APPENDIX 18

Yorks Creek
Diversion
Constraints Analysis

Yorks Creek Diversion Constraints Analysis

Technical Study Report

Geomorphological Assessment

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Final

November 2019

FLUVIAL SYSTEMS

Glendell Continued Operations Project

Geomorphological Assessment for Yorks Creek Diversion Constraints Analysis

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November 2019

Please cite as follows:

Gippel, C.J. 2019. Geomorphological Assessment for Yorks Creek Diversion Constraints Analysis. Glendell Continued Operations Project. Fluvial Systems Pty Ltd, Stockton. Umwelt (Australia), Newcastle, November.

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Document History and Status

Document	Geomorphological Assessment for Yorks Creek Diversion Constraints Analysis. Glendell Continued Operations Project
Ref	
Date	15-11-2018
Prepared by	Christopher Gippel

Revision History

Revision	Revision Date	Details	Authorised	
			Name/Position	Signature
A	16-02-2018	Draft for Review	Chris Gippel Geomorphologist	
B	22-02-2018	Draft for Review	Chris Gippel Geomorphologist	
C	14-03-2018	Draft for Review	Chris Gippel Geomorphologist	
D	21-05-2018	Draft for Review	Chris Gippel Geomorphologist	
Final	15-11-2019	Final	Chris Gippel Geomorphologist	

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Executive Summary

This report provides geomorphic information to support the conceptual design of a proposed diversion of Yorks Creek. Site constraints mean that the diversion design can only partially mimic the geomorphic form of the existing section of Yorks Creek that is proposed to be diverted.

To inform the diversion design, the geomorphological characteristics of existing Yorks Creek from upstream of Mount Owen Mine access road to its junction with Bowmans Creek, and Bowmans Creek from upstream of the proposed confluence of the proposed Yorks Creek diversion to downstream of the existing Yorks Creek confluence, were described. The load and grain-size of sediment transported from upper Yorks Creek to the site of the proposed diversion was estimated. Additionally, regional terrain analysis was undertaken to locate potential alternative reference sites that had geomorphic form similar to that of the proposed diversion. A review of the performance of similar diversions was undertaken by critical review of selected literature. Finally, a set of diversion design objectives was drafted.

The methodology employed a field survey of channel morphology and large wood dimensions and density. Streams were also characterised using terrain analysis applied to a Digital Elevation Model (DEM) based on a thinned version of a 1 × 1 m point data grid generated from a LiDAR survey, provided by Glencore. Digital aerial photography at 0.5 m × 0.5 m pixel resolution provided by Glencore, and low resolution historical aerial photographs, were also used to characterise the geomorphology of the streams. Alternative reference reaches were sought across the local region by applying terrain analysis to the Geoscience Australia (GA) National Digital Elevation Model (DEM) 1 Second Hydrologically Enforced product to find reaches draining small-moderate sized catchments and having either low slope longitudinal profiles, or steep longitudinal profiles within gorge stream types.

The main results and conclusions of the investigation were:

1. The channel of Bowmans Creek was found to have highly variable morphology through hydrologically homogeneous reaches, suggesting complex local channel adjustment to erosive and depositional processes. As a result there was no statistically significant change in channel dimensions downstream of the existing Yorks Creek junction. Given the inherent stability of the channel, rapid and large magnitude adjustment of Bowmans Creek channel downstream of the proposed diversion would not be expected. Rather, adjustment would take place incrementally over decades.
2. The natural reaches of Yorks Creek in the Study Area downstream of Mount Owen Mine Access Road comprise:
    - a narrow, variable-width floodplain with a notch-shaped channel:
        - on average 1.5 – 2.5 m wide at the bed,
        - on average 5 – 6 m wide at morphological bankfull level,
        - on average 1.3 – 2.3 m deep at bankfull level,
        - relatively steep banks on average 45 – 60 degrees,
    - channel bed formed in cohesive fine-grained material of silty sand, with gravel present in places,
    - channel banks formed in cohesive sediment, with stability enhanced by surface grass cover on the bank tops and bank sides fortified by tree and shrub root mats,
    - channel downstream bed level variation on average 0.3 – 0.4 m amplitude, with on average 7 – 8 m spacing between low points,
    - large wood density of on average 4 – 18 items per 100 m, items on average 0.17 – 0.22 m diameter, with most items spanning the full channel width and often found in jams comprising multiple items
    - a riverine corridor on average 40 – 80 m wide (comprising channel and floodplain)
    - a bed slope on average 0.0045 – 0.0093,
    - sinuosity of 1.3 – 1.6
3. The long-term average annual sediment load delivered from upper Yorks Creek catchment to the proposed diversion was estimated to be 1630 tonnes per year. The majority of the sediment load

delivered to the proposed diversion would comprise suspended clay and silt, with a smaller proportion of sand up to 2 mm diameter.

4. Stream reaches with slopes similar to the upper low slope (0.002 m/m) reach and lower steep (0.04 m/m) gorge reach of the proposed diversion were rare in the region, but a small number of similar reaches were found that could serve as reference reaches.
    a. The 1 second resolution of the DEM was too low to allow sufficiently accurate characterisation of the cross-sectional morphology of the low slope reference reaches.
    b. Broad characteristics of the steep gorge reference reaches were:
        - Mean bed slopes in the range 0.015 – 0.024
        - Waterfalls and/or steep cascades present
        - Sinuosity in the range 1.2 – 1.7
        - Valley side slopes in the range 20 – 34% (11.5 – 18.6º)
        - Bed widths in the range 20 – 60 m
5. The review of literature found that the geomorphic performance of diversions was mixed. A problem with the information on this subject is that the data are often flawed due to the widespread use of subjective visual assessment methodologies. These methods are known to have poor reproducibility, are not always based on sound geomorphic principles, and not well-suited to application of statistical testing.
    a. A review of 60 diversions in the Bowen Basin, Queensland found that sediment transport and vegetation condition were the most critical factors determining diversion performance.
    b. Regular monitoring reports of data collected over the period 2014 – 2017 from four diversions in the Mount Owen Complex were inconclusive mainly because the methodology was subjective and statistical analysis was not employed.
    c. Although the quality of the Mount Owen Complex geomorphic monitoring data was limited by the subjective methodology employed, this report grouped the data into control (unimpacted by diversions) and impact (diversion) sites and applied statistical tests for difference in means. The analysis found that there was no statistical difference between the 2014 and 2017 data for the impact sites, while the control sites had statistically lower scores in 2017 than in 2014. Also, the results suggested that in 2017 the control sites were more unstable than the impact sites and this was related to a decline in the scores in the control sites in 2017. The stability of the impact sites did not change between 2014 and 2017.
6. A set of design objectives for the diversion were prepared based on a philosophy of minimising capital and maintenance costs, maintaining environmental values, incorporating natural geomorphological forms and processes typical of the existing Yorks Creek or alternative regional reference reaches, achieving an acceptable degree of physical stability, and minimising risks to downstream riverine environments.
7. An alternative and complementary approach to the diversion design philosophy of mimicking the geomorphic form and process and hydraulic character of the existing stream channel is to follow Australian Coal Association Research Program (ACARP) design and monitoring criteria based on characteristics of regional stream systems and replication of the natural stream processes. It is recommended that where possible the York Creek design follow ACARP guidelines.

1.0 Introduction

1.1 Glendell Continued Operations Project

The Glendell Coal Mine is an existing open cut coal mine located in Hunter Valley in NSW, approximately 20 km northwest of Singleton. As part of the life-of-mine planning for the Glendell Coal Mine, the existing Glendell Pit (also known as the Barrett Pit) will be expanded to the north through the existing Yorks Creek corridor. The Glendell Continued Operations Project (Project) involves diversion of Yorks Creek to the west around the proposed pit extent, shifting its confluence with Bowmans Creek to a point 4.2 km upstream of the existing confluence (Figure 1). The Project also involves relocation of Hebden Road to the west of the proposed pit extent, construction of a heavy vehicle access road from Glendell through to Liddell Mine crossing Bowmans Creek via a proposed bridge, and construction of a mine infrastructure area (MIA) facility beyond the extent of the pit (Figure 1). This report is focused on constraints associated with the Yorks Creek diversion component.

1.2 Purpose of the Report

This Geomorphological Assessment for Yorks Creek Diversion Constraints Analysis is mainly concerned with:

- describing the geomorphological character of existing Yorks Creek, to provide a benchmark, or reference dataset, to assist conceptual design of the diversion,
- locating, and describing the geomorphological character of, stream reaches within the region that could serve as alternative reference reaches to assist conceptual design of the diversion, and
- assessing the potential impacts of the proposed diversion on the geomorphological character of Bowmans Creek

The scope of work for this Technical Report included:

- Site inspection to obtain primary field data.
- Review of the previous relevant literature.
- Characterisation of the existing geomorphic forms and processes within Yorks Creek, including sediment load.
- Assessment of potential impacts of the diversion project on geomorphic forms and processes within Bowmans Creek.
- Characterisation of the morphology of potential reference stream reaches located within the region.
- Review of performance of similar nearby diversions.
- Establishment of design objectives for the diversion project.
- Description and graphical conceptual design of opportunities to provide geomorphic form and function within the current proposed diversion footprint to best meet the diversion project objectives.

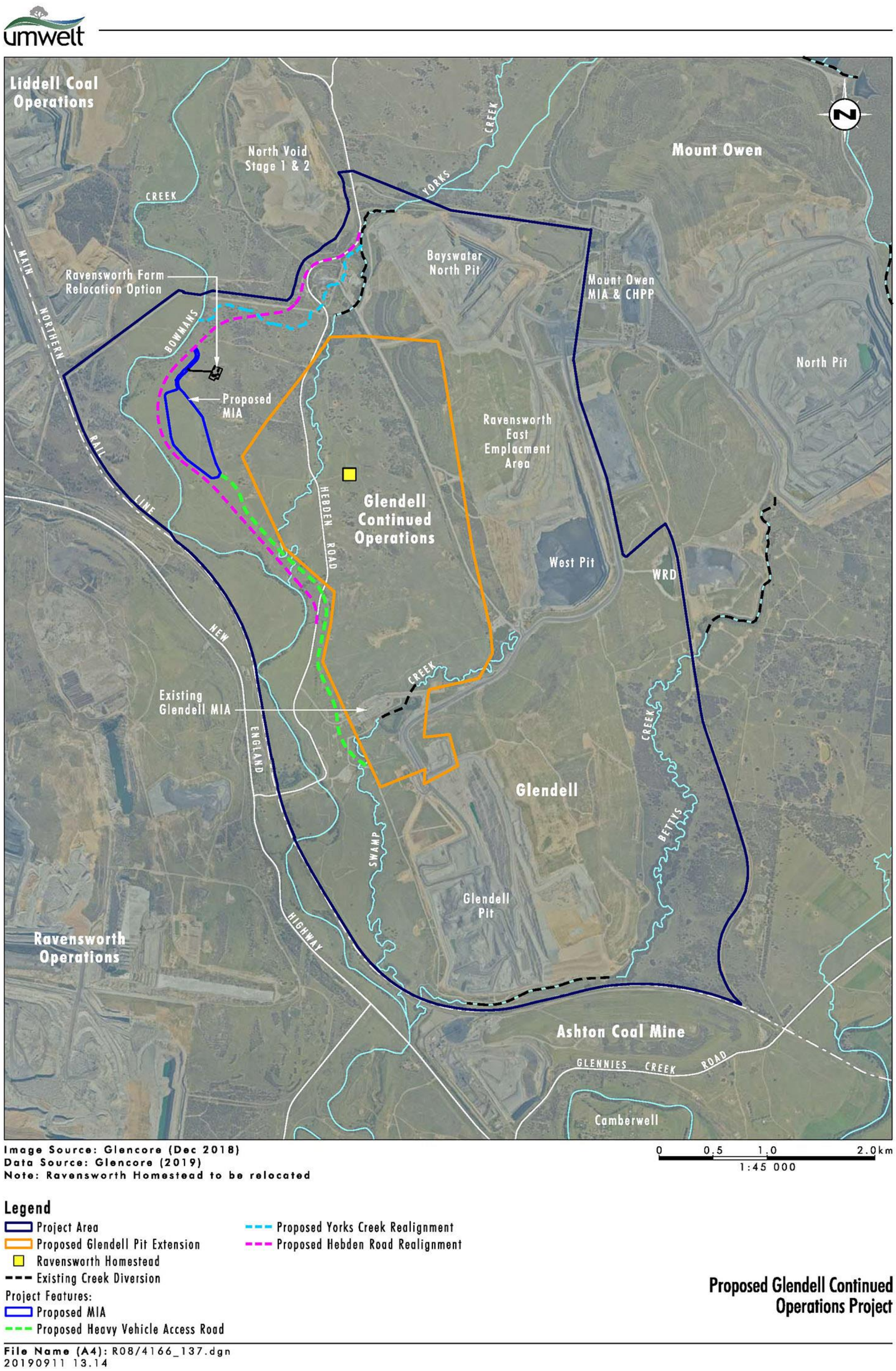

Figure 1. Study Area, showing key project features of Glendell Continued Operations Project and existing features. Source: Umwelt.

2.0 Methodology

2.1 Study Area

The Study Areas of this Technical Report were appropriate to the main topics under investigation:

Characterisation of existing Yorks Creek morphology, and assessment of potential impacts of the proposed diversion on Bowmans Creek morphology:

- Yorks Creek from approximately 350 m upstream of Mount Owen Mine access road, downstream through an existing diversion, crossing the Ravensworth East Haul Road (abbreviated here to Haul Road), crossing Hebden Rd, then to its existing confluence with Bowmans Creek; and
- Bowmans Creek from at least 200 m upstream of the confluence of the proposed diversion to at least 200 m downstream of the existing Yorks Creek confluence (in some respects, Bowmans Creek was investigated further up- and downstream).

Bowmans Creek and Yorks Creek in the Study Area were divided into six reaches according to hydrological, morphological or management factors that were relevant to this investigation (Figure 2).

Characterisation of Yorks Creek sediment load delivered to the proposed diversion:

- Yorks Creek headwaters to near the starting point of the proposed diversion at Mount Owen Mine access road

Assessment of regional sediment transport processes, and characterisation of the morphology of regional reference sites:

- Bowmans Creek, Glennies Creek, Bayswater Creek and Saddlers Creek catchments for reference sites.
- Bowmans Creek, Glennies Creek and Bayswater Creek catchments for regional sediment transport processes.

2.2 Data

2.2.1 Primary Data

A preliminary field inspection of the Study Area was undertaken by the project team on 25 January 2018. Measurements of stream morphology and large instream wood in Yorks Creek downstream of near the start of the proposed diversion were made in the field by Dr Christopher Gippel of Fluvial Systems Pty Ltd on 7 February 2018. Sediment processes in Yorks Creek from the headwaters downstream to near the start of the proposed diversion were investigated in the field by Dr Gippel on 30 April 2018.

2.2.2 Spatial Elevation Data

The investigation relied heavily on detailed topographic data and aerial photography. Airborne Laser Scanning (ALS), also known as Light Detection and Ranging (LiDAR), data covering the area west and south of near the start of the proposed diversion to Bowmans Creek were supplied by Glencore. Metadata were not supplied, but the data were from the most recently flown survey. The data were supplied in a post-processed form, as a thinned version of a 1 × 1 m point data grid. These data were converted to a 0.25 × 0.25 m Digital Elevation Model (DEM), although the actual accuracy is no better than the 1 m resolution of the original point data.

Areas outside the coverage area of the supplied LiDAR were represented by Geoscience Australia (GA) National Digital Elevation Model (DEM) 1 Second Hydrologically Enforced product, derived from the National DEM SRTM 1 Second and National Watercourses, Lakes and Reservoirs (http://www.ga.gov.au/elvis/). In the region of interest, the DEM is provided as a 26.49 × 26.49 m grid.

2.2.3 Spatial Water and Land Characteristics Data

The drainage network was represented by National Surface Hydrology Lines (Regional) downloaded from Australian Government (https://data.gov.au/dataset/surface-hydrology-lines-regional). In the study area, these lines correspond to the blue lines on 1:25,000 topographic map sheet.

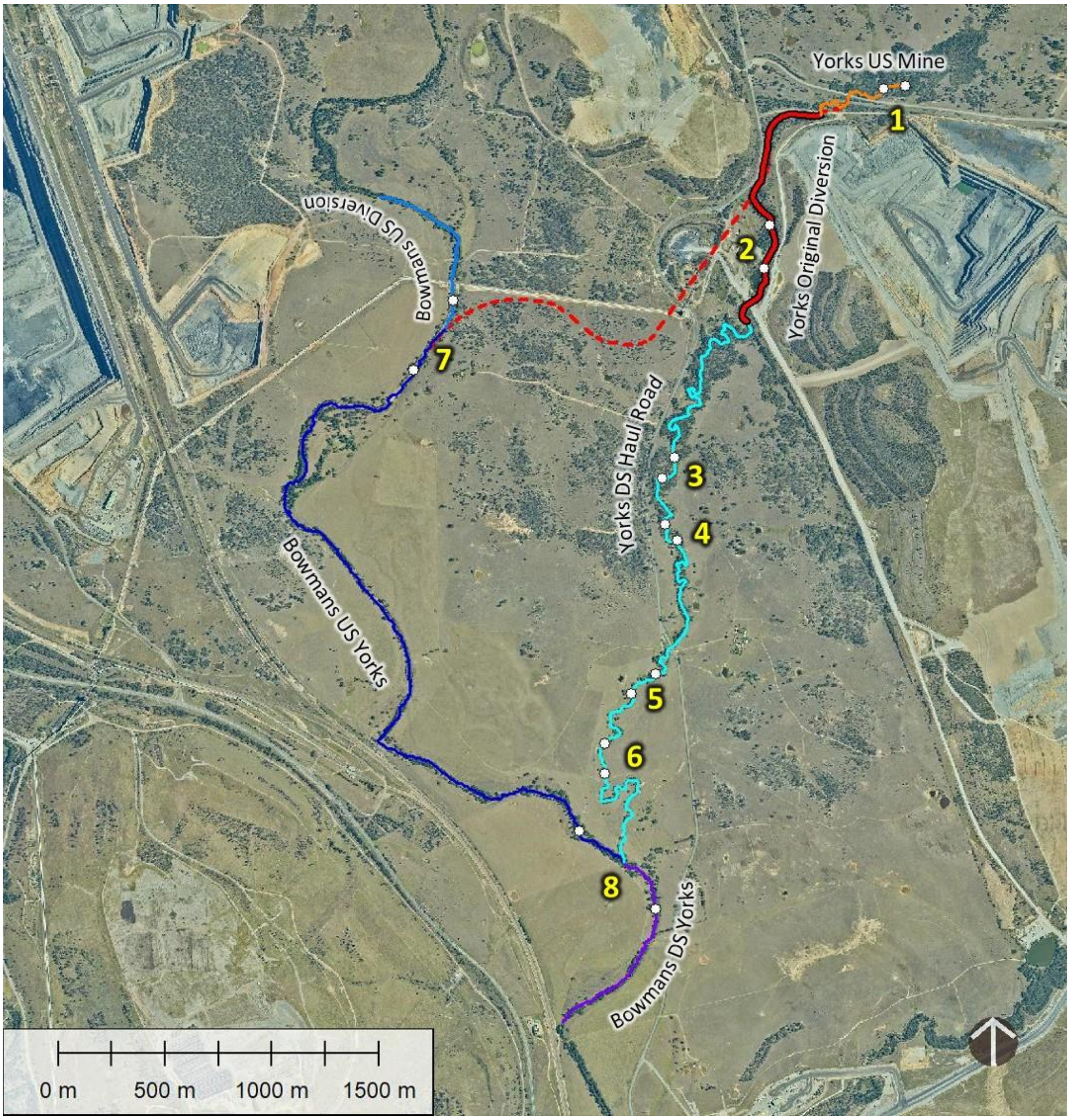

Figure 2. Six reaches of Bowmans and Yorks creeks, and associated 8 field survey reaches, defined for the Study Area. Survey reaches extended between the marked boundaries.

Gully erosion extent and severity and extent of streambank erosion was represented by the spatial layer Erosion Gully and Streambank – Landform and Condition Dataset downloaded from State Government of NSW, Office of Environment and Heritage (OEH) (http://data.environment.nsw.gov.au/dataset/erosion-gully-and-streambank-landform-and-condition-dataset206b0). The mapping for this data is typically carried out at 1:25 000 scale using topographic maps as a base. The data are not recent, with collection over the period 1 Jan 1991 to 1 June 1993.

Geology data were obtained from the online version of Geoscience Australia Bedrock and Surficial Geology, compiled at 1:1 million scale (http://services.ga.gov.au/gis/services/GA_Surface_Geology/MapServer/WMSServer?request=GetCapabilities&service=WMS). The data included lithostratigraphic extents and descriptions, and fault locations.

Soil Landscapes of Central and Eastern NSW is a compilation of all 39 published soil landscape maps that cover central and eastern NSW, based on standard 1:100,000 and 1:250,000 topographic sheets. The mapping provides an inventory of soil and landscape properties of the area and identifies major soil and landscape qualities and constraints. These data were obtained from the online version of Office of Environment and Heritage (2017) Soil Landscapes of Central and Eastern NSW, NSW Office of Environment and Heritage, Sydney (http://data.environment.nsw.gov.au/dataset/published-soil-landscapes-of-central-and-eastern-nsw37d37). Descriptions of the Soil Landscape units were downloaded from http://www.environment.nsw.gov.au/eSpade2Webapp.

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

Land cover was taken from GlobCover, and initiative of European Space Agency (ESA) and the Université Catholique de Louvain. These global land cover maps were based on Envisat MERIS Fine Resolution (300 m grid) mode data. These data were obtained from the online version of GlobCover (http://due.esrin.esa.int/page_globcover.php).

Over the period 1997-2002, the National Land and Water Resources Audit (NLWRA) (http://lwa.gov.au/programs/national-land-and-water-resources-audit) coordinated and commissioned a range of assessments that encompassed Australia's land, water and biodiversity. All the information gathered on sediment supply, transport and deposition in river systems can be found at National Land and Water Resources Audit (2001). The methodology is reported in Prosser et al. (2001a, 2001b). The spatial resolution of the NLWRA was too coarse to include small catchments the size of Yorks Creek. Processes Yorks Creek were extrapolated from information from its larger parent catchment (Bowmans Creek) and adjacent catchments. The streams theme had 39 attributes, with12 of these relevant to sediment supply, transport and deposition. For this investigation, four attributes of key relevance were selected to represent sediment transport processes:

- fsedout_kt/y: Predicted river link mean annual load of suspended sediment under current conditions. This was divided by catchment area to convert to scale-independent specific yield of suspended sediment, specsed_t/ha/y (tonnes per hectare per year).
- nfsedout_kt/y: Predicted river link mean annual suspended sediment yield under pre-European (natural) conditions. This was converted to specific yield of suspended sediment.
- sedratio: Predicted ratio of current suspended sediment load to natural suspended sediment load.
- cseddepth_m: Predicted depth of coarse sediment deposition on river bed since European settlement (metres).

The NLWRA is discontinued and resources are no longer available online. However, an archived copy of the original data was available.

2.2.4 Aerial Photography

Digital aerial photography at 0.5 m × 0.5 m pixel resolution dated 5 January 2018, for the area covered by the LiDAR, was supplied by Glencore.

The online resource World Imagery was used for areas outside the extent of 2018 aerial imagery. The World Imagery data for the Study Area was flown 6 and 17 January 2015, at a resolution 0.46 m and accuracy 10.2 m.

Approximately georeferenced historical black and white aerial photographs dated 15/11/1958, 7/01/1967, 22/07/1983 and 2/05/2002 were supplied by Umwelt. These photographs were re-rectified using reference features that were present in the 1950s (certain roads, tracks, buildings, and significant trees) to allow direct comparison of channel position over time. Given the low resolution of the photographs, distortion of the images, and rectification error, as well as riparian vegetation obscuring the view of the ground, the accuracy of comparison of channel alignment between photographs was approximately ±30 m at any location.

2.2.5 Proposed Mine Infrastructure and Proposed Diversion Alignment Information

The proposed project diversion and road alignments were supplied in digital vector form by Umwelt. In addition, a longitudinal profile of the elevation of the thalweg of the proposed diversion at 20 m steps was supplied in hard copy form by Umwelt. These elevation data were transcribed and associated with the alignment vector.

2.2.6 Hydraulic Data

The hydraulics of Bowmans Creek and Yorks Creek in the Study Area were previously modelled by WSP (2017a) and WSP (2017b). WSP (2017a) described a catchment rainfall-runoff flood model and channel hydraulic model of existing Yorks Creek, while WSP (2017b) described a catchment rainfall-runoff flood model and channel hydraulic model of the proposed diversion channel, and Bowmans Creek from upstream of the diversion confluence to downstream of the existing Yorks Creek confluence. Flood inundation extents were supplied as digital files for the models described in WSP (2017b).

2.3 Digital Terrain Analysis

Terrain analysis is concerned with the automated analysis of landforms using digital elevation data sets within a Geographic Information System (GIS). Terrain analysis was undertaken using the GIS application Global Mapper™ V15.2.5 25 June 2014 Build (Blue Marble Geographics).

2.3.1 Stream Line Definition – Bowmans and Yorks Creeks

The thalweg (lowest point on a channel) profile of Bowmans Creek and Yorks Creek was generated using the ‘Generate Watershed’ function of Global Mapper™. This function uses the standard 8-direction pour point algorithm (D-8) (Jenson and Domingue, 1988) to generate a drainage network from the DEM, after first filling depressions in the DEM. The procedure traces the thalweg path from downstream to upstream according to the selected resolution. A resolution of 0.5 m was chosen as a balance between the time required to undertake the computation, the complexity of the channel morphology and the resolution of topographic data. The resultant thalweg represents the most tortuous drainage path that water would take at very low flow. This thalweg line was smoothed using an automatic function in GIS to simulate the central flow path at a moderate in-channel flow rate.

The stream lines identified by terrain analysis were exported as point elevations at 1 m spacing to characterise longitudinal channel form. High points in the data representing bridges and culverts were deleted prior to channel form characterisation.

2.3.2 Longitudinal Channel Bed Form Characterisation –Yorks Creek

The longitudinal channel bed form of Yorks Creek was characterised by:

- Mean bed slope
- Sinuosity
- Variation in bed elevation

Reach mean bed slope was calculated by applying linear regression to smoothed thalweg data. Reach sinuosity was measured using smoothed thalweg data to represent channel length and valley length was the straight or broad curvilinear length between up- and downstream ends of selected reaches.

Variation in bed elevation is highly scale-dependent. The LiDAR-based topographic data were limited to 1 m resolution at best, which means that high frequency variations in channel bed elevation were not represented in the data. Also, there was high potential for noise introduced by error in the original elevation data and the stream line definition method.

The variation in longitudinal form was characterised from the unsmoothed thalweg profile data, by identifying significant low points in the profile as having two adjacent upstream and two adjacent downstream points at higher elevation. The significant high point between two low points was taken to be the point of highest elevation between the two low points. Longitudinal variation was then characterised by the fall in elevation from a high point to the adjacent downstream low point, as well as the distance between consecutive low points. This algorithm identified low points separated by a minimum distance of 3 m to the adjacent low point. Field inspection of Yorks

Creek suggested that this scale was appropriate to characterise the dominant frequency of longitudinal form variation, although a degree of variation in bed elevation over shorter longitudinal distances was also observed.

2.3.3 Cross-Sectional Channel Form Characterisation – Bowmans and Yorks Creeks

The cross-sectional form of Bowmans Creek and Yorks Creek was characterised by:

- Bed width
- Width between inset benches (if present)
- Top width at morphologically defined bankfull level
- Water width at morphologically defined natural levee level (Yorks Creek only)
- Water width at the modelled 10 year ARI flood event (Bowmans Creek only)
- Channel/floodplain corridor total width (Yorks Creek only)
- Depth from bankfull level to lowest point on the bed

Cross-sections were automatically extracted from the DEM at 100 m spaced intervals along the smoothed thalweg lines. This procedure generated 60 cross-sections for both Bowmans and Yorks creeks. Cross-sectional channel dimensions were then measured manually using GIS tools.

2.3.4 Location and Characterisation of Potential Alternative Diversion Reference Reaches

The proposed diversion comprises two main reaches of contrasting bed slopes. Site constraints mean that the proposed slope of the upper reach (0.002 or 1 in 500) is lower than that of the existing Yorks Creek that is to be diverted, while the proposed slope of the lower reach (0.04 or 1 in 25) is higher than that of the existing Yorks Creek that is to be diverted. It is proposed to excavate the lower reach through a low hill, which will create a gorge stream type, which is not found in the existing Yorks Creek.

While some characteristics of the existing Yorks Creek provided reference data to inform the design of geomorphic features of the proposed diversion, alternative reference stream reaches were sought within the local region. Ideally, reference sites would drain a catchment area similar to that of the proposed diversion, which is around 15 - 20 km^2. Two types of stream were sought: (i) those of relatively low gradient, and (ii) those of relatively high gradient, preferably situated within gorges.

The region of interest was the catchments draining the northern side of the Hunter River between Goulburn River and Glennies Creek junctions. Yorks Creek is situated centrally within this region. The total area of this region was 1216 km^2, with the two largest catchments being Bowmans Creek (225 km^2) and Glennies Creek (439 km^2). Saddlers Creek catchment also drained from this region.

The available LiDAR data covered only part of the region of interest. The best available topographic data for the intended purpose was the GA National DEM 1 Second Hydrologically Enforced product. The 26.5 m grid resolution is too coarse for accurate characterisation of relatively small streams, with this problem compounded by the general failure of the stream network to closely follow stream course alignments that were visible on aerial photography. Furthermore, the DEM was generated using data obtained by a radar scanner mounted on the February 2000 Space Shuttle Endeavour mission, with the surface representing radar reflections from the vegetation canopy, buildings and the ground. Although not ideal, the topographic data were considered adequate for the primary purpose of screening for potential reference sites.

A drainage network was generated using the ‘Generate Watershed’ function of Global Mapper™. Depressions in the DEM were filled to a maximum depth of 10 m, with the watershed areas and drainage network generated at 5 × 5 m resolution. To limit the number of streams generated, the minimum stream length was 500 m, and the minimum accumulated area for a cell to be considered part of a stream was 0.5 km^2. The resulting stream network had fewer small streams than the National Watercourses, Lakes and Reservoirs network, as expected, but it aligned much better to the topography of the hydrologically enforced DEM. Stream links with the majority of their length crossing lakes and reservoirs were deleted from the generated network.

The terrain analysis characterised each stream link (length of stream between the joins of other links, called nodes) using a number of geomorphic variables. These included the estimated drainage area and average slope, which were the primary variables used to filter the results:

- The catchment area filter identified stream links draining catchment areas in the range 8 – 100 km^2

- The high slope filter identified stream links with mean slope greater than 0.01 (1 in 50)
- The low slope filter identified stream links with mean slope less than 0.004 (1 in 250)

2.4 Field Surveyed Channel Character

2.4.1 Sample Reaches

Eight short reaches were identified for field sampling of channel character variables (Figure 2). The sample reaches in Yorks Creek were selected to be representative of the three Study Area reaches and the sample reaches in Bowmans Creek were in the vicinity of the existing confluence of Yorks Creek and the confluence of the proposed diversion. The sample reaches in Yorks Creek were 105 – 156 m long and the Bowmans Creek reaches were longer (Table 1).

Table 1. Length of field sample reaches.

Reach Number	Creek	Reach Length (m)
1	Yorks	105
2	Yorks	223
3	Yorks	136
4	Yorks	146
5	Yorks	158
6	Yorks	156
7	Bowmans	395
8	Bowmans	563

2.4.2 Cross-Sectional Dimensions

Each sample reach on Yorks Creek was walked along the channel, stopping at 10 – 20 m intervals to measure:

- bed width,
- top width at interpreted morphological bankfull level, and
- depth from bankfull to the lowest point on the bed.

These measurements were mostly made with a retractable tape measure, with a laser rangefinder used in the larger Yorks Creek Original Diversion reach (Sample reach 2). A total of 20 sections were measured in each sample reach, except for Yorks Creek Upstream of the Mine (Sample Reach 1), which was shorter, where 14 sections were measured.

2.4.3 Large Wood Density and Dimensions

Large wood dimensions and density were measured at each sample reach on Yorks Creek. Large wood was defined as fallen timber within the bankfull channel, at least 100 mm diameter and at least 1 m in length. Clusters of two or more items of wood were termed jams. Each item of wood encountered in the sample reaches was measured for:

- diameter in the centre of its length,
- length, noted as spanning the full width of the channel, or if not, measured, and
- whether present as an element of a jam or as an isolated item

2.4.4 Bed Materials and Channel Stability

In Yorks Creek downstream of the Mount Owen mine access road, and in Bowmans Creek, bed material size distribution was qualitatively classified as clay/silt, sand, gravel, cobble or boulder, according to the Wentworth scale. Channel stability was subjectively assessed, mainly in terms of the coverage of riparian vegetation, presence of root mats in exposed banks and knickpoints in the bed.

In Yorks Creek upstream of Mount Owen mine access road to its headwaters, bed material size distribution was measured at three locations using Wolman Pebble Count method (Wolman, 1954), measuring the B-axis dimension of 100 particles selected at random from the surface. For practical measurement reasons, the lower size threshold of 8 mm (i.e. inclusive of medium gravel and coarser sizes) was used. The particle size data were converted to distributions of percent finer by weight, corrected for bias in sampling using the method of Leopold (1970). At one site, close to Mount Own mine access road, a 5 kg sample was taken from the top 100 mm using a trowel. The particle size distribution of this sample was determined by ALS Environmental Services Newcastle, following AS 1289.3.6.1-2009 (Standards Australia, 2009), using sieves down to 75 µm. The method of laser diffraction was used as an alternative to hydrometer for the finer silt and clay sizes.

2.5 Sediment Yield of Yorks Creek Catchment

2.5.1 Review of Catchment Sediment Yield Prediction

A recent review of sediment yield processes by Dutta (2016) revealed that by the 1930s the three major factors determining soil erosion had been identified: sensitivity of soil to erosion, potential erosivity of rainfall, and runoff and soil protection afforded by plant cover. Other factors have since been identified: topography, crop management, and land management practice. Dutta (2016) listed 9 empirical models, 16 physically-based models, and 10 conceptual models, used to predict soil erosion. Sediment delivery ratio (SDR) is the fraction of sediment eroded from hillslopes, gullies and channel banks that is delivered to the catchment outlet. SDR is nearly always less than 1, and varies throughout a catchment as a function of various factors such as precipitation, land cover, topography, and soil characteristics. SDR may reach 0.1 as watershed area reaches 100 km^2 (Dutta, 2016). Sediment yield models combine erosion estimation with SDR. Dutta (2016) listed 5 physically-based and 1 numerical sediment yield models.

In an application that utilised readily available global datasets, Ali and De Boer (2010) adopted the catchment erosion model of Thornes, whereby erosion rate is a function of soil erodibility coefficient, slope and percentage vegetation cover. Ali and De Boer (2010) hypothesised that SDR was a function of travel time of surface runoff from catchment cells to the nearest downstream channel.

Shi et al. (2014) suggested a partial least squares regression model to predict sediment yield based on a number of catchment attributes. In 107 catchments with diverse physiographic features and land uses in China, the most important variable for the specific sediment yield was agricultural land use, which exhibited a positive regression coefficient, indicating that agricultural land use is a primary sediment source. The second most important variable was the areal percentage of forest cover, which had a negative regression coefficient.

Haghizadeh et al. (2009) applied a grid-based distributed erosion potential method (EPM) to the Upper Sezar River catchment, Iran. Average annual sediment production was calculated as function of annual rainfall, catchment area, average annual air temperature, soil resistance to erosion (function of geology and soil type), land cover, land conservation actions, and slope. Sediment deposition (retention) was modelled as a function of catchment perimeter, length and mean slope. Sediment yield was then calculated as the product of sediment production and sediment retention.

Javed et al. (2016) used a Sediment Yield Index (SYI) based on annual precipitation, catchment area, drainage density, average slope, and vegetative cover (F), where F was based on the classes: Agricultural land, Dense forest, Open forest, Open scrub, Exposed rock, Stone query, Wasteland, Settlement and Waterbody.

The GIS-based Sediment Assessment Tool for Effective Erosion Control (SATEEC), was developed to estimate soil loss and sediment yield for any location within a watershed using the well-known Revised Universal Soil Loss Equation (RUSLE) and a spatially distributed sediment delivery ratio (Lim et al., 2005). RUSLE estimates annual soil loss per unit area from rill and inter-rill erosion caused by rainfall splash and overland flow, but not from gully and channel erosion. Lim et al. (2005) estimated SDR as a function of catchment area.

While many examples of application of sediment yield modelling can be found in the literature, few of these report model accuracy relative to well measured sediment yield data. Empirical sediment yield data provide a useful guide to the potential sediment yield of catchments with similar climate, geology, land cover and drainage network. Sedimentation surveys of small dams in granite catchments in the Bathurst area of New South Wales by Mahmoudzadeh et al. (2002) found that land use was the main factor determining erosion rates and sediment yields. Cultivated catchments produced, on average, 3.1 t/ha/yr whereas grazed pasture and forest/woodland catchments exported 2.2 and 0.8 t/ha/yr, respectively. Mahmoudzadeh et al. (2002) regarded the yields for cultivated and grazed catchments high by Australian standards. In ungullied shale catchments of western Sydney where rainfall erosivity and soil erodibility are relatively constant, a single urban catchment produced 6.5 t/ha/yr and cropped catchments an average of 6.7 ± 1.99 t/ha/yr (Erskine et al., 2003). Grazed woodland/forest and grazed pasture exported averages of 2.5 ± 0.57 and 2.9 ± 1.02 t/ha/yr, respectively. Again, Erskine et al. (2003) regarded these yields to be high by Australian standards. Sedimentation surveys of dams in small sandstone drainage basins near Sydney again demonstrated that land use was the dominant factor determining sediment yields and soil loss rates (Erskine et al., 2002). Cultivated basins produce an average sediment yield of 7.1 t/ha/yr whereas grazed pasture and forest/woodland basins export averages of 3.3 and 3.1 t/ha/yr, respectively. As with the other two dam sediment surveys, the authors regarded these yields to be high by Australian standards.

In the above brief review of sediment yield studies, sediment generally refers to suspended sediment. Bedload is supplied to a river link from tributary links and from gully and riverbank erosion. The period between 1880 and 1920 has been recognised as one of widespread channel incision in southeast Australia (Eyles, 1977). Incision was initiated by disturbance from grazing and ploughing of the otherwise highly erosion-resistant protective vegetation covering valley drainage lines (Zierholz et al., 2001). Prior to gully formation, most valleys in the Southern Tablelands of Australia with catchment areas up to 150 km^2 were characterised by narrow alluvial flats with dense grassland and sedgeland vegetation (typically sedge and *Poa* tussock) (Eyles, 1977), later termed swampy meadows. Some of these swampy meadows featured scour pools without connecting channels, which early explorers termed chain-of-ponds. There is evidence that the post-European settlement episode of incision followed earlier Holocene phases of incision followed by aggradation, which is consistent with observations made in other regions of the world (Prosser and Slade, 1994). Thus, widespread incision is not a phenomenon exclusive to the post-European settlement historical period.

One difficulty in estimating sediment load from incised catchments is that incision typically evolves through well-recognised stages, with the rate of sediment release varying through time. The classic Channel Evolution Model (CEM) of Schumm et al. (1984) (Figure 3) describes five stages of channel response, with the changes occurring at a point over time, or as a spatial process whereby the five stages could be distributed within a catchment. Incision is inherently self-healing because after the bank erosion phase begins, widening results in lower bed shear stress, which is followed by bed aggradation. A cycle would typically take in the order of 1000s of years to complete, with incision expected to occur rapidly and episodically, and aggradation slowly and incrementally.

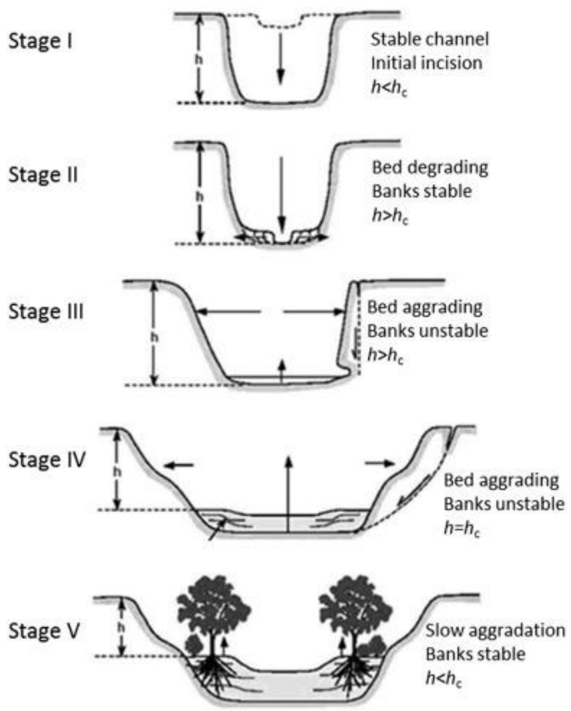

Figure 3. Channel Evolution Model (CEM) of Schumm et al. (1984). *h* is bank height and h_c is critical bank height for mass movement. Source: Thompson et al. (2016).

In the SedNet model, which formed the basis of sediment modelling undertaken for the NLWRA (Prosser et al., 2001a, 2001b), it was assumed that half the sediment derived from riverbank and gully erosion contributed to the bedload budget and the other half contributed to the suspended load budget (Hughes et al., 2003). The estimated total supply of bedload to a river link was compared to sediment transport capacity of the link, which was a function of the river width, slope, discharge, particle size of sediment and hydraulic roughness of the channel. If the sediment load was in excess of transport capacity, the excess was deposited and the yield to the link immediately downstream equalled the sediment transport capacity. If the loading to the outlet was less than the sediment transport capacity there was no net deposition in the link. Bedload transport was evaluated for particles with a mean diameter of 2 mm (i.e. upper size range of sand), as this corresponded with the average size of bed material observed in typical sediment slug deposits in Australian rivers (Hughes et al., 2003). In five catchments draining to Westernport Bay, Victoria, all having extensive sand slugs formed in historical times due to accelerated post-European erosion, bed load made up 21 – 25% of the total load for four catchments and 42% for one. Estimated total yield varied over the range 0.20 – 0.61 t/ha/yr for the five catchments.

2.5.2 Estimation of Sediment Yield Based on Catchment Similarity

On the basis of the above review of sediment yield modelling, it was concluded that whilst data and modelling tools were available to model the sediment yield of Yorks Creek, given the lack of empirical sediment load data for calibration, all methods would produce uncertain results. The alternative method employed here was to map existing predicted sediment yield from catchments adjacent to Yorks Creek modelled in the river basin sediment budget component of the National Land and Water Resources Audit (Prosser et al., 2001a, 2001b). From the values of sediment yield associated with these catchments, the most appropriate value for Yorks Creek was selected on the basis of similarity of the catchments with Yorks Creek catchment in terms of the attributes:

- Topography
- Geology
- Soil characteristics
- Land cover
- Gully and stream bank erosion density

This spatial data comparison was supported by field observations made on a walk of the entire length of Yorks Creek, including determination of bed material particle size distribution.

3.0 Results

3.1 Field measured variables

3.1.1 Cross-Sectional Dimensions

The field measurements revealed Yorks Creek to have a trapezoidal shape with low width-to-depth ratio and steep banks (Table 2). The channel was more variable in width than depth (Table 2).

Table 2. Results of Yorks Creek field channel dimension measurement

Sample reach	Mean (m)	Std dev (m)	1 Std dev range (m)	2 Std dev range (m)
Bed width				
1	2.2	0.4	1.8 - 2.6	1.3 - 3.1
2	3.5	1.3	2.2 - 4.8	1.0 - 6.0
3	1.7	0.4	1.3 - 2.1	0.9 - 2.5
4	1.5	0.3	1.3 - 1.8	1.0 - 2.0
5	1.9	0.4	1.5 - 2.3	1.1 - 2.8
6	2.6	0.8	1.7 - 3.4	0.9 - 4.2
Bankfull width				
1	4.9	1.2	3.8 - 6.1	2.6 - 7.3
2	19.9	8.5	11.4 - 28.3	2.9 - 36.8
3	5.7	0.9	4.8 - 6.7	3.9 - 7.6
4	4.5	0.8	3.7 - 5.2	2.9 - 6.0
5	5.7	1.2	4.5 - 6.9	3.2 - 8.1
6	5.1	1.2	3.9 - 6.3	2.7 - 7.4
Bankfull depth				
1	1.3	0.2	1.1 - 1.5	0.8 - 1.8
2	3.3	0.9	2.4 - 4.2	1.5 - 5.1
3	2.3	0.5	1.8 - 2.7	1.3 - 3.2
4	2.3	0.3	2.0 - 2.6	1.6 - 2.9
5	2.3	0.3	2.0 - 2.6	1.7 - 2.9
6	2.1	0.3	1.8 - 2.4	1.6 - 2.7
Mean bank angle (degrees) - calculated				
1	44			
2	22			
3	48			
4	57			
5	51			
6	59			

3.1.2 Large Wood Density and Dimensions

The field measurements revealed Yorks Creek to have a variable density of mostly small diameter large wood, with the majority of items spanning the full channel width and forming jams (Table 3). Wood that did not span the full channel width averaged 3 m in length, and ranged 1.2 – 9.0 m in length. Jams comprised up to 6 items of wood. The large wood in the channel reflected the riparian vegetation source material, which mostly comprised small to moderate-sized casuarina trees. The exception was the Yorks Creek Original Diversion reach (Sample reach 2), which had very little wood present (Table 3). A number of imported angular boulders up to 1 m diameter were present in the bed in this reach.

Table 3. Results of Yorks Creek field large wood measurement

Sample reach	N (items counted)	Density (items per 100 m)	Mean diameter (mm)	Std dev diameter (mm)	% of items full width	% of items in jam
1	19	18	213	90	84%	37%
2	2	1	210	14	0%	0%
3	21	15	171	79	90%	67%
4	18	12	187	67	61%	89%
5	24	15	215	100	65%	67%
6	7	4	204	75	100%	100%

3.1.3 Bed Materials and Channel Stability

Yorks Creek bed material was dominantly cohesive silty-sand, with gravel present. Bowmans Creek (Sample reaches 7 and 8) had a cobble bed (Table 4). All channels were considered relatively stable. No knickpoints were observed and the riparian zones were well covered by grass and/or trees. Yorks Creek had steep banks, but the material was cohesive and fortified by root mats (Table 4). Bowmans Creek banks showed no evidence of recent slumping or an unusual degree of fluvial erosion.

Table 4. Results of assessment of bed material and channel stability

Sample reach	Bed material presence					Channel stability		
	Silt/clay	Sand	Gravel	Cobble	Dominant	Bed knickpoints	Riparian vegetation cover	Bank shrub/tree root mats
1	Yes	Yes	Yes	Little	Gravel	No	Grass/trees	Yes
2	Yes	Yes	No	No	Silt-sand	No	Grass/trees	Yes
3	Yes	Yes	Yes	No	Silt-sand	No	Grass/trees	Yes
4	Yes	Yes	Yes	No	Silt-sand	No	Grass/trees	Yes
5	Yes	Yes	Yes	No	Silt-sand	No	Grass/trees	Yes
6	Yes	Yes	Yes	Yes	Gravel	No	Grass/trees (narrow)	Yes
7	Little	Yes	Yes	Yes	Cobble	No	Grass/trees (narrow)	Variable
8	Little	Yes	Yes	Yes	Cobble	No	Grass/trees	Variable

3.2 Historical Channel Alignment Change

The available aerial photography did not show evidence of significant natural changes (exceeding detectable limit of 30 m) in channel alignment between 1958 and 2018 for both Bowmans Creek and Yorks Creek (Figure 4).

However, a 1.46 km long section of Yorks Creek was artificially replaced with a 1.39 km length diversion channel some time since mining began (Figure 4).

There is no evidence in the available aerial photography that the Yorks Creek Original Diversion was constructed on mine infill. The 1983 and 2002 photographs indicate that the current diversion channel alignment was established at those times (Figure 5). The location of the open cut mining pit varied in the 1983, 2002 and 2018 photographs, but did not impinge on the current alignment of the diversion channel (Figure 5). According to NSW Department of Planning and Environment (2015, p.3), the Ravensworth East mine (formerly the Swamp Creek Mine operated by Hebden Mining Company until 1991), which covers the area in question, commenced operations in the 1960s. Historical aerial photography from 1967 indicates that while Liddell Coal Operations Mine to the north-west had commenced operation, the area to become Swamp Creek Mine was still grazing land (Figure 4). The 1983 and 2002 photographs suggest that the alignment of Hebden Road was maintained through time, with open cut pits flanking the road. The course of Yorks Creek appears to have been diverted between the pits, close to Hebden Road and the mine infrastructure area. Nevertheless, it is possible that Yorks Creek in this area was mined and infilled prior to 1983.

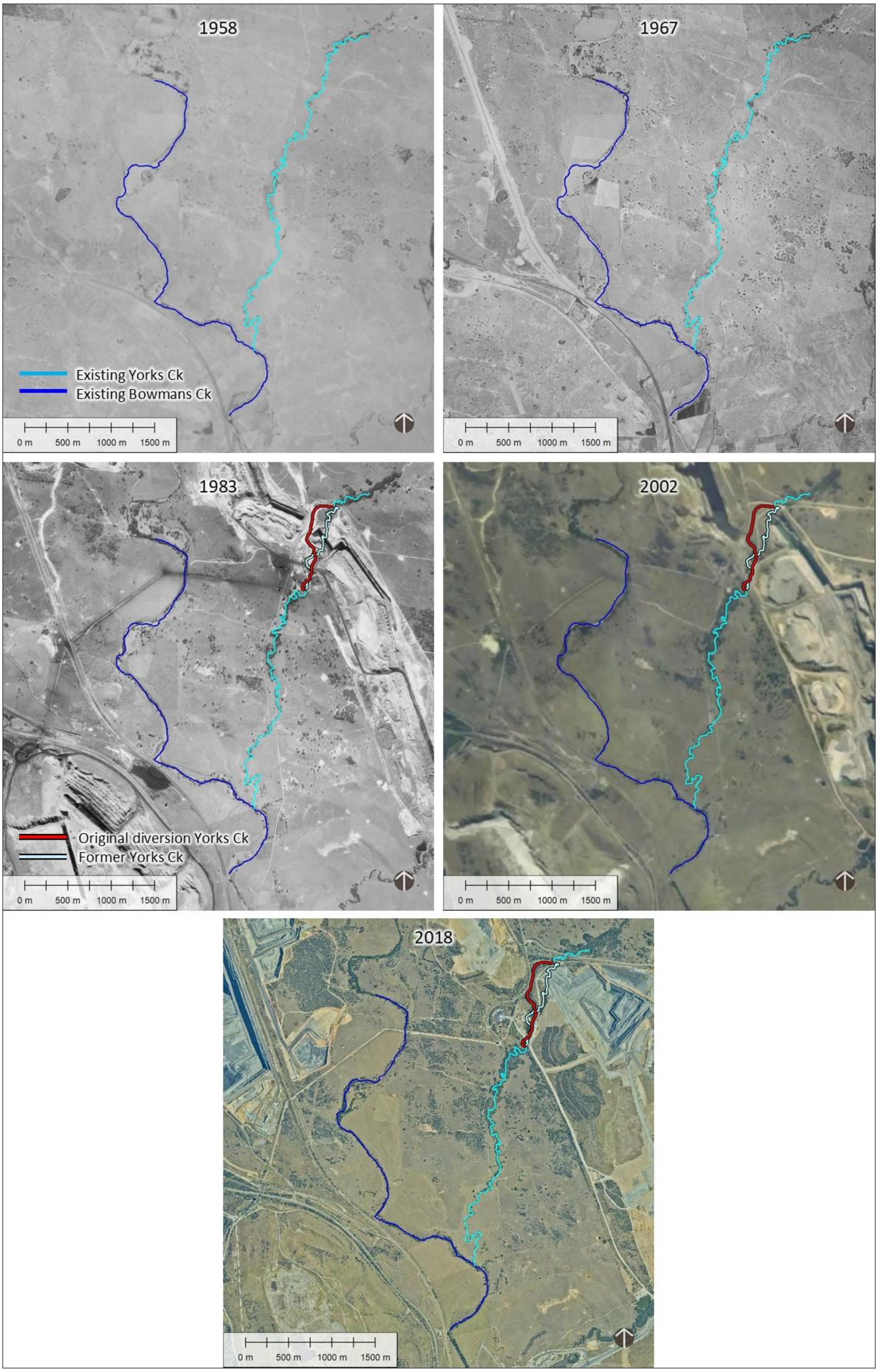

Figure 4. Historical aerial photography showing channel position.

Figure 5. Historical aerial photography showing detail of original diversion of Yorks Creek.

3.3 Terrain analysis – Yorks Creek

3.3.1 Longitudinal Profile Slope and Sinuosity

Yorks Creek had a relatively even bed slope along its length (Figure 6). The slope measured from linear regression through smoothed 1 m-spaced bed elevation data revealed the natural channel was steeper in the reach Upstream of the Mine than the reach Downstream of the Haul Road, with the Original Diversion reach having a slope midway between these two reaches (Table 5).

The sinuosity of Yorks Creek channel Upstream of the Mine was classed as ‘sinuous’ (1.3 – 1.5), the Original Diversion reach was classed as close to ‘straight’ (1.0 - 1.1), and Downstream of the Haul Road was classed as ‘meandering’ (>1.5) (Table 5).

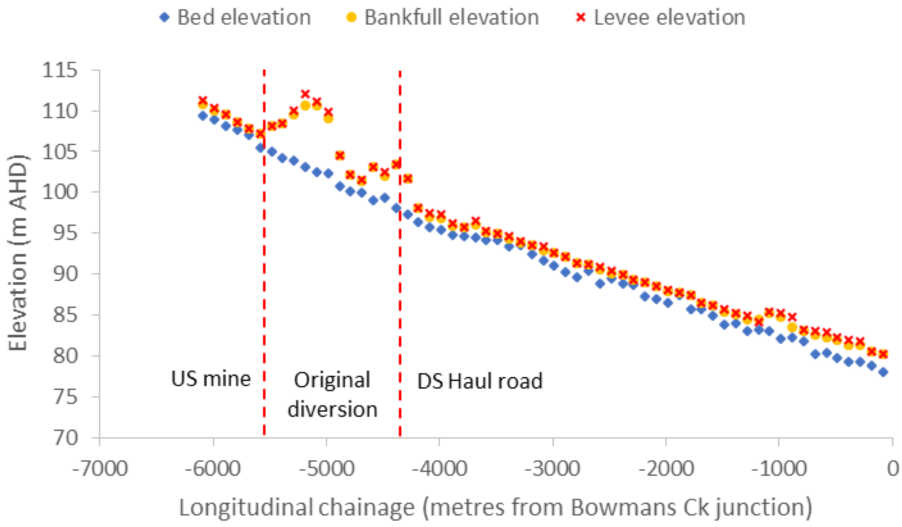

Figure 6. Yorks Creek downstream elevation at 100 m point spacing, from LiDAR-based DEM.

Table 5. Measured valley and channel slope, and sinuosity, of Yorks Creek.

Reach	Valley slope	Channel slope (fall V in H)	Sinuosity
US Mine (US Mount Owen Access Road)	0.01213	0.00926 (1 in 108)	1.31
US Mine (DS Mount Owen Access Road)	0.01327	0.01013 (1 in 99)	
Original Diversion	0.00691	0.00604 (1 in 166)	1.14
DS Haul Road to Bowmans Creek	0.00704	0.00453 (1 in 221)	1.55

3.3.2 Cross-Sectional Dimensions

The resolution of the LiDAR data was such that at most locations the bed of Yorks Creek was depicted by a single point. The exceptions were in a few wider locations, mostly in the Original Diversion reach, where the bed was depicted by two points (Figure 7). Width at the interpreted morphological bankfull level and the levee crest level was highly variable (Figure 7). The interpreted corridor width (valley wall to valley wall) was also highly variable, but noticeably widened downstream of the Haul Road (Figure 7). Channel depth was less variable than width, with most values around 2 m or less, except in the Original Diversion reach, which was noticeably deeper (Figure 7).

The channel morphological dimensions measured from the LiDAR-based DEM were summarised for each reach using mean and standard deviation (Table 6).

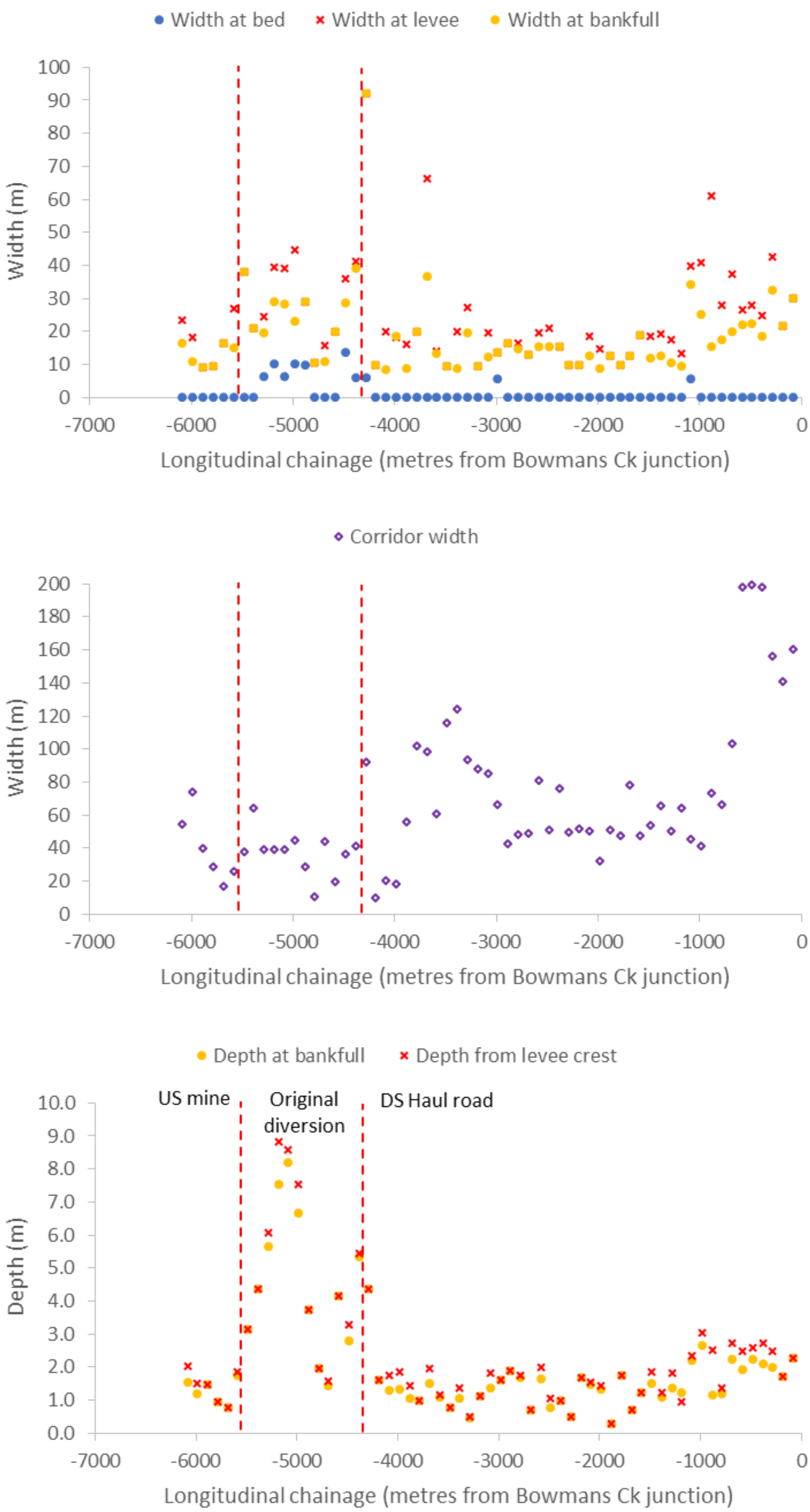

Figure 7. Yorks Creek downstream widths and depths at 100 m point spacing, from LiDAR-based DEM.

Table 6. Statistical summary of Yorks Creek morphology measured at 10 m spaced transects from LiDAR-based DEM.

Reach	Width Mean (Std dev) (m)				Depth Mean (Std dev) (m)	
	At bed	At bankfull	At levee	Corridor	At bankfull	At levee
US Mine	-	12.9 (3.5)	17.3 (7.2)	39.8 (21.1)	1.3 (0.4)	1.4 (0.5)
Original Diversion	9.0 (2.9)	24.7 (9.1)	29.9 (11.4)	37.1 (13.3)	4.6 (2.2)	4.9 (2.4)
DS Haul Rd to Bowmans Ck	-	17.9 (13.6)	23.6 (16.5)	79.1 (47.3)	1.5 (0.7)	1.7 (0.8)

3.3.3 Longitudinal Bed Variability

The longitudinal bed morphology of Yorks Creek was variable in elevation, but was not classified as pool-riffle, as by definition, riffles are a characteristic of gravel and cobble bed streams, while Yorks Creek has a cohesive, fine-grained bed. Nevertheless, the channel was characterised by a sequence of shallow and deeper sections. The spacing of these features was highly variable, averaging approximately 7 – 8 m (low point to low point) in the undisturbed reaches, and somewhat longer in the Original Diversion reach (Table 7). The fall in elevation from high to low points was highly variable, averaging approximately 0.3 – 0.4 m in the undisturbed reaches, and slightly less in the Original Diversion reach (Table 7). A few of the downstream height differentials exceeded 1 m, but most represented subtle variation of the bed levels.

Table 7. Statistical summary of Yorks Creek longitudinal bed profile variability measured at 1 m spacing from LiDAR-based DEM.

Variable	Statistic	US Mine	Original diversion	DS Haul Road
Frequency of low/high points	Points per 100 m	13	10	14
Spacing of low points	Mean	7.6	9.5	7.1
	Standard deviation	3.5	5.1	3.7
	90 th-percentile	12.5	15.0	11.7
	10 th-percentile	4.0	4.8	3.7
	99 th-percentile	17.1	27.8	19.7
Fall in elevation, high to low points	Mean	0.33	0.29	0.43
	Standard deviation	0.22	0.24	0.37
	90 th-percentile	0.65	0.57	1.01
	10 th-percentile	0.06	0.05	0.08
	Maximum	0.90	1.30	1.96

3.4 Downstream Variation in Channel Morphology of Bowmans Creek

The bed profile of Bowmans Creek was variable, which manifested in the field as a series of pools separated by shallow flow over riffles or hyporheic flow. Interpreted low bench, mid-bench and bankfull levels were highly variable in the downstream direction, although the elevation of the modelled 10 yr ARI flood water surface was less variable (Figure 8). Channel width and depth variables were variable, but displayed no apparent downstream trend, except for a section of channel about 0.5 km downstream of the confluence of proposed diversion. This section of channel, about 800 m long, was wider and shallower than the rest of Bowmans Creek in the Study Area. The 1958 aerial photograph shows this section bare of vegetation and covered in sand, so it was possibly disturbed by the record flood in Feb 1955.

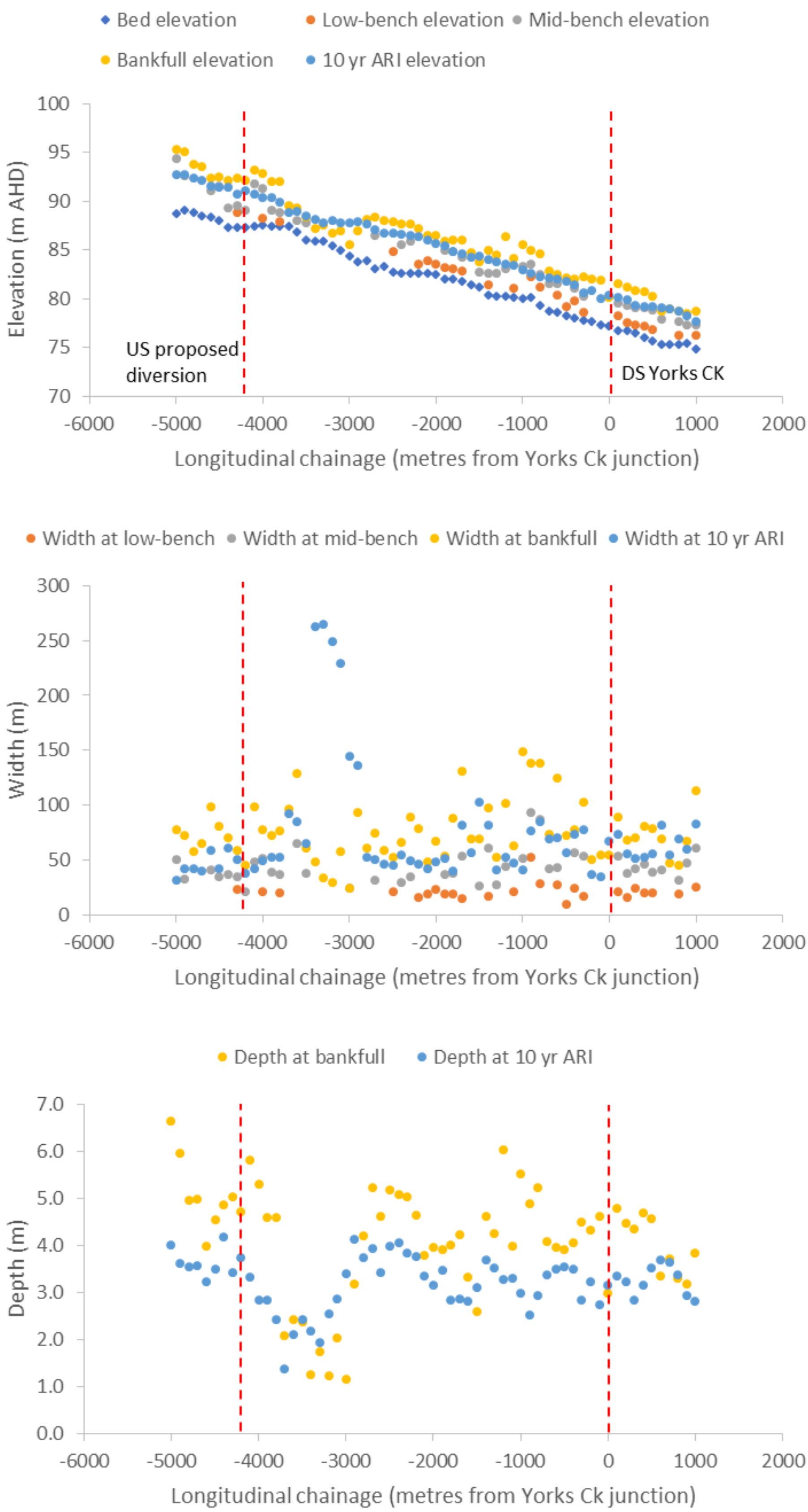

Figure 8. Bowmans Creek downstream morphology at 100 m point spacing, from LiDAR-based DEM.

The depth and width data were divided into three reaches: (1) Upstream of the proposed diversion, (2) Between the proposed diversion and Yorks Creek, and (3) Downstream of Yorks Creek. A two-sample t-test for difference in means was applied, assuming unequal variances. This test revealed that the bankfull depth was significantly wider ($\alpha = 0.05$) upstream of the proposed diversion than for the two reaches downstream of the proposed diversion (Table 8), but width was not significantly different between the three reaches (Table 9). This result indicates that Bowmans Creek was not markedly wider or deeper in response to the additional flow from Yorks Creek. This implication of this is that the location of the Diversion confluence with Bowmans Creek is not constrained by the existing morphology of the Creek.

Table 8. Statistical t-test of difference in means of depth at bankfull level.

Reach	Between the proposed diversion and Yorks Creek	Downstream of Yorks Creek
Upstream of the proposed diversion	Significantly different	Significantly different
Between the proposed diversion and Yorks Creek	-	Not significantly different

Table 9. Statistical t-test of difference in means of width at bankfull level.

Reach	Between the proposed diversion and Yorks Creek	Downstream of Yorks Creek
Upstream of the proposed diversion	Not significantly different	Not significantly different
Between the proposed diversion and Yorks Creek	-	Not significantly different

3.5 Yorks Creek Sediment Yield and Load

3.5.1 Catchment and Drainage

The Yorks Creek catchment was subdivided into three catchments that will form the final landform of the Mount Owen Continued Operations (MOCO) Project (Figure 9):

- Yorks Creek natural catchment,
- the approved Swamp Creek catchment diversion to Yorks Creek, and
- the Mount Owen Mine Rehabilitation area

Yorks Creek currently comprises only the natural catchment, but this Technical Report assessed the future landform scenario.

Under the future scenario, when the Swamp Creek catchment diversion and the Mount Owen Mine Rehabilitation area are connected to Yorks Creek, the runoff will enter Yorks Creek just upstream of Mount Owen Mine access road via the most downstream left bank tributary (WSP 2017a, Fig 3-1, p. 6). Depending on the design of the inflow channel and any creek fortification and rehabilitation works that might be undertaken, this additional flow could impact the morphology and sediment transport processes in Yorks Creek downstream of the inflow point. The geomorphic response with the highest likelihood would be increased channel width and depth, particularly in the tributary, but also in Yorks Creek downstream of the tributary (although some of this reach has already been fortified with rock). Any channel erosion would release additional suspended and bed sediment load to Yorks Creek, and the additional flow would increase sediment transport capacity of the creek. Overall, in the short-term, until the creek adjusted to the modified flow regime, sediment load delivered to the proposed diversion would be higher than that estimated in this Technical Report, which does not account for these potential channel adjustment processes. Of relevance to this issue are dams on the former Swamp Creek tributaries north of Mount Owen which will trap a significant proportion of the coarse fraction of sediment transported from their catchments.

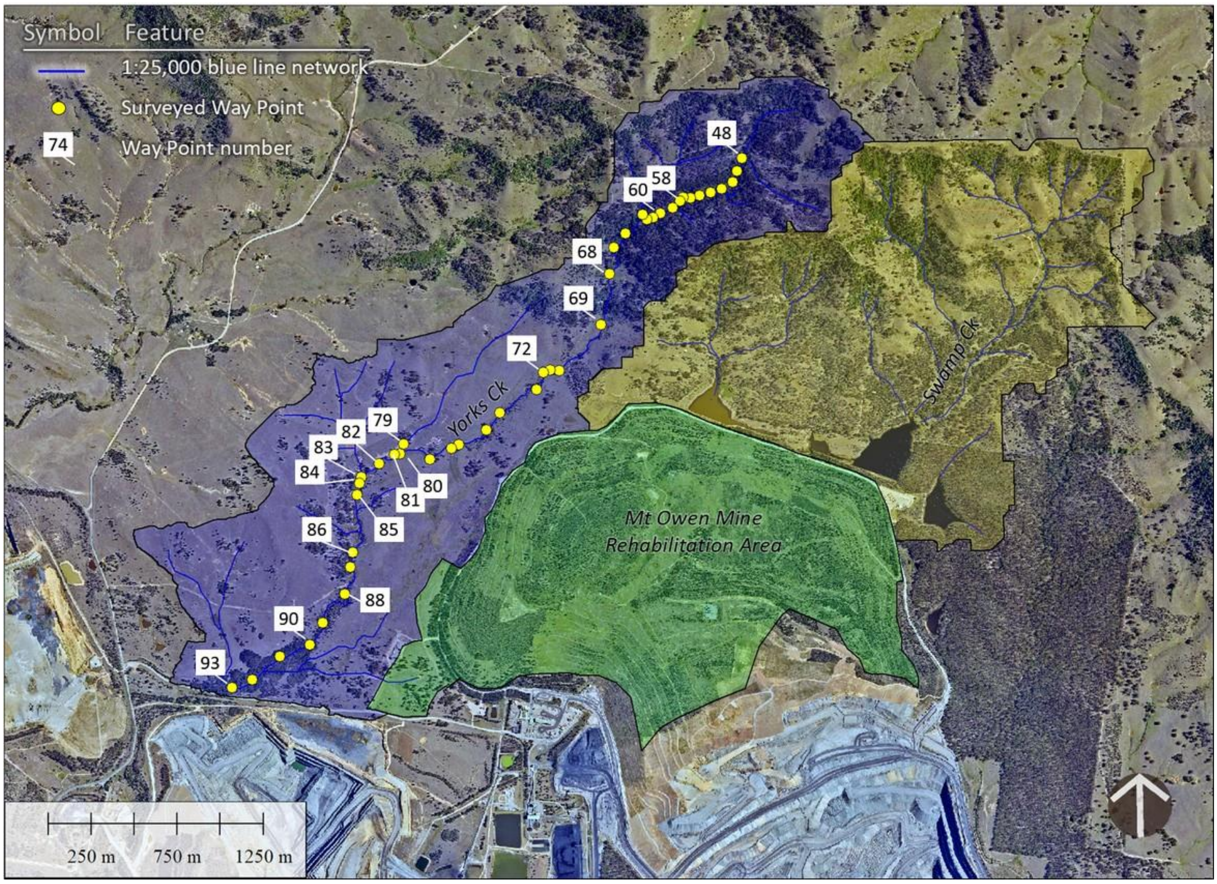

Figure 9. The three catchments comprising Yorks Creek drainage system under the MOCO Project future scenario. All Way Points (WP) recorded during the field inspection are indicated, with numbered WPs referred to in the text of this report.

3.5.2 Topography, Geology and Soils

The Study Area ranged in elevation from 110 to 446 mAHD (Figure 10). The headwaters were characterised by steep slopes, with the creek channel having cobble/boulder-sized bed material and occasional cascades and waterfalls formed in lengths of exposed bedrock, with examples at WP 58 and WP 60 (Figure 9) (Figure 11). The mid-reaches of Yorks Creek flowed over a relatively low gradient plain, with the lower reaches skirting the base of a low hill to the west. Swamp Creek catchment was mostly steep and hilly landform, with the Mount Owen Mine Rehabilitation Area (not complete at the date of elevation data capture depicted in Figure 10) having a formed domed hill morphology (Figure 10). The dams in Swamp Creek catchment that abut the Overburden emplacement areas will act as sediment detention basins in the landform over the long term. There is no intention to remove them, so they will gradually silt up over time. By the time this occurs, the landform would be more stable.

The geology of the study area comprised two units, the Permian Saltwater Creek Formation (mainly mudstone) in the headwaters and the Carboniferous Seaham Formation (mainly sandstone) in the mid- and lower catchment (Figure 12). These two units are separated by a fault, which manifests as a 2 m high rock knickpoint in Yorks Creek (WP 72, Figure 9) (Figure 13). The geology of the Study Area would provide material of a range of particle sizes in weathered and eroded parent rock material, from silts and clays in the mudstone, sand in the sandstone, gravel and cobbles in the conglomerate, and cobble- and boulder-sized material in fractured and weathered bedrock subject to mass movement in the headwaters.

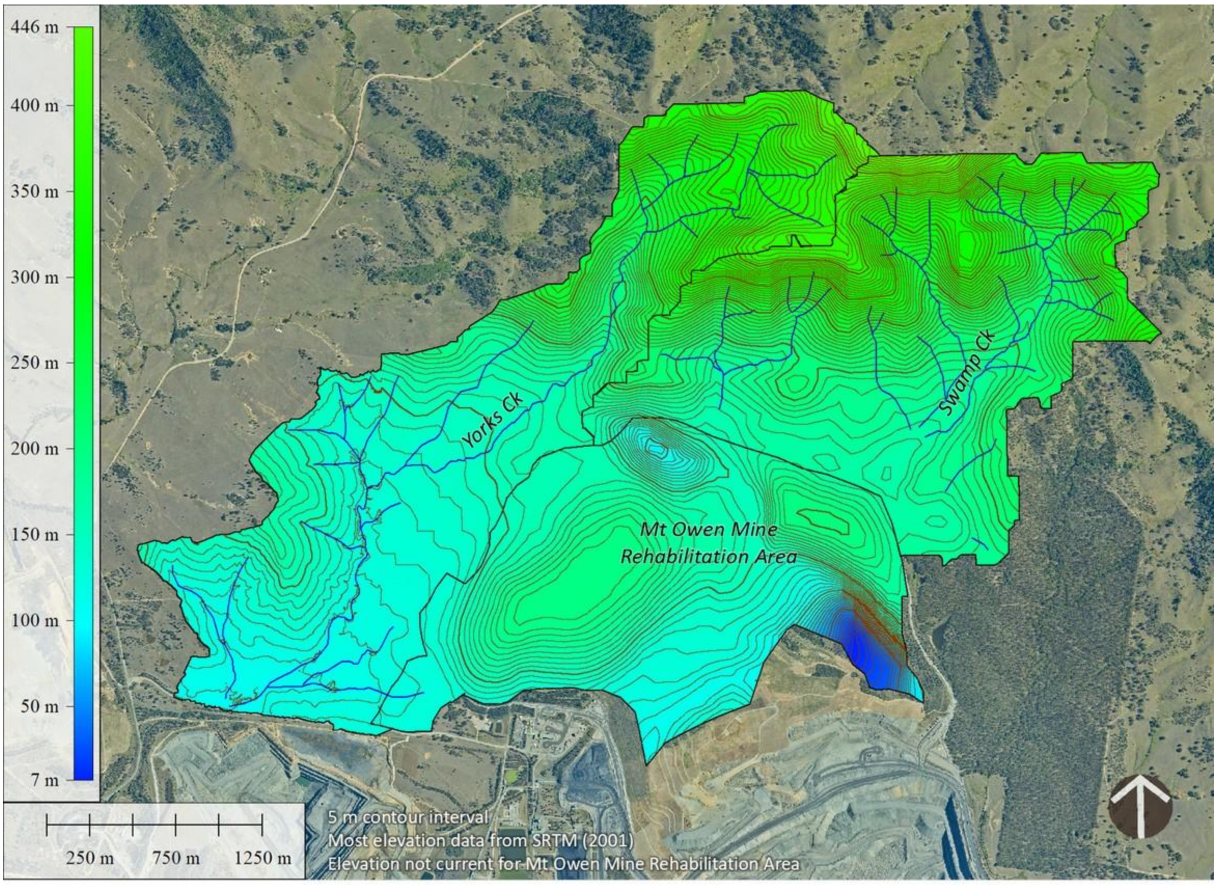

Figure 10. Topography of Yorks Creek catchment upstream of the proposed diversion.

Figure 11. Waterfall 4.5 m high in Yorks Creek at WP 58, and cascade with 6 m fall at WP 60.

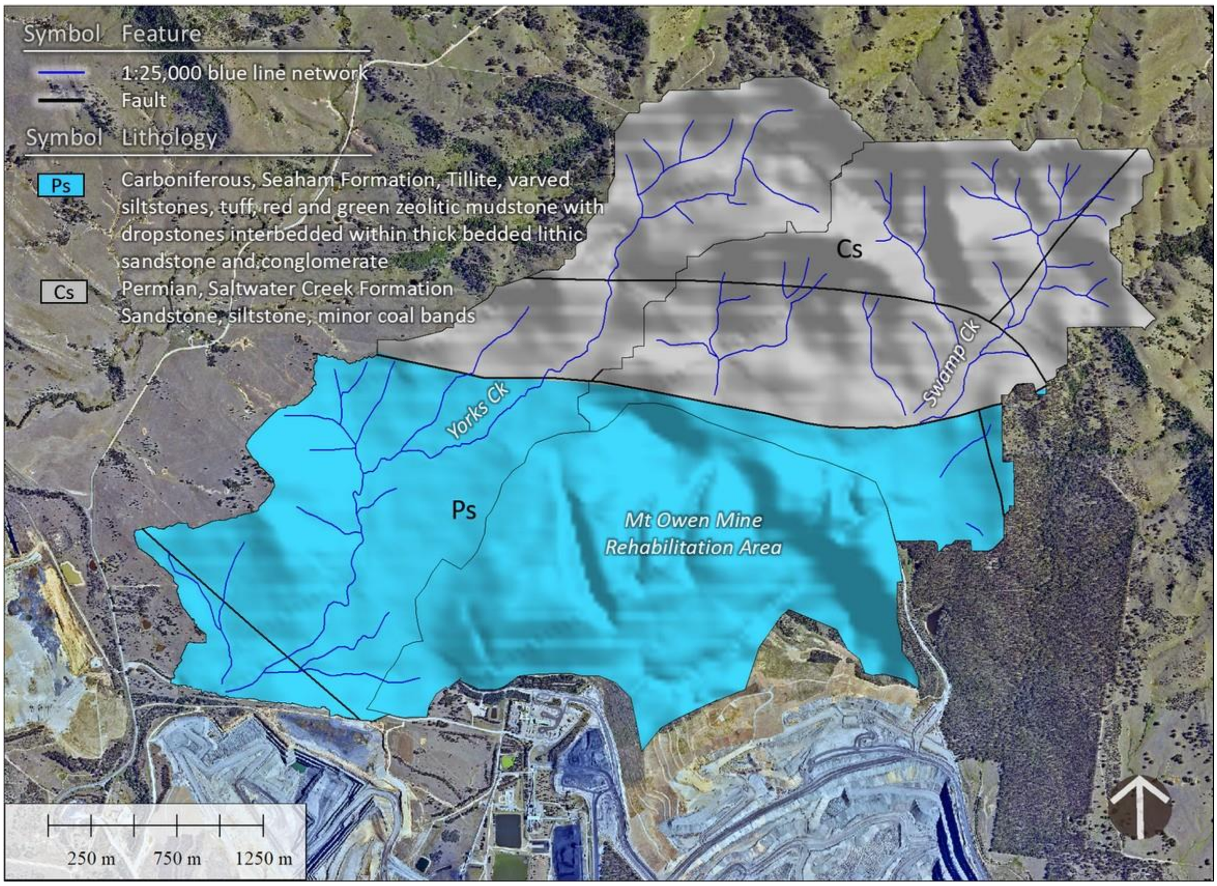

Figure 12. Geology of Yorks Creek catchment upstream of the proposed diversion.

Figure 13. Rock knickpoint in Yorks Creek at fault line, WP 72.

The distributions of the two Soil Landscapes are closely related to topography and geology (Figure 14). The Rosevale Soil Landscape would generate relatively low sediment yields due to the generally low erodibility of the soil types and high coverage of vegetation protecting the soils from erosion hazard. Some mass movement would be expected in the steeper slopes of this Soil Landscape (Table 10). The Bayswater Soil Landscape has potential to generate significant sediment yields due to the generally high erodibility and erosion hazard associated with the Yellow Solodic and Alluvial soil types in particular (Table 10).

The distributions of the Soil and Land Resources units was strongly related to topography and also geology (Figure 15). Streambank erosion hazard was not observed across the entire Study Area, but sheet erosion hazard was ubiquitous (Table 11). Localised gully erosion hazard was present in Ravensworth, Gundy Gundy and Waverly units, but widespread in Isis unit (Table 11). The start of the Isis unit is mapped about 500 m upstream of the fault at WP 72, at WP 69 (Figure 9). Here the channel gradient starts to decline, and flows within sloping valley sides with occasional exposed cobble-sized weathered colluvial material in the banks (Figure 16).

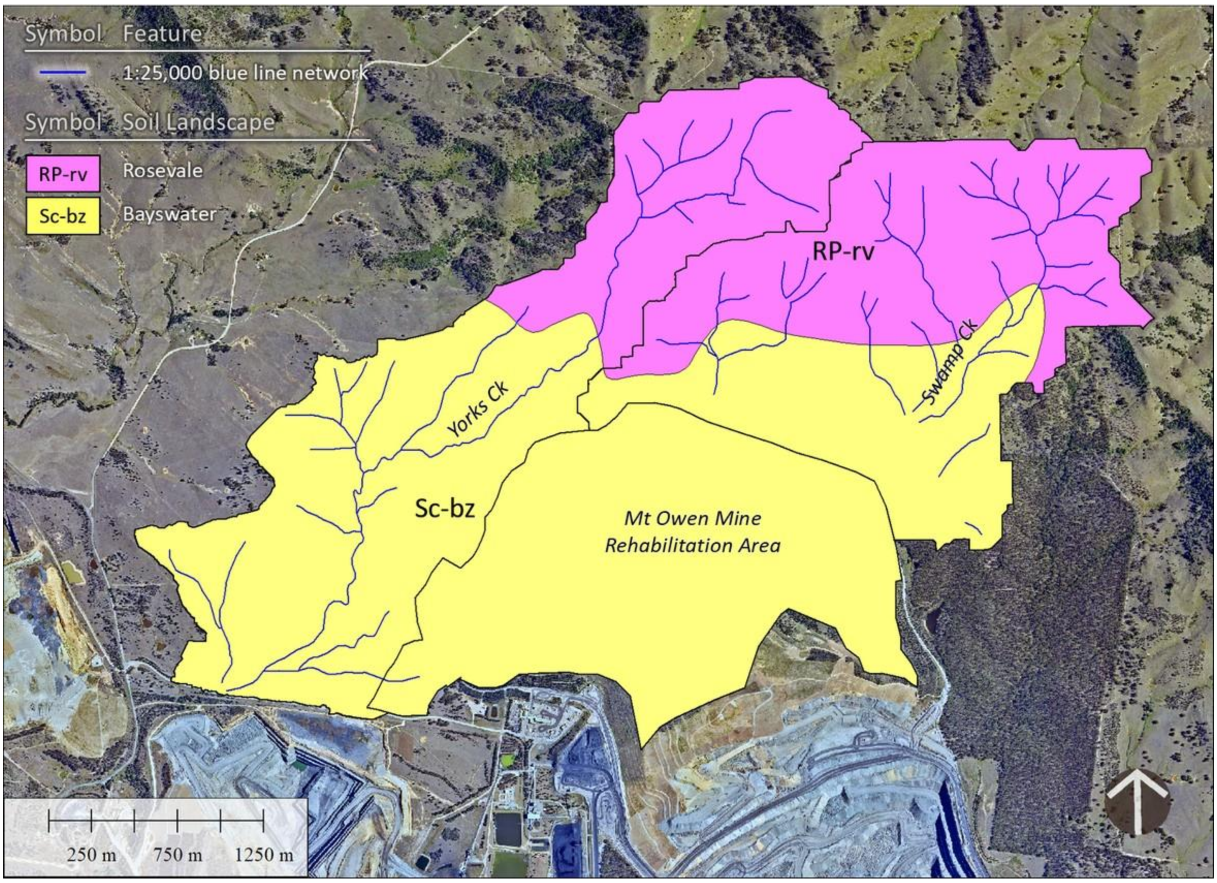

Figure 14. Soil Landscapes of Yorks Creek catchment upstream of the proposed diversion. The classification of the artificially formed Mount Owen Rehabilitation Area is likely to be incorrect.

Table 10. Erosion characteristics of the Soil Landscape units of Yorks Creek catchment.

Soil Landscape	Soil Profile Types	Erodibility and erosion hazard
Bayswater	The main soils are Yellow Solodic and Yellow and Brown Podzolic soils occurring on slopes, and Alluvial Soils in drainage lines.	Moderate sheet and gully erosion is common on slopes. Gullies (to 3 m) are associated with the highly erodible Yellow Solodic soils, which present a very high to extreme erosion hazard. Salt scalds and associated erosion are common in some areas. Alluvial soils have moderate erodibility and very high erosion hazard.
Rosevale	The main soils are Red and Brown Podzolic Soils on the upper to lower slopes and on the steeper sections of footslopes of the Isismurra and Woolooma Formations. Yellow Soloths occur on midslopes and Euchrozems also occur on upper slopes. Rock outcrop is common.	Minor to moderate sheet erosion on cleared areas. Some mass movement on steeper slopes. Erodibility of all soil types are low or moderate. Erosion hazard is very high for the minor soil types Brown Earths, Shallow Sands (Lithosols).

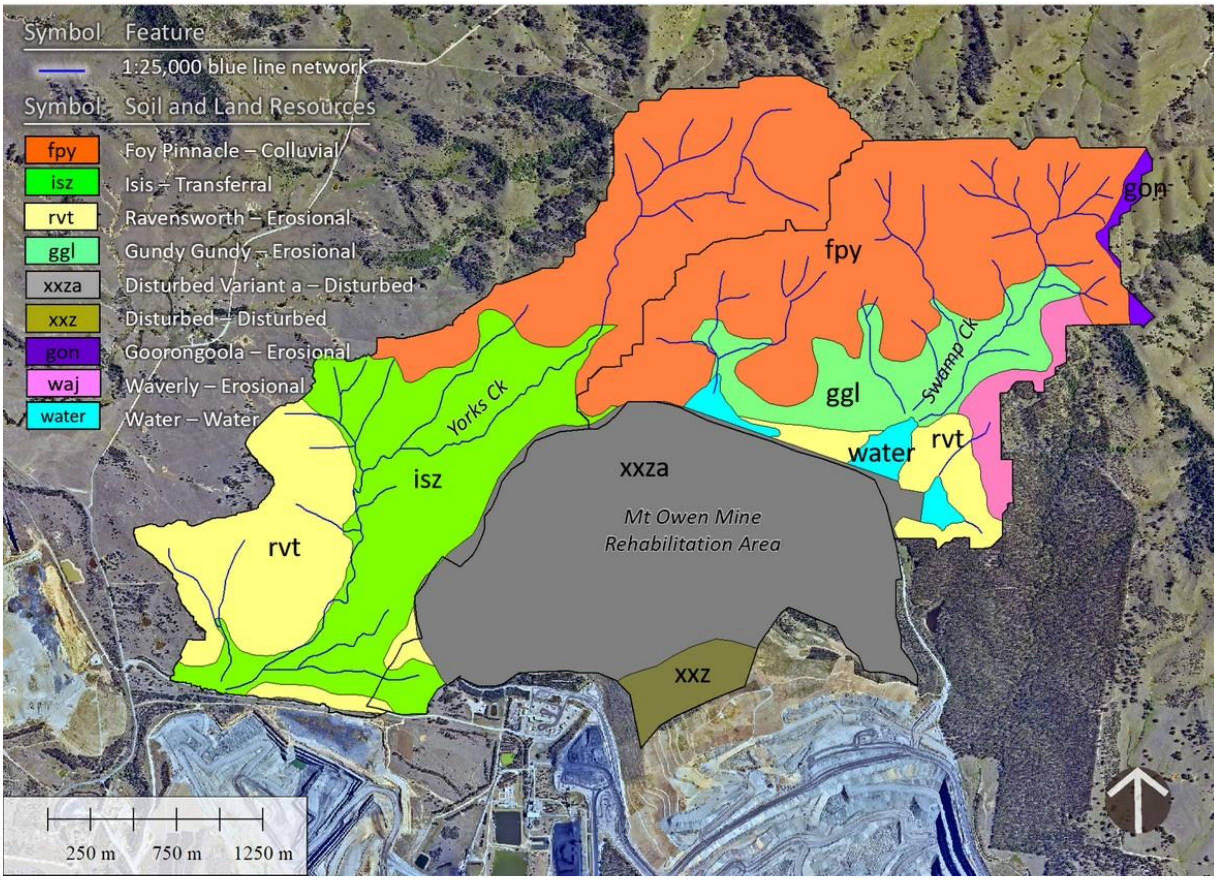

Figure 15. Soil and Land Resources of Yorks Creek catchment upstream of the proposed diversion.

Table 11. Observed water erosion hazards of the Soil and Land Resources units of Yorks Creek catchment. Water unit not included.

Soil and Land Resources unit	Erosion hazard type		
	Gully	Sheet	Streambank
Foy Pinnacle	Not observed	Widespread	Not observed
Isis	Widespread	Widespread	Not observed
Ravensworth	Localised	Widespread	Not observed
Gundy Gundy	Localised	Widespread	Not observed
Disturbed Variant a	Not assessed	Not assessed	Not assessed
Disturbed	Not assessed	Not assessed	Not assessed
Goorongoola	Not observed	Widespread	Not observed
Waverly	Localised	Widespread	Not observed

Figure 16. Yorks Creek at the transition from Foy Pinnacle to Isis Soil and Land Resources unit.

3.5.3 Land Cover

The GlobCover land cover categories were arranged in order from lowest risk of surface erosion (closed forest, open to closed forest, open forest, mosaic vegetation) to highest risk (shrubland, grassland, sparse vegetation, rainfed croplands and artificial surface). Land cover area was calculated for each category for the Yorks Creek catchments (Figure 17). With respect to land cover, Swamp Creek, with a high percentage of forest cover, had the lowest risk of surface erosion. Mount Owen Rehabilitation Area had the highest risk of surface erosion, and Yorks Creek natural catchment was in-between. Drainage from the Mount Owen Rehabilitation Area would not be released to the catchment until good ground vegetative cover is achieved, which would change its risk of surface erosion to low. The inclusion of this area, particularly the sparse/unvegetated area (approx. 40% or rehab area), in the erosion risk assessment likely overstates the sediment load. Considering these three catchments combined, the land cover distribution was similar to that of the entire Bowmans Creek catchment, within which Yorks Creek is situated (Figure 18).

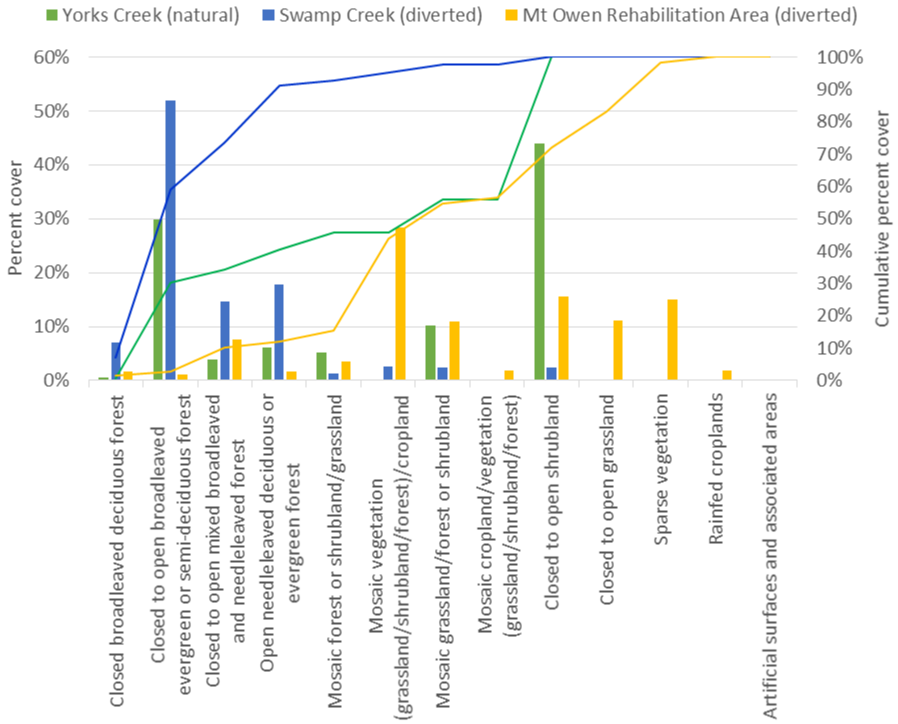

Figure 17. Percent and cumulative catchment area cover of the thirteen GlobCover land cover categories for the three Yorks Creek catchments. Categories arranged left to right in order from lowest to highest risk of surface erosion. Note that drainage from Mount Owen Rehabilitation Area would not be released to the catchment until good ground vegetative cover is achieved.

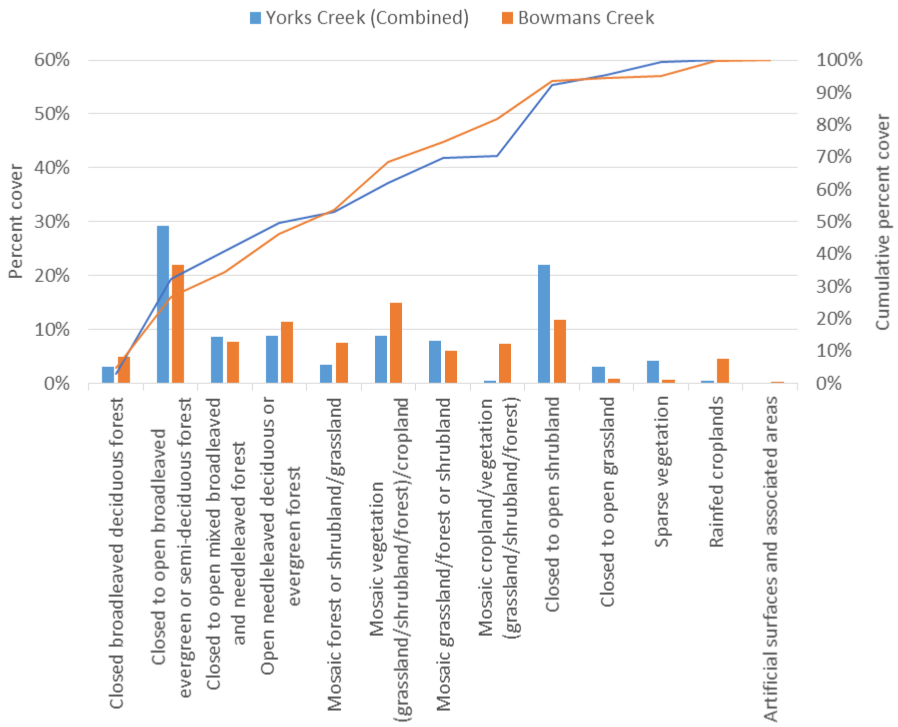

Figure 18. Percent catchment area cover of the 13 GlobCover land cover categories for the combined three Yorks Creek catchments compared with the entire Bowmans Creek catchment. Categories arranged left to right in order from lowest to highest risk of surface erosion.

3.5.4 Gullies and Streambank Erosion

Incised main channel and tributary gullies were observed in the field from WP 79, located 35 m upstream of the junction of a tributary of Yorks Creek. Here the channel had a 1.1 m knickpoint in uncohesive material, marking the upstream extent of a major gully system in lower Yorks Creek (Figure 19). A distance of 65 m downstream from the tributary knickpoint, at WP 81, in the main channel of Yorks Creek, another knickpoint 0.9 m high set in silt/clay bed material was observed (Figure 19). In this area, the channel was wide, with a flat bed filled with a deep deposit silt/clay material almost completely covered with stands of emergent macrophytes and grass (Figure 20). The banks at the outside edge of the incised channel were near vertical and showed evidence of erosion from local direct raindrop impact and floodplain runoff draining to the channel (Figure 20). Further downstream the incision showed evidence of older age, with less steep banks and more vegetation cover on the banks (Figure 21). At a distance downstream of about 1.1 km from the upstream boundary of the gully system, the incision was significantly infilled, had moderately sloping banks, and dense riparian, bank and channel vegetation (Figure 22), enhanced by revegetation efforts by Glencore.

The age of the incision in Yorks Creek was not determined, but aerial photographs from 1958 onwards suggest that the full extent of the gully system was established by 1958, and since that time it did not expand to any significant degree. The main change observed on the aerial photographs is increasing riparian vegetation cover over time (Figure 23). The evidence suggests that the incision in Yorks Creek is in the advanced stages of recovery in Schumm's CEM (Figure 3).

Figure 19. Upstream boundary of incised gully system in Yorks Creek.

Figure 20. Upper reach of incised gully system in Yorks Creek.

Figure 21. Mid-reach of incised gully system in Yorks Creek.

Figure 22. Lower-reach of incised gully system in Yorks Creek.

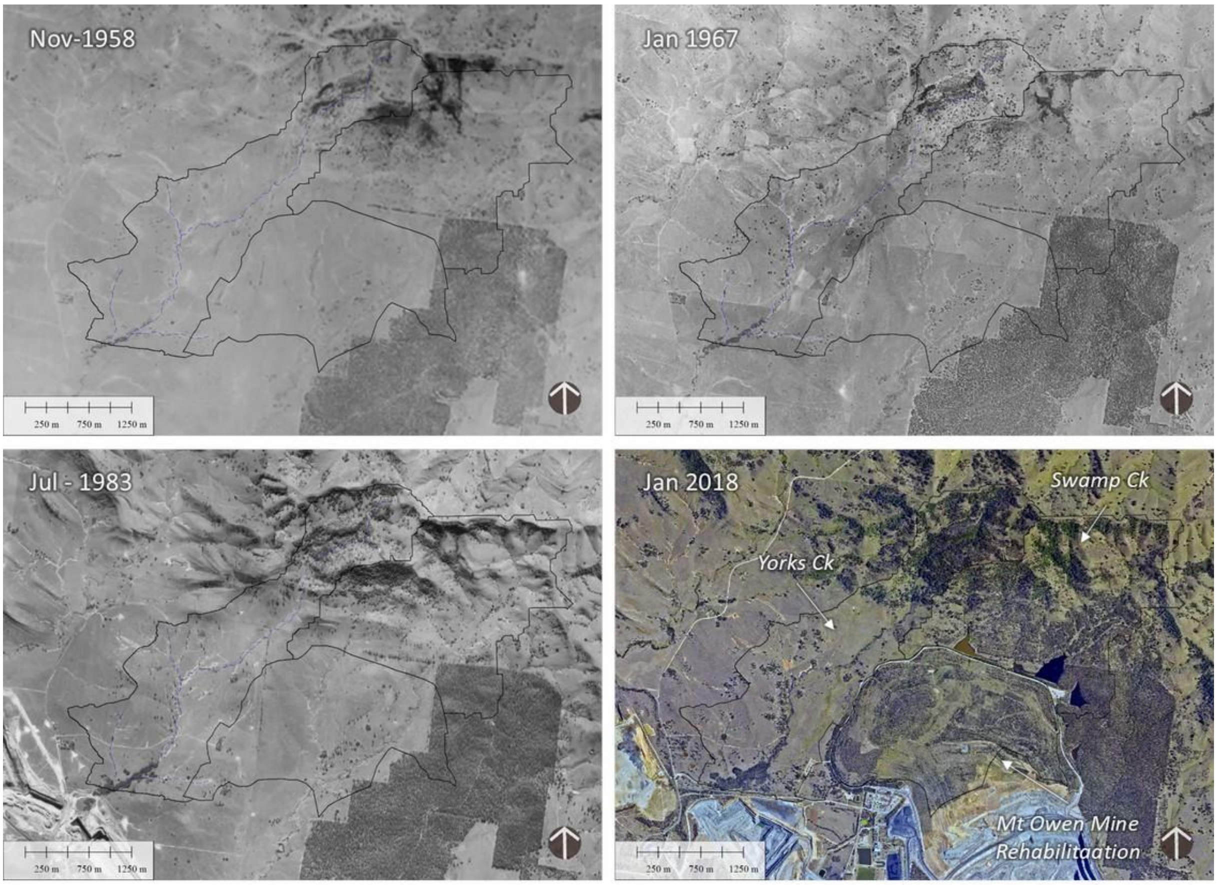

Figure 23. Historical aerial photography of Yorks Creek and ultimately reporting to the proposed Diversion.

Gullies and streambank erosion are widespread in the region of the Study Area (Figure 24). A comparison of the distribution of gully erosion severity in Bowmans Creek catchment and the natural Yorks Creek catchment revealed that Yorks Creek had a higher density of extreme gully erosion. Combining all categories of gully erosion, and assuming the future scenario of expanded Yorks Creek catchment area, the density of gullying in combined Yorks Creek catchment was 0.59 km/k^2, which is similar to the value of 0.64 km/k^2 for Bowmans Creek catchment.

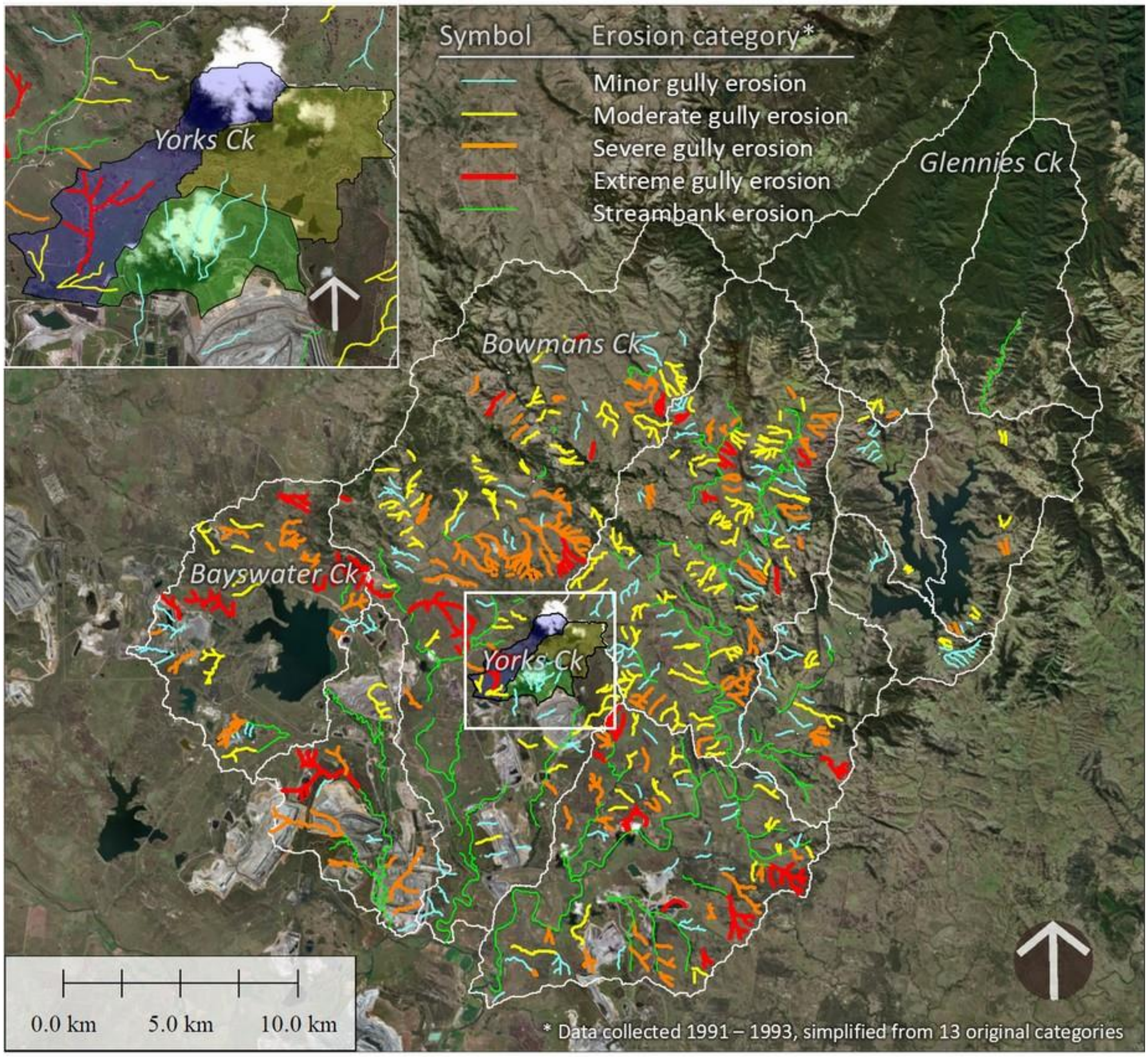

Figure 24. Simplified representation of the Gully and Streambank – Landform and Condition Dataset (OEH), mapped in 1991 – 1993, for Bayswater, Bowmans and Glennies creek catchments.

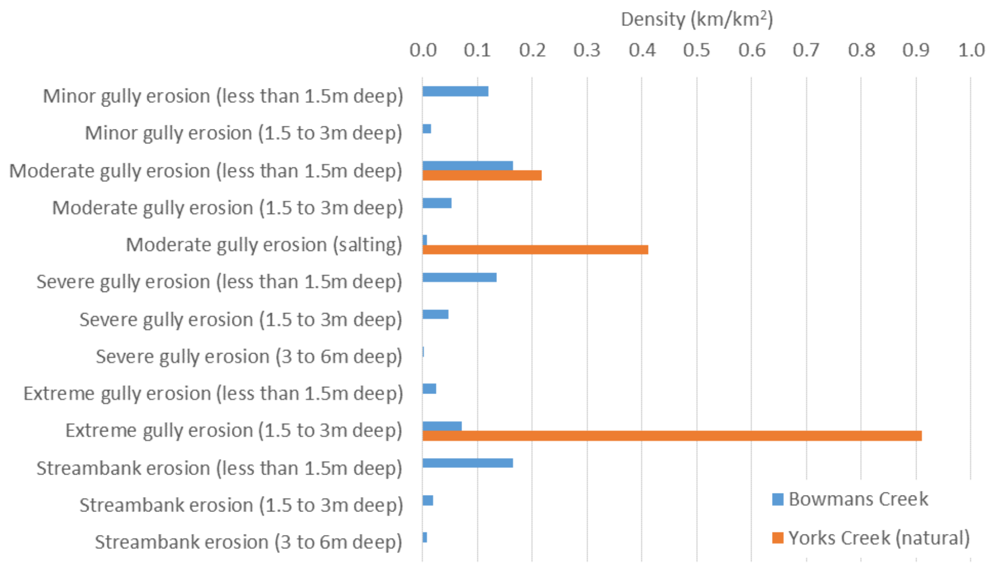

Figure 25. Distribution of all 13 categories of the Gully and Streambank – Landform and Condition Dataset (OEH), mapped in 1991 – 1993, for Bowmans and Yorks creek catchments. Erosion categories listed top to bottom in order of severity.

3.5.5 Estimated Sediment Yield

Modelled average annual sediment yield of catchments in the region of Yorks Creek Study Area revealed considerable variation over the range 0.047 – 3.335 t/ha/yr (Figure 26). This variability is mostly related to degree of disturbance, as the natural (pre-European) sediment yields were predicted to be fairly uniform across the region (Figure 26). Only one link in the region was predicted to have excess coarse sediment deposited on the bed: Bowmans Creek, with a depth of 0.1 m. The location of this aggradation was not detailed in the modelled data, but bed sediment aggradation was not observed in Bowmans Creek in the vicinity of Yorks Creek and further downstream, where the bed was gravel and cobble.

Given that Yorks Creek is similar to Bowmans Creek in two key factors that determine sediment yield, gully density and land cover, the modelled sediment yield for Bowmans Creek was considered applicable to Yorks Creek. This value, 1.264 t/ha/yr, is on the low end of the yield values measured by Mahmoudzadeh et al. (2002), Erskine et al. (2002) and Erskine et al. (2003), but these yields were regarded by the authors to be high by Australian standards. Assuming the future scenario with Yorks Creek draining its natural catchment plus the diverted Swamp Creek and Mount Owen Mine Rehabilitation Area catchments, the catchment area of 1289.8 ha would deliver to the proposed diversion, as a long-term average, 1630 tonnes per year.

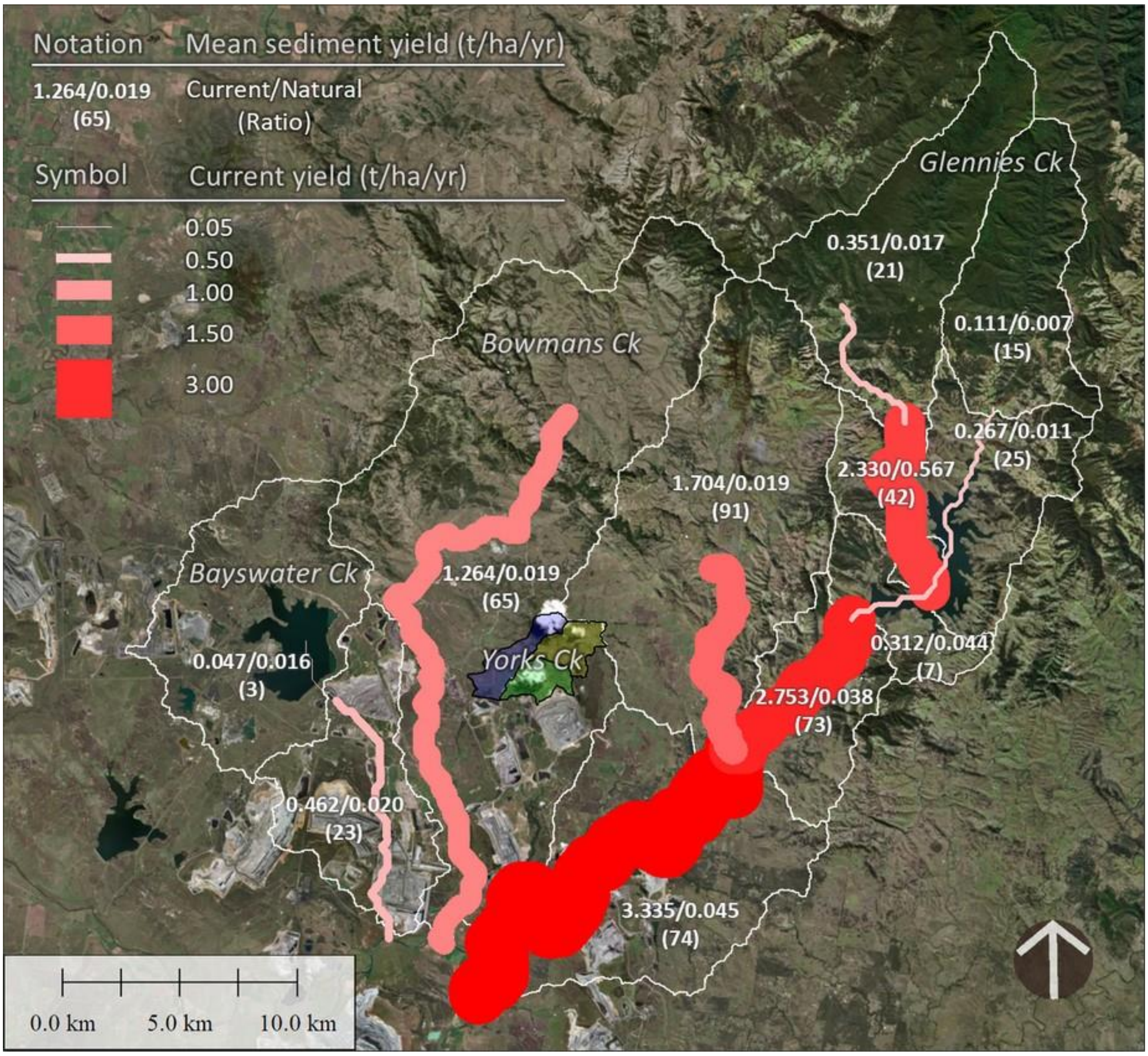

Figure 26. Mean annual sediment yield for stream links modelled by NLWRA (2001), for Bayswater, Bowmans and Glennies creek catchments.

3.5.6 Sediment Particle Size Distribution

The particle size distribution of surface bed material (greater than 8 mm in diameter) determined in the field using the Wolman Pebble Count technique at three locations on Yorks Creek (WP 48, WP 68 and WP 90) (Figure 9) indicated decreasing size in the downstream direction (Figure 27), as expected. The median sizes for particles greater than 8 mm in diameter at the two headwater sites were 161 mm and 107 mm, while the median size at the downstream site was 35 mm (Figure 27). A sample of surface bed material taken at WP 93 (Figure 9) was analysed in a laboratory for the complete range of particle sizes (Figure 28). The distribution of the gravel and cobble size material was similar in this sample to that sampled in the field at WP 90. About 45% of this sample was finer than the smallest size measured using the Wolman Pebble Count technique (8 mm diameter). Field observations suggested that sand was a minor component of the bed material, and this was confirmed by the particle size analysis which found that sand formed the smallest proportion of the sample size classes. The sample was 27% cobble (>60 mm), 33% gravel (>2 mm), 12% sand (>75 µm) and 28% silt and clay (<75 µm), with a median size of 26.3 mm. The gravel and cobble component of the bed material was well embedded within the fines, with release of a sample requiring prying with a metal rod.

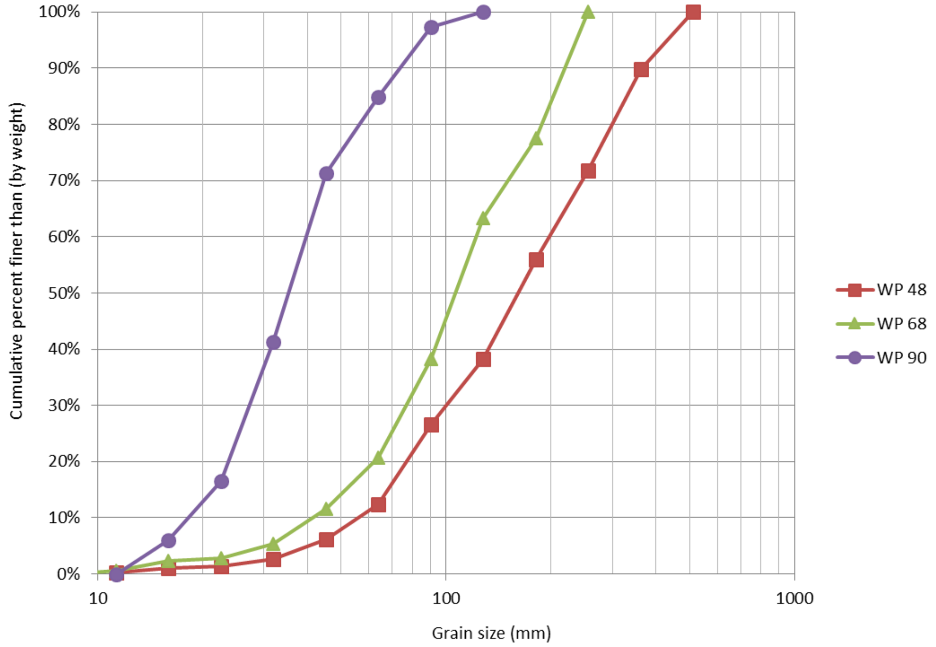

Figure 27. Particle size distribution (particles > 8mm diameter) of surface bed material at three locations on Yorks Creek.

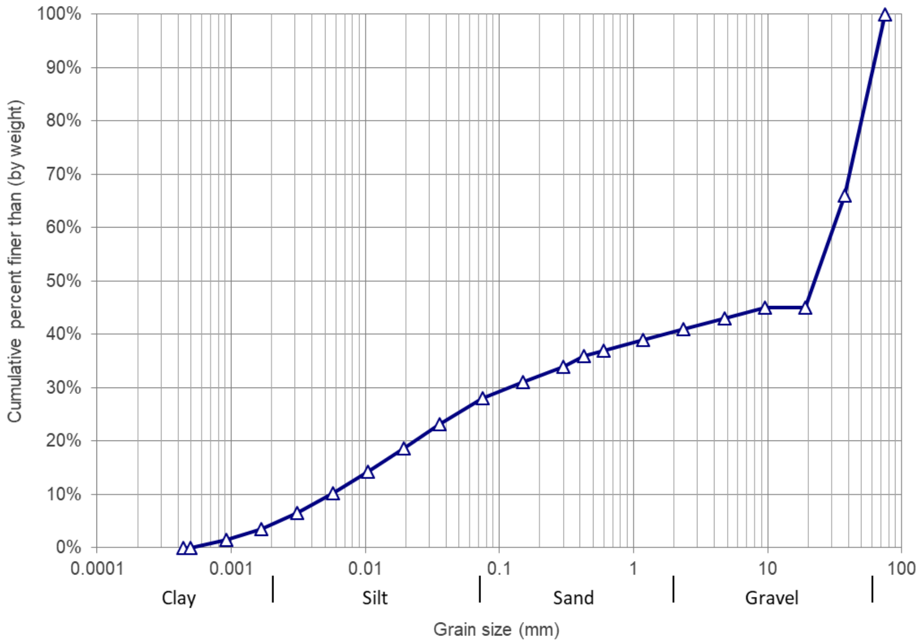

Figure 28. Particle size distribution of surface bed material at WP 93 on Yorks Creek.

It is highly unlikely that the dominantly coarse-grained material found in the bed of upper Yorks Creek catchment would be transported to the proposed diversion. Throughout Yorks Creek catchment, including the creek downstream of Mt Own Mine Access Road to its junction with Bowmans Creek, the size of the material on the bed reflected adjacent source areas. The only cobble-sized material found in Yorks Creek downstream of Mount Owen Mine Access Road was in the backwater of Bowmans Creek (Table 4), which was the likely source of the sediment. The dominant bed material in lower Yorks Creek was fines (Table 4). This reflects both the composition of the adjacent bank material, and the nature of suspended sediment derived from the upstream catchment and deposited on the bed during the recession limbs of flood events. On the basis of available data and observations, it was assumed that the majority of the sediment load delivered to the proposed diversion would comprise suspended clay and silt, with a smaller proportion of sand up to 2 mm diameter.

3.6 Review of Hydrology and Hydraulics with Respect to Geomorphology

3.6.1 Catchment Areas

Various estimates of the catchment areas of Yorks and Bowmans creeks have been reported. Bowmans Creek formerly had a flow gauge upstream of Yorks Creek named 210042 Foy Brook @ Ravensworth (Foy Brook is an alternative name for Bowmans Creek), which operated from 1956 to 1999. The coordinates given by Engineers Australia (2015, p. 30) place this gauge close to the junction of the proposed diversion, with a quoted catchment area of 170 km^2, while Boyd (1979) indicated a catchment area of 205 km^2.

WSP (2017b) developed a XPSWMM hydrological model of Bowmans Creek using the most recent Australian Rainfall and Runoff 2016 Guidelines (ARR16). WSP (2017b, Table 1, pp. 6 - 8) provided sub-catchment areas of the model, which were mapped and labelled in WSP (2017b, Fig 2, p. 6). The model covered Bowmans Creek down to Yorks Creek junction, and also included Yorks Creek. Sub-catchment prefixes identify them as belonging to Bowmans (BC) or Yorks (YC) creeks. Yorks Creek comprised 21 sub-catchments totalling 1842.9 ha. Bowmans Creek (plus one Swamp Creek sub-catchment) comprised 31 sub-catchments totalling 21,504 ha. At a point approximately 1200 m downstream of the proposed diversion, WSP (2017b, p. 4) estimated the catchment area of Bowmans Creek at 195 km^2.

The surface water assessment undertaken for the project (GHD, 2019a, Table 8-1) provided revised catchment areas for the existing, proposed (Year 13), approved conceptual final landform, and proposed conceptual final landform. The existing catchment area of Bowmans Creek upstream of Yorks Creek was estimated to be 189.53 km^2, and this was estimated to increase to 200.81 km^2 under conditions of the proposed conceptual final landform due to increased area of lower Bowmans Creek. The current Yorks Creek has a catchment area of 16.56 km^2; under proposed conditions (Year 13) the diversion would reduce the catchment of the existing creek to 1.4 km^2, with the proposed diversion draining an area of 14.0 km^2. Under existing conditions Yorks Creek increases the catchment area of Bowmans Creek at the junction by 8.7%, while under proposed conditions (Year 13) the diversion would increase the catchment area of Bowmans Creek at the junction by 7.4%. Under conditions of the proposed conceptual final landform, the diversion would increase the catchment area of Bowmans Creek at the junction by 7.5%. The similarity of these increases in catchment area at the junctions suggests that the expected morphological adjustment of Bowmans Creek in response to the diversion would be of a similar scale to that which can be observed at the existing junction of Yorks Creek and Bowmans Creek.

3.6.2 Flood Magnitudes

Using 19 years of observed data from Foy Brook Creek @ Ravensworth gauge 210042, Boyd (1979) estimated the 10 year ARI flood peak to be 69 m^3/s using interpolation of the observed annual flood series, 40 m^3/s using the Rational Statistical Method and 138 m^3/s using the Regional Flood Frequency Method. The Rational Method failed to produce a reasonable estimate. Boyd (1979) also estimated the magnitude of the 2 and 5 year ARI flood events.

As part of the work undertaken in design of a diversion of Bowmans Creek downstream of the Study Area, Fluvial Systems (2009) used the 44-year long observed annual series from 1956 to 1999 for Foy Brook Creek @ Ravensworth gauge 210042 to estimate the magnitude of the 10 year ARI flood at 138 m^3/s. Fluvial Systems (2009) also estimated the 20 year ARI flood peak at 184 m^3/s and the 100 year ARI flood peak at 320 m^3/s.

The XPSWMM ARR16 model of WSP (2017b, Table 2, p. 8) estimated the Bowmans Creek 10 year ARI flood at 189.8 m^3/s and the 100 year ARI flood peak at 412.3 m^3/s. These values are somewhat higher than those estimated by Fluvial Systems (2009) on the basis of observed flood data. WSP (2017b) also provided alternative estimates of the 100 yr ARI flood peak using ARR87 and from other studies, ranging from 581 to 772 m^3/s. The Regional Flood Frequency Method estimated the 10 year ARI flood peak at 215 m^3/s, which is somewhat higher than the result of Boyd (1979). More recently, the flooding assessment undertaken for the project (GHD, 2019b, Table 8-1) estimated the Bowmans Creek 10% AEP 1% flood peak at 197.7 m^3/s and the AEP flood peak at 428.3 m^3/s, which are similar to the estimates of WSP (2017b). This suggests that the methodology was robust, as these studies used a similar approach.

The XPSWMM ARR16 model of WSP (2017b, Table 2, p. 8) estimated the Yorks Creek 10 year ARI flood at 16.04 m^3/s and the 100 year ARI flood peak at 38.33 m^3/s. The XP-RAFTS Yorks Creek approved final landform model estimated for the location at Mount Owen Access Road a 10 year ARI flood at 33.62 m^3/s, 20 year ARI flood at 41.18 m^3/s, and the 100 year ARI flood peak at 55.86 m^3/s (WSP, 2017a, Table 3.5, p. 13). WSP (2017b) explained that the differences related to the use of ARR16 in the Liddell Extension model (WSP, 2017b) and ARR87 in the MOCO model (WSP, 2017a), with the lower estimates of WSP (2017b) preferred. More recently, the flooding assessment undertaken for the project (GHD, 2019b, Table 8-1) estimated the Bowmans Creek 10% AEP 1% flood peak at 17.0 m^3/s and the AEP flood peak at 36.2 m^3/s, which are similar to the estimates of WSP (2017b).

3.6.3 Flood Velocities (Yorks Creek)

WSP (2017b) provided modelled estimates of mean channel velocity for three flood magnitudes at three locations (Table 12). The flood velocities did not increase markedly from the 10 year to the 100 year ARI flood event, because flow was out of bank in the 10 year event, and much of the additional flow of the 20 year and 100 year events was on the floodplain.

Table 12. Modelled velocities for three flood magnitudes at three locations on Yorks Creek. Source: WSP (2017b, Tables 4.1, 4.2, 4.3).

Location	Mean channel velocity (m/s)		
	100 yr ARI	20 yr ARI	10 yr ARI
Yorks Creek at Mount Owen Mine Access Road	0.19	0.16	0.14
Yorks Creek at Hebden Road crossing, 40 m upstream in channel	1.16	0.99	0.93
Yorks Creek at Government Property (Lot 4 DP 232149)	1.45	1.28	1.20

3.7 Template of the Proposed Diversion and Design Considerations

The proposed diversion extends from Mount Owen Mine Access Road to Bowmans Creek over a distance of 2747.7 m (Figure 29). The diversion comprises two sections with contrasting bed gradients. The first 150 m from Bowmans Creek is relatively low gradient, then over the next 250 m to chainage 400 m the diversion has a relatively steep gradient of 0.04, or 1 in 25. The remainder of the diversion has a low gradient of 0.002, or 1 in 500 (Figure 29). No section of the existing Yorks Creek that will be diverted possesses these gradients (Table 5).

The sinuosity of the diversion alignment is 1.15, similar to the Yorks Creek Original Diversion reach (Table 5).

The bed width of the proposed diversion is 13 m from Bowmans Creek to chainage 880 m, after which it increases to 35 m. The wider of these two widths is comparable to the corridor widths of the existing Yorks Creek upstream of Mount Owen Mine Access Road reach, and the Yorks Creek Original Diversion reach, but much narrower than the corridor width of existing Yorks Creek downstream of the Haul Road reach (Figure 7 and Table 6).

The upper half of the proposed diversion will necessarily be constructed through some sections of fill, while the lower half will require excavation to a depth of up to 16 m (Figure 29). The fill presents a design challenge in terms of the geochemistry and geotechnical properties of the fill, which should not cause contamination and which should have tolerable resistance to fluvial erosion. The excavated section presents a design challenge as there is a risk of valley wall sub-aerial erosion creating unstable bank gullies and rills, as well as contributing sediment to the diversion channel.

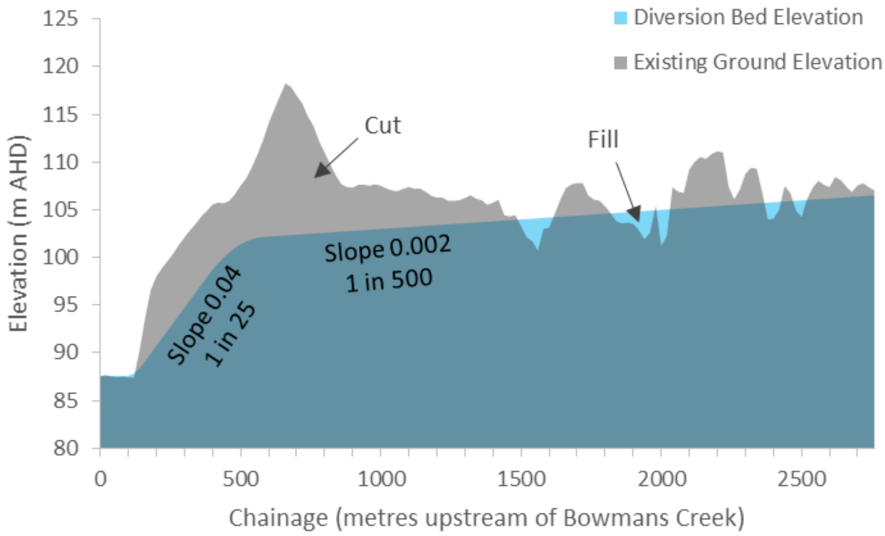

Figure 29. Proposed diversion bed profile and existing ground levels, at 20 m point spacing, from LiDAR-based DEM and WSP Drawing LEP-WSP-55.02.03.00-CV-0136, dated 09-08-2017.

3.8 Terrain Analysis – Regional Reference Reaches

3.8.1 Distribution of Potential Reference Reaches

An adequately realistic drainage network covering the Saddlers, Bayswater, Bowmans and Glennies creeks catchments region was automatically generated from the 1 Second Hydrologically Enforced DEM (Figure 30). Criteria were applied to this network to select steep and low gradient reaches that had potential to serve as reference reaches for the proposed diversion. Although the criteria covered relatively wide ranges of catchment area and mean slopes, only a small number of links were located that had potential to act as reference reaches (Figure 31).

The drainage pattern over the majority of the region was dendritic, with upland streams flowing at the base of V-shaped valleys between well defined interfluves. Steep stream reaches were mostly associated with headwater streams draining small catchment areas, but a few were located mid-catchment (Figure 31). Gorge river types were rare in this region, occurring only where a stream cut southwards through a NW – SE trending interfluve to the adjacent valley. Two gorges of a significant size were found on Campbells Creek (Figure 32) and upper Bowmans/Lincolns Creek (Figure 33). These two sites have potential to serve as reference reaches for the steep reach of the proposed diversion. A few other steep reaches were found in the region that crossed an interfluve, but with more gently sloping valley side slopes. These sites could offer potential to serve as reference reaches but were not characterised in detail here.

Stream links of very low bed slope and small catchment area would normally be associated with a plateau landscape, which did not occur in the region. Nevertheless, a small number of low slope stream links were found (Figure 31). The morphology of the low slope stream links was poorly defined by the low-resolution DEM. While the terrain analysis methodology likely located most of the low slope links with potential to serve as reference reaches, their proper geomorphological characterisation would require high resolution LiDAR and/or field assessment.

Some of the low slope stream links were located within or adjacent to mines, and were possibly disturbed. Two mid-catchment low slope links were found on Bowmans Creek in the vicinity of the Bowmans/Lincolns creeks gorge (Figure 33). Although draining relatively large catchment areas (45.1 and 85.8 km^2), these links had a narrow band of woody riparian vegetation and were not incised. Lower Saddlers Creek (Figure 34) could possibly serve as a low slope reference reach, but detracting from these links were their relatively large catchment areas (69.3 and 84.8 km^2), lack of woody riparian vegetation, and incised channel form.

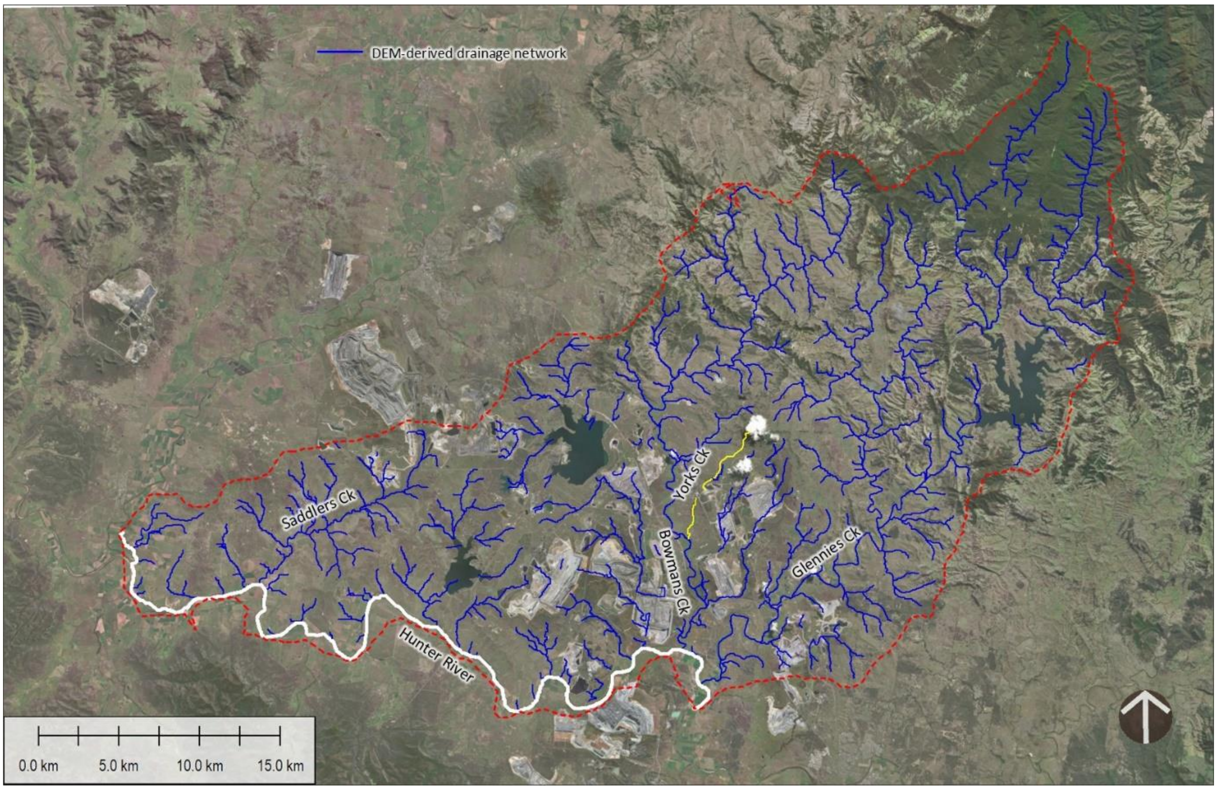

Figure 30. Drainage network generated automatically from the GA National 1 Second Hydrologically Enforced DEM, covering Saddlers, Bayswater, Bowmans and Glennies creeks catchments region.

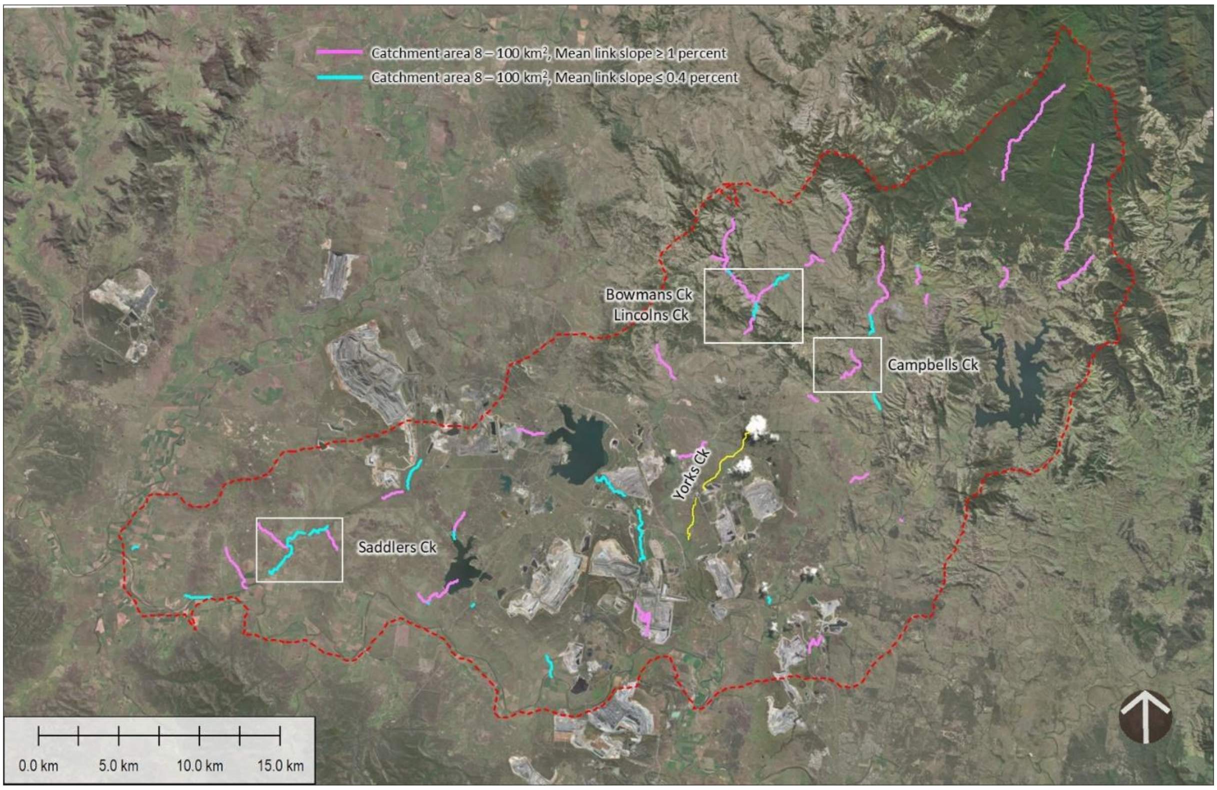

Figure 31. Steep and low slope stream links that matched reference reach criteria. The three most promising reference reach areas are indicated by boxes. Yorks Creek is also depicted.

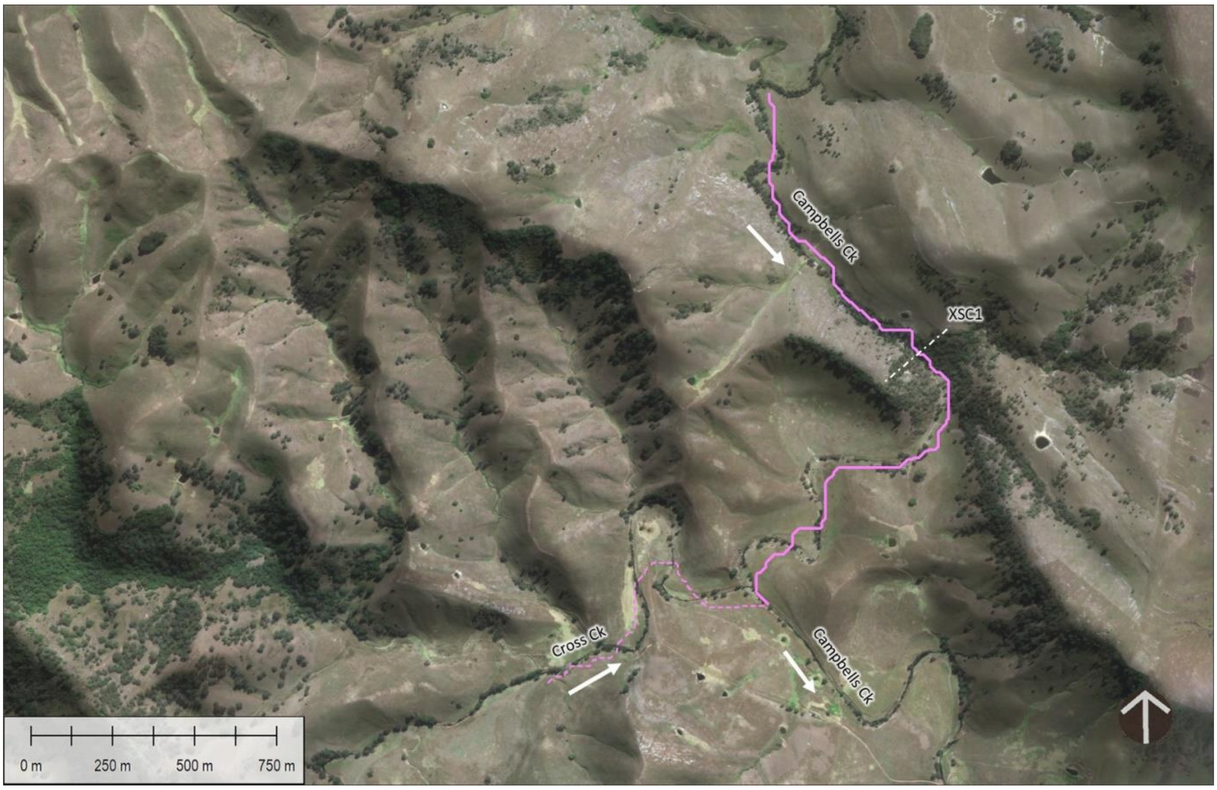

Figure 32. Gorge on Campbells Creek with steep stream link (pink).

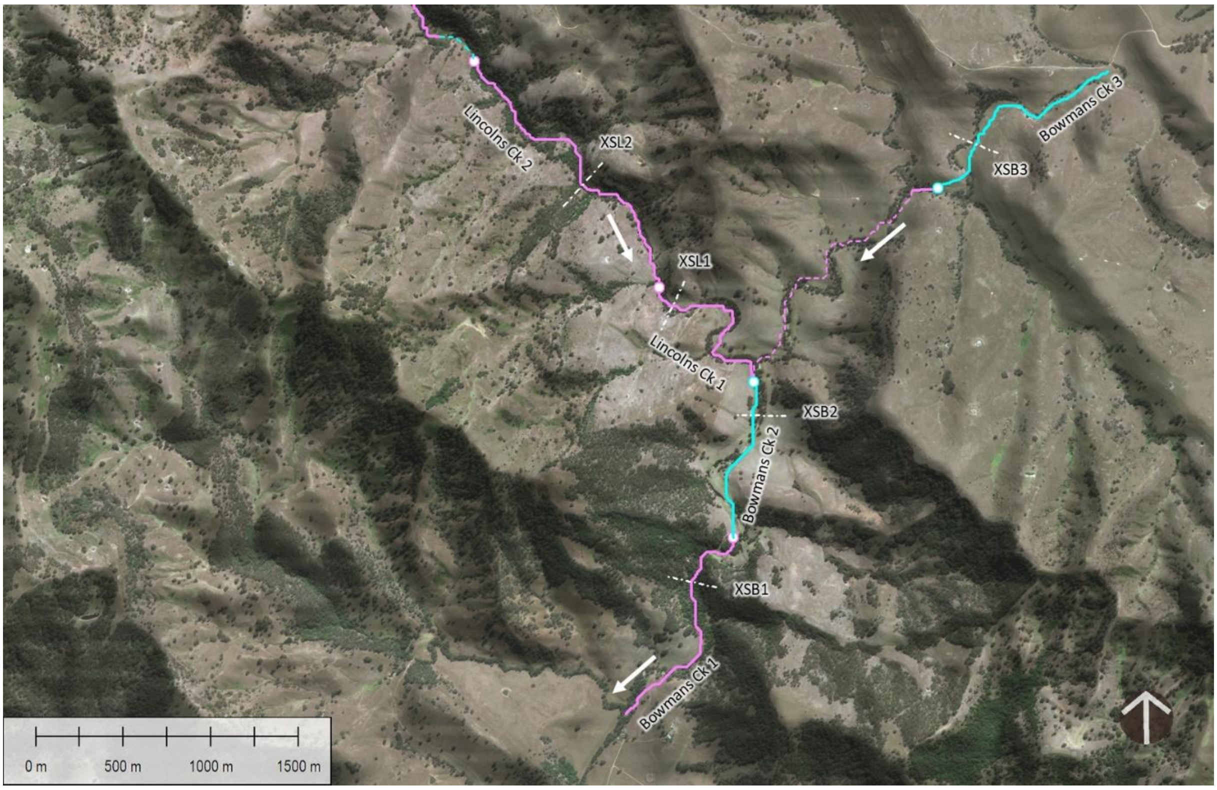

Figure 33. Gorges on Bowmans/Lincolns creeks with steep stream links (pink), and low slope stream links (blue) on Bowmans Creek.

Figure 34. Low slope stream links (blue) on Saddlers Creek.

3.8.2 Steep Gorge Links

The steep gorge stream links were characterised by catchment area, long profile mean slope, sinuosity, and, measured at a representative cross-section, valley side slopes and bed width (Table 13). Campbells Creek gorge appeared to have a centrally located waterfall or very steep cascade about 10 m high, but the bed slope was otherwise about half as steep as the lower zone of the proposed diversion. The gorge was about 15 to 20 m deep and about 160 m wide at the top (Figure 35). Bowmans Creek gorge appeared to have a series of three waterfalls or very steep cascades about 5 – 8 m high, but the bed slope was otherwise less than half as steep as the lower zone of the proposed diversion. In places, the gorge was more than 25 m deep and more than 300 m wide at the top (Figure 36Figure 35). The lower Lincolns Creek gorge link comprised two steeper reaches between a central flatter reach, with an average bed slope about half as steep as the lower zone of the proposed diversion. The gorge was about 20 m deep and about 255 m wide at the top (Figure 37). The upper Lincolns Creek gorge link was relatively straight and had a fairly even bed slope just greater than half as steep as the lower zone of the proposed diversion. The gorge was more than 40 m deep and more than 340 m wide at the top (Figure 37).

Table 13. Morphological characteristics of steep gorge links. Sinuosity measured from aerial photograph; other variables measured from DEM.

Stream link	Catchment area (km^2)	Longitudinal form		Cross-sectional form		
		Mean bed slope (m/m)	Sinuosity	Side slope left	Side slope right	Bed width (m)
Campbells Ck	32.8	0.019	1.38	26% (14.4º)	21% (12.0º)	20
Bowmans Ck 1	88.1	0.015	1.45	20% (11.5º)	21% (12.1º)	50
Lincolns Ck 1	29.3	0.022	1.65	28% (15.5º)	21% (11.7º)	60
Lincolns Ck 2	27.7	0.024	1.17	34% (18.6º)	34% (18.6º)	55

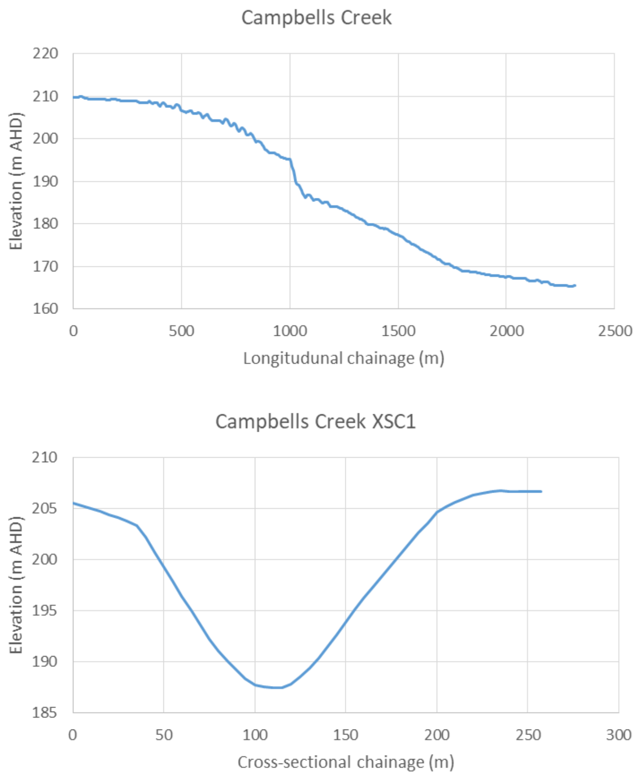

Figure 35. Long profile and cross-section of Campbells Creek gorge link.

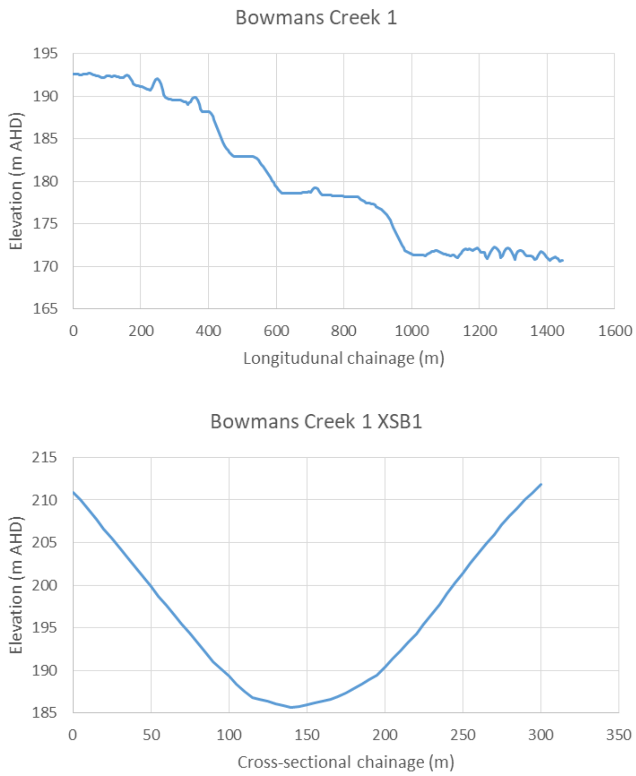

Figure 36. Long profile and cross-section of Bowmans Creek 1 gorge link.

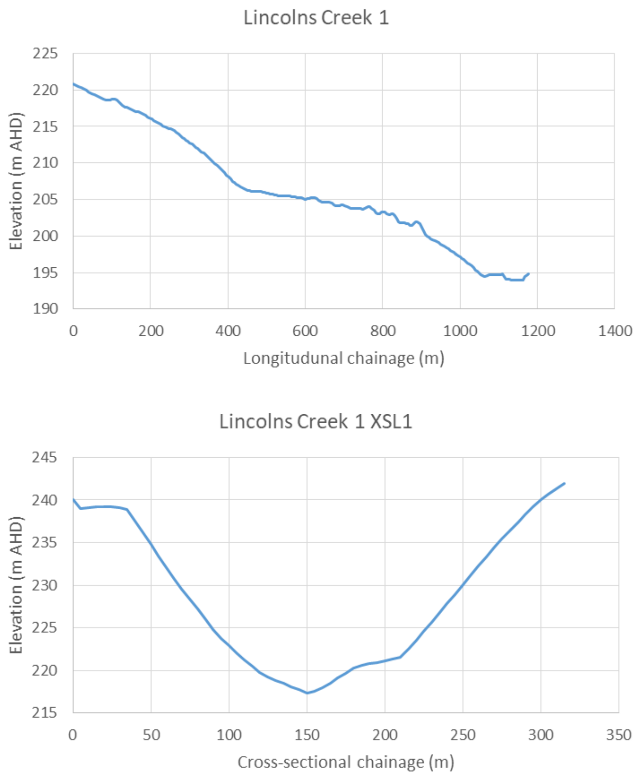

Figure 37. Long profile and cross-section of Lincolns Creek 1 gorge link.

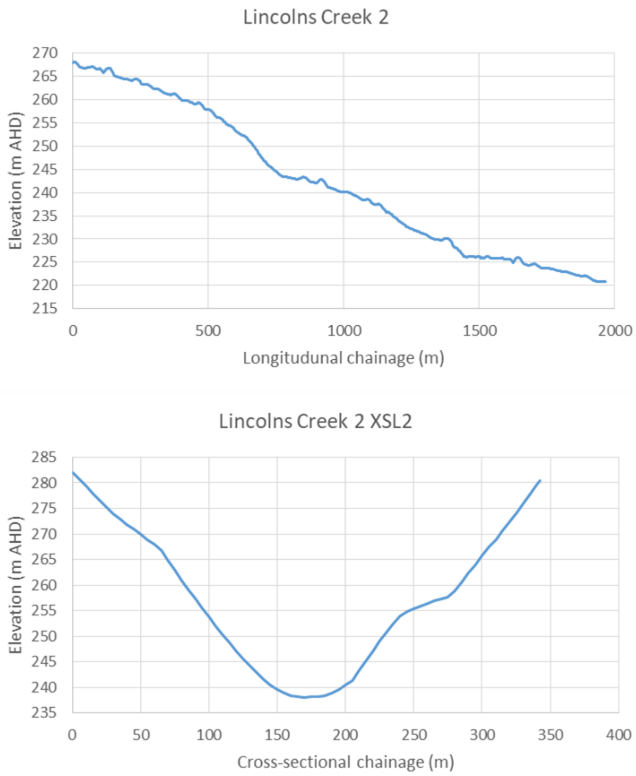

Figure 38. Long profile and cross-section of Lincolns Creek 2 gorge link.

3.8.3 Low Slope Links

The low slope stream links were characterised by catchment area, long profile mean slope, sinuosity, and, measured at a representative cross-section, channel depth, channel top width, channel bed width and riverine corridor width (width of channel and associated floodplain) (Table 14). Bowmans Creek link downstream of the gorge had a low, apparently uneven slope, similar in mean slope to the upper zone of the proposed diversion. The low sinuosity channel was about 1.2 m deep and about 35 m wide at the top, but this measurement would be unreliable from the available LiDAR (Figure 39). Bowmans Creek upstream of the gorge had a relatively even slope about twice that of the upper zone of the proposed diversion. The sinuous channel was very shallow, but the morphology was difficult to determine from the low resolution LiDAR-derived DEM (Figure 40Figure 35). The lower Saddlers Creek link had an even bed slope, somewhat steeper than the upper zone of the proposed diversion. The sinuous channel appeared to be incised within a variable width riparian corridor, about 230 m wide at the sample cross-section (Figure 41). The upper Saddlers Creek link had an even bed slope slightly less than twice that of the lower zone of the proposed diversion. The meandering channel appeared to be deeply incised within a variable width riparian corridor, about 390 m wide at the sample cross-section (Figure 42).

Table 14. Morphological characteristics of low slope links. Sinuosity measured from aerial photograph; other variables measured from DEM. nd is not determinable from the DEM.

Stream link	Catchment area (km^2)	Longitudinal form		Cross-sectional form			
		Mean bed slope (m/m)	Sinuosity	Channel depth (m)	Channel top width (m)	Channel bed width (m)	Corridor width (m)
Bowmans Ck 2	85.8	0.0022	1.24	1.2	35	nd	120
Bowmans Ck 3	45.1	0.0039	1.44	<1.0	nd	nd	85
Saddlers Ck 1	84.8	0.0031	1.43	2.2*	105*	10	230
Saddlers Ck 2	69.3	0.0036	1.54	5.1*	250*	35	390

* incised channel dimensions

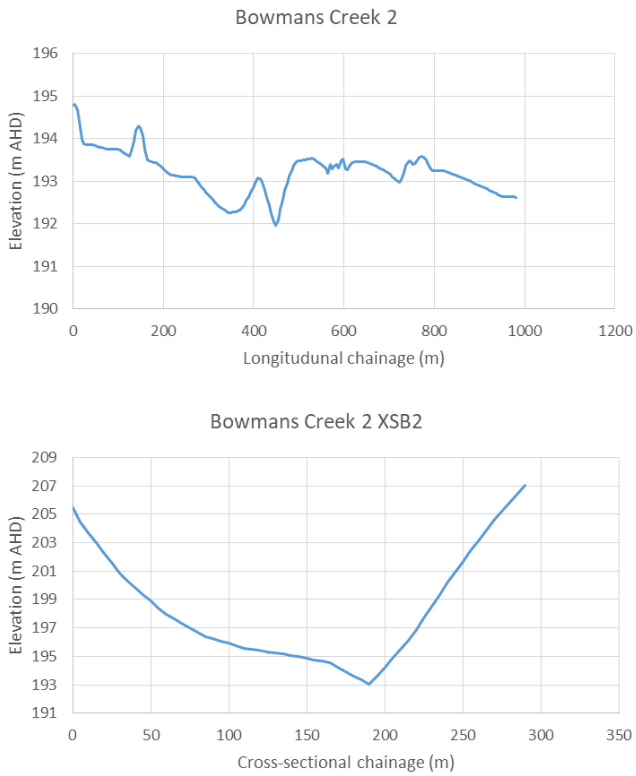

Figure 39. Long profile and cross-section of Bowmans Creek 2 low slope link.

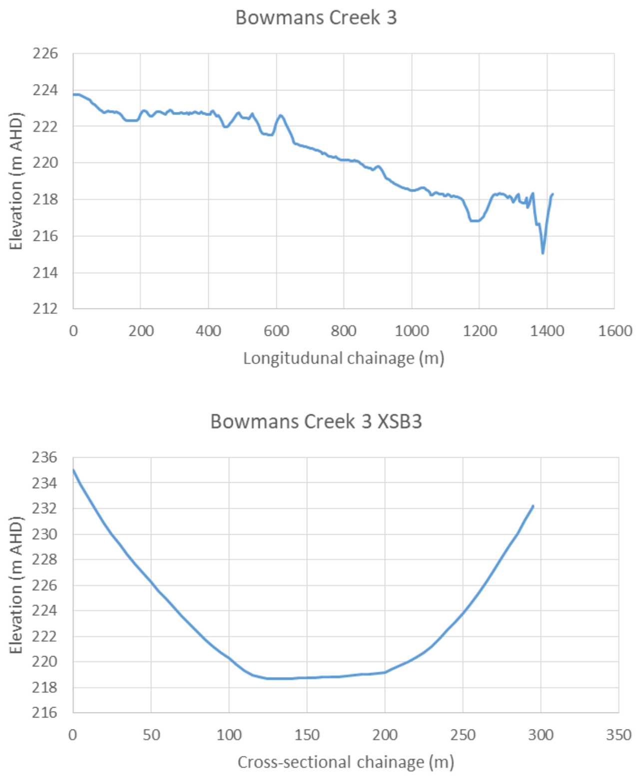

Figure 40. Long profile and cross-section of Bowmans Creek 3 low slope link.

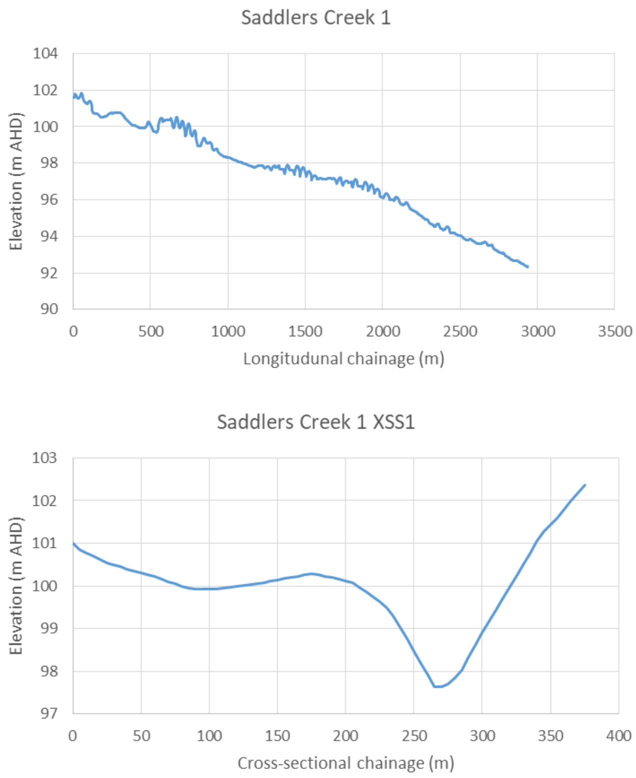

Figure 41. Long profile and cross-section of Saddlers Creek 1 low slope link.

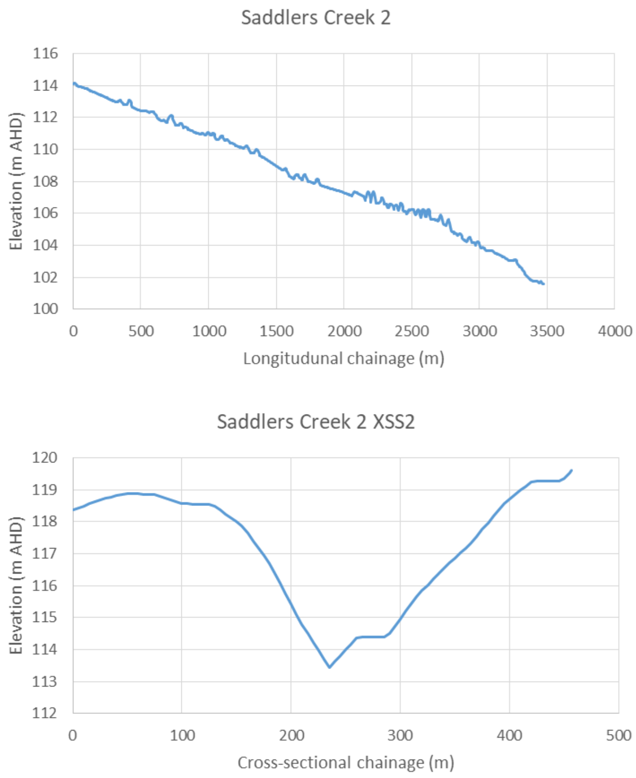

Figure 42. Long profile and cross-section of Saddlers Creek 2 low slope link.

4.0 Discussion

4.1 Potential Impacts of the Proposed Diversion on Bowmans Creek

The proposed diversion will increase the contributing catchment area of Bowmans Creek over a distance of approximately 4.2 km by 7.4 to 7.5%, and increase the 10 year ARI flood magnitude over that reach by about 8%. These increases would be expected to result in a geomorphic response in width, depth, slope, roughness or sinuosity, or a combination of all these aspects. The channel of Bowmans Creek was found to have highly variable morphology through hydrologically homogeneous reaches, suggesting complex local channel adjustment to erosive and depositional processes. As a result there was no statistically significant change in channel dimensions downstream of the existing Yorks Creek junction. Given the inherent stability of the channel, rapid and large magnitude adjustment of Bowmans Creek channel downstream of the proposed diversion would not be expected. Catastrophic release of sediment, loss of riparian zone, incision, or change of alignment are unlikely. Rather, adjustment would take place incrementally over decades. It is preferable to allow this type of adjustment to proceed and achieve a new equilibrium morphology, rather than attempt to prevent it from occurring, which would require ongoing investment that ultimately could prove futile.

4.2 The Geomorphological Character of Yorks Creek

The natural reaches of Yorks Creek in the Study Area downstream of near Mount Owen Mine Access Road comprise:

- a notch-shaped channel:
    - on average 1.5 – 2.5 m wide at the bed,
    - on average 5 – 6 m wide at morphological bankfull level,
    - on average 1.3 – 2.3 m deep at bankfull level,
    - relatively steep banks on average 45 – 60 degrees,
- channel bed formed in cohesive fine-grained material of silty sand, with gravel present in places,
- channel banks formed in cohesive sediment, with stability enhanced by surface grass cover on the bank tops and bank sides fortified by tree and shrub root mats,
- channel downstream bed level variation on average 0.3 – 0.4 m amplitude, with on average 7 – 8 m spacing between low points,
- large wood density of on average 4 – 18 items per 100 m, items on average 0.17 – 0.22 m diameter, with most items spanning the full channel width and often found in jams comprising multiple items
- a riverine corridor on average 40 – 80 m wide (includes channel)
- a bed slope on average 0.0045 – 0.0093,
- sinuosity of 1.3 – 1.6

The channel morphology was not accurately characterised by the available LiDAR-based DEM. The DEM characterised the channel as triangular in shape, i.e. failing to depict the flat bed, with an exaggerated bankfull width and underestimated depth. The bankfull width estimated from the LiDAR data was at least double that measured in the field. This can be partly explained by different perceptions and interpretations of morphological bankfull level in the field compared with desktop viewing of cross-sections. The downstream bed level variation measured from the DEM was similar in amplitude to that measured in the field.

The above described character of Yorks Creek is an adequate basis for designing a diversion channel that mimics its geomorphic form and process, but the constraints of the proposed diversion template create a challenge for implementing this design philosophy.

4.3 The Sediment Load of Yorks Creek

The long-term average annual sediment load delivered from upper Yorks Creek catchment to the proposed diversion was estimated to be 1630 tonnes per year. The majority of the sediment load delivered to the proposed diversion would comprise suspended clay, silt and sand, up to 2 mm diameter. The proportions of these size classes would vary along the length of the stream.

4.4 The Geomorphological Character of Reference Reaches

Stream reaches with slopes similar to the upper low slope (0.002 m/m) reach and lower steep (0.04 m/m) gorge reach of the proposed diversion were rare in the region, but a small number of reaches were found that could serve as reference reaches. The low slope reaches were not well characterised by the low-resolution LiDAR-derived DEM and would require field inspection to reliably measure their morphology. The broad morphological character of the steep gorge reaches was determined from the low-resolution DEM, but field inspection would be required to obtain more detailed morphological information. Also, these reaches had larger catchment areas than the proposed diversion, so the dimensions would need to be scaled accordingly. Although these reaches had larger catchment areas than the diversion, they were situated steep headwater zones. Broad characteristics of the steep gorge reference reaches were:

- Mean bed slopes in the range 0.015 – 0.024 m/m
- Waterfalls and/or steep cascades present
- Sinuosity in the range 1.2 – 1.7
- Valley side slopes in the range 20 – 34% (11.5 – 18.6º)
- Bed widths in the range 20 – 60 m

None of the reaches had slope of 0.04 over a length of about 250 m, as proposed for the short gorge reach of the diversion. Otherwise comparable natural streams were generally less steep than 0.04 but lost elevation in short steps through waterfalls and cascades.

5.0 Review of Performance of Similar Diversions

5.1 Geomorphic Performance Assessment Methodologies

Assessment of geomorphic condition in stream health assessment is often done using a subjective, rapid, visual assessment methodology, with the trajectory of change assessed by comparing scores from surveys made over time.

Given the difficulty of identifying in the field whether the processes associated with geomorphological instability are active and in which direction, reliably rating the degree of instability through visual assessment is an almost impossible task. This reality has not discouraged the practice of attempting to rate bank and bed stability using rapid visual inspection in river monitoring programs. Rapid, visual geomorphological stability assessment has long been included in the US EPA bioassessment protocols, and this appears to have normalised this approach among those considering river health from an ecological habitat, or engineering, perspective. Examples of Australian stream condition assessment methods that include a rapid assessment of geomorphic stability include the widely-used Index of Stream Condition (ISC) (Ladson et al., 1999) and AusRIVAS (Nichols et al., 2002; EPA Victoria, 2003), and the more obscure Index of Diversion Condition (IDC) (White and Hardie, 2001) and CSIRO Ephemeral Stream Assessment (Tongway and Ludwig, 2011).

The reproducibility of subjective assessment approaches is rarely tested during method development or application, so the contribution of operator variability to apparent geomorphic change is not known or considered. In the second benchmarking of stream condition of the ISC, undertaken in 2004, the original (1999) bed stability metric was removed because this property of streams was found to be highly variable and it was difficult to establish the metric on the basis of one field inspection. Most of the differences in physical form scores were due to random site selection (Department of Sustainability and Environment, 2005). Another criticism that can often be levelled at applications of these assessment methodologies is failure to consider statistical power and randomness when planning the number of sample sites and the sample site locations. These issues create difficulties in applying tests of statistical significance to the data to test hypotheses about differences between sites, or trends over time. Although statistical testing is universally regarded a cornerstone of the scientific method, it is rarely employed in this type of monitoring.

A more serious flaw with subjective visual-based geomorphic assessments is that they are based on a fundamental misunderstanding of geomorphic processes. These methods are couched in the simple notion that channels with the appearance of stability imparted by stable forms and surfaces are desirable, while channels with bed material or banks that move are undesirable. Even natural processes such as channel avulsion are regarded as undesirable. A review by Florsheim et al. (2008) found that bank erosion is an important component of the natural disturbance regime of river systems and is integral to long-term geomorphic evolution of fluvial systems and to ecological sustainability. Bank erosion is therefore a desirable attribute of rivers, even though most river health assessments view *any* bank erosion negatively.

As a general rule, geomorphologists do not use rapid visual assessment to investigate stream processes, preferring to use reliable, objective, quantitative approaches with known error, and using statistical tests to measure change or condition relative to a set of objective standards that relate to project objectives. Conventional methods of determining change over time include measuring change on aerial photographs taken over time, repeatedly measuring cross-sections and bed long profiles using on-ground professional survey, and repeatedly measuring three-dimensional topography over large areas using LiDAR-generated DEMs. These approaches to physical form assessment can be complemented by repeated measurement of bed material particle size distributions, large wood dimensions and density, and riparian vegetation structure. These variables can be measured using conventional, reliable, instrumental methods.

5.2 Review of Performance of Sixty Diversions in the Bowen Basin

An extensive review of the performance of 60 stream diversions in Queensland was undertaken by White et al. (2014). The methodology relied on the Index of Diversion Condition (IDC). This was referred to by White et al. (2014) as a semi-quantitative scoring approach, which means that it uses subjective judgement rather than instrumental measurement, so the results should be regarded with caution.

The majority of the sampled diversions were located in the Bowen Basin. Seventeen of the diversions had utilised the ACARP stream power, shear stress and velocity design criteria developed by Hardie and Lucas (2002). These were generally considered to be in moderate to good condition. However, a substantial proportion of sampled diversions were judged to be in poor to moderate condition and require management intervention to put them on a trajectory of improving condition. Only six of the diversions were rated by the IDC to be in good or very good condition.

Diversions constructed prior to release of the ACARP guidelines in 2002 tended to suffer from accelerated erosion, largely as a result of:

- Inadequate design width
- Increased bed slope as a result of shortening the channel length
- Increased velocities
- Absence of vegetation on the banks
- Highly dispersive soils
- Increased incidence of rill erosion and piping on banks

White et al. (2014) noted that after release of the ACARP guidelines in 2002 there were significant changes in the way diversions were designed and constructed, including:

- Drop structures were not included
- Diversions had bed gradient similar to the adjoining natural stream
- Channels had inset benches and floodplains rather than simple trapezoidal shape
- Sediment transport was considered
- Spoil piles were located away from streams
- Overland flow entry provision was improved
- Geomorphology and riparian vegetation was considered in the design process

The review found that five factors consistently influenced and limited the performance of diversions:

1. Sediment supply and transport:
    a. Sediment supply to the diversion
    b. Change in sediment transport
2. Vegetation condition
3. Occurrence of major flooding in early years of diversion establishment
4. Overland flow drainage
5. Criteria interpretation and diversion reach transitions

Sediment transport and vegetation condition were found to be the most critical factors determining diversion performance.

5.3 Examples of Unstable Diversions

An example of a diversion requiring modification was provided by Hardie et al. (1994). In this case, a 7.8 km diversion of the Isaac River in Queensland widened from 40 to 80 m and bends migrated by up to 40 m, while at the same time the natural reaches up- and downstream remained stable. Hardie et al. (1994) found that the while the diversion was constructed with the same bed width as the natural river channel, it lacked the inset bench that was a feature of the natural channel. This natural morphology adjusted to increase channel capacity at times of high flood flow. In addition, the diversion bank vegetation cover was not as good as that found in the natural channel.

A second example of a diversion requiring remediation is the 4 km diversion of the Goulburn River, built in 1981 along the southern and eastern boundaries of the Ulan Mine Complex, NSW. The diversion channel was excavated primarily into bedrock and partly into a deep weathering profile that lies above the bedrock and is 10 – 20 m deep. This diversion was later recognised as having poor visual amenity, impaired ecological function, and accelerated bank erosion. The problems were related to inadequacies in the original design, which was in keeping with the standards at the time but which would not satisfy current practice, such as that specified in ACARP guidelines (Hardie and Lucas, 2002) or Department of Natural Resources and Mines (2014). While the diversion met legal requirements, it was recognised that a remediation plan was required to achieve long-term stability (Glencore, 2016).

5.4 Performance of Mount Owen Complex (MOC) Diversions

5.4.1 Methodology

The Mount Owen Complex contains four diversions that have been the subject of routine monitoring since 2014:

- Upper Bettys Creek Diversion
- Middle Bettys Creek Diversion
- Lower Bettys Creek Diversion
- Glendell MIA Diversion (previously referred to as Swamp Creek Diversion)

The monitoring program also includes reference sites on Bowmans Creek, Main Creek, Swamp Creek and Yorks Creek. SLR (2014) and Engeny (2018) noted the existence of historical monitoring data collected prior to 2014, dating back to 2009, but these data were not reviewed here. A standard methodology and permanent site markers were adopted in 2014, allowing direct comparison of data over time.

Two subjective rapid assessment methodologies were employed to monitor the MOC diversions:

- Modified version of the Rapid Appraisal of Riparian Condition (RARC)
- CSIRO Ephemeral Stream Assessment of physical channel stability

The CSIRO Ephemeral Stream Assessment method (Tongway and Ludwig, 2011) includes scores for 8 categories:

- Vegetation on channel bed
- Vegetation on channel banks
- Shape of channel cross-section
- Longitudinal morphology
- Particle size of materials on bed
- Nature of channel bank materials
- Nature and shape of bank edge
- Nature of regulation of lateral flow into the channel

A score is awarded for each category and summed, with a maximum score of 32. This score is converted to a percentage. The score are then classified according to a 5-point geomorphic stability scale of <50 Very active, 50 – 59 Active, 60 – 69 Potentially stabilising, 70 – 80 Stable and >80 Very stable. Apart from the difficulty, even for a professional geomorphologist, in rating these complex forms and processes from a single visual inspection, an obvious flaw with this system is that it would rate an aggrading (depositional) site as stable, when it is in fact geomorphologically active. As with most other similar rapid physical assessment systems, it is not grounded in geomorphic theory. In addition, to avoid one form of bias, the technician should do the survey blind, i.e. without having seen the previous survey data. Given the subjective nature of the assessment, this method is not likely to be reproducible, i.e. different technicians doing the same assessment at the same time would be unlikely to produce the same result. That is because each technician will have their own bias in interpreting the relationship between the geomorphic forms they are viewing and the score. Training might reduce bias, but the technicians applying this method do so without training.

The RARC method (Jansen et al., 2005; Jansen et al., 2007) includes scores for:

- Longitudinal continuity and width of riparian canopy and proximity to nearest patch of native vegetation;
- Vegetation cover for canopy, understorey and ground structural layers
- Vegetation cover for canopy, understorey and ground structural layers for natives

- Cover of standing dead trees, leaf litter, and fallen logs; and
- Presence of native vegetation regeneration, native tussock and grasses and reeds.

The scores for these five categories are tallied to provide an overall score indicating riparian health. These scores are then classified according to a 5-point scale of Very Poor, Poor, Average, Good and Excellent. Assigning scores is a semi-quantitative process. For example, cover is scored according to three classes of percentage cover, logs and tree diameters are measured for minimum diameter, and widths and distances are measured before being placed within classes.

A literature search suggested that neither the CSIRO Ephemeral Stream Assessment method nor the RARC have been published in peer reviewed scientific journals. RARC was published as an industry guideline brochure and in one conference proceedings (Jansen, 2005) and CSIRO Ephemeral Stream Assessment method was published as a book chapter (Tongway and Ludwig, 2011). They cannot be regarded as mainstream methods established in the scientific literature, and the original monitoring report did not provide a justification for their application to the MOC diversion monitoring program.

The survey methodology also involved cross-section topographic surveys undertaken by non-professionals. SLR (2014) measured each transect by stretching a tape measure between two monumented points and measuring distance to the ground at approximately 0.5 m intervals. This method did not collect data relative to Australian Height Datum (AHD). HLM (2016a, 2016b) collected comparable data from each site using a dumpy level and staff. Engeny (2018) did not undertake topographic survey. They produced coarse plots of longitudinal profiles extracted from 1 m contours (source not stated), which they referred to using the contradictory term "longitudinal cross section". HLM (2016ba; 2016b) plotted cross-section data for each year from 2010 to 2016 for all sites, but there is no evidence in any monitoring report that the cross-section survey data were used to assess erosion and deposition processes, or to compare with or support the subjective CSIRO Ephemeral Stream Assessment scores.

In the first monitoring report by SLR Consulting (2014), it was noted that "*In future inspections any visible changes that occur since the preceding inspection will be documented by comparison to the photos taken during the previous surveys*". The later monitoring reports did not provide any evidence that photographs were compared from year to year.

5.4.2 Results of Monitoring

The following monitoring reports were reviewed:

- SLR (2014): 2014 monitoring of RARC, CSIRO Ephemeral Stream Assessment and cross-section surveys
- HLM (2016a): 2015 monitoring of RARC and cross-section surveys
- HLM (2016b): 2016 monitoring of RARC and cross-section surveys
- Engeny (2018) 2017 monitoring of RARC and CSIRO Ephemeral Stream Assessment

Only the RARC surveys were conducted in each year, and CSIRO Ephemeral Stream Assessment data can be compared between 2014 and 2017.

The 2015 and 2016 RARC scores in HLM (2016a) and HLM (2016b) respectively were identical for every indicator category, which is a highly improbable result. Not only that, the classified overall results for 2015 and 2016 were identical to those for 2014 in SLR (2014) (See HLM, 2016b, Table 3, p. 55). Again, this seems like an improbable result. Engeny (2018) noticed an error for Yorks Creek Site YC2 in HLM (2016a) and HLM (2016b), which indicated a rating of Poor, when the raw scores indicated a rating of Average. Engeny (2018, Table 5.3, pp. 27-31) did not report the 2016 RARC results of HLM (2016b), listing only the 2015 results. The comparison of data provided by Engeny (2018, Table 5.3, pp. 27-31) suggests there has been virtually no change in the riparian condition between 2014 and 2017. Lower Bettys Diversion 10 (LBD10) improved from Average to Good in 2017, Lower Bettys Diversion 3 (LBD3) improved from Poor to Average in 2017, Swamp Creek 1B (SC1B) improved from Very Poor to Poor in 2017, and Yorks Creek 2 (YC2) improved from Poor to Average in 2015. The remaining 37 sites showed no change over the surveys, with one site, Middle Bettys Diversion 7 (MBD7), not assessed in 2017.

Engeny (2018, Table 3.12, pp. 20-22) reported CSIRO Ephemeral Stream Assessment scores for 2017 and compared the classified overall index scores with the 2014 scores from SLR (2014). For each site they noted whether geomorphic stability was static, improved or decreased. Fourteen sites were static, seventeen decreased and ten improved. There was no particular pattern to these changes, and Engeny (2018) did not attempt to explain the result. Engeny (2018) did not undertake statistical analysis of the data to determine if the claimed changes were significant, or were not significant, in which case they should be considered static.

There are insufficient sites to statistically analyse change at the diversions individually. However, the data can be grouped as control sites, which include 7 reference sites on Bowmans, Yorks and Main creeks, and 14 natural sites within or upstream or downstream of diversions (total of 20 sites), and impact sites, which are on diversions (total of 21 sites). The data from 2014 and 2017 were compared for these two groups of sites (i.e. control and impact) using a paired two sample t-test for difference of means ($\alpha = 0.05$). The result was that there was no statistical difference between the 2014 and 2017 data for the impact sites, while the control sites had statistically lower scores in 2017 than in 2014. The scores were also compared between the two groups of sites for both 2014 and 2017 using a two sample y-test for difference of means assuming unequal variance ($\alpha = 0.05$). The result was that in 2014 there was no statistical difference between the control and impact sites, while in 2017 the control sites has statistically lower scores (poorer stability). These results suggest that in 2017 the control sites were more unstable than the impact sites and this was related to a decline in the scores in the control sites in 2017. The stability of the impact sites did not change between 2014 and 2017.

Table 15. Tests for statistical difference of means in CSIRO Ephemeral Stream Assessment overall scores, control and impact sites, 2014 and 2017.

	2014 Impact sites	2017 Control sites	2017 Impact sites
2014 Control sites	Not statistically different	Statistically different (lower scores in 2017)	-
2014 Impact sites	-	-	Not statistically different
2017 Control sites	-	-	Statistically different (lower scores in control sites)

6.0 Diversion Design Objectives

6.1 Background to Hydraulic Criteria

A set of design objectives were established for the Project. The objectives were based on a philosophy of minimising capital and maintenance costs, maintaining environmental values, incorporating natural geomorphological forms and processes typical of the existing Yorks Creek or alternative regional reference reaches, achieving an acceptable degree of physical stability, and minimising risks to downstream riverine environments.

An alternative and complementary approach to the diversion design philosophy of mimicking the geomorphic form and process and hydraulic character of the existing stream channel is to follow Australian Coal Association Research Program (ACARP) design and monitoring criteria based on characteristics of regional stream systems and replication of the natural stream processes. ACARP guidelines were based on the findings of a series of research projects conducted between 1999 and 2002 on performance of existing diversions (White et al., 2014). One of the elements of the ACARP guidelines often used for diversion design is a table of hydraulic criteria. The criteria form part of the Department of Natural Resources and Mines (2014) guidelines for diversions, but with a cautionary note that:

> "*The hydraulic criteria of the existing watercourse should be used as first preference to develop design parameters for the watercourse diversion. The ACARP guideline values (Table 1) were derived to assist watercourse diversion design within the Bowen Basin for velocity, stream power and shear stress. The designer should also consider other design principles where relevant when undertaking the design process*."

Table 1 referred to above (DNRM, 2014, p. 33) is reproduced here (Table 16). The reference cited for the critical hydraulic values provided by DNRM (2014) was Hardie and Lucas (2002).

A similar table of criteria was provided in SKM (2009). Parsons Brinkerhoff (2010) and Kellogg Brown & Root (2013) (Table 17), quoting the source as Hardie and Lucas (2002) [also referred to as ACARP (2002)] and/or Vernon (2008) [also referred to as DERM (2008) and a later version as DERM (2011)]. The table differs from that provided by DNRM (2014) (Table 16) in values for stream power and bed shear stress for the 50 year ARI flood.

A third table of criteria was provided by White et al. (2014), also citing Hardie and Lucas (2002) as the source. This table was referred to by White et al. (2014) as "*(…ACARP design criteria)…adopted by Queensland regulators in 2002*". In this case, differing sets of criteria were provided for the three different stream types incised, limited capacity and partly bedrock controlled (Table 18). While 'incised' and 'partially bedrock controlled' have conventional meanings with respect to geomorphic stream type, White et al. (2014) did not define the meaning of 'limited capacity'. 'Capacity' could refer to sediment transport or discharge, or both, and the term 'limited' is relative. The criteria values suggest 'limited capacity' refers to channels on the lower end of the energy spectrum and relatively small in size relative to their flood discharge magnitudes, but they could also be of an expected size with high roughness. The upper limits of the ranges of these criteria (for incised and bedrock stream types) were recognised as "*ACARP guidelines*" by Mount Owen Complex (MOC) Creek Diversion Plan (Glencore, 2017, p.11).

Tables of ACARP-derived hydraulic criteria thresholds (Table 16, Table 17 and Table 18) should be used with caution in diversion design, for a number of reasons:

1. The tables were based on observations made in the Bowen Basin, Queensland and might not apply in other locations.
2. More than one version of the criteria exists, and the original version was specific to geomorphic stream type.
3. The original threshold values were specified as a range for stream power and velocity, while later versions only specified and upper limit of stream power, velocity and shear stress (presumably on the assumption that erosion was the main management issue); the lower thresholds are important to prevent excessive sedimentation of stream channels.
4. It seems inconsistent to specify the same thresholds for bed shear stress for vegetated and unvegetated channels, when it is well established in the literature that vegetation cover markedly increases resistance to scour and sediment transport, and when different values are given for the related variables stream power and velocity.

5. Department of Natural Resources and Mines (2014) recommended that the hydraulic criteria of the existing watercourse should be used as first preference over ACARP hydraulic thresholds to develop design parameters for the watercourse diversion.

Table 16. Guideline values for average stream powers, velocity and shear stresses for streams within the Bowen Basin. Source: DNRM (2014, p. 33).

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

Table 17. Guideline values for average stream powers, velocity and shear stresses for streams within the Bowen Basin. Source: Vernon (2008).

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

Table 18. Typical values for dependent variables identified for sample stream reaches; ACARP design criteria adopted by Queensland Government in 2002. Source: White et al. (2014).

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

6.2 Basis of Yorks Creek Diversion Design Objectives

The ACARP design principles were based on research and practice in the Bowen Basin, Queensland. Although the hydraulic criteria might require modification to suit other areas, they are a reasonable starting point for any diversion project, including Yorks Creek. The most comprehensive Australian diversion design guidelines, which incorporate ACARP principles, were produced by Department of Natural Resources and Mines (2014). It is recommended that the York Creek design follow these guidelines.

Hancock (2001) made specific recommendations about geomorphic design elements for diversions and rehabilitation works in the Hunter Valley:

- Maintenance of the degrees of freedom of the stream – that is the ability of the stream to migrate in its channel boundaries, to incise to a stable bedrock/armoured gravel/vegetation control which will not transmit upstream
- Provision of flow variability along the stream channel (pool/riffle sequences)
- Provision of meanders as part of the degrees of freedom of the stream
- Use of indigenous vegetation to form controls on the system – schedules 1 and 2 streams
- Mixed bed controls (woody debris or competent rock at spacing) on larger defined streams
- Use of vegetation to form the bank controls, and ecosystem structure
- Provide as much diversity in channel design and vegetation system as the site allows!"

Department of Infrastructure, Planning and Natural Resources (2005) and Hancock (2001) supported the design principle that achievement of streams with healthy functioning ecosystems required incorporation of geomorphic variability, stability, resilience and dynamic equilibrium. Rivers are naturally dynamic, so temporal variability in geomorphic forms is to be expected, and the dynamic nature of river geomorphology could be critically important for maintenance of stream health.

The design philosophy of Department of Infrastructure, Planning and Natural Resources (2005) and Hancock (2001) is consistent with that of Department of Natural Resources and Mines (2014).

6.3 Summary of Key Design Objectives

Physical Stability

The design process for the diversion should consider the ACARP hydraulic guidelines (Table 18), but more importantly, design of the morphology and instream features should be guided by the morphologic and hydraulic characteristics of the existing creek, and the need to meet a range of objectives. The limited available modelled flood velocities in Yorks Creek downstream of the existing mine (Table 12) suggests that hydraulically this channel falls within the ACARP range for the limited capacity stream type (Table 18). Although confirmation of this requires additional modelling data, this suggests that these ACARP values could inform the diversion design.

Physical stability criteria apply to the channel bed and banks, floodplain surfaces, and valley walls. Valley walls are subject to both fluvial erosion and surface rainfall impact and runoff impacts. The design needs to minimise the risk of excessive valley wall erosion in the lower half of the diversion.

Physical form

The physical form should provide a similar degree of variability as the existing Yorks Creek. This means that measures of bank and bed variability in cross-section and long-profile should be similar. It might not be possible to achieve similarity of variability of form in the planform (i.e. sinuosity, radius of curvature).

This objective is based on the assumption that biological diversity is correlated with physical diversity, through creation of hydraulic diversity.

In the upper low gradient zone, the cross-section profile will likely consist of a central rectangular channel with longitudinal and cross-sectional variability, set within a floodplain. Dimensions will be based on stability and hydraulic considerations, as well as the existing Yorks Creek morphology and the morphology of the alternative reference sites.

In the lower high gradient zone, replication of the natural creek gradient is not possible due to constraints set by the diversion template. Dimensions will be based on stability and hydraulic considerations, as well as the morphology of the alternative reference sites The cross-section will likely consist of a low flow channel set within benches. The construction material is likely to be rock, with high porosity. Flow will likely be subsurface except at times of flood peak, however flow could be forced to the surface by use of a geotextile layer or a less porous surface layer that can support dense vegetation cover, if this is deemed an important ecological value.

In the confluence zone, there may be value in creating a backwater pond/stilling basin for improved habitat at the confluence. This could be an opportunity to add to the physical diversity in Bowmans Creek, at times of medium to high flow in Bowmans Creek.

Large wood

Ideally, large wood should be sustainably supplied to the diversion channel by the riparian trees. Until such time that the trees are large enough to create significant wood loading, the diversion should be stocked with wood at an agreed density. The density will be less than the existing Yorks Ceek, as it is anticipated that wood will be naturally recruited to the channel. The large wood should be relatively stable when installed. Anchoring with weights or cables should be employed only if wood stability cannot be achieved by other means.

Bed and bank materials

In sections of the diversion where gradients, velocities and bed shear stresses are similar to the existing Yorks Creek, the bed and bank materials can be similar to the existing creek. Where the bed shear stress exceeds the range of the existing creek, more erosion resistant materials will be required. The material selection should be based on agreed physical stability criteria. The fill material used in the upper low gradient zone should be free of contamination and have high cohesivity. Levels of contamination must be within EPA standards for clean cut and fill.

Riparian vegetation

Riparian vegetation should be similar to the assumed floristics of the local drainage lines before disturbance from agriculture, assuming this is known, and is not constrained by other factors.

Depending on the assessment of the riparian vegetation in the existing Yorks Creek, there is potential for improving the condition of riparian vegetation in the diversion.

Aquatic invertebrates and fish

The diversion should provide instream habitat sufficient that the diversity of aquatic organisms is not lower than observed in the existing Yorks Creek. Aquatic habitat surveys should confirm the need for the establishment of aquatic fauna habitat. Both the high gradient and low gradient zones of the design template will present difficulties for replicating the existing physical habitat.

Reptiles and mammals in riparian zone

The diversion should provide riparian habitat sufficient that the diversity of reptiles and mammals in is not lower than observed in the existing Yorks Creek.

Hydrological integrity

Yorks Creek is intermittent, which means that its main contribution to the hydrology of Bowmans Creek, and in turn, the Hunter River, is storm flow. There could be tolerable loss of baseflow in the rising and recession limbs of storm hydrographs due to higher permeability of the bed and bank materials of the diversion. The permeability of the materials will decrease over time.

The acceptance of loss of some baseflow is based on the assumption that it is a small volume, and the risks and complexities of preventing total loss of baseflow, through placing a clay liner beneath the bed of the diversion, are high enough that it is not warranted.

This objective will require demonstration that loss of flow to the sub-surface and risk of failure into the pit shell is minor.

Sediment transport

The diversion should have a similar capacity to transport sediment as the existing Yorks Creek. This means that there will be no net change (on the long-term time scale of approximately 10 years) to sediment load entering Bowmans Creek, both bed load and suspended load.

This objective requires consideration in the design for sediment sources, sediment depositional zones, and sediment transport capacity.

Aesthetic values

The appearance of the diversion should meet an agreed standard of landscape aesthetic value.

Cost

The design should be cost effective, with the objective of meeting the objectives for the least cost of construction and maintenance.

Conditions set by regulators or legislation, or advised by conventional guidelines

All legislated conditions must be met.

Monitoring

The monitoring program for channel morphology should be of a before-after and control-impact design. The before-after criteria will set the absolute limits of allowable change in channel dimensions and position. The control-impact criteria will allow change in the diversion to be within the range observed in a control site. The monitoring methodology should use objectively measured data and avoid rapid visual assessment approaches. The sampling design should provide sufficient statistical power to have the capacity to detect change over time.

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