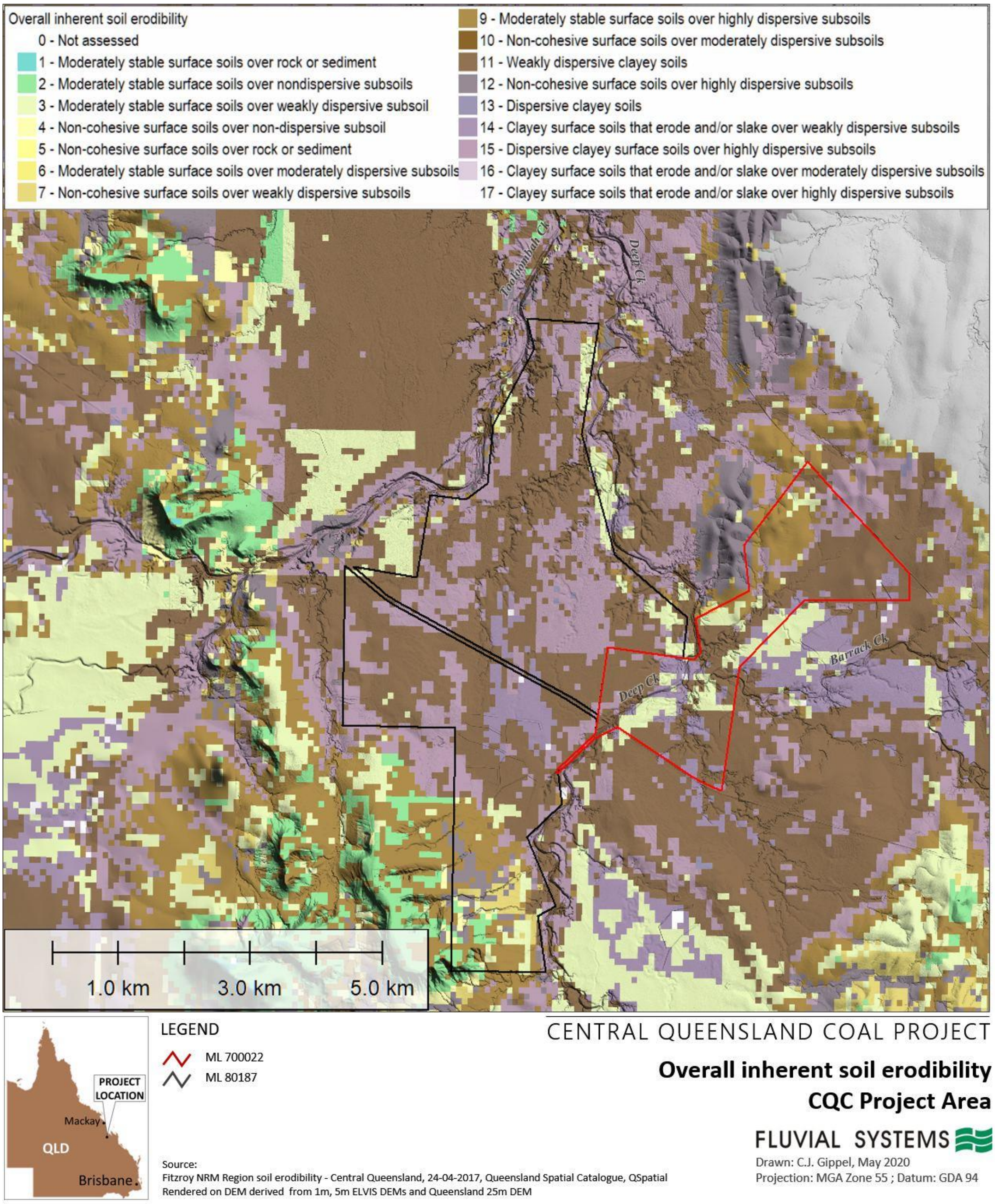
Drawn: C.J. Gippel, May 2020
Projection: MGA Zone 55 ; Datum: GDA 94

Figure 16. Surface Soil Erodibility in CQC Project area.



Source:
Fitzroy NRM Region soil erodibility - Central Queensland, 24-04-2017, Queensland Spatial Catalogue, QSpatial
Watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019, Queensland Spatial Catalogue, QSpatial
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
World Topographic Map, Global Mapper
Styx River catchment auto-generated from 1m, 5m ELVIS DEMs and Queensland 25m DEM

Figure 17. Overall Inherent Soil Erodibility in Styx River catchment.



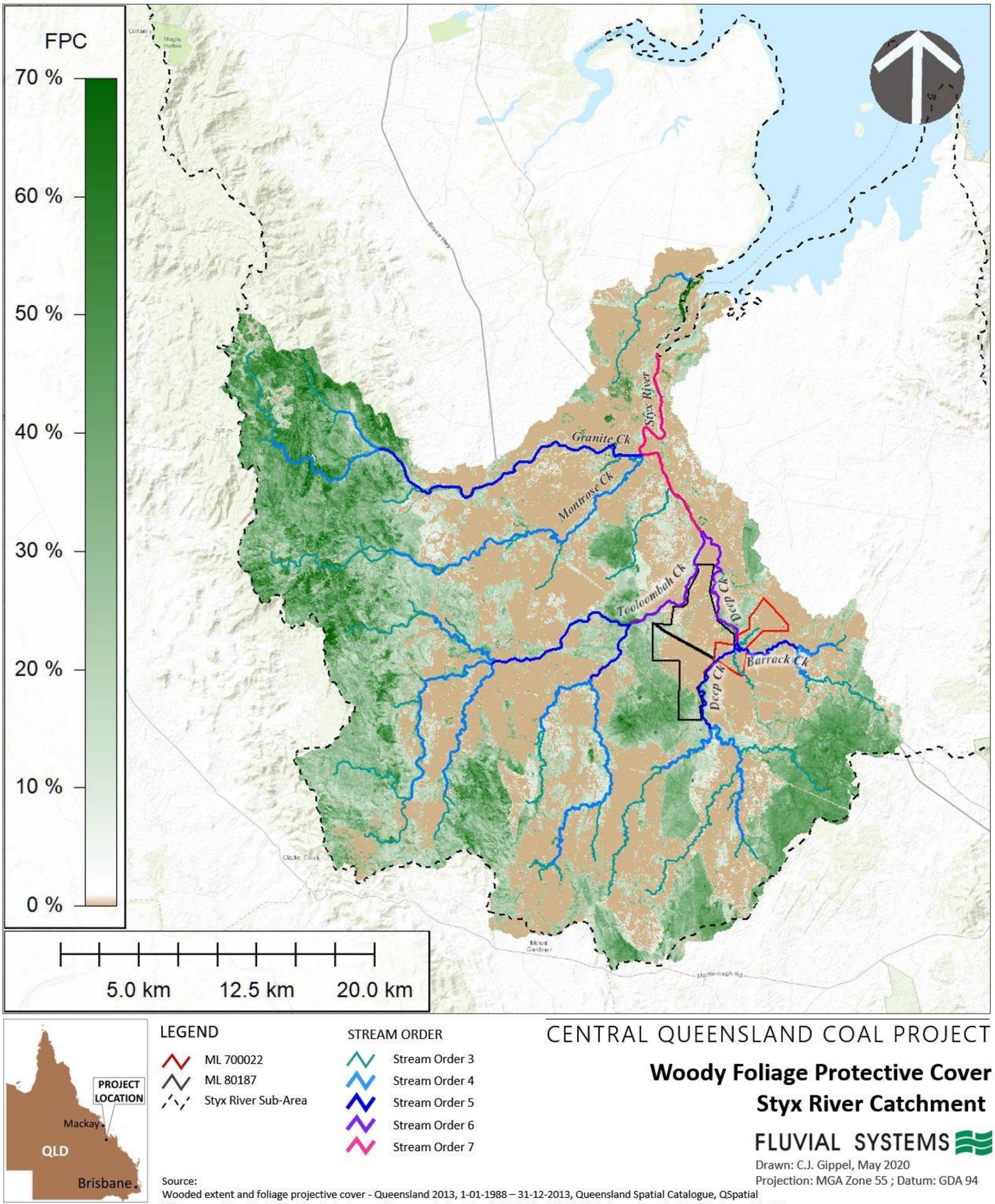
Source:
Fitzroy NRM Region soil erodibility - Central Queensland, 24-04-2017, Queensland Spatial Catalogue, QSpatial
Rendered on DEM derived from 1m, 5m ELVIS DEMs and Queensland 25m DEM

Drawn: C.J. Gippel, May 2020
Projection: MGA Zone 55 ; Datum: GDA 94

Figure 18. Overall Inherent Soil Erodibility in CQC Project area.

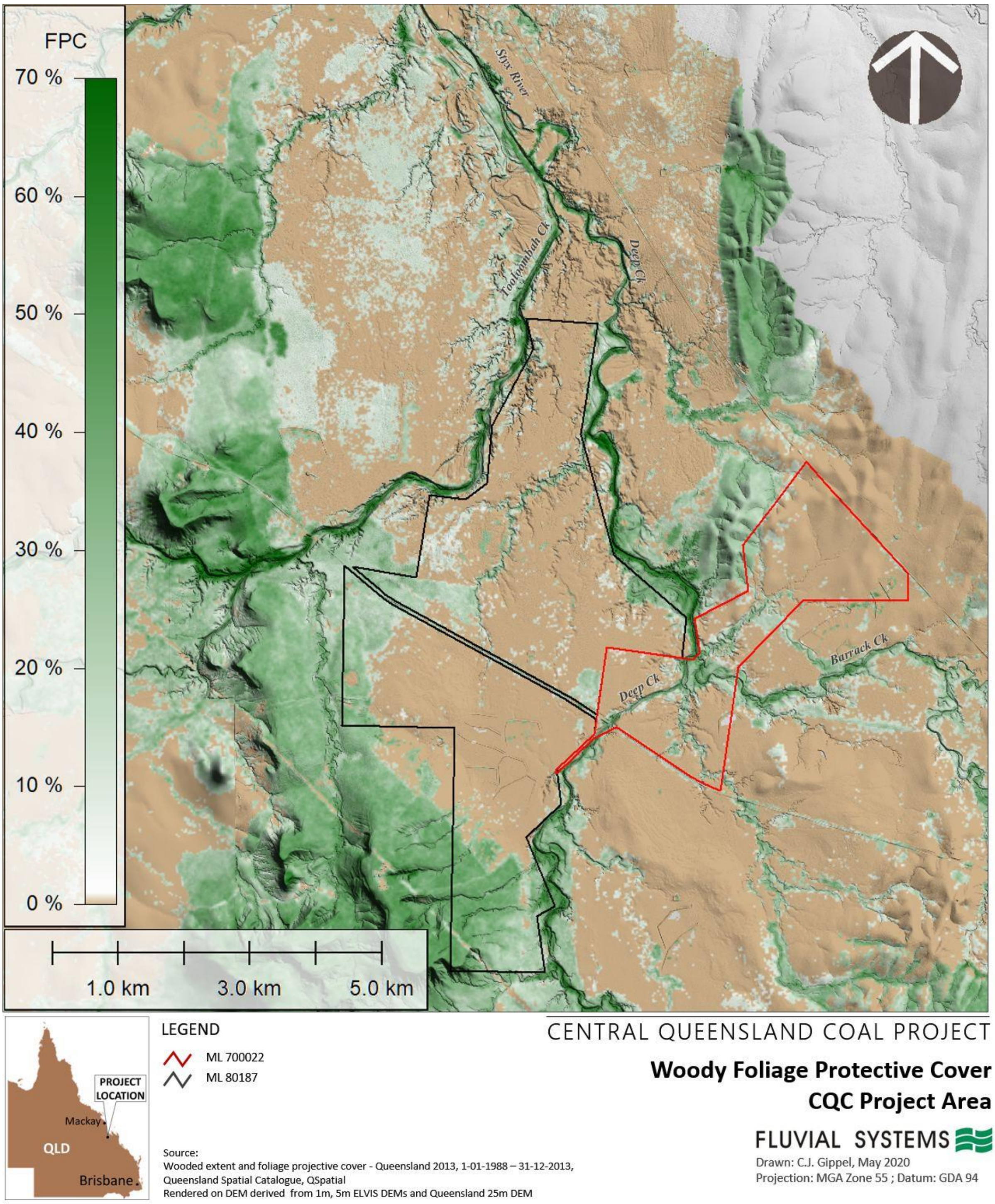
3.1.9 Woody foliage protective cover

The distribution of woody vegetation over the Styx River catchment was strongly correlated with topography, with higher elevation headwater areas being forested, and lowland areas either lightly wooded or devoid of woody vegetation (Figure 19). Most of the CQC Project area had very low cover, or no cover, of woody vegetation (Figure 20). Moderate levels of woody vegetation cover were present within the incised channels of the major watercourses, but the vegetation did not extend to the surrounding Pleistocene terraces (Figure 20).



Source:
Wooded extent and foliage projective cover - Queensland 2013, 1-01-1988 – 31-12-2013, Queensland Spatial Catalogue, QSpatial
Watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019, Queensland Spatial Catalogue, QSpatial
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
World Topographic Map, Global Mapper
Styx River catchment auto-generated from 1m, 5m ELVIS DEMs and Queensland 25m DEM

Figure 19. Woody foliage protective cover for the Styx River catchment.



Source:
Wooded extent and foliage projective cover - Queensland 2013, 1-01-1988 – 31-12-2013,
Queensland Spatial Catalogue, QSpatial
Rendered on DEM derived from 1m, 5m ELVIS DEMs and Queensland 25m DEM

Drawn: C.J. Gippel, May 2020
Projection: MGA Zone 55 ; Datum: GDA 94

Figure 20. Woody foliage protective cover for the CQC Project area.

3.1.10 1953 land cover

The CQC Project area was almost entirely forested in 1953 (Figure 21). Clearing had taken place in limited areas near Ogmore and along Kooltandra Road. Otherwise the lowland part of the Styx River valley was densely forested. A marked vegetation boundary existed in 1953 on land now within the CQC Project area. This vegetation boundary was used as the boundary between Somerby and Plainview Land Systems. The vegetation associated with Somerby is Eucalypt woodland (Table 3). In 1953, the riparian zones of watercourses within the Styx River catchment were densely vegetated.

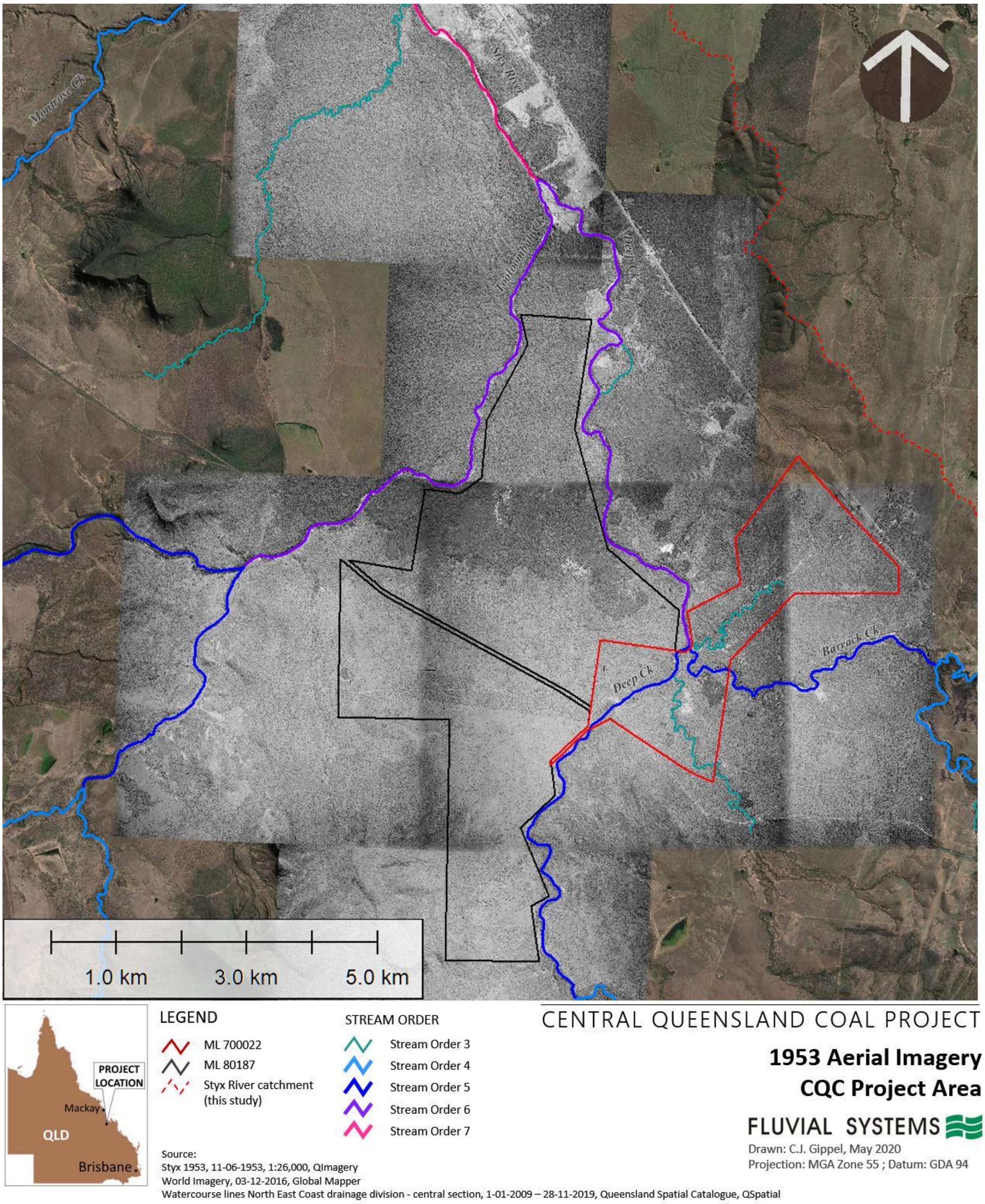
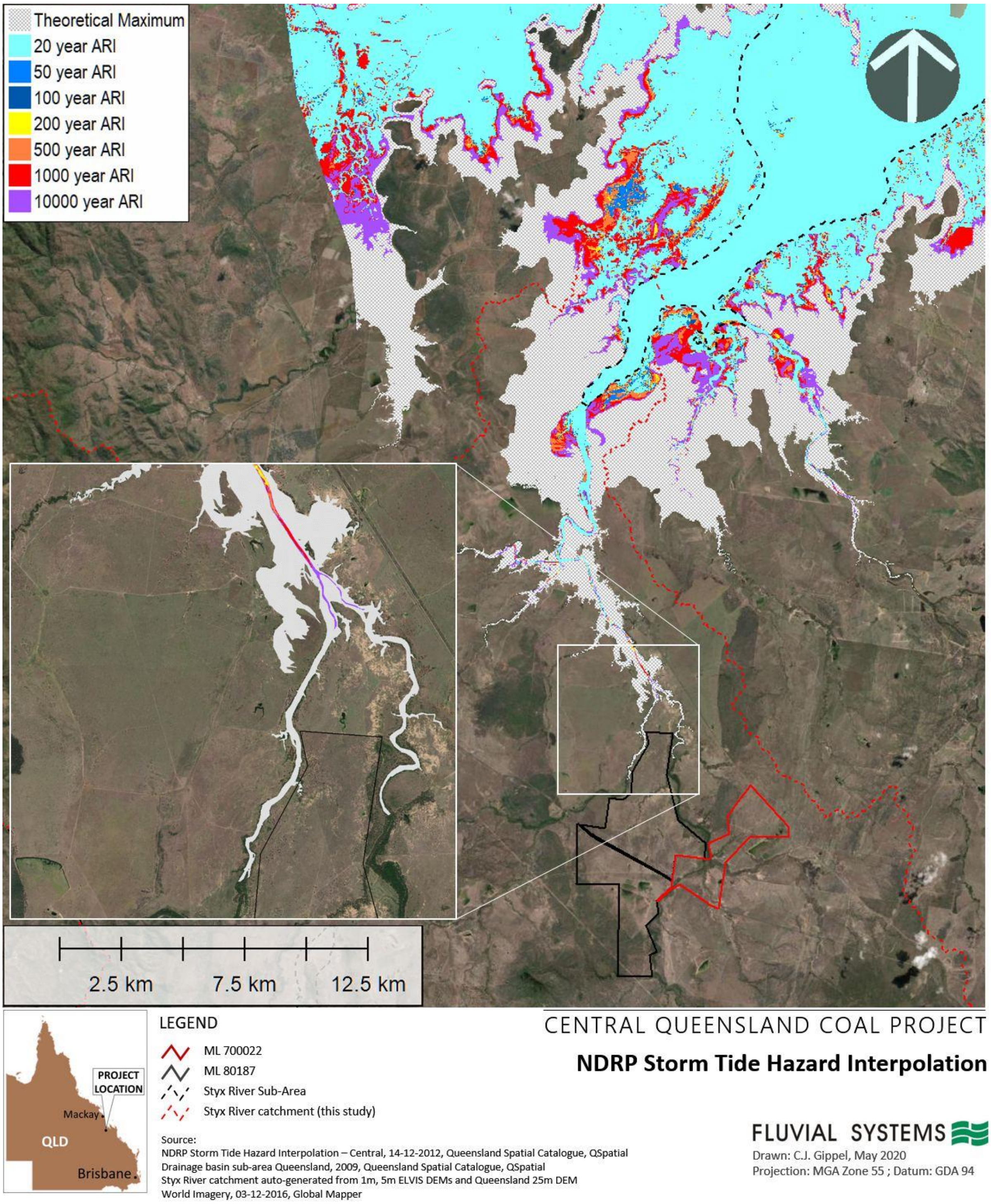


Figure 21. Land cover depicted on rectified and stitched 1953 aerial imagery over the CQC Project area.

3.1.11 NDRP Storm Tide Hazard Interpolation, highest astronomical tide and Styx River downstream limit

The theoretical maximum tide event extended 4.5 km upstream of the junction of Tooloombah and Deep Creeks. The 1000 year ARI event almost reached the junction Tooloombah and Deep Creeks (Figure 22).

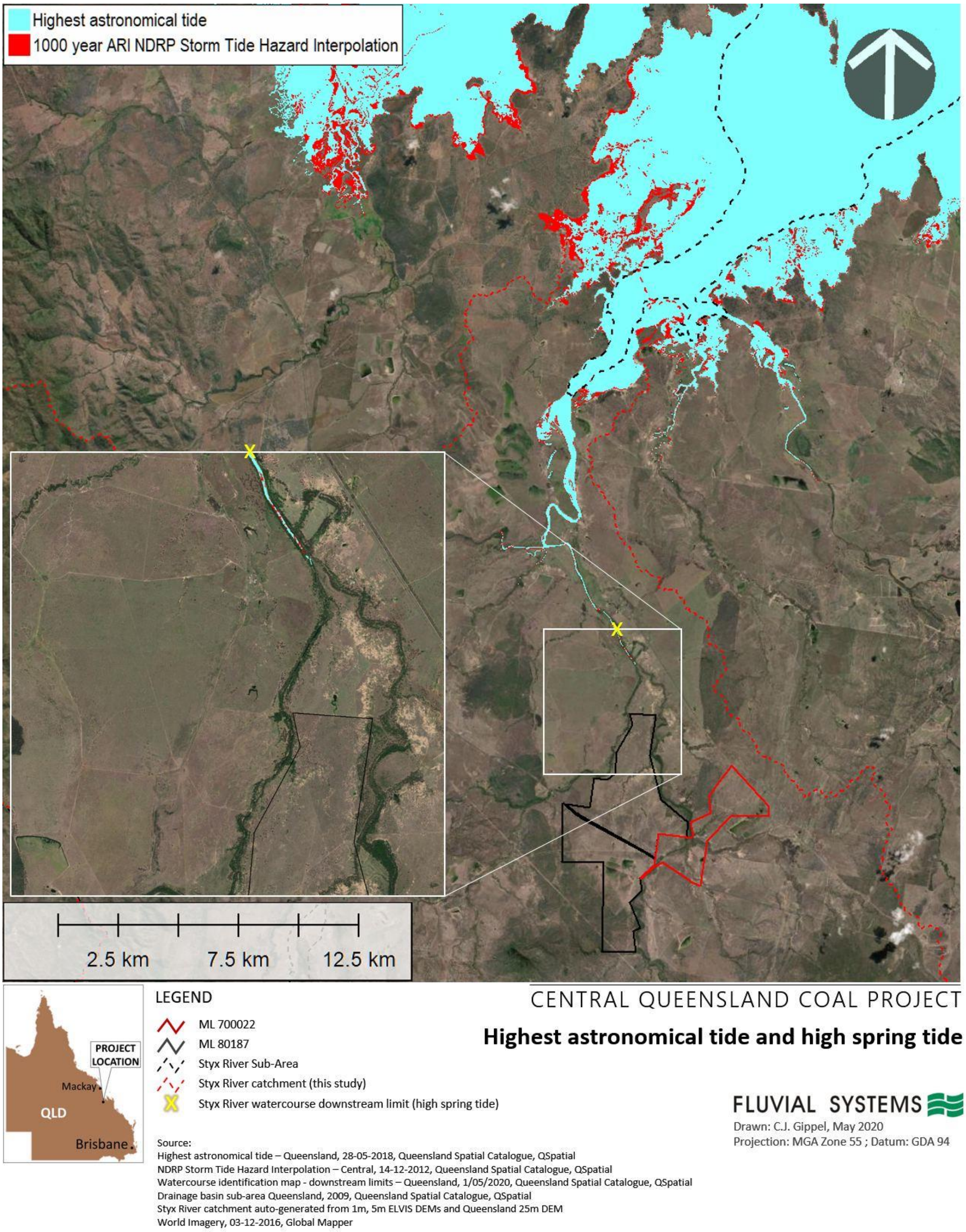
The highest astronomical tide extended to the junction of Tooloombah and Deep Creeks (Figure 23).The Styx River downstream limit, corresponding to the point to which the high spring tide ordinarily flows and reflows, was marked 1.72 km downstream of the highest astronomical tide (Figure 23). The position of the normal high spring tide limit was drawn 106 m further upstream than the maximum upstream extent of the NDRP Storm Tide Hazard Interpolation 20, 50 and 100 year ARI events. The LiDAR data did not suggest the existence of a physical barrier in the river at that location. The apparent discrepancy could reflect the accuracy of the NDRP Storm Tide Hazard Interpolation mapping or inconsistent observations of the position of the normal spring tide limit depending on the presence of the tidal bore and sedimentation and scouring of bars near the tidal limit.



Source:
NDRP Storm Tide Hazard Interpolation – Central, 14-12-2012, Queensland Spatial Catalogue, QSpatial
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
Styx River catchment auto-generated from 1m, 5m ELVIS DEMs and Queensland 25m DEM
World Imagery, 03-12-2016, Global Mapper

Drawn: C.J. Gippel, May 2020
Projection: MGA Zone 55 ; Datum: GDA 94

Figure 22. NDRP Storm Tide Hazard Interpolation for the CQC Project area.



Source:
Highest astronomical tide – Queensland, 28-05-2018, Queensland Spatial Catalogue, QSpatial
NDRP Storm Tide Hazard Interpolation – Central, 14-12-2012, Queensland Spatial Catalogue, QSpatial
Watercourse identification map - downstream limits – Queensland, 1/05/2020, Queensland Spatial Catalogue, QSpatial
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
Styx River catchment auto-generated from 1m, 5m ELVIS DEMs and Queensland 25m DEM
World Imagery, 03-12-2016, Global Mapper

Figure 23. Highest astronomical tide and high spring tide limit for the CQC Project area.

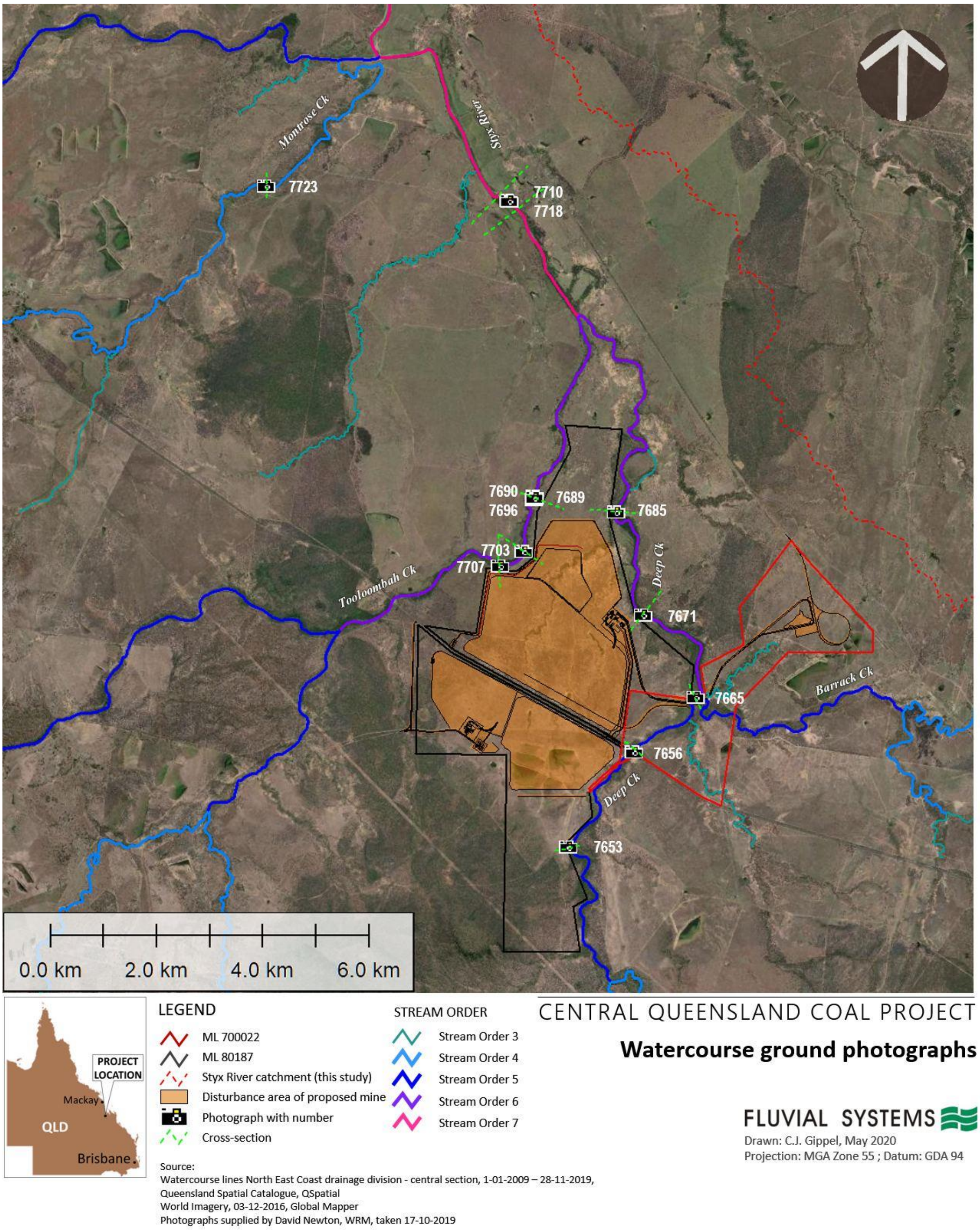
3.2 Reach- and Point-Scale Characteristics

3.2.1 Watercourse site geomorphic characteristics

The basic geomorphic character of the main watercourses in the CQC Project area (Table 23) was determined at a number of selected locations where ground photographs were taken (Figure 24). Geomorphic character was determined from aerial photography, ground photographs (Figure 25, Figure 26 and Figure 27), cross-sections drawn from LiDAR data at the locations of the ground photographs (Figure 28, Figure 29 and Figure 30), and long profiles along the main watercourses (Figure 31) drawn from the LiDAR data (Figure 32 and Figure 33).

Table 23. Geomorphic character of the main watercourses in the CQC Project area at selected locations. NA is not available.

Creek	Location (photo #)	Bed material (dominant listed first)	Mean stream link slope (m/m)	Sinuosity	Dimensions (active 10 yr ARI channel)	Morphology
Deep Creek	7653	Sand	0.0768	1.26 (low)	W: 80 m D: 7.0 m	Incised with inset bench
Deep Creek	7656	Sand / Mud	0.0656	1.07 (low)	W: 60 m D: 3.8 m	Incised with inset bench
Deep Creek	7665	Mud	0.0855	1.04 (low)	W: 70 m D: 6.5 m	Incised with inset bench
Deep Creek	7671	Mud	0.0620	1.08 (low)	W: 90 m D: 8.0 m	Incised with inset bench
Deep Creek	7685, at junction of creek in ML80187	Sand / Mud	0.0726 (upstream) 0.1013 (downstream)	1.26 (low)	W: 80 m D: 9.1 m	Incised with inset bench
Barrack Creek	Within ML700022	NA	0.0597	1.70 (meandering)	W: 20 m D: 3 m	Incised with inset bench
Tooloombah Creek	7707	Gravel / Cobble / Sand	0.0650	1.12 (low)	W: 100 m D: 9.2 m	Incised with wide inset floodplain
Tooloombah Creek	7703	Cobble / Gravel / Sand	0.0600	1.12 (low)	W: 150 m D: 8.9 m	Incised with wide inset floodplain
Tooloombah Creek	7690	Cobble / Gravel / Sand / Bedrock outcrop	0.0591	1.12 (low)	W: 100 m D: 9.9 m	Incised with narrow inset floodplain
Styx River	7718 and 7710	Fine sand	0.0354	1.06 (low)	W: 480 – 570 m D: 9.0 – 10.0 m	Incised with wide inset floodplain



Source:
Watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019, Queensland Spatial Catalogue, QSpatial
World Imagery, 03-12-2016, Global Mapper
Photographs supplied by David Newton, WRM, taken 17-10-2019

Figure 24. Locations of watercourse ground photographs, and associated cross-sections.

Figure 25. Deep Creek ground photographs.

Figure 26. Tooloombah Creek ground photographs.

Figure 27. Styx River and Montrose Creek ground photographs.

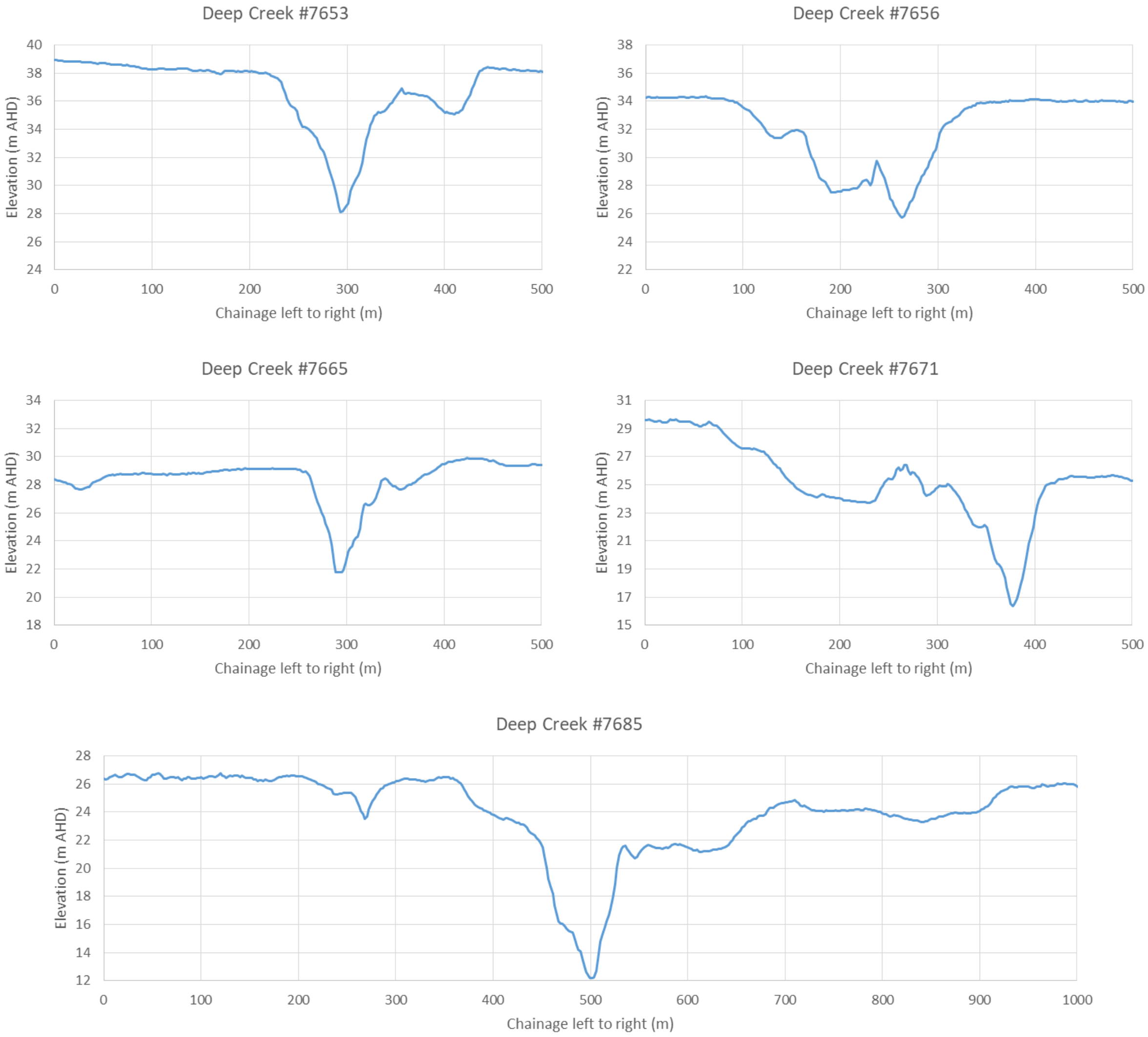


Figure 28. Deep Creek cross-sections.

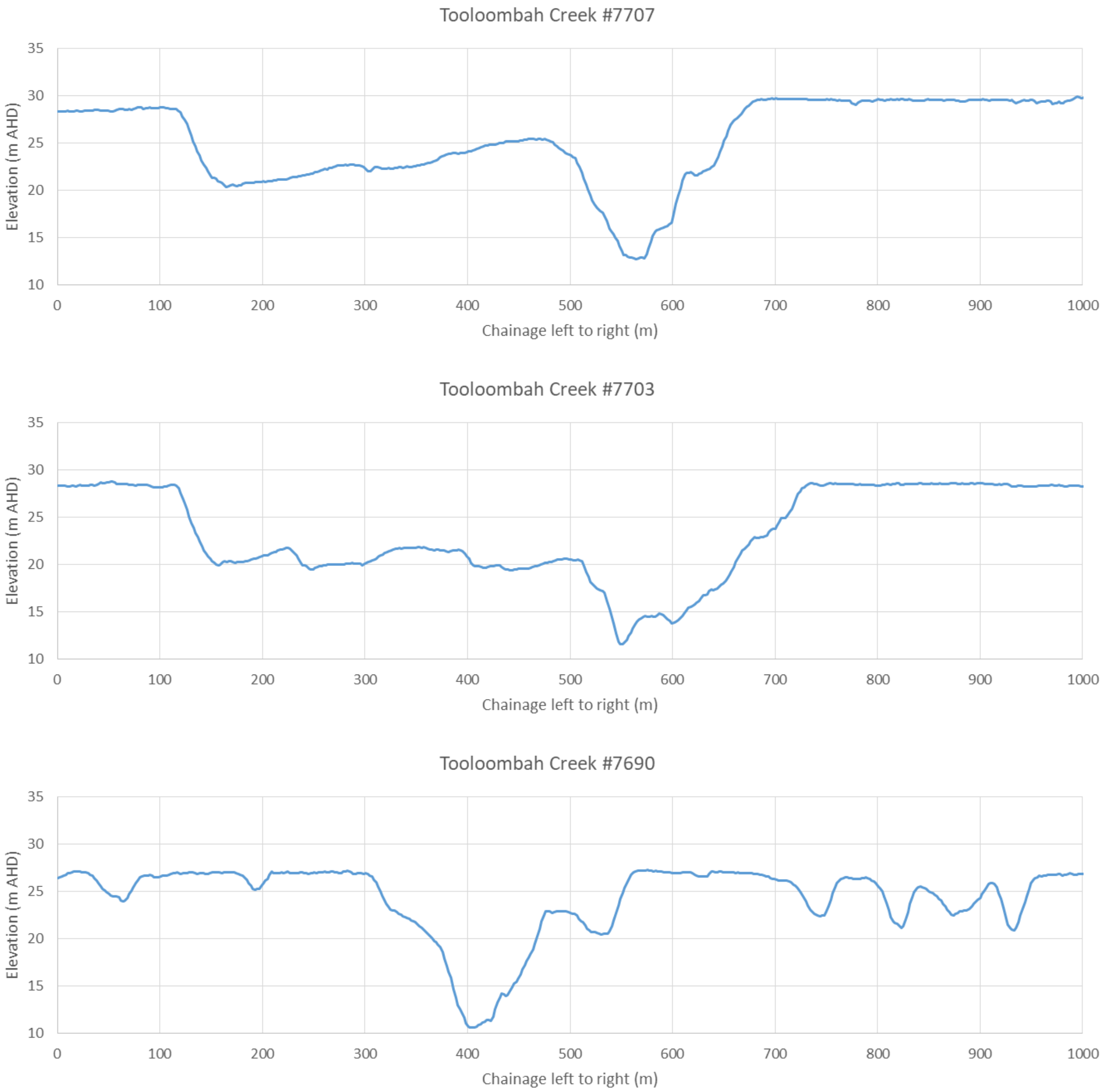


Figure 29. Tooloombah Creek cross-sections.

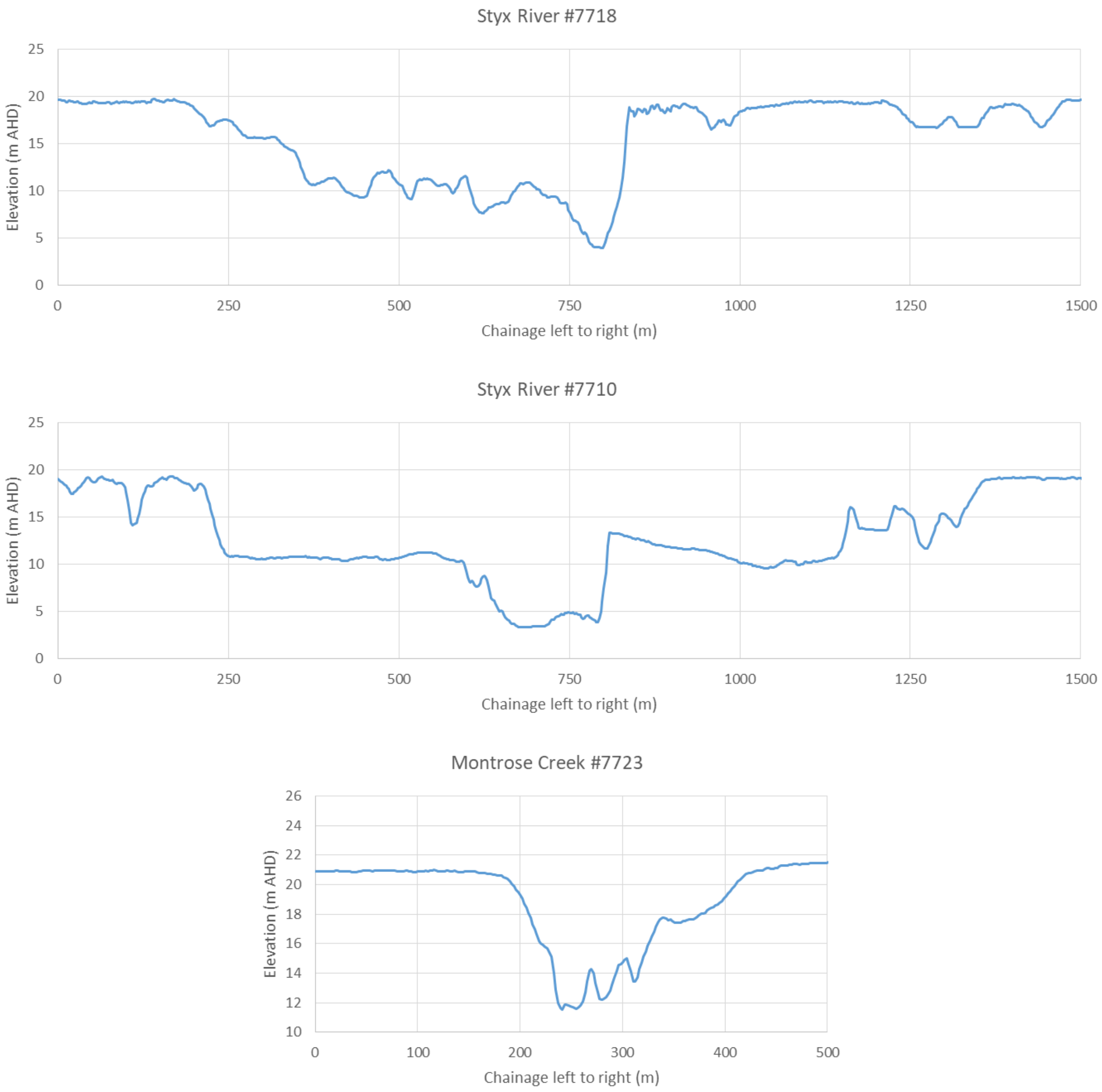
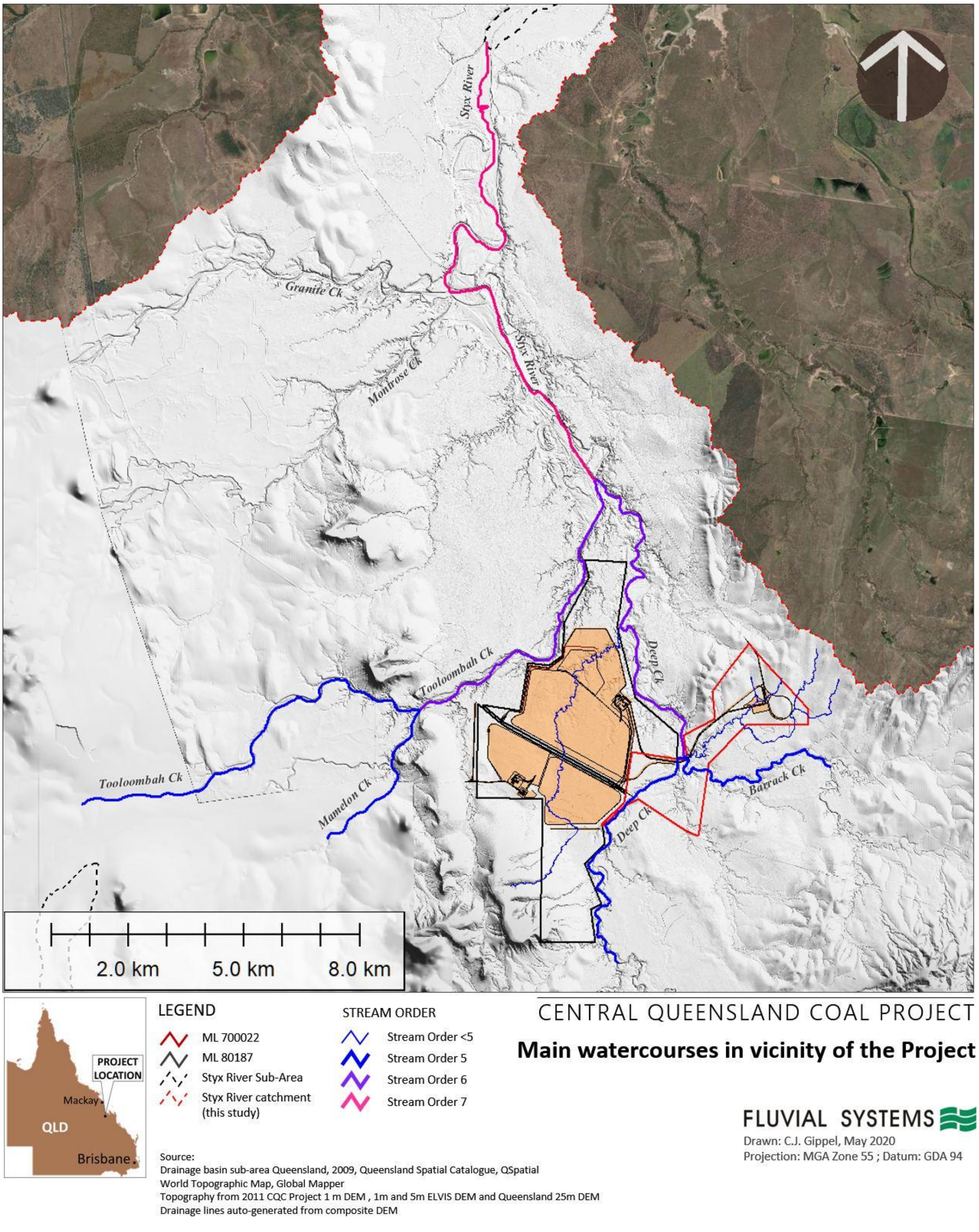


Figure 30. Styx River and Montrose Creek cross-sections.



Source:
Drainage basin sub-area Queensland, 2009, Queensland Spatial Catalogue, QSpatial
World Topographic Map, Global Mapper
Topography from 2011 CQC Project 1 m DEM , 1m and 5m ELVIS DEM and Queensland 25m DEM
Drainage lines auto-generated from composite DEM

Figure 31. Main watercourses in the vicinity of the CQC Project area.

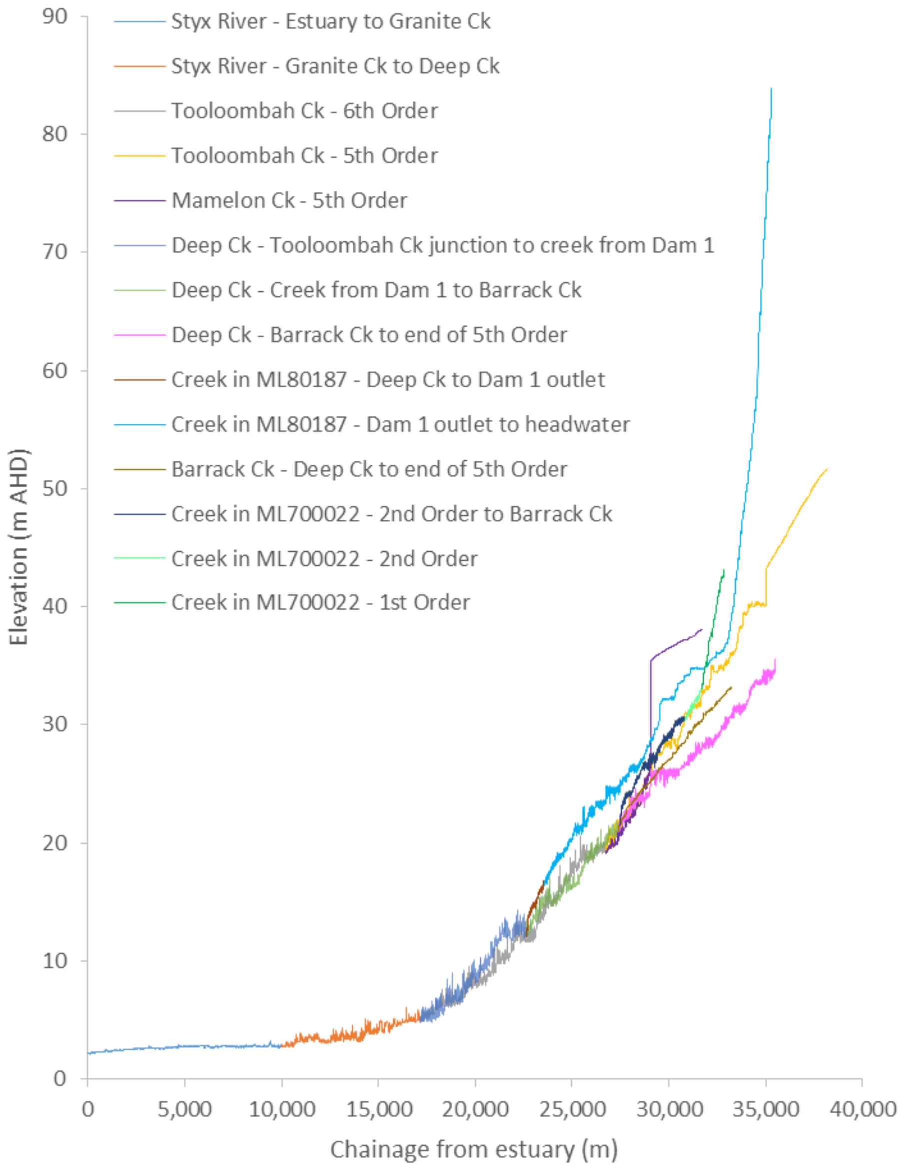


Figure 32. Long profiles of all main watercourses in the vicinity of the CQC Project area. Note: Discontinuity in Mamelon Creek and Toolombah Creek 5th Order corresponds with boundaries of LiDAR.

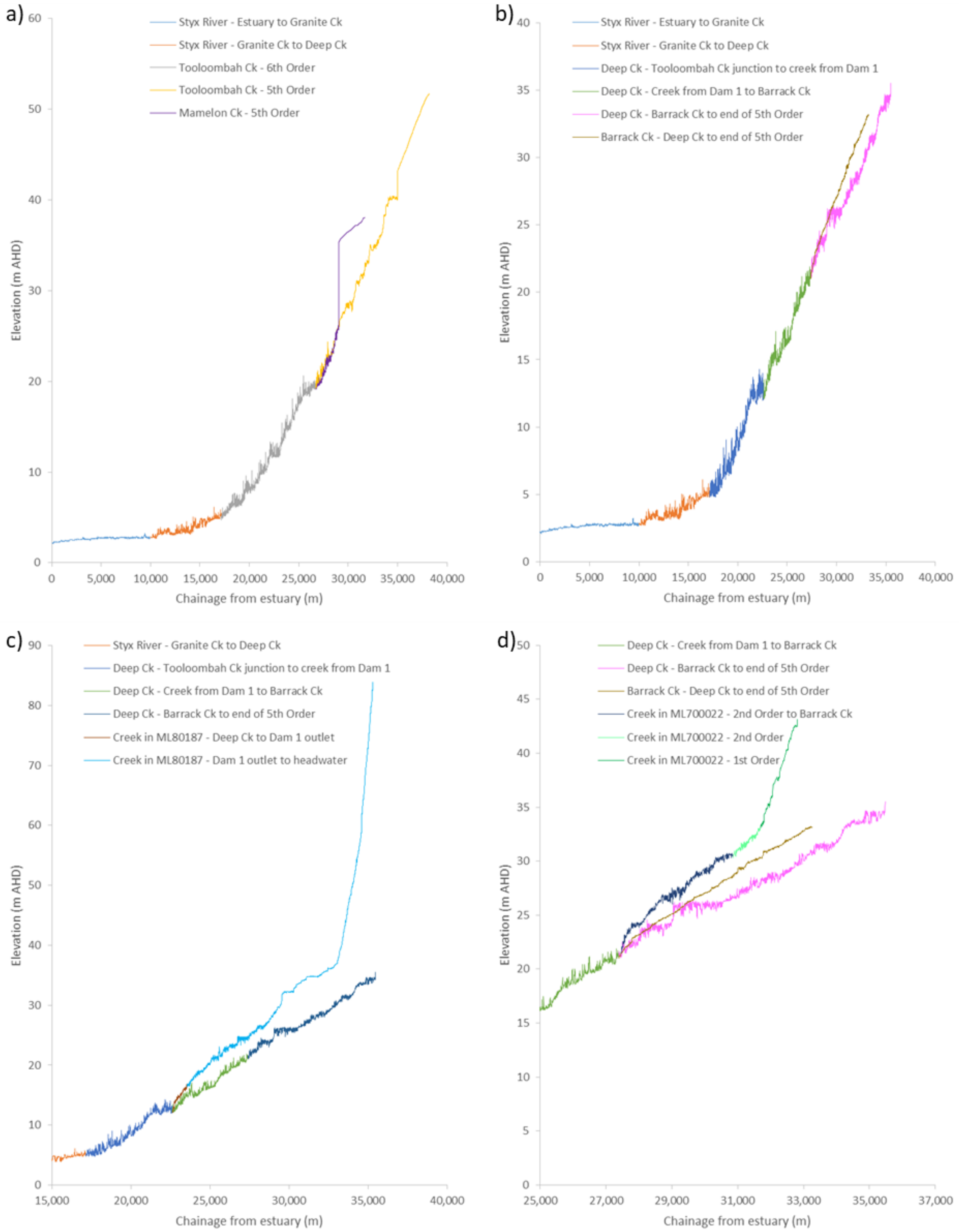


Figure 33. Long profiles of: a) Styx River/Tooloombah Creek watercourses, b) Styx River/Deep Creek/Barrack Creek watercourses, c) Deep Creek/creek in ML 80187 watercourses and d) Barrack Creek/creek in ML 700022 watercourses. Note: 1. Discontinuity in Mamelon Creek and Toolombah Creek 5th Order corresponds with boundaries of LiDAR; 2. Variable vertical exaggeration.

The active channels of the main watercourses in the CQC Project area were deeply incised into a broad plain of older alluvium. The active channel comprised depositional benches and inset floodplains formed through the Holocene from a mix of material sourced from the catchments in recent times plus reworked older Pleistocene material. The main channels were thus considered partly confined by the older alluvium unit. The threshold sinuosity to separate low sinuosity and meandering in River Styles® classification is 1.3 (Brierley and Fryirs, 2002). By this definition, sinuosity was low, except for Barrack Creek, which most likely had fine-grained bed material. The bed material determined from ground photographs ranged from fine-grained mud (silt and clay) to coarse cobble size. The thresholds of landform slope classes used by Speight (2009) were level <0.01, very gentle 0.01 – 0.03, gently inclined 0.03 – 0.10, moderately inclined 0.10 – 0.32, steep 0.32 – 0.56, very steep 0.56 – 1.00, precipitous >1. In contrast, River Styles® assessments typically classify stream bed slopes >~0.01 m/m as 'steep', slopes ~0.003 – ~0.01 low to moderate slope and <~0.003 low slope. By the classification of Speight (2009), all of the main streams in the CQC Project area were in the gently inclined landform class, but by River Styles® convention they would all be considered steep. The difference is related to Speight's (2009) classification covering all landforms, while River Styles® is river-specific and did not follow the existing convention. Also, River Styles® surveys are typically limited to Third Order streams and larger, ignoring the steep headwater streams. Thus, relative to large lowland rivers, the streams in the Styx valley could be considered steep, but relative to the full spectrum of drainage lines found in a typical east coast catchment, they are not particularly steep.

3.2.2 Stream geomorphic type, condition and fragility

Stream geomorphic type (equivalent to River Styles®) was determined for the main watercourses in the CQC Project area using the information collected for this report (Table 24). Fragility is based on the adjustment potential of streams under the three categories: channel attributes (geometry, size and connection to floodplain), planform (lateral stability, number of channels and sinuosity) and bed character (bedform and bed materials). The fragility ratings for each river type were taken from River Styles® literature. Condition was rated Moderate for all stream reaches on the basis that the incised nature of the channels was natural (i.e. this was not a characteristic that would automatically result in a low condition in this area), riparian vegetation was impaired in terms of width and continuity but present in most places, and gullies were contributing suspended sediment to the streams at a rate higher than what would be expected in an unimpaired catchment. (Cook and Schneider, 2006).

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. Streams reaches with high fragility and poor condition are rated low priority, while reaches with low fragility that are in good geomorphic condition are rated the highest priority for protection. On this basis, the high fragility Tooloombah Creek, Deep Creek and Styx River (non-tidal) would be lower priority for rehabilitation than Barrack Creek and Styx River (upper-tidal). However, there are other reasons that might influence the prioritisation of rivers for rehabilitation. In the Styx valley, where reduction of sediment load to the Great Barrier Reef is an established objective (Department of Agriculture, Water and the Environment, 2018), the main criterion for prioritisation would be the potential to generate suspended sediment. This would shift the focus to alluvial gullies (not generally assessed in River Styles®), and particular river bends with a recognised rapid migration rate.

Table 24. Geomorphic type of the main watercourses in the CQC Project area.

Watercourse	Valley Setting	Channel	Sinuosity	Dominant particle size	Geomorphic Type	Geomorphic condition	Fragility
Deep Creek	Partly confined	Continuous/ single	Low	Sand / fine	Planform Controlled, Low Sinuosity Sand/Fine	Moderate	High
Tooloombah Creek	Partly confined	Continuous/ single	Low	Cobble	Planform Controlled Low Sinuosity Cobble	Moderate	High
Barrack Creek	Partly confined	Continuous/ single	Meandering	Fine	Planform Controlled Meandering Fine Grained	Moderate	Medium
Styx River (non-tidal)	Partly confined	Continuous/ single	Low	Sand	Planform Controlled, Low Sinuosity Sand	Moderate	High
Styx River (upper tidal)	Partly confined	Continuous/ single	Low	Sand	Planform Controlled Tidal	Moderate	Low

3.2.3 Distribution of velocity and bed shear stress (BSS) under the 10% and 1% AEP flood events

Under both the 10% AEP and 1% AEP event conditions the velocity on the floodplain areas was mostly less than 1 m/s (Figure 34 and Figure 35 respectively). Grassed floodplains would have low risk of scour under these conditions, although there would be moderate risk for exposed soil surfaces (Table 18). Under the 10% AEP event conditions, the channel velocities were mostly less than 2 m/s (Figure 34), while under the 1% AEP event conditions, the channel velocities exceeded 2 m/s in some areas, but were mostly less than 3 m/s (Figure 35). These velocities would be associated with expected sediment transport processes, and expected scour of banks in some exposed locations on the outside of meander bends. Well vegetated banks would have lower risk of bank erosion (Table 18).

Under both the 10% AEP and 1% AEP event conditions the BSS values on the floodplain areas was mostly less than 25 N/m^2 (Figure 36 and Figure 37 respectively). Grassed floodplains would have low risk of scour under these conditions, although there would be moderate risk for exposed soil surfaces (Table 18). Under the 10% AEP event conditions, the channel BSS values were mostly less than 100 N/m^2, with some short sections up to 200 N/m^2 (Figure 36). Under the 1% AEP event conditions, the channel BSS values exceeded 100 N/m^2 over longer reaches, and some short sections exceeded 200 N/m^2 (Figure 37). These values of BSS would be associated with expected sediment transport processes, with sand, gravel and cobble sized material subject to mobilisation. Also, this distribution of BSS would be associated with expected scour of banks in some exposed locations on the outside of meander bends. Well vegetated banks would have lower risk of bank erosion (Table 18).

The modelled velocity and bed shear stress values suggest that the watercourses in the CQC Project area are geomorphologically active, with bed sediment transport and channel migration process to be expected. The grassed floodplain surfaces would be depositional rather than erosional zones. Well-vegetated banks would have significantly lower risk of erosion than banks formed by exposed soils.

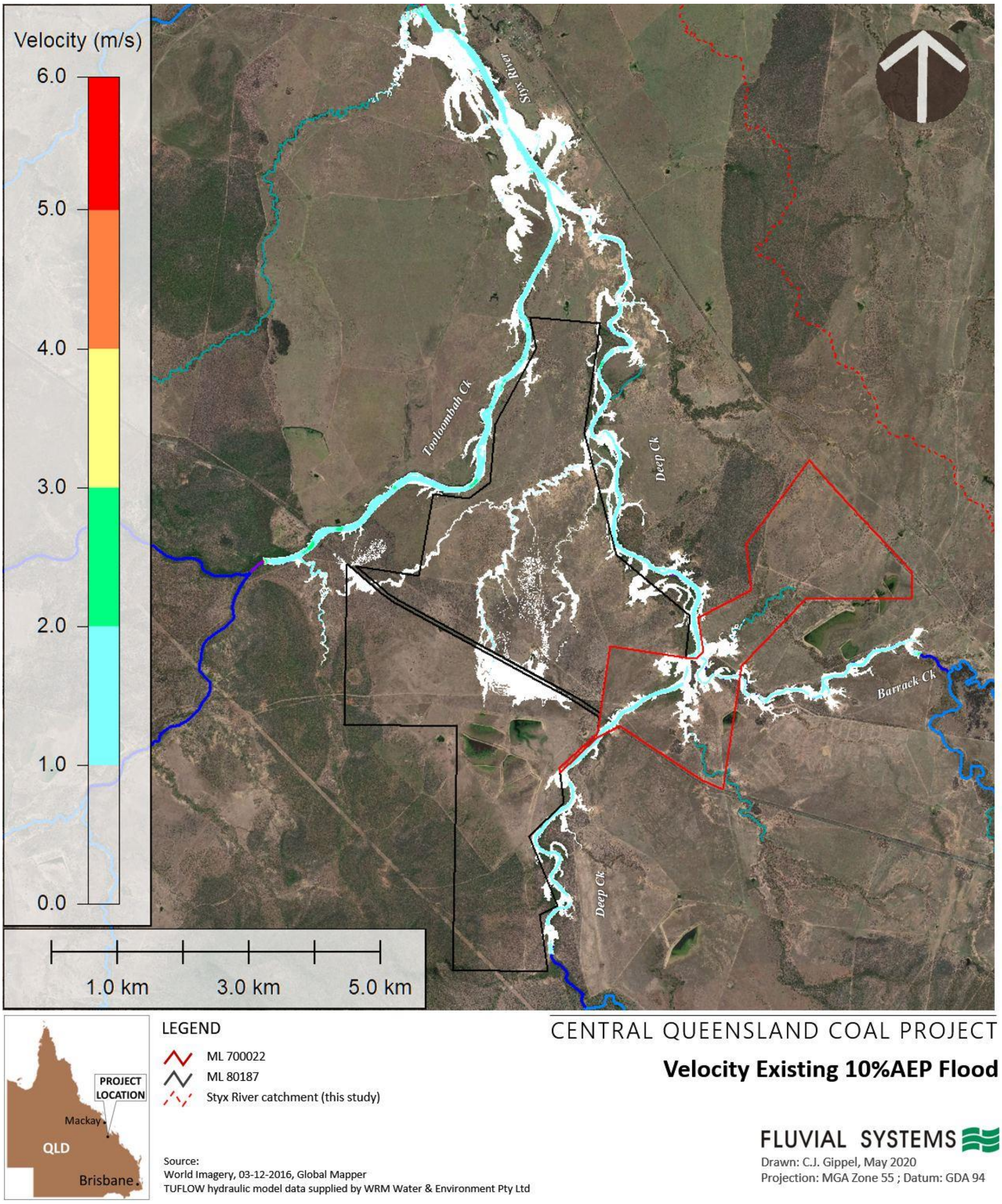


Figure 34. Distribution of velocity classes, modelled for the 10% AEP flood event under the existing scenario. A small number of cells with values exceeding 4 m/s can be considered outliers.

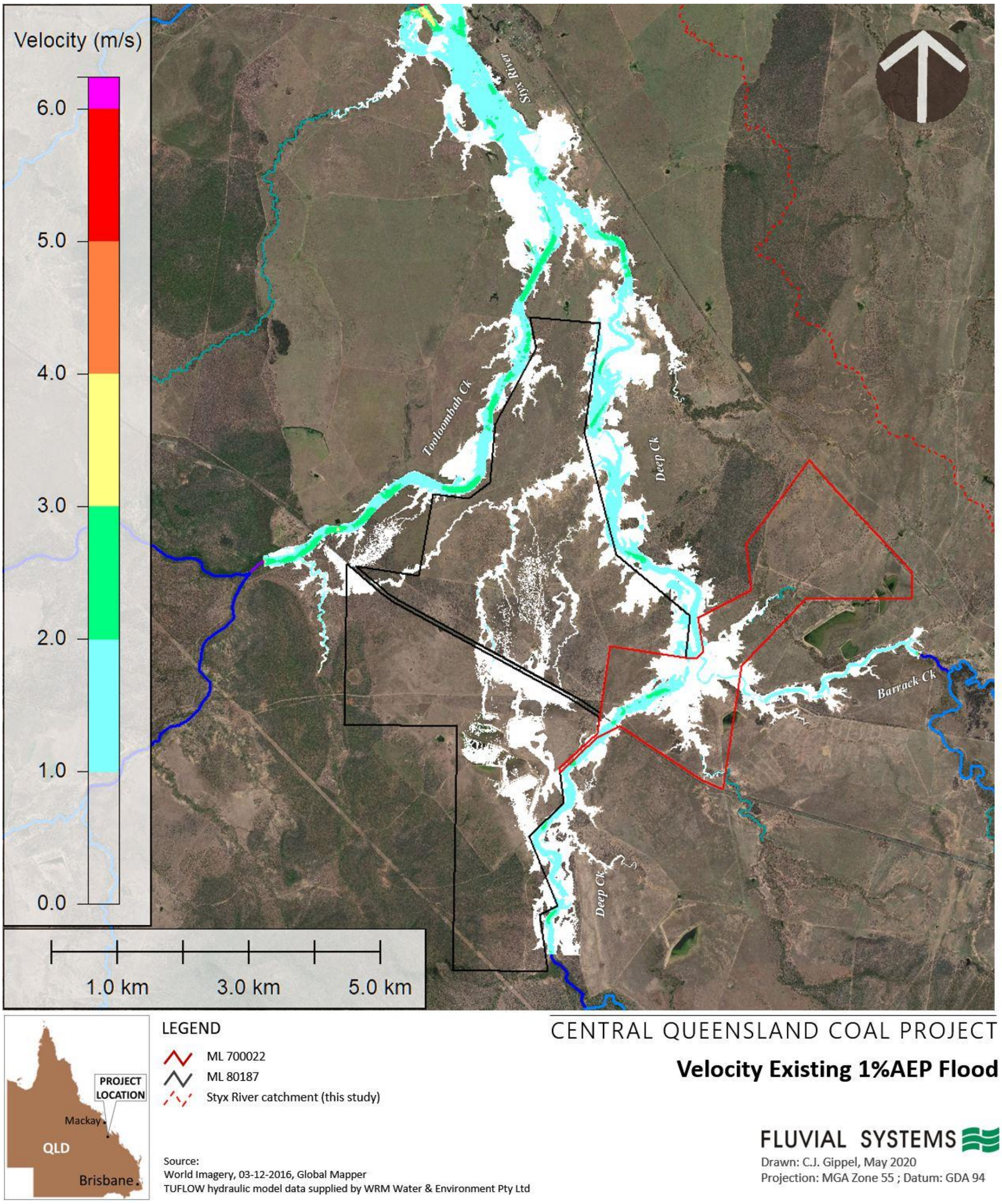
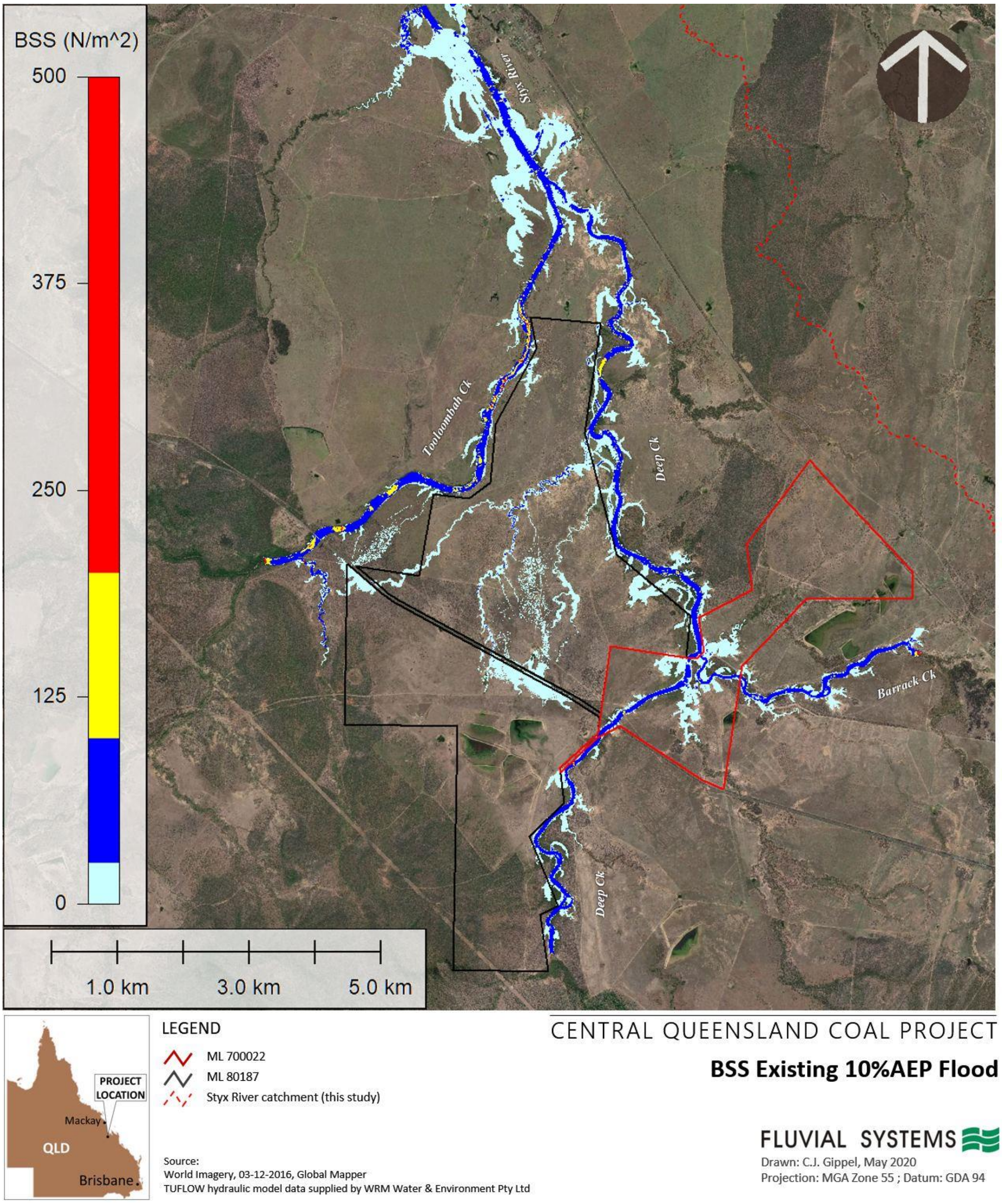
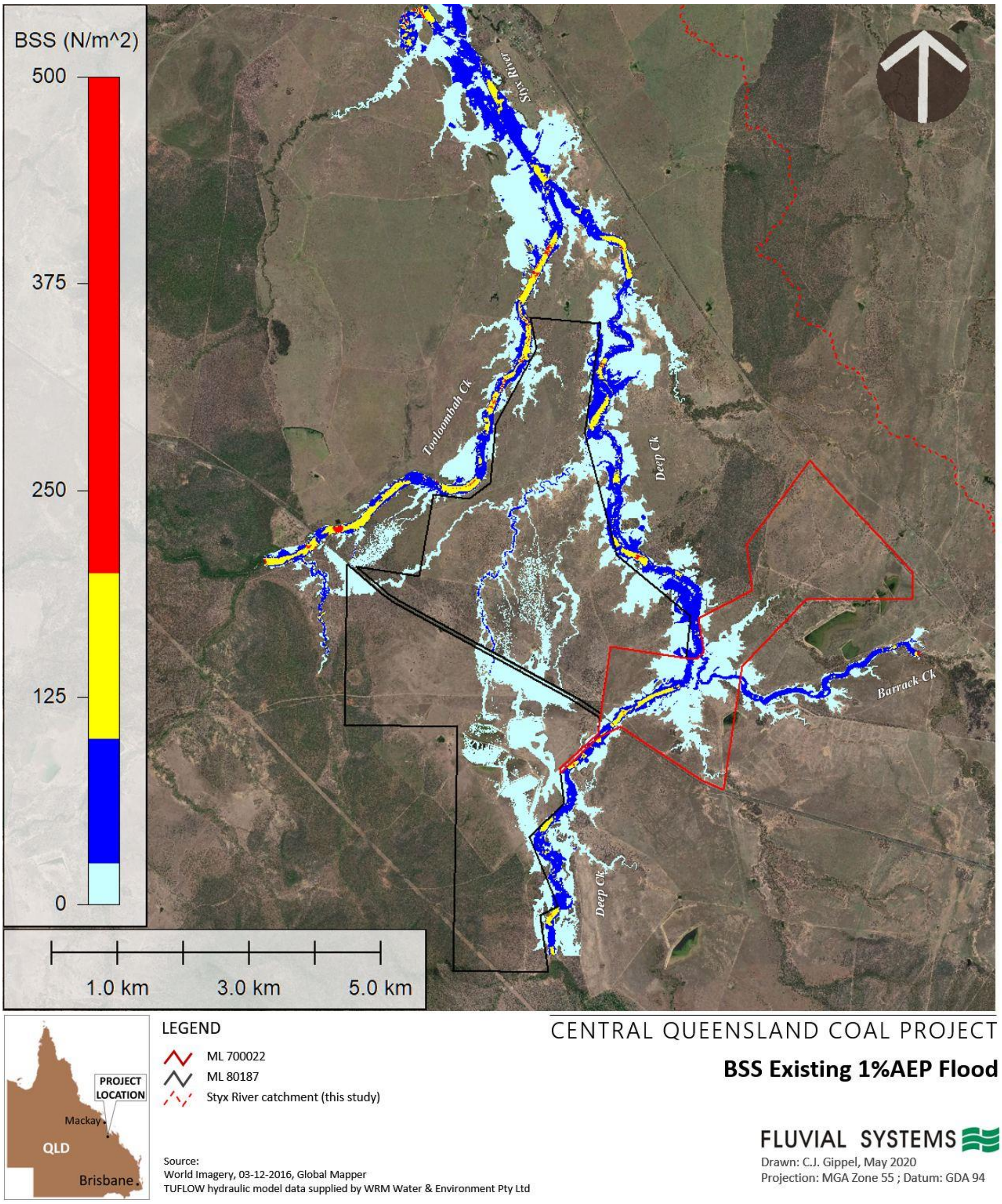


Figure 35. Distribution of velocity classes, modelled for the 1% AEP flood event under the existing scenario. A small number of cells with values exceeding 4 m/s can be considered outliers.



Source:
World Imagery, 03-12-2016, Global Mapper
TUFLOW hydraulic model data supplied by WRM Water & Environment Pty Ltd

Figure 36. Distribution of bed shear stress (BSS) classes, modelled for the 10% AEP flood event under the existing scenario. A small number of cells with values exceeding 500 N/m^2 were excluded as outliers.



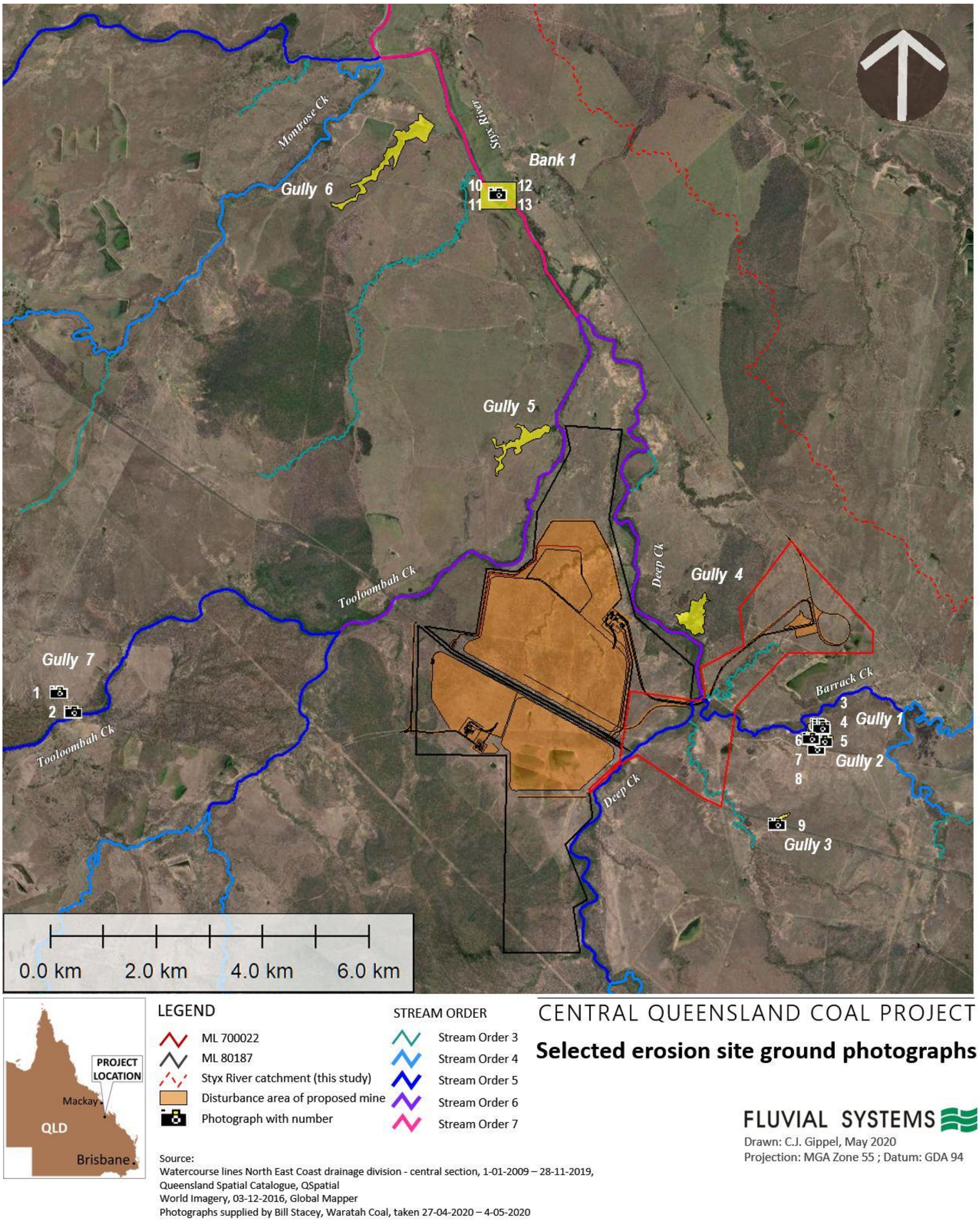
Source:
World Imagery, 03-12-2016, Global Mapper
TUFLOW hydraulic model data supplied by WRM Water & Environment Pty Ltd

Figure 37. Distribution of bed shear stress (BSS) classes, modelled for the 1% AEP flood event under the existing scenario. A small number of cells with values exceeding 500 N/m^2 were excluded as outliers.

3.3 River Bank and Gully Erosion Rates

3.3.1 Selected sites

Erosion rates were investigated at six gully sites and one river bank site (Figure 38). Gully site 7 was not analysed because of a lack of LiDAR data in that area. Gullies 4, 5 and 6 were not inspected in the field. Ground photographs were available for Gullies 1 (Figure 39), 2 (Figure 40), 3 and 7 (Figure 41). One site of notable bank erosion was investigated on the Styx River (Figure 42).



CENTRAL QUEENSLAND COAL PROJECT

Selected erosion site ground photographs

Drawn: C.J. Gippel, May 2020
Projection: MGA Zone 55 ; Datum: GDA 94

Source:
Watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019, Queensland Spatial Catalogue, QSpatial
World Imagery, 03-12-2016, Global Mapper
Photographs supplied by Bill Stacey, Waratah Coal, taken 27-04-2020 – 4-05-2020

Figure 38. Locations of selected gully and bank erosion site ground photographs.

Figure 39. Gully 1 ground photographs.

Figure 40. Gully 2 ground photographs.

Figure 41. Gully 3 and Gully 7 ground photographs.

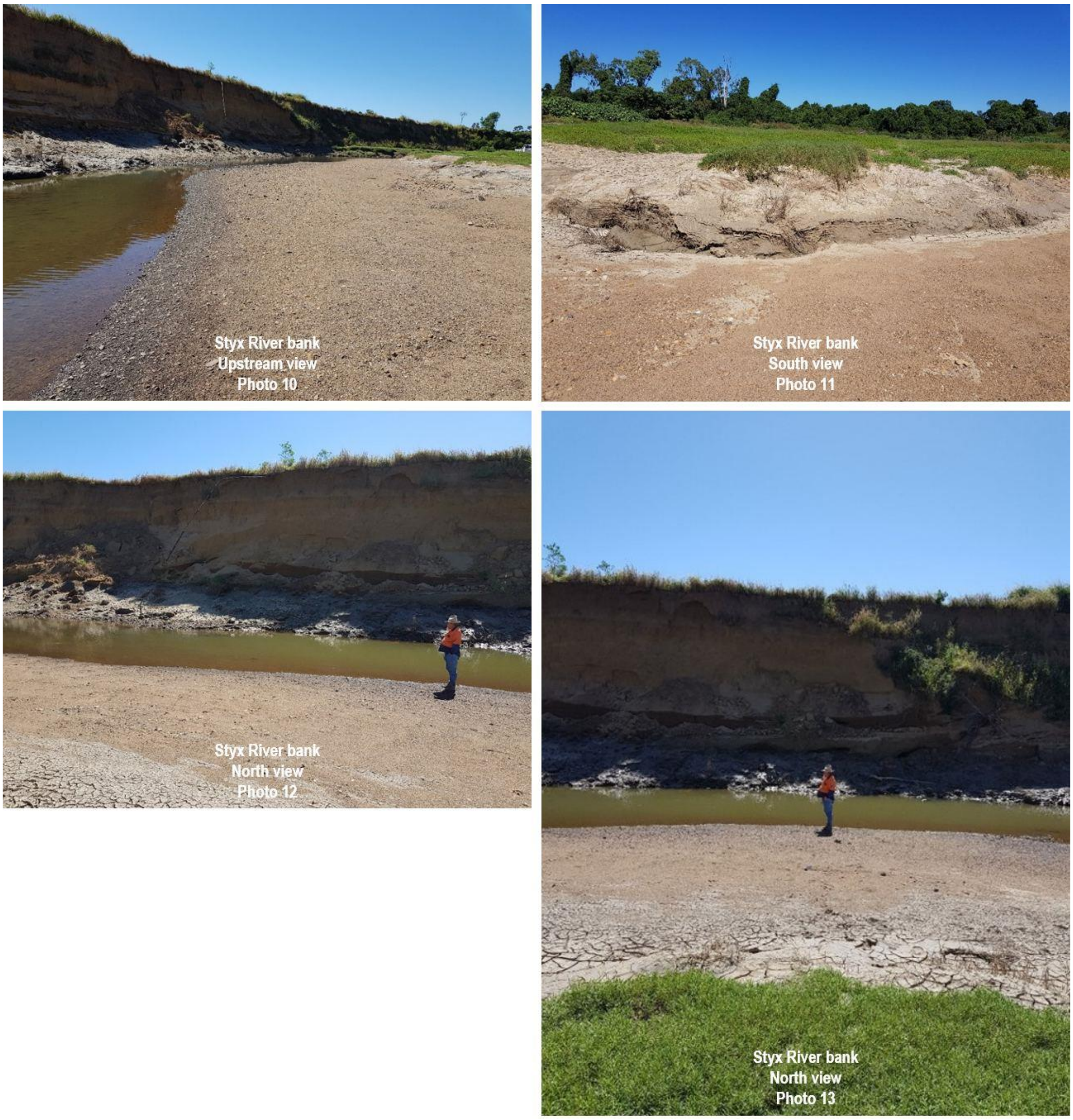


Figure 42. Styx River bank erosion site ground photographs.

3.3.2 Gully morphology

Using the alluvial gully classification system of Brooks et al. (2007), Gullies 1, 3 and 7 were linear, Gully 2 was amphitheatre, and Gully 4 was dendritic. Gullies 5 and 6 were much larger than the others, and could also have been classified as small incised tributaries. They were both linear systems, but Gully 5 also contained dendritic elements.

Gully morphology was defined using high positive profile curvature to identify sharp edges. Gully 1 had four main headcuts that migrated between the 2009 and 2011 surveys, although there were other locations on the gully system that also migrated (Figure 43). The main knickpoints were at least 1 m high, and migrated 13 to 20 m between the surveys. Gully 2 was of the amphitheatre type, but it also had at least two identifiable headcuts that migrated significant distances between the 2009 and 2011 surveys (Figure 43). Gully 3 was a small gully with one migrating headcut. The knickpoint was 1.5 m high and it migrated 30 m between the 2009 and 2011 surveys

(Figure 44). Gullies 4 (Figure 45), 5 (Figure 46) and 6 (Figure 47) did not have any edges that migrated significant distances between the 2009 and 2011 surveys.

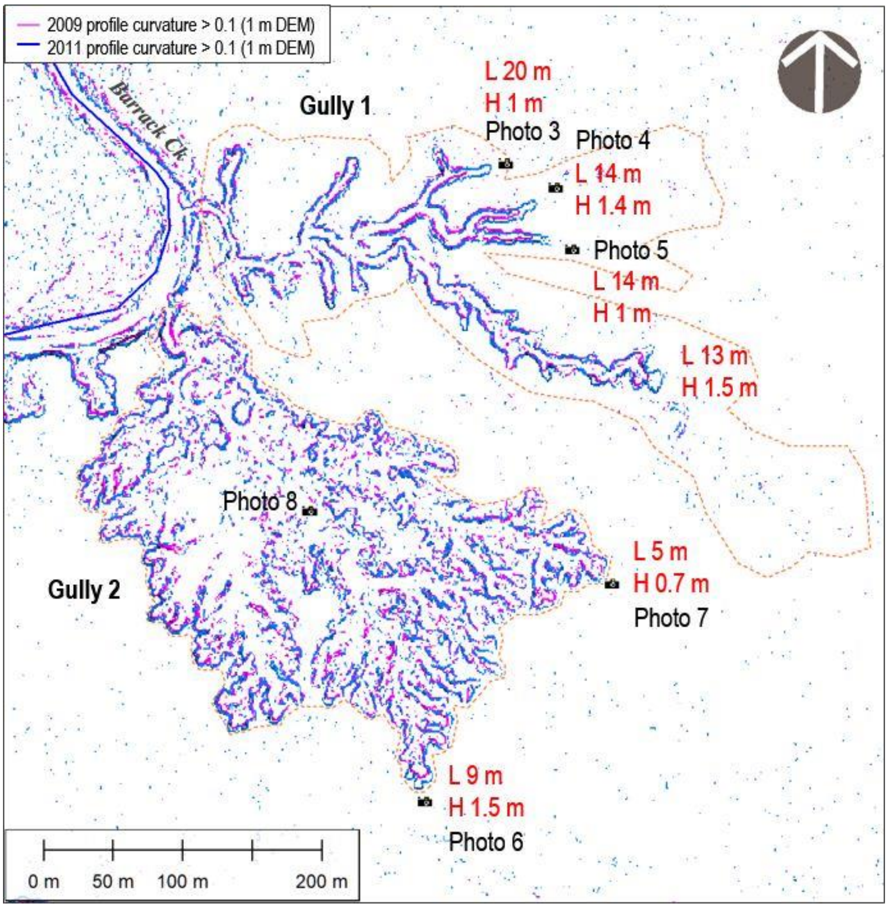


Figure 43. Gullies 1 and 2 edges defined by high profile curvature for 2009 and 2011 LiDAR. Annotations indicate height of knickpoints (H) and the distance (L) that the knickpoints migrated between the 2009 and 2011 surveys.

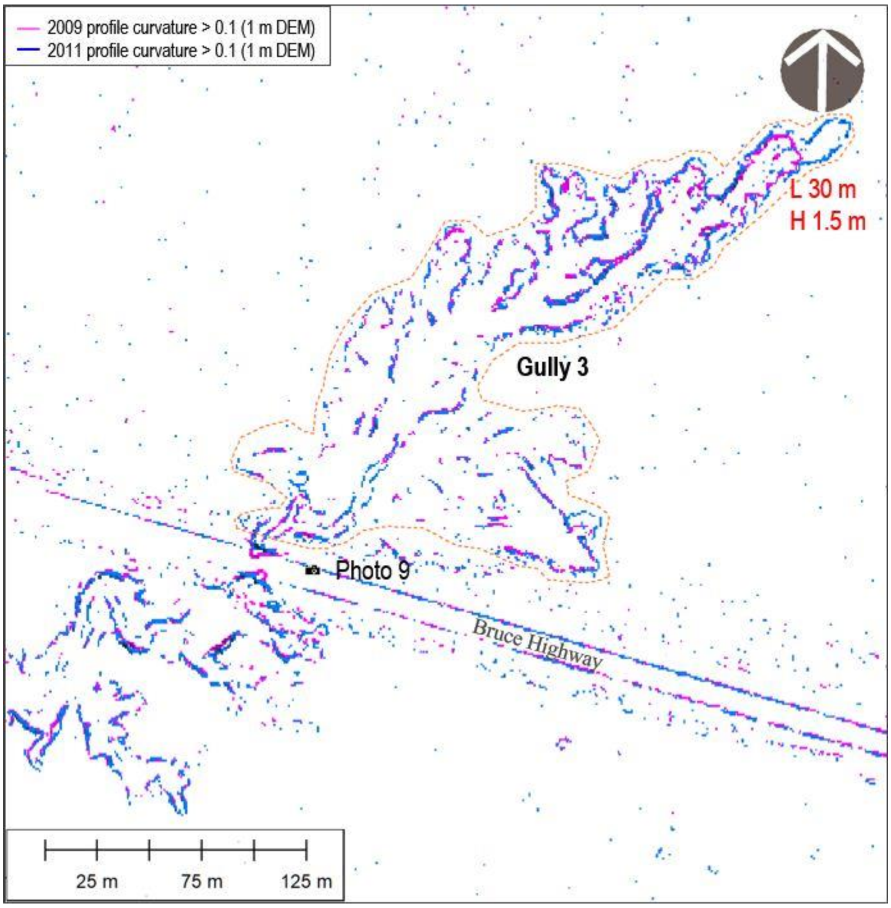


Figure 44. Gully 3 edges defined by high profile curvature for 2009 and 2011 LiDAR. Annotations indicate height of the main knickpoint (H) and the distance (L) that the knickpoint migrated between the 2009 and 2011 surveys.

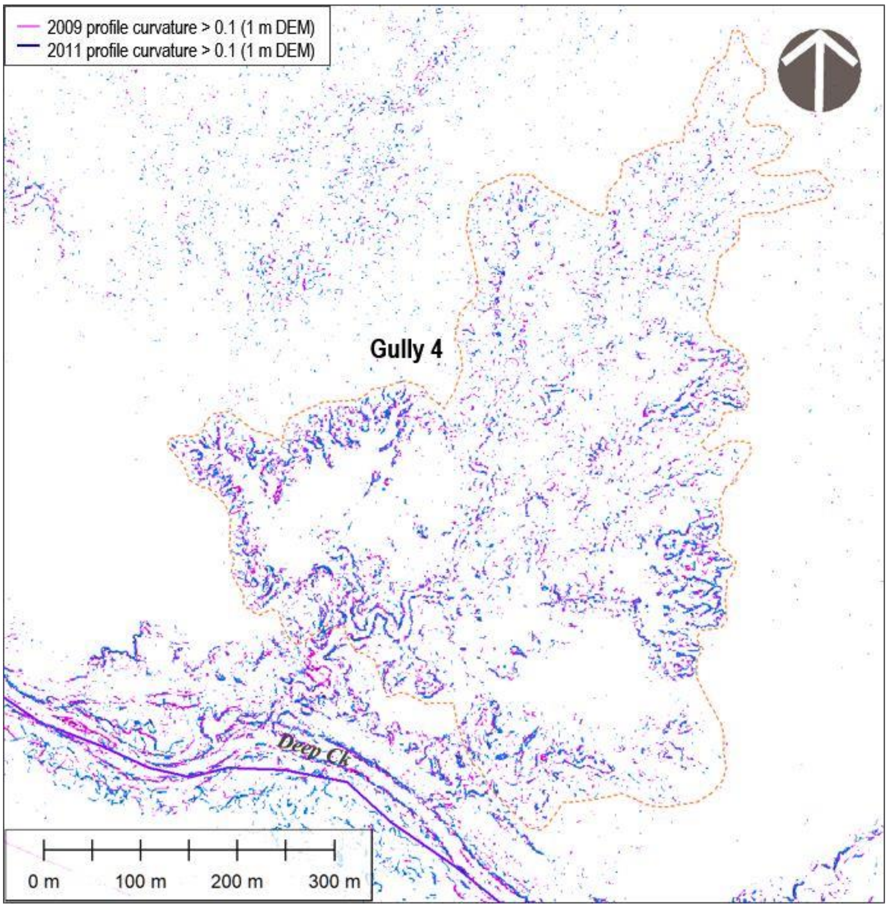


Figure 45. Gully 4 edges defined by high profile curvature for 2009 and 2011 LiDAR. None of the gully edges migrated significantly between the 2009 and 2011 surveys.

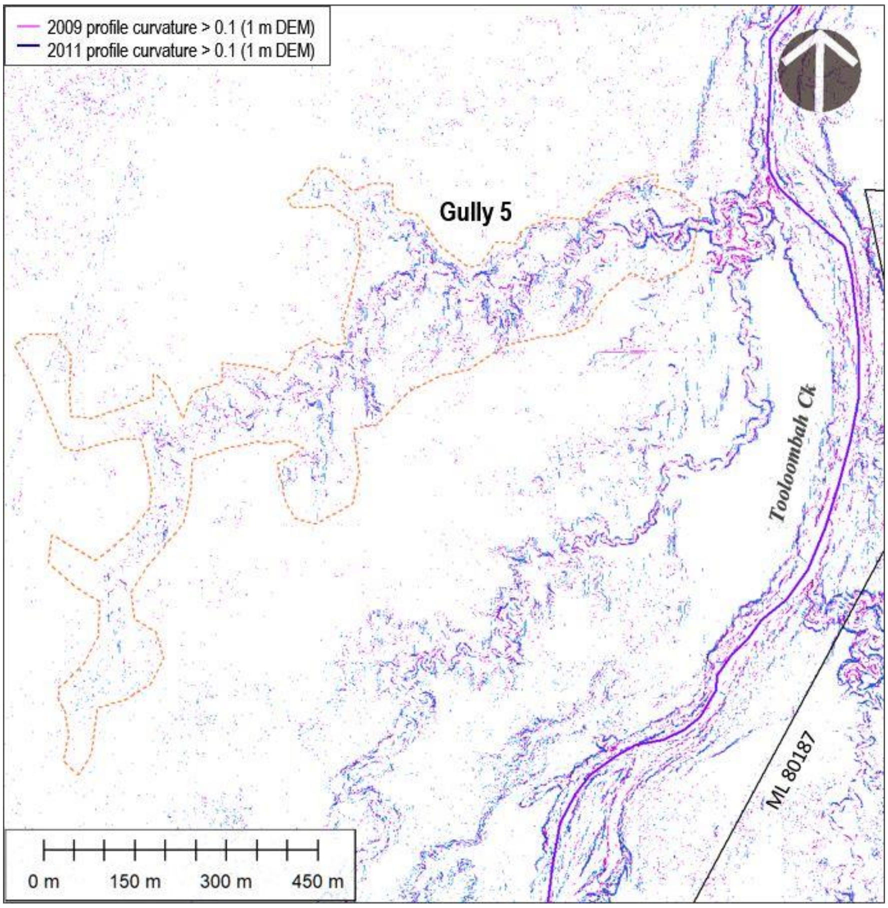


Figure 46. Gully 5 edges defined by high profile curvature for 2009 and 2011 LiDAR. None of the gully edges migrated significantly between the 2009 and 2011 surveys.

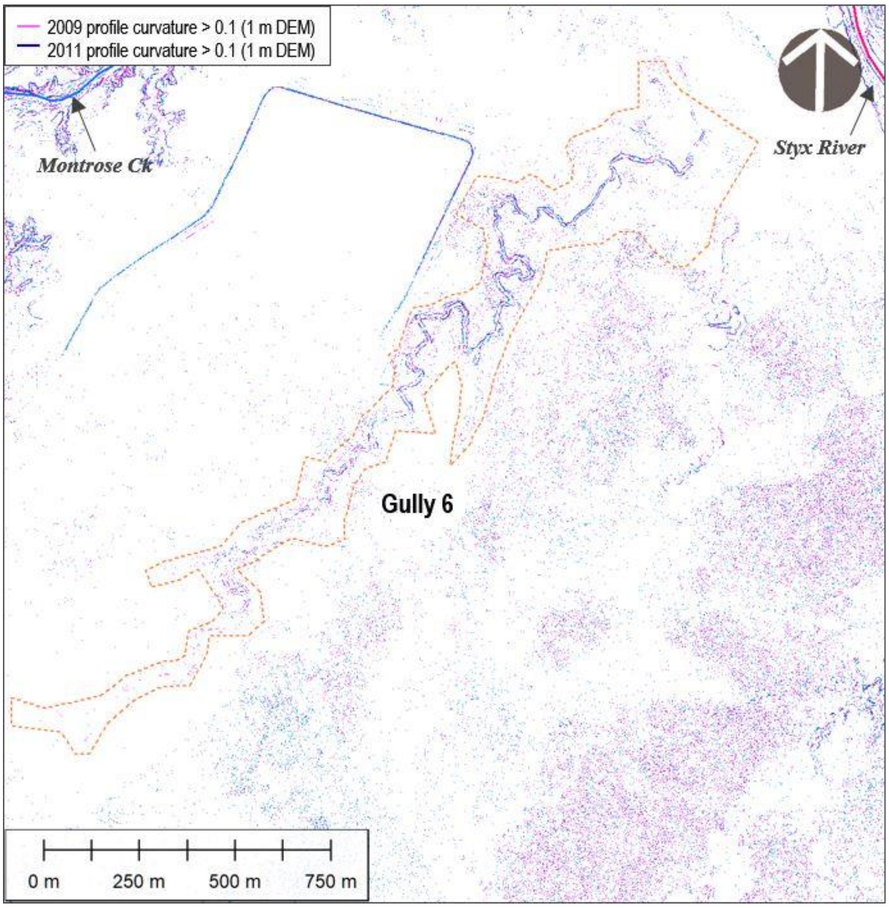


Figure 47. Gully 6 edges defined by high profile curvature for 2009 and 2011 LiDAR. None of the gully edges migrated significantly between the 2009 and 2011 surveys.

3.3.3 Gully morphological change 2009 to 2011

The mass of soil eroded from Gullies 1 – 6 between the 2009 and 22011 LiDAR surveys was estimated by measuring the mean difference in the ground elevation of the two surveys over the gully areas, and correcting this for the background difference in elevations of the two surveys. The background elevations of the two surveys differed between the sites, and also within the sites, i.e. around the perimeters of the gullies. Repeated measures of the mean differences at each gully site suggested that the error in estimation of this background difference was ±0.005 m. This was assumed to be the main source of error in the estimate of difference in gully volume between the 2009 and 2011 surveys. There would be other errors related to point cloud density and incorrect classification of points, but these would have been difficult to estimate. Volume of eroded material was converted to mass assuming a specific gravity of 2.65, i.e. the eroded material was assumed to be all mineral, with low void space.

The yield of eroded material varied over a wide range across the six gullies (Table 25). The highest yield was from Gully 2, with a globally very high annualised rate of soil loss of 2,670 t/ha/yr. Gullies 1, 3 and 4 also produced high yields of sediment, with annualised rates of soil loss of 1,049, 732, and 558 t/ha/yr. Gullies 5 and 6 were relatively benign, with Gully 5 effectively stable (within error bounds), and Gully 6 having a small positive yield.

Table 25. Area, and change in mean elevation, volume and mass of gullies between 2009 and 2011 LiDAR surveys.

Variable	Gully 1	Gully 2	Gully 3	Gully 4	Gully 5	Gully 6
Gully area (m^2)	63,751	64,779	25,237	249,044	239,526	450,933
LiDAR background elevation difference 2011-2009 (m)	0.02213 ±0.005	0.01286 ±0.005	0.02648 ±0.005	-0.04910 ±0.005	0.06518 ±0.005	-0.08931 ±0.005
Corrected mean gully elevation difference 2011-2009 (m)	-0.03513 ±0.005	-0.10986 ±0.005	-0.02114 ±0.005	-0.02790 ±0.005	-0.00318 ±0.005	-0.00569 ±0.005
Volume eroded 2009-2011 (m^3) [range incorporates error]	4,365 3,743-4,986	11,285 10,771-11,799	1,205 920-1,490	9,061 7,437-10,685	1,472 -845-3,788	3,763 457-7,070
Annualised mass erosion rate (t/ha/yr) [range incorporates error]	1,049 900-1,199	2,670 2,549-2,792	732 559-905	558 458-658	94 -54-242	128 16-240

3.3.4 Styx River bank morphological change 1953 – 2018

At the site under investigation just downstream of Ogmore Road bridge, the 1953 aerial photograph shows the left bank of the Styx River densely forested, and the right bank cleared (Figure 48). By 1975 the majority of the left bank in this area had also been cleared, but the uncleared patches of vegetation remained intact until 2018. By 1985 the toe of the right bank and the low flow channel had migrated to the right. By 2004 the top of the bank on the bend had reached the edge of the track that was formerly ~20 m from the edge. By 2016 the track had been moved inland and the top and toe of the bank had migrated a significant distance to the right. There appears to have been little to no change between 2016 and 2018 (Figure 48).

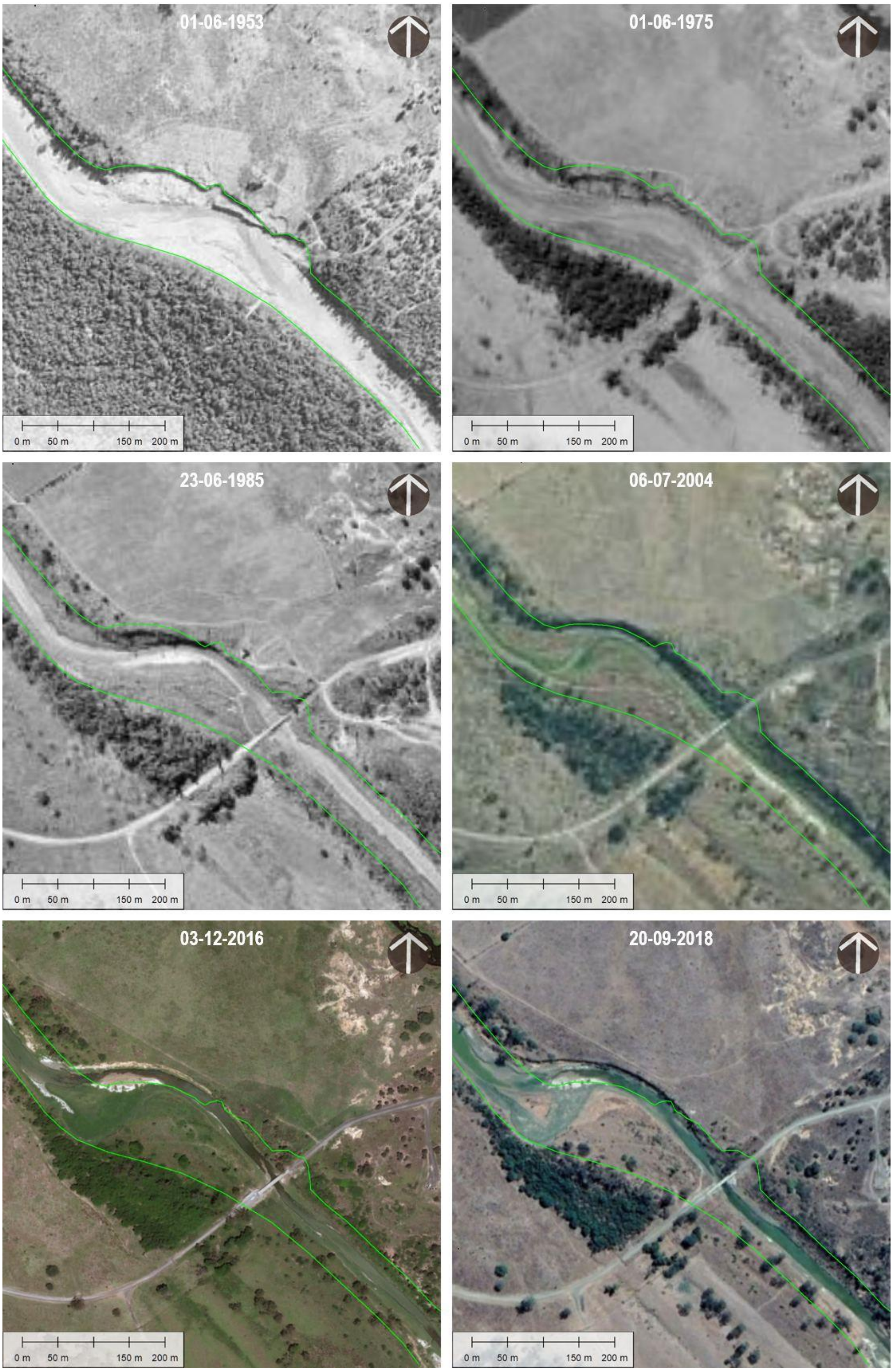


Figure 48. Bend on the Styx River just downstream of Ogmore Road Bridge as it appears on rectified aerial photographs from 1953 to 2018.

3.3.5 Styx River bank morphological change 2009 – 2011

High positive profile curvature clearly delineated the bank tops of the Styx River at the site under investigation just downstream of Ogmore Road bridge (Figure 49). The high profile curvature rasters were automatically converted to vectors that marked the top of bank edge (Figure 50). In this area, the elevation of the cleared flat land on the top of the right bank of the river that was unaffected by erosion was on average 0.162 m higher on the 2009 LiDAR than on the 2011 LiDAR. A correction was made to the data prior to subtracting the 2009 and 2011 DEMs. A comparison of the LiDAR data indicated that over the 259 m long eroded section, which had a mean bank height of 8.5 m, the mean eroded width was 8.2 m (maximum 16 m) and total volume eroded was 18,056 m^3. This compares to a total of 31,151 m^3 eroded from the 6 gullies over the same period (Table 25). It appears that about half of the bank migration that has occurred in this location between 1953 and 2018 (up to about 30 m) occurred between 2009 and 2011 (Figure 50).

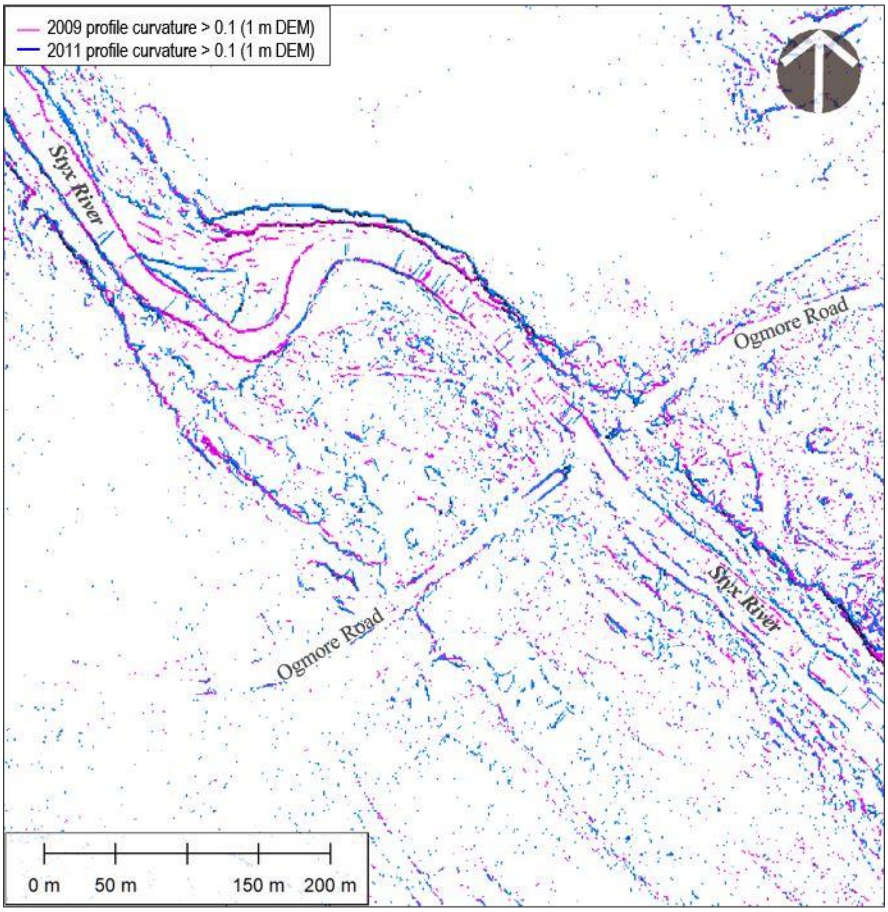


Figure 49. Morphology of the bend on the Styx River just downstream of Ogmore Road Bridge defined by high profile curvature for 2009 and 2011 LiDAR.

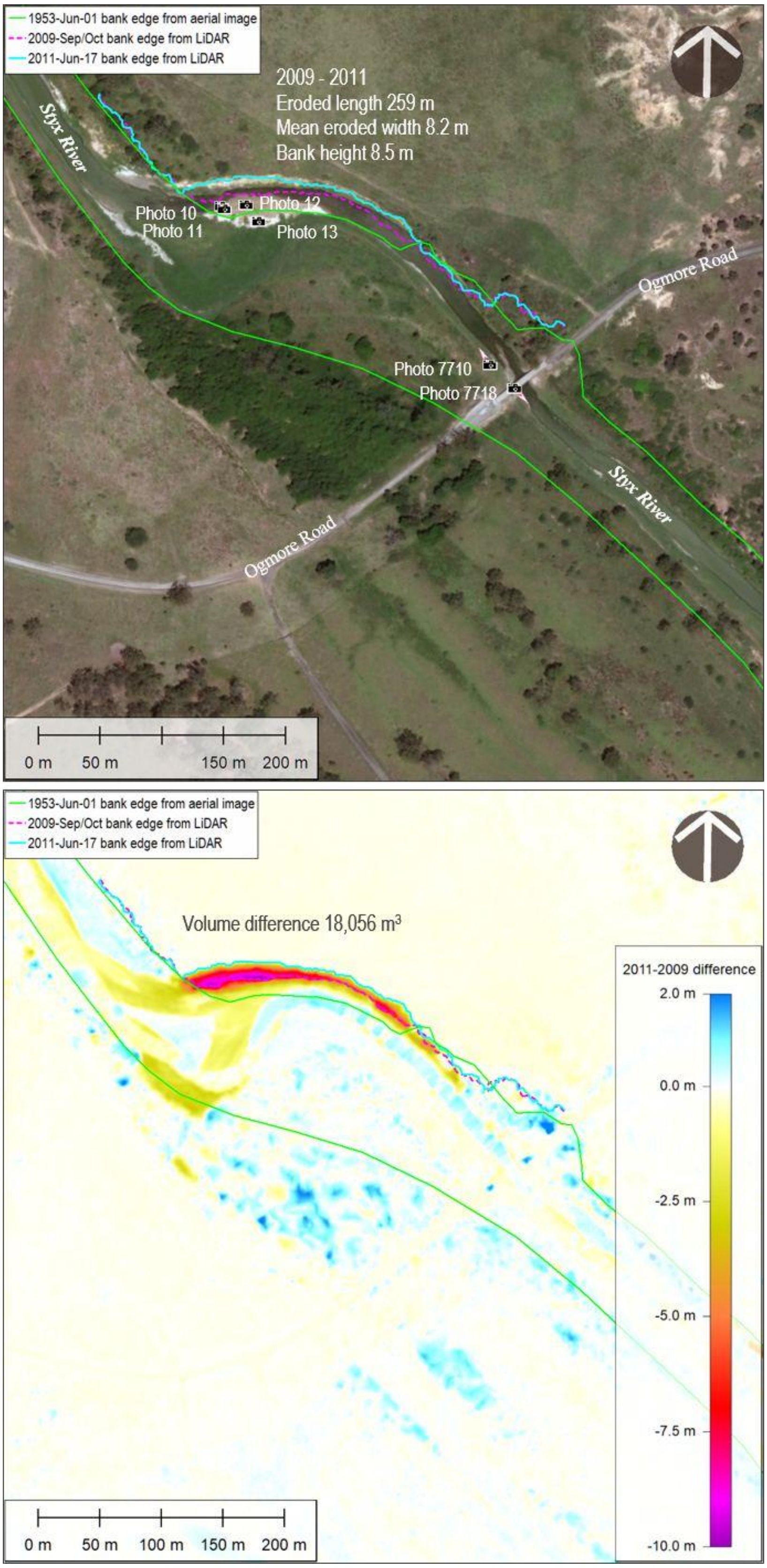


Figure 50. Morphology of the bend on the Styx River just downstream of Ogmore Road Bridge, showing 2009 and 2011 bank top edges automatically defined by profile curvature (top) and 2009 to 2011 eroded volume difference automatically calculated from the LiDAR elevation data (bottom).

4.0 Impact assessment

4.1 Hydrologic and Hydraulic Impacts

4.1.1 Drainage flow paths and flood extents under Existing and Developed (P8) scenarios

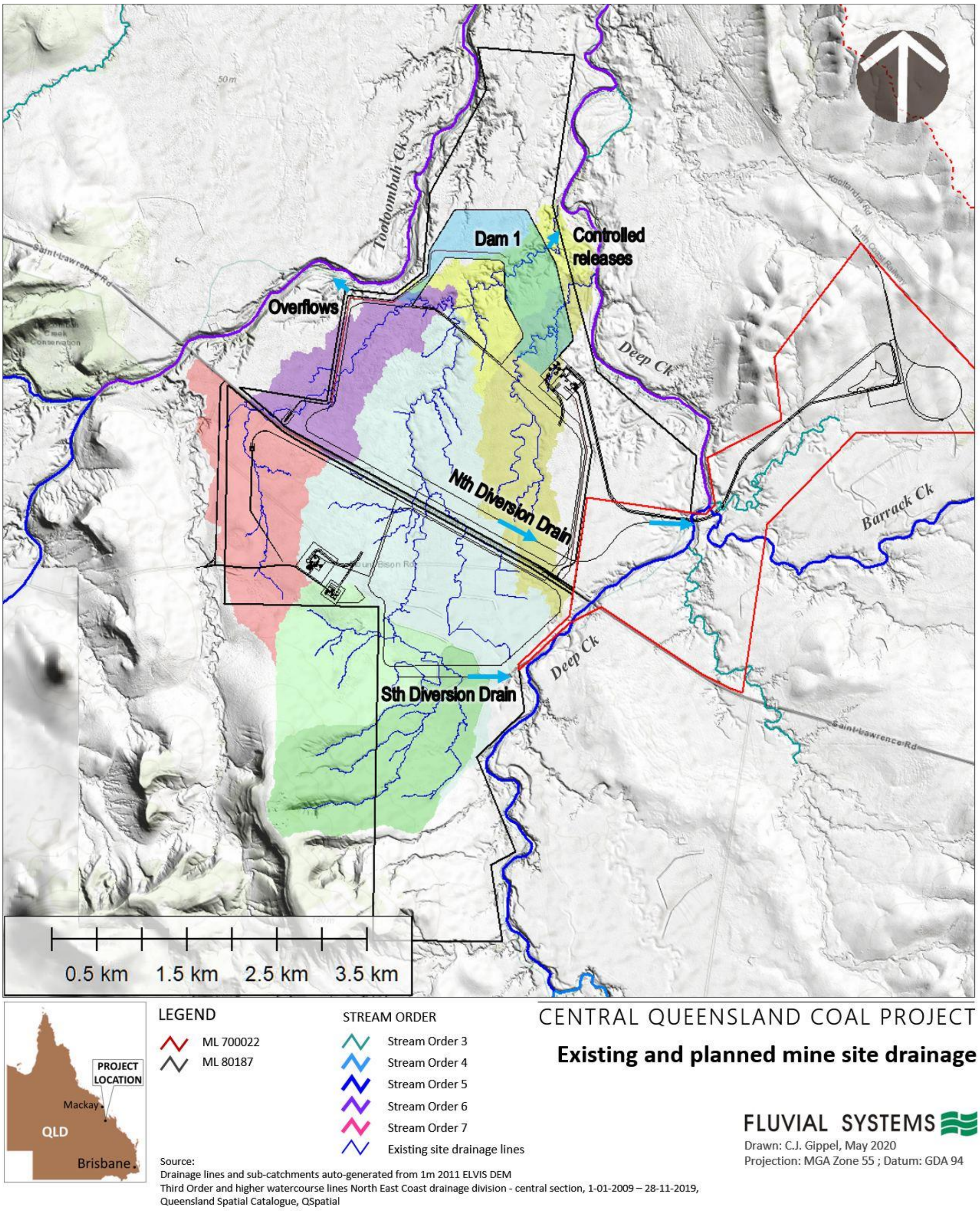
The mine surface water arrangement was described by WRM Water & Environment (2020) (Figure 51). The main hydrologic impact during the early stages of development (up to and including P8) would be diversion of the southern catchment area via the Northern Diversion Drain to Deep Creek, just upstream of Barrack Creek junction. The majority of the remainder of the catchment area would discharge to Dam 1, which would then be managed to deliver the collected runoff to the tributary creek that currently discharges water from this catchment to Deep Creek. Dam 1 would have an overflow discharge to Tooloombah Creek. Under Existing conditions, the two most western sub-catchments that drain to the mine site (mauve and peach coloured sub-catchments in Figure 51) flow in a northeast direction and discharge to Deep Creek. Under the developed scenario, the flow from these sub-catchments would be diverted northwards around the western boundary of the mine to discharge to Tooloombah Creek (Figure 51).

While the total amount of surface water discharging from the mine area to Deep Creek would be little changed, its distribution and timing would be altered. From the outflow of the Northern Diversion Drain to the outflow from Dam 1, Deep Creek would have slightly higher storm flow than under the existing situation. From the outflow from Dam 1, Deep Creek would generally have slightly lower storm flow than under the existing situation, but periodically flows would be higher when controlled releases were made from Dam 1. Open Cut 1 would be active from 2029 onwards, at which time the Southern Diversion Drain would become active. The Developed Stage P8 was evaluated here, during which time the Northern Diversion Drain would be active.

Maps of flood inundation extent for the 10% AEP (Figure 52) and 1% AEP (Figure 53) flood events illustrate how the surface water management arrangements direct floodwater from sub-catchments, and overbank flow from Deep Creek in the case of the 1% AEP event, around the mine site. The redistribution of these flows would have negligible impact on the extent of flood inundation of the floodplains of Deep Creek, Tooloombah Creek and Styx River (Figure 52 and Figure 53).

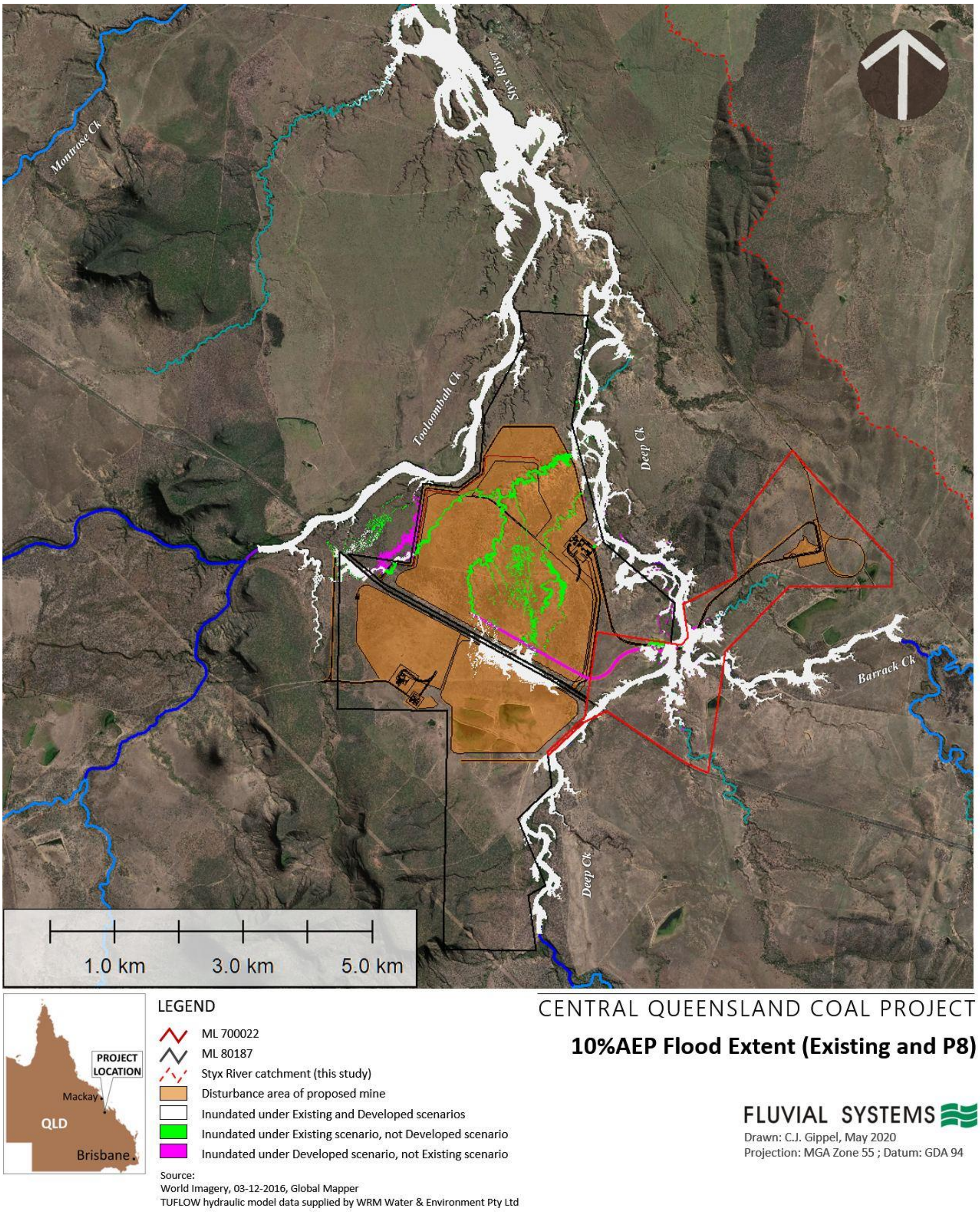
4.1.2 Distribution of velocity under the Developed (P8) scenario

For areas inundated under both the Existing and Developed P8 scenarios there was negligible difference in velocity distribution. Under both the 10% AEP and 1% AEP events, areas inundated under the Developed scenario, but not the Existing scenario, i.e. the Northern Diversion Drain, and the western sub-catchments, had velocities generally less than 1 m/s (Figure 54 and Figure 55), which would be stable under good grass cover (Table 18). The exceptions were under the 1% AEP event: (i) in the 400 m-long area where drainage from the western sub-catchments concentrates and then discharges to Tooloombah Creek, and (ii) where sub-catchments upstream of the mine discharge to the Northern Diversion Drain (Figure 55). In these areas, velocity is greater than 1 m/s but less than 2 m/s. These area will require maintenance of good vegetation cover and regular monitoring of stability, plus preparation of a plan to fortify them with rock rip-rap should significant incision occur. The end of the Northern Diversion Drain where it discharges to Deep Creek has a short section where velocity exceeds 2 m/s (Figure 55). To ensure stability, this section of the Drain will require fortification with rip-rap.



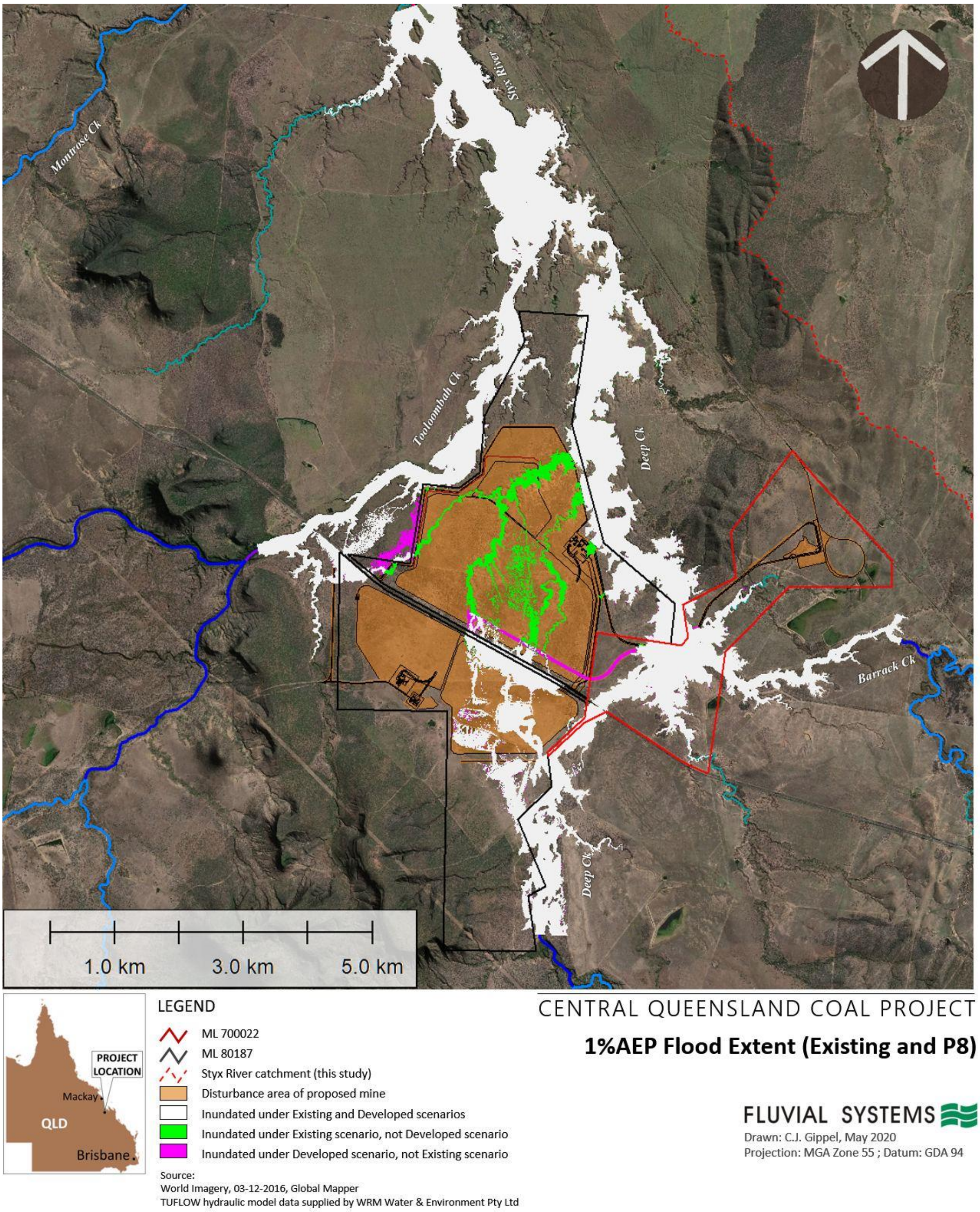
Source:
Drainage lines and sub-catchments auto-generated from 1m 2011 ELVIS DEM
Third Order and higher watercourse lines North East Coast drainage division - central section, 1-01-2009 – 28-11-2019, Queensland Spatial Catalogue, QSpatial

Figure 51. Proposed mine water management arrangements. Based on information in WRM Water & Environment (2020).



Source:
World Imagery, 03-12-2016, Global Mapper
TUFLOW hydraulic model data supplied by WRM Water & Environment Pty Ltd

Figure 52. Modelled 10% AEP flood inundation extent under Existing and Developed P8 scenarios.



Source:
World Imagery, 03-12-2016, Global Mapper
TUFLOW hydraulic model data supplied by WRM Water & Environment Pty Ltd

Figure 53. Modelled 1% AEP flood inundation extent under Existing and Developed P8 scenarios.

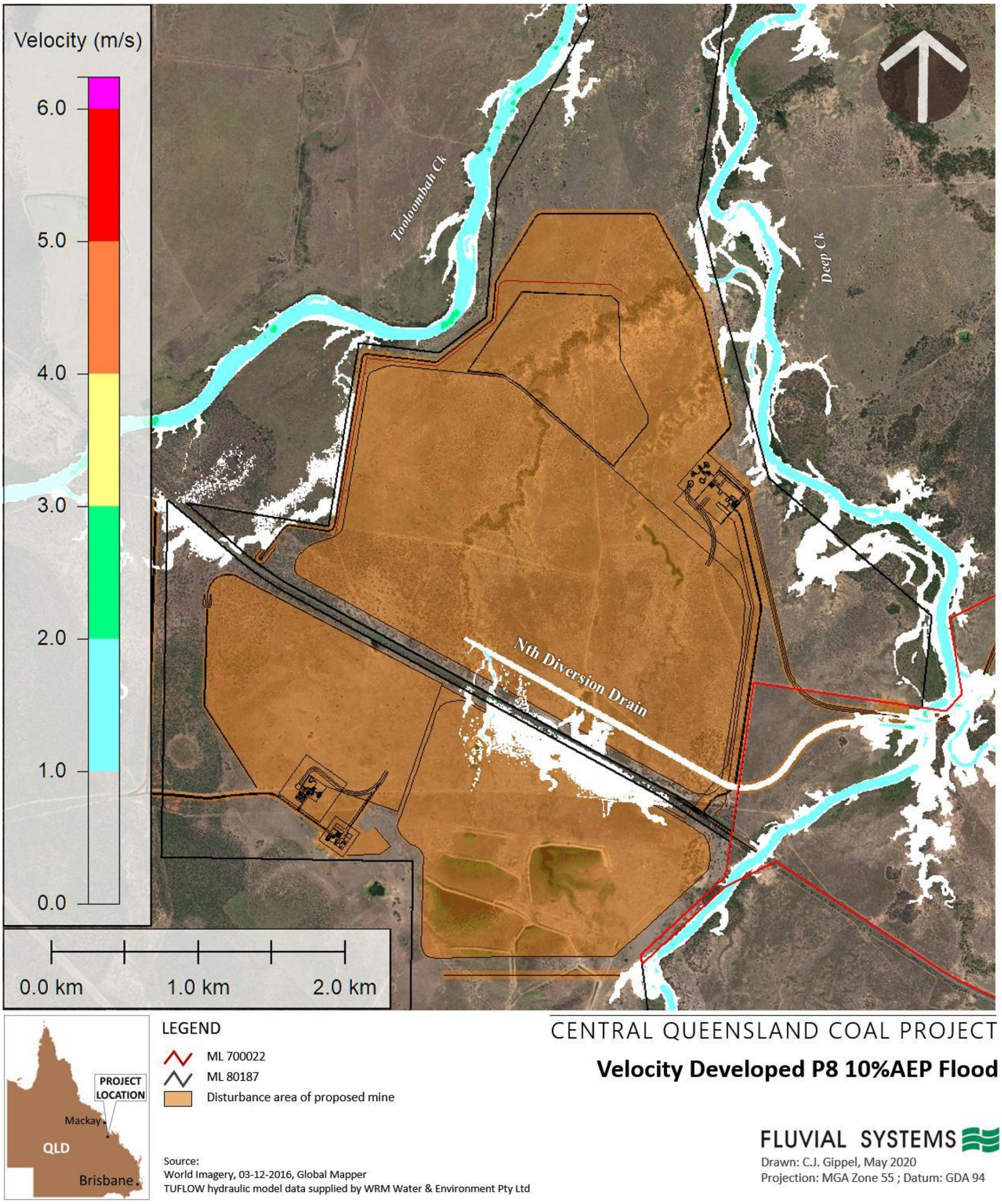


Figure 54. Modelled 10% AEP velocity under Developed P8 scenario. A small number of cells with values exceeding 4 m/s can be considered outliers.

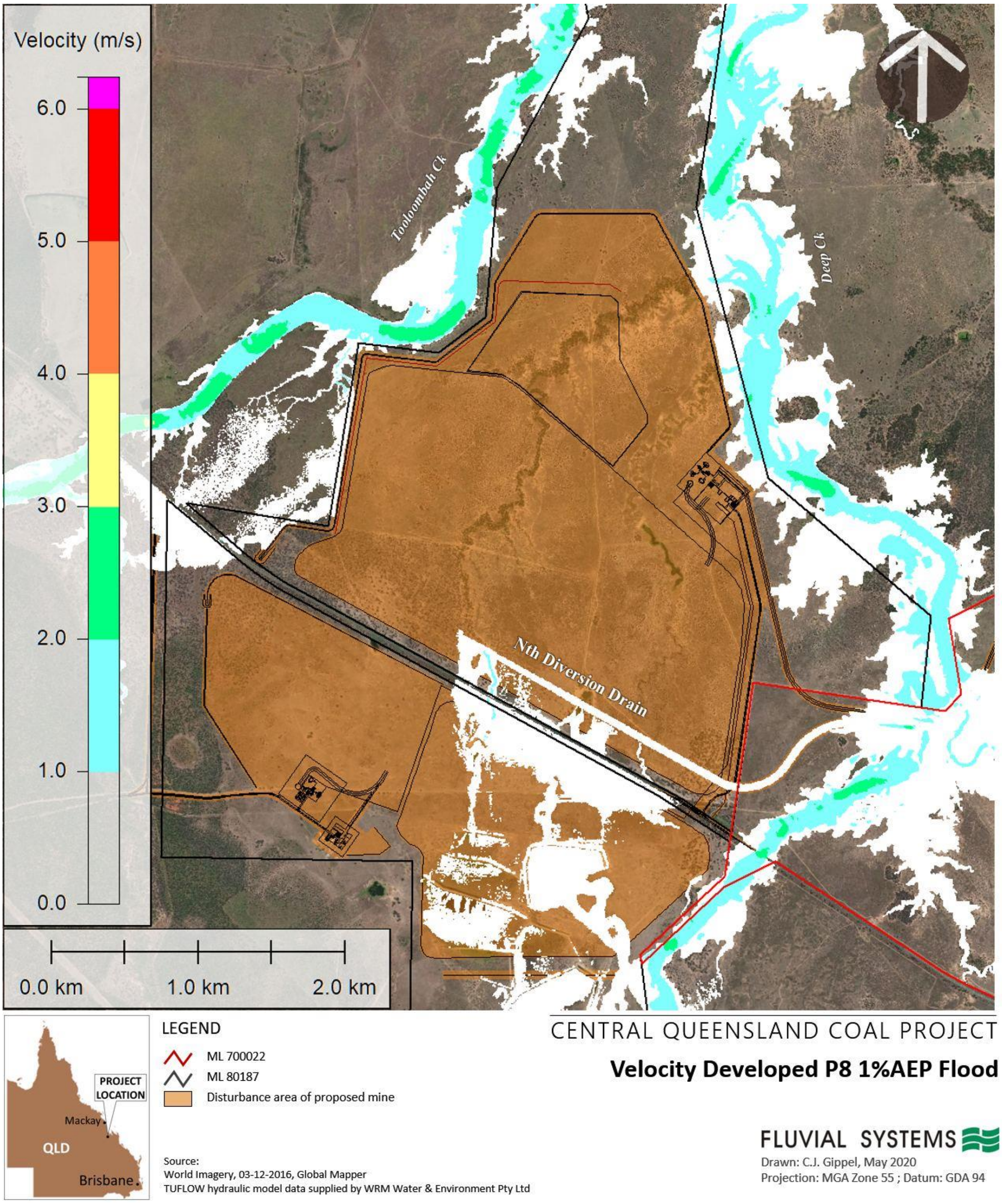
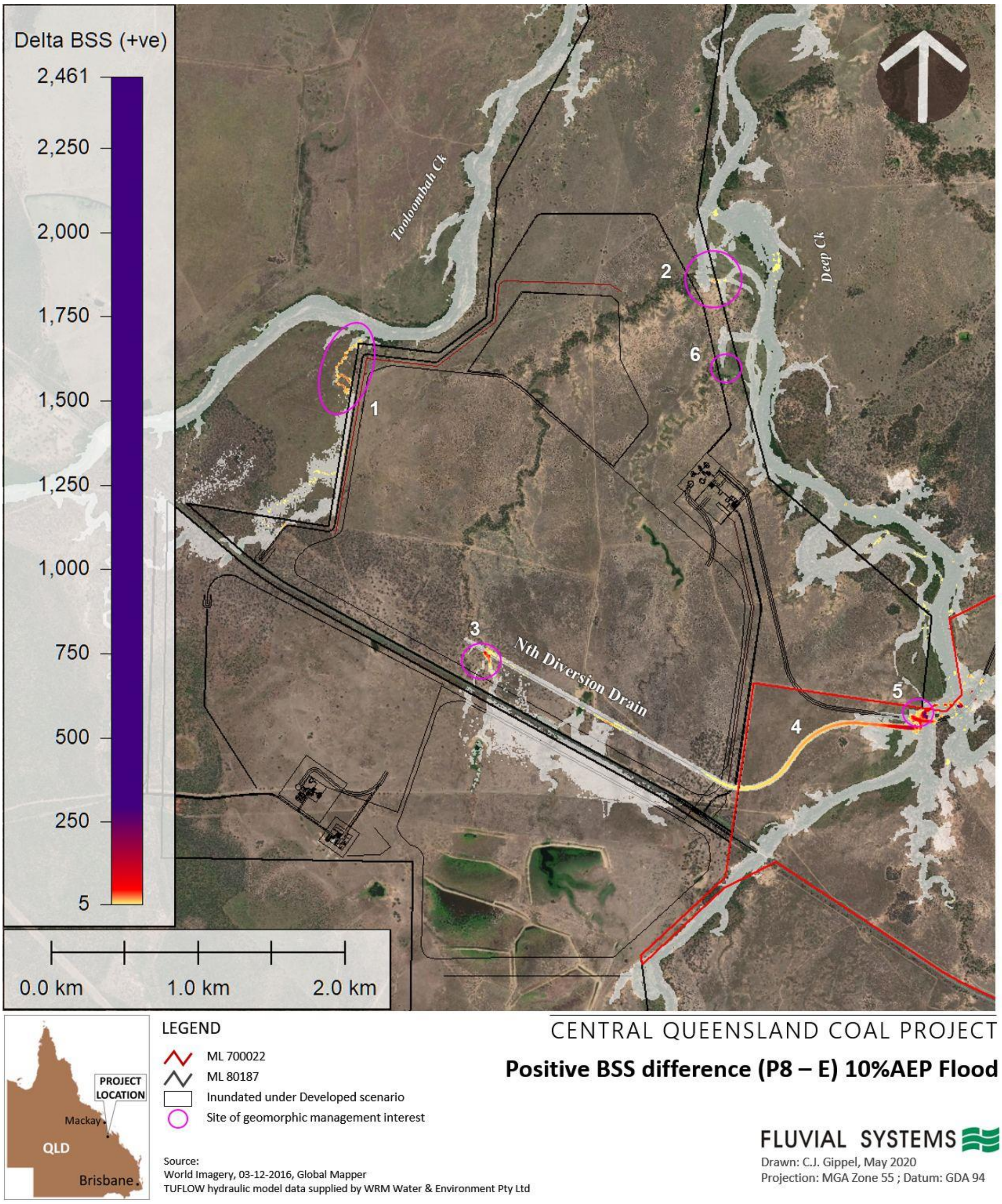


Figure 55. Modelled 1% AEP velocity under Developed P8 scenario. A small number of cells with values exceeding 4 m/s can be considered outliers.

4.1.3 Distribution of bed shear stress (BSS) under the Developed (P8) scenario

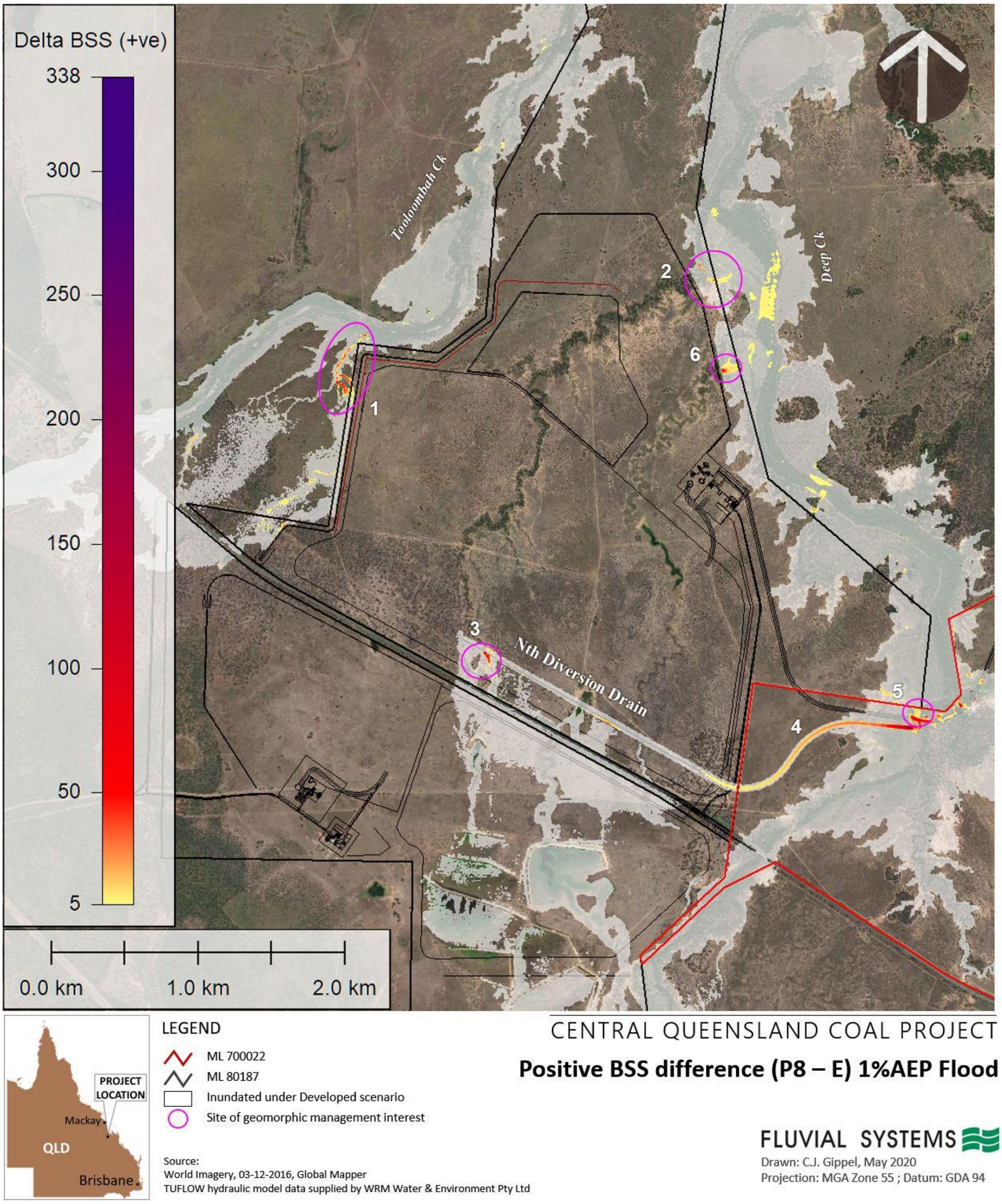
For areas inundated under both the Existing and Developed scenarios, as with velocity, there was negligible difference in bed shear stress (BSS) distribution. One notable exception was at the proposed rail bridge crossing over Deep Creek (Site 6 in Figure 56 and Figure 57). The bed shear stress at the bridge crossing was over 2000 N/m^2 under the 10% AEP event (Figure 56). Bed scour could be expected at this location. Under the 10% AEP and 1% AEP events, areas inundated under the Developed scenario, but not the Existing scenario, i.e. the

Northern Diversion Drain, and the western sub-catchments, had BSS values generally less than 200 N/m^2 (Figure 56 and Figure 57), which would be stable under good grass cover (Table 18).



Source:
World Imagery, 03-12-2016, Global Mapper
TUFLOW hydraulic model data supplied by WRM Water & Environment Pty Ltd

Figure 56. Difference in modelled 10% AEP BSS for Developed P8 and Existing scenarios. Only positive differences are shown.



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Positive BSS difference (P8 – E) 1%AEP Flood

Source:
World Imagery, 03-12-2016, Global Mapper
TUFLOW hydraulic model data supplied by WRM Water & Environment Pty Ltd

Drawn: C.J. Gippel, May 2020
Projection: MGA Zone 55 ; Datum: GDA 94

Figure 57. Difference in modelled 1% AEP BSS for Developed P8 and Existing scenarios. Only positive differences are shown.

Six locations were highlighted where the BSS values associated with the Developed P8 scenario were high enough to warrant monitoring and/or mitigation.

1. The 400 m-long area where drainage from the western sub-catchments concentrates, then discharges to Tooloombah Creek.
2. Discharge channel from Dam 1 to Deep Creek.

3. Where sub-catchments upstream of the mine discharge to the Northern Diversion Drain.
4. The Northern Diversion Drain, particularly the lower 500 m.
5. At the proposed rail bridge crossing over Deep Creek.
6. An isolated location near Dam 1 wall.

Sites 1 and 3 are risk areas for gully formation. They will require maintenance of good vegetation cover and regular monitoring of stability, plus preparation of a plan to fortify them with rock rip-rap should significant incision occur. Site 4, the lower end of the Northern Diversion Drain where it discharges to Deep Creek, will require fortification with rip-rap. Site 2 is likely to require fortification with rip-rap to eliminate the risk of formation of knickpoints that could migrate towards Dam 1 embankment. This is a risk with a high consequence. Site 5, at the proposed rail bridge crossing over Deep Creek, was predicted to experience bed scour. This risk can be managed by designing the bridge crossing in accordance with civil engineering design standards.

Site 6 was an isolated area about 50 × 50 m near Dam 1 wall with modelled increase in BSS and velocity for the 1% AEP event. Under the 1% AEP event this area was inundated to a depth of about 1 m, but it was not inundated under the 10% AEP event. Examination of the topography and modelled flood water levels revealed this risk area to be a localised high point where under the P8 scenario the flood water surface fell 0.13 m over a distance of 50 m. Under the Existing scenario, 1% AEP floodwaters would spread westward into the small creek, and the fall in water surface elevation was only 0.04 m. Confinement due to the dam wall locally increasing the water surface slope explained the increased BSS and velocity in this location. Even so, under the P8 scenario, the BSS at Site 6 was less than 80 N/m^2 and velocity was less than 1.7 m/s, so provided this area remains vegetated, the risk of scour of the surface would be low (Table 18).

4.2 Sodicity of Waste Rock

Waste rock comprises overburden and interburden material extracted as part of mining operations. Waste rock generally consists of large sized, blocky material. CDM Smith (2018d, p. 8-35) analysed and classified composite waste rock and potential coal reject samples in accordance with the indicative criteria for saline and sodic material. The salinity classification was medium, while the sodicity classification was very high. This was confirmed by RGS Environmental (2020).

Sodicity of waste rock and coal reject composite samples were very high, with Exchangeable Sodium Potential (ESP%) in the range 28.9% to 42.7%. According to the standard criteria, values of ESP% greater than 20% are considered very high. As pointed out by CDM Smith (2018d, p. 8-35), strongly sodic materials are likely to be dispersive and have problems with structural stability. In addition, sodic materials often have unbalanced nutrient ratios that can lead to macro-nutrient deficiencies, so often require the addition of fertilisers for successful rehabilitation. The soil management and rehabilitation procedures described in Chapter 11 of SEIS Version 3 (CQC, 2020), RGS Environmental (2020) and Engeny Water Management (2020a) address the issue of management of waste rock.

4.3 Potential Sediment Loads

The average total sediment (TSS) load of the entire Fitzroy Basin (139,159 km^2 monitored area) over the 7 year period 2009/10 to 2015/16 was 6,821,429 tonne (Table 5-40 in CDM Smith, 2018, p. 5-92). This equates to a mean specific sediment yield of 0.164 t/ha/yr. Consistent with this, Bartley et al. (2017) quoted average measured TSS load for the Fitzroy River at Rockhampton of 2,300,000 tonnes per year, which equates to a mean specific sediment yield of 0.17 t/ha/yr. The modelled mean specific sediment yield from the Styx catchment was 0.3 t/ha/year (Bartley et al., 2017).

CDM Smith (2018b) made an assessment of the sediment loads generated from the Mamelon property under the current grazing land use. Shellberg and Brooks (2013) were quoted as reporting cattle grazing as a primary agent for accelerating gully erosion on highly-erodible sodic soils. Central Queensland Coal has committed to destocking the majority of the Mamelon property, which, along with implementation of engineered erosion and sediment controls, CDM Smith (2018) predicted would result in reduced sediment load to the Styx River, and thus, to the GBR.

Given the lack of local data for the Styx catchment, CDM Smith (2018b) estimated erosion for land under grazing using the HowLeaky? model developed for the Eden Bann Weir EIS. This model used best available soil, vegetation and soil nutrient information for two representative soil types at Yaamba and Rockwood in Central Queensland. Land use and management comprised three grazing regimes to represent potential current land use practice. The model used estimates of sediment yield from floodplain land for these three grazing regimes. Low stocking pasture 44% October yielded 0.34 t/ha/yr, Moderate stocking pasture 34% October (C) yielded 0.72 t/ha//yr, and Excess stocking pasture 20% October (D) yielded 1.6 t/ha/yr. On upland slopes, Moderate stocking pasture 34% October (C) yielded 1.9 t/ha/yr (CDM Smith, 2018b, Table 5-42, p. 5-95). In *Table 5-45 Estimated annual pollutant load for ML 80187* and *Table 5-46 Estimated annual pollutant load for ML 700022*, CDM Smith (2018b, p. 5-98) multiplied these specific yield estimates by the surface area of ML 80187 (1,748 ha of floodplain and 121 ha of upland slopes) and by the surface area of ML 700022 (535 ha of floodplain and 52 ha of upland slopes) to give total load of sediment per year. These tables express the result in t/ha, but this appears to be an error, as the load would be in tonnes per year. The values range from 595 to 2,797 for floodplain land on ML 80187, and 182 to 856 for floodplain land on ML 700022. Engeny Water Management (2020b) recalculated the existing sediment load using the same specific yield estimates quoted by CDM Smith (2018b), arriving at averages of 4,500 t/yr from Mamelon property, and 537 t/yr from ML 700022, for a total of 5,037 t/yr. This equates to an average existing specific yield of 0.72 t/ha/yr.

CDM Smith (2018b, p. 5-123 to 5-126) applied a RUSLE model to estimate sediment soil loss from the Mamelon property under conditions of construction disturbance. The results indicated mean specific sediment yield of 67 to 1,392 t/ha/yr. CDM Smith (2018b) proposed that with engineering sediment and erosion controls, this could be reduced to 3 to 70 t/ha/yr. These would be considered very high rates of sediment yield. Engeny Water Management (2020b) re-calculated the average annual sediment loss from the majority of the disturbance area (1,272 ha) under worst-case operational conditions to be 219,570 tonne, which equates to a specific sediment yield of 173 t/ha/yr. The average specific yields from 6 sub-areas ranged from 53 to 420 t/ha/yr. It was pointed out by Engeny Water Management (2020b) that these were conservative estimates and actual sediment loss from the waste rock dump slopes was proposed to be mitigated by a number of controls.

Engeny Water Management (2020b) estimated the worst-case operational mean specific sediment yield with adopted controls in place over the combined Mamelon property, offset areas within the Mamelon property, and disturbance area. The total was 2,297 t/yr, or mean specific sediment yield of 0.37 t/ha/yr. This represents an approximate halving of the sediment yield compared to the existing scenario.

The conceptual Erosion and Sediment Control Plan produced by Engeny Water Management (2020a) pointed out that CQC intends to destock the majority of the Mamelon property to allow for the natural regeneration of vegetation. It was assumed this would reduce sediment generation from the Project area as the vegetation communities within the riparian corridors regenerated without being subjected to ongoing grazing pressures. Otherwise, the Plan focused on erosion and sediment control measures during construction and operation phases of the mine.

5.0 Monitoring and Mitigation

5.1 Monitoring

Geomorphic monitoring should be undertaken using objective, scientifically sound methods, following a BACI (Before/After/Control/Intervention) design. Also, the monitoring should target areas where this assessment predicted the risk of geomorphic instability would be greatest (Table 26). The foundation of the recommended approach to monitoring is topographic survey at targeted risk areas, repeated every year for 3 years, and then either every five years, or after every flood event exceeding the 5 yr ARI event. Ideally this should be done using LiDAR technology, although intensive ground survey would also be acceptable. It will be necessary to identify control reaches that are also monitored, away from the influence of the CQC Project. The monitoring principle is to characterise the degree of change at the control areas and use this to set the tolerance for change in the target 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 rely only 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. However, regular (monthly) visual inspections that involve fixed photo points and completion of standard documentation could support the less frequent survey data by potentially providing early detection of change.

Table 26. Target sites for geomorphic process monitoring and mitigation.

Site	Location	Mitigation	Monitoring
1.	The 400 m-long area where drainage from the western sub-catchments concentrates, then discharges to Tooloombah Ck	Ensure good vegetation cover	YES
2.	Discharge channel from Dam 1 to Deep Creek	Rip-Rap	YES
3.	Where sub-catchments upstream of the mine discharge to the Northern Diversion Drain	Ensure good vegetation cover	YES
4.	The Northern Diversion Drain, particularly the lower 500 m (likely to also apply to the Southern Diversion Drain)	Construct to civil engineering design	YES
5.	At the proposed rail bridge crossing over Deep Creek	Construct to civil engineering design	YES
6.	An isolated location near Dam 1 wall.	Ensure good vegetation cover	YES

5.2 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. Mitigation of the impacts of accelerated sediment delivery to the drainage system, and then to the Great Barrier Reef is an established objective (Department of Agriculture, Water and the Environment, 2018). This can be achieved through vegetation management, maintaining complete vegetation cover over hillslope, river bank and floodplain surfaces. Grass provides good resistance to erosion on hillslopes and small gently sloping drainage channels, but forest, with tree, shrub and ground cover, is preferable on steep land, larger drainage channels and river banks.

In general, the surface water management works should follow standard civil engineering design principles. All diversion drains and diversion banks will be designed with geotechnically and erosionally stable batter slopes (Engeny Water Management, 2020a).

This report draws particular attention to the need for fortification of the outlet from Dam 1 to Deep Creek, and the lower 500 m of the Northern Diversion Drain (Sites 2 and 4 in Table 26). This report also draws particular attention to the 400 m-long area where drainage from the western sub-catchments concentrates and then discharges to

Tooloombah Creek, where sub-catchments upstream of the mine discharge to the Northern Diversion Drain, and an isolated location near Dam 1 wall, which will require maintenance of good vegetation cover in order to remain at low risk of surface scour (Sites 1, 3 and 6 in Table 26).

The need for application of mitigation measures over the life of the mine would be triggered by unexpectedly large change in morphology identified through monitoring. The most appropriate response would need to be assessed at the time.

6.0 Conclusion

Repeatable methods were used to characterise geomorphological attributes of the CQC Project area. Most of the stream reaches were in a stable, moderate geomorphic condition. One migrating bend on the Styx River was identified as a significant source of sediment to the river. No knickpoints or zones of major geomorphic instability were observed on the mapped watercourses. However, the area contains a significant number of alluvial gullies and small tributaries incised into old alluvium. These are potentially sources of high sediment loads to the river system, and thus the Great Barrier Reef.

The risk of erosion of the channels and floodplains was assessed using the method of maximum permissible bed shear stress and velocity, with the hydraulic variables modelled as part of the flood study. This assessment found that the overall risk of rapid and significant geomorphic change in Tooloombah and Deep creeks and Styx River due to the proposed mining activity was negligible to low.

Geomorphic monitoring should include topographic survey of target areas, identified by this study as being at higher risk of geomorphic instability. Surveys should be repeated every year for 3 years, and then either every five years, or after every flood event exceeding the 5 yr ARI event. 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 geomorphic change identified through monitoring. The most appropriate response would need to be assessed at the time.

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