TECHNICAL REPORT

03

Updated flooding and hydrology assessment

Appendix O N2N erosion potential and fluvial geomorphology assessment

NARROMINE TO NARRABRI PROJECT

Flooding and Hydrology - Technical Note 17 - N2N Erosion Potential and Fluvial Geomorphology Assessment

Technical Report

ARTC Inland Rail

Revision 0

13 July 2022

Executive summary

Inland Rail – Narromine to Narrabri

Inland Rail is a 1,700km national freight rail line that will connect Melbourne and Brisbane. The Narromine to Narrabri section (N2N) is one of 13 individual projects that make up the overall program of works in Victoria, New South Wales and Queensland. It comprises 306km of new rail track in a “greenfield” environment and passes through farmland and forested areas.

An Environmental Impact Statement (EIS) was submitted to the NSW Department of Planning and Environment (DPE) in November 2020 and placed on public exhibition until February 2021. The EIS has been subject to a number of queries and clarifications and remains under review at the time of writing this report, June 2022.

The new rail track will be built on a series of earth embankments and through cuttings that cross natural rivers and creeks. Bridges and culverts will be constructed at watercourse crossings to allow water to flow under the railway.

It is understood that construction of Inland Rail could alter the natural conditions of the watercourses. At the design stage of the project, a key objective is to minimise potential impacts on the natural flood regime so that, wherever possible, natural flow conditions would be maintained.

It is possible that where watercourse flows are concentrated through new structures, the flow velocity could increase above the natural conditions. If the increased velocity is greater than the erosion threshold velocity of the channel bank or floodplain, then scour, lateral erosion and gullying could occur.

Study Objectives

This study has completed an assessment of erosion threshold values at 24 bridge and culvert locations between Narromine and Narrabri to provide an indication of the expected findings from site specific assessments of the erosion threshold velocity to be used in detailed design. The study has been based on:

– A literature review of recommended velocity limits in commonly used engineering guidelines and standards.
– Geotechnical assessment of erosion potential based on soil testing results and site observations.
– A geomorphological review of erosion potential, supported by observations at the 24 selected sites.

Existing flood erosion design guidelines and standards

There are a number of existing design guidelines that are referenced by engineers when planning new infrastructure projects. These include:

– Austroads Guide to Road Design (Part 5, 2021 and Part 5B, 2013)
– Best Practice Erosion and Sediment Control (International Erosion Control Association, Australasia (IECA, 2008)
– Landcom ‘Blue Book’: Managing Urban Stormwater: Soils and Construction (2004)
– Hydraulic Engineering Circulars (HEC) 14, 18 and 23
– Gippel *et al.* (2008); White *et al.* (2014); Gippel (2020)

These design guidelines consider the threshold velocity at which erosion is likely to occur in a range of soil conditions and flood durations. The extent of vegetation cover is also taken into account, as this helps to bind soils together and also reduce velocities.

There are some differences between the reviewed guidelines but, for the soil conditions between Narromine and Narrabri, the erosion threshold velocities can be summarised as:

– Between 1.0m/s to 2.0m/s for stiff to hard clays.
– Up to 0.5m/s for silts and sands with no vegetation cover. Flood velocities should be higher than this to maintain hydraulic capacity and avoid siltation.

– Between 1.5m/s to 2.5m/s or more if there is good vegetation cover.
– 2.0m/s for shallow flows across grassy floodplains.

Site investigation results

Site inspections were carried out on selected watercourses between Narromine and Narrabri between 8 – 11 February 2022.

Geotechnical calculation of erosion threshold velocity

In geotechnical analysis, it is usual to use more than one method for estimating engineering parameters. Judgement and site knowledge is then used to decide the most appropriate parameters to be adopted. An assessment of the theoretical erosion potential was undertaken at each site based on four established methods:

1. The Erodibility Index Method (Annandale, 1995).
2. Design of Reinforced Grass Waterways (CIRIA Report No. 116, Hewlett *et al.*,1987).
3. The relationships between critical velocity and mean grain size (Briaud, 2008).
4. Indirect relationship between the erodibility of a soil and its plastic index observed from research works by Hanson *et al.* (2010, 2011), Wahl *et al.* (2009), and Shewbridge *et al.* (2010).

Results indicated that:

– Channel banks and floodplains with a high clay content were estimated to have erosion threshold velocities ranging from 1.2m/s at Wallaby Creek, to 4.5m/s at CH697.901, with the average being around 2.1m/s.
– Channel boundary materials with a high silt and sand content are expected to be more erodible (i.e. moderate erodibility) than clay-rich soils (low erodibility). Loose sand bed material is highly erodible.
– Dispersive erosion associated with soils tested as dispersive was not commonly observed at the study sites.

Geomorphological investigations

Geomorphological characteristics of the selected watercourses were assessed in conjunction with the geotechnical analysis. Results indicated:

– The watercourses observed typically have clay-rich banks and highly mobile coarse sand beds.
– Sand movement along channel beds is a natural occurrence and should not be obstructed. Velocities through culverts with high bed loads should have sufficient hydraulic capacity to maintain sediment throughput. If velocities are too low, sedimentation, culvert blockages and upstream deposition could occur. This should be considered if an overarching velocity QDL limit of 0.5m/s is adopted for unprotected soils.
– The presence of existing erosion within a watercourse provides the best indicator of potential future erosion. Natural flow velocities are variable across the river cross section and are affected by factors such as bed slope, roughness, channel sinuosity, trees, large woody debris and bank vegetation. Sites with high modelled flow velocities did not necessarily correlate with areas of existing erosion. Geomorphological characteristics of the watercourse should, therefore, be considered when assessing the erosion potential, for example lateral channel migration along the outer banks of meander bends.
– The presence of dispersive soils should be considered during design and planning for construction works, although it was noted that site investigations found soils show less visible evidence of dispersion that predicted by geotechnical test results. In areas of dispersive soils, bare soil exposure time should be limited, and surfaces rehabilitated and revegetated as soon as is practicable after construction.

Conclusions

Erosion threshold velocities should be reviewed by a geotechnical engineer and soil / erosion specialist (geomorphologist) as part of the detailed design. On the basis of the 24 sites inspected, it was found that:

– The erosion threshold velocity for unprotected surfaces was generally above 1.0m/s (excluding mobile sand beds in creeks).

- The erosion threshold velocity for areas with cohesive clays and / or good vegetation cover was generally above 2.0m/s.
- Vegetation cover improves surface stability and reduces the likelihood of erosion.
- Increases in existing velocities should consider both the erosion threshold velocity and geomorphological form of the watercourse: creeks with a high bed load / sand bed should have sufficient velocity to promote natural movement of bed materials and prevent adverse sedimentation. Ideally, design velocities in the creek bed would be sufficient to mobilise the sandy bed sediment, but lower than the erosion threshold velocity of the channel bank material.
- Detailed design and proposed erosion controls should consider natural geomorphological processes and should be reviewed by a geomorphologist.

The authors

The authors of this report are experienced in geotechnical engineering and geomorphology:

Dr Chi Fai Wan – Dams geotechnical engineer specialised in soil erosion problems

Chi Fai Wan has over 37 years of post-graduate experience, principally in the field of dam engineering, including embankment and concrete dams. Wan has specialist skills in internal erosion of embankments, having researched this aspect for his doctoral thesis. Wan also has specialist skills in safety risk assessments for dams. He has published prolifically during his career and was a guest lecturer in Dams Engineering Courses at the Sydney University in 2019, and at the University of New South Wales in 2009, 2018 and 2019.

Dr Lucy Ellis - Geomorphologist

Dr Lucy Ellis has experience of consultancy and research projects in a variety of environments and landscapes. Her work has ranged from strategy/management planning studies and option assessments for coastlines and rivers, through to detailed investigations, recommendations, and remediation design for engineering projects. She has international experience in the USA, New Zealand, Java, Papua New Guinea, and Bangladesh, as well as in the UK and here in Australia.

In her fluvial geomorphological capacity, she has worked on a diverse range of projects; from small-scale bank erosion assessments to large-scale assessments of major river systems. This has included catchment-scale audits, assessments of river change to specific inputs and rehabilitation recommendations at the reach-scale.

Professor Roger Moore – Geomorphologist –peer review

Professor Roger Moore is Global Technology Leader for Geoscience and Engineering Geology at Jacobs. He is a UK Registered Ground Engineering Adviser, Chartered Geologist, and Fellow of the Institution of Civil Engineers and Geological Society of London. Roger is also Emeritus Professor of Applied Geomorphology at the University of Sussex, convening MSc teaching and supervising PhD research since 2010.

With over 30 years' experience in commercial practice, he is a global subject matter expert in onshore and offshore engineering geomorphology, geohazards, land stability reports, ground investigation, survey and monitoring, modelling and prediction, sediment budgets, risk analysis and mitigation. This capability and experience has been applied to national policy advice, strategic planning and development, environmental and nuclear safety cases, transport routing, master planning, asset inventory, feasibility studies, cliff instability and coastal erosion, slopes and landslides, scour and deposition, natural disaster response, ground condition and behaviour assessments, climate change prediction, impacts of natural environment processes, design and site supervision of civil protection and land stabilisation schemes.

Roger has co-authored eight industry practice publications and over 60 journal articles. He is an editor of the Journal of Landslides and the Quarterly Journal of Engineering Geology and Hydrogeology.

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Acronyms and Abbreviations

Acronym	Description
AEP	Annual Exceedance Probability
ARTC	Australian Rail Track Corporation
ASC	Australian Soil Classification
DCA	Drainage Control Area
DPE	NSW Department of Planning and Environment
EIS	Environmental Impact Statement
ETV	Erosion Threshold Velocity
FHAR	N2N EIS Flooding and Hydrology Report (2022)
IECA	International Erosion Control Association, Australasia
JGHD	Jacobs GHD Joint Venture
LWD	Large Woody Debris
N2N	Inland Rail between Narromine to Narrabri
NRAR	Natural Resources Access Regulator
PIR	Preferred Infrastructure Report
QDL	Quantitative Design Limit
TUFLOW	Hydraulic and hydrodynamic 2D flood modelling software

1. Introduction

1.1 General

Inland Rail between Narromine and Narrabri comprises 306km of new rail line in a greenfield environment. The rail will be constructed on a series of embankments and in cuttings that will include cross drainage structures (bridges and culverts) to preserve natural water flows in creeks and floodplains.

The N2N project includes approximately 606 reinforced concrete box culverts of varying sizes and 75 bridges. These are located in creek lines and extend onto flood plains. A number of flood relief culverts are located within floodplains to allow flood levels to equalise on either side of the rail embankment to reduce the hydrostatic head build up on the upstream side.

An Environmental Impact Statement (EIS) was submitted to the NSW Department of Planning and Environment (DPE) in November 2020 and placed on public exhibition until February 2021. At the time of writing (June 2022), the EIS is now in the Response to Submissions Stage, and any issues will be addressed in a Submissions report and / or Preferred Infrastructure Report.

A key concern has been potential impacts from the N2N project on the existing flood regime and in particular the risk of erosion and scour at drainage culverts and bridges where flood flows pass under the rail embankment.

In order to control this risk, guidelines have been established for assessing the change in flood regime before and after Inland Rail, defined by DPE and the Natural Resources Access Regulator (NRAR). These guidelines are referred to as Quantitative Design Limits (QDLs) and cover a range of flood criteria including afflux, velocity, flood hazard and flood duration for flood events up to and including the 1%AEP flood (1 in 100 year event).

This technical report focuses on the potential for erosion and scour resulting from changes in flow velocities at structures under the N2N section of Inland Rail.

1.2 Objective

The objective of this technical report is to provide preliminary advice on the potential velocity threshold for erosion at culverts and bridge structures on the N2N proposal.

This advice is additional to the modification of the N2N proposal boundary included within the Preferred Infrastructure Report (PIR), through the creation of drainage control areas (DCAs). The DCAs would provide additional space in which to reduce velocities and manage potential erosion risks.

Further site-specific assessment, investigations, soil testing and analysis would be expected at the detailed design stage for individual structure locations.

1.3 Approach and methodology

The velocity QDLs provide for an experienced geotechnical or scour / erosion specialist to establish alternative soil erosion threshold velocities. A review of typical values for the erosion threshold velocity was carried out for the N2N project by a fluvial geomorphologist specialising in bank erosion and morphological change, and a dams engineer with a geotechnical and hydraulic engineering background, specialising in soil erosion.

The approach and methodology was as follows:

1. Review of existing erosion and scour design guidelines, relevant technical papers and geomorphological / geotechnical data already collated and collected for the N2N project. A summary is presented in Section 2.1, with a detailed review in Appendix A.
2. Assessment of culvert and bridge sites based on modelled reference design flows and velocities (see Section 1.3.1); geomorphological conditions and soil type / characteristics (Australian Soils

Classification (ASC, developed by Isbell, 1996)) mapping and existing geotechnical observations and testing (FHAR, 2022; summarised in Section 2.3.1).

3. Classification of bridges and culverts based on their potential for scour or bank erosion in relation to the variables assessed for the FHAR (2022).
4. Selection of bridges and culverts representative of the different classifications for more detailed site investigations. Twenty-four sites were selected and visited. Site visit findings and geotechnical calculations assessing pragmatic acceptable erosion velocity thresholds and the locations of existing erosion are presented in Appendix B and summarised in Sections 4 and 4.1. Maps showing site visit locations and other key features are presented in Appendix C.
5. Comparison of desk study findings and site observations to compare existing and design velocities from the reference model with assessed erosion threshold velocities and presence of existing erosion. Recommendations for management and mitigation of erosion are given (see Sections 4.3 and 5).

1.3.1 N2N Velocity Data

This study uses data obtained from the N2N hydraulic reference model, as reported in the FHAR (2022). This TUFLOW model is based on a 10m grid. In particular, the geotechnical calculations and geomorphological observations referenced the included 1%AEP flood event velocities and duration of flow. Model inputs and outputs were also used to calculate stream power (i.e. flow velocity, depth and bed slope) and Results in this report are based on a TUFLOW 10m grid resolution.

Modelled flood behaviour is typically heterogenous as a function of the hydraulic model routing predicted flows through the design grid mesh. In reality, however, greater flow variability would be expected within a 3D flow structure. Considerable velocity variability would be expected, ranging from the maximum thalweg flow velocities to slow flowing or even reverse flows in backwaters. The reference model captures some, but not all, of this variability.

Reference model design velocities cited in this study have been calculated on the basis of a reach-averaged maximum velocity across the rail corridor for the 1%AEP event. i.e. an average of 20m upstream, at the rail centreline and 20m downstream of the structure. This average maximum velocity either side of the culvert takes into consideration potentially higher velocities on either the upstream or downstream side of the culvert. When considering potential erosion at the structure, the peak velocity lasts for a short duration and erosion over this time will be limited. An average of the maximum upstream and downstream values is therefore considered to be appropriate for this analysis.

1.4 Limitations

This report has been prepared by JacobsGHD IR Joint Venture (JacobsGHD) for ARTC and may only be used and relied on by ARTC for the purpose agreed between JacobsGHD and the ARTC as set out in section 1.2 of this report.

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2. Literature review and desk top studies

The first step in estimating an erosion threshold velocity was to review existing standards, guidelines and technical papers and to undertake a theoretical analysis based on soil type and particle size.

2.1 Commonly used industry references for velocity thresholds

2.1.1 Reviewed guidelines and standards

A review of key industry standards and guidelines for velocity thresholds for erosion is provided in Appendix A, Section A-1, and summarised below. Standards and guidelines reviewed were:

– Austroads Guide to Road Design (Part 5, 2021 and Part 5B, 2013).
– Best Practice Erosion and Sediment Control (International Erosion Control Association, Australasia (IECA, 2008)).
– Landcom ‘Blue Book’: Managing Urban Stormwater: Soils and Construction (2004).
– Hydraulic Engineering Circulars (HEC) 14 (2006), 18 (2012) and 23 (2009).
– Gippel *et al.* (2008); White *et al.* (2014); Gippel (2020).

2.1.2 Factors influencing erosion potential

The review indicated that the standards are broadly consistent in their conclusions, which can be summarised as follows:

– Channel erosion is influenced by the erodibility of bed and bank materials, density and type of vegetation, bedslope and erosivity / duration of flows. Flow erosivity is controlled by the velocity and, in some cases, quantity of sediment transported.
– The presence of vegetation significantly improves channel resistance. Austroads (2013) assumes that native species and tussock grass form 50% stable cover. However, once taller than 50mm this, vegetation can significantly impede flows. Gippel (2020) indicates that the type of vegetation can significantly impact channel and floodplain erodibility. Turf provides the highest protection, with permissible velocities of up to 2.4m/s and bunch grass / annuals as low as 0.8m/s.
– Sedimentation can be problematic once velocities drop below a certain value; 0.5m/s as a general rule in grassed channels (Austroads, 2013) or if structures are not adequately maintained to preserve their required hydraulic capacity (IECA, 2008).
– There are differences in opinion regarding channel material erodibility. For example, Austroads (2021) indicates that hard clay soils are more resistant than sands and small to medium gravel, with maximum allowable stream velocities of 2m/s. However, in IECA (2008) and Austroads (2013), maximum values of 0.9m/s are given for Vertosols and fine texture-contrast soils, which are dense clays. Modelled bed slopes for this project are a maximum of 2% for bridge sites and 3% for culverts. Therefore, the minimum velocity threshold specific to the conditions along the N2N project alignment using IECA (2008, Table A28) and Austroads (2013, Table 2.6) for easily erodible soils would be in the order of 1.1m/s at bridges and 1.0m/s at culverts.
– Landcom (2004) and Gippel (2020) both consider the duration of flows. Landcom (2004) indicate that natural vegetation, while less effective than artificial stabilisation, can allow increases in allowable velocity of between 0.7m/s (in erodible soils during long duration floods) and 1.3m/s (in resistant soils during short duration floods). Gippel (2020) indicates that bare clays are resistant to flows of over 1m/s if flow duration is below 4 hours. This increases to 20 hours with average grass cover and indefinitely with good grass cover.
– Gippel *et al*. (2008) and Gippel (2020), indicate that stiff clays are less likely to be eroded if flows are turbid, with maximum permissible velocities increasing from 1.1m/s to 1.5m/s. Similarly, White *et al*. (2014), indicate reduced maximum velocities in limited capacity creeks (i.e. those where sediment supply was limited).

2.1.3 Summary of reported permissible erosion threshold velocities

The review of common existing industry guidelines indicates the following maximum permissible velocities (see Appendix A for referenced tables):

– Table A.7.1 (Austroads Part 5, 2021) indicates that stiff to hard clays have maximum allowable stream velocities of 1m/s-2m/s.
– Table A.7.2 (Austroads Part 5B, 2013; Table A28 in IECA, 2008) indicates permissible velocities of 1m/s in easily erodible soils and 1.3m/s in resistant soils, assuming natural vegetation cover of 50% and bed slopes of less than or equal to 3%.
– Table A.7.4 (IECA, 2008) indicates that stiff clay soils with no surface protection have allowable velocities of 1.1m/s, with sandy soils having allowable velocities of 0.4-0.5m/s. IECA (2008) also indicates that dispersive soils can erode at low velocities and should not be left bare.
– Table A.7.5 (Landcom, 2004) indicates critical velocities of between 1.2m/s and 1.8m/s (depending on length of inundation) in moderately erodible materials with good vegetation cover.
– Table A.7.6 (Gippel *et al*., 2008 and Gippel, 2020) indicates that stiff clays, which were typical channel materials along the N2N project, have a maximum permissible velocity of 1.5m/s.
– Table A.7.7 (Gippel *et al*., 2008 and Gippel, 2020) indicates that in easily erodible soils any form of vegetation would result in a maximum permissible velocity of 0.8m/s, rising to 2.4m/s for grass with a dense root system. Soils along the N2N project are typically of low to medium erodibility and would be expected to remain stable at higher velocities than those indicated by Gippel. It is also noted that in shallow flows, e.g. across grassy floodplains, threshold velocities would be at least 2.0m/s.
– Table A.7.8 (White *et al*., 2014) indicates that incised vegetated channels have guideline maximum velocities of 1.5-2.5m/s for 2%AEP floods (i.e. a conservative value for the 1%AEP flood).
– Figure A.7.1 (Gippel, 2020) indicates that clay soils with average grass cover can withstand velocities of over 1m/s for up to 20 hours. However, this is conservative when compared to Figure A.7.4 (Hewlett *et al*., 1987) and Figure A.7.5 (compiled from various sources), which indicate that soils with poor grass cover can withstand flows of 1m/s for around 40 hours – longer than the modelled duration for the assessed sites.

In summary, the existing guidelines recommend erosion threshold velocities of:

– Up to 0.5m/s for loose sands and highly erodible soils with no vegetation cover.
– Between 1.0m/s to 2.0m/s for stiff to hard clays.
– 2.0m/s for shallow flows across grassy floodplains.
– Between 1.5m/s and 2.5m/s or more if there is good vegetation cover.

2.2 Geotechnical erosion potential assessment

2.2.1 Comparison of erodibility potential assessment methods

In geotechnical analysis, it is usual to use more than one method for estimating engineering parameters. Judgement and site knowledge is then used to decide the most appropriate parameters to be adopted, based on the outcome of the multi-approach analysis.

Four methods have been considered for assessing the erosion potential from a geotechnical perspective:

1. The Erodibility Index Method (Annandale, 1995).
2. The design of grass reinforced waterways (Hewlett *et al*.,1987).
3. The relationships between critical velocity and mean grain size (Briaud, 2008).
4. Indirect relationship between the erodibility of a soil and its plastic index observed from research works by Hanson *et al.* (2010, 2011), Wahl *et al.* (2009), and Shewbridge *et al.* (2010).

More detailed explanations of the analysis procedures of the above four methods are presented in Sections A-2-2 to A-2-4 of Appendix A.

Table 2.1 provides a summary comparison of the four reviewed methods, together with the merits and limitations of each. Methods 1 to 3 are based on field or laboratory tests and hence are expected to provide more reliable prediction of erodibility potential based on available soil data and results from hydraulic assessment. Due to this reason and also because they make the most use of available hydraulic and soil data, these three methods were used in this erosion potential assessment. Method 4 was not used in the assessment of erodibility potential of the selected sites in the current study as it is only a qualitative method, only applies to cohesive soil, and does not take into account hydraulic conditions. However, Method 4 can be considered as an additional check for sites with cohesive soils if more reliable data on soil plasticity are available in later design stages.

Table 2.1 ***Comparison of** erodibility potential assessment methods*

Method of assessment	Merits	Limitations
Method 1 – Erodibility Index (Annandale, 1995)	– Based on more than 150 case studies – Calculates stream power, *P*, that takes into consideration predicted hydraulic conditions – Calculates Erodibility (Kirsten) Index, K_h, that takes into account available soil properties – Sound methodology based on many case studies – Method used internationally	– Does not provide a direct estimate for the threshold velocity for initiating erosion – Does not consider duration of flow – Does not consider effects of vegetation cover – Does not consider dispersivity of soil – Available soil data may not be representative if boreholes are at a considerable distance from the site
Method 2 – Erosion potential along grassed waterways (Hewlett *et al.*, 1987)	– Based on field testing – Provide an estimate of the threshold velocity for initiating erosion. – Hydraulic conditions represented by flow velocity – Consider flow duration that is known to be an influence factor for initiating erosion – Consider surface protection – Sound methodology based on lots of field testing – Developed for artificial slopes in the UK, but adopted as a guideline for studies internationally, including in Australia and velocity and ground cover are the governing factors.	– Does not consider soil properties – Does not consider dispersivity of soil – In many cases, flow duration is unknown and has to be estimated / assumed
Method 3 – Critical Velocity based on Mean Grain Size (Briaud, 2008)	– Based on laboratory testing on many different types of soils – Hydraulic conditions represented by flow velocity – Sound methodology with empirical relationship based laboratory erosion testing	– Does not consider duration of flow – Only applicable to bare soil with no surface protection – Does not consider dispersivity of soil – Particle size distribution data, and D_{50} are not available. In particular if fine-grained soils are involved, particle size analysis for the fine fraction is usually not available. – Available soil data may not be representative if boreholes are at a considerable distance from the site is usually not available.
Method 4 – Indirect relationship between erodibility and plastic index (various, see Appendix A, Section A-2-4)	– Simplicity	– Qualitative assessment only – Applicable to cohesive soils only – Does not consider hydraulic condition – Does not consider dispersivity of the soil – High uncertainty in the relationship between erosion rate index and plastic index

Method 1 (Annandale, 1995) and Method 2 (Hewlett *et al*.,1987) were used to estimate the erodibility potential in the current study. Method 3 was used only to assess the erodibility of non-cohesive granular soils (sand-sized or coarser) which do not have vegetation cover (e.g. bed sediments). Method 4 is not recommended for use in this study because it is a qualitative method, and also because of the high uncertainty in the relationship between erodibility and plastic index of a soil.

2.2.2 Soil properties

Assessment of soil properties was based on:

– Observation of soil type and condition on site.

– Judgement based on simple testing of plasticity (the thread test) and dispersivity (Emerson crumb) on small soil samples collected from site, e.g. from river bank, which are common field tests done by geotechnical engineers for understanding engineering properties of soils.

– Soil data shown in borehole and test pit logs and laboratory testing on soil samples from these boreholes and test pits. Note, however, that relevant boreholes and test pits may be some distance from the selected test sites and the soil data may be representative of floodplain conditions, rather than channel materials. This information should be confirmed as part of the detailed design.

2.3 Fluvial geomorphology

2.3.1 Building on the EIS Flooding and Hydrology Assessment Report

This study builds on previous work presented in the updates to the geomorphology sections within Technical Report 3 of the N2N EIS – Flooding and Hydrology Assessment Report (FHAR 2022).

The geomorphology assessment conducted for the FHAR was used to develop an understanding of the existing functioning, sediment dynamics and hydraulics of watercourses along the proposal. This involved a review of:

– Available aerial imagery.

– Ground level photographs taken previously during the EIS assessment process.

– 1:250,000 geology and soils mapping.

– River Styles classifications (using methodology defined by Brierley and Fryirs, 2003).

– Geotechnical information / reports conducted for the proposal.

Further details are provided in the geomorphology section of the FHAR and summarised in the following sections.

2.3.2 Regional Watercourse Assessment

Initially, a regional assessment of 81 watercourses conducted for the FHAR was screened to identify any patterns e.g. in Australian Soil Classification soil type, geotechnical unit (taken from the Geotechnical Interpretation Report, JGHD, 2020) or River Styles fragility could be observed.

Prior to the assessment, it was hypothesised that there would be a link between ASC soil type and location of erosion. However, a review of available geotechnical investigation data indicated that, while the ASC mapping was broadly accurate (see maps in Appendix C), there were many factors that contributed to soil erodibility in the study area. Gully erosion and floodplain degradation was observed in areas of Sodosols, particularly those associated with the ‘Cobocco’ Soil Landscape (extent shown on maps in Appendix C) e.g. downstream of the proposed culvert at Kickabil Creek) and around Narrabri (e.g. south of the Namoi River at the proposed bridge). However, there were also many intact areas of floodplain. As well as dispersive Sodosols, other soil types also have a high potential for erosion, such as Vertosols in the basalt outwash plains and alluvial Chromosols.

Local vegetation coverage was also found to be a significant factor in preventing erosion. Gullying is thought to be associated with areas cleared of vegetation, largely in agricultural areas, or where livestock have damaged topsoils.

2.3.3 Watercourse morphology / erosion relationship

This screening process indicated that the morphology of the watercourse was more likely to be a predictor of existing in-stream erosion that velocity values alone. Larger incised sinuous channels were more likely to show signs of in-channel erosion than those which were smaller or less sinuous. Meandering channels flowing across the Keelindi Alluvial Plains (between CH595 and CH633.5) and Basalt Mesa Plains (CH686 – CH731) were particularly susceptible to lateral erosion under existing conditions.

There are several different planform morphologies within the study area, which each behave differently in response to flows.

- Meandering, sinuous watercourses tend to erode laterally along the outer bank of a bend. The focus of erosion is typically just after the apex of a bend, with associated sediment deposition forming point bars along the inner bank. Many of the watercourses assessed had variably sinuous channels, in that low sinuosity reaches are separated by acute bends, or series of bends. The channel response to disturbance depends on the location of that disturbance in relation to the natural locus of erosion.
- Anastomosing watercourses are those composed of many wandering, semi-independent channels, separated by large islands, generally excised from the continuous floodplain. Anabranches tend to remain static, or avulse to occupy minor channels following floods. However, some watercourses have a ‘pseudo-anastomosing” morphology, for example where a tributary capture or artificial alteration has caused a multi-thread, but mobile channel, which would migrate in the same way as a meandering channel.
- Low sinuosity, sand bed watercourses act as conveyor belts for the high supply of sediment from sandstone uplands to the east. The loose sand is easily mobilised, and subsurface flows can occur below the channel bed.
- Chain of ponds watercourses comprise irregular deep, permanent pools separated by vegetation-stabilised bars (Rutherfurd *et al.,* 2000). The morphology is typically stable unless disturbed by changes to flow or sediment regime.

2.3.4 Watercourse impact sensitivity

The FHAR provided a relative sensitivity assessment of the watercourses. This looked at the erosivity of flows, stabilising effect of in-channel and floodplain vegetation and erodibility of channel materials. The parameters used to assess flow erosivity (unit stream power during modelled bankfull 20% AEP flows and maximum velocities during the modelled 1%AEP flood) and erodibility of channel materials are discussed in the geotechnical erosion potential assessment conducted for this study (see Appendix A, Section A-2), whereas the FHAR assessment used a more generalised qualitative approach.

The FHAR sensitivity for watercourses assessed during this study was as follows:

- High sensitivity watercourses were associated mainly with the larger incised, sinuous creeks within the Keelindi Alluvial Plains and Basalt Mesa / Pilliga Plains sections. These rivers have high to very high velocities and stream power and are actively eroding. These watercourses are as follows: Macquarie River, Milpulling Creek, Castlereagh River, Tenandra Creek, Mungery Creek, Quanda Quanda Creek, Teridgerie Creek, Baradine Creek, Talluba Creek and the Namoi River.
- Medium sensitivity watercourses were typically medium size creeks, with moderate modelled velocities and / or stream power. This includes the broad, low to medium energy creeks of the Keelindi Alluvial Plains, Basalt Mesa Plains and Pilliga Forest, together with larger low energy watercourses such as Bohena Creek. The chain of ponds creeks, Bohena Creek and Tinegie Creek, all scored near the top of the medium sensitivity bracket, and these should be considered separately given their morphology.
- Low sensitivity watercourses were identified as being low energy, low velocity overland flows or minor watercourses. These were largely unnamed watercourses or overland flow within the Basalt Mesa Plains and Pilliga Forest. Named low sensitivity watercourses included Stockyard Creek.

The FHAR assessment concluded that impacts of the N2N project were anticipated to be detectable, may be locally significant, but that recovery is expected to be short term. Impacts could occur due to sedimentation and culvert blockage, particularly at watercourse crossings along Eumungerie Road, Old Mill Road and through the Pilliga.

3. Narromine to Narrabri site investigations

Site inspections were carried out on selected watercourses between Narromine and Narrabri between 8 – 11 February 2022.

Sites were selected based on the following criteria:

– Sites with different geomorphological units along the proposed alignment.
– Sites with potential existing erosion sensitivity.
– Sites that were publicly accessible, or where permission for access had been granted.
– Sites near existing culverts and bridges under roads that would provide an indication of potential erosion conditions.

The list of assessed sites inspected is presented in Table 3.1.

Table 3.1 Sites assessed in the field for this study

Appendix B Reference	Chainage [km]	Structure No.	Watercourse Name
B-1	553169	250-Clvrt553169	Minor Watercourse
B-2	553970	250-Clvrt553970	Wallaby Creek
B-3	562344	**250-BR562344**	Macquarie River
B-4	568919	250-Clvrt568919	Minor Watercourse
B-5	595239	**250-BR595239**	Ewenmar Creek
B-6	599110	250-Clvrt599110	Goulburn Creek
B-7	602663	**250-BR602663**	Emogandry Creek
B-8	609715	**250-BR609715**	Kickabil Creek
B-9	616680	**250-BR616680**	Milpulling Creek
B-10	633677	**250-BR633677**	Marthaguy Creek
B-11	651728	**250-BR651728**	Castlereagh River
B-12	686020	250-Clvrt686020	Overland Flow
B-13	697901	250-Clvrt697901	Unnamed Creek
B-14	700017	**250-BR700017**	Mungery Creek
B-15	704588	**250-BR704588**	Quanda Quanda Creek
B-16	720990	**250-BR747768**	Unnamed Creek
B-17	747768	**250-BR651728**	Baradine Creek
B-18	767941	**250-BR767941**	Stockyard Creek
B-19	773535	250-Clvrt773535	Tinegie Creek
B-20	779635	**250-BR779635**	Talluba Creek
B-21	802534	250-Clvrt802534	Minor Watercourse
B-22	828222	**250-BR828222**	Bohena Creek
B-23	844116	**250-BR844116**	Namoi River
B-24	847500	**250-BR844116**	Narrabri Creek

4. Site investigation findings

4.1 Geotechnical assessment of erosion potential

4.1.1 General

A geotechnical assessment of erosion potential at the selected bridge and culvert locations was carried out between 8 and 11 February 2022, in conjunction with a geomorphological assessment (see Section 2.3). The results of both studies inform an overall assessment of the potential erodibility, noting both the geotechnical soil conditions and the geomorphological characteristics of the channel or flood plain.

This section provides a summary of the findings of the site-based geotechnical erosion assessment using the methodology outlined in Section 2.2.1. Detailed results and calculations are presented in Appendix B for each of the assessed sites.

4.1.2 Observed erosion vs mapped ASC soil classifications

The initial hypothesis was that there would be a correlation between the mapped ASC soils and observed patterns of erosion. A review of existing geotechnical test results and anecdotal evidence from JGHD geotechnical specialists had also indicated that soils along the N2N project corridor were generally erodible and prone to either dispersion, aeolian erosion or entrainment by overland flows.

Contrary to this assumption, however, site investigations found that the majority of locations were characterised by watercourse channel materials that were generally of very low or low erodibility. This was largely due to the presence of resistant clays. It is likely that, even in soils where there is a relatively low proportion of clay, the cohesion afforded by the clay is sufficient to significantly improve the resistance of the channel material.

4.1.3 Erosion potential in dispersive vs non-dispersive soils

The guidelines for estimating erosion threshold velocities reviewed in Section 2.1.1 do not generally distinguish between dispersive and non-dispersive soils. In dispersive soils, clay particles can spontaneously disperse into water without any hydraulic shear drag caused by the flow. However, dispersive behaviour is affected by impurities in water. Even a low percentage of dissolved solids in water can suppress dispersive behaviour of clay (Wan, 2005). Good vegetation cover can also bind the soil particles together and increase the erosion resistance of a clayey soil even if the clay fraction of the soil is dispersive.

Geomorphological observations indicated the presence of features that are typically characteristic of dispersive soils, including sink holes, piping erosion, seepage notches, rilling and gullying. However, simplified testing conducted during the site investigations indicated that soils, in general, did not exhibit dispersive behaviour, i.e. it is the soil composition, rather than the dispersive nature of the clay which has a more dominant effect in erosion feature formation. The following factors were considered when assessing the predominant causes of erosion:

– Sands and Silts are typically erodible. However, vegetation can stabilise the surface such that widespread erosion does not occur.
– Clayey Sands are less erodible than pure sands and silts. However, the erodibility increases as the fraction of clay in the soil decreases.
– Dispersion tests are conducted on the clay fraction of a soil only. Therefore, even though the clays themselves may be dispersive, the soil as a whole was less so, especially if the clay fraction of the soil is very low. This is likely to be the case at locations such as Marthaguy Creek and the Castlereagh River.
– Clay soils were typically fissured, particularly in the highly reactive soils of the basalt outwash plains between about CH633.5 and CH747.5. In these areas, it is possible that the fissure weaknesses have resulted in preferential rainwater erosion of the clay fraction. The material, therefore, becomes porous, leading to further rainwater ingress. Fissuring increases in dry conditions, so seasonal weather

patterns affect erodibility. The theoretical calculations used for the erosion potential assessment consider the scour effects due to river flow and do not take fissuring into account.

– In other cases, soils with a high clay content were tested to be dispersive, but no visible signs of dispersion were observed on site, e.g. Kickabil Creek. It is likely that the dispersive behaviour of the soil would be suppressed if there is a moderate amount of dissolved solid in the water.

Where soils are identified as dispersive by geotechnical testing or have dispersive-type features, the design should consider specific management measures (see Section 5 and site-specific assessments in Appendix B).

4.1.4 Estimated erosion threshold velocities

The potential for erosion was assessed on the basis of site investigations and calculations summarised in Appendix A, Section A-2. Erodibility classes (i.e. low to very high) are defined in Table A.7.13 (Appendix A)

– For clay soils, the erosion threshold velocity was assessed to be above 1.4m/s and around 2.0m/s on average, particularly given the dense stabilising vegetation that was present at the time of the site visit.
– For loose sandy soils (i.e. the highly mobile bed material), this was reduced to around 0.5m/s using Method 3 (Briaud, 2008), which is applicable to bare soil surfaces. This velocity threshold for sand could be increased to 1.0m/s if suitable vegetation cover could be established on the soil surface. However, it should be noted that mobilisation of bed material is desirable to maintain the natural throughput of sediment.
– The dense Clayey or Silty Sands channel boundary materials encountered in the Pilliga were assessed to be able to have erosion threshold velocities in the order of 2.0m/s to 2.5m/s.
– There were only three watercourses assessed to have a moderate to high erodibility: Macquarie River, Milpulling Creek and the Castlereagh River (noting that Baradine Creek could not be assessed). These watercourses both had high calculated stream power, high Erodibility Index and dispersive clays. Threshold velocities for Macquarie River and Milpulling Creek were 1.4m/s, with 2m/s for the Castlereagh River, all below the existing reached-averaged 1%AEP velocity.

The theoretical estimate of erosion threshold velocities should be considered in conjunction with the geomorphological characteristics of the watercourse that could give rise to localised changes in erosion potential, for example on meander bends or rapid changes in bed gradient.

4.2 Fluvial geomorphology assessment of erosion potential

4.2.1 General

This section summarises the findings of the geomorphological erosion site-based assessment. A detailed overview of each watercourse assessed is presented in Appendix B with location maps presented in Appendix C.

It should be noted that prior to JGHDs site visit, conditions had been generally wet with some localised flooding, particularly in the Narrabri area. Higher than average rainfall conditions had promoted vegetation growth around watercourses.

4.2.2 Natural flow variability and geomorphological response

Natural watercourses have a complex flow structure which both depends on, and affects, the channel morphology. An understanding of this inter-relationship is helpful when assessing the likely impact of artificial alteration and when attempting to design a structure which works with, rather than against, the natural watercourse dynamics. A brief summary of key relevant aspects these relationships is as follows:

– Watercourses have a 3D flow structure which typically consists of several elements. Primary currents flow downstream, but are retarded by boundary friction and deflected by curvature-induced centrifugal forces, forming helical secondary currents. As the current rotates around a bend, centrifugal force also causes displacement and superelevation of water towards the outer bank. Separation of flow structure at the bend apex causes a smaller reverse rotation cell to form along the outer bank. Therefore, in a regular meander, it would be expected that the thalweg (the zone of deepest, fastest flow) would impinge the outer bank just after the apex of a meander, below the surface. This is usually the locus of erosion. Correspondingly, the lowest velocities are found along the inner banks of meander bends, where secondary currents shoal across the point bar. These backwater eddies are typically sites of deposition. In some cases, eddy currents are strong enough for reverse flows to occur. Reverse flows have been modelled in the unusual chain of pools morphology of the Bohena River. This pattern of erosion and deposition, in its most simplistic form causes lateral, downstream migration of meander bends, e.g. Marthaguy Creek and Quanda Quanda Creek.

– In anastomosing and braided rivers, there is a similar variability in flow velocity through the water column (see Section 2.3.3 for an explanation of these morphologies). Anastomosing rivers may be considered independent channels, with a corresponding flow structure unless close to anabranch confluences. Braided rivers have a more complex structure, due to the interconnecting anabranch channels. However, mid-channel and lateral bars typically move downstream through scour of the bar head (i.e. higher velocities), and deposition at the downstream toe (i.e. lower velocities). Baradine Creek is an example of a braided river at the proposed crossing site.
– Bed profile: natural watercourses can have highly variable bed elevations, which can be appreciably modified during floods, particularly along watercourses with highly mobile sand beds. Watercourses along the proposal vary from virtually trapezoidal channels (e.g. those in the Pilliga Forest, such as Stockyard Creek, see Appendix B, A-18) to those with significant in-channel features (e.g. Castlereagh River and Quanda Quanda Creek). The latter creates natural surges and ebbs in flow velocity, e.g. low velocity pools with intervening higher velocity riffles
– As well as changes in bed elevation, variability of channel width can cause velocity variability. Changes in width can occur due to the presence of mid-channel and lateral bars, resistant channel material, dense in-channel vegetation and large woody debris (LWD). Patterns of erosion and deposition are related to this variability in velocity, with sediment preferentially deposited in areas of slower flow.
– Flow patterns within a channel change dramatically with flood stage. This may result in different patterns of erosion and deposition. For example, during flood events in meandering rivers, the thalweg straightens as the discharge increases to improve flow efficiency. In extreme cases, this may hasten meander cutoff or result in the formation of chute channels through point bars. During declining flows following peak flood, as sinuosity is regained.
– In addition, river bank failures often occur as floods recede. If water levels fall rapidly, steep hydraulic gradients can occur at the bank face, leading to high excess pore-water pressures within the bank which take time to dissipate. This mechanism is known as rapid drawdown induced slope instability and can contribute to bank failure (Thorne and Tovey, 1981; Duncan, Wright and Brandon, 2014). Banks may fail due to drawdown for some time after a flood has subsided.
– Gully erosion is typically induced by flow concentration on unprotected surfaces. This can occur for a number of reasons. Concave slopes or surface depressions can cause overland flows to converge, both increasing their volume and velocity. If vegetation is patchy, this can exacerbate the problem by channelling flows into specific locations. Once gullies have formed, they themselves concentrate flows, and tend to enlarge and headcut (i.e. the gully head erodes upstream). Gully networks were identified near Gouburn Creek, Milpulling Creek and within the Namoi River system floodplain.

4.2.3 Location of existing erosion

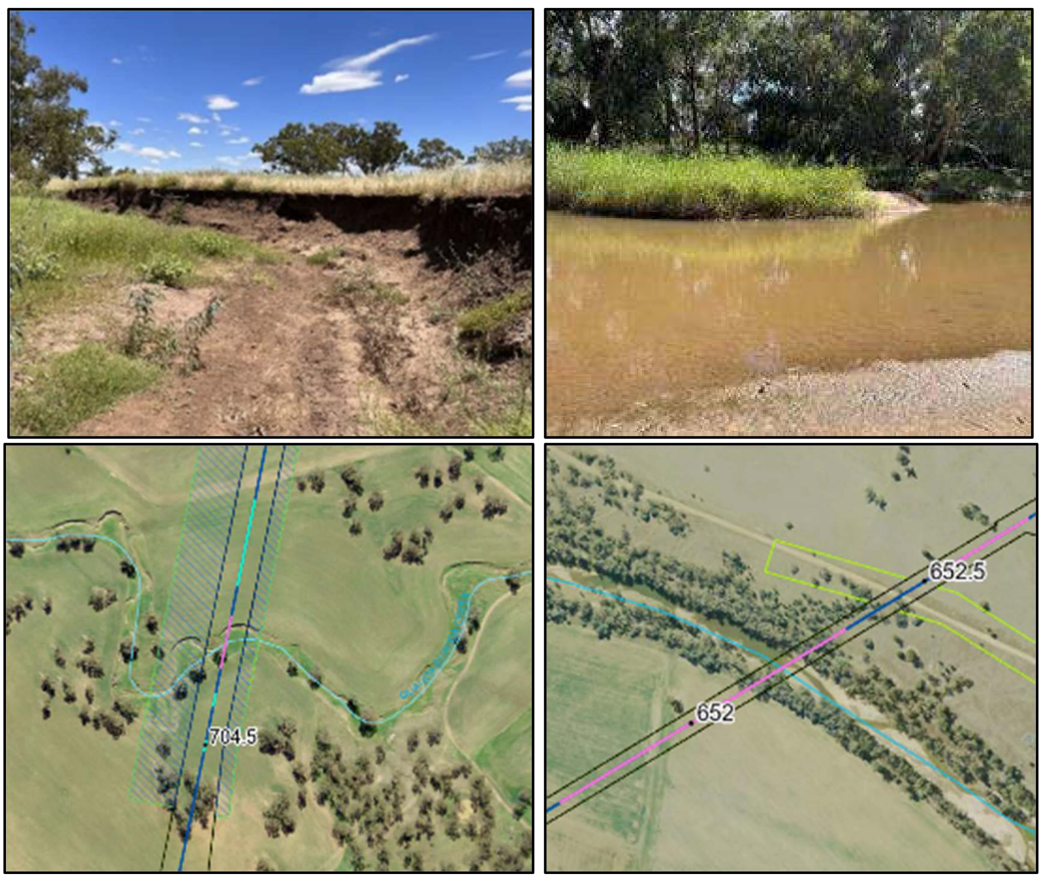
During the site investigation, observations were made of existing erosion at and adjacent to the selected locations. The presence and cause of erosion was assessed against the modelled existing flow velocities and the draft QDL velocities in effect at that time (i.e. 1.0m/s for protected surfaces or 0.5m/s for unprotected surfaces, and design velocity exceedances of not more than 0.5m/s).

Site observations indicated that the majority of unprotected areas did not show signs of active erosion, even when existing modelled flow velocities were higher than the baseline QDL erosion threshold velocity limit. For example, at 250-BR609715 (Kickabil Creek) and Culvert 250-Clvrt686020, areas characterised by grassland and cropping, predicted existing velocities were above 1.5m/s in places, but no visible erosion was observed (see Figure 4.1 and Appendix B, B-8 and B-12). Kickabil Creek flows through potentially highly erodible Sodosols associated with the Cobocco Soil Landscape, whereas the watercourse at CH686.020 flows through Chromosols.

Left photograph is the Kickabil Creek floodplain with modelled velocities of over 2m/s; Right photograph is at CH686.020 with modelled velocities of between 1.5-2m/s to west of proposed crossing, showing intact, vegetated surface.

Figure 4.1 Areas of modelled high velocities but no observed floodplain erosion.

Erosion was observed in some areas, such as the highly sinuous Quanda Quanda Creek which is actively eroding laterally. Detailed design should consider the channel geomorphology at this location with the proposed crossing being located at the apex of an acute bend (see Figure 4.2). In addition, Quanda Quanda Creek flows through an area of Vertosols (deep cracking clays) that might be expected to be less erodible than the Sodosols characteristic of the Castlereagh River area.



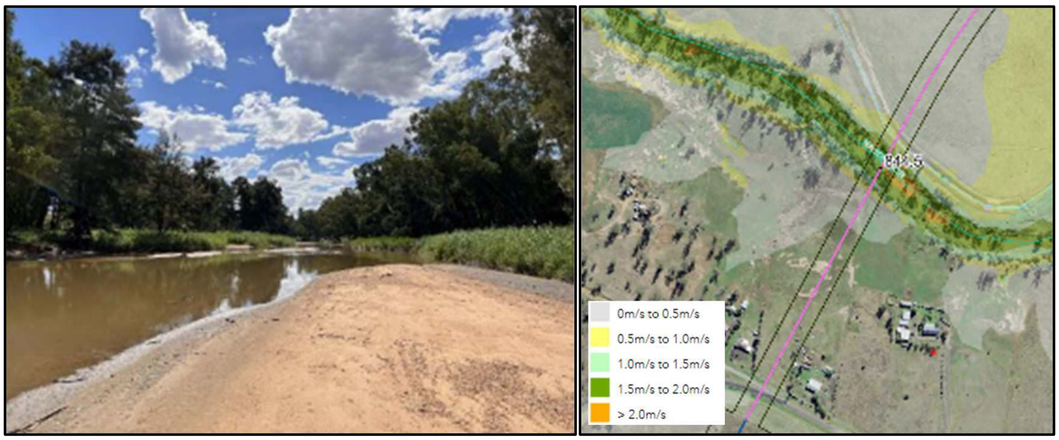
Left photographs show lateral erosion of the incised, meandering Quanda Quanda Creek (1%AEP Vmax = 1.5m/s). Right photographs show the depositional environment of the low sinuosity Castlereagh River (1%AEP Vmax = 3.0m/s)

Figure 4.2 Effect of channel planform morphology on presence of existing erosion

Both the Namoi River and Castlereagh River were modelled as having 1%AEP maximum velocities at just under 3m/s within the main channel, yet the river channels had little observed bank erosion, both on aerial imagery or on site (see Figure 4.3). The morphology of the watercourse was observed to be a controlling factor for the presence of existing erosion, rather than flow velocities. As discussed above, the depositional Castlereagh River has low sinuosity at the proposed bridge site, although acute bends are present in reaches upstream and downstream.

Floodplains for the Castlereagh and Namoi rivers are characterised by Sodosols and modelled velocities in in these areas were lower than in the main channel. The well-vegetated floodplain of the Castlereagh shows no visible erosion near the proposed crossing site. In contrast, the floodplain of the Namoi River is gullied, with aeolian erosion and loss of soil and vegetation, possibly partly the result of recent flooding in November 2021.

The examples above illustrate the importance of site-specific conditions. Factors such as watercourse morphology and presence of established vegetation are important in determining whether erosion is present or not.



Left photograph shows the depositional environment of the rapidly flowing Castlereagh River. Right photograph shows modelled existing 1%AEP velocities for the Namoi River, indicating no observable in-channel erosion where flows are very rapid, and erosion of the floodplain where flows are slow.

Figure 4.3 Areas of high velocity channel flow but no observed erosion, but erosion of low velocity floodplain

4.2.4 Sediment transport

Many watercourses have highly mobile sand beds and act as “conveyor belts” to transport material downstream. Sands originate from uplands in the east and the bedload has a virtually unlimited supply. Thus, under natural conditions, material moved downstream is replaced by material from upstream.

Site observations identified sediment deposition within the channel bed at a number of existing culverts and bridges. Some existing culverts are too shallow to accommodate high sediment load and this has affected the morphology and geomorphological functioning of the watercourse, e.g. at Ewenmar Creek.

Detailed design of bridges and culverts should therefore consider whether design velocities are sufficient to avoid adverse sedimentation. Culvert invert levels should also consider minimising disruption to sediment transport through the affected reaches to reduce the possibility of upstream deposition / downstream scour, or vice versa. This is especially important in watercourses where flows are rapid and subsurface flows are common.

4.2.5 Channel boundary materials

Within the study area, watercourses typically comprise clay-rich banks with highly mobile coarse sand beds. The degree of theoretical stability is proportional to the quantity of clay (i.e. erosion resistant banks are associated with a higher proportion of clay). The least geotechnically stable watercourses of those studied are within the Macquarie Floodplain and Keelindi Alluvial Plains Geomorphological Units (see Table 4.1), which have a higher proportion of silt and sand in the channel boundary materials. The most geotechnically stable watercourses are those flowing through clay-rich basaltic soils.

Geotechnical test results indicate dispersive or moderately dispersive clays (Emerson Class 2.1 or 2.2) are present at sites CH553.169, Wallaby Creek, Kickabil Creek, Milpulling Creek, Marthaguy Creek, Castlereagh River, CH697.701, Stockyard Creek and Tinegie Creek. However, as discussed in Section 4.1.3, this test is only conducted on the clay fraction of the soil, which can be relatively minor. Vegetation and sediment-laden flows also limit dispersion. Erosion in these areas is more likely to occur during intense rainfall events following drought years, where relatively pure water is suddenly introduced to an unprotected dispersive surface. Watercourses which were thought to show indicators of dispersion, such as Goulburn Creek, Emogandry Creek and Quanda Quanda Creek, were found to be erodible due to either the sand content or clay fissuring.

The higher resistance of bank and sub-bed (i.e. below the mobile sand bed) materials result in higher erosion threshold velocities, compared to the erodible mobile sandy bed material. Ideally, design velocities should seek a balance, both preserving the natural throughput of sandy bed material, while avoiding increasing the likelihood of erosion in the more resistant bank materials on the other.

4.2.6 Existing in-channel structures, roads and tracks

While on site, the performance of existing in-channel structures associated with existing roads and tracks was assessed in terms of the geomorphological functioning of the assessed watercourses. Observations were as follows:

– Sediment deposition causing partial blockage of existing road culverts is common. In extreme cases, this has significantly affected the geomorphological functioning of the affected watercourses for some distance upstream and downstream of the structures. For example Ewenmar, Goulburn and Emogandry Creeks along Old Mill Road have shallow culverts(see Appendix B, B-5, B-6 and B-7). These are prone to sedimentation of the incised active channels that are present upstream and downstream of the affected reach, particularly at the road crossing of Ewenmar Creek. Some watercourses have avoided this with the construction of bridges, e.g. Milpulling Creek (see Appendix B, B-9) or use of much taller culverts, e.g. Kickabil Creek (see Appendix B, B-8).
– Tracks and roads have been constructed perpendicular to the prevailing flow direction. Some watercourses do not have culverts. Watercourses are channelised to funnel flood flows off the tracks (e.g. Mungery Creek and adjacent watercourses, see Appendix B, B-13 and B-14)). Embankments have been built to encourage this concentration of flow. In other cases, earth embankments are present adjacent to tracks and roads which can affect flood flows, for example along Pilliga Forest Way (see Appendix B, B-19 and B-21).

4.3 Comparison of geotechnical and geomorphological erosion potential

Results of the combined geotechnical and geomorphological assessments are presented in Table 4.1**.** Differences in the assessment of potential erosion risks between the geotechnical assessment, based on estimated erosion threshold velocity and the geomorphological assessment are summarised as follows:

– For larger rivers, the assessed geotechnical threshold velocity was generally lower than the modelled existing flow velocity. The Macquarie and Castlereagh Rivers were assessed to have a higher probability of erosion than the more northerly rivers. From a geomorphological perspective, the large rivers have the potential to erode but observations do not indicate appreciable existing channel erosion, other than across the Namoi floodplain.
– The project alignment across the majority of meandering or variably sinuous watercourses avoids the most erosive reaches, i.e. at the bend apex, e.g. at the proposed Macquarie River and Castlereagh River bridges. Therefore, even though the geotechnical erosion potential is moderate to high, the geomorphological erosion potential was assessed to be lower than might be expected. The bridge across Milpulling Creek also avoids a bend apex, but there are other factors, such as gullying and evidence of active lateral erosion, that indicate high geomorphic erosion potential.
– Conversely, significant erosion was observed at some watercourse crossings where the geotechnical erodibility was assessed as being low. Erosion has occurred due outer bank erosion around sinuous meanders despite the cohesive clay banks, e.g. at the proposed Emogandry Creek and Quanda Quanda Creek bridge sites. It is believed that Marthaguy Creek and Baradine Creek could fall into this category (noting that site observations were only possible upstream of the proposed crossings). These watercourses were sinuous, and erosion would be associated with lateral meander erosion.

- Watercourses in the Pilliga Forest had geotechnical assessed threshold velocities higher than the 1%AEP design velocity, despite the presence of dispersive clays and sandy channel materials. These results were supported by the geomorphological assessment of these watercourses that indicated a low geomorphological erosion potential.
- Watercourses where the geotechnical and geomorphological assessments gave a similar result include Wallaby Creek (Moderate erosion potential), the Macquarie River (Moderate erosion potential), Milpulling Creek (High erosion potential) and several of the smaller watercourses that were assessed as having a low erosion potential (568.919, 686.020, 720.990 and watercourses in the Pilliga Forest).

Table 4.1 Summary of estimated watercourse erosion threshold velocity and erodibility

Appendix B Reference	Chainage	Watercourse Name	Mapped ASC Soil Type	Geomorphological Unit[11]	Observed Soil Type	Rationale	Existing Reach Av. Max. Velocity (1%AEP, m/s)[2]	Design Reach Av. Max. Velocity (1%AEP, m/s)	Modelled % increase in 1%AEP Design Velocity vs 1%AEP Existing Velocity	Assessed Threshold Velocity based on Method 2 (Hewlett *et al.*, 1987; m/s)	% Difference between Threshold Velocity and 1%AEP Design Velocity	Assessed % Probability of Initiation of erosion based on Method 1 (Annandale, 1995; Wibowo *et al.*, 2005)	Assessed Erodibility	Observed erosion and geomorphological potential for erosion
B-1	553169	Minor Watercourse (Culvert)	Chromosols (alluvial)	Macquarie Floodplain	Hard Sandy Clay	Soil has a high sand content although it is classified as Clay. Erodibility assessed as Moderate mainly due to the high sand content and relatively high velocity.	1.1	1.4	27%	1.6	14%	< 1%	L/M	Indistinct grassy swale. Low erosion potential.
B-2	553970	Wallaby Creek (Culvert)	Chromosols (alluvial)	Macquarie Floodplain	Soft Sandy Clay	Soil sample from site is Clay with low plasticity. The high Sand content explains the Moderate erodibility and relatively high velocity. Sand particles could be felt when doing the Thread Test.	1.1	1.2	9%	1.2	0%	< 50%	M	Incised, anastomosing, moderately sinuous with laterally eroding low-flow banks and bed scour, but erosion is confined to the low-flow channel. Moderate erosion potential.
B-3	562344	Macquarie River (Bridge)	Dermosols / Sodosols	Macquarie Floodplain	Hard Silty Clay	The Silty Clay has relatively high erosion resistance, but erodibility is assessed as Moderate due to the relatively high stream power.	1.6	1.5	-6%	1.4	-7%	~50%	M	Deeply incised, moderately sinuous with discrete failures where large trees had fallen. Moderately dense in-channel and riparian vegetation. Moderate erosion potential.
B-4	568919	Minor Watercourse (Culvert)	Chromosols (alluvial)	Undulating Alluvial Plains	Very Stiff Sandy Clay	Soil found on site is very stiff Clay with medium to high plasticity. High expected erosion resistance. Erodibility is assessed to be Very Low because of (1) the low stream power, and (2) flood modelling data indicate that flood flow will only last for 40 min. Existing erosion features were likely caused by erosion along fissures, sinkholes and piping channels due to poor grass cover.	0.8	1.1	38%	>3.0	173%	<< 1%	VL	Indistinct, low sinuosity within minor incised pools. Sparse grass and no riparian corridor. Low erosion potential.
B-5	595239	Ewenmar Creek (Bridge)	Alluvium / Sodosol	Keelindi Alluvial Plains	Very Stiff Silty Clay	Soil found on site is Silty Clay which is consistent with BH2007, but samples of Sand were extracted from TP2022. Assessment based on the soil being a Silty Clay indicates Very Low to Low erodibility. However, it can be increased to Moderate to High if more Sand is found at the site.	1.3	1.8	38%	2	11%	< 1%	VL/L	Geomorphological functioning significantly impacted by deposition within and adjacent to culverts under Old Mill Road. Slightly incised, anastomosing, sinuous within a narrow but well-vegetated riparian corridor. Low erosion potential due to the prevalence of deposition .
B-6	599110	Goulburn Creek (Culvert)	Sodosols	Keelindi Alluvial Plains	Very Stiff Clay	Soil observed on site is medium to high plasticity Clay and consistent with BH2067. Erodibility is assessed as Very Low considering the erosion resistance of the Clay is high.	0.7	1	43%	2	100%	<< 1%	VL	Geomorphological functioning significantly impacted by diversion and deposition along Old Mill Road. Slightly incised, anastomosing, variable sinuosity within a narrow riparian corridor. Gullying of downstream floodplain. High erosion potential.
B-7	602663	Emogandry Creek (Bridge)	Cobocco / Sodosols	Keelindi Alluvial Plains	Very Stiff Sandy Clay	Soil observed on site appears slightly plastic. is medium to high plasticity Clay and consistent with BH2067. Erodibility is assessed as Low to Very Low considering the design velocity is relatively high, and the creek has poor grass cover at some spots.	1.8	1.7	-6%	1.4	-18%	<< 1%	L/VL	Incised, sinuous channel with outer bank erosion and high cut banks. Narrow, densely vegetated riparian corridor and in-channel vegetation. Gullying of floodplain upstream and downstream. High erosion potential.
B-8	609715	Kickabil Creek (Bridge)	Cobocco / Sodosols	Keelindi Alluvial Plains	Very Stiff Silty Clay	BH2010 shows both stiff Clay layer and dense sand layer. Coarse sand and gravels were observed both upstream and downstream of the culvert. If the soil is predominantly Sand/Gravel, erodibility is Medium to High. If, however, the soil is predominantly Clay, erodibility is assessed as Low.	1.5	1.4	-7%	2	43%	<< 1%	L Clay, M/H Sand	Incised, sinuous creek with well-defined low-flow channel and dense riparian vegetation. Moderate erosion potential.
B-9	616680	Milpulling Creek (Bridge)	Cobocco / Sodosols	Keelindi Alluvial Plains	Very Stiff Silty Clay	Coarse Sand was observed on river banks. Erodibility assessed as Medium to High. Average design flow velocity is expected to exceed threshold velocity for soil with poor grass cover.	1.6	2	25%	1.4	-30%	~ 1%	M/H	Incised, actively meandering, multi-thread. sinuous channel with a mobile sand bed. Sparsely vegetated, with virtually no riparian corridor. Gullying of floodplain upstream and downstream. High erosion potential.
B-10	633677	Marthaguy Creek (Bridge)	Chromosols	Basaltic Alluvial Plains	Stiff Sandy Clay	BH2015 shows both Dense Sand and Stiff Clay layers. Coarse Sand was observed on river banks. Erodibility assessed for Sand is High. If soil is Clay, erodibility will be Low.	1.6	1.6	0%	1.8	13%	< 1%	L Clay, H Sand	Incised, actively meandering, highly sinuous channel with a highly mobile sand bed. Narrow riparian corridor. Occasional agricultural use of mid-channel island. High erosion potential.
B-11	651728	Castlereagh River (Bridge)	Alluvium / Sodosol	Basaltic Alluvial Plains	Stiff to Hard Sandy Clay	TP2049 shows Very Dense Sand, and BH2018 shows both Sand and Clay layers. Site observation found Coarse Sand deposited on river bed. River banks were covered with heavy vegetation and soil type was difficult to identify. Erodibility is assessed as Moderate to High due to high design velocity exceeding threshold, and relatively erodible soils if they are Sands.	3	2.8	-7%	2	-29%	> 50%	M/H	Deeply incised, moderately sinuous channel with a highly mobile sand bed. Evidence of past meander migration. Densely vegetated banks and narrow riparian corridor. High erosion potential but no active erosion observed on site.
B-12	686020	Overland Flow (Culvert)	Chromosols	Basaltic Colluvial Plains	Stiff Sandy Clay	BH2058 shows both Sand and Clay layers, but TP2132 and TP2133 both show Hard Clay. Land has good vegetation cover. Erodibility is assessed as Very Low to Low considering the low stream power.	Not assessed in this study, as 1%AEP velocities are zero						VL to L	Unconfined flows across grassy agricultural fields. Low erosion potential.

[1] Geomorphological Unit is taken from the FHAR (2022).
[2] Velocity is averaged across a 40m reach, from 20m upstream to 20m downstream of each structure, using reference modelling from the FHAR (2022)

Appendix B Reference	Chainage	Watercourse Name	Mapped ASC Soil Type	Geomorphological Unit[11]	Observed Soil Type	Rationale	Existing Reach Av. Max. Velocity (1%AEP, m/s)[2]	Design Reach Av. Max. Velocity (1%AEP, m/s)	Modelled % increase in 1%AEP Design Velocity vs 1%AEP Existing Velocity	Assessed Threshold Velocity based on Method 2 (Hewlett *et al.*, 1987; m/s)	% Difference between Threshold Velocity and 1%AEP Design Velocity	Assessed % Probability of Initiation of erosion based on Method 1 (Annandale, 1995; Wibowo *et al.*, 2005)	Assessed Erodibility	Observed erosion and geomorphological potential for erosion
B-13	697901	Unnamed Creek (Culvert)	Chromosols	Basalt Mesa Plains	Very Hard Sandy Clay	EP2011 and TP2074 show Clayey Sand and Sandy Clay. Samples collected on site are medium to high plasticity clay with good erosion resistance. Erodibility assessed as Very Low based on samples collected on site, and considering the short duration of the design flow.	0.7	0.4	-43%	4.5	1025%	<< 1%	VL	Flow is artificially channelised through an embankment along Goorianawa Road. Dense trees with little understorey vegetation. Moderate erosion potential.
B-14	700017	Mungery Creek (Bridge)	Chromosols	Basalt Mesa Plains	Very Dense Clayey Sand	TP2074 shows both Sands and Clays. Erodibility is assessed as Very Low to Low if soil is predominantly Clay. If soil is predominantly Sand, erodibility will be Moderate to High.	1.2	1.2	0%	2	67%	< 1%	VL/L Clay, M/H Sand	Flow is artificially channelised through an embankment along Goorianawa Road. Dense trees and understorey vegetation. Moderate erosion potential.
B-15	704588	Quanda Quanda Creek (Bridge)	Vertosols	Basalt Mesa Plains	Very Stiff Sandy Clay	Erodibility is assessed as Very Low because the high plasticity clay observed on site has high erosion resistance, and also because of the short duration of the design flow. Observed existing erosion features may be due to erosion through fissures and sinkholes due to surface runoff.	1.5	1.5	0%	3	100%	<< 1%	VL	Incised, highly sinuous, laterally eroding with highly variable bed elevation. No appreciable riparian corridor, agricultural use of floodplain. High erosion potential
B-16	720990	Unnamed Creek (Culvert)	Vertosols	Basalt Mesa Plains	Clay-	Not fully assessed due to lack of site geotechnical data, but resistant clay channel material observed on site.	1.2	1.5	25%	Likely to be as high as 3m/s depending on flow duration-	100%	-	Likely to be L	Unconfined, low sinuosity, well-vegetated channel with no riparian corridor. Low erosion potential.
B-17	747768	Baradine Creek (Bridge)	Alluvial sands	Pilliga Forest	-	Observed some distance upstream of bridge site.	2.8	2.8	0%	N/A	N/A	N/A	VL Clay, M/H Sand	Variably sinuous, incised high-flow channel. Mobile sand bed creating a braided low-flow channel in places. Densely vegetated riparian corridor and banks. High erosion potential where bedrock is not present.
B-18	767941	Stockyard Creek (Bridge)	Alluvium / Sodosols	Pilliga Forest	Dense to Very Dense Silty, Clayey Sand	TP2099 shows Clayey Sand. Observation on site indicates soils are predominantly Silty or Clayey Sand. Erodibility is assessed as Moderate to High if the soils are Sand. However, if the soil is Clay and good vegetation cover is provided, erodibility will be Very Low	0.8	0.8	0%	2.5	213%	<< 1%	VL Clay, M/H Sand	Slightly incised, low sinuosity with a highly mobile sand bed and resistant, well-vegetated banks. Low erosion potential
B-19	773535	Tinegie Creek (Culvert)	Colluvium / Sodosols	Pilliga Forest	Dense to Very Dense Clayey Sand	TP2101 shows Sand. Site observation indicates soil is predominantly Sand. Erodibility is assessed as Medium to High. However, if soil is Clay, erodibility will be Very Low considering the very low stream power.	0.4	0.4	0%	2.5	525%	<< 1%	VL/L Clay, M/H Sand	Poorly defined channel. Reported to be chain of ponds, but this morphology not observed at the proposed crossing. Dense woodland but sparse understorey. Low erosion potential.
B-20	779635	Talluba Creek (Bridge)	Alluvium / Rudosols	Pilliga Forest	Dense to Very Dense Silty Sand	TP2102 shows Sand. Site observation indicates soil is predominantly Sand. Erodibility is assessed as Medium to High. However, if soil is Clay, erodibility will be Very Low to Low considering the very low stream power.	1.3	1.3	0%	2.5	92%	~ 1%	VL Clay, M Sand	Slightly incised, low sinuosity with a highly mobile sand bed and resistant, well-vegetated banks. Low erosion potential.
B-21	802534	Minor Watercourse (Culvert)	Alluvium / Sodosols	Pilliga Forest	Dense to Very Dense Silty Sand	TP2102 shows Sand. Site observation indicates soil is predominantly Sand. Erodibility is assessed as Medium. However, if soil is Clay, erodibility will be Very Low considering the very low stream power.	0.3	0.3	0%	2	567%	<< 1%	L/M	Artificial channel, floods are attenuated by a road maintenance embankment and vegetation upstream of the proposed culvert. Low erosion potential.
B-22	828222	Bohena Creek (Bridge)	Alluvium / Sodosols	Namoi Floodplain	Hard Sandy Clay	BH2046 shows Sandy Clay. Soils observed on river banks are Sands. Erodibility is assessed as Low to Moderate considering the moderately high design flow velocity and poor vegetation cover at spots.	2.1	2.1	0%	1.5	-29%	< 1%	L Clay, M/H Sand	Chain of ponds within a variable sinuosity high flow channel. Dense riparian and in-channel vegetation. Moderate erosion potential, but high sensitivity due to rare morphology and unusual flow structure.
B-23	844116	Namoi River (Bridge)	Sodosols	Namoi Floodplain	Hard Clay (or Very Dense Sand)	BH2049 shows both Sand and Clay. Sample taken on site is Clay with medium to high plasticity. Erodibility is assessed as Low if soil is Clay. If the soil is Sand, erodibility will be Moderate to High.	2.9	2.8	-3%	2	-29%	<< 1%	VL/L	Interlinked network of incised, sinuous channels with gullying, sparsely vegetated floodplain. Moderately to densely vegetated banks. High erosion potential.
B-24	847500	Narrabri Creek (Bridge)	Sodosols	Namoi Floodplain	Stiff Clay	Soil sample taken from left bank is medium to high plasticity Clay. Erodibility is assessed as Very Low to Low. However, Sand and Silt were also observed on the river bank, and these are relatively erodible (Moderate to High).	Geomorphological and soil assessment only[3]						L/M	

[3] The geomorphology and soils of Narrabri Creek were assessed on site opportunistically, as an extension of the Namoi River assessment.

5. General erosion management and mitigation recommendations

Site specific recommendations have been provided on the summary sheets in Appendix B. General recommendations for reducing impacts to watercourses are as follows:

5.1 Erosion and sedimentation management

– The presence of existing erosion features, such as gullies and sheet wash, are good indicators of the potential for future erosion and should be considered in the detailed design.

– Similarly, the absence of existing erosion features due to stabilising elements, such as vegetation cover or clay rich banks are good indicators of the location's ability to withstand future erosion.

– Sedimentation was, in general, found to be more prevalent than erosion at existing culverts and bridges. The large quantities of sand originating from uplands to the east has resulted in many of the watercourses having highly mobile sand beds. Therefore, it will be important to size and locate culvert and bridge piers correctly, and consider whether design velocities are sufficient to support the hydraulic performance of the culvert and reduce maintenance requirements. Culvert invert levels should also be considered carefully to avoid disrupting sediment transport through the affected reaches, i.e. at or close to the base of the mobile sand bed. This would reduce the possibility of upstream deposition / downstream scour.

– Detailed design should consider the potential for lateral migration along sinuous watercourses, i.e. outwards movement of meander bends, particularly if structures cross at or just after the apex of a bend. The recent bridge / ford failure where Cumbil Road crosses Baradine Creek provides a good example (see Appendix B, B-17).

– Avoid introduction of preferential pathways for erosion (e.g. along a concrete / dispersive soil boundary). Compact backfill around structures in accordance with specifications.

– Bridge pier design should consider impacts on river flows and velocities that could give rise to scour, lateral erosion or deposition. For example, the pier for the existing rail bridge at Narrabri has resulted in deposition and an acute diversion of the thalweg towards the left bank (Appendix B, B-24).

– Consider fencing areas where livestock / native fauna are present to avoid topsoil damage and improve revegetation success. However, flood debris impact and capture should be considered.

5.2 Vegetation

– Limit vegetation removal to retard flood flows, maintain the stabilising effects of roots and protect against direct rainsplash erosion. If trees need to be removed for e.g. bridge construction, leaving a stump with the root structure intact would help preserve surface integrity during revegetation.

– If vegetation removal is required, revegetate as soon as possible following construction to avoid preferential erosion of bare surfaces. Vegetation should replicate that removed or, if unsuitable or weed-dominated, selected with reference to successfully established local vegetation. Import of topsoil may be required. Use of earth berms or natural fibre matting / logs may be required within gullies or on steeper slopes to attenuate flows and capture sediment.

– Erosion management should consider loss of vegetation cover under drought or bushfire conditions.

5.3 Soil stabilisation and protection

– Use of gypsum to stabilise dispersive clays is not recommended in the vicinity of watercourses to avoid adverse changes to water quality. However, consider the use of non-dispersive capping material in these areas, where necessary. Effective compaction, surface cover and revegetation is particularly important in areas of dispersive soils.

– Bridge abutments along large watercourses with rapid velocities should have robust surface protection

Additional general erosion management and mitigation measures are recommended in the FHAR (2022).

6. Conclusions

This report presents the results of the geotechnical erosion potential and geomorphological assessments used to estimate the potential for erosion on watercourses crossed by the N2N project. Erosion threshold velocities have been calculated at 24 proposed bridge and culvert locations between Narromine and Narrabri and considered in the context of the geomorphological form of the watercourse.

6.1 Industry guidelines and standards

The review of commonly used industry guidelines and standards indicated:

- An erosion threshold velocity of up to 0.5m/s for loose sands.
- An erosion threshold velocity of between 1m/s to 2m/s for stiff clays.
- The erosion threshold velocity increases if there is any vegetation cover and increases significantly with good vegetation cover.

6.2 Geotechnical erosion potential

The geotechnical erosion potential assessment found that the soils in the study area were typically cohesive, clay-rich soils, with a very low to low erosion potential. The erosivity of the soils increases with silt and sand content. These clay-rich soils tend to form the channel banks, sub-bed and floodplain. Watercourse bed materials, in contrast, typically comprised loose, coarse sands.

Channel banks and floodplains with a high clay content were estimated to have maximum erosion threshold velocities ranging from 1.2m/s at Wallaby Creek, to 4.5m/s at CH697.901, with the average being around 2.1m/s. Site-specific assessments of estimated erosion threshold velocities (using Method 2, Hewlett *et al.*, 1987) equalled or exceeded the values stipulated by the reviewed industry guidelines and standards noted above.

The majority of watercourses were assessed to have a very low to low probability of erosion initiation (i.e. there was a 1% chance or less probability of erosion occurring in any given year). Only Wallaby Creek, Macquarie River and the Castlereagh River were assessed to have a 50% probability of erosion initiation. However, existing erosion was found to be limited or absent along these rivers. Thus, the potential for erosion is high, and should be considered during detailed design.

6.3 Geomorphological considerations

Watercourse geomorphology was found to strongly influence the presence and location of erosion. Natural flow variability means that certain locations are prone to erosion, such as around the apex of actively eroding meander bends and where flows are concentrated, e.g. in gully systems. From a geomorphological perspective, the watercourses assessed to have the highest erosion potential were those with actively meandering morphology. Potential for lateral erosion associated with higher velocities around bends and active meanders should be considered in these locations, even if the geotechnical assessment indicates a high erosion threshold velocity and low erodibility. This is particularly so if proposed structures are located near the outer bank of a meander bend apex.

While on site, the performance of existing in-channel structures associated with existing roads and tracks was assessed in terms of the geomorphological functioning of the observed watercourses. Some watercourses have been artificially straightened or realigned to facilitate construction of these tracks and roads, which has caused disruption to the geomorphological functioning of watercourses. In these cases, the geomorphological erosion potential was higher than the geotechnical erosion potential or natural creek dynamics would indicate, e.g. Goulburn Creek and Mungery Creek.

In some cases, the geotechnical erosion potential may indicate moderate or high erodibility, but observations and site-specific morphology result in a low geomorphological erosion potential. For example, the Castlereagh River has a calculated geotechnical erosion threshold velocity of 2.0m/s – less than the modelled existing 1%AEP flow velocity of 3.0m/s, but there was no evidence of channel erosion at the proposed bridge crossing.

Sedimentation was found to be a greater problem than erosion at existing in-channel structures. The high mobile bedload of the watercourses requires sufficient sediment throughput to avoid blockage and disruption of the natural sediment transport mechanisms.

The true potential for erosion should therefore consider the modelled flow velocity, the erosion threshold velocity (determined from geotechnical conditions) and also the channel geomorphology. This is particularly so for sensitive watercourses, such as sinuous channels, where lateral erosion is observed.

6.4 Erosion potential in dispersive vs non-dispersive soils

Prior to this study's site visit, evidence indicated that soils in the study area were highly erodible, with widespread dispersion. Reviewed industry standards and erosion potential assessment methodologies did not account for dispersive soils, other than to indicate that dispersion can occur at low velocities (IECA, 2008). Dispersive soils are present within the study area. However, true dispersion was not observed at the majority of assessed sites, largely due to the presence of stabilising vegetation and turbid flows. Dispersive-type features were observed, but these tended to be associated with silty, sandy or fissured clay soils.

At sites where dispersive soils have been identified through laboratory testing, it would be impractical to attempt to restrict dispersion through imposition of velocity limits, as dispersive erosion is most likely to occur in bare soils exposed to intense rain (i.e. clear water), e.g. during construction, following a drought or flows with a low suspended sediment load. This would, instead, be mitigated by successful construction management measures and post-construction rehabilitation, which would be an integral part of any modern project.

6.5 Site-specific erosion threshold velocities vs observed erosion

The findings of this study are presented in Table 6.1, which summarises Table 4.1. A key is provided below the table.

Table 6.1 ***Modelled velocities, assessed erosion threshold velocity, probability of erosion initiation and geotechnical / geomorphological erosion potential (summarised from Table 4.1; see this table for full headings)***

Appendix B Reference	Chainage	Watercourse Name	Existing Reach Av. Max. Velocity (1%AEP, m/s)	Design Reach Av. Max. Velocity (1%AEP, m/s)	1%AEP Design Velocity vs 1%AEP Existing Velocity	Assessed Erosivity Threshold Velocity	Threshold Velocity vs 1%AEP Design Velocity	Assessed % Probability of Initiation of erosion	Assessed Geotech. Erodibility	Geomorph. Erosion Potential
B-1	553169	Minor Watercourse	1.1	1.4	27%	1.6	14%	< 1%	L/M	L.
B-2	553970	Wallaby Creek	1.1	1.2	9%	1.2	0%	< 50%	M	M
B-3	562344	Macquarie River	1.6	1.5	-6%	1.4	-7%	~50%	M	M
B-4	568919	Minor Watercourse	0.8	1.1	38%	>3.0	173%	<< 1%	VL	L
B-5	595239	Ewenmar Creek	1.3	1.8	38%	2	11%	< 1%	VL/L	L
B-6	599110	Goulburn Creek	0.7	1	43%	2	100%	<< 1%	VL	H
B-7	602663	Emogandry Creek	1.8	1.7	-6%	1.4	-18%	<< 1%	L/VL	H
B-8	609715	Kickabil Creek	1.5	1.4	-7%	2	43%	<< 1%	L Clay, M/H Sand	M
B-9	616680	Milpulling Creek	1.6	2	25%	1.4	-30%	~ 1%	M/H	H
B-10	633677	Marthaguy Creek	1.6	1.6	0%	1.8	13%	< 1%	L Clay, H Sand	H
B-11	651728	Castlereagh River	3	2.8	-7%	2	-29%	> 50%	M/H	H (but no erosion observed)
B-12	686020	Overland Flow	Not assessed in this study as 1%AEP velocities are zero						VL to L	L
B-13	697901	Unnamed Creek	0.7	0.4	-43%	4.5	1025%	<< 1%	VL	M

Appendix B Reference	Chainage	Watercourse Name	Existing Reach Av. Max. Velocity (1%AEP, m/s)	Design Reach Av. Max. Velocity (1%AEP, m/s)	1%AEP Design Velocity vs 1%AEP Existing Velocity	Assessed Erosivity Threshold Velocity	Threshold Velocity vs 1%AEP Design Velocity	Assessed % Probability of Initiation of erosion	Assessed Geotech. Erodibility	Geomorph. Erosion Potential
B-14	700017	Mungery Creek	1.2	1.2	0%	2	67%	< 1%	VL/L Clay, M/H Sand	M
B-15	704588	Quanda Quanda Creek	1.5	1.5	0%	3	100%	<< 1%	VL	M
B-16	720990	Unnamed Creek	1.2	1.5	25%	As high as 3m/s	100%	-	L	L
B-17	747768	Baradine Creek	2.8	2.8	0%	-	-	-	VL Clay, M/H Sand	L
B-18	767941	Stockyard Creek	0.8	0.8	0%	2.5	213%	<< 1%	VL Clay, M/H Sand	L
B-19	773535	Tinegie Creek	0.4	0.4	0%	2.5	525%	<< 1%	VL/L Clay, M/H Sand	L
B-20	779635	Talluba Creek	1.3	1.3	0%	2.5	92%	~ 1%	VL Clay, M Sand	L
B-21	802534	Minor Watercourse	0.3	0.3	0%	2	567%	<< 1%	L/M	L
B-22	828222	Bohena Creek	2.1	2.1	0%	1.5	-29%	< 1%	L Clay, M/H Sand	M/H
B-23	844116	Namoi River	2.9	2.8	-3%	2	-29%	<< 1%	VL/L	H
B-24	847500	Narrabri Creek	Geomorphological and soil assessment only[4]						L/M	

Table 6.2 Key to Table 6.1

Variable	Key		
1%AEP Design Velocity vs 1%AEP Existing Velocity	Design Velocity ≤ Existing Velocity	Design Velocity > 110% of Existing Velocity	Design Velocity >120% of Existing Velocity
Assessed Erosivity Threshold Velocity	Threshold Velocity >0.5m/s		Threshold Velocity <0.5m/s
Threshold Velocity vs 1%AEP Design Velocity	Threshold Velocity ≥ Design Velocity	Threshold Velocity <90% of Design Velocity	Threshold Velocity <80% of Design Velocity
Assessed % Probability of Initiation of erosion	≤1% probability of erosion initiation	Between 1%-50% probability	≥50% probability of erosion initiation
Assessed Geotech. Erodibility	Very Low (VL) to Low (L)	Low / Moderate (L/M) and Moderate (M)	Moderate / High (M/H) and High (H)
Geomorphological Erosion Potential	Very Low (VL) to Low (L)	Low / Moderate (L/M) and Moderate (M)	Moderate / High (M/H) and High (H)

The findings of this study indicate that modelled existing velocities provide a useful indicator of erosion susceptibility. However it is also important to consider other factors. Of the 24 watercourses studied:

– Wallaby Creek had reference design reach-averaged velocities more than 10% over the existing velocity, and six more watercourses had design velocities more than 20% over (553169, 568919, Wallaby Creek, Ewenmar Creek, Goulburn Creek, Milpulling Creek and the Castlereagh River). Of these, only Milpulling Creek and the Castlereagh River had assessed erosion threshold velocities that were lower than the design reach-averaged velocity. However, Milpulling Creek is eroding but the Castlereagh River has a depositional environment.

– Goulburn Creek has a reference 1%AEP design velocity which exceeds the existing velocity, and also has a high potential for geomorphological erosion. However, both existing and design velocities are well within the assessed erosion threshold velocity. Artificial alteration of the creek and the lack of riparian corridor are likely to have increased the erosion susceptibility and contributed to gullying of the floodplain.

[4] The geomorphology and soils of Narrabri Creek were assessed on site opportunistically, as an extension of the Namoi River assessment.

– Emogandry Creek, Bohena Creek and the Namoi River system had assessed threshold velocities that were lower than the existing reach-averaged velocity. However, these rivers have very different geomorphological characteristics and patterns of erosion. Emogandry Creek is an incised meandering channel, with outer bank erosion. Bohena Creek has a chain-of-ponds morphology, and is sensitive to change. In-channel erosion within the Namoi River system was not observed to be widespread, but instead confined to floodplains.

This assessment acknowledges the importance of flow velocities in triggering erosion and has shown that consideration should be given to other factors that can influence channel and floodplain stability. To gain a clear picture of watercourse functioning and determine which are naturally prone to erosion, it is essential to also assess the geotechnical soil properties and likely geomorphological response of watercourses, particularly those with laterally eroding meandering channels. The findings of this assessment can be adopted to refine structure design during the next phases of the project, to be compatible with and support the natural functioning of the watercourses.

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TECHNICAL REPORT 03

Updated flooding and hydrology assessment

Appendix A Literature review

NARROMINE TO NARRABRI PROJECT

A-1 Industry guidelines for erosion threshold velocities

This section presents a review of industry standards for maximum erosion threshold velocities. This includes references for both construction and watercourse geomorphology. The implications of these results are discussed further in Section 4.3.

A-1-1 Austroads Guide to Road Design Part 5, and 5b: Drainage

The Austroads Guide to Road Design (2013 and 2021) has become the most widely recognised industry standard for watercourse design and construction. Part 5a considers artificial pipes and watercourses, and is not relevant to this review.

Part 5: Drainage – General and Hydrology Considerations

Austroads (2021) proposes the following advisable velocities within culverts and unprotected stream beds (see Table A.7.1). The following is noted:

- Flows within culverts are higher than the maximum allowable velocity of unprotected stream beds. Therefore, flows will decelerate for some distance downstream of the culvert and bed and bank protection may be required.
- If the culvert has a steep slope, and the culvert velocity exceeds the allowable value, an energy dissipator will be required.

However, if the channel has good vegetation cover, the permissible velocity can be increased.

Table A.7.1 Table 3.10 from Guide to Road Design Part 5: Drainage – General and Hydrology Considerations indicating desirable maximum flow velocities in culverts or unprotected stream beds (p48)

Table 3.10: Desirable maximum flow velocities in culverts or unprotected stream beds

Stream bed soil type	Maximum advisable culvert velocity (m/s)	Maximum allowable stream velocity (m/s)
Silt	1.0–1.5	< 0.3
Clay, soft	1.0–1.5	0.3–0.6
Clay, stiff	1.2–2.0	1.0–1.2
Clay, hard	1.2–2.0	1.5–2.0
Sand, fine	1.0–1.5	< 0.3
Sand, coarse	1.0–1.5	0.4–0.6
Gravel, 6 mm	1.0–1.5	0.6–0.9
Gravel, 25 mm	1.2–2.0	1.3–1.5
Gravel, 100 mm	2.5	2.0–3.0
Rocks, 150 mm	3.5	2.5–3.0
Rocks, 300 mm	3.5	4.0–5.0

Source: Derived from DTMR (2010b) and VicRoads (2003).

Part 5B: Drainage – Open Channels, Culverts and Floodways

This method assumes that the channel will remain stable provided the average velocity of the design flow is below a threshold value (see Table A.7.2). It can be seen that the threshold velocity in this case is dependent on the channel gradient and surface cover. It is observed that reduction in vegetation cover under conditions as drought or bushfire should be accounted for in areas prone to these impacts and bare-earth design values used.

The soil types used have been superseded by Australian Soil Classification terminology, with the following typical correlations:

- Kraznozems are equivalent to Ferrosols (iron-rich subsoils).
- Red earths are equivalent to Kandosols (weakly structured, non-calcic subsoils).
- Black earths are equivalent to Vertosols (>35% clay with strong shrink-swell properties).

– Texture-contrast soils are those which have an abrupt change in texture between the A and B horizons, and could be either Kurosols (acidic), Sodosols (sodic) or Chromosols (other), depending on the characteristics of the subsoils.

It is noted that, in normal grassed channels, as a general rule, the channel velocity should not fall below 0.5m/s to avoid adverse siltation. Vegetation height longer than 50mm can significantly affect flows. Grass 0.75m long can severely retard flows (see Table A.7.3). However, these values are for design channels, rather than natural watercourses.

Table A.7.2 Table 2.6 from Guide to Road Design Part 5B: Drainage – Open Channels, Culverts and Floodways, indicating recommended maximum velocities for channels

Table 2.6: Recommended maximum velocities (design) for consolidated, bare channels and vegetated channels

Channel gradient (%)	Permissible velocities (m/s) when fraction of stable surface cover(1) is:			
	0.02	0.5	0.7	1.0
Erosion resistant soils (e.g. krasnozems and red earths)				
0.5	0.8	1.8	2.4	2.8
1	0.7	1.6	2.1	2.8
2	0.6	1.4	1.8	2.5
3	0.5	1.3	1.7	2.4
4		1.3	1.6	2.3
5		1.2	1.6	2.2
6			1.5	2.1
8			1.5	2.0
10			1.4	1.9
15			1.3	1.8
20			1.3	1.7
Easily eroded soils (e.g. black earths and fine surface texture – contrast soils)				
0.5	0.6	1.3	1.6	2.3
1	0.5	1.2	1.5	2.1
2	0.5	1.1	1.4	1.9
3	0.4	1.0	1.3	1.8
4		1.0	1.2	1.7
5		0.9	1.2	1.6
6			1.1	1.6
8			1.1	1.5
10			1.1	1.5
15			1.0	1.4
20			0.9	1.3

1 Applies to surface consolidated, but not cultivated.

Notes: Assume the following species under average conditions will provide the fraction of cover indicated:

- *Kikuyu, pangola and well maintained couch species – 1.0.*
- *Rhodes grass, and poorly maintained couch species – 0.7.*
- *Native species, tussock grasses – 0.5.*

Source: Adapted from Department of Environment and Resource Management (2012).

Table A.7.3 Table 2.3 from Guide to Road Design Part 5B: Drainage – Open Channels, Culverts and Floodways, guide to vegetation retardance

Table 2.3: Guide to the selection of vegetal retardance

Density of stand (see Note 1)	Average length of vegetation (mm)	Degree of retardance	Examples
Thick	Longer than 750	A	Rhodes grass in ungrazed scrub soil waterway.
Thick	280 to 610	B	Wheat 660 mm tall in 180 mm rows Rhodes grass.
		B	Kikuyu under maximum fertility conditions, long and green.
		B	African star grass. Lucerne (see Note 2).
Thick	150 to 250	C	Most grasses can be held at this retardance with mowing or grazing e.g. Rhodes grass, couch grass, carpet grass, native grasses.
Thick	50 to 150	D	African star grass, kikuyu or couch grass, all under heavy grazing.
Thick	Less than 50	E	Mowed lawn. Any grass burned short.
Fair	Longer than 750	B	–
Fair	280 to 610	C	Rhodes grass under low fertility conditions .
Fair	150 to 250	D	African star grass under low fertility conditions.
Fair	50 to 150	D	–
Fair	Less than 50	E	–

Note: Values of n = 0.15 and greater have been used for fields of standing sugar cane.
1 Thickness of vegetation has an important bearing on retardance, possibly more important than species.
2 Vegetal retardance curves have been based on tests in experimental channels.
Source: Based on Soil Conservation Handbook and Kouwen et al. (cited in DTMR 2010, p. 8–9).

A-1-2 Best Practice Erosion and Sedimentation Control (IECA, 2008)

IECA’s guidelines are a comprehensive review of best practice for erosion and sedimentation control for Australian conditions. These guidelines are typically used in construction projects and to provide advice for e.g. EIS erosion mitigation strategies.

Principle 5.2 indicates that maximum allowable flow velocities should be assessed for individual (artificial) drainage systems based on surface conditions, and bed slopes adjusted accordingly such that this maximum allowable velocity is not exceeded (p2.17). This principle indicates the following allowable velocities:

– Grass-lined channels: 1.5-2m/s
– Rock-lined channels (diameter 100mm to 350mm): 1.5-3.0m/s

It is suggested that, if velocities are too high channel width, depth and bed slope can be artificially altered to attenuate flows. If this is not possible, check dams can be placed across the channel or channel liners (e.g. erosion control mats) can be used to limit bed scour.

Principle 5.3 notes that drainage channels should have sufficient gradient and surface conditions to reduce sedimentation if the required hydraulic capacity is not preserved (e.g. if structures are not adequately maintained).

Appendix A includes Tables A23 to A28, which provide detailed allowable flow velocities for different soil, surface cover and soil conditions. These are summarised as follows:

– Table A23 provides allowable velocities for bare, unlined channels (see Table A.7.4). This table provides basic recommendations for dispersive soils. However, as discussed in Section A-2-4, allowable velocities for cohesive clays can be much higher than 1.1m/s, indicating that these values are conservative.
– Table A24 indicates that allowable velocities for channels with established grass should be 1.0-1.5m/s in easily erodible soils (e.g. black earths and fine surface texture-contrast soils) and 1.5-2.0m/s in

erosion-resistant soils (e.g. kraznozems and red earth soils) (this is similar to Austroads (2013) Table 2.6 (See Table A.7.2)).

Table A.7.4 Table A23 from IECA 2008, Appendix A, indicating allowable velocities for various unlined soil types

Table A23 – Allowable flow velocity for various channel linings

Type	Description	Allowable velocity	Comments
Open earth (unlined channels)	Extremely erodible soils	0.3 m/s	• Dispersive clays are highly erodible even at low flow velocities and therefore must be either treated (e.g. with gypsum) or covered with a minimum 100 mm of stable soil. • Highly erodible soils may include: Lithosols, Alluvials, Podzols, Siliceous sands, Soloths, Solodized solonetz, Grey podzolics, some Black earths, fine surface texture-contrast soils and Soil Groups ML and CL. • Moderately erodible soils may include: Red earths, Red or Yellow podzolics, some Black earths, Grey or Brown clays, Prarie soils and Soil Groups SW, SP, SM, SC. • Erosion-resistant soils may include: Xanthozem, Euchrozem, Krasnozems, some Red earth soils and Soil Groups GW, GP, GM, GC, MH and CH (also refer to Appendix C).
	Sandy soils	0.45 m/s	
	Highly erodible soils	0.4 to 0.5 m/s	
	Sandy loam soils	0.5 m/s	
	Moderately erodible soils	0.6 m/s	
	Silty loam soils	0.6 m/s	
	Low erodible soils	0.7 m/s	
	Firm loam soils	0.7 m/s	
	Stiff clay very colloidal soils	1.1 m/s	

– Table A26 indicates that turf-lined channels should have an allowable velocity of 1.5 – 2.0m/s, and indicates that allowable velocities will vary with soil and rock size, type and cover, where used.
– Tables A25 and A27 and parts of Tables A24 and A26 provide allowable velocities for artificial linings, and are not relevant for this study.
– Table A28 is virtually identical to Austroads (2020b) Table 2.6 (See Table A.7.2), providing allowable flow velocities for degrees of vegetation cover.

Appendix C discusses the importance of vegetation cover, and the necessity for rapid revegetation following disturbance. This section also discusses ways to manage dispersive soils, emphasising the need to maintain surface cover (C11, C14, Exp-C22, Exp C24, ExpC58). It is suggested that non-dispersive topsoil would be required for revegetation (Exp-C24, pC27), or treatment with gypsum is required (Section C11, pC11). It is commented that vegetation should not be the sole erosion control measure. However, for this project, it would not be appropriate to introduce gypsum to watercourse channel materials, as this could impact water quality. Dispersive soils are also discussed in Section C14. This section comments that risks associated with revegetation include:

– Erosion related to rainfall during the revegetation period.
– Failure of revegetation due to e.g. insufficient water or displacement of plant seed (although it is not indicated why this should be more of a problem than in other soils).
– Headcutting gullies or rills (down-system) causing erosion of the revegetated area.

A-1-3 Landcom 'Blue Book': Managing Urban Stormwater: Soils and Construction (2004)

Landcom's 'Blue Book' is widely used to provide erosion management and mitigation advice for all types of erosion (whether associated with watercourses or not). Section 4.1 discusses specific watercourse erosion control measures, including providing maximum design velocity thresholds (see Table A.7.5). However, these values are given for temporary water diversion structures (Section 5.4.4, p5-23). Watercourses are classified based on the objectives for the riparian corridor. It is considered that the N2N project falls under Category 3 due to the limited watercourse reach that will be impacted. This category aims to minimise sedimentation and nutrient transfer by providing bank stability, protecting water quality and protecting native vegetation. This is achieved by emulating a naturally functioning stream and providing opportunity for vegetated habitat refuges.

Table A.7.5 Table 5.2 Managing Urban Stormwater (Landcom, 2004), maximum design velocities in waterways

Table 5.2 Maximum Design Flow Velocities in Waterways (compiled from various sources)

Material			Critical velocity (m/second)	
Type	Thickness (m)	Aggregate size (mm)		
Gabions and reno mattresses	0.50	120-250	6.4	
	0.50	100-200	5.8	
	0.30	100-150	5.0	
	0.30	70-120	4.2	
	0.25	70-100	3.6	
	0.17	70-100	3.5	
	Weight each (kg)		Turbulent flow	Normal flow
Loose rock (assume 100 percent soil cover)	1,000		4.8	6.6
	500		4.2	5.7
	100		3.3	4.5
	50		2.8	3.8
	10		2.3	3.0
	Form			
Revetment mattresses	Storm mattress		>6.0	
	200 mm fp		6.0	
	125 mm fp		4.0	
	100 mm fp		2.0	

Assume that all soils with 10 percent or more dispersible fines have high erodibilities. Of those with less, soils with *K*-factors below 0.02 have low erodibilities, those between 0.02 and 0.045 have moderate erodibilities, while those above 0.045 have high erodibilities.

In addition, the figures here assume slope gradients of less than 10 percent and, where appropriate, good (>80 percent) ground cover. If good ground cover is not expected to be maintained properly (might die back seasonally or during short periods of drought) and is critical to the system, reduce all velocities by 1.0 metre per second. Alternately, seek the manufacurer's advice if these conditions are unlikely to be met.

Material	Critical velocity (m/second)											
	Inundation <6 hours			Inundation <12 hours			Inundation <24 hours			Inundation <48 hours		
	Soil erodibility			Soil erodibility			Soil erodibility			Soil erodibility		
	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
High performance bonded plastic fibres (vegetated)	7.0	7.0	7.0	6.0	6.0	6.0	5.0	5.0	5.0	4.0	4.0	4.0
Plastic fibres with netting	5.0	5.0	5.0	4.3	4.3.	4.3	3.6	3.6	3.6	3.0	3.0	3.0
Mesh reinforced pregrown turf	3.0	2.7	2.4	2.6	2.3	2.0	2.3	2.0	1.8	2.0	1.8	1.6
Kiku yu	2.5	2.2	1.9	2.1	1.9	1.6	1.9	1.7	1.4	1.6	1.4	1.2
Jute or coir mesh (close weave, bitumen sprayed)	2.3	2.0	1.7	1.9	1.7	1.5	1.7	1.5	1.3	1.5	1.3	1.1
Coconut/ jute fibre mats	2.3	2.0	1.7	1.9	1.7	1.5	1.7	1.5	1.3	1.5	1.3	1.1
Couch ,carpet grass, Rhodes grass, etc.	2.0	1.8	1.4	1.7	1.5	1.2	1.5	1.4	1.1	1.3	1.2	0.9
Bare soil	0.7	0.5	0.3	0.6	0.4	0.3	0.5	0.4	0.2	0.4	0.3	0.2

A-1-4 Hydraulic Engineering Circulars (HEC) 14, 18 and 23

HEC 14, 18 and 23 are those concerned with the hydraulic design of energy dissipation, scour protection and erosion control at culverts and bridges (US Department of Transportation 2006, 2012 and 2009 respectively). These industry standard guidelines were reviewed for velocity threshold guidelines. However, while velocity control is discussed at length, specific thresholds are not mentioned.

A-1-5 Gippel *et al*. (2008); White *et al* (2014); Gippel (2020).

The FHAR summarises the findings of Gippel *et al*. (2008) and Gippel (2020), which review maximum permissible velocity values developed for artificial channels in the USA (using the findings of Sprague, 1999; Fischenich and Allen (2000) and Fischenich (2001), among others) and applying them to natural watercourses in the Bowen Basin, Australia. However, the approach used only indicates whether a material subject to erosion falls into the category of stable or unstable (i.e. it does not predict degrees of instability). It can be assumed that the further away is the velocity from the threshold of instability, the higher the risk of erosion.

The initial method looks at the upper and lower thresholds of maximum permissible velocity defined on the basis of the range of soil types expected for the channel and floodplain areas (see Table A.7.6).

Table A.7.6 ***Maximum permissible velocities for channels formed in a range of materials (after Gippel et al., 2008; Gippel, 2020)***

Bed material (USD soil description)	Maximum permissible velocity (m/s)	
	Clear water [3]	Water transporting fine suspended solids [4]
Loam [1]	0.8	1.1
Stiff clay, very colloidal [2]	1.1	1.5
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

Notes:

Plastic clay soil; mixture of clay, sand, and/or gravel, with minimum fines (silt and clay) content of 36%
Moderately to highly plastic clay; mixtures of clay, sand, and/or gravel, with minimum clay content of 36%
Water with concentrations of suspended solids less than 1,000 mg/L
Water with concentrations of over 1000 mg/L, possibly over 20,000 mg/L

The clear water case represents the worst case scenario, with watercourses in the study area anticipated to have much higher sediment concentrations, particularly during flood events.

The values given in Table A.7.6 assume a bare channel surface (i.e. no grass or other lining or vegetation) and a flow depth of one metre. Vegetation failure usually occurs at much higher levels of flow intensity than for soil (Gippel *et al.* (2008), Gippel (2020)). The values given in Table A.7.6 and Table A.7.7 are average values for channels, and assume a reasonable depth of flow. In addition, the values in Figure A.7.1 assume average, uniform stands of each type of cover. In shallow flow situations, as would generally occur on floodplains, it is safe to assume that surfaces covered with sod-forming grass would generally tolerate velocities of up to 2m/s (Gippel, 2020).

Table A.7.7 ***Maximum permissible velocities for channels with slopes of 0% to 5% in easily eroded soils lined with grass (after Gippel et al., 2008; Gippel, 2020)***

Cover	Permissible velocity (m/s)
Sod forming grass: Bermuda grass	1.8
Sod forming grass: Buffalo grass, Kentucky bluegrass, smooth brome, blue grama	1.5
Grass mixture	1.2
Bunch grass: Lespedeza sericea, weeping love grass, *ischaemum* (yellow blue stem), kudzu, alfalfa, crabgrass	0.8
Annuals	0.8
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 (Gippel *et al.,* 2008) recommended application of a factor of safety to U_{max} "when flow duration exceeds a couple of hours". Graphs are provided in Fischenich (2001) (taken from Gippel, 2020) for factoring according to event duration (Figure A.7.1, compare with Figure A.7.4). The duration of flood events naturally varies, although in general the higher the magnitude, the longer the duration.

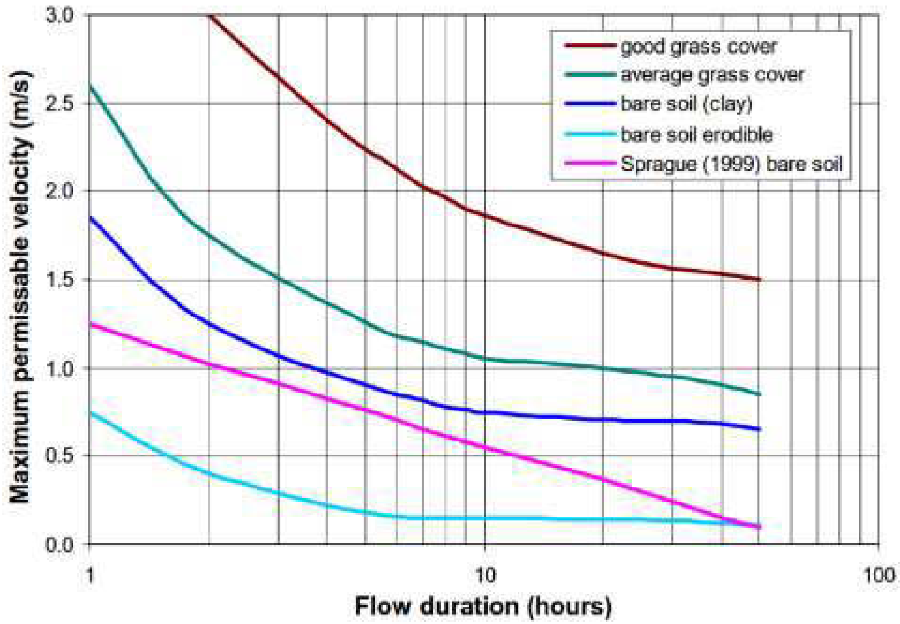


Figure A.7.1 Erosion limits as a function of flow duration (taken from Gippel, 2020)

Perhaps of more relevance to the study area are recommendations provided in White *et al.* (2014), which provides guideline values for Australian streams in the Bowen Basin, updated from the original Australian Coal Association Industry's Research Programme (ACARP, 2000; 2001 and 2002) reports. ACARP guidelines are now frequently used as industry and government standards for geomorphological assessment and remediation design. It should, however, be noted that these guidelines were adopted for channel realignments for mines, i.e. disturbed conditions, rather than natural creeks. The guidelines do not differentiate between vegetated or unvegetated channels for the 2% AEP event, presumably due to the low likelihood of occurrence (Gippel, 2020). It is noted that the maximum permissible velocities increase with size of flood, indicating an achievable guideline. Therefore, although not explicitly stated in the report, it can be assumed that the 1%AEP event would have a higher guideline maximum velocity. Adopting the given 2% AEP values provides a conservative guideline.

Table A.7.8 Maximum permissible velocities modified from ACARP's original design criteria, adopted by Queensland Government in 2002 (after White et al., 2014)

Flood Scenario	Guideline Maximum Velocity (m/s)
Incised Channels	
50% AEP (no vegetation)	1.0
50% AEP (vegetation)	1.5
2% AEP	1.5-2.5
Limited Capacity[5]	
50% AEP (no vegetation)	0.5
50% AEP (vegetation)	1.1
2% AEP	0.9-1.5
Bedrock Controlled	
50% AEP (no vegetation)	1.3
50% AEP (vegetation	1.8
2% AEP	2.0-3.0

[5] It is assumed that this refers to creeks with a limited sediment carrying capacity, which may be more prone to erosion

A-2 Geotechnical erosion potential assessment

A-2-1 Geotechnical erosion resistance of soil

This section discusses accepted industry standard methods used to assess the theoretical geotechnical erosion potential of soils at the inlet and outlet of the watercourse crossings along the proposed railway embankment.

The method used for JGHDs geotechnical assessment is based on the research work by Hewlett *et al.* (1987), Kirsten (1982, 1988), Annandale (1995), and Briaud (2008). In brief, the potential for scour erosion depends on the following key factors:

- Flow rate and flow velocity.
- Duration of flow.
- Gradient of flow channel.
- Soil properties including:
  - Particle size distribution, and mean particle size
  - Soil density (for granular soils), and consistency (for clays)
  - Plasticity of cohesive soils, usually defined in terms of Atterberg Limits
  - Dispersivity
- Surface protection, e.g. condition of vegetation cover.
- Visible evidence of soil characteristics indicating a propensity for erosion, such as desiccation and fissuring of the ground surface and presence of sinkholes, is discussed from a geomorphological perspective in Section 4 and Appendix B.

Discussions are focused on scour erosion of soil, as design flow velocities for a 1%AEP flood are unlikely to be high enough to cause erosion in rock.

A-2-2 Erodibility Index Method

The Erodibility Index, K_h, initially developed by Kirsten (1982) to characterize the excavatability of materials, was used by Annandale as an indicator of the relative ability of earth materials to resist the erosion capacity of water. Application of the Erodibility Index Method is based on an erosion threshold that relates the relative magnitude of the erosive capacity of water and the relative ability of earth and engineered earth materials to resist scour.

In the Erodibility Index Method, Annandale (1995) established a relationship between Stream Power, P, and the Erodibility Index, K_h, by analysing published and field data for a wide variety of earth material types and flow conditions, and found relationship shown in Figure A.7.2. Wibowo *et al.* (2005) applied logistic regression to the data set analysed by Annandale and plotted 1%, 50%, and 99% contours to quantify the likelihood of scour erosion (see Figure A.7.3)

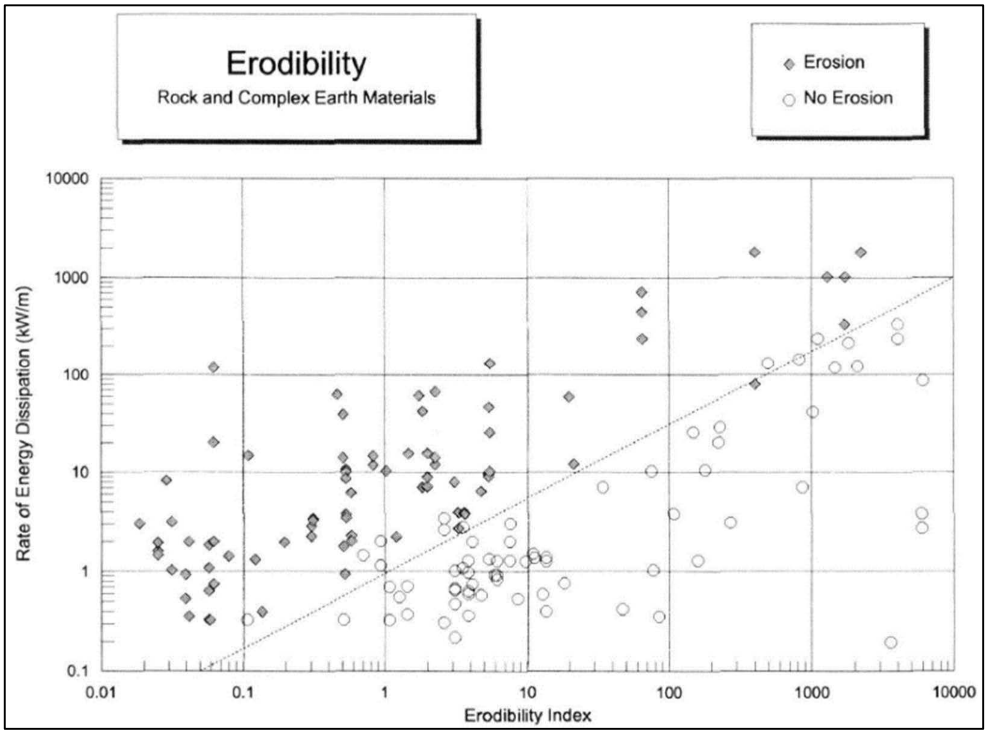


Figure A.7.2 Erodibility threshold for rock and other complex earth materials (Annandale 1995)

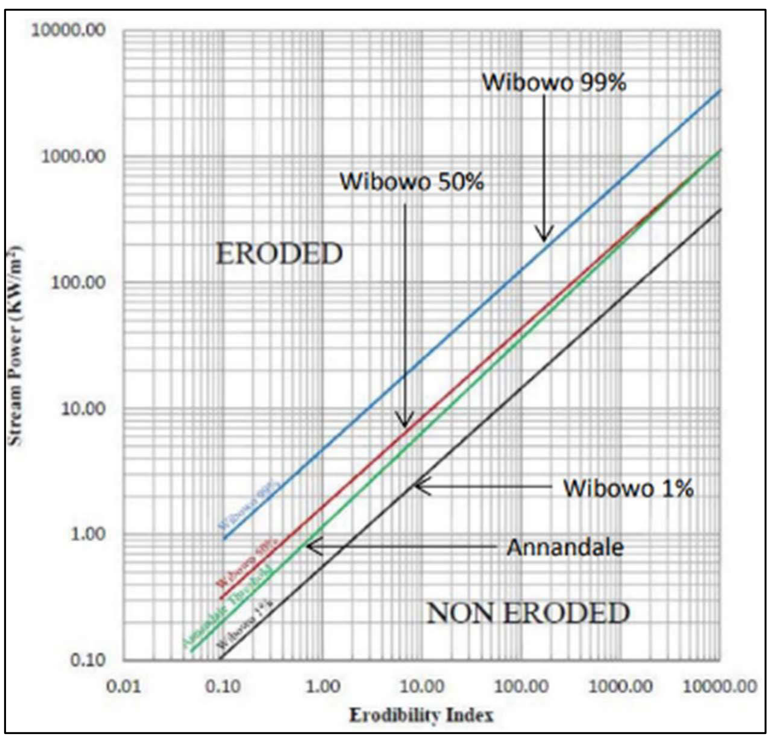


Figure A.7.3 Comparison of erodibility thresholds by Wibowo et al. (2005) and Annandale (2010)

Estimation of Stream Power

In order to assess the erodibility threshold using Figure A.7.2, the rate of energy dissipation has to be estimated. Annandale (1995) considered the erosion power of water was due to turbulence that caused both pressure fluctuations and energy loss. He suggested that the rate of energy dissipation could represent the relative magnitude of fluctuating pressure, and thus the erosive power of the water. The rate of energy dissipation is also named as the stream power, *P*, and can be estimated using the following formula that describes flow at the flow channel boundary:

$$P = \tau_w u = \gamma q S_f \qquad \text{Equation (1)}$$

Where:

- P : represents the stream power [W/m^2]
- τ_w : is the hydraulic shear stress at the flow boundary [N/m^2]
- u : is the mean flow velocity [m/s]
- γ : is the unit weight of water [9810 N/m^3]
- q : is the flow rate per unit width of the flow channel [m^2/s]
- S_f : is the channel bed gradient or can be interpreted as the drop of the energy grade line.

It should be noted that the calculation of stream power in the context of Annandale's (1995) method is different from that used in the FHAR. Stream power can be derived in different ways, based on energy dissipation per unit time or based on work done per unit time. The different equations produce similar results, indicating the works done by the flow. Equation 1 assesses stream power per unit area, whereas other methods calculate total stream power or width-averaged unit stream power (the latter used in the FHAR, 2022).

Kirsten (1982) Erodibility Index

The Erodibility Index is another key parameter for estimation of erodibility threshold using Figure A.7.2. According to Annandale (1995), the erosion resistance of an earth material can be quantified by the material's erodibility index, K_h. K_h is based on Kirsten (1982, 1988) ripability index for which a rational relationship was established between flywheel power of excavation equipment and the ripability of any given soil or rock material. Kirsten (1982) defined K_h as the scalar product of a number of parameters as shown in equation (2).

$$K_h = M_s K_b K_d J_s \qquad \text{Equation (2)}$$

Where:

- K_h : is the Kirsten ripability index
- M_s : is the mass strength number
- K_b : is the particle/block size number
- K_d : is the discontinuity bond shear strength number
- J_s : is the relative ground structure number

Estimation of Mass Strength Number, M_s

For cohesionless granular soils such as sands and gravels, guidance of estimation of the value of M_s is given in Table A.7.9.

Table A.7.9 Mass strength number for granular soil (from Table 1, Annandale, 1995)

Consistency	Identification in Profile	SPT Blow Count	Mass Strength Number (M_s)
Very loose	Crumbles very easily when scraped with geological pick	0-4	0,02
Loose	Small resistance to penetration by sharp end of geological pick	4-10	0,04
Medium dense	Considerable resistance to penetration by sharp end of geological pick	10-30	0,09
Dense	Very high resistance to penetration of sharp end of geological pick - requires many blows of pick for excavation	30-50	0,19
Very dense	High resistance to repeated blows of geological pick - requires power tools for excavation	50-80	0,41
Note: Granular materials in which the SPT blow count exceeds 80 to be taken as rock - see Table 3.			

For cohesive soils, guidance of estimation of the value of M_s is given in Table A.7.10.

Table A.7.10 Mass strength number for cohesive soil (Table 2, Annandale 1995)

Consistency	Identification	Vane Shear Strength (kPa)	Mass Strength Number (M_s)
Very soft	Pick head can easily be pushed in up to the shaft of handle. Easily moulded by fingers.	0-80	0,02
Soft	Easily penetrated by thumb; sharp end of pick can be pushed in 30 mm - 40 mm; moulded by fingers with some pressure.	80-140	0,04
Firm	Indented by thumb with effort; sharp end of pick can be pushed in up to 10 mm; very difficult to mould with fingers. Can just be penetrated with an ordinary hand spade.	140-210	0,09
Stiff	Penetrated by thumbnail; slight indentation produced by pushing pick point into soil; cannot be moulded by fingers. Requires hand pick for excavation.	210-350	0,19
Very stiff	Indented by thumbnail with difficulty; slight indentation produced by blow of pick point. Requires power tools for excavation.	350-750	0,41
Note: Cohesive materials of which the vane shear strength exceeds 750 kPa to be taken as rock - see Table 3.			

Estimation of Particle/Block Size Number, K_b

For cohesionless granular soils, the particle/block size number can be determined directly based on the following equation proposed by Kirsten (1992):

$$K_b = 1000\,(D_{50})^3 \qquad \text{Equation (3)}$$

Where:

D_{50} : mean grain size in millimetres, i.e. the fraction of the soil finer than this size represents 50% of the total weight of the soil sample

For intact cohesive soils, the value of K_b is set to 1 as recommended in Annandale (1995).

Estimation of Discontinuity Bond Shear Strength Number, K_d

In cohesive and non-cohesive granular earth material, the intergranular bond shear strength number, K_d, is estimated by the following equation:

$$K_d = \tan\phi \qquad \text{Equation (4)}$$

Where:

ϕ : represents the residual friction angle of the granular earth material

Estimation of Relative Ground Structure Number, J_s

The relative ground structure number, J_s, represents the relative ability of earth material to resist erosion due to the structure of the ground. When assessing intact material, such as massive rock or fine-grained massive clay, or when assessing non-cohesive granular soils, the value of J_s is set to one (1) as recommended in Annandale (1995).

A-2-3 CIRIA Report 116 – Design of Reinforced Grass Waterways

Hewlett *et al.* (1987) presented their research findings on the potential for erosion along grassed waterways in CIRIA Report 116, which sets out the procedure for the planning, design and construction of steep grassed waterways. Hewlett *et al.* (1987) carried out more than 90 full-scale field trials at Jackhouse Reservoir in UK to test the scour erosion resistance of earth surfaces with various types of surface protection, including:

- Concrete block surfacing (tied or untied blocks, and also in-situ concreting)
- Woven fabric surface protection
- 2-dimensional mesh
- 3-dimensional open mat
- Bitumen-bonded 3-dimensional mesh
- Plain grass
- Subsoil

Observation from the field experiments and analysis of test data from earlier research by Whitehead, *et al.* (1976) indicated that, for earth slope surface with plain grass cover, the erosion resistance is dependent on (1) flow velocity, and (2) duration of flow, as shown in the velocity-duration diagram in Figure A.7.4. The field trials performed by Hewlett *et al*. were carried out for flow velocities as high as 8.2 m/s and flow durations as long as 3.5 hours. For field tests performed on plain grass surfaces, the field tests carried out by Hewlett *et al*. did not last longer than 3 hours. For flow durations longer than 3 hours and up to about 100 hours, Hewlett *et al*.'s erosional stability curves were based on test data from Whitehead *et al*. (1976) as shown in Figure A.7.5 (Hughes and Thornton, 2015).

According to Hewlett *et al*. (1987), "good grass cover" in Figure A.7.4 (also used in Figure A.7.5) means a dense, tightly-knit turf established for at least two growing seasons. "Poor grass cover" consists of uneven tussocky grass growth with bare ground exposed or a significant portion of non-grass weed species. Newly sown grass is likely to have a poor cover for much of the first season. Presumably, an "average grass cover" is something in between good and poor cover.

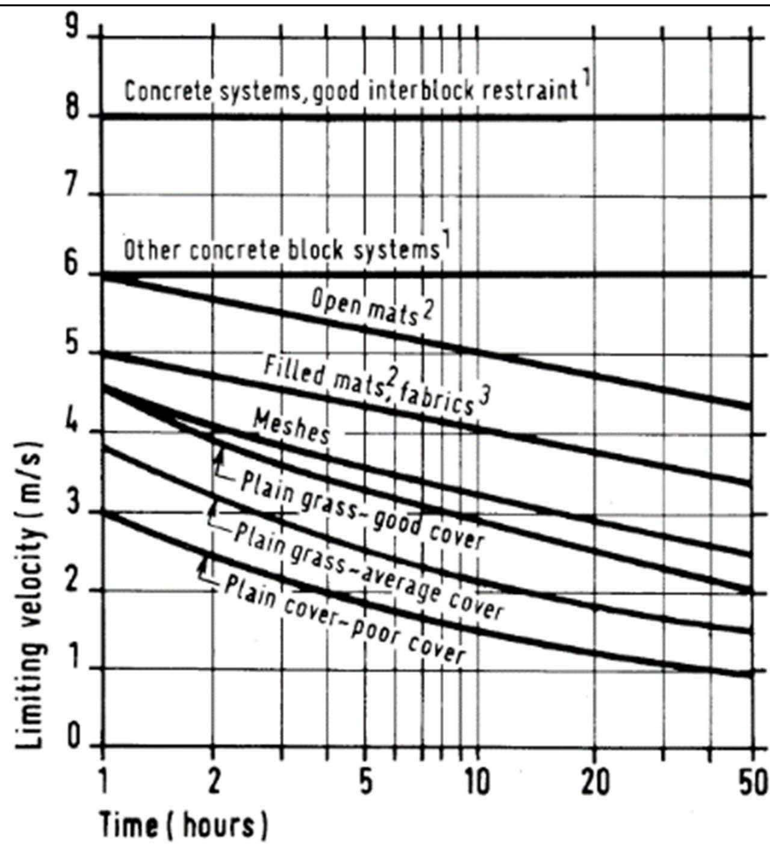
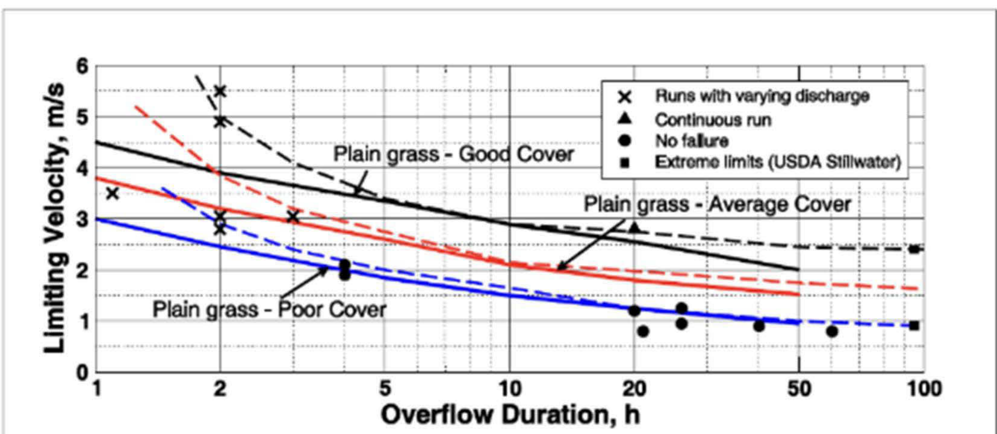


Figure 9 *Recommended limiting values for erosion resistance of plain and reinforced grass*

Notes:
1. Minimum superficial mass 135 kg/m^2, see Section 4.3.3 for other criteria.
2. Minimum nominal thickness 20 mm.
3. Installed within 20 mm of soil surface, or in conjunction with a surface mesh.
4. See Section 4.3.2 for other criteria for geotextile reinforcement.
5. These graphs should only be used for erosion resistance to unidirectional flow. Values are based on available experience and information at date of this report.
6. All reinforced grass values assume well-established, good grass cover.
7. Other criteria (such as short-term protection, ease of installation and management, susceptibility to vandalism, etc) must be considered in choice of reinforcement.

Figure A.7.4 ***Potential for initiation of scour erosion based on flow velocity, duration of flow and type of ground surface protection (Figure 9, CIRIA Report 116, Hewlett et al., 1987)***



Note: Solid curves were proposed by Hewlett *et al.,* (1987)
Dotted curves were proposed by Whitehead *et al.,* (1976)

Figure A.7.5 ***Test data points for long duration erosion tests and erosion stability curves proposed by Whitehead et al. (1976) on slopes with plain grass cover, and erosion stability curves proposed by Hewlett et al. (1987) (Hughes and Thornton, 2015)***

A-2-4 Other methods for assessment of erodibility of soils

Erodibility of non-cohesive granular soils

In the 2007 Ralph B. Peck Award Lecture, Professor Briaud introduced some fundamental aspects of soil and rock erosion, and presented four case studies on erosion making use of the erosion function apparatus to quantify the erodibility of a soil or rock. Based on his extensive laboratory testing using the erosion function apparatus, and erosion test data from previous research by others, Briaud explained that an important soil parameter in erosion study is the threshold for erosion, which can be defined as the critical shear stress, τ_c, or the critical flow velocity, V_c. Figure A.7.6 shows a plot of the critical velocity as a function of the mean grain size, D_{50}. This function is better defined for granular soils, in particular sands and fine gravels, by Equation (5) (see Figure A.7.6, equation is for D_{50} >0.1mm).

$V_c = 0.35 (D_{50})^{0.45}$ Equation (5)

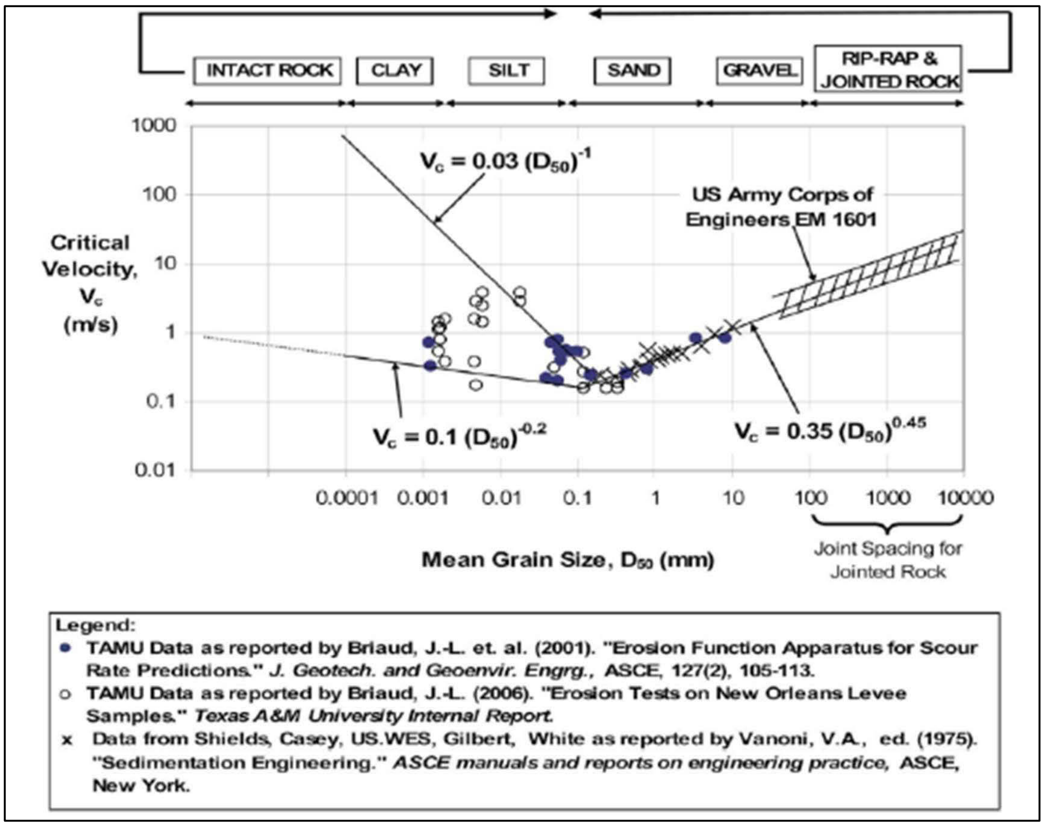


Figure A.7.6 Critical velocity as function of mean grain size (Briaud 2008)

Erodibility of fine-grained cohesive soils

The erosion rate of a soil can, in general, be defined by Equation (6).

$\varepsilon = k_d\ (\tau - \tau_c)$ Equation (6)

Where:

ε : represents the erosion rate in [m/s]
k_d : a detachment rate coefficient [m^3/N/s]
τ : hydraulic shear stress causing scour erosion [N/m^2]
τ_c : critical hydraulic shear stress for initiation of erosion [N/m^2]

The detachment rate coefficient, k_d, in Equation 6 is a parameter that indicates the rate of erosion instead of the threshold for erosion. k_d and τ_c are properties of the soil material and are affected by various factors such as soil composition, compaction characteristics and degree of cementation. Although k_d is an indicator of the rate of erosion, it can serve as an indicator of erosion resistance of fine-grained cohesive soils (e.g. silt and clay) as shown in Table A.7.10. Some soil erosion testing showed that, for cohesive soils, K_d apparently varied with plastic index, decreasing with increasing plasticity, and consistent with the erosion classification chart of Briaud (2008) (See Figure A.7.7). Therefore, the erodibility of a cohesive soil can be qualitatively estimated indirectly from the plastic index of the soil using Table A.7.11 and Figure A.7.7.

Table A.7.11 ***Characterisation of erodibility based on the detachment rate coefficient (USACE and USBR 2015)***

Erodibility	k_d (cm^3/N/s)	k_d (ft3/lb/hr)
Very erodible	1 to 5 (or more)	0.5 to 2 (or more)
Erodible	0.05 to 2	0.02 to 1
Moderately Resistant	0.01 to 0.5	0.005 to 0.2
Resistant	0.001 to 0.4	0.0005 to 0.2
Very resistant	0.0005 (or less) to 0.1	0.0002 (or less) to 0.1

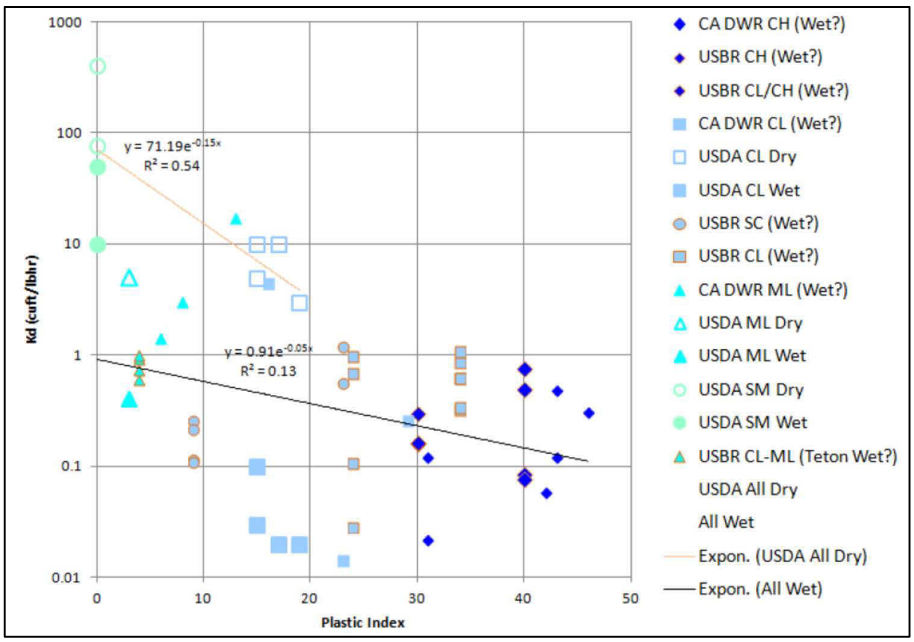


Figure A.7.7 ***k_d versus Plastic Index from tests by Hanson et al. (2010, 2011), Wahl et al. (2009), and Shewbridge et al. (2010) (USACE and USBR, 2015)***

Erodibility of dispersive soils

Dispersive soils occur when soil aggregates collapse as individual clay particles disperse into solution spontaneously when the soil gets wet by fresh water. This collapse of the soil structure causes the soil to slump and lose porosity.

Clay minerals are found in the form of layers with the successive layers bonded by van der Waal forces and by readily exchangeable cations, which balance charge deficiencies in the clay mineral structure. The charge deficiencies occur due to isomorphous substitution of the cations within the crystal structure. This leads to net negative charge on the clay crystal surface. In dispersive clay, the bonding by van der Waals forces is weak and easily separated by cleavage of adsorption of water when the clay is wetted. A water molecule has a dipolar positive and negative charge which allows the molecule to be attracted to the negatively charged clay surface and to the cations, hence weakening the bonding between the layers of the clay mineral. This results in the clay particles spontaneously dispersing in water.

Dispersive soils are expected to be highly erodible even subjected to negligible flow velocity, although a high content of dissolved solid in the water may suppress the dispersive behaviour of the dispersive clay (i.e. dispersion decreases with water impurity content).

Four different laboratory tests measure the dispersivity of the clay fraction of the soil samples taken from selected boreholes: Emerson Crumb, Pinhole Dispersion, double-hydrometer, and Exchangeable Sodium Percentage (ESP) tests. From experience (Wan, 2005), the various dispersivity tests usually give contradicting results, as they test slightly different electrochemical behaviour of the soil sample. Therefore, to avoid confusion, the current study only used the results of the Emerson Crumb test. Emerson Class 1 is considered highly dispersive; Emerson Class 2.1 dispersive and Class 2.2 moderately dispersive.

Application of reviewed methods

The review of available methods of calculating the geotechnical erodibility potential indicated that each method had merits and limitations with relation to this study. Therefore, a combination of methods was used to provide a balanced view of the erosion potential at the assessed sites. Table A.7.12 provides a summary of the calculations used for the assessments in Appendix B, with Table A.7.13 providing the criteria used for the erosion potential assessment.

Table A.7.12 Comparison of proposed methods for assessment of erosion potential

Erodibility assessment method	Input Parameters		Output	Comment
	Hydraulic Condition	Soil/ Rock Parameters		
Method 1 – Erodibility Index Method (Annandale 1995)	– Water unit weight, γ – Unit flow rate per unit width of channel, q – Channel bed gradient, S_f – Derived Parameter: – Unit Stream Power, P $P = \gamma q S_f$	– Mass Strength Number, Ms Particle/Block Size Number, K_b – Discontinuity Bond shear strength number, K_d – Relative ground structure number, J_s (Estimation of the above parameters requires knowledge of the *in situ* soil density, hardness and friction angle) – Derived parameter: – Erodibility index, K_h $K_h = M_s K_b K_d J_s$	– The position of (K_h, P) on a log–log plot indicating if erosion threshold is exceeded (see Figure A.7.2 in Appendix A). – Predicted probability of initiation of erosion based on Wibowo et al (2005) probability contours on the (K_h, P) log-log plot (see Figure A.7.3 in Appendix A).	**Merits:** – Calculate stream power, P, that takes into consideration predicted hydraulic conditions – Calculate Erodibility Index, K_h, that takes into account available soil properties – Sound methodology based on many case studies **Limitations** – Does not consider duration of flow – Does not consider effects of vegetation cover – Does not consider dispersivity of soil – Available soil data may not be representative if boreholes are at a considerable distance from the site
Method 2 – Erosion potential along grassed waterways (Hewlett *et al.,* 1987)	– Flow velocity, V – Flow duration, t	– Type of surface protection (subsoil, grass cover, etc.)	– Threshold flow velocity, V_c, for initiating erosion (see Figure A.7.4 in Appendix A)	**Merits:** – Hydraulic conditions represented by flow velocity – Consider flow duration that is known to be an influence factor erosion – Consider surface protection – Sound methodology based on lots of field testing **Limitations** – Does not consider soil properties – Does not consider dispersivity of soil – In many cases, flow duration is unknown and has to be estimated/ assumed

Erodibility assessment method	Input Parameters		Output	Comment
	Hydraulic Condition	Soil/ Rock Parameters		
Method 3 - Critical Velocity estimated from Mean Grain Size (Briaud, 2008)		– Particle size distribution of soil, in particular the mean particle size, D_{50}	– Threshold flow velocity, V_c, for initiating erosion (see Table A.7.6 in Appendix A)	**Merits:** – Hydraulic conditions represented by flow velocity – Sound methodology with empirical relationship based laboratory erosion testing
				Limitations – Does not consider duration of flow – Only applicable to bare soil with no surface protection – Does not consider dispersivity of soil – Particle size distribution data, and D_{50} are not available. In particular if fine-grained soils are involved, particle size analysis for the fine fraction is usually not available.
Method 4 – Indirect relationship between Erodibility and Plastic Index		– Plastic Index of soil	– Qualitative assessment of the erodibility of a cohesive soil (see Table A.7.11 and Figure A.7.7 in Appendix A)	**Merits:** – Simplicity
				Limitations – Qualitative assessment only – Applicable to cohesive soils only – Does not consider hydraulic condition – Does not consider dispersivity of the soil – High uncertainty in the relationship between erosion rate index and plastic index

The erosion potential of individual sites is qualitatively described as Very Low (VL), Low (L), Moderate (M), High (H) or Very High (H) considering the results of analysis using one or more of Methods 1 to 3 with assessment criteria summarised in Table A.7.13.

Table A.7.13 Assessment criteria for erosion potential

Method of assessment	Description of erosion potential	Criteria
Method 1 – Erodibility Index Method (Annandale 1995)	– Very Low (VL) – *Low (L)*[1] – Moderate (M) – *High (H)*[1] – Very High (VH)	Refer to probability contours presented by Wibowo *et al*. (2005) (see Figure A.7.3 in Appendix A): – Probability of erosion < 1% – *Probability between 1%-25%* – Probability ~ 50% – *Probability between 75% and 99%* – Probability > 99%
Method 2 – CIRIA Report 116 (Hewlett *et al*., 1987)	– Very Low (VL)[2] – Moderate (M)[3] – Very High (VH)	– $V_c >= 2 \times V$ – $V_c \sim V$ – $V_c <= 0.5 \times V$
Method 3 – Critical Velocity based on Mean Grain Size (Briaud 2008)	– Very Low (VL) – Moderate (M) – Very High (VH)	– $V_c >= 2 \times V$ – $V_c \sim V$ – $V_c <= 0.5 \times V$

Notes:

1. Wibowo *et al*. (2005) did not give values for Low or High Erosion Potential, and the given values have been adopted for this study.
2. V_c represents critical velocity for initiation of erosion estimated using the respective method.
3. V represents the flow velocity from hydraulic modelling.

TECHNICAL REPORT 03

Updated flooding and hydrology assessment

Appendix B Site visit summary sheets

NARROMINE TO NARRABRI PROJECT

B-1 Minor Watercourse, 250-Clvrt553169 – 8/2/22 2:20pm

Modelled Existing 1%AEP Vmax = 1.3m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material*	Vegetation	Erosion Observations	QDL Exceedance Observations[6]
Densely vegetated indistinct grassy swale flowing into a farm dam. Overland flows are impacted by Pinedean Road. Flattening of in-channel vegetation indicates recent flows.	Banks and floodplain comprise shallow sandy clay residual soil overlying weathered granite.	Weed-filled channel with sparse trees at culvert crossing. Floodplain is grassed pasture with sparse remnant trees	Small dam downstream of proposed culvert crossing site. Existing culvert under Pinedean Road is partially blocked.	Many broad culverts along this section of the proposal. Minor pooling upstream of embankment, edge effects and vegetation artefacts.

*Note: bed and bank materials were assessed for these summary sheets using a combination of on-site observation and nearby geotechnical investigations

Photographic Record

Upstream	Downstream	Downstream End of Existing Culvert	Erosion around Farm Dam
			

Discussion and Recommendations

As general

[6] Note: QDL exceedances discussed in these site visit summary sheets were based on those mapped at the time of the site visit.

B-1-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Highest flow velocity, *V* (m/s)	Highest *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	1.30 – 1.48	1.59 – 2.00	0.0037 – 0.0038	13.0 – 19.5	0.058 – 0.074

Note : Stream Power, $P = \rho\, D\, V\, S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits	Emerson Class / Dispersivity	Shear Strength
BH2065 (to west); TP2006 to east	– CI, Sandy Clay with trace gravel – Fines content 58% – Estimated D_{50}: 0.01mm	Hard	Medium plasticity	N/A	2.2	N/A

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.19 given soil is HARD (stiff) Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., $K_d = \tan \phi$ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s\, K_b\, K_d\, J_s$ = 0.095	Erosion threshold probability contour (Wibowo *et al.* 2005) – Stream Power, *P*, for 1% chance of initiating erosion : 0.10 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.3 kW/m^2	– Estimated *P* is smaller than 0.074 kW/m^2. – Chance of initiating erosion is less than 1%	Very low (VL)	Low (L) to Moderate (M)
Hewlett *et al.* (1987) Ground Cover	Conditions: – Poor/no grass cover – Flow duration = 13.0 – 19.5 hr	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.2 m/s	– Highest flow velocity us 1.30 – 1.48 m/s over a duration of 13.0 – 19.5 hrs. – Average velocity is assumed to be approximately 0.7 m/s – Assuming highest velocity of flow will last for 6.0 – 9.5 hrs only, the threshold velocity for initiation of erosion is 1.6 m/s.	– On average, flow velocity is expected to be lower than threshold velocity for initiation of erosion.	Low (L)	
Critical velocity based on D_{50} (Briaud 2008)	Conditions: – D50 is approximately 0.01 mm. – Soil is fine-grained (cohesive)	Threshold flow velocity to mobilise soil particle (Briaud 2008) is between: $0.1\,(D_{50})^{-0.2}$ = 0.25 m/s, and $0.03\,(D_{50})^{-1}$ = 3.0 m/s		– Threshold velocity to initiate erosion in cohesive soil falls into a wide range. – Estimated highest flow velocity (1.30 – 1.48 m/s) for the 1%AEP event falls within the lower and upper bound threshold velocities for initiating erosion	Moderate (M)	
Dispersivity of soil	Emerson Class = 2.2			– Soil is moderately dispersive	Moderate (M)	

B-2 Wallaby Creek, 250-Clvrt553970 – 8/2/22 2:40pm

Modelled Existing 1%AEP Vmax = 1.1m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Creek flows through a large box culvert (bridge) at Pinedean Road. Compound, sinuous channel with incised active channel within a larger incised trench.	Banks and floodplain comprise shallow sandy clay residual soil overlying weathered granite.	Weed-filled channel with sparse trees at culvert crossing. Floodplain is grassed pasture with sparse remnant trees. Flood debris caught on fencing crossing watercourse.	Both banks are eroding and undercut upstream of the proposal and road. Degraded morphology does not indicate rapid erosion: berm protects base of bank. Minor scour downstream of culvert, with small mid-channel bar downstream of mid-channel wall.	Edge effects	Cross-section indicates that channel is perched above surrounding farmland

Photographic Record

Upstream	Downstream	Upstream with Flood Debris and Incised Channel	Minor scour with mid-channel bar downstream of culvert
			

Recommendations

- Topography to be checked for elevated channel, which may cause issues with flood-flow returns downstream. Additional proposed culverts to the east should mitigate this effect.
- Assessed maximum permissible velocity is 1.2m/s – the lowest of the assessed watercourses. However, the banks below the existing bridge are well vegetated and less steep than up and downstream, indicating that successful establishment of vegetation will reduce erosion. Bank protection measures, such as artificial surface protection (e.g. jute mesh or a suitable geofabric), may be required along the channel adjacent to the culvert to reduce additional bank erosion while vegetation is being established.

B-2-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, V (m/s)	Average DV value (m²/s)	Approximate flow gradient, S_f	Flow Duration, T, (hr)	Unit Stream Power, P (kW/m²)
1%AEP	1.17 – 1.32	1.56 – 1.62	0.0037 – 0.0039	21.5 – 27.8	0.057 – 0.062

Note : Stream Power, $P = \rho\, D\, V\, S_f$, where ρ equals 9.8 kN/m³, represents the unit weight of water

Soil sample from upstream right bank

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits	Emerson Class / Dispersivity	Shear Strength
TP2006 (on floodplain to east)	– CL Sandy Clay with trace gravel to 0.5m – SP Poorly graded sand 0.5 – 0.7m – Fines content 58% for CL materials – Estimated D_{50}: 0.01mm for CL materials.	Hard	Low plasticity	N/A	2.2	N/A
Soil sample taken from upstream right bank (see photo)	– Sandy clay	Soft	Very low plasticity, though soil can be moulded into a thread, but only in short segments	No data, but expected very low plastic index and liquid limit		

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.04 given soil is Soft Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.4 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s\, K_b\, K_d\, J_s$ = 0.016	Given estimated K_h = 0.016, and referring to Wibowo et al 2005: – Stream Power, P, for 1% chance of initiating erosion : 0.02 kW/m² – Stream Power, P, for 50% chance of initiating erosion: 0.08 kW/m²	– Estimated P is between 0.057 and 0.062 kW/m². – Chance of initiating erosion based on the average stream power is slightly below 50%	Moderate (M)	Moderate (M)
Hewlett *et al.* (1987) Ground Cover	Conditions: – Poor grass cover along river bank. – Flow duration = 21.5 – 27.8 hr	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.1 m/s	– Highest flow velocity us 1.17 – 1.32 m/s over a duration of 21.5 – 27.8 hrs. – Average velocity is assumed to be approximately 1.25 m/s – Assuming highest velocity of flow will last for 25 hrs only, the threshold velocity for initiation of erosion is 1.2 m/s.	– On average, flow velocity is expected to close to threshold velocity for initiation of erosion.	Moderate (M)	
Critical velocity based on D_{50} (Briaud 2008)	Conditions based on TP2006: – D_{50} is approximately 0.01 mm. – Soil is fine-grained (cohesive)	Threshold flow velocity to mobilise soil particle (Briaud 2008) is between: 0.1 $(D_{50})^{-0.2}$ = 0.25 m/s, and 0.03 $(D_{50})^{-1}$ = 3.0 m/s	– Estimated threshold velocity is 1.6 m/s.	– Estimated highest flow velocity (1.17 – 1.32 m/s) for the 1%AEP event is below the average threshold velocity of 1.6 m/s for initiating erosion	Low (L) to Moderate (M)	
Dispersivity of soil	Emerson Class = 2.2			– Soil is moderately dispersive	Moderate (M)	

B-3 Macquarie River, 250-BR562344 – 9/2/22 8:00am

Modelled Existing 1%AEP Vmax = 1.6m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Deeply incised, moderately sinuous channel with a high elevation in-trench bench and levees. Active channel is around 50m wide, with elongated alternating lateral bars. The broad flood trench accommodates up to around the 20%AEP flood.	Banks and floodplain comprise very deep (20-30m) alluvial soils, overlying residual soil, then low strength sandstone. Reported as being a bedrock-controlled channel, but no bedrock outcropping was observed, although outcrops may be found upstream. Clayey silt observed along bank.	Dense grasses, mid-storey plants and moderately dense mature trees. Plentiful. LWD in places (snags, branches and fallen trees). Invasive willows were observed at other locations, but were not observed at the N2N project crossing point.	Trees lining channel have caused localised erosion on failure. Erosion pattern is consistent with meandering channels, with outer bank erosion opposite lateral bars. This is more pronounced along the more sinuous upstream reaches. High suspended loads are producing turbid water. Water was turbid, indicating a high suspended load (fine sediment)	Edge effects	Mature trees may require clearance during construction of the bridge.

Photographic Record

Looking upstream at erosion (probably from a falling tree) on the right bank, near the N2N project crossing.	Downstream	Looking from active channel bank top up inner bench face	Looking south from inner bench towards outer trench wall	Looking southwest across floodplain
				

Discussion and Recommendations

– The Macquarie River is proposed to be crossed by a broad bridge, which spans the 1%AEP floodplain, and which will limit impacts to the active channel and floodplain.

– Localised impacts may occur due to removal of stabilising vegetation (e.g. mature trees and grasses, whose roots stabilise the topsoil). Rapid revegetation of these areas would reduce impacts.

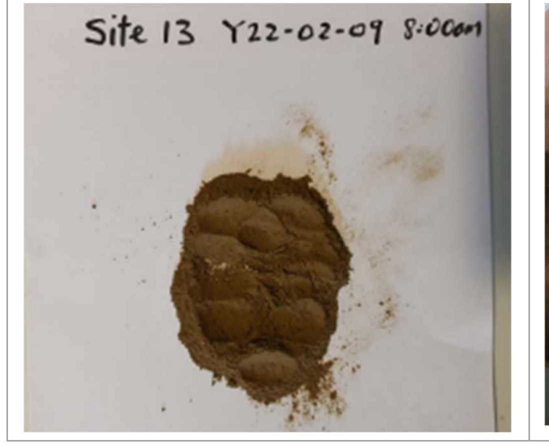
– Bridge piers should be located and sized to minimise impacts to flow and sediment dynamics. If possible, the active channel should be bridged entirely, with piers located on the high elevation in-trench bench.

B-3-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.68 – 0.81 m/s	1.46 -2.73	0.017 – 0.018	Unknown (assume > 24hr)	0.243 – 0.482

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Soil sample taken from track leading to left bank	Thread test for plasticity
	

Geotechnical Observations and Soil Erodibility

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits	Emerson Class / Dispersivity	Shear Strength
BH2002, TP2010; BH2003	Floodplain comprises silty clay or clayey silt topsoil, overlying silty clay	Hard	Medium to high	N/A	N/A	N/A
Soil sample taken from track leading to left bank (See photo)	Light brown silty clay.		Medium to high plasticity (see photo on Thread Test)		Soil crumb does not appear to be dispersive in distilled water	

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.19 given soil is Hard Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s$ = 0.095	Given estimated K_h = 0.095, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.10 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.32 kW/m^2	– Estimated *P* is between 0.243 and 0.482 kW/m^2. – The relatively high stream power is due to the relatively high gradient of flow. – Chance of initiating erosion due to average stream power is slightly higher than 50%.	Moderate (M)	Moderate (M) to Low (L)
Hewlett *et al.* (1987) Ground Cover	Conditions: – Poor grass cover in places along river bank. – Flow duration assumed longer than 24 hrs	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.0 m/s	– Highest flow velocity is 1.17 – 1.32 m/s. – Average velocity is assumed to be approximately 1.25 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is 1.4 m/s.	On average, flow velocity is expected to be lower than the threshold velocity for initiation of erosion.	Moderate (M) to Low (L)	
Critical velocity based on D_{50} (Briaud 2008)	Conditions based on TP2006: – No data on D_{50}. – Soil is fine-grained (cohesive)			Particle size data not available	N/A	
Dispersivity of soil	N/A			Soil does not appear to be dispersive	N/A	

B-4 Minor Watercourse, 250-Clvrt 568919 – 8/2/22 4:00pm

Modelled Existing 1%AEP Vmax = 0.9m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Creek flows through a moderately large box culvert (bridge) at Eumungerie Road. Channelised at road. Discontinuously, slightly incised channel through hardsetting topsoil.	Banks and floodplain comprise deep sandy clay residual soils.	Sparsely vegetated, with some in-channel reeds. Grassy, narrow riparian corridor, with agricultural alteration close to channel. Flood debris caught in fence across channel	Both banks are eroding and undercut upstream of the proposal and road. Degraded morphology does not indicate rapid erosion: berm protects base of bank. Minor scour pool downstream of culvert.	Edge effects	Cross-section indicates that channel is perched above surrounding farmland

Photographic Record

Looking upstream at scour pool and flood debris below Eumungerie Road	Looking downstream at slightly incised pool	Discontinuous, slightly incised pool typical of dispersive soils	Cropping on floodplain, with indistinct channel
			

Discussion and Recommendations

- Topography to be checked for elevated channel, which may cause issues with flood-flow returns downstream.
- Existing erosion would be mitigated to avoid extension of the incised pool, e.g. through infilling with suitable material and revegetation (which may require artificial surface protection).
- As per general recommendations.

B-4-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, V (m/s)	Average DV value (m²/s)	Approximate flow gradient, S_f	Flow Duration, T, (hr)	Unit Stream Power, P (kW/m²)
1%AEP	0.96 – 1.26	0.39 -0.43	0.0089 – 0.0094	0.23 – 0.40	0.034 – 0.040

Note : Stream Power, $P = \rho\, D\, V\, S_f$, where ρ equals 9.8 kN/m³, represents the unit weight of water

Thread test done on soil sample taken on erosion gully in flood plain downstream of twin cell culvert

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
BH2067	CI-CH, Sandy Clay with trace gravel	Very Stiff	Medium to high	N/A	N/A	SPT-N 29, 31, 39 Pocket penetrometer test > 500 kPa
Soil sample from erosion gully in flood plain downstream of twin culvert	Brown Sandy Clay, Medium to High plasticity		Medium to high (See photo on Thread Test)			

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Very Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s\, K_b\, K_d\, J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, P, for 1% chance of initiating erosion : 0.18 kW/m² – Stream Power, P, for 50% chance of initiating erosion: 0.55 kW/m²	– Estimated P is between 0.034 and 0.040 kW/m². – Chance of initiating erosion is lower than 1%	Very Low (VL)	Very Low (VL)
Hewlett *et al.* (1987) Ground Cover	Conditions: – Very poor grass over flood plain. – Flow duration = 0.23 – 0.40 hr	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c > 3.0 m/s	– Highest flow velocity is 0.39 – 0.43 m/s over a duration of 0.23 – 0.40 hrs. – Average velocity is assumed to be approximately 0.41 m/s – Assuming highest velocity of flow will last for 0.31 hrs only, the threshold velocity for initiation of erosion is > 3.0 m/s.	– On average, flow velocity is expected to substantially lower than the threshold velocity for initiation of erosion.	Very Low (VL)	
Critical velocity based on D_{50} (Briaud 2008)	Conditions based on BH2067: – No data on D_{50}. – Soil is fine-grained (cohesive)			– Particle size data not available	N/A	
Dispersivity of soil	N/A			– Soil does not appear to be dispersive	N/A	

B-5 Ewenmar Creek, 250-BR595239 – 9/2/22 9:30am

Modelled Existing 1%AEP Vmax = 1.4m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Sinuous, incised creek with compound channel, with a generally well-defined, incised active channel (about 2m wide and 1m deep) flowing within a broader incised flood trench. Undersized, partially blocked culverts under Old Mill Road are significantly affecting flow and sediment dynamics, with complete infilling of channels upstream and downstream of the road. There are 2 anabranches above and below Old Mill Road, but these have been artificially joined to create the road crossing.	Coarse, loose sandy bed with clay drapes. Banks comprise silty clay. Floodplain is hardsetting silty clay with some gravel. Bank undercutting and sink holes indicate dispersive clays.	Inner floodplain, riparian corridor and blocked section of active channel are densely vegetated with reeds and moderately dense mature trees. Reeds within the flow path of the recent flood have been flattened. Flood debris is caught in fences across channel. Active channel has little to no vegetation, but moderate LWD.	Geomorphological functioning of the creek is significantly impacted at the road crossing. The natural creek has sightly incised, undercut banks, indicating some downcutting. Highly mobile silty sand bed with clay drapes has been subject to significant livestock trampling. Sink hole observed on floodplain between creek and road, indicating dispersive soils.	Edge effects, vegetation artefacts and impacts of existing creek blockage. Some constriction of flood flows, but the design model appears to be treating the embankment as a dam, rather than as a bridge.	Hydroline is not accurate. Owner reports that confluence between Ewenmar Creek and upstream tributary was moved upstream when Old Mill Road Creek crossing was constructed. Flood flows occupy this tributary, and pooled water was present.

Photographic Record

Looking upstream from Old Mill Road at well-defined active channel and flood debris Note creek blockage upstream of fence line.	Looking downstream at undersized, blocked culvert under Old Mill Road.	Looking towards right bank of blocked creek reach, with flood debris caught in fence Note lack of active channel due to creek blockage	Narrow, incised active channel downstream of the proposed crossing. Note livestock trampling, LWD and mud staining on vegetation from recent flooding	Small sinkhole on floodplain between proposed crossing and Old Mill Road
				

Discussion and Recommendations

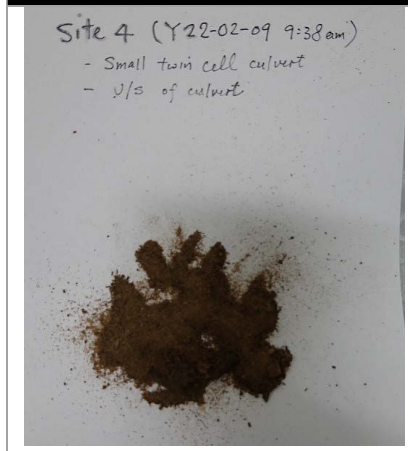
- The geomorphological functioning of the existing creek is being significantly affected by the partially blocked culverts under Old Mill Road. Modelled flood flows (1%AEP) are attenuated by nearly 0.5m/s between 20m upstream of the N2N project and 20m downstream, and it would be anticipated that the road would cause appreciably more attenuation. This has caused sediment deposition both up and downstream of the road, such that the active channel has been completely infilled. It is likely that this infilling has caused a reduction in existing flood flow velocities and an increase in flood stage.
- It is suggested that, as well as constructing the proposed bridge over Ewenmar Creek, consideration is given to increasing the size of the culverts under Old Mill Road and restoring the geomorphological, hydrologic and hydraulic functioning of the creek. This would improve the functionality of the proposed bridge, allow velocities to remain consistent along the reach, reduce flood levels and improve flow connectivity. An added benefit would be raising road levels, which would reduce road closure and access restrictions during flooding.
- Extension of the proposed bridge to accommodate the 1%AER could reduce QDL departures, but it is recommended that consideration is given to improving the road culverts before this is considered.
- Design consideration would be given to the location of proposed bridge piers to avoid adverse impacts to the active channel flow. A meander bend runs under the proposed bridge, and this would be avoided.
- Fencing to limit livestock trampling following construction is recommended to allow successful revegetation.

B-5-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	1.09 – 1.30	1.41 - 1.55	0.007 – 0.008	Unknown (assumed 24 hrs)	0.096 – 0.121

Note : Stream Power, $P = \rho\ D\ V\ S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Grey silty clay sample from upstream side of twin cell culvert	Thread Test on silty clay sample from upstream side of twin cell culvert
	

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
BH2007, TP2022	CI-CH, Sandy Clay with trace gravel	Very Stiff	Medium	12 / 43 / 31	N/A	N/A
Sample from downstream of twin cell culvert	Grey Silty Clay		Medium to High Plasticity (See photo on Thread Test)		Does not disperse in distilled water	

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Very Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s\ K_b\ K_d\ J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.18 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.55 kW/m^2	– Estimated *P* is between 0.096 and 0.121 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average to good grass over along creek. – Flow duration assumed longer than 24 hrs	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c > 1.8 m/s	– Highest flow velocity is 1.09 – 1.30 m/s. – Average velocity is assumed to be approximately 1.2 m/s. – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is 2.0 m/s which is significantly higher than the average flow velocity.	– On average, flow velocity is expected to lower than the threshold velocity for initiation of erosion.	Low (L) to Moderate (M)	Low (L) to Moderate (M)
Critical velocity based on D_{50} (Briaud 2008)	Conditions based on BH2007 and TP2022: – Particle size distribution curve for sample taken from TP2022 is a Clayey SAND with D_{50}.= 0.12 mm. – Soil sample taken during site visit shows the soil is fine-grained (cohesive).	Threshold flow velocity to mobilise soil particle (Briaud 2008) if based on SAND sample in TP2022 whose D_{50} = 0.12 mm is: $0.35\ (D_{50})^{0.45}$ = 0.13 m/s.		– Soil sample taken from the creek is medium plastic clay, so the SAND sample from TP2022 is likely to be non-representative of site condition	N/A	
Dispersivity of soil	N/A			– Soil does not appear to be dispersive	N/A	

B-6 Goulburn Creek, 250-Clvrt599110– 9/2/22 10:50am

Modelled Existing 1%AEP Vmax = 0.7m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Creek location has been modified during construction of Old Mill Road. Creek is narrow, slightly incised and low sinuosity. Floods spread overbank, crossing Old Mill Road, before coalescing into narrow channels downstream.	Coarse, loose sandy bed with clay drapes. Banks comprise silty clay. Floodplain is silty clay with some gravel. Bank material is sandy, plastic clay.	Channels are sparsely vegetated with LWD. Floodplain is densely grassed with sparse mature trees, although gully networks are denuded of topsoil and vegetation.	Banks are slightly incised, with gully networks downstream of the N2N project (where modelled velocities are below 1m/s). Deposition is of more concern around Old Mill Road, where channel alignment and attenuated velocities have caused deposition. Flows are turbid, indicating transport of fine sediment.	QDL exceedances are mapped upstream and downstream of the N2N project. Some are edge effects at velocity thresholds. Area 1 appears to be due to vegetation artefacts within an agricultural field. Area 2 shows an area of minor velocity increases (typically <0.1m/s) but is within an area of existing gullying.	Hydroline is not accurate. The approximate alignment is mapped below. Old Mill Road was being resurfaced at the time of observation. It is not known whether this was due to flood damage or scheduled resurfacing. The former is assumed. Access to private land was not permitted at the time of observation.

Photographic Record

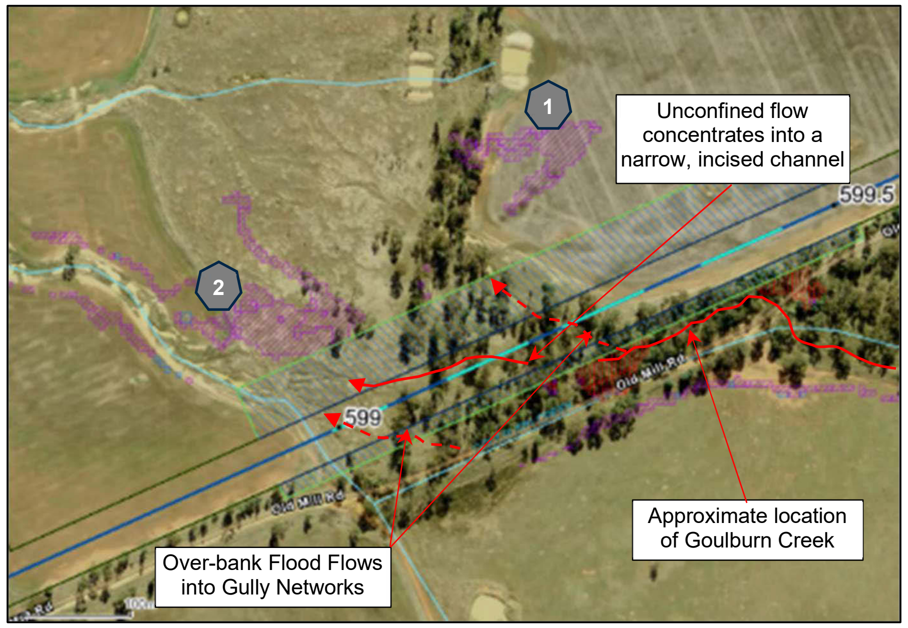
Looking downstream at slightly incised active channel, upstream of fence, flows are unconfined	Gully networks on private property north of proposal	Looking upstream from culvert under Old Mill Road	Partially blocked, recently cleared culverts under Old Mill Road	Looking downstream from culvert under Old Mill Road
				

Discussion and Recommendations

– Continuity of active channel has been significantly altered during construction of Old Mill Road. Active channel appears to have been realigned to run to the north of Old Mill Road, causing significant disturbance to geomorphological, hydrologic and hydraulic functioning. Unlike Ewenmar Creek, reinstatement of the natural channel alignment would not be possible, given the current road alignment.

– Detailed hydrologic and hydraulic modelling for this creek has been carried out, without significant differences in output. Therefore, flow attenuation measures would be required downstream of culverts 250-Clvrt598994 and 250-Clvrt599110 to avoid exacerbating the existing gully networks outside the drainage control area. It is noted that the area is not agricultural land or pasture, and should not affect agricultural output. Recommended measures include:

- Detailed observation of the gullied area to better understand the geomorphological processes acting and presence of active headcuts.
- Construction of earth berms across the gullies to retard flood flows and encourage sediment deposition within the incised channels.
- Establishment of vegetation in denuded areas, which may require surface ripping and import of topsoil for a successful outcome.

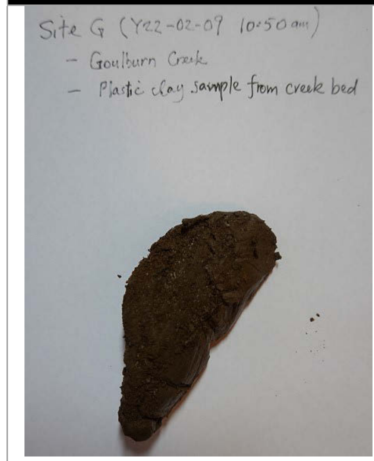


B-6-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.75 – 1.20	0.60 – 0.95	0.0049 – 0.0052	15.51 – 26.89	0.029 – 0.048

Note : Stream Power, $P = \rho\ D\ V\ S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Soil sample from creek bed	Thread test on soil sample from creek bed
	

Geotechnical Observations and Soil Erodibility

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
BH2067	CI-CH, Sandy Clay with trace gravel	Very Stiff	Medium to high	N/A	N/A	Very high SPT-N 29, 14, 22, 20, 25, 38, 36… Pocket Penetrometer Test minimum 300 kPa, mostly > 600 kPa
Soil sample from creek bed	Grey plastic CLAY		Medium to high plasticity (see photo on Thread Test)			Does not dispersive in distilled water

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Very Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s\ K_b\ K_d\ J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.18 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.55 kW/m^2	– Estimated *P* is between 0.029 and 0.048 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Very Low (VL)
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average to good grass over along creek. – Flow duration = 15.51 – 26.89 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.8 – 2.0 m/s	– Average flow velocity is 0.75 – 1.20 m/s over a duration of 15.51 – 26.89 hrs. – Average velocity is assumed to be approximately 1.0 m/s. – Assuming highest velocity of flow will last for 16 hrs only, the threshold velocity for initiation of erosion is approximately 2.0 m/s.	– On average, flow velocity is expected to substantially lower than the threshold velocity for initiation of erosion.	Very Low (VL)	
Critical velocity based on D_{50} (Briaud 2008)	Conditions based on BH2067: – Soil sample taken during site visit shows the soil is fine-grained (cohesive)	Threshold flow velocity to mobilise soil particle (Briaud 2008) not estimated without data on mean particle size D_{50}.		– Threshold velocity not assessed with no data on D_{50}.	N/A	
Dispersivity of soil	N/A			– Soil is not dispersive in distilled water	N/A	

B-7 Emogandry Creek, 250-BR602663 – 9/2/22 11:40am

Modelled Existing 1%AEP Vmax = 2.0m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Sinuous slightly incised creek flowing within a deep flood trench, which contains the majority of the 1%AEP flood. Undersized culvert below Old Mill Road has resulted in deposition upstream and downstream.	Coarse, loose sandy bed with gravel. Active channel banks are low and comprise silty clay. Trench banks are considerably taller, and are largely low-angled, except where over-steepened along the outer bank of the meander downstream of Old Mill Road	Inner floodplain and riparian corridor are densely vegetated with reeds and grasses respectively, and moderately dense trees of varying size. Considerable quantities of LWD.	Geomorphological functioning of the creek is impacted at the road crossing. Undersized culverts have caused deposition. The eroding banks show dispersive characteristics, including seepage erosion and fluting.	Minor edge effects downstream of the proposed crossing point.	Hydroline is not accurate, but bridge is wide enough to accommodate the actual channel location.

Photographic Record

Looking upstream from Old Mill Road at well-defined active channel and loose sand bed with gravel deposited upstream of culvert	Looking downstream from Old Mill Road at channel blocked by sediment and LWD, with eroding bank in background	Close-up of LWD across channel	Tall, eroding right bank downstream of Old Mill Road, showing morphological characteristics of dispersive soil
			

Discussion and Recommendations

- If trees are removed to allow bridge construction, root systems should be left intact to avoid localised erosion.
- Measures to minimise dispersive-type features along bridge abutments and around bridge piers would be adopted, e.g. suitable compaction, use of reinforced soil cover and rapid revegetation (including use of surface protection, if required).

B-7-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.67 – 0.70	0.31 – 0.39	0.014	Not known (assumed 24 hrs)	0.043 – 0.054

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
BH2009	– CL-CI, Sandy Clay with gravel – Fines content 55%	Very Stiff	Low to medium	11 / 26 / 15	5	High SPT-N 17, 42, 32, 34… Pocket Penetrometer Test > 600 kPa
– Sand/gravels deposited upstream of twin cell culvert – Clayey SAND/Sandy CLAY on upstream right bank – No sample collected.			Appears slight plastic			

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Very Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s = 0.205$	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.18 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.55 kW/m^2	– Estimated *P* is between 0.043 and 0.054 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Low (L) to Very Low (VL)
Hewlett *et al.* (1987) Ground Cover	Conditions: – Poor grass over along creek. – Flow duration assumed to be 24 hrs	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.8 – 2.0 m/s	– Average flow velocity is 0.67 – 0.70 m/s. – Average velocity is assumed to be approximately 0.68 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 1.4 m/s which is higher than the average flow velocity.	– On average, flow velocity is expected to lower than the threshold velocity for initiation of erosion.	Low (VL)	
Critical velocity based on D_{50} (Briaud 2008)	Conditions based on BH2009: • Soil sample taken during site visit shows the soil is fine-grained (cohesive)	Threshold flow velocity to mobilise soil particle (Briaud 2008) not estimated without data on mean particle size D_{50}.		– Threshold velocity not assessed with no data on D_{50}.	N/A	
Dispersivity of soil	N/A			– Emerson Class 5 implies soil is non-dispersive	Neutral	

B-8 Kickabil Creek and Floodplain, 250-BR609715 – 9/2/22 12:30pm

Geomorphological Observations of Floodplain (see over for creek observations)

Floodplain Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Dispersive silty clay	Area is densely grassed, with closely-spaced trees, with virtually continuous tree canopy.	Erosion was not observed on the floodplain	Modelled existing and design velocities in this area seem strongly affected by vegetation artefacts, and are unlikely to be accurate	Hydroline is not accurate, but bridge is wide enough to accommodate the actual channel location. 1% AER flood modelled as flowing away from, rather than towards creek, which is unlikely.

Photographic Record

Looking north from Kickabil Road at proposed crossing	Looking south from Kickabil Road at proposed crossing	Looking north at area of mapped QDL exceedance in agricultural field	Area modelled as having existing flood flows over 2m/s
			

Ctd. over

Geomorphological Observations of Kickabil Creek

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Sinuous, slightly incised, narrow creek, which splits into two channels upstream of Kickabil Road, but is single thread downstream.	Coarse, loose sandy bed with gravel and some imported cobbles. Silty clay banks.	Floodplain and riparian corridor are densely vegetated with reeds and grasses respectively, and dense trees of varying size. Little in-channel vegetation, but some LWD.	No significant erosion was observed. Creek is slightly incised, but berms present at the base of the banks does not indicate active downcutting.	See previous page.	Hydroline is not accurate, but bridge is wide enough to accommodate the actual channel location. Observations at the proposed bridge location were not possible.

Modelled Existing 1%AEP Vmax (at proposed bridge = 1.493m/s

Photographic Record – taken from Kickabil Road east of proposed bridge location.

Looking upstream from Kickabil Road at Kickabil Creek	Kickabil Creek culvert entry	Looking downstream from Kickabil Road at Kickabil Creek	Kickabil Creek culvert exit
			

Discussion and Recommendations

- Observations indicate that predicted velocities seem high, particularly through the dense woodland areas, where surface roughness and lack of observed erosion would indicate low velocity flood flows. Maximum modelled velocities occur within dense woodland, rather than along Kickabil Creek, which seems unlikely. Flood flow directions away from the creek also seem unlikely.
- It is suggested that QDL departures within this area are due to issues with model inputs, rather than being of concern during operation.
- Hydrologic and hydraulic modelling through this area seems to be affected by vegetation artefacts, and this should be considered during detailed design.
- The proposed bridge is broad enough to accommodate 1%AEP flood. However, it crosses a densely vegetated area, and some clearance is anticipated. This could introduce preferential pathways for flood flows, and consideration would be given to rapid revegetation and flow attenuation measures in these areas.
- Bridge piers would be located away from the active channel of the creek.

B-8-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.99 – 1.01	0.60 – 0.82	0.011	Not known (assumed 24 hrs)	0.065 – 0.088

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
BH2010	– CI, Silty Clay down to 0.9m – Clay has fines content = 64% – SM Dense Silty SAND from 0.9 – 2.0m – SP Very dense Poorly graded SAND below 2.0 m	Very Stiff SANDs are Dense and Very Dense	Medium	N/A	2.1	Very high SPT-N 29., 63
Coarse sand and gravels observed upstream of culvert No sample collected.			Soils at banks do not appear plastic			

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Very Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion: 0.15 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.45 kW/m^2	– Estimated *P* is between 0.065 and 0.088 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Low (L) if soil is predominantly stiff clay. Moderate (M) to High (H) if soil is predominantly sand.
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.8 – 2.0 m/s	– Average flow velocity is 0.99 – 1.01 m/s. – Average velocity is assumed to be approximately 1.0 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 2.0 m/s.	– On average, flow velocity is expected to be lower than the threshold velocity for initiation of erosion.	Very Low (VL) to Low (L)	
Critical velocity based on D_{50} (Briaud 2008)	– Based on BH2010, soil at shallow depth is likely to be Dense Sand. – Coarse SAND with gravels was observed on lower part of river banks during site visit. – D50 is unknown but assumed equal to 2 mm.	Threshold flow velocity to mobilise soil particle (Briaud 2008), assuming a D_{50} of 2 mm, is $0.35 (D_{50})^{0.45}$ = 0.48 m/s		– Design velocity of 0.99 -1.01 m/s is higher than the threshold velocity for initiating erosion in coarse sand, estimated to be 0.48 m/s.	Moderate (M) to High (H)	
Dispersivity of soil	Emerson Class 2.1			– Emerson Class 2.1 implies clay is dispersive.	Moderate (M) – High (H)	

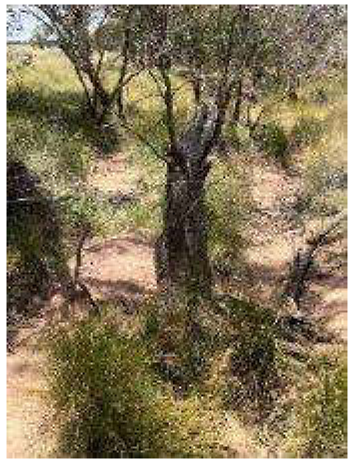
B-9 Milpulling Creek, 250-BR616680 – 9/2/22 1:25pm

Modelled Existing 1%AEP Vmax = 1.6m/s

Geomorphological Observations to west of crossing for information only

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Sinuous, slightly incised channel, within active meander belt. Gully networks up and downstream of proposed bridge. Proposed alignment crosses two tributaries to south with no culvert.	Coarse sandy bed, indicating high bedload and unlimited upstream sediment supply.	Floodplain and riparian corridor are densely grassed, with sparse trees. Some in-channel vegetation and considerable quantities of LWD caught on bridge piers and trees.	Gullying upstream and downstream (only observed on aerial photographs) appears to be inactive and showing signs of recovery. Channel is incised and meander outer banks are eroding. High bedload is deposited during falling limb of flood, causing significant differences in bed elevation.	Pooling of floodwaters against proposed embankment	Observed at Milpulling Road, to west of proposed bridge, as access to private property was not possible. Bridge seems large for creek size, indicating large floods.

Photographic Record

Looking upstream from Milpulling Road	Looking downstream from Old Mill Road at channel blocked by sediment and LWD, with eroding bank in background	Close-up of LWD across channel
		

Discussion and Recommendations

- Proposed bridge site was not observed, but aerial photograph assessment indicates active outer bank erosion and meander bend migration. Gullying was also observed, but this appears to be recovering. Site assessment of the creek crossing would be carried out to inform detailed design when access can be arranged.
- Possible meander migration would be assessed at the bridge site to limit lateral migration adversely affecting the bridge piers and abutments.
- Measures for dispersive soils would be adopted.
- Existing mapped velocities upstream of the proposed bridge site are appreciably higher than downstream, with a clear change at the proposed crossing. The reason for this is currently unclear.

B-9-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	1.62 – 1.93	1.43 – 1.70	0.01	Unknown (assumed 24 hrs)	0.140 – 0.167

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
TP2029	– CL-CI, Silty Clay with trace gravel. – Particle size distribution curve shows fines content is 37% indicating that the soil is a Clayey SAND. – Mean particle size, D_{50} = 0.5 mm	Very Stiff to Hard	Medium	18 / 46 / 28	2.1 (at 0.3 – 0.5m, and at 1.6 -1.8m)	N/A
Coarse SAND was seen on the river banks (no sample collected)			Soil on river banks appears to be SAND and non-plastic			

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Very Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.15 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.45 kW/m^2	– Estimated *P* is between 0.140 and 0.167 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	
Hewlett *et al.* (1987) Ground Cover	Conditions: – Poor grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.8 – 2.0 m/s	– Average flow velocity is 1.62 – 1.93 m/s. – Average velocity is assumed to be approximately 1.8 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 1.4 m/s.	– On average, flow velocity is expected to be higher than the threshold velocity for initiation of erosion.	Moderate (M) to High (H)	Moderate (M) to High (H)
Critical velocity based on D_{50} (Briaud 2008)	– Based on TP2029, soil is likely to be Clayey Sand. – Coarse SAND was observed on river banks during site visit. – D_{50} of sample taken from TP2029 is 0.5 mm.	Threshold flow velocity to mobilise soil particle (Briaud 2008), assuming a D_{50} of 0.5 mm, is $0.35 (D_{50})^{0.45}$ = 0.26 m/s		– Design velocity of 1.62 -1.93 m/s is higher than the threshold velocity for initiating erosion in SAND, estimated to be 0.26 m/s.	High (H)	
Dispersivity of soil	Emerson Class 2.1			– Emerson Class 2.1 implies clay is dispersive.	Moderate (M) – High (H)	

B-10 Marthaguy Creek, 250-BR633677 – 9/2/22 2:20pm

Modelled Existing 1%AEP Vmax = 1.8m/s

Geomorphological Observations from Oxley Highway Upstream of Proposed Bridge

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Highly sinuous anastomosing channel, showing evidence of active meander migration. Proposed bridge crosses two sinuous anabranches separated by a large island.	Coarse, loose sandy bed with regular, alternating lateral bars. Highly mobile, deep bed. Banks are largely residual soils comprising clayey sand with gravel	The mid-system island is sometimes cultivated. The riparian corridor is narrow with dense trees, grasses and rushes, surrounded by agricultural land.	Piping erosion at bridge abutments was observed indicating poor compaction around structures and possible dispersion.	Edge effects.	Observations were made at Oxley Highway bridge, as access to proposed bridge site was not possible.

Photographic Record

Looking upstream from Oxley Highway	Looking downstream from Oxley Highway	Lateral bar deposited under bridge	Piping erosion near left bank of bridge abutment	
				

Discussion and Recommendations

- Detailed geomorphological assessment of the site is recommended during detailed design since access to the proposed bridge site was not possible during the site visit.
- Bridge piers would be located away from the active anabranches, with care taken to account for any meander migration that may be anticipated within the design life of the N2N project.
- Testing along the Oxley Highway indicates dispersive soils, supported by the presence of piping erosion close to the bridge abutments. Measures to minimise dispersion along bridge abutments and around bridge piers would be adopted, e.g. suitable compaction, use of abutment protection, such as geofabric-lined gabions, use of non-dispersive capping materials and rapid revegetation (including use of surface protection, if required).

B-10-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.70 -0.74	0.49 – 0.52	0.015	Unknown (assumed 24 hrs)	0.072 – 0.076

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations and Soil Erodibility at Oxley Highway

Borehole / Testpit Number	PSD, USCS Classification	Consistency / .	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
BH2015	– Particle size distribution curve for sample at 0.5 – 0.95m shows fines content of 35%, suggesting soil sample is a SAND but not Sandy CLAY as described. – SP, SC, Dense, Very Dense Poorly Graded SAND, Clayey SAND with trace gravel – SP, Medium Dense at 6 – 9.5 m – Clay SAND at 9.5 – 10.0m – CI, CH at below 10.0m	Dense to Very Dense SAND CLAYs are Stiff	Low	12 / 25 / 13	2.1 at (0.5 – 0.95m)	Very high SPT-N, 55, 50, 34 27, 31…
Coarse SAND was seen on the river banks (no sample collected)						

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.19 given soil is Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s$ = 0.095	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion: 0.1 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.30 kW/m^2	– Estimated *P* is between 0.072 and 0.076 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Low (L) (if soil type is predominantly stiff clay) High (H) (if soil type on site is predominantly sand.)
Hewlett *et al.* (1987) Ground Cover	Conditions: – Poor to average grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.4 m/s	– Average flow velocity is 0.70 – 0.74 m/s. – Average velocity is assumed to be approximately 0.72 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 1.8 m/s.	– On average, flow velocity is expected to be lower than the threshold velocity for initiation of erosion.	Low (L)	
Critical velocity based on D_{50} (Briaud 2008)	– Based on BH2015, soil is predominantly Sand (SC, SP). – Coarse SAND with gravels was observed on lower part of river banks during site visit. – D_{50} is unknown but assumed equal to 0.25 mm.	Threshold flow velocity to mobilise soil particle (Briaud 2008), assuming a D_{50} of 2 mm, is $0.35 (D_{50})^{0.45}$ = 0.19 m/s		– Design velocity of 0.70 – 0.74 m/s is higher than the threshold velocity for initiating erosion in SAND, estimated to be 0.19 m/s.	High (H)	
Dispersivity of soil	Emerson Class 2.1			– Clay particles in Clayey SAND are dispersive.	High (H)	

B-11 Castlereagh River, 250-BR651728 – 9/2/22 3:30pm

Modelled Existing 1%AEP Vmax =3.0m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Low sinuosity, deeply incised river at the threshold between meandering and braided planforms, with a mixture of lateral and mid-channel bars.	Deep, loose sandy bed, with clay drapes in backwaters. Bank and floodplain materials are deep alluvial soils, largely comprising sandy clay.	Broad sand bars within or aligning the active channel are unvegetated. Lateral bars have dense rushes which flatten during floods. Dense trees and grass cover within riparian corridor, with sparser trees on floodplain. LWD present, and caught on National Park Road bridge piers.	No erosion observed. Assume that some bank erosion occurs during large floods, but the environment is largely depositional due to high mobile, virtually supply unlimited bedload. High volumes of sediment have been deposited upstream of the National Park Road bridge.	Edge effects within floodplain.	Lateral and mid-channel bars were elevated to well over 1m above the water level at the time of observation. Terrabile Creek enters just upstream of proposed crossing, with flood breakout flows between this tributary and the right bank of the main channel.

Photographic Record

Looking upstream from proposed bridge location	Looking downstream from proposed bridge location	Elevated lateral bar at proposed bridge location	Elevated bars and LWD caught on National Park Road bridge	Floodplain above right bank
				

Discussion and Recommendations

- The Castlereagh River is thought to have the highest flood velocities of any inland river in Australia. However, no visible signs of erosion could be observed.
- Consideration would be given to the effect of the Terrabile confluence and flood breakouts between the two watercourses just upstream of the proposed crossing
- The large quantities of sandy bed material would be mobilised in most flood events, and rapidly deposited during the falling limb of the flood.
- Testing indicates dispersive soils, but no visible evidence of dispersion was observed on site. Measures to minimise dispersion along bridge abutments and around bridge piers would be adopted, e.g. suitable compaction, use of non-dispersive capping materials and rapid revegetation (including use of surface protection, if required).
- Ideally, bridge piers would avoid the active channel, or be located on existing in-channel bars, noting that the location of these may change rapidly during flood events, but their longevity would be assessed for detailed design.

B-11-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	1.54 1.56	5.77 – 6.55	0.011	Unknown (assumed 24 hrs)	0.622 – 0.706

Note : Stream Power, $P = \rho\, D\, V\, S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
TP2049	– SP Silty SAND with gravel down to 0.8m • SAND with 31% fines content; D50 = 0.28 mm – CI, Clayey Sand with gravel 0.8 – 1.5m – SP below 1.5m	Very Dense Hard Very Dense	Low	11 / 26 / 15	2.2	DCP 9 – 25 down to 0.4m
BH2018	– CI, Sandy Clay down to 3 m – SC, Clayey SAND 3 – 5 m – CI-CH, Silty CLAY with sand, 5 – 6.5m – SP, Silty SAND 6.5 – 8.4 m – SC, Clayey SAND 8.5 – 12.5 m – SANDSTONE below 12.5 m	Very Stiff to Hard	Low	10 / 30 / 20		High SPT-N 28, 43, 53, 73, 58… Pocket Penetrometer Test > 600 kPa
• Dense vegetation cover on both banks. • Coarse SAND deposited on river bed. • No soil sample taken						

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Stiff to Hard Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s\, K_b\, K_d\, J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.15 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.45 kW/m^2 – Stream Power, *P*, for 90% chance of initiating erosion: 1.5 kW/m^2	– Estimated *P* is between 0.622 and 0.706 kW/m^2. – Chance of initiating erosion is between 50% and 99%.	Moderate (M) to High (H)	Moderate (M) to High (H)
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.8 m/s	– Average flow velocity is 1.54 – 1.56 m/s. – Average velocity is assumed to be approximately 1.55 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 2.0 m/s.	– On average, flow velocity is expected to lower than the threshold velocity for initiation of erosion.	Low (L) to Moderate (M)	
Critical velocity based on D_{50} (Briaud 2008)	– Based on BH2015, soil is predominantly Sand (SC, SP). – Coarse SAND with gravels was observed on lower part of river banks during site visit. – D_{50} of SAND sample in TP2049 is 0.28 mm.	Threshold flow velocity to mobilise soil particle (Briaud 2008), assuming a D_{50} of 2 mm, is $0.35\,(D_{50})^{0.45}$ = 0.20 m/s		– Design velocity of 1.54 – 1.56 m/s is higher than the threshold velocity for initiating erosion in SAND, estimated to be 0.20 m/s.	High (H) to Very High (VH)	
Dispersivity of soil	Emerson Class 2.2			– Clay particles in Clayey SAND are dispersive.	High (H)	

B-12 Overland Flow, 250-Clvrt686020 – 10/2/22 9:30am

Modelled Existing 1%AEP Vmax = Not Available

Geomorphological Observations

Contemporary Channel Morphology	Floodplain Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Unconfined overland flows across agricultural fields.	Clay, with surface sand deposits	Tall grasses, ploughed fields, with stands of sparse to moderately dense trees.	Deposition of sand in road drain. No other erosion observed	Edge effects and vegetation artefacts.	Modelled velocities seem high given surface roughness and topography

Photographic Record

Looking north near proposed culvert location	Coarse sand accumulating in road drain	Area of modelled high velocities (1.5-2m/s) to west of proposed crossing (looking south)	Area of modelled high velocities (1.5-2m/s) to west of proposed crossing (looking north)
			

Discussion and Recommendations

– Observations indicate that predicted velocities seem high (>1.5m/s in places), as surface roughness, topography adjacent to Box Ridge Road (i.e. road drains and berms) and lack of observed erosion would indicate low velocity flood flows.

– The majority of QDL departures within this area appear to be due to issues with the model DEM, rather than being of concern during operation. Many are due to edge effects at velocity thresholds. Others are found along the edge of woodland areas, indicating the model has viewed vegetation as a dam, rather than as an area where flows can pass freely, and where velocities would be attenuated by the tree trunks.

– Validation of the reference modelling would be carried out during detailed design.

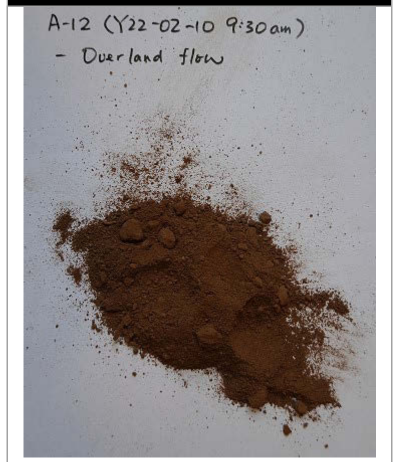
B-12-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, V (m/s)	Average DV value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, T, (hr)	Unit Stream Power, P (kW/m^2)
1%AEP	0.65 -0.71	0.06 – 0.12	0.0051	Unknown (assumed 24 hrs)	0.003 – 0.006

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Sample collected from road side, Grey Silty SAND



Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
BH2058	– SM, Silty SAND 0 – 0.5m – CI, Sandy Clay 0.5 – 8.0m – SC, Clayey SAND 8.0 – 11.5m – CI-CH, Sandy CLAY 11.5m – 15.5m – SANDSTONE below 15.5m	Dense Hard Dense Hard	High	14 / 55 / 41	N/A	Very high SPT-N 37, 21, 26, 26, 38… Pocket Penetrometer Test > 600 kPa
TP2132	– Silty CLAY top soil 0 – 0.3m – CI-CH, Silty CLAY 0.3 – 3.0m	Hard	Medium	18 / 43 / 25	5	DCP 11 – 24 (0 – 1.0m)
TP2133	Clay with Sand – PSD (0.3 – 0.5m) shows a fines content of 78%	Hard	High	14 / 52 / 38	N/A	N/A
Overland flow site, with good grass cover, and some trees (No soil sample collected)						

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, P, for 1% chance of initiating erosion: 0.15 kW/m^2 – Stream Power, P, for 50% chance of initiating erosion: 0.35 kW/m^2 – Stream Power, P, for 90% chance of initiating erosion: 1.5 kW/m^2	– Estimated P is between 0.003 and 0.006 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Very Low (VL) to Low (L)
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average to good grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 2.0 m/s	– Average flow velocity is 0.65 – 0.71 m/s. – Average velocity is assumed to be approximately 0.68 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 2.5 m/s.	– On average, flow velocity is expected to substantially lower than the threshold velocity for initiation of erosion.	Very Low (VL)	
Critical velocity based on D_{50} (Briaud 2008)	– Based on BH2058 and TP2132 and TP2133, soil is Clayey SAND and Sandy CLAY, and predominantly CLAY. – D_{50} is unknown but likely to be much finer than 0.01 mm considering the very high fines content.	Threshold flow velocity to mobilise soil particle (Briaud 2008), assuming a D_{50} of 0.005 mm, is between $0.1 (D_{50})^{-0.2}$ = 0.28 m/s and $0.03 (D_{50})^{-1}$ = 6 m/s		– The estimated average threshold velocity is approximately 3 m/s which is higher than the design velocity of 0.65 – 0.71 m/s.	Low (L) to Moderate (M)	
Dispersivity of soil	Emerson Class 5			– Clay is non-dispersive.	Neutral	

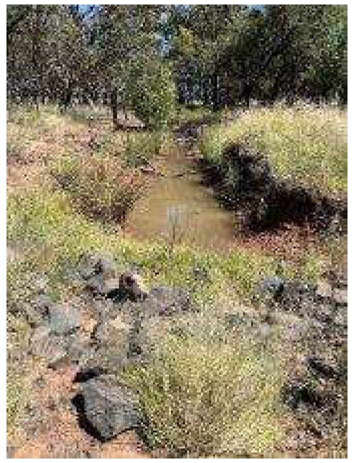
B-13 Unnamed Creek, 250-Clvrt697901 – 10/2/22 10:40am

Modelled Existing 1%AEP Vmax = 0.8m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Materials	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
The creek has been artificially channelised downstream of Goorianawa Road, presumably to concentrate flood flows through a controlled point, possibly between farm dams. Embankments have been constructed along the north-western edge of the road to funnel flows. Overland flows take flood waters off road to south of creek crossing.	Silty, clayey sand topsoil, coarse sand on road.	Clumps of dense grass, with areas denuded of vegetation. Moderately dense trees in riparian corridor and on floodplain.	Channelised bank is eroding and shows signs of dispersion, with small headcuts and scour adjacent to and within riprap.	Edge effects and vegetation artefacts. Pooling of water along proposed embankment to the north.	Hydroline is not in correct location. Channelised flow is to the north of the marked position.

Photographic Record

Looking downstream at channelised section of the creek	Close-up of fissured bed materials	Looking downstream from edge of road easement towards proposed bridge.	Overland flow deposits from northwest edge of Goorianawa Road	Looking west at approximate location of culvert
				

Discussion and Recommendations

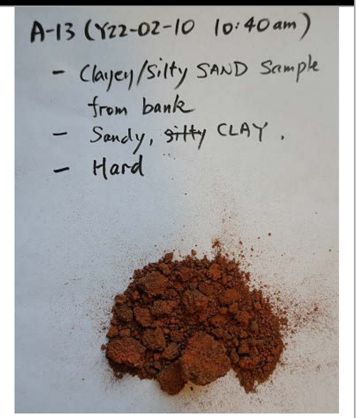
- Vegetation would not have a significant retarding effect, particularly during dry years.
- Artificial embankment along Goorianawa Road funnel flood flows into the artificial channel, indicating that, prior to alteration, unconfined flood flows were problematic.
- Observations indicate that predicted velocities seem high, particularly within existing farm dams and dense trees, where flows would be expected to attenuate, rather than accelerate. The narrow road embankment does not appear to have been picked up by the relatively coarse grid of the reference model, so no funnelling effect is shown.
- QDL departures within this area appear to be partly due to issues with the model DEM, rather than being of concern during operation. Many are due to edge effects at velocity thresholds. There are also modelled of flows less than 1m/s where water is unable to pass through the embankment north of the creek, and is diverted south into the creek. However, this area has stabilising vegetation, and the additional flows are not anticipated to have adverse impacts. This would be addressed during detailed design.

B-13-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, V (m/s)	Average DV value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, T, (hr)	Unit Stream Power, P (kW/m^2)
1%AEP	0.23 -0.62	0.07 – 0.29	0.011	0.07 – 0.92	0.007 – 0.031

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Thread Test on Sample 1 taken from bank	Soil Sample 2 from bank
	

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
EP2011 / TP2074	– SC, Clayey Sand with trace gravel – PSD (0.2 – 0.4m) shows 27% fines content, indicating soil sample is SAND, with D_{50} = 0.22 mm	Very Dense	Medium	13/ 40 / 27 (0.9 – 1.1m)	2.2	
Sample 1 from bank	– Sandy Silty CLAY		Thread Test (see photo).			
Sample 2 from bank	– Sandy CLAY	Very Stiff, Hard				

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, P, for 1% chance of initiating erosion : 0.15 kW/m^2 – Stream Power, P, for 50% chance of initiating erosion: 0.35 kW/m^2 – Stream Power, P, for 90% chance of initiating erosion: 1.5 kW/m^2	– Estimated P is between 0.007 and 0.031 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average to good grass over along creek. – Flow duration = 0.07 – 0.92 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 4.5 m/s for poor grass cover.	– Average flow velocity is 0.23 – 0.62 m/s over a duration of 0.07 – 0.92 hrs. – Average velocity is assumed to be approximately 0.4 m/s – Assuming highest velocity of flow will last for 0.5 hrs only, the threshold velocity for initiation of erosion is approximately 4.5 m/s which is significantly higher than the design flow velocity.	– On average, flow velocity is expected to substantially lower than the threshold velocity for initiation of erosion.	Very Low (VL)	Very Low (VL) (Soil samples collected on site are CLAY which show high erosion resistant properties)
Critical velocity based on D_{50} (Briaud 2008)	– Based on TP2074 and samples taken from site, the soil is a very hard Sandy CLAY – D_{50} is unknown	Threshold flow velocity to mobilise soil particle (Briaud 2008) not estimated without data on D_{50} of CLAY samples.			N/A	
Dispersivity of soil	Emerson Class 2.2			– Emerson Class 2.2 – Apparently Sample 2 is not dispersive in distilled water.	Neutral	

B-14 Mungery Creek, 250-BR700017 – 10/2/22 9:45am

Modelled Existing 1%AEP Vmax = 1.3m/s

Geomorphological Observations

Contemporary Channel Morphology	Floodplain Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
The creek has been artificially channelised downstream of Goorianawa Road, presumably to concentrate flood flows through a controlled point between farm dams. Embankments have been constructed along the north-western edge of the road to funnel overland flows.	Silty, clayey sand topsoil, coarse sand on road.	Dense grass with moderately dense trees in riparian corridor and on floodplain.	Channelised bank shows minor erosion. The surface of Goorianawa Road has been eroded.	Edge effects and vegetation artefacts. Pooling of water along existing road embankment and proposed embankment to the north.	Hydroline is not in correct location. Channelised flow is to the north of the marked position.

Photographic Record

Looking north near proposed culvert location	Coarse sand accumulating in road drain	Eroded ford on Goorianawa Road at Mungery Creek crossing	Mungery Creek upstream of Goorianawa Road
			

Discussion and Recommendations

- Similar to A13 regarding modelled velocities, with modelled flows probably appearing high due to vegetation artefacts and the coarse grid of the reference model.
- QDL departures within this area appear to be partly due to issues with the model DEM, rather than being of concern during operation. Many are due to edge effects at velocity thresholds. There are also modelled flows over 1m/s where water is unable to pass through the embankment north of the creek, and is diverted south into the Creek. If this is of concern, an additional culvert could be added at around CH700.5 or the proposed culvert location moved to better accommodate overland flows. This flow path is not expected to cause significant adverse impacts due to the small catchment area and ease of implementing effective mitigation measures, such as introducing vegetation or construction of flow attenuation berms.
- During detailed design, model issues would be assessed to ensure that the culvert is in the optimal location.

B-14-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m²/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m²)
1%AEP	0.81 - 0.91	0.19 – 0.67	0.011 – 0.012	Unknown (assumed 24 hrs)	0.020 – 0.079

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m³, represents the unit weight of water

Geotechnical Observations and Soil Erodibility

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
TP2074	– SC, Clayey Sand with trace gravel – PSD of soil sample at 0.2 - 0.4m from TP2074 shows – Fines content of 27%, including soil is SAND. – D_{50} is approximately 0.25 mm	Very Dense	Medium	13 / 40 / 27 (0.9 -1.1m)	N/A	
No soil sample taken from site						

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Very Dense Sand (from TP2074) Particle/Block size number, K_h = 1 (assumed or slightly cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion: 0.1 kW/m² – Stream Power, *P*, for 50% chance of initiating erosion: 0.30 kW/m² – Stream Power, *P*, for 90% chance of initiating erosion: 1.5 kW/m²	– Estimated *P* is between 0.02 and 0.079 kW/m². – Chance of initiating erosion is lower than 1%	Very Low (VL)	Very Low (VL) to Low (L) (if soil is predominately clay) Moderate (M) to High (H) (if soil is predominately sand).
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.8 m/s	– Average flow velocity is 0.81 – 0.91 m/s. – Average velocity is assumed to be approximately 0.86 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 2.0 m/s.	– On average, flow velocity is expected to be lower than the threshold velocity for initiation of erosion.	Low (L)	
Critical velocity based on D_{50} (Briaud 2008)	– Based on TP2074, soil is Very Dense Clayey SAND. – D_{50} is approximately 0.25 mm.	Critical velocity for granular materials with D_{50} = 0.25 mm is approximately 0.19 m/s		– The estimated average threshold velocity is approximately 0.19 m/s which is lower than the design velocity of 0.81 – 0.91 m/s.	Moderate (M) to High (H)	
Dispersivity of soil	Not tested				Neutral	

B-15 Quanda Quanda Creek, 250-BR704588 – 10/2/22 1:40pm

Modelled Existing 1%AEP Vmax = 1.5m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Materials	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Highly sinuous, deeply incised channel. Meanders are at both active channel and macro-scale. Bed elevation is highly variable, with deep pools along meander bends and significantly higher. Depth of incision is limited by resistant residual rock. Lateral erosion is predominant.	Deep cracking clays with gravel and sand lenses. Creek incised into residual rock at base.	Clumps of dense grass, with areas denuded of vegetation. No appreciable riparian corridor. Floodplain is agriculture.	Assessment of historic aerial imagery (Google Earth) indicates appreciable outer bank erosion of meanders through dispersion and direct flow entrainment during floods.	Edge effects and vegetation artefacts.	Modelled velocities seem high within upstream farm dam, where attenuation would be expected.

Geotechnical Observations and Soil Erodibility (note GI locations are 4km to north and south of bridge crossing and may not be applicable).

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI	Emerson Class / Dispersivity	Shear Strength	Erodibility
BH2025, TP2230							

Photographic Record

Looking downstream at laterally eroding outer bank at proposed bridge crossing	Cracking, dispersive clays with seepage notches exposed along outer bank of meander at proposed crossing	Deep scour pool and tall bank with gravel lenses	Looking upstream at higher elevation bed upstream of scour pool	Looking north at proposed bridge crossing, with agricultural land-use floodplain
				

Discussion and Recommendations

- Consideration would be given to extending the bridge to the north to accommodate potential lateral erosion of meander bend, as successfully limiting bank erosion would be difficult, given the meandering planform morphology and dispersive soils. Limiting the natural lateral erosion is likely to result in increased lateral erosion and possible downcutting downstream.
- Further assessment would be recommended during detailed design.

B-15-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.23 -0.62	0.07 – 0.29	0.011	0.07 – 0.92	0.007 – 0.031

Note : Stream Power, $P = \rho\, D\, V\, S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Thread Test on clay sample taken from upper part of bank	Brown Sandy CLAY sample at lower depth (~2m) from top of bank
	

Geotechnical Observations (note GI locations are 4km to north and south of bridge crossing and are not considered applicable).

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
BH2025, TP2230						
Grey Silty CLAY sample taken from upper part of river bank			Low to medium (see photo on Thread Test)			
Brown Sandy CLAY sample taken from lower depth (~2m from top of bank)		Very Stiff				

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s\, K_b\, K_d\, J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion: 0.15 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.35 kW/m^2 – Stream Power, *P*, for 90% chance of initiating erosion: 1.5 kW/m^2	– Estimated *P* is between 0.007 and 0.031 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Very Low (VL) However, fissuring of the soil and preferential winnowing of clays may result in dispersive-type features, such as seepage notches and sink holes.
Hewlett *et al.* (1987) Ground Cover	Conditions: – Poor grass over along creek. – Flow duration = 0.07 – 0.92 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 3.0 m/s	– Average flow velocity is 0.23 – 0.62 m/s over a duration of 0.07 – 0.92 hrs. – Average velocity is assumed to be approximately 0.43 m/s – Assuming highest velocity of flow will last for 0.5 hrs only, the threshold velocity for initiation of erosion is approximately 3.0 m/s.	– On average, flow velocity is expected to substantially lower than the threshold velocity for initiation of erosion.	Very Low (VL)	
Critical velocity based on D_{50} (Briaud 2008)	– D_{50} is unknown but likely to be much finer than 0.01 mm considering the very high fines content.	Threshold flow velocity to mobilise soil particle (Briaud 2008) not assessed without data on D_{50}			N/A	
Dispersivity of soil	No testing				Neutral	

B-16 Unnamed Creek, 250-Clvrt720990 – 10/2/22 3:10pm

Modelled Existing 1%AEP Vmax = Not Available

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Materials	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Laterally unconfined, broad creek with sinuous active channel that is imperceptible in places (at proposed culvert location).	Deep cracking clays	Channel is densely vegetated with reeds and other aquatic vegetation. No riparian corridor. Floodplain is agricultural land-use.	Watercourse appears low energy. Incised section was observed on aerial photographs, but dense vegetation obscured views of this.	Edge effects and pooling against embankment.	Modelled velocities seem high within upstream farm dam, where attenuation would be expected.

Photographic Record

Looking upstream at pool in creek upstream of track crossing	Cracking, dispersive clays with seepage notches exposed along outer bank of meander at proposed crossing	Deeply cracked clays in channel bed	Looking northeast towards uplands, showing agricultural ploughed field
			

Discussion and Recommendations

- Creek is a tributary of Bucklanbah Creek.
- There are QDL exceedances due to previously unconfined flood flows pooling against the embankment to the south, running north into the creek. Velocities will depend heavily on crop status at the time of flooding; bare soils will result in higher velocities than when crops are established. Other exceedances are due to edge effects at velocity thresholds.
- Further assessment would be recommended during detailed design. This would enable suitable flow attenuation measures to be implemented, if required.

B-16-1 Geotechnical Erosion Potential Assessment

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / PI LL)	Emerson Class / Dispersivity	Shear Strength
TP2276	CI-CH, Silty Clay with trace sand and gravel	Stiff to Very stiff	Medium to high	13 / 49 / 36	5	
Highly plastic clay with trace of fine sand observed on the banks No soil sample taken			Medium to high (see photo on sample taken from bank)			

Highly plastic clay sample taken from bank

Assessment of soil erodibility under the 1% Design Flood event

No geotechnical assessment due to lack of site geotechnical data. However, the highly plastic clay observed on the banks is expected to have high resistance against scour erosion. Emerson Class test confirms that the clay is non-dispersive.

B-17 Baradine Creek – 10/2/22 3:30pm

Geomorphological Observations at Cumbil Road – bridge failure

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations
Incised, broad, braided channel, with a sinuous macro-morphology (i.e. flood trench).	Banks comprise hardsetting clays with gravel. Loose sandy bed with some gravel.	Flood debris caught high on trees within high flow trench, from recent floods. Densely vegetated banks with mature trees.	Lateral erosion had exploited the structure / soil interface. Deep rilling in the road to the north indicates highly erodible soils.

Photographic Record

Undercut bridge looking north	Undercut bridge apron	Bridge failure due to lateral erosion and undercutting	Looking downstream at eroded section	Deep rilling in road to north
				

No geotechnical assessment due to lack of site geotechnical data. The culvert damage indicates high stream power.

Discussion and Recommendations

- This site was visited to gain an understanding of the mechanisms of bridge failure. The bridge appeared to be a ford-type structure, designed to be overtopped during high flows.
- The main cause of failure was lateral erosion around the right bank tie-in. Seepage erosion through the riprap forming the structure foundation had also failed, particularly at the downstream end.
- Failure indicates importance of considering lateral erosion and structure foundations during detailed design.

B-18 Stockyard Creek, 250-BR767941 – 10/2/22 4:55pm

Modelled Existing 1%AEP Vmax = 0.8m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Narrow, well-defined, low sinuosity creek.	Loose, coarse sandy bed with some gravel.	Densely vegetated riparian corridor and floodplain, with grasses, mid-storey brush and trees. Reeds, grasses and bushes mid-channel.	Creek transports virtually unlimited supply of sand from uplands upstream.	None	Hydroline is not in correct location.

Photographic Record

Looking downstream from Pilliga Forest Way	Looking upstream from Pilliga Forest Way	Loose sandy bed upstream of Pilliga Forest Way	Looking upstream towards proposed bridge crossing
			

Discussion and Recommendations

- Stockyard Creek is typical of creeks in the Pilliga, which act as conveyors transporting sand from the uplands to the south through the woodland.
- Removal of dense vegetation could cause preferential erosion along disturbed area, particularly given the presence of highly erodible sand and clayey sand. Vegetation reestablishment would be a key factor in successful rehabilitation.
- No velocity QDL exceedances at this location, but duration exceedances upstream of embankment and downstream of road, but these appear to be edge effects.

B-18-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.61 -0.80	0.33 – 0.53	0.005	Unknown (assumed 24 hrs)	0.016 – 0.026

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
TP2099	– SP, (Clayey) Sand with trace gravel – PSD on sample taken at 1.5 – 1.7m shows fines content of 16% and D_{50} = 0.4mm	Dense to Very Dense	Very low	12 / 20 / 8 (1.5 – 1.7m)	2.1 (1.5 -1.7m)	
No soil sample taken	Soil along flow channel is predominately silty SAND.					

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., $K_d = \tan \phi$ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion: 0.1 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.30 kW/m^2 – Stream Power, *P*, for 90% chance of initiating erosion: 1.5 kW/m^2	– Estimated *P* is between 0.016 and 0.026 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Very Low (VL) is soil is clay. Moderate (M) to High (H) is soil is predominantly sand,
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average to good grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 2.0 m/s	– Average flow velocity is 0.61 – 0.80 m/s. – Average velocity is assumed to be approximately 0.7 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 2.5 m/s.	– On average, flow velocity is expected to substantially lower than the threshold velocity for initiation of erosion.	Very Low (VL)	
Critical velocity based on D_{50} (Briaud 2008)	– Based on TP2099 and is Silty, clayey SAND and clay is moderately dispersive. – Sample from TP2099 shows D_{50} is 0.4mm.	Threshold flow velocity to mobilise soil particle (Briaud 2008), assuming a D_{50} of 0.4 mm, is $0.35 (D_{50})^{0.45}$ = 0.23 m/s		– The estimated average threshold velocity is approximately 0.23 m/s which is lower than the design velocity of 0.61 – 0.80 m/s.	Moderate (M) to High (H)	
Dispersivity of soil	Emerson Class 2.1			– Clay is moderately dispersive but fraction of clay in soil is small	Neutral	

B-19 Tinegie Creek, 250-Clvrt773535 – 10/2/22 5:10pm

Modelled Existing 1%AEP Vmax = 0.4m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Indistinct channel	Loose, coarse sandy bed with some gravel.	Densely vegetated, with grasses and trees.	No visible erosion. Loose sand on road.	None	Channel was hard to find

Photographic Record

Looking downstream from Pilliga Forest Way	Looking upstream from Pilliga Forest Way	Looking upstream towards
		

Discussion and Recommendations

- Tinegie Creek has a poorly defined channel.
- Removal of dense vegetation could cause preferential erosion along disturbed area, particularly given the presence of highly erodible sand and clayey sand. Vegetation reestablishment would be a key factor in successful rehabilitation.
- No velocity QDL exceedances at this location, but duration exceedances upstream of embankment and downstream of road, but these appear to be vegetation artefacts

B-19-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.28 -0.33	0.07 – 0.10	0.008	Unknown (assumed 24 hrs)	0.005 – 0.008

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
TP2101	(SP), Clayey Sand with trace gravel PSD of sample taken at 0.7 – 0.9m shows fines content of 28%, and a D_{50} = 0.5mm	Dense to Very Dense	Low	14 / 27 /13 (0.7 – 0.9m)	2.1 (0.7 – 0.9m)	
No soil sample taken from site	Soil appears to be predominantly sand					

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.15 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.35 kW/m^2 – Stream Power, *P*, for 90% chance of initiating erosion: 1.5 kW/m^2	– Estimated *P* is between 0.005 and 0.008 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Very Low (VL) if soil is predominantly clay. Medium (M) to High (H) if soil is predominantly sand.
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average to good grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 2.0 m/s	– Average flow velocity is 0.28 – 0.33 m/s. – Average velocity is assumed to be approximately 0.3 m/s. – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 2.5 m/s.	– On average, flow velocity is expected to substantially lower than the threshold velocity for initiation of erosion.	Very Low (VL)	
Critical velocity based on D_{50} (Briaud 2008)	– Based on TP2101, soil is poorly graded SAND with a fines content of 28%. Fines has low plasticity. – PSD shows D_{50} is 0.5mm.	Threshold flow velocity to mobilise soil particle (Briaud 2008), assuming a D_{50} of 0.5 mm, is between $0.35 (D_{50})^{0.45} = 0.26$		– The estimated average threshold velocity is approximately 0.26 m/s which is slightly lower than the design velocity of 0.28 – 0.33 m/s.	Moderate (M) to High (H)	
Dispersivity of soil	Emerson Class 2.1			– Clay fraction in the soil is moderately dispersive.	Medium (M) to High (H)	

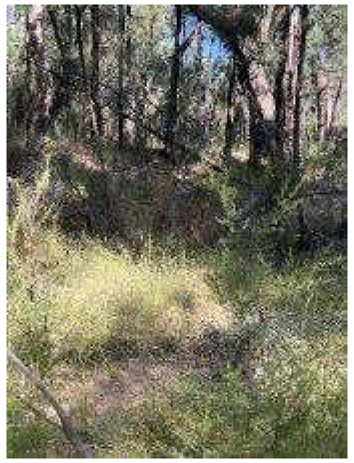
B-20 Talluba Creek, 250-BR779635 – 10/2/22 5:20pm

Modelled Existing 1%AEP Vmax = 1.3m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Indistinct channel	Loose, coarse sandy bed with some gravel.	Densely vegetated, with grasses and trees. LWD flood debris caught on trees.	No visible erosion. Loose sand on road and on sand bed.	Minor area upstream of Pilliga Forest Way	Hydroline is not in correct location

Photographic Record

Looking upstream at proposed bridge crossing	Looking downstream from proposed bridge crossing	Right bank at proposed bridge crossing	Left bank at proposed bridge crossing	Flood debris caught on trees downstream of Pilliga Forest Way
				

Discussion and Recommendations

- Talluba Creek is typical of creeks in the Pilliga, which act as conveyors transporting sand from the uplands to the south through the woodland.
- Removal of dense vegetation could cause preferential erosion along disturbed area, particularly given the presence of highly erodible sand and clayey sand. Vegetation reestablishment would be a key factor in successful rehabilitation.
- Small area of velocity QDL exceedance at this location appears to be vegetation artefact.

B-20-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	1.02 – 1.22	1.42 – 1.92	0.008	Unknown (assumed 24hrs)	0.111 – 0.151

Note : Stream Power, $P = \rho\ D\ V\ S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits	Emerson Class / Dispersivity	Shear Strength
TP2102	– SP, Silty Sand with trace gravel – PSD of soil sample taken at 0.2 – 0.5m shows a fines content of 18% and a D50 of 0.28mm.	Dense to Very Dense	-	-	-	DCP 4 -25 (0 – 0.9m)
No soil sample taken from site	Observation indicated the dry creek bed was covered with sand					

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments		Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s\ K_b\ K_d\ J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.15 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.35 kW/m^2 – Stream Power, *P*, for 90% chance of initiating erosion: 1.5 kW/m^2	– Estimated *P* is between 0.111 and 0.151 kW/m^2. – Chance of initiating erosion is approximately 1%	Very Low (VL)	Very Low (VL) to Low (L) if soil is predominantly clay. Moderate (M) to High (H) if soil is predominately sand.	
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average to good grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 2.0 m/s	– Average flow velocity is 1.02 – 1.22 m/s over a duration of 15.51 – 26.89 hrs. – Average velocity is assumed to be approximately 1.12 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 2.5 m/s.	– On average, flow velocity is expected to be lower than the threshold velocity for initiation of erosion.	Low (L)		
Critical velocity based on D_{50} (Briaud 2008)	– Based on TP2102, soil is Poorly Graded SAND, and observation on site indicated the creek bed was deposited with sand. – PSD shows D_{50} is 0.28mm.	Threshold flow velocity to mobilise soil particle (Briaud 2008), assuming a D_{50} of 0.28 mm, is $0.35\ (D_{50})^{0.45}$ = 0.20 m/s		– The estimated average threshold velocity is approximately 0.2 m/s which is lower than the design velocity of 1.02 – 1.22 m/s.	Moderate (M) to High (H)		
Dispersivity of soil	Not tested					Neutral	

B-21 Overland Flow, 250-Clvrt802534 – 10/2/22 6:00pm

Modelled Existing 1%AEP Vmax = 0.3m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
This watercourse appears to be a man-made channel constructed to remove water from Pilliga Forest Way.	Loose, coarse sandy bed with gravel on banks and on road. More iron-rich than further east (sediment is redder)	Grasses with moderately dense trees.	Sheetwash erosion of banks	Minor area upstream of Pilliga Forest Way and into artificial channel downstream.	Hydroline is not in correct location

Photographic Record

Looking upstream at channel above Pilliga Way	Looking downstream at proposed bridge crossing	Looking northeast along Pilliga Forest Way, showing embankment along road easement due to maintenance
		

Discussion and Recommendations

- Observations do not indicate a natural channel at this location, but rather artificial depressions designed to remove flood flows from Pilliga Way.
- Removal of dense vegetation could cause preferential erosion along disturbed area, particularly given the presence of highly erodible sand and clayey sand. Vegetation reestablishment would be a key factor in successful rehabilitation.
- Velocity QDL exceedances at this location appear to be due be partially due to the road maintenance embankment. The modelled design floods of >2m/s (upstream of the proposed culvert, rather than associated with the structure) seem unlikely due to the location of the exceedance, presence of the maintenance embankment and density of existing vegetation.

B-21-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.22 – 0.24	0.07 – 0.08	0.006	Unknown (assumed 24 hrs)	0.004 – 0.005

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Coarse sand sample taken from downstream bank

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits	Emerson Class / Dispersivity	Shear Strength	Erodibility
TP2102	– SP, Silty Sand with trace gravel – PSD of sample at 0.2 – 0.5m shows fines content of 18%, and D_{50} of 0.28mm.	Dense to Very Dense	-	-	-	DCP 4 – 25 (0 – 0.9m)	
Sample taken from downstream bank	Soil is coarse SAND (see photo)		Appears non-plastic				

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Very Dense SAND. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., $K_d = \tan\phi = 0.5$ (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s = 0.205$	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.15 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.35 kW/m^2 – Stream Power, *P*, for 90% chance of initiating erosion: 1.5 kW/m^2	– Estimated *P* is between 0.004 and 0.005 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Very Low (VL) if soil is predominantly clay. Moderate (M) if soil is predominantly sand.
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.8 m/s	– Average flow velocity is 0.22 – 0.24 m/s. – Average velocity is assumed to be approximately 0.23 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 2.0 m/s.	– On average, flow velocity is expected to be considerably lower than the threshold velocity for initiation of erosion.	Very Low (VL)	
Critical velocity based on D_{50} (Briaud 2008)	– Based on TP2102, soil is poorly graded SAND and sample taken from downstream bank shows the soil is coarse SAND. – Sample in TP2102 shows D_{50} = 0.28 mm.	Threshold flow velocity to mobilise soil particle (Briaud 2008), assuming a D_{50} of 0.28 mm, is $0.35 (D_{50})^{0.45} = 0.2$ m/s		– The estimated average threshold velocity is 0.2 m/s which is approximately equal to the design velocity of 0.22 – 0.24 m/s.	Moderate (M)	
Dispersivity of soil	No test				Neutral	

B-22 Bohena Creek, 250-BR828222 – 11/2/22 10:30pm

Geomorphological Observations at Newell Highway Bridge

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
Broad, moderately sinuous incised creek. Rare chain of pools morphology with variably located and spaced pools separated by indistinct, often swampy flow paths.	Coarse sandy bed material, with clay banks	Moderate to very dense in-channel vegetation with some mature trees. Riparian corridor varies in width. Riparian Corridor and floodplain are moderately to densely vegetated	Headcutting within the access tracks to the east and west of the Newell Highway indicates erosive soils. Large in-channel depositional bars.	Edge effects	Reverse flows can occur, indicating strong secondary currents.

Geotechnical Observations and Soil Erodibility

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI	Emerson Class / Dispersivity	Shear Strength	Erodibility
BH2046	(SC), Sandy Clay	Hard	Medium	-	-		

Modelled Existing 1%AEP Vmax = 2.069m/s

Photographic Record

Looking upstream from right bank at minor deposition downstream of Newell Highway bridge piers	View through Newell Highway bridge piers	Right bank bridge abutment protection	Small headcut in track to west of Newell Highway
			

Discussion and Recommendations

– The existing bridge appears have little adverse impact, the features of which would be considered during detailed design.
– Bridge abutments and access tracks require measures to control dispersion.

Proposed bridge at approximate CH834.7 is discussed following the geotechnical erosion potential assessment for the Newell Highway bridge crossing (see over)

B-22-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.91 – 1.41	1.26 – 2.00	0.005 – 0.006	Unknown (assumed 24 hrs)	0.061 – 0.118

Note : Stream Power, $P = \rho\, D\, V\, S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits	Emerson Class / Dispersivity	Shear Strength
BH2046	(SC), Sandy Clay	Hard	Medium	-	-	
No soil sample collected from site						

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Hard Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., $K_d = \tan \phi$ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s\, K_b\, K_d\, J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.15 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.35 kW/m^2 – Stream Power, *P*, for 90% chance of initiating erosion: 1.5 kW/m^2	• Estimated *P* is between 0.061 and 0.118 kW/m^2. • Chance of initiating erosion is approximately 1%	Very Low (VL)	Low (L) to Moderate (M)
Hewlett *et al.* (1987) Ground Cover	Conditions: – Poor grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.0 m/s	– Average flow velocity is 0.91 – 1.41 m/s. – Average velocity is assumed to be approximately 1.2 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 1.5 m/s.	• On average, flow velocity is expected to be lower than the threshold velocity for initiation of erosion.	Low (L) to Moderate (M)	
Critical velocity based on D_{50} (Briaud 2008)	– No data on particle size distribution and D_{50}	Threshold flow velocity to mobilise soil particle (Briaud 2008) not estimated.				
Dispersivity of soil	No testing				Neutral	

Geomorphological Observations at proposed bridge at approximately CH834.7

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
As before	Coarse sandy bed material, with clayey sand banks and sandy levees	Moderate to very dense in-channel vegetation with some mature trees, making in-channel observation and access difficult. In-channel vegetation has been flattened by the recent flood in places. Riparian corridor varies in width. Riparian Corridor and floodplain are moderately to densely vegetated.	Bar deposition and pools have created a very variable elevation bed.	Edge effects, vegetation artefacts	Reverse flows can occur, indicating strong secondary currents. Flows are likely to be far more complex than modelled.

Geotechnical Observations and Soil Erodibility

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI	Emerson Class / Dispersivity	Shear Strength	Erodibility
BH2047	(SC), Sandy Clay	Hard	Low	-	-		

Modelled Existing 1%AEP Vmax = 2.1m/s

Photographic Record

Looing upstream at in-channel pool	Looking upstream at confluence between Bohena Creek at tributary crossing alignment at about CH834.6	Dense in-channel vegetation
		

Discussion and Recommendations

– Detailed assessment of channel morphology would be required during detailed design to avoid adverse impact from bridge piers, particularly around the outer bank of the bend at about CH835. It was not possible to access this location during this study.

B-23 Namoi River, 250-BR844116 – 11/2/22 10:30pm

Modelled Existing 1%AEP Vmax = 2.9m/s

Geomorphological Observations

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
River is an incised, moderately sinuous channel.	Sandy clay with gravel bed and banks.	Considerable LWD caught on banks, nearly at bankfull levels. Channel and floodplain are densely grassed, with trees within narrow riparian corridor.	Topsoil removal, denudation and gully erosion on floodplain to south of river at proposed bridge crossing location.	Edge effects	River could not be accessed at proposed bridge crossing.

Photographic Record

Deflation and denudation, looking north from Bohena Lane	Looking northeast at gullying on Namoi Floodplain from Bohena Lane	Looking downstream from right bank, downstream of Cooma Road in Narrabri, some distance above the proposed crossing	Looking upstream at the Cooma Road crossing.
			

Discussion and Recommendations

- The Namoi River, Narrabri Creek and Bohena Creek form an interconnected network of channels and floodplains during floods. The proposed bridge spans the entire network.
- Removal of dense vegetation could cause preferential erosion along disturbed area, particularly given the presence of highly erodible sands, and high predicted velocities.
- The Namoi system floodplain is gullied or has deflation hollows in places (as indicated). To avoid exacerbating these features, earth berms may be required to retard flows and encourage sediment deposition in gullies, particularly in areas that are anticipated to have flow disruption due to construction of bridge piers. In severe cases, gully stabilisation works may be required. Deflation hollows would require infilling with less erodible material (e.g. introduction of cohesive clay-rich soils) and stabilised. A detailed site assessment is recommended during detailed design.
- Vegetation establishment or reestablishment would be a key factor in successful rehabilitation. This may require import of suitable topsoil and artificial surface protection in places.

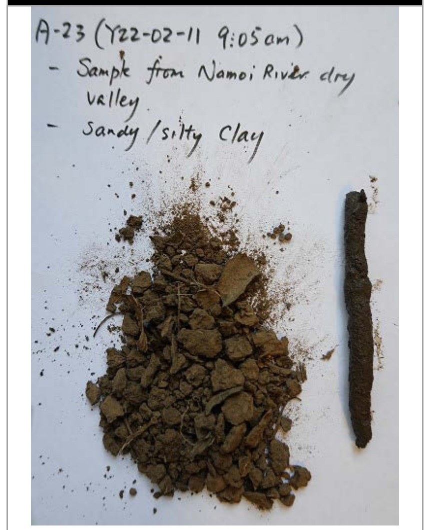
B-23-1 Geotechnical Erosion Potential Assessment

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.63	0.50 – 0.57	0.009	Unknown (assumed 24 hrs)	0.044 – 0.050

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Clay sample taken from dry channel of Namoi River with Thread Test



Geotechnical Observations

Borehole / Testpit Number	PSD, USCS Classification	Consistency / Density	Plasticity	Atterberg Limits (PL / LL / PI)	Emerson Class / Dispersivity	Shear Strength
BH2049	– CI-CL, Clay with sand at 0 – 2.1m – SP, SC SAND, Clayey SAND at 2.1 – 5.6m – CI, Sandy CLAY below 5.6m – PSD done on sample at 3.5-3.95m shows a fines content of 17% and D_{50} = 0.32mm, indicating the soil is a SAND.	Hard Dense to Very Dense	High	15 / 51 / 36 (0.5 – 0.95m)	-	Very high SPT-N 34, 40, 55… Pocket Penetrometer Test > 600 kPa
Clay sample taken from dry river channel			Medium to High (see photo on Thread Test)		Soil sample is not dispersive in distilled water	

Assessment of soil erodibility under the 1% Design Flood event

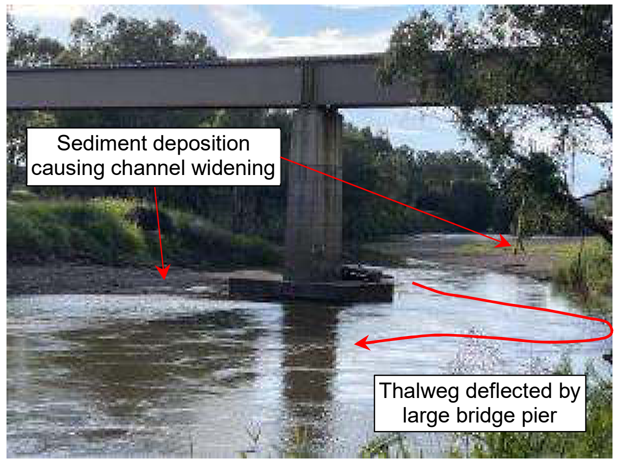
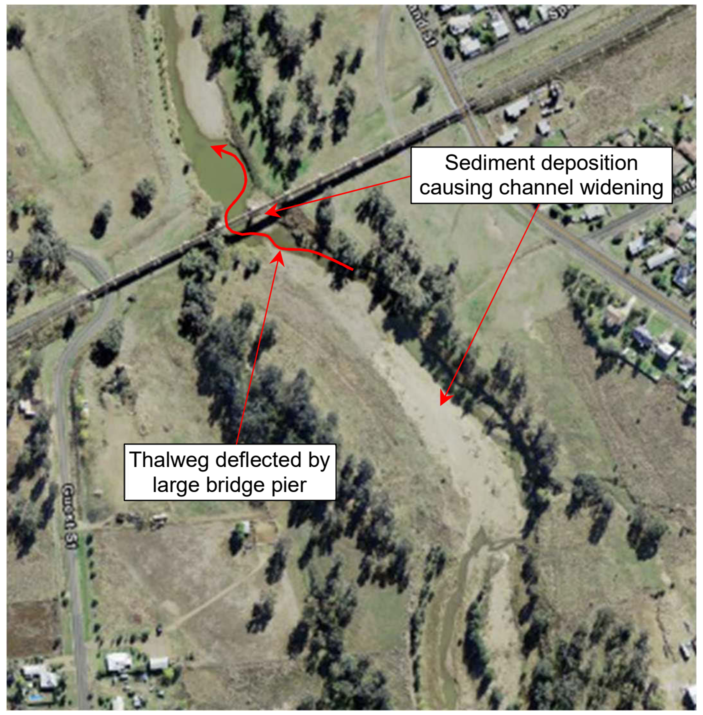
Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.41 given soil is Hard Clay or Very Dense Sand Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s$ = 0.205	Given estimated K_h = 0.205, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.15 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.35 kW/m^2 – Stream Power, *P*, for 90% chance of initiating erosion: 1.5 kW/m^2	– Estimated *P* is between 0.044 and 0.050 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Low (L) if soil is predominantly high plasticity clay. Moderate (M) to High (H) if soil is sand.
Hewlett *et al.* (1987) Ground Cover	Conditions: – Average grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.8 m/s	– Average flow velocity is 0.63 m/s. – Average velocity is assumed to be approximately 0.35 m/s – Assuming highest velocity of flow will last for 12 hrs only, the threshold velocity for initiation of erosion is approximately 2.0 m/s.	– On average, flow velocity is expected to be lower than the threshold velocity for initiation of erosion.	Low (L)	
Critical velocity based on D_{50} (Briaud 2008)	– Based on BH2049, sand has a D50 of 0.32mm, but soil on site appears to be predominantly clay.	Threshold flow velocity to mobilise soil particle (Briaud 2008), assuming a D_{50} of 0.32 mm, is between $0.35 (D_{50})^{0.45}$ = 0.218 m/s		– The estimated average threshold velocity is approximately 0.21 m/s which is higher than the design velocity of 0.63 m/s. This is assuming that the soil is sand.	Moderate (M) to High	
Dispersivity of soil	Test not done				Neutral	

B-24 Narrabri Creek, 250-BR844116 – 11/2/22 10:30pm

Geomorphological Observations at Dangar Street and at Rail Crossing

Contemporary Channel Morphology	Bed and Bank Material	Vegetation	Erosion Observations	QDL Exceedance Observations	Other Notes
River is an incised, moderately sinuous channel.	Organic-rich clay banks with gravel to cobble point bars at rail crossing. At Dangar Road crossing, banks are clayey sand.	Considerable LWD caught on banks, nearly at bankfull levels. Channel and floodplain are densely grassed, with trees within narrow riparian corridor.	At Dangar Road Bridge, piping erosion was observed along the sandy bank and along bridge piers	Edge effects	Difference in pile size has had significantly different impact on creek functioning.

Photographic Record

Deflation and denudation, looking north from Bohena Lane	Dangar Road Bridge across Narrabri Creek, with LWD and small lateral bar	Aerial view of rail bridge, showing deflection of thalweg and sediment deposition / channel widening	Dangar Road Bridge, showing negligible impact
			

Discussion and Recommendations

– The observed response of Narrabri to different bridge designs indicates the care required to provide a bridge design that is suitable for the functioning of the creek. The Dangar Road Bridge, with its narrow piers has caused negligible impact to the adjacent reaches. The single, large pier of the rail bridge has caused significant diversion of the thalweg, resulting in deposition upstream. In turn, this appears to have caused widening of the creek and lateral erosion of both left and right banks at and downstream of the bridge.

B-24-1 Geotechnical Erosion Potential Assessment – NOTE test location is upstream of proposed crossing

Design Hydraulic Conditions

Design Flood Event	Average flow velocity, *V* (m/s)	Average *DV* value (m^2/s)	Approximate flow gradient, S_f	Flow Duration, *T*, (hr)	Unit Stream Power, *P* (kW/m^2)
1%AEP	0.63	0.50 – 0.57	0.009	Unknown (assumed 24 hrs)	0.044 – 0.050

Note : Stream Power, $P = \rho D V S_f$, where ρ equals 9.8 kN/m^3, represents the unit weight of water

Geotechnical Observations

Borehole / Testpit Number
– Soils at river bank near Dangar Road Bridge consist of silt, sand and clay – Clay sample taken from left bank of Dangar Road Bridge

Assessment of soil erodibility under the 1% Design Flood event

Methods	Assessment			Comments	Erodibility assessment based on individual method	Overall Assessment of Erodibility
Annandale (1995) Erosion Index Method	Mass Strength Number, M_s = 0.19 assuming soil is Stiff Clay. Particle/Block size number, K_h = 1 (for cohesive soil) Discontinuity Bond Strength No., K_d = tan ϕ = 0.5 (assumed) Relative Ground Structure No., J_s = 1	Erodibility Index, $K_h = M_s K_b K_d J_s = 0.095$	Given estimated K_h = 0.095, and referring to Wibowo et al 2005: – Stream Power, *P*, for 1% chance of initiating erosion : 0.1 kW/m^2 – Stream Power, *P*, for 50% chance of initiating erosion: 0.30 kW/m^2 – Stream Power, *P*, for 90% chance of initiating erosion: 1.0 kW/m^2	– Estimated *P* is between 0.044 and 0.050 kW/m^2. – Chance of initiating erosion is lower than 1%	Very Low (VL)	Very Low (L) to Low (L) However, silt and clay along river bank with poor grass cover are likely to be more erodible.
Hewlett *et al.* (1987) Ground Cover	Conditions: – Poor grass over along creek. – Flow duration assumed to be 24 hrs.	Threshold velocity to initiate erosion (Figure 9, CIRIA Report 116): V_c = 1.2 m/s	– Average flow velocity is 0.63 m/s. – Average velocity is assumed to be approximately 0.32 m/s – Assuming highest velocity of flow will last for 16 hrs only, the threshold velocity for initiation of erosion is approximately 1.5 m/s.	– On average, flow velocity is expected to be lower than the threshold velocity for initiation of erosion.	Low (L)	
Critical velocity based on D_{50} (Briaud 2008)	– D_{50} is unknown.	Threshold flow velocity to mobilise soil particle (Briaud 2008) not estimated without knowledge on D_{50}.				
Dispersivity of soil	No test			– Clay sample is not dispersive in distilled water but shows slaking.	Neutral	

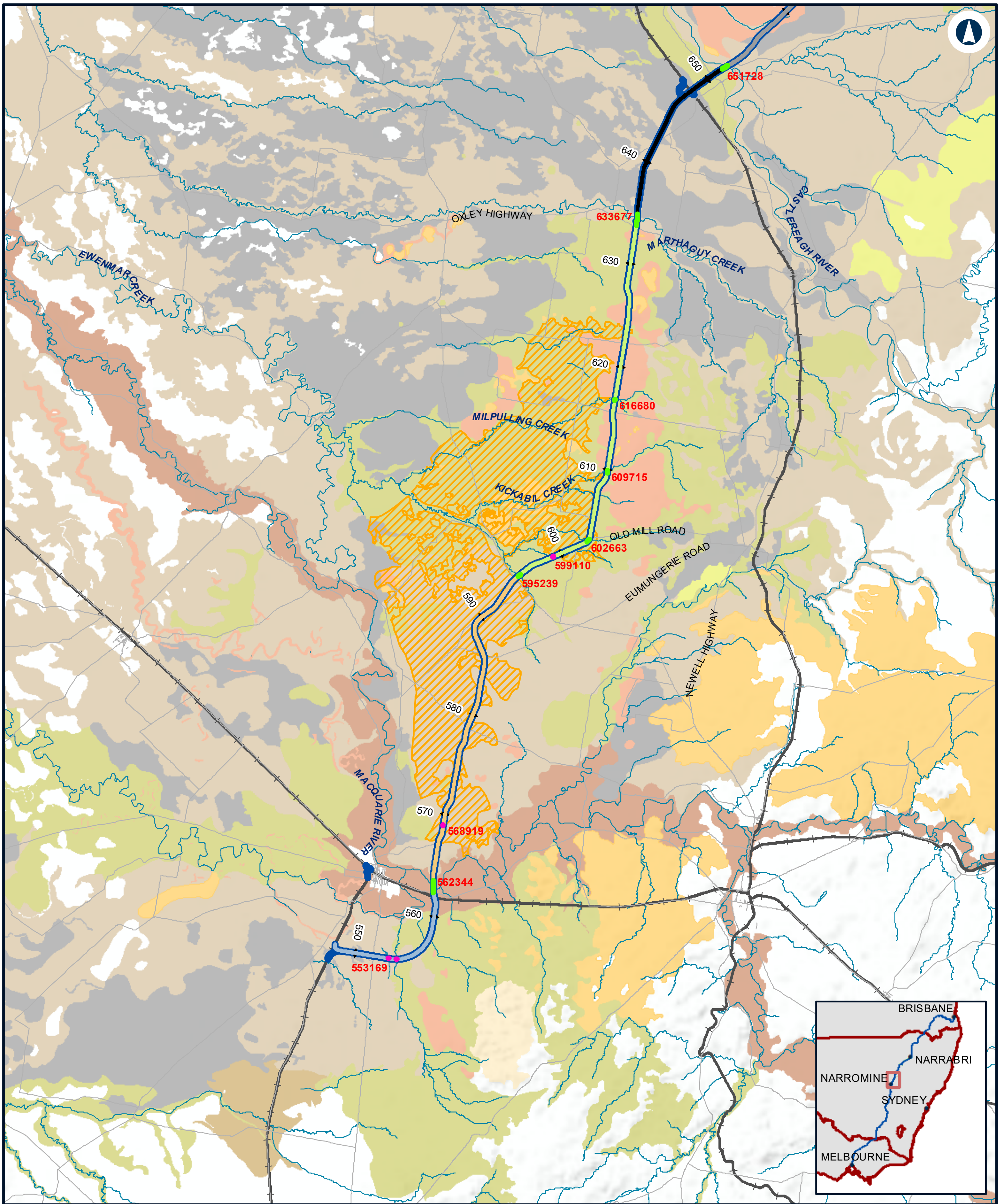
TECHNICAL REPORT 03

Updated flooding and hydrology assessment

Appendix C Erosion potential and fluvial geomorphology assessment maps

Showing location of site visits and key features mentioned in the report.

NARROMINE TO NARRABRI PROJECT



NARROMINE TO NARRABRI

Erosion Potential and Fluvial Geomorphology Assessment - Map

Attachment 3-1 of 3

0 10 20 Km

Coordinate System: GDA 1994 MGA Zone 55

ARTC makes no representation or warranty and assumes no duty of care or other responsibility to any party as to the completeness, accuracy or suitability of the information contained in this GIS map. The GIS map has been prepared from material provided to ARTC by an external source and ARTC has not taken any steps to verify the completeness, accuracy or suitability of that material. ARTC will not be responsible for any loss or damage suffered as a result of any person whatsoever placing reliance upon the information contained within this GIS map.

Date: 19/04/2022 Paper: A4
Author: JacobsGHD Scale: 1:500,000
Data Sources: Basemap layers: NSWSS;

LEGEND

- Railway
- Road
- Watercourse
- Assessed site - bridge
- Assessed site - culvert

Geomorphic unit

- Macquarie Floodplain
- Undulating Agricultural Plains
- Keelindi Alluvial Plains
- Basaltic Alluvial Plains
- Basaltic Colluvial Plains
- Cobboco soil landscape

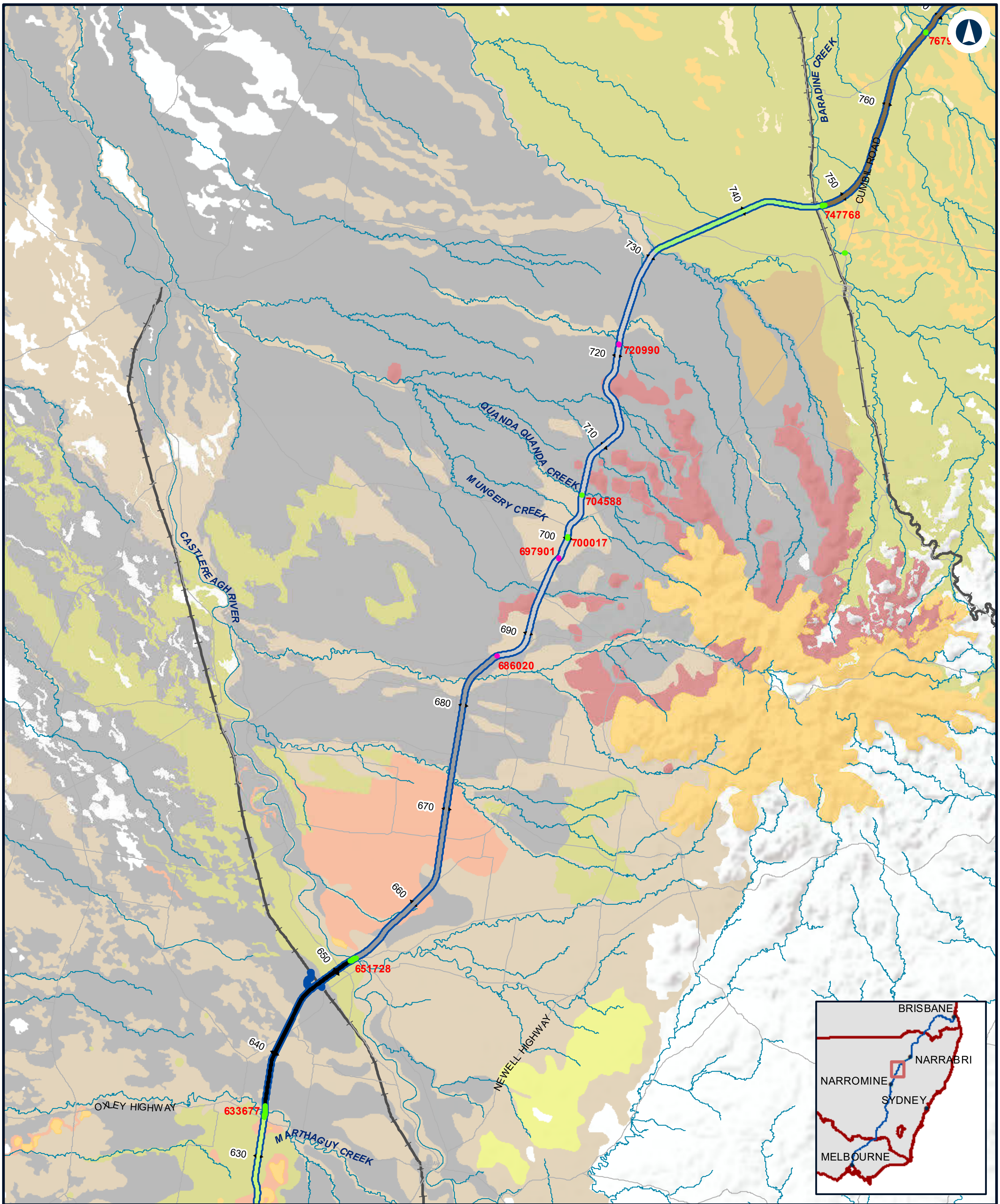
Australian Soil Classification

- Chromosols
- Dermosols
- Kandosols
- Kurosols
- Kurosols, Natric
- Rudosols
- Rudosols and Tenosols
- Sodosols
- Vertosols

INLAND RAIL

ARTC

The Australian Government is delivering Inland Rail through the Australian Rail Track Corporation (ARTC), in partnership with the private sector.



NARROMINE TO NARRABRI Erosion Potential and Fluvial Geomorphology Assessment - Map

Attachment 3-2 of 3

0 10 20 Km

Coordinate System: GDA 1994 MGA Zone 55

Date: 19/04/2022 Paper: A4
Author: JacobsGHD Scale: 1:500,000
Data Sources: Basemap layers: NSWSS;

LEGEND

- Railway
- Road
- Watercourse
- Assessed site - bridge
- Assessed site - culvert

Geomorphic unit

- Keelindi Alluvial Plains
- Basaltic Alluvial Plains
- Basaltic Colluvial Plains
- Basalt Mesa Plains
- Pilliga Plains
- Pilliga Forest

Australian Soil Classification

- Chromosols
- Ferrosols
- Kandosols
- Kurosols
- Kurosols, Natric
- Rudosols
- Rudosols and Tenosols
- Sodosols
- Vertosols

INLAND RAIL ARTC

The Australian Government is delivering Inland Rail through the Australian Rail Track Corporation (ARTC), in partnership with the private sector.

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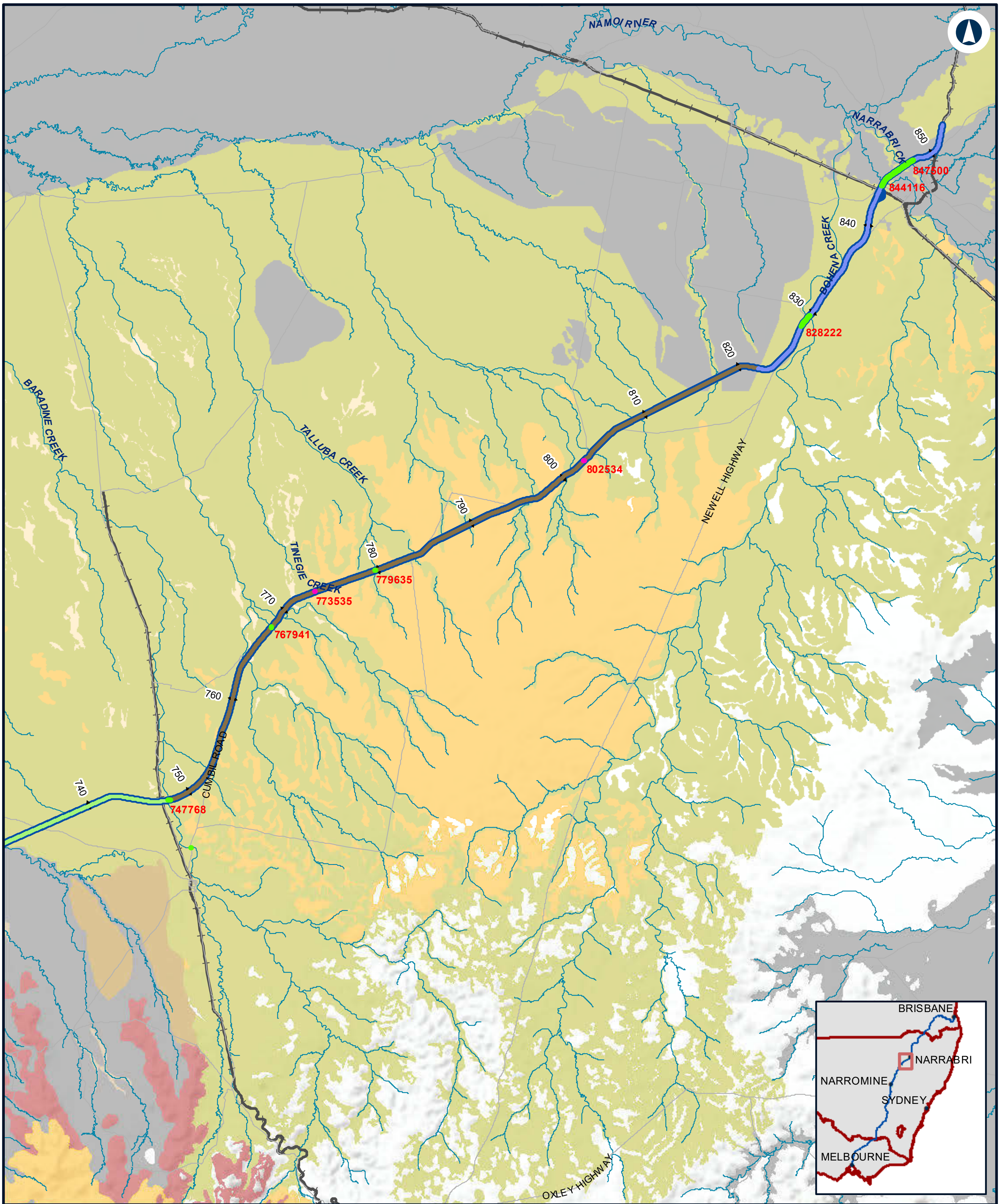

NARROMINE TO NARRABRI Erosion Potential and Fluvial Geomorphology Assessment - Map

Attachment 3-3 of 3

0 10 20 Km

Coordinate System: GDA 1994 MGA Zone 55

Date: 19/04/2022 Paper: A4
Author: JacobsGHD Scale: 1:500,000
Data Sources: Basemap layers: NSWSS;

LEGEND

- Railway
- Road
- Watercourse
- Assessed site - bridge
- Assessed site - culvert

Geomorphic unit

- Pilliga Plains
- Pilliga Forest
- Namoi Floodplain

Australian Soil Classification

- Chromosols
- Ferrosols
- Kurosols
- Rudosols
- Rudosols and Tenosols
- Sodosols
- Vertosols

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Jacobs GHD