Menangle Quarry Modification to Development Consent 85/2865

Fluvial Geomorphology Assessment

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September 2019

Menangle Sand and Soil Supplies Pty Ltd

FLUVIAL SYSTEMS

Menangle Quarry Modification to Development Consent 85/2865

Fluvial Geomorphology Assessment

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Executive Summary

This report provided a comprehensive geomorphic assessment of the geomorphic character of the Nepean Gorge in the Stage 8 area proposed for sand and gravel extraction, as well as an assessment of the potential impact of extraction and restoration on geomorphic character. This work was undertaken as part of the response to a letter by Donette Holm, Principal Legal Officer, Legal Services, Department of Planning & Environment to Luke Walker, Minter Ellison, dated 19 June 2019 (Ref EF18/47183) listing matters which should be addressed by the Applicant in order for the Respondent to be in a position to fully assess the environmental impact of the proposal.

The main objective of this report was to objectively identify river banks and depositional benches and define their boundaries to inform refinement of the riverside and landward boundaries of the extraction areas. This work was undertaken using standard methodologies of terrain analysis using best available information.

The various terrain analysis indexes, as well as the cross-section morphometric indexes, produced very consistent results, suggesting that the channel bench landforms were reliably identified. It is likely that the resource is mainly confined to these channel benches. Elsewhere, the resource would likely be present as a sandy drape of variable thickness overlying rocky debris from the cliffs and steep slopes of the gorge. Much of this area was at the expected angle of repose of a talus slope. It might still be economic to extract the material from the slopes, depending on its thickness and practical difficulties presented by the slope.

The methodology allowed objective identification of bank edges, both riverside and landward, that could be used to refine the extraction boundaries based on the objective of maximising the retention of the channel bank face. However, there would be practical difficulties implementing this approach, as multiple edges were present, the edges were highly variable in location and elevation, and they were discontinuous. These data could provide a morphology-based rationale for delineation of the riverside boundaries of the extraction areas, but this is a matter that requires careful consideration of various other factors not covered in this report. The landward side of the extraction areas would best be determined by field survey using an excavator or other soil sampling technique.

Bed shear stress data suggests that during floods, scattered patches of scour could occur, although it is likely that on the falling limbs of hydrographs some or all of the scoured areas could infill, or partially infill, with coarse sediment, with revegetation occurring between flood events. This is a natural and expected process that would occur regardless of extraction operations. The risk of scour of the operations area can be reduced by retaining as much vegetation as possible, revegetating disturbed land as quickly as possible, and protecting the 10 m wide horizontal top of the setback area (if vegetation cover is disturbed) with appropriate erosion resistant material.

After consideration of additional data, including the geomorphological assessment contained within this report, the boundaries of the extraction area and the approach to treatment of the setback area were amended. To preserve native trees and maintain bank stability it is proposed to retain all of the native trees within the horizontal setback area with a diameter at breast height (DBH) exceeding 0.1 m. This approach would result in a topography that was variable in both the cross-sectional and longitudinal directions. Also, the width of the setback area would vary depending on the location of the trees within it. The hydraulics of the amended scenario were not described in this report.

A tree canopy elevation model was created by subtracting the high vegetation LiDAR data from the ground strike LiDAR data and then cropping the resulting 1 m grid to include only heights exceeding 5 m. The model identified the likelihood of trees exceeding 0.1 m DBH being present on the longitudinal profile of the setback, but the data were not considered to be of sufficient accuracy to locate the position of individual tree stems across the setback area. Tree canopy was present along 66% of the length of the horizontal setback area in the northern extraction area and 57% of the length of the horizontal setback area in the southern extraction area. The modelling suggested that the elevation of the final landform of the setback area could vary between 64 and 71 m AHD. The bank slopes would be within the existing range of 1:2 to 1:4 (V:H), and the longitudinal slope of the setback area would vary from almost flat to 1:2 (V:H), although on formed areas, the maximum longitudinal slope would be less than 1:5 (V:H).

1. Introduction

1.1 Background and scope of this report

This report was undertaken under instruction from Luke Walker and Adele Veness, Minter Ellison, acting for Menangle Sand and Soil Supplies Pty Ltd in the matter of Menangle Soil and Sand Pty Ltd v Minister for Planning, LEC Proceedings 2018/342158.

In reference to the s34 conference in the above proceedings which was terminated on 14 June 2019 by Commissioner Chilcott, Donette Holm, Principal Legal Officer, Legal Services, Department of Planning & Environment wrote to Luke Walker, Minter Ellison, on 19 June 2019 (Ref EF18/47183) listing matters which should be addressed by the Applicant in order for the Respondent to be in a position to fully assess the environmental impact of the proposal. This report addresses some of those listed matters. The matters to be addressed are within item number 1), extracted from the letter of 19 June 2019 below:

1) Clarify proposed locations and activities

- The Applicant should provide an updated set of plans which clarifies and provides certainty for the proposed extraction boundaries, both riverside and landward limits.
    - The plans should also clarify that sub-stage labelling from A to M is from north to south, as there are mislabelling issues in the most recent set of enlarged figures provided on 12 June 2019 (e.g. the velocity output maps for the various sub-stages), in contrast to what was presented in the Extension Project Briefing Paper May 2019. An example of the inaccurate extraction boundaries on the enlarged figures includes sub-stage 8B, 8C and 8L where the proposed riverside boundary of extraction and the 64 m AHD is ~ 10 to 20 m inaccurate in the horizontal, suggesting extraction activities would occur riverside of the 64 m AHD mark. In contrast, sub-stage 8G has the proposed extraction boundary landward of the 64 m AHD boundary.
- The designation of the extraction boundaries on the figures is unsatisfactory. Each substage should be represented by standalone maps, where proposed riverside extraction boundaries match the 64 m AHD contour + 10 m re-graded setback zone. It must also be acknowledged that all contours presented in this fashion would be derived from the 1 m digital elevation model (LiDAR), which in itself may have a 0.15 – 0.3 m vertical uncertainty translating to horizontal inaccuracies.
- For sub-stages A, B, C, K, L and M:
    - Present each sub-stage base map with the 64 m AHD contour + 10 m setback as the riverside boundary of activities and overlay these maps on an ortho-photograph.
    - Designate the ‘re-graded setback’ zone along with the location of existing tracks;
    - Mark the areas landward of proposed extraction as zones of restoration vs extracted and rehabilitated zones.
- For sub-stages D to L:
    - Present each sub-stage base map with the 64 m, 67 m and 70 m AHD contours as options for the designated ‘no works’ riverside boundary of activities and overlay these maps on an ortho-photograph;
    - Designate in these sub-stages the ‘no mechanical works’ on the riverside boundary and the landward side of extraction, along with the location of existing tracks;

- For each sub-stage:
    - derive an existing topographic cross-section at mid-stage location with true-to-scale locations of boundaries for extraction, no works and landward restoration boundary;
    - on each cross-section identify proposed river channel cross-section (post extraction) with designated minimum batter angles of 1:50 (as relevant) and no more than 1:5 for the riverside extraction batter.
- Provide details of the 'active' pit design, showing location of working face etc.

This report contains technical information, prepared for the purpose of informing others involved in the process of fully addressing the above requirements. This report contains maps prepared primarily for the purpose of geomorphic assessment; they were not intended as final maps to specifically address the matters above, although some of the maps might contain information that would appear on such final maps. The extraction area boundaries drawn on maps in this report were limited to the boundaries of the sub-stage areas perpendicular to the river (current at 19 June 2019). The longitudinal riverside or landward boundaries were not drawn on the maps, as review of the alignment of these boundaries is the subject of this report.

With respect to the first dot point above: "*The plans should also clarify that sub-stage labelling from A to M is from north to south…*", this report uses the sub-stage labelling convention of EMM (2018) *Environmental Assessment Menangle Quarry Extension*. That report arranged extraction sub-stage area labels alphabetically in a north to south direction (Figure 1).

Note that the Stage 8 extraction area boundaries on the original staging plan depicted in Figure 1 were current at the time this geomorphological assessment began, in July 2019. Partly in response to the geomorphic assessment of operations based on those boundaries, the extraction area boundaries were revised, so the boundaries in Figure 1 are no longer current.

With respect to the third dot point above "*For sub-stages A, B, C, K, L and M…*" and the fourth dot point above "*For sub-stages D to L…*", this report assumes that the intent was to specify matters separately for the northern extraction area sub-stages (a, b and c) and the southern extraction area sub-stages (d – m), respectively, i.e. the fourth dot point also includes sub-stage m.

With respect to the fourth dot point above "*For sub-stages D to L…*[in this report, including sub-stage m] *present each sub-stage base map with the 64 m, 67 m and 70 m AHD contours as options for the designated 'no works' riverside boundary of activities*…", as no technical basis was provided for the alternative contour elevations 67 m and 70 m AHD, this report assumes that these are suggested starting points for an investigation of potential alternative riverside boundaries. This report aims to inform this matter by investigating, in addition to these suggested contours, potential alternative riverside boundaries that are based on geomorphic form and process.

With respect to the fifth dot point above "…*derive an existing topographic cross-section at mid-stage location*…", to avoid subjectivity in cross-section location, 24 cross-sections were automatically extracted in GIS along an automatically-defined river channel centreline at a fixed spacing of 200 m, starting at Menangle Weir. Of these, 8 were located just upstream of the weir and in Stage 7 area, and 16 were in Stage 8. In number and location, the cross-sections objectively and adequately represented the geomorphic character of the river rather than being subjectively placed centrally within each sub-stage area. This objective strategy for cross-section placement resulted in the extraction sub-stages being adequately sampled.

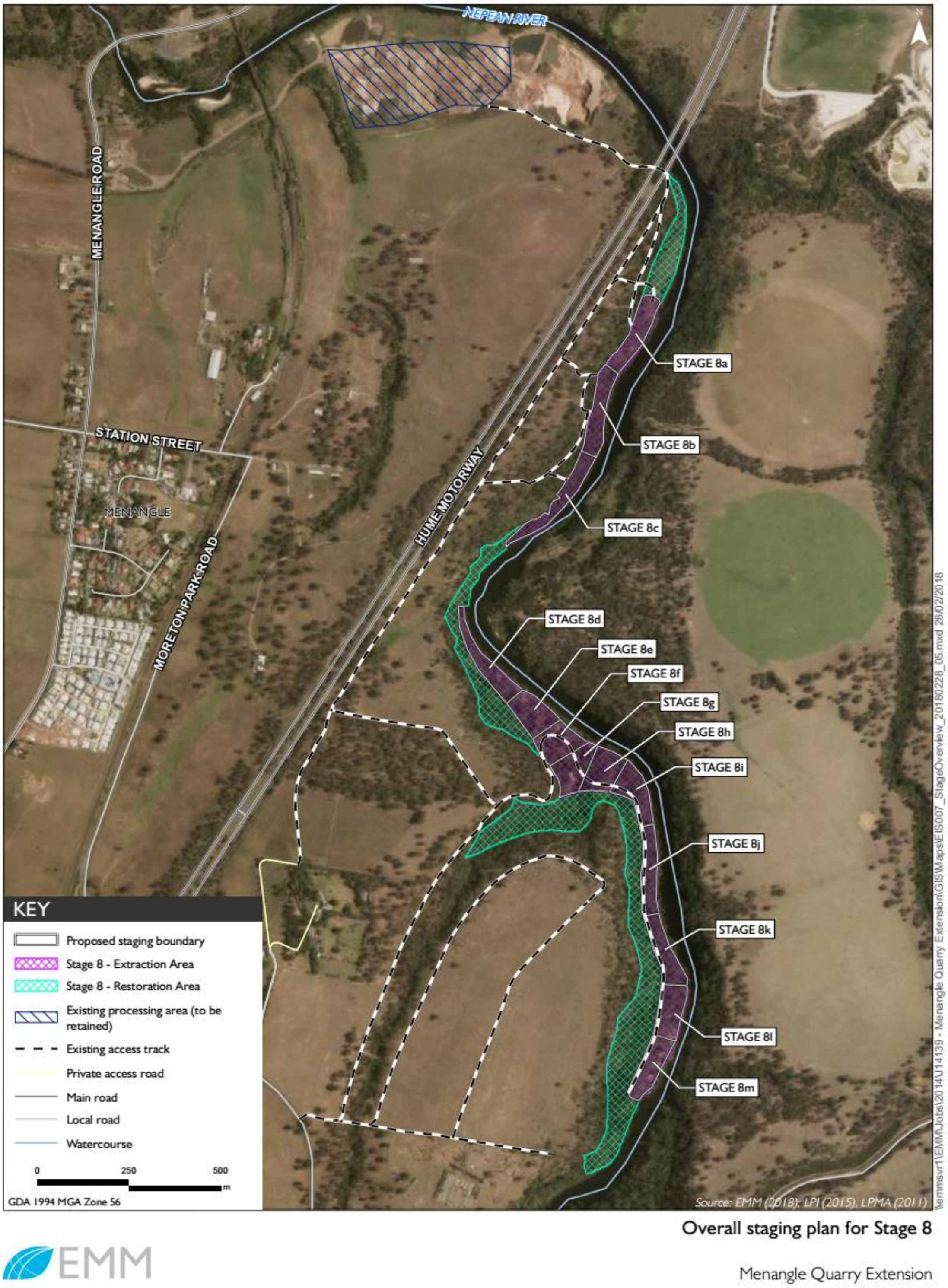

Figure 1. Original staging plan for Stage 8. Extracted from EMM (2018, Appendix E) DA 85/2865 MOD1, Response to DOI-Water comments of 21 February 2018. Note that the extraction boundaries have since been revised.

1.2 Study area

The core part of the Study Area covered by this report was the Nepean River gorge within Stage 8 extraction area and associated restoration areas (Figure 1), although some aspects of the river downstream to Bergins

Weir and a short distance upstream of the extent of Stage 8 area were also investigated to provide comparison or context.

1.3 Proposed extraction operations

The environmental impact statement for the current operations (Riley, 1987) described the proposed floodplain mining operation for stages 1, 2, 6 and 7 as "…*leave a bank 3 to 5 metres above low water level and to cut into the floodplain, leaving a surface with a slope of 1 in 40 towards the channel. Extraction will proceed out onto the floodplain for distances of the order of 200 to 300 metres except for the NSW Trotting Club and Campbelltown City Council land, where extraction will only extend to approximately 150 m from the bank*."

NSW Department of Water Resources (1992) listed interim management strategies developed to limit increased rates of riverbed and bank erosion resulting from sand and gravel extraction. For the situation in the Study Area, the relevant strategy would be "*Where there are no controls to prevent bed lowering, excavation is limited to harvesting the tops of bars and islands above low flow water level. The only exception to this is where proponents are willing to backfill any excavated holes with suitable material. In these relatively rare cases, strict limits are placed on the sizes of holes at any one point in time and buffers must be maintained to isolate excavations from the active flow*".

The proposal for Stage 8 extraction under review here was to setback the extraction area a minimum of 10 m from the 64 m AHD contour, leaving the lower portion of the river bank undisturbed (EMM, 2017). Extraction would be to a level of 62 m AHD, which is 1 m above the low flow water level. The pit would be filled to a level of 64 m with unsaleable coarse mineral particles and organic material screened from the extracted resource, known as scalps (EMM, 2017). This proposal is consistent with the approach described by Riley (1987) (above) for the current Stage 7 operations and the interim guidelines of NSW Department of Water Resources (1992) (above). The elevation of 64 m AHD appears to be based on past experience, although EMM (2018) stated that a water level of 64 m corresponded to a flow of 100 m^3/s, and flow was less than this for 99% of the time. Thus, 64 m does not necessarily correspond with a geomorphic boundary, and was related to a flow duration, not a flood frequency.

1.4 Objectives

The main objective of this report was to objectively identify river banks and depositional benches and define their boundaries to inform refinement of the riverside and landward boundaries of the extraction areas.

As correctly pointed out by Donette Holm in her letter to Luke Walker on 19 June 2019 (first dot point), the riverside extraction boundaries provided in EMM (2017) did not necessarily follow the 64 m AHD contour (the proposed boundary). Thus, one objective of this report was to delineate the 64 m AHD contour and the boundary of the 10 m re-graded setback zone, landward of the 64 m AHD contour. The setback would be re-graded to a slope of 1 in 50, so the landward top edge of the setback would be at 63.8 m AHD. A related objective was to evaluate the potential of alternative boundaries set at the 67 m and 70 m AHD contours for the southern extraction area (sub-stages 8d to 8m). Further, as discussed between the parties at the s34 conference on 14 June 2019, this report investigates potential alternative riverside extraction area boundaries that are based on geomorphic form and process rather than an arbitrary or traditional fixed contour elevation.

As with the riverside extraction boundaries, the landward extraction boundaries provided in EMM (2017) were indicative only. Criteria for establishing the landward extraction boundaries were not provided in EMM (2017), although it was stated that the extraction area would be between 64 m AHD and 92 m AHD (p. 71); based on the typical width of the 'terraces', the 1 ha sub-stages would be approximately 50 m wide by 200 m long (EMM, 2017, p. 38). This report investigates potential landward extraction area boundaries that are based on geomorphic form and process. In this context, the key geomorphic process was risk of scour, evaluated using modelled bed shear stress.

This report uses terrain analysis to define geomorphic boundaries on the basis of topography. An alternative or supplementary approach is to sample soil profiles by taking cores or excavating pits. This was not done for this report, but in late July 2018, Brett Jarvis of Benedict independently undertook sediment excavations over the Stage 8 area to improve knowledge of resource availability. The results of that survey are not included in this report.

1.5 Qualifications and experience

I hold a PhD in hydrology and fluvial geomorphology awarded from the University of NSW in 1989 and a BSc (Hons I) awarded from the University of Newcastle, NSW in 1982.

Since I obtained my doctorate, I have worked continuously for 29 years in the water resources sector, undertaking academic research and consultancy. My expertise is evidenced by my numerous peer reviewed scientific publications in this field, including being co-author of the international text book *Stream Hydrology: An Introduction for Ecologists* (2004) [Wiley]. I also have expertise in technical aspects of methodologies required to undertake hydrological analysis, including hydrological and hydraulic modelling, and spatial analysis (objective numerical characterisation of landforms) using Geographic Information Systems (GIS).

Currently, my employment is:

- Consultant Hydrologist and Geomorphologist, Fluvial Systems Pty Ltd, Newcastle, a company I founded in 1999 that provides specialist services in fluvial geomorphology and hydrology to the water resources sector.

- Adjunct Senior Research Fellow, Australian Rivers Institute, Griffith University, Queensland, since 2012.

Previously I have been employed, or worked on a Fellowship, at:

- Changjiang Water Resources Protection Institute, Ministry of Water Resources (China), High-end Foreign Recruitment Programme Visiting Fellow (Sep – Oct 2013)

- College of Water Resources and Hydropower Engineering, Wuhan University (China), High-end Foreign Recruitment Programme Visiting Fellow (Nov – Dec 2013, May – Jul 2014, June – July 2015)

- Fellow in the Department of Resource Management and Geography, Melbourne School of Land and Environment, The University of Melbourne (1999 – 2012)

- The University of Melbourne (Senior Research Fellow 1990 – 1999); The University of NSW (Teaching Fellow 1985 – 1989); Adelaide University (Tutor 1983 – 1984)

- Visiting Fellow, Loughborough University (U.K.) and Exeter University (U.K.) (1992 – 1993) – Australian Bicentennial Fellowship and British Council Academic Links and Interchange Scheme Grant

This report is independent and impartial.

2. Methodology

2.1 Identification of natural landform elements and boundaries

2.1.1 Topographic and bathymetric data and aerial photography

The digital terrain data utilised here was provided by NSW Spatial Services, Department of Finance, Services and Innovation, available from ELVIS - Elevation and Depth - Foundation Spatial Data, Version 0.1.1.0 (http://elevation.fsdf.org.au/). In this area, point cloud LiDAR (Light Detection and Ranging) data collected from flights over the period 26 February 2011 to 23 March 2011 was used. The C3 LAS data set contains point data in LAS 1.2 format sourced from a LiDAR from an ALS50ii (Airborne Laser Scanner) sensor. The processed data has been manually edited to achieve ICSM classification level 3 whereby the ground class contains minimal non-ground points such as vegetation, water, bridges, temporary features, jetties etc. This data has an accuracy of 0.3 m (95% Confidence Interval) vertical and 0.8 m (95% Confidence Interval) horizontal with a quoted minimum point density of 1.03 laser pulses per square metre. However, the ground strike point density varied over the Study Area, with average point density within the gorge terrain of 1 pulse every 3.5 square metres. This lower pulse density is explained by dense vegetation and steep terrain within the gorge. Despite the relatively low density of points in the gorge, NSW Spatial Services provides a 1 m square cell DEM (digital elevation model) covering this area. In this report, the 1 m DEM was reproduced using the ground point cloud data, after first editing erroneously identified ground points that were clearly on the river water surface, as identified from aerial photography.

It is important to recognise that the vertical and horizontal accuracy of the point cloud data within the gorge is not as high as the metadata suggests. For the purpose of characterisation of terrain over large areas or modelling river hydraulics, the topography would be adequately represented by a 5 m grid DEM.

The bathymetry of the river from Menangle Weir to the upstream end of Stage 8 extraction area was surveyed by Marine Pollution Research Pty Ltd over two days in early June 2019 using a boat-mounted sounder, with the point data processed to a map of depth contours at 0.5 m interval. The GIS application Global Mapper™ V20.1.0 Feb 25 2019 Build (Blue Marble Geographics) was used to further process the bathymetry data. After masking the surveyed area, the contours were gridded to a 2 m grid and given a negative sign. The river flow was low at the time, and assumed to be at 61 m AHD over the length of the weir pool, so 61 m was added to the negative depth grid to derive a bathymetry grid to AHD, which was then merged with the 1 m LiDAR-based grid.

The aerial photography utilised in this report was NSW Imagery dated 23/07/2018, downloaded directly to GIS from the Spatial Services WMS (Web Map Service). This is the same image that currently appears in Spatial Service's Six Maps (https://maps.six.nsw.gov.au/).

2.1.2 Terminology and criteria for defining landform elements

The environmental impact statement for the current operations (Riley, 1987) termed the morphological elements that contain the resource 'in-channel benches', while EMM (2017) referred to these elements throughout the Environmental Assessment as 'terraces'. Using the definitions of Office of Environment and Heritage (2017), which were borrowed from the 'Landforms' chapter of the *Australian Soil and Land Survey Field Handbook* (Speight, 2009), the geomorphological elements of main interest for resource extraction are properly termed 'channel benches' (Table 1), and should not be referred to as terraces, which are a different landform element. A bench is a type of 'flat', which Speight (2009) specified had a maximum slope of 3% (Table 1). Under the landform classification of Speight (2009), morphological elements with slope exceeding 3% are termed 'slopes'. When bench topography is represented by small grid cells up to 5 m, slopes of individual cells would be expected to exceed 3% even though the overall bench element might be a flat.

The geomorphological elements likely to be found in the Study Area were defined using the criteria of Speight (2009) (Table 1), with slope classes defined by a range of slopes (Table 2). Alternative criteria for defining steep slopes and cliffs in underground mining assessments (Department of Planning, 2014) (Table 3) were applied to the Nepean Gorge just south of the Study Area (BHP Billiton Illawarra Coal, 2012). These criteria were adopted for this report to allow comparison with that study.

Talus (Table 1) slope deposits form at the foot of cliff faces, often in the form of a cone, or a planar surface following the base of a cliff line. A talus slope is at the angle of repose. Rockfall starts with the detachment of rocks from bedrock slopes. The fall of rocks stops abruptly due to energy lost through collisions and friction forces that act on the rock during transport over slope surfaces (Dorren, 2003). When rockfall occurs on slopes covered with vegetation, the evidence for talus cones is less distinct (Dorren, 2003; Loye et al., 2008). Jaboyedoff (2003) reported that talus cones usually have angles of inclination in the range 27° to 37°. The talus cones investigated by Albjär et al. (1979) (from various regions) had mean slope gradients of 25° to 35°. On the basis of these studies, potential talus slopes were defined as having slope between 26.6° [1(V):2(H)] and 36.9° [3(V):4(H)] and being located at the base of cliffs. Land falling within this range of slopes was regarded as potential talus slope, as it is possible to find non-talus slopes (i.e. not an accumulation of rock at the base of a cliff) in landscapes within this slope range.

Table 1. Characteristics of standard landform elements with potential to be found in the Study Area (Speight, 2009).

Landform element	Definition
Bank (Stream)	very short, very wide slope, moderately inclined to (stream precipitous, forming the marginal upper parts of a stream bank) channel and resulting from erosion or aggradation by channelled stream flow.
Channel bench	flat at the margin of a stream channel aggraded and, in part, eroded by overbank and channelled stream flow; an incipient floodplain. Channel benches have been referred to as 'low terraces', but the term 'terrace' should be restricted to landform patterns above the influence of active streamflow.
Cliff	very wide, cliffed (greater than 72°) maximal slope usually eroded by gravitational fall as a result of erosion of the base by various agencies; sometimes built up by marine organisms (cf. Scarp).
Cliff footslope	slope situated below a cliff, with its contours generally parallel to the line of the cliff, eroded by sheet wash or water-aided mass movement, and aggraded locally by collapsed material from above.
Flat	planar landform element that is neither a crest nor a depression and is level or very gently inclined (<3% tangent approximately).
Footslope	moderately to very gently inclined waning lower slope resulting from aggradation or erosion by sheet flow, earth flow or creep (cf. Pediment)
Hillslope	gently inclined to precipitous slope, commonly simple and maximal, eroded by sheet wash, creep or water-aided mass movement. A typical element of mountains, hills, low hills and rises
Talus	moderately inclined or steep waning lower slope, consisting of rock fragments aggraded by gravity.

Table 2. Slope classes for landform elements (Speight, 2009).

Slope class	Range of slope		
	Tangent %	Degrees	Ratio
Level	0 – 1	0 – 0.6	0(V):0(H) - 1(V):100(H)
Very gently inclined	1 – 3	0.6 – 1.7	1(V):100(H) - 1(V):33.3(H)
Gently inclined	3 – 10	1.7 – 5.7	1(V):33.3(H) - 1(V):10(H)
Moderately inclined	10 – 32	5.7 – 17.7	1(V):10(H) - 1(V):3.1(H)
Steep	32 – 56	17.7 – 29.2	1(V):3.1(H) - 1(V):1.8(H)
Very steep	56 – 100	29.2 – 45.0	1(V):1.8(H) - 1(V):1(H)
Precipitous	100 – 300	45.0 – 71.6	1(V):1(H) - 1(V):0.33(H)
Cliffed	>300	> 71.6	> 1(V):0.33(H)

Table 3. Slope classes for steep slopes and cliffs (NSW Department of Planning (2014).

Slope class	Range of slope		
	Tangent %	Degrees	Ratio
Steep slope	33 – 200	18.4 – 63.4	1(V):3(H)
Cliff and minor cliff	>200	> 63.4	2(V):1(H)

2.1.3 Formation of channel benches

This report has a focus on identifying natural channel benches. The reason for this is that channel benches are composed of fluvially-deposited sand, gravel and fines, which is the material of interest for resource extraction. Assuming adequate sediment supply, benches form in rivers in locations determined by the hydraulics of the river. The hydraulics are determined by the interaction of the flow with the morphology of the river. In rocky gorges like the Nepean River in the Study Area, the broad location of benches is determined by the alignment of the river course, which over the scale of hundreds of years can be considered fixed. In other words, if benches are destroyed by catastrophic floods, or modified by sand and gravel extraction operations, they will reform in the same location. The role of vegetation is to stabilise the bench surface, and perhaps increase the rate of sediment deposition, but the existence of vegetation on a river bank is not a primary determinant of where a bench will form.

Vietz et al. (2007) undertook a detailed study of bench formation on the Ovens River, Victoria. They included a good description of the hydraulic and hydrologic conditions that form benches. Interestingly, the role of vegetation was not mentioned at all:

> *"A placid reverse flow environment is responsible for the deposition of fine-grained sediment on benches. Benches are not necessarily maintained by flows that just inundate the bench surface, but seemingly by most flows greater than bench inundation, with both magnitude and particularly duration important. In the concave benches investigated, the reverse flow environment was present throughout the full range of flows from bench inundation up to bankfull. In particular, as flow depth over the bench increases there appears to be a level where the velocity environment is most conducive to deposition, prior to velocities increasing again as the flow level nears bankfull.*

There was no scour of the bench surfaces during the detailed monitoring period of more than one year. Even at bankfull flows large low-velocity reverse-flow environments were evident and were associated with deposition rather than erosion."

2.1.4 Using terrain analysis to define landform elements in three-dimensional space

The procedures used to identify the natural landform elements and boundaries in the Study Area followed standard methods of terrain analysis, which is the automated analysis of landforms using digital elevation data sets. The analysis involves application of algorithms within a GIS (Geographic Information System) at detailed scales over wide areas to map characteristics of interest. Terrain analysis was undertaken using two difference GIS applications, Global Mapper™ V20.1.0 Feb 25 2019 Build (Blue Marble Geographics) and SAGA (System for Automated Geoscientific Analyses) GIS (http://www.saga-gis.org; Institute of Geography, Section for Physical Geography, Klimacampus and University of Hamburg, Germany) (Cimmery, 2007-2010; Böhner et al., 2006; Böhner et al., 2008).

For the purpose of defining landforms, slope was evaluated at a 5 m grid resolution. Polygons were then created to define land within cliff, steep slope, potential talus slope, non-steep slope, and level to very gently inclined slope classes (Table 2 and Table 3). The perimeter of the Nepean River Gorge was delineated by the upper steep slope boundary. Landform classification was undertaken within this gorge area.

A number of different methods have been proposed for automatically classifying landforms based on topographic data (e.g. Guisan et al., 1999; Schmidt and Hewitt, 2004; Iwahashi and Pike, 2007; Niculiță and Niculiță, 2011). The methods available in SAGA were tested for applicability to the Study Area, then parameter values of selected methods were refined through a second stage of testing.

The Topographic Position Index (TPI) was proposed by Guisan et al. (1999) and elaborated by Weiss (2001). An example application of TPI to landform classification in the Carpathian Mountains, Slovakia can be found in Barka et al. (2011). The TPI algorithm compares the elevation of each cell in a DEM to the mean elevation of a specified neighbourhood around that cell. Positive TPI values represent locations that are higher than the average of their surroundings, as defined by the neighbourhood (ridges). Negative TPI values represent locations that are lower than their surroundings (valleys). TPI values near zero are either flat areas (where the slope is near zero) or areas of constant slope (where the slope of the point is significantly greater than zero). The TPI algorithm in SAGA divides the terrain into 10 landform classes that can represent all landforms across the world, so a particular region will not necessarily have all of these classes present. Within the gorge of the Study Area, application of the TPI algorithm on the 5 m resolution DEM produced only two landform classes, open slopes and plains. The plains were interpreted as potential channel benches.

The Terrain Surface Classification (TSC) was proposed by Iwahashi and Pike (2007). This unsupervised classification method divides an area into landform classes using three taxonomic criteria: slope gradient, local convexity, and surface texture. To subdivide increasingly subtle topography, grid cells sloping at less than the mean gradient of the input DEM are classified by designating mean values of successively lower-sloping subsets of the study area (nested means) as taxonomic thresholds, thereby increasing the number of output categories from the minimum 8 to 12 or 16 (Table 4). According to Iwahashi and Pike (2007), the classifications reflect physiographic regions, geological structure, and landform as well as slope materials and processes; fine-textured terrain categories tend to correlate with erosional topography or older surfaces, coarse-textured classes with areas of little dissection.

Within the gorge of the Study Area, application of the TSC algorithm on the 5 m resolution DEM produced all 8 landform classes. Texture and convexity were not considered strong distinguishers of potential channel bench landforms. Thus, landform elements within the gentle classes (5 – 8) (Table 4) were interpreted as potential channel benches.

Table 4 The 8 landform classes of the terrain surface classification (TSC) algorithm of Iwahashi and Pike (2007).

	Surface geometry	Slope gradient	
		Steep	**Gentle**
I	fine texture, high convexity	1	5
III	fine texture, low convexity	3	7
II	coarse texture, high convexity	2	6
IV	coarse texture, low convexity	4	8

Curvature is a measure of the surface roundness of an area. Curvature is large for a curve with a small radius and is zero for a straight line (Li et al., 2015). As explained by Li (2015), curvature of a two-dimensional curve in the x-z plane is a function of first- and second-order derivatives. There is no straightforward extension of the second-order derivative (i.e. slope of the slope) for a three-dimensional surface (Li, 2015). On a gridded surface, curvature at a particular point is often characterized by curvature of a local quadratic surface that fits grid values in a least-square sense (Li, 2015). Curvature can be divided into plan (horizontal) curvature and profile (vertical) curvature (Gallant and Wilson, 2000) (Figure 2). Following the publication of Roberts (2001), curvature has been widely used to interpret geophysical data, including mapping of glaciovolcanic landforms (e.g. Pederson, 2016).

Profile curvature is useful for defining the boundaries of linear river features bank toe, bank top, and floodplain or channel bench extent (valley toe). These edges would be distinguished from low curvature surfaces on the basis of a curvature threshold, which would depend on the quadratic model used to define curvature, the grid resolution, and the nature of the terrain. Conceptually, an objective definition of the river bank edge in cross-section is provided by the point of maximum convex-linear profile curvature (Figure 2). Essentially, this is an objective definition of the bank inflexion cross-section geomorphic point of Navratil et al. (2006).

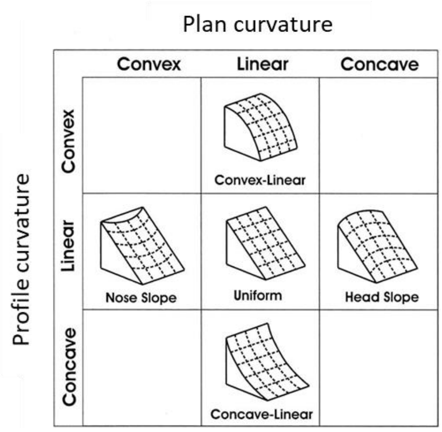

Figure 2. Types of profile and plan curvature used to classify landforms. Adapted from Rieke-Zappa and Nearing (2005).

Within the gorge of the Study Area, curvature was calculated for the 1 m resolution DEM, as the objective was to accurately define linear edges. Cells with curvature greater than -0.006 and less than 0.006 occurred on plane landform surfaces, and were considered non-edge features. Cells with curvature less than or equal to -0.006 were considered potential bench toe edge features, and cells with curvature greater than or equal to 0.006 were considered potential bench/bank top edge features. Linear groups of high curvature cells were selected as valid bench/bank top zones and linear groups of low curvature cells were selected as valid bench toe edge features. Polygons were automatically drawn to enclose groups of high and low curvature cells using the Coverage area (Concave hull) function of Global Mapper™ GIS. Lines were then automatically drawn through these polygons using the Create area skeletons/Centrelines function of Global Mapper™ GIS. These objectively determined lines defined potential bench/bank top edge and bench toe edge features.

2.1.5 Using morphometric indexes to define channel edges in two-dimensional cross-section space

Prior to availability of high resolution DEMs and terrain analysis tools in GIS, river edge features, primarily bankfull bank top, were defined either visually or objectively using morphometric indices applied to cross-section topographic data. The visual method is not repeatable, but morphometric indices remain valid.

Wolman (1955) defined bankfull stage as the stage at a given cross-section at which, in a plot of the width-to-depth ratio (R) against stage, the curve breaks sharply and the width becomes exceedingly large. Riley (1972) and Radecki-Pawlik (2002) interpreted this to mean that under this method, bankfull stage should correspond with the stage at which the ratio (R) is at a minimum. From a set of channel widths for given depths across the cross-section, the minimum value of the ratio:

$$R = \frac{W(i)}{\bar{D}\,(i)} \tag{1}$$

is sought, where,

W = water surface width

$\bar{D}$ = mean depth

$i = 1, 2, 3 \ldots n - 1th$ measurements

Riley (1972) found that the bankfull channel defined by the minimum width-depth ratio (whether using maximum or mean depth) was a function of the actual bankfull channel size and shape. The bankfull level defined by this index tended to be nearer the channel bed for channels with shallow profiles and gently sloping banks, and nearer the actual bankfull for rectangular-shaped channels. As an alternative, Riley (1972) proposed the bench index BI, whereby:

$$BI = \frac{W(i) - W\,(i+1)}{D\,(i) - D(i+1)} \tag{2}$$

where W and i are defined above and

D = maximum depth

Riley (1972) realised that the accuracy of the bench index method depended on the spacing of the survey data, but considered the spacing he employed (3 feet) provided satisfactory accuracy. Riley (1972) suggested that in a plot of the bench index (BI) against stage, for decreasing values of stage, BI shows a marked peak near the actual bankfull stage. This is known as the first (highest in the cross-section) bench index maximum.

The bankfull edge indices R and BI were computed from the 24 cross-sections automatically extracted along an automatically-defined river channel centreline at a fixed spacing of 200 m, starting at Menangle Weir.

The identification of minima of R and maxima of BI from cross-sections is dependent on the resolution of the survey data. The objective was to accurately define linear edges, so cross-section elevation data were extracted from the 1 m DEM at 0.5 m spacing. The minimum width-depth ratio and bench index methods were not conceived with such high resolution data in mind. When high resolution data are used, it is necessary to filter the many peaks and troughs that are identified. Two approaches were taken to this problem. The first approach was to automatically fill the sinks (depressions) in the cross-section profile prior to calculating the morphometric indexes. It was found that this method enhanced the significance of upwards convex high points at the expense of benches with flat or concave morphology. The preferred alternative method was to apply a sensitivity filter in selection of minima of R and maxima of BI. Three levels of sensitivity were applied. The first level selected all points that had both immediately adjacent values higher (for BI), or lower (for R), in elevation than that of the point. The second level of sensitivity required the additional criterion that on one side, two adjacent points had to be progressively higher (or lower) in elevation than that of the point. The third level of sensitivity required this criterion to apply to both sides of the point. Experimentation with the sensitivity filter found that the second level produced a reasonable number of minima of R and maxima of BI.

2.2 Bed shear stress as an indicator of erosion risk

In cross-section, mean bed shear stress (N/m^2) (τ) is calculated as:

$$\tau = \rho g R S \qquad (3)$$

where,

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

S = the energy slope of the flow (m/m).

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

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

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

A channel is stable when:

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

Tables of maximum permissible bed shear stress appear in many channel design, engineering and hydraulics publications (e.g. Chow, 1981; Chang, 1988), and they are all based on values given by the U.S. Bureau of Reclamation (Lane, 1952; Carter, 1953). Bare (unvegetated) sandy soils have a maximum permissible bed shear stress of around 2 N/m^2 while silts and clays resist bed shear stress up to around 12 N/m^2. When soil is covered by vegetation its resistance to scour is considerably enhanced. A critical shear stress in the range 100 – 200 N/m^2 is a reasonable guide to the shear stress required to remove typical native or pasture grass cover found on floodplains and hence initiate stripping of the floodplain surface (Blackham, 2006).

Advisian provided modelled bed shear stress data for this report, with the data being current at 19 June 2019, i.e. these data represent the sub-stage boundaries current at that time. They used a two-dimensional TUFLOW hydraulic model on a 1 m topographic grid to predict the spatial distribution of peak bed shear stress values for existing conditions and the mid-works scenario for the 50%, 5%, 1% and 0.2% AEP (average exceedance probability) events.

For each cell, bed shear stress is calculated in TUFLOW as:

$$\tau = \frac{\rho g V^2 n^2}{y^{\frac{1}{3}}} \qquad (5)$$

where,

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

n = Manning's roughness coefficient of the cell

y = water depth of the cell (m)

Equations 3 and 5 are not equivalent, but comparison of the 5% AEP event bed shear stress distribution calculated by Riley (1987) for stages 1 – 7 using a standard one-dimensional model (i.e. Equation 3) with the distribution calculated by the TUFLOW model suggests that the two approaches produced similar results. Thus, the maximum permissible bed shear stress thresholds reported above are appropriate for interpretation of the TUFLOW modelled bed shear stress distributions. Based on information from the literature and local soil type, values of maximum permissible bed shear stress were assigned to risk categories for initiation of fluvial scour of floodplain soils in the Study Area (Table 5).

Table 5. Risk categories of maximum permissible velocity and bed shear stress for initiation of fluvial scour of channel bench soils in the Study Area.

Risk of initiation of scour	Shear stress (N/m^2)	
	Well-vegetated surface	Exposed soil surface
Low	< 100	< 1.6
Moderate	101 – 200	1.7 – 4.0
High	> 200	> 4.0

The TUFLOW model was configured to output time series data at a 30 min time-step, with the peak shear stress value corresponding to the highest value over the duration of the event. The modelled bed shear stress was extracted in GIS from the gridded model output at the 24 cross-sections used to characterise the gorge morphology (see above). Data were extracted at 0.5 m spacing. This report provides data for the smallest modelled flood (50%AEP) and the 1%AEP flood to illustrate the range of shear stress values likely to be experienced. The concept of a design flow, below which extraction should cause minimum harm (e.g. 20 year average recurrence interval or 5%AEP flood), is important in setting the final extraction area boundaries, but was not particularly relevant to this investigation of geomorphic processes.

Note that the actual peak bed shear stress would have occurred at a point in time in-between the 30 minute outputs, but given the relatively long duration of the Nepean River flood hydrographs, this was not considered a serious weakness of the analysis. The TUFLOW model was also configured to output time series data at 5 minute intervals at the centroid of five of the sub-stage extraction areas. Evaluation of these data was not included in this report because it would not have altered the conclusions.

3. Results and Discussion

3.1 Landform element character

The morphology of the Nepean Gorge in the Study Area was highly variable and complex, making it difficult to characterise and generalise. The slope-based landform classification (Appendix 1, 7.1) revealed an insignificantly small area that would be regarded as flats, being level or very gently inclined (<3% slope), although this area would have been greater if a grid larger than 5 m had been used. Channel bench surfaces were defined by areas of contiguous pixels of non-steep slope, mostly less than approximately 5°. The gorge had areas of cliff on the upper margins, and also adjacent to the river. Potential talus was widespread, which was expected for a gorge environment. Most of the walls of the gorge were in the steep slope class.

The TPI plain landform (Appendix 1, 7.2) provided the simplest (single class) representation of channel benches. The TSC (Appendix 1, 7.3) divided the bench areas into four classes based on convexity and texture, but the overall bench boundaries were almost identical to those defined by the TPI.

Characterisation of bench morphology in three dimensions by terrain analysis was supplemented by characterisation of benches in two dimensions at cross-sections using morphometric indexes (Appendix 2 and Appendix 3). The areas defined as channel benches by terrain analysis were similarly identified as benches on cross-sections through these features using the Riley Bench Index and the Width-Depth ratio.

The consistency of the results provided by the slope-based, TPI and TSC landform element indexes, as well as the cross-section morphometric indexes, suggests that the channel bench landforms were reliably identified. It is likely that the resource is mainly confined to these channel benches. Elsewhere the channel margins were sloping quite steeply downwards towards the river and, apart from a narrow bank area adjacent to the river, the resource would likely be present as a sandy drape of variable thickness overlying rocky debris from the cliffs and steep slopes of the gorge. Much of this area was at the expected angle of repose of a talus slope. It might still be economic to extract the material from the slopes, depending on its thickness and practical difficulties presented by the slope. The extraction areas with benches were 8a, 8l and 8m, and to a lesser extent 8e, 8g, 8f, 8i. Extraction areas 8b, 8c, 8d, 8h, 8j and 8k were mostly on steeply sloping land.

It was possible to use topographic profile curvature (Appendix 1, 7.4) to objectively identify bank edges, both riverside and landward, that could be used to refine the extraction boundaries based on the objective of maximising the retention of the channel bank face. However, there would be practical difficulties implementing this approach, as multiple edges were present, the edges were highly variable in location and elevation, and they were discontinuous.

3.2 Distribution of bed shear stress

The distribution of peak bed shear stress was mapped spatially over the Study Area (Appendix 1) and also at cross-sections (Appendix 4).

The distribution of peak bed shear stress for the existing 50% AEP event (Appendix 1, 7.5) was generally within the range that a fully vegetated surface would resist scour, and net deposition would be expected due to settling of suspended sand during the falling limb of the hydrograph. However, there were some locations where the bed shear stress was near 200 N/m^2, which presents a risk of scour even for vegetated surfaces. These areas were 8c, 8l, 8m and the landward side of 8e and 8f. The mid-works 50% AEP scenario (Appendix 1, 7.6) resulted in marginally increased bed shear stress in these areas.

The distribution of peak bed shear stress for the existing 1% AEP event (Appendix 1, 7.7) exceeded the range that a fully vegetated surface would resist scour in 8a, 8c, 8l and 8m. There were also areas of high shear stress in 8e, 8f, 8i, 8j and 8k. The mid-works 1% AEP scenario (Appendix 1, 7.8) resulted in marginal changes in bed shear stress in these areas, but the risk of scour would remain in the same class. Area 8e would become more stable.

Under flood conditions, some areas of the Study Area had modelled bed shear stress values rated in the high risk of initiation of scour class, for both the existing and mid-works scenarios. This suggests that during floods, scattered patches of scour could occur, although it is likely that on the falling limbs of hydrographs some or all of the scoured areas could infill, or partially infill, with coarse sediment, with revegetation occurring between flood events. This is a natural and expected process that would occur regardless of extraction operations. With extraction operations present, under flood conditions, the unvegetated pit and surrounds would be exposed to risk of scour although the pit itself would likely be an ineffective flow area. The risk of scour of the operations area can be reduced by retaining as much vegetation as possible, revegetating disturbed land as quickly as possible, and protecting the 10 m wide horizontal top of the setback area (if vegetation cover is disturbed) with appropriate erosion resistant material.

3.3 Relationship between contours and channel benches

Maps of the 64 m, 67 m, 70 m contours, and 10 m setback from 64 m contour were provided, as requested (Appendix 1, 7.9). The benches, with boundaries defined by the TPI, were plotted for the Stage 8 area, along with the closest contour to each bench edge (to 1 m contour interval resolution) between 64 m and 70 m (Figure 3, Figure 4, Figure 5, and Figure 6). These maps also depicted elevation of the bench surfaces, to illustrate their variability in slope and elevation. The interface of the bench with the gorge wall was marked on these maps on the basis of linear features of high negative curvature, delineated automatically in GIS. As strong negative curvature was not a continuous feature, this procedure produced lines that were discontinuous. These discontinuous lines were manually joined to produce a continuous boundary.

The 64 m contour coincided with one of the bench levels found in the river, with the most prominent channel bench in the gorge found on the right bank between chainage 2300 m and 2900 m. Elsewhere, weakly defined benches were found at about this level on the left bank, but it was not a dominant characteristic of the morphology. In general, an extraction boundary based on the 64 m contour would allow extraction of all the bench material, but a boundary based on the 67 m or 70 m contours would alienate bench material in 8l and 8m. A boundary set at 67 m or 70 m in areas 8f, 8g, 8h, 8i, and 8j would preserve a higher length of bank face for a relatively small movement of the boundary in the landward direction.

Menangle Sand and Soil informed that a 1(V):1(H) (45°) angle is required at the rear (landward) side of the horizontal setback area down to the base of the pit (at 62 m AHD). For a horizontal setback from 64 m AHD, the batter would be 2 m deep and 2 m across. Elevating the riverside boundary of the setback would shift the base of the pit away from the river. For a horizontal setback from 70 m AHD, the batter would be 8 m deep and 8 m across. Considering the narrow nature of the benches, in places it would not be possible to extract down to 62 m AHD. While an 8 m high pit wall formed by retained bank material might not scour during flood, there is a possibility that saturation of the wall by high flows that inundate part or all of the wall (from the river side, or both sides if overtopped) could result in slumping of the pit wall if the rate of flood recession was faster than the rate at which the soil naturally drains (although being sandy, this would be relatively fast). This is an important consideration in deciding where the riverside boundary of the extraction setback should be established, given that a key management objective is to protect the geomorphic integrity of the river bank.

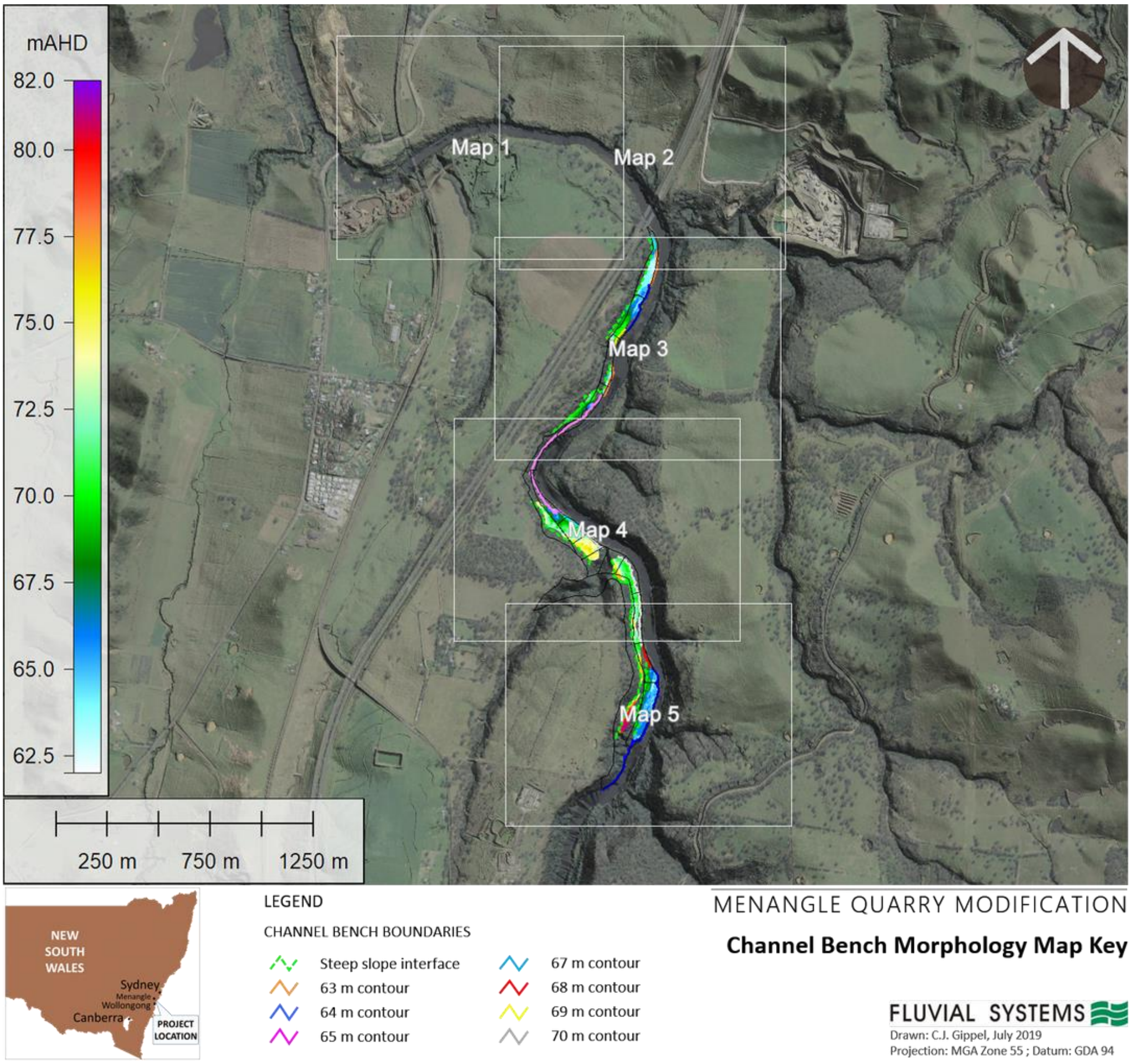

Figure 3. Channel bench morphology map key. The original indicative extraction area boundaries are shown for reference.

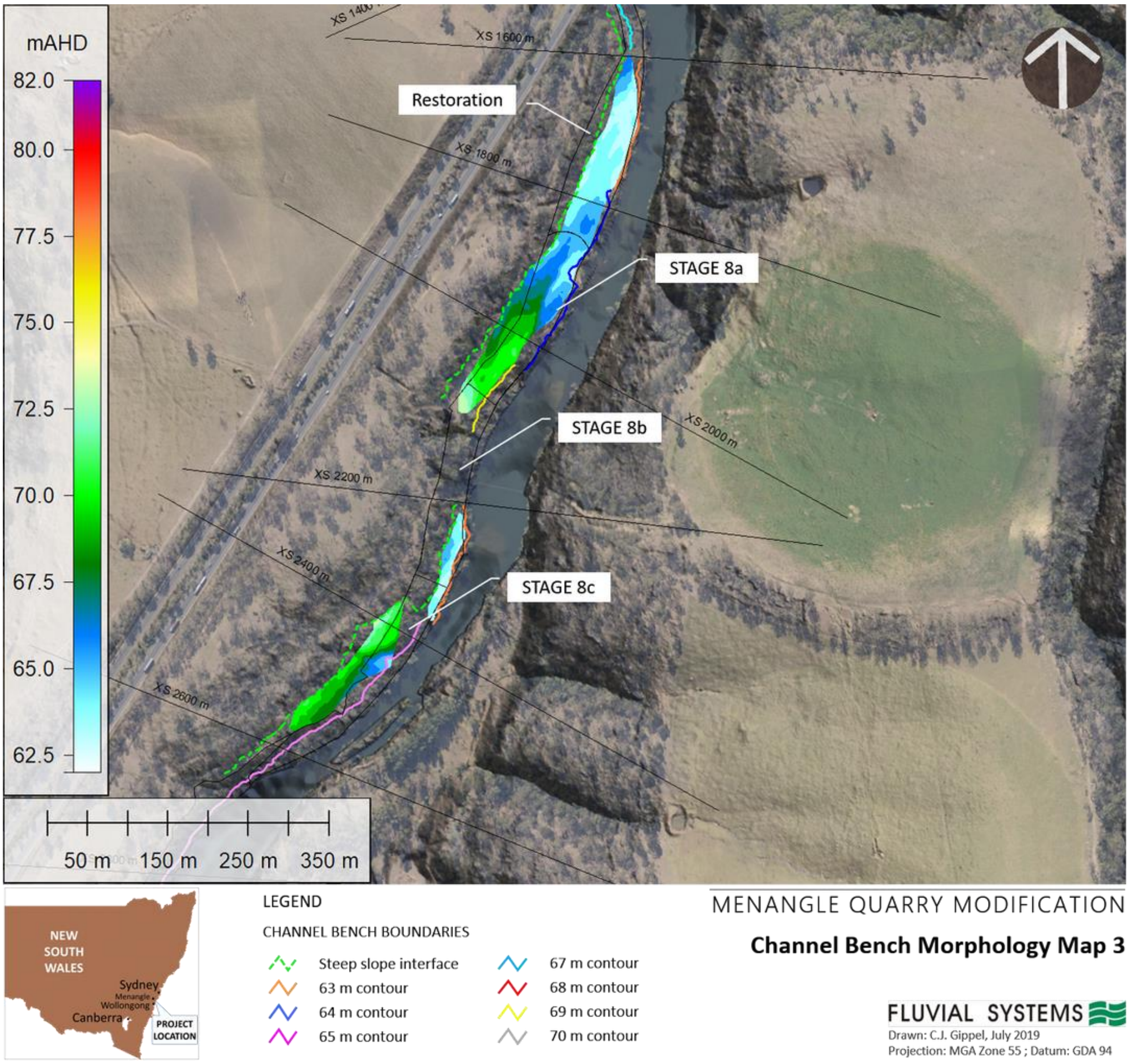

Figure 4. Channel bench morphology Map 3. The original indicative extraction area boundaries are shown for reference.

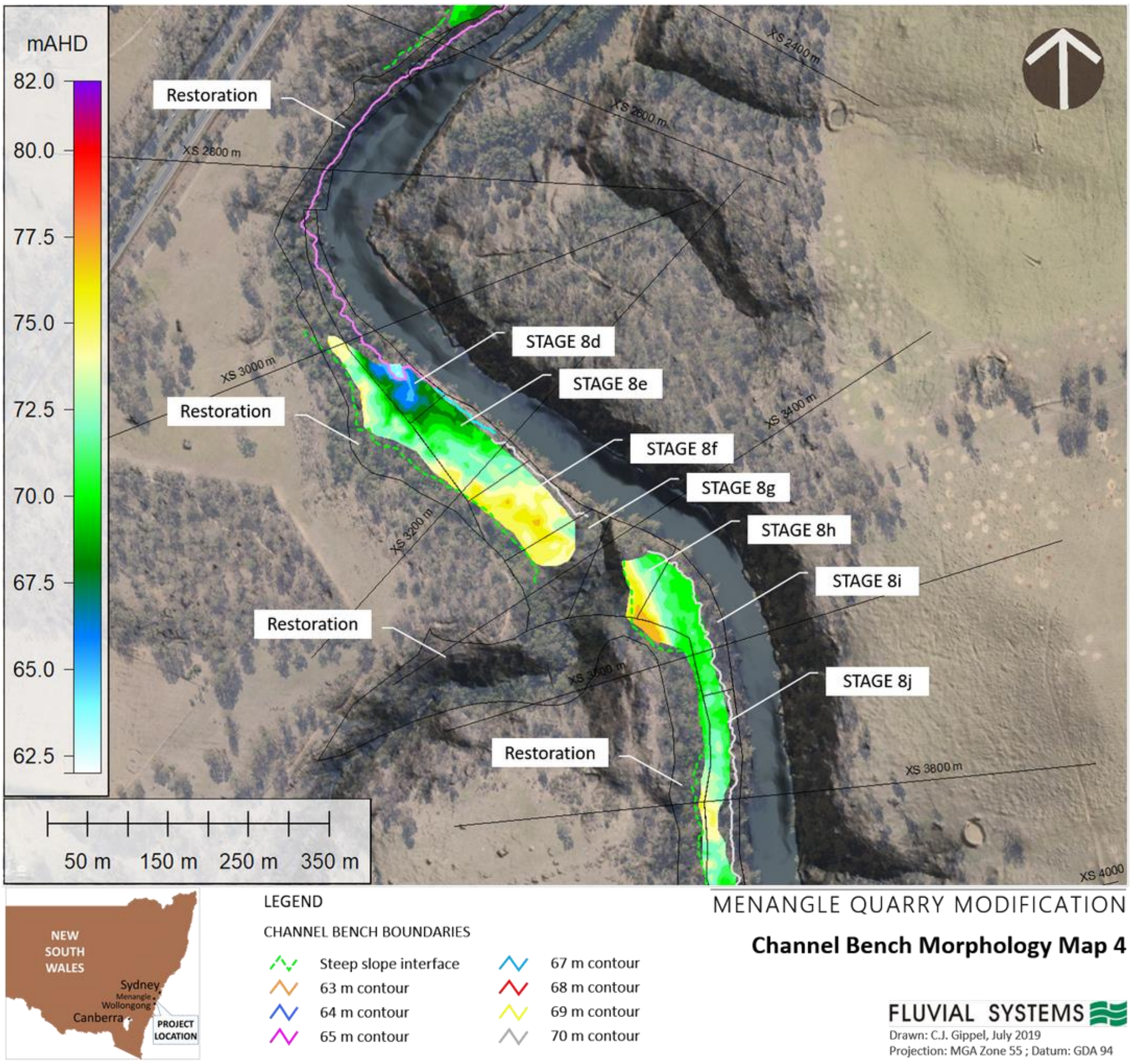

Figure 5. Channel bench morphology Map 4. The original indicative extraction area boundaries are shown for reference.

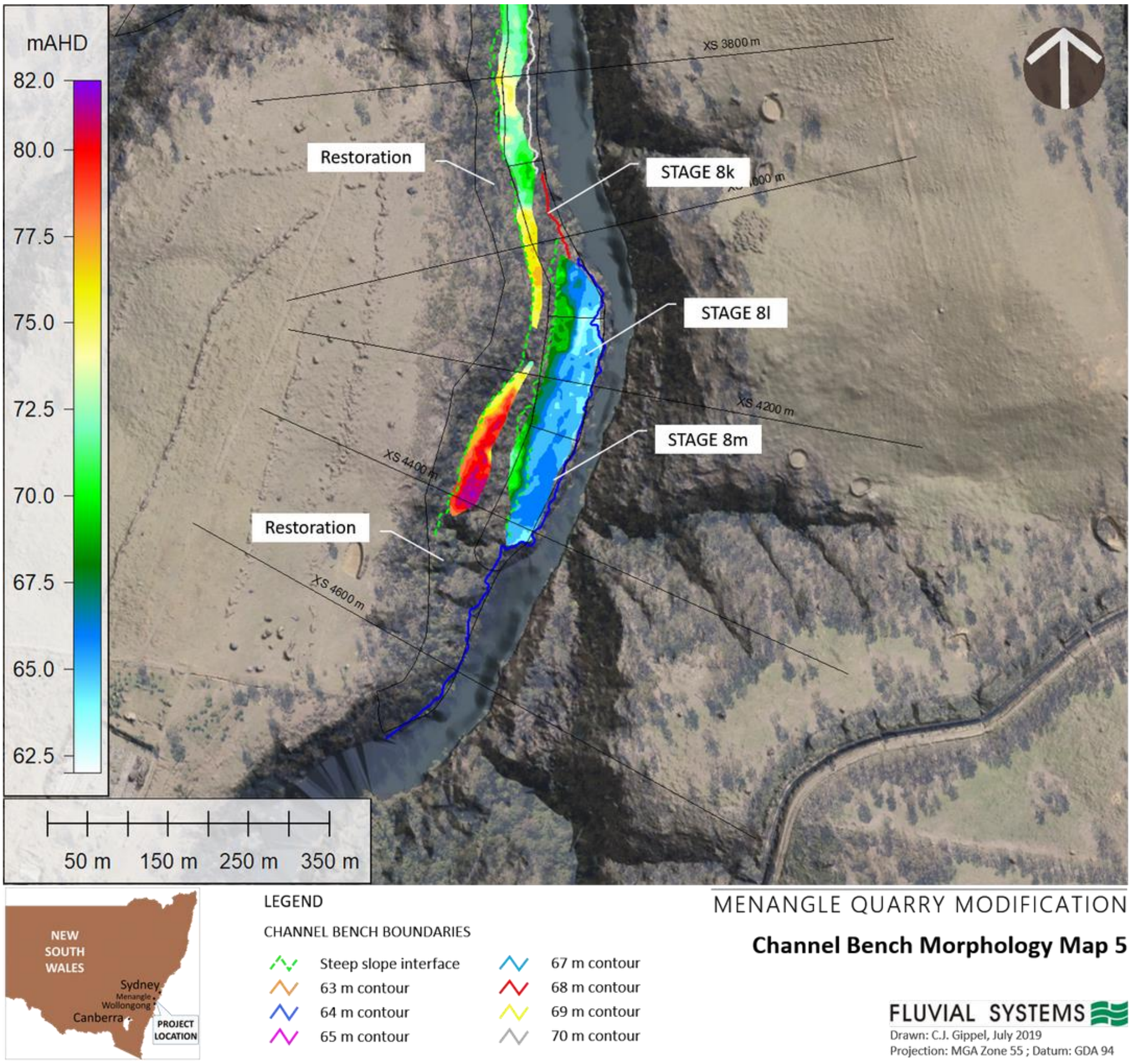

Figure 6. Channel bench morphology Map 5. The original indicative extraction area boundaries are shown for reference.

3.4 Morphologic delineation of extraction area boundaries

The data produced in this report could provide a morphology-based rationale for delineation of the riverside boundaries of the extraction areas, but this is a matter that requires careful consideration of various other factors not covered in this report. While variable elevation boundaries might preserve additional height of the bank face in some locations, this would increase the risk of slumping of the bank, and constrain the volume of accessible resource.

Resource extraction could be maximised by extending the landward boundary to the rock face of the gorge. In many places this rock face would be covered by a layer of soil. While an exposed rock face would not present a risk of instability, the interface between the rock and the overlying soil would be subject to risk of erosion from local surface runoff generated on the slope above. Even if the boundary is set a certain distance from the rock face, the formed slope between the re-vegetation area and the extraction area would in most places be steeper than the current slope and would be subject to increased risk of erosion from local surface runoff. The topographic analysis undertaken in this report roughly identified the location of the rock face in some areas, but in areas of sloping land this is not straightforward. It is recommended that the landward side of the extraction area would best be determined by field survey using an excavator or other soil sampling technique.

4. Conclusion of Geomorphic Assessment

The consistency of the results provided by the various terrain analysis indexes, as well as the cross-section morphometric indexes, suggests that the channel bench landforms were reliably identified. It is likely that the resource is mainly confined to these channel benches. Elsewhere the channel margins were sloping quite steeply downwards towards the river and, apart from a narrow bank area adjacent to the river, the resource would likely be present as a sandy drape of variable thickness overlying rocky debris from the cliffs and steep slopes of the gorge. It might still be economic to extract the material from the slopes, depending on its thickness and practical difficulties presented by the slope.

It was possible to objectively identify bank edges, both riverside and landward, that could be used to refine the extraction boundaries based on the objective of maximising the retention of the channel bank face. However, there would be practical difficulties implementing this approach, as multiple edges were present, the edges were highly variable in location and elevation, and they were discontinuous.

The provided modelled bed shear stress data suggests that during floods, scattered patches of scour could occur, although it is likely that on the falling limbs of hydrographs some or all of the scoured areas could infill, or partially infill, with coarse sediment, with revegetation occurring between flood events. This is a natural and expected process that would occur regardless of extraction operations. The risk of scour of the operations area can be reduced by retaining as much vegetation as possible, revegetating disturbed land as quickly as possible, and protecting the 10 m wide horizontal top of the setback area (if vegetation cover is disturbed) with appropriate erosion resistant material.

The data produced in this report could provide a morphology-based rationale for delineation of the riverside boundaries of the extraction areas, but this is a matter that requires careful consideration of various other factors not covered in this report. While variable elevation boundaries might preserve additional height of the bank face in some locations, this would increase the risk of slumping of the bank, and constrain the volume of accessible resource. It is recommended that the landward side of the extraction areas would best be determined by field survey using an excavator or other soil sampling technique.

5. Topography of Proposed Setback Area

5.1 Proposed amended setback and final landform

In consideration of a request made by the Department of Planning and Environment (DPIE) for further information during the on-site Section 34 conference on 14 June 2019 and in their letter of 19 June 2019, and the additional data produced from that request, including the geomorphological assessment contained within this report, EMM (2019) provided a memorandum that included, among other things, an amended extraction area (including staging diagrams) and proposed amendments to the treatment of the setback that will protect all native trees within the setback area.

One of the elements of the amended extraction area is increased distance between the northern and southern extraction areas from about 200 m to about 450 m, which reflects the high bed shear stresses and low potential for resource on this outside bend of the Nepean River, as identified by the geomorphological assessment contained within this report. The revised setback will still be based on the 64 m AHD riverside contour, but to preserve native trees and maintain bank stability it is proposed to retain all of the native trees within the horizontal setback area with a diameter at breast height (DBH) exceeding 0.1 m. This setback approach will locally extend the setback in the landward direction by up to 7.5 m. In other words, the total setback from the 64 m contour will be up to 17.5 metres wide in areas where there are trees.

The setback area 10 m landward from the 64 m contour is sloping in most places, so where a tree exceeding 0.1 m DBH is present, its preservation will nearly always result in a localised area of land around the base of the tree that is higher than 64 m AHD. The amended setback approach will thus result in a final landform with varying ground levels in the horizontal setback area. The width and elevation of the setback area will vary depending on the location of the trees within it. The unmodified area of bank will be lower and narrower where a tree is close to the riverside (64 m AHD contour) boundary of the setback area, while it will be higher and wider where a tree is located on the landward boundary of the setback area. The setback area will be close to level at 64 m AHD and 10 m wide where no trees exceeding 0.1 m DBH are found in the setback area. This approach will result in a riverbank of varied topography.

5.2 Reason for modelling setback landform and tree presence

On 30 August 2019, at a without prejudice meeting with Department of Planning and Environment (DPIE) at Minter Ellison offices, Governor Macquarie Tower 1 Farrer Place Sydney, EMM presented, among other things, the proposed amendments to the treatment of the setback. While it was known at the meeting that the amended approach would result in a topography that was variable in both the cross-sectional and longitudinal directions, the variability had not been quantified. This was partly due to the difficulty and uncertainty associated with modelling the final landform of the setback area. In this respect, a key unknown was the distribution of trees exceeding 0.1 m DBH within the setback area. This section of the geomorphology report develops a model of tree canopy distribution and then uses the model to estimate the degree of topographic variability in the final landform of the setback area.

5.3 Methodology for setback landform and tree canopy model

The boundary of the 10 m wide setback, with the riverside boundary at 64 m AHD, was delineated in this report (Figure 60, Figure 61, Figure 62 and Figure 63). The linear extent of this 10 m wide setback was cropped to the proposed amended northern and southern extractions areas. The topography of the land within these setback areas was characterised by the NSW Spatial Services (ELVIS - Elevation and Depth - Foundation Spatial Data) 1 m LiDAR-derived DEM.

GIS was used to characterise the downstream pattern of the ground elevation of the two setback areas based on the longitudinal profiles of maximum, minimum and average ground elevations, measured in the perpendicular, within a 5 m buffer either side of the centrelines. As the horizontal setback area is 10 m wide, these statistics reflect the topography of the land within the 10 m setback zone. The alternative would have been to plot individual elevation profiles along the 64 m AHD contour riverside boundary (minimum elevation), the setback area centreline (middle elevation), and the landward setback boundary (maximum elevation), but the sinuous alignment of the setback area would have created three lines of different lengths, which would have been difficult to directly compare. The profile of the minimum elevation was set by the 64 m AHD contour riverside boundary, although there was some minor variability around this elevation due to slight smoothing of the contour line. Also used to characterise the topography of the setback area was the longitudinal slope of the land along the landward boundary of the setback area, and the cross-sectional slope of the setback along the length of the setback area.

The NSW Spatial Services (ELVIS - Elevation and Depth - Foundation Spatial Data) point cloud LiDAR data was classified using the conventional scheme, which includes three vegetation classes:

- Low vegetation 0 – 0.3 m high (essentially sensor noise)
- Medium vegetation 0.3 – 2.0 m high
- High vegetation > 2 m high

The high vegetation point data was extracted from the point cloud data set, as potentially representing trees exceeding 0.1 m DBH. The criterion used to define a tree to be retained within the setback area (described above) does not depend on height, but tree height is known to be related to DBH, although the relationship would be species-specific. The Study Area contains three TECs (threatened ecological communities), one of which, River Flat Eucalypt Forest, would be found in the setback area. River Flat Eucalypt Forest has a highly variable dominant tree stratum, with 14 eucalypts being listed as possible dominant species, depending on the location (Office of Environment & Heritage, 2019). Within Stage 8, the tree canopy within the River Flat Eucalypt Forest is dominated, almost exclusively, by Bangalay x Sydney Blue Gum (*Eucalyptus bangalay x saligna*).

Diameter-height relationships were not available for *Eucalyptus bangalay x saligna*, but the literature includes relationships for plantation *Eucalyptus grandis x E. Urophylla* (a hybrid of flooded gum) in Espírito Santo and

Bahia states, Brazil (Filho et al., 2018) and plantation *Eucalyptus saligna* (Sydney blue gum) in the Uasin Gishu district of Kenya (Kimondo, 1995). In a sample of over 85,000 trees, Filho et al. (2018) found only about 10 trees that exceeded 0.1 m DBH being shorter than 10 m. In Kimondo's (1995) sample of 365 trees exceeding 0.1 m DBH, all were taller than 10 m, with 49 trees in the range 10 – 15 m tall. It would be expected that for the same diameter, thinned plantation trees would tend to be taller than naturally occurring trees, and given the differences in species and differences in soils and climate compared to the Study Area, it would be reasonable to assume from these studies that the majority of trees in the Study Area exceeding 0.1 m DBH would be at least 5 m high. This is consistent with Specht's (1970) definition of a tree as a woody plant more than 5 m tall, usually with a single stem. The selected 5 m threshold would exclude most of the lantana, although the exotic species Privet (*Ligustrum lucidum*), which is present, mainly in the northern extraction area, will be included in the definition of tree used here, even though these exotic trees will be removed.

A tree canopy elevation model was created for the Study Area by subtracting the high vegetation LiDAR data from the ground strike LiDAR data and then cropping the resulting 1 m grid to include only heights exceeding 5 m. The profile of the tree canopy elevation within the 10 m wide setback area was then characterised by the longitudinal profile of maximum tree elevation within a 5 m buffer either side of the centreline of the two extraction areas. This procedure identified the likelihood of trees exceeding 0.1 m DBH being present on the longitudinal profile of the setback, but the data were not considered to be of sufficient accuracy to locate the position of tree stems across the setback area. These data indicated where along the longitudinal profile the setback area ground elevation would likely be higher than 64 m AHD due to retention of trees, and where it would likely be reduced to 64 m AHD due to the absence of trees. The model would likely over-estimate the proportion of the setback with trees to be retained for the following reasons:

- The model does not distinguish between native and non-native species (the latter would be removed);
- Some trees greater than 5 m high would be smaller than 0.1 m DBH (which would be removed);
- The model characterised the tree canopy, which manifests as spaced, roughly-circular, areas in the case of isolated trees, and contiguous areas in the case of stands of trees, whilst the tree stems that produce the canopy occur at spaced points; and
- Some tree canopies projecting into the 10-m setback area would belong to trees whose stem was beyond the setback area: (i) landward of the setback boundary (which would be within the extraction area), and (ii) riverside of the setback boundary (which would be on the undisturbed area of the bank).

5.4 Results of setback landform and tree canopy model

When compared with aerial photography, over the wider Nepean River area, the tree canopy height model predicted tree presence in the areas where they would be expected (Figure 7). In detail, the model satisfactorily identified individual isolated trees, and the tops of individual trees within areas of closed canopy (Figure 7).

Tree canopy was present along 66% of the length of the horizontal setback area in the northern extraction area (Figure 8) and 57% of the length of the horizontal setback area in the southern extraction area (Figure 9). This difference possibly reflects the presence of Privet in the northern extraction area. The topography of the land within the northern 10 m-wide setback area was clearly divided into two different areas. Over the downstream 270 m, the bank was steeply sloping at 1:2 to 1:4 (V:H), giving a large range in land elevation in the cross-sectional direction from 64 m AHD to up to 69.6 m AHD (Figure 8). Over the upstream 290 m, the bank slope varied from 1:3 to 1:30 (V:H), with the range in land elevation in the cross-sectional direction from 64 m AHD to up to 67.5 m AHD (Figure 8). The longitudinal slope along the landward (high) boundary of the setback was highly variable, with 6% of the length having slope exceeding 1:5 (V:H) and 22% of the length having slope exceeding 1:10 (V:H) (Figure 8).

The topography of the land within the southern 10 m-wide setback area was also divided into two different areas. Over the downstream 1100 m, the bank was steeply sloping at 1:1.3 to 1:4 (V:H), giving a large range in land elevation in the cross-sectional direction from 64 m AHD to up to 71.5 m AHD (Figure 9). Over the upstream 440 m, the bank slope varied from 1:3.4 to 1:80 (V:H), with the range in land elevation in the cross-sectional direction from 64 m AHD to up to 66.9 m AHD (Figure 9). The longitudinal slope along the landward (high) boundary of the setback was highly variable, with 9% of the length having slope exceeding 1:5 (V:H) and 28% of the length having slope exceeding 1:10 (V:H) (Figure 9).

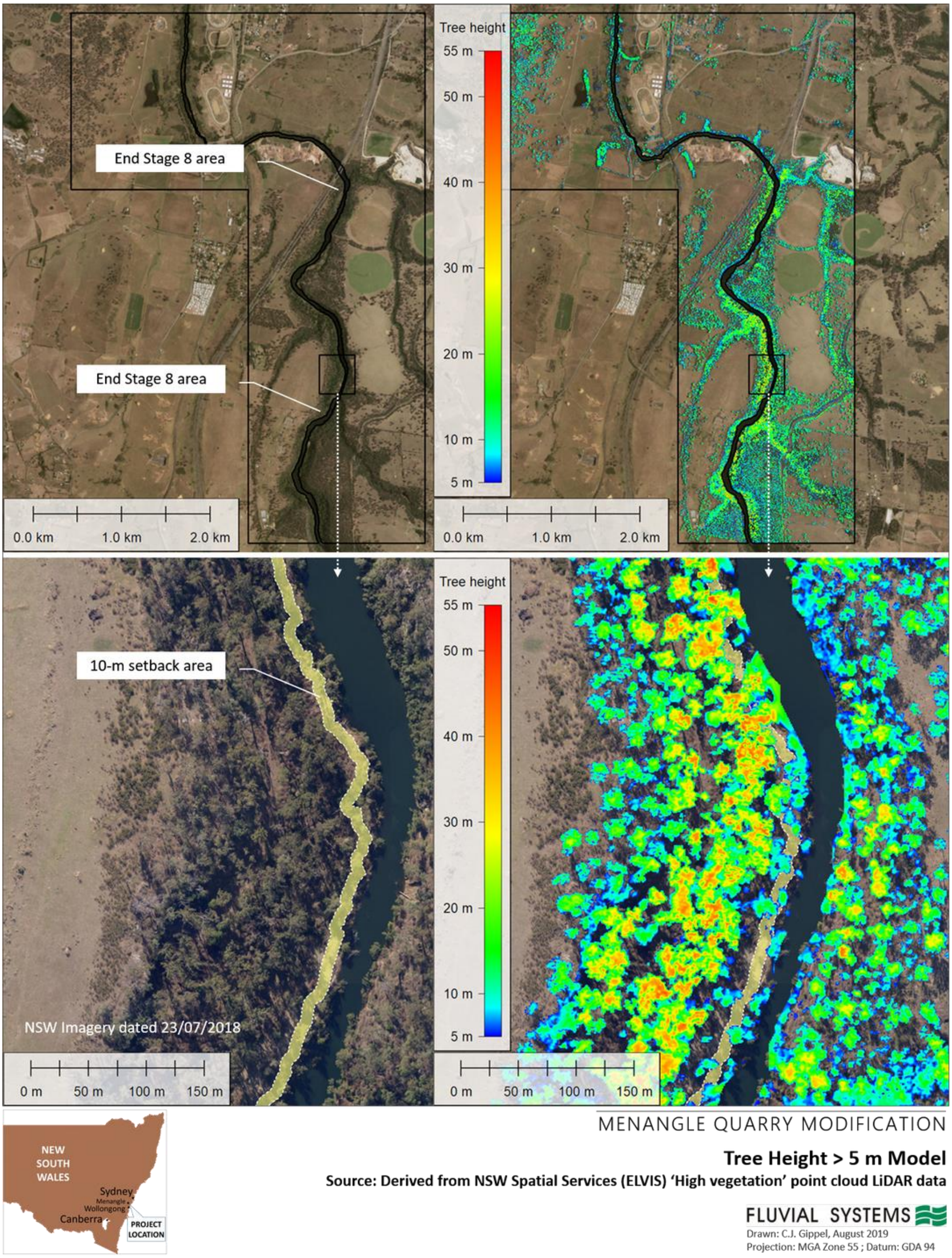

Figure 7. Modelled tree canopy height, based on high vegetation classified LiDAR point cloud data. The lower figures show results for a short section of the river to illustrate the level of detail provided by the tree model.

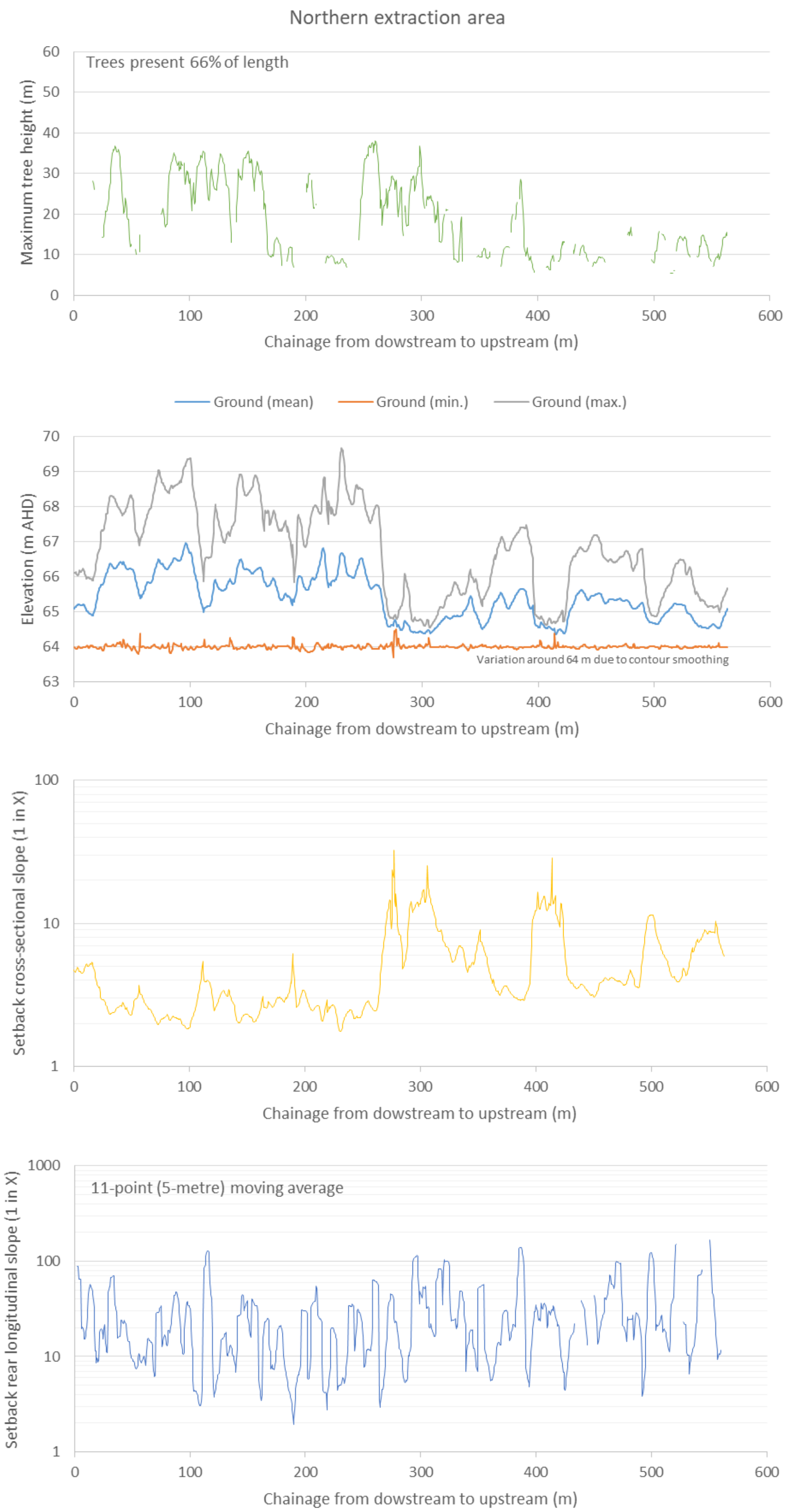

Figure 8. Topography of northern extraction area setback area, including modelled tree canopy presence.

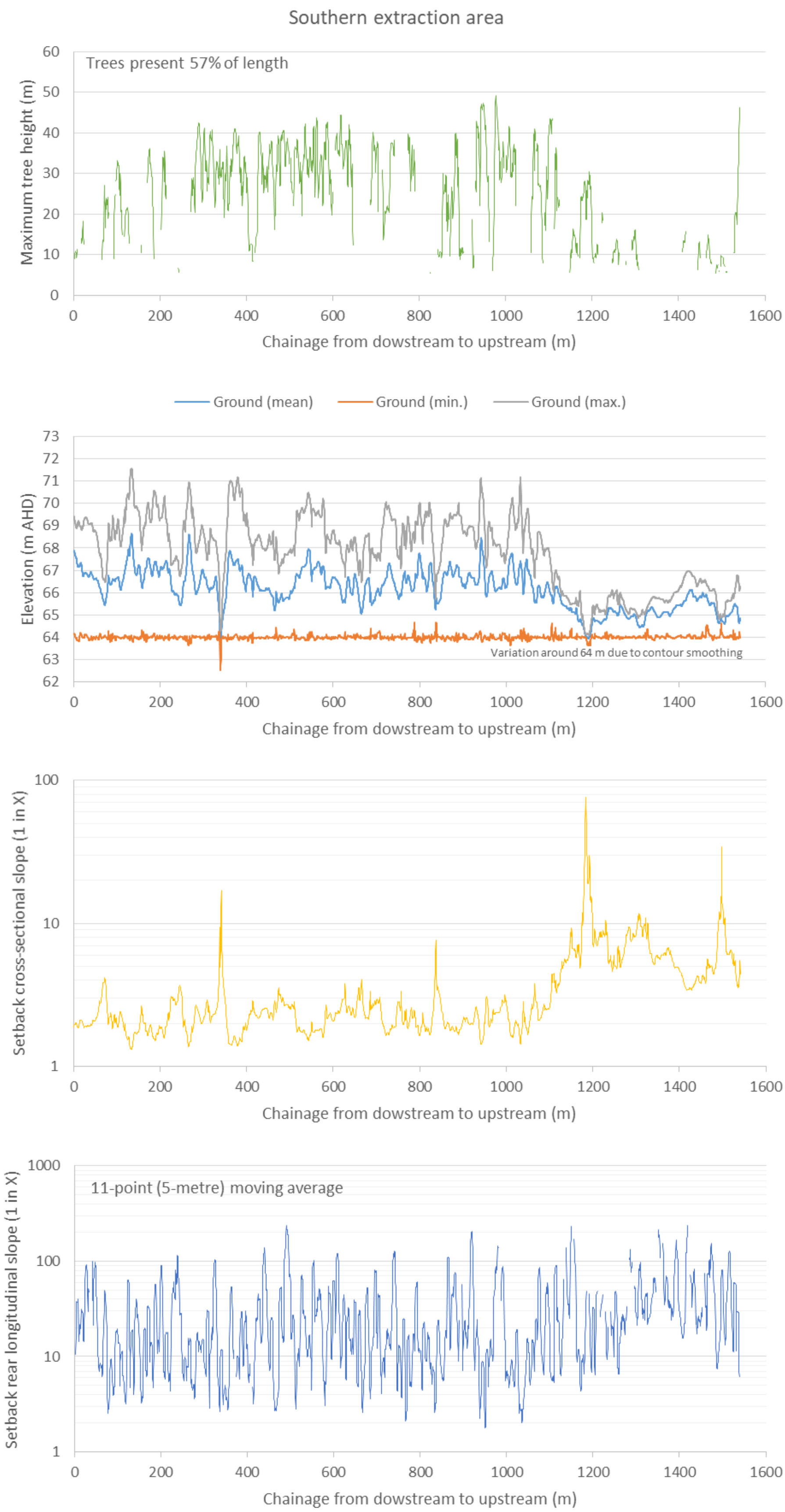

Figure 9. Topography of southern extraction area setback area, including modelled tree canopy presence.

5.5 Degree of topographic variability in the final landform of the setback area

The proposed amendments to the treatment of the setback that will protect all native trees within the setback area will give rise to a highly variable landform along the setback area, in both the cross-sectional and longitudinal directions. Although they are not common, areas with longitudinal slope steeper than 1:5 (V:H) occur within the existing environment along the 10 m-wide setback area. This would be an appropriate maximum slope when forming land between high and low points along the setback area.

Although the model suggested that tree canopy was present along 66% of the length of the horizontal setback area in the northern extraction area and 57% of the length of the horizontal setback area in the southern extraction area, for various reasons outlined in this report, the coverage of land containing tree stems to be retained will be lower than this. Nevertheless, the analysis undertaken in this report clearly suggests that the proposed amendments to the treatment of the setback will result in retention of a substantial number of native trees, many of them taller than 20 m. The modelling suggested that the elevation of the final landform of the setback area could vary between 64 and 71 m AHD. The bank slopes would be within the existing range of 1:2 to 1:4 (V:H), and the longitudinal slope of the setback area would vary from almost flat to 1:2 (V:H), although on formed areas the longitudinal slopes will be less than 1:5 (V:H).

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7. Appendix 1. Terrain Indexes, Bed Shear Stress, and Contour Maps

Notes:

1. The data on the maps are at 5 m grid cell resolution, except for profile curvature, which is at 1 m grid cell resolution.
2. Contours were based on 1 m grid cell LiDAR-derived DEM.
3. Some maps indicate bathymetry within the area Menangle Weir to the upstream extent of Stage 8 extraction area. The bathymetric elevation grid was derived from a sonar survey undertaken in June 2019 by Marine Pollution Research Pty Ltd.
4. The data on the maps extends laterally to the limit of the gorge/channel terrain delineated by contiguous polygons of steep slope terrain, as defined by Speight (2009).
5. The boundaries of the Stage 8 sub-stages are modified from those in EMM (2017), as this report was intended to inform review and possible refinement of the boundaries. The modification was to remove riverside and landward boundaries, and extend the downstream boundaries perpendicular to the channel to the low flow water surface and the upper limit of the gorge/channel terrain.
6. Maps 1 and 2 extend over the Stage 7 extraction area, which is not the subject of this report. Data for the Stage 7 area was included for comparison with data from Stage 8 area. Compared to Stage 8, extraction is active in Stage 7, and Stage 7 is downstream of the Nepean Gorge geomorphic landform.

7.1 Slope-based landforms

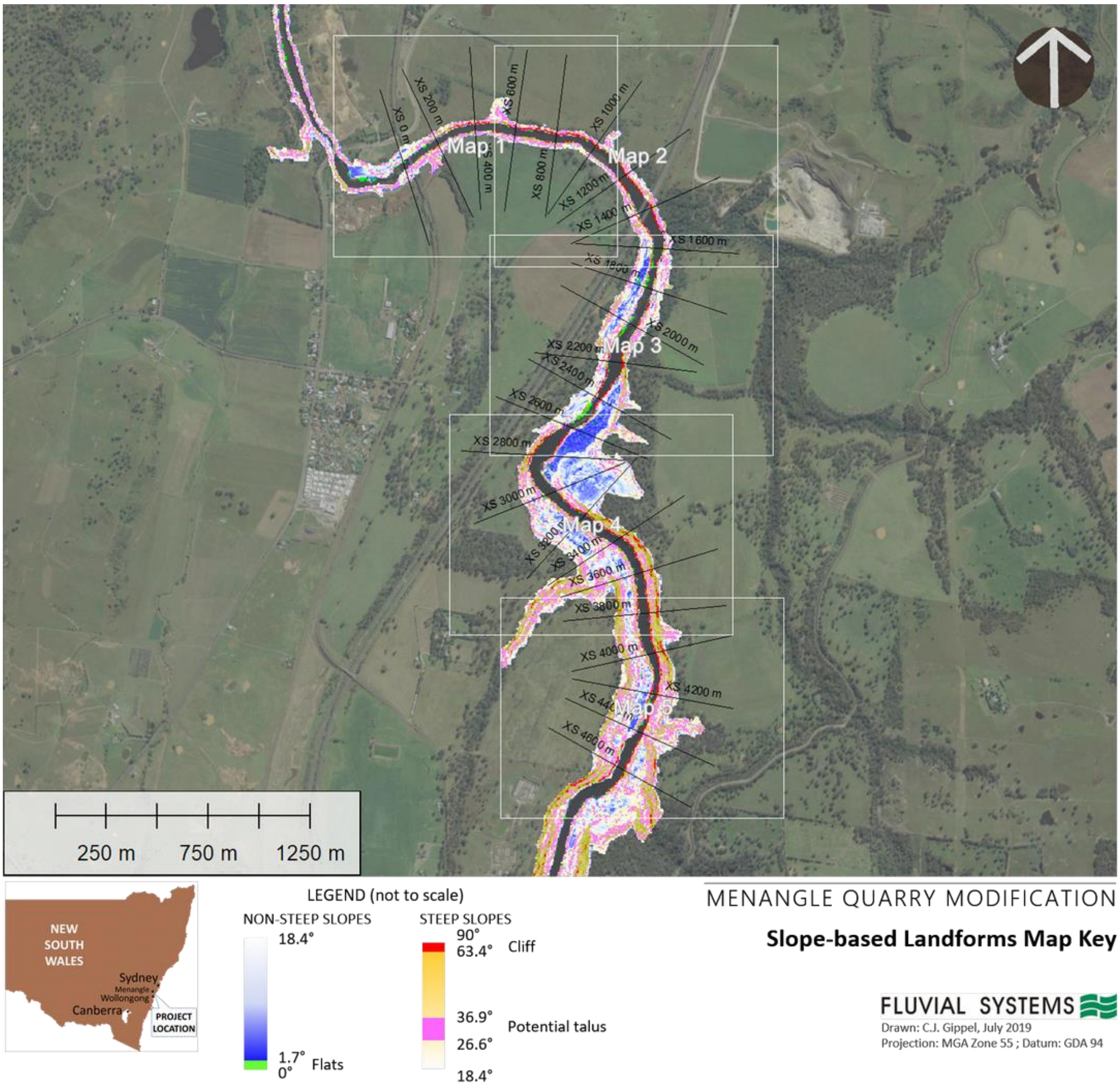


Figure 10. Slope –based landforms map key.

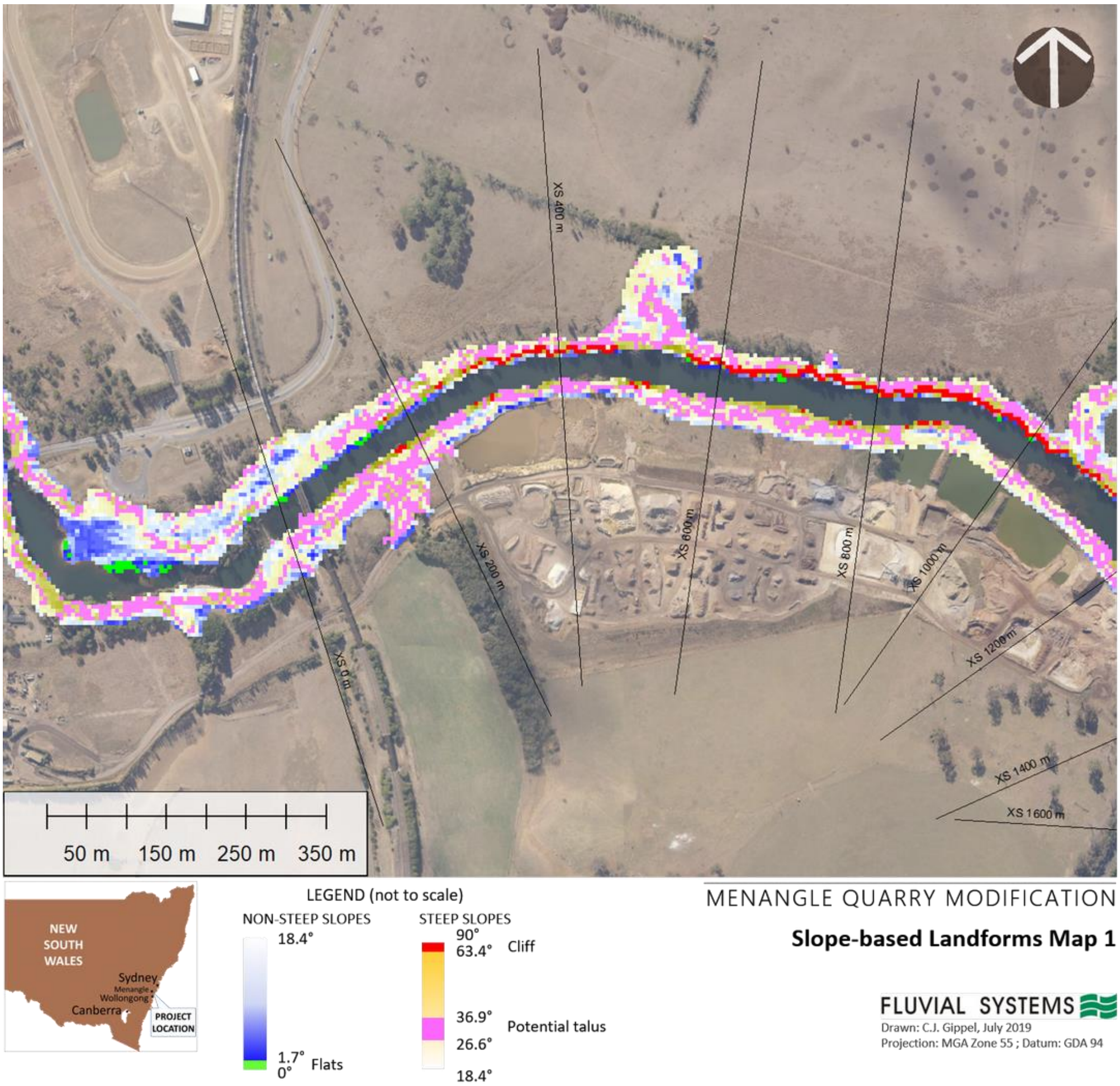


Figure 11. Slope –based landforms Map 1.

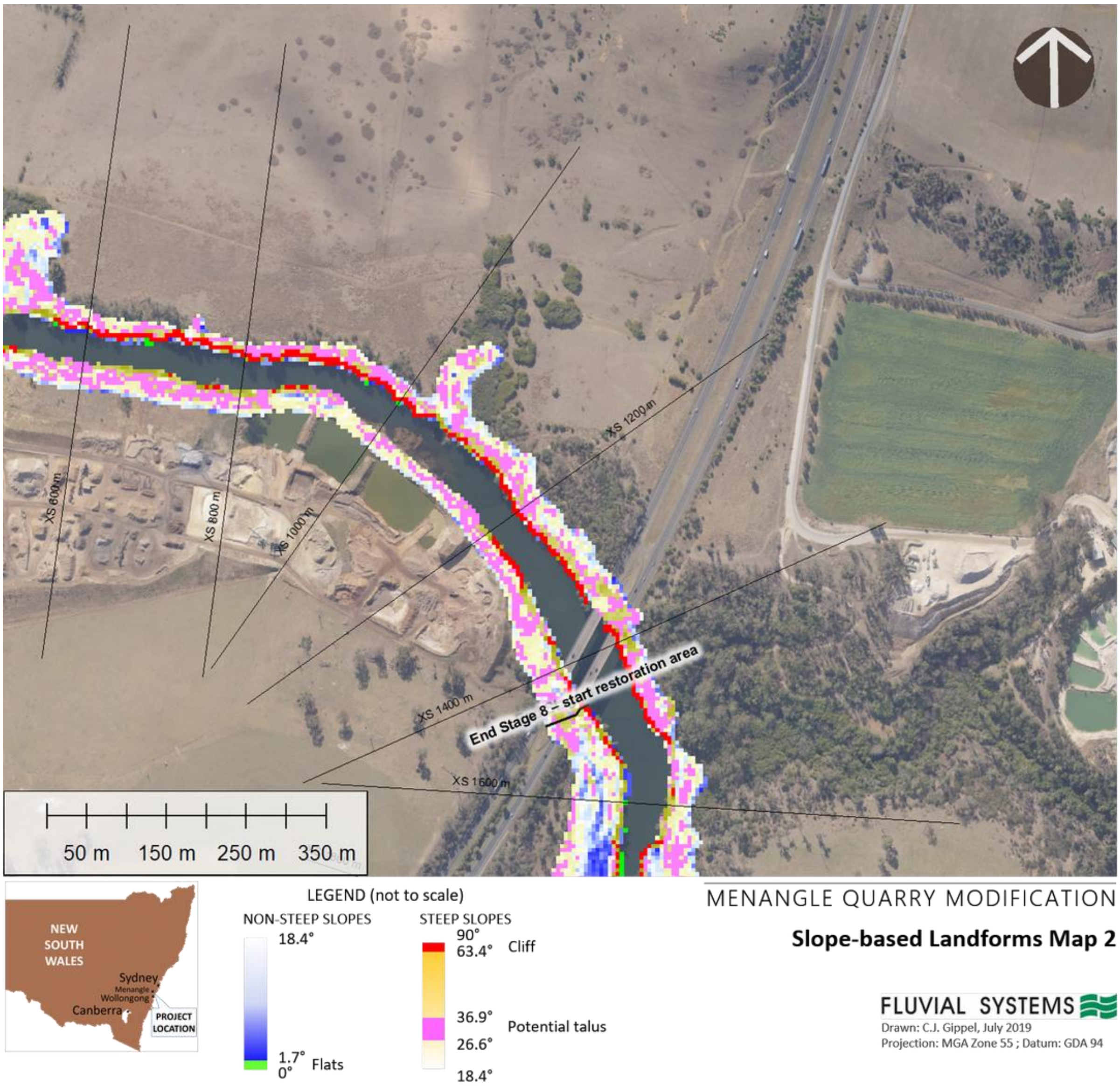


Figure 12. Slope –based landforms Map 2.

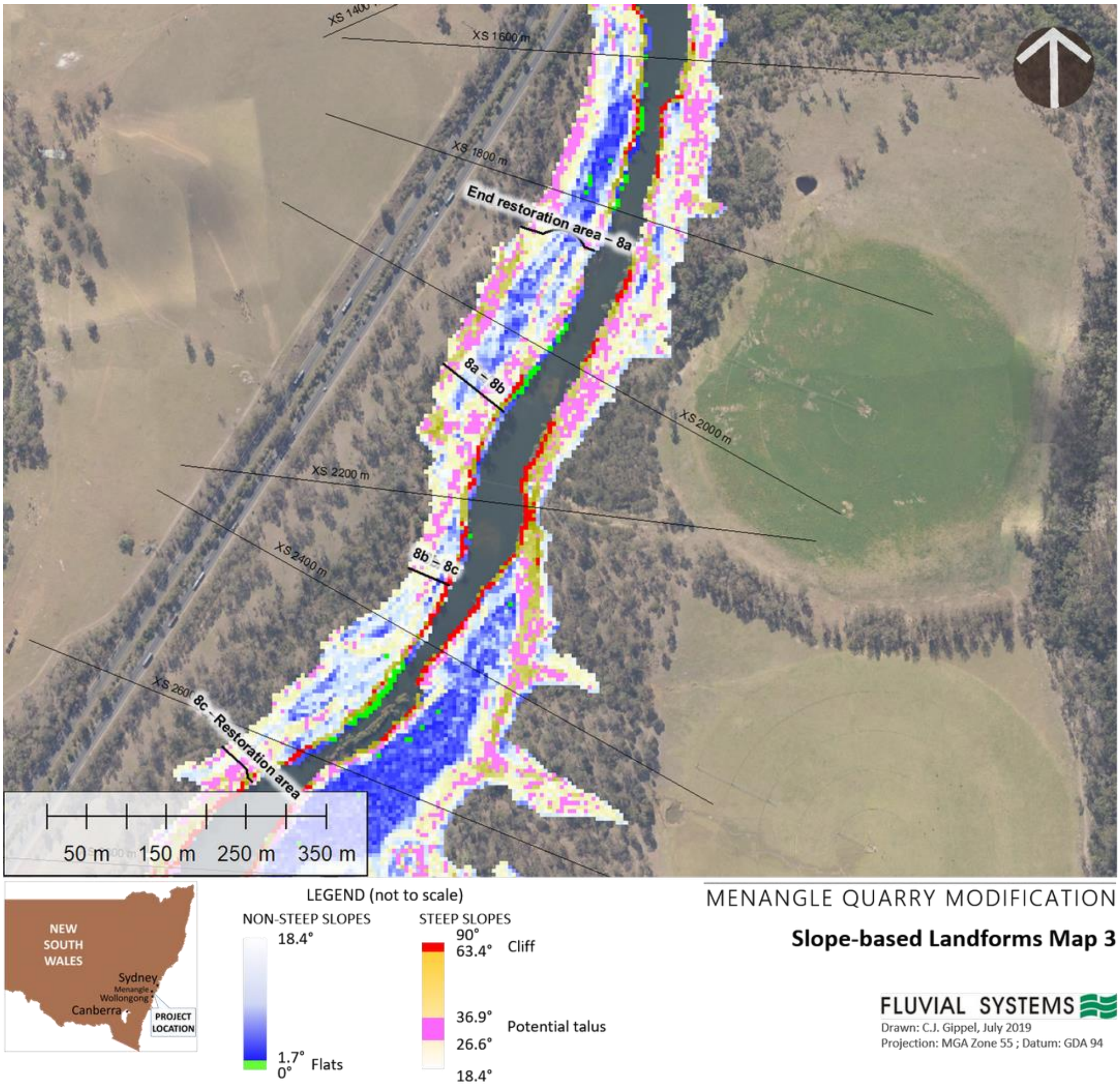


Figure 13. Slope –based landforms Map 3.

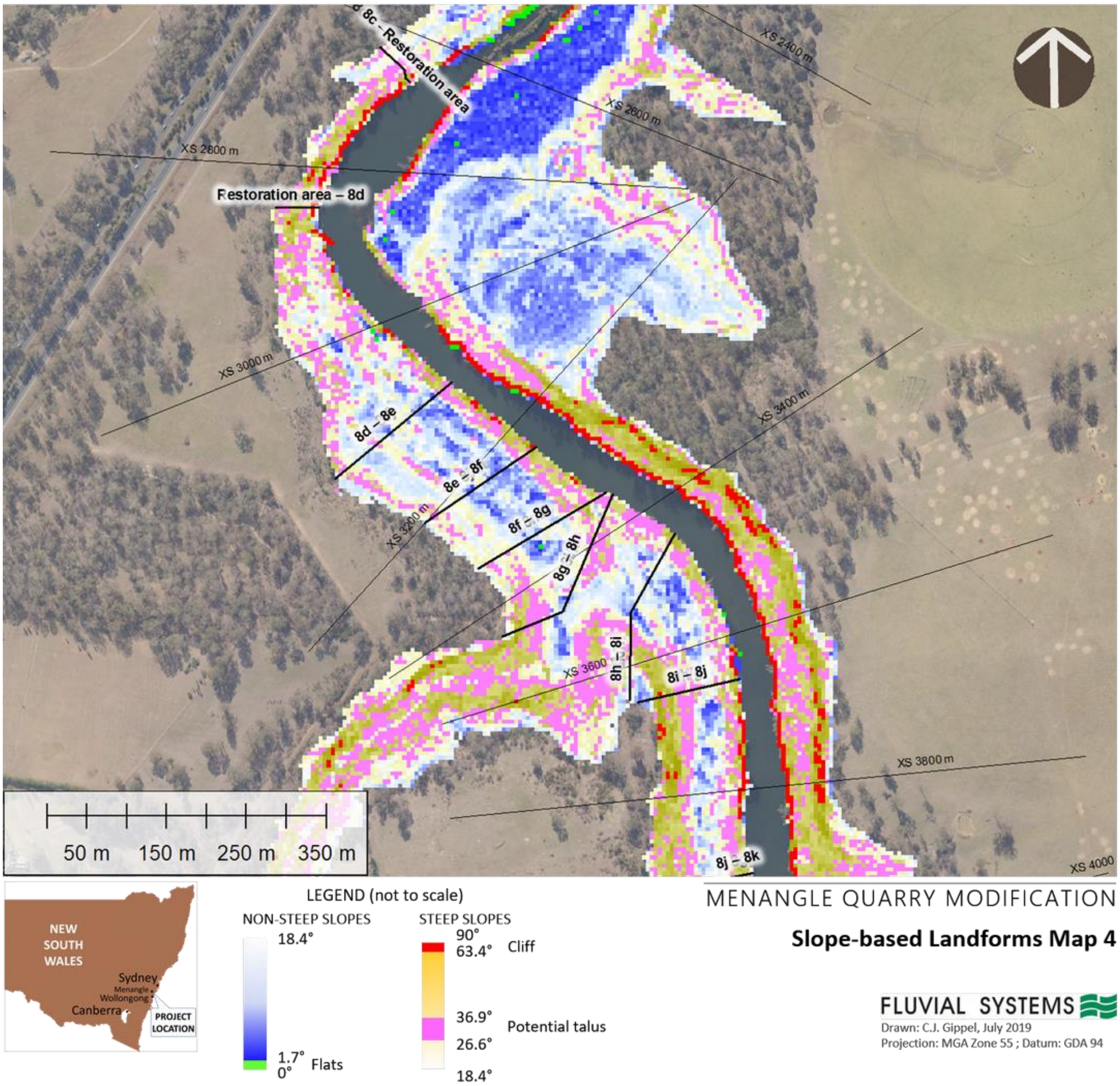


Figure 14. Slope –based landforms Map 4.

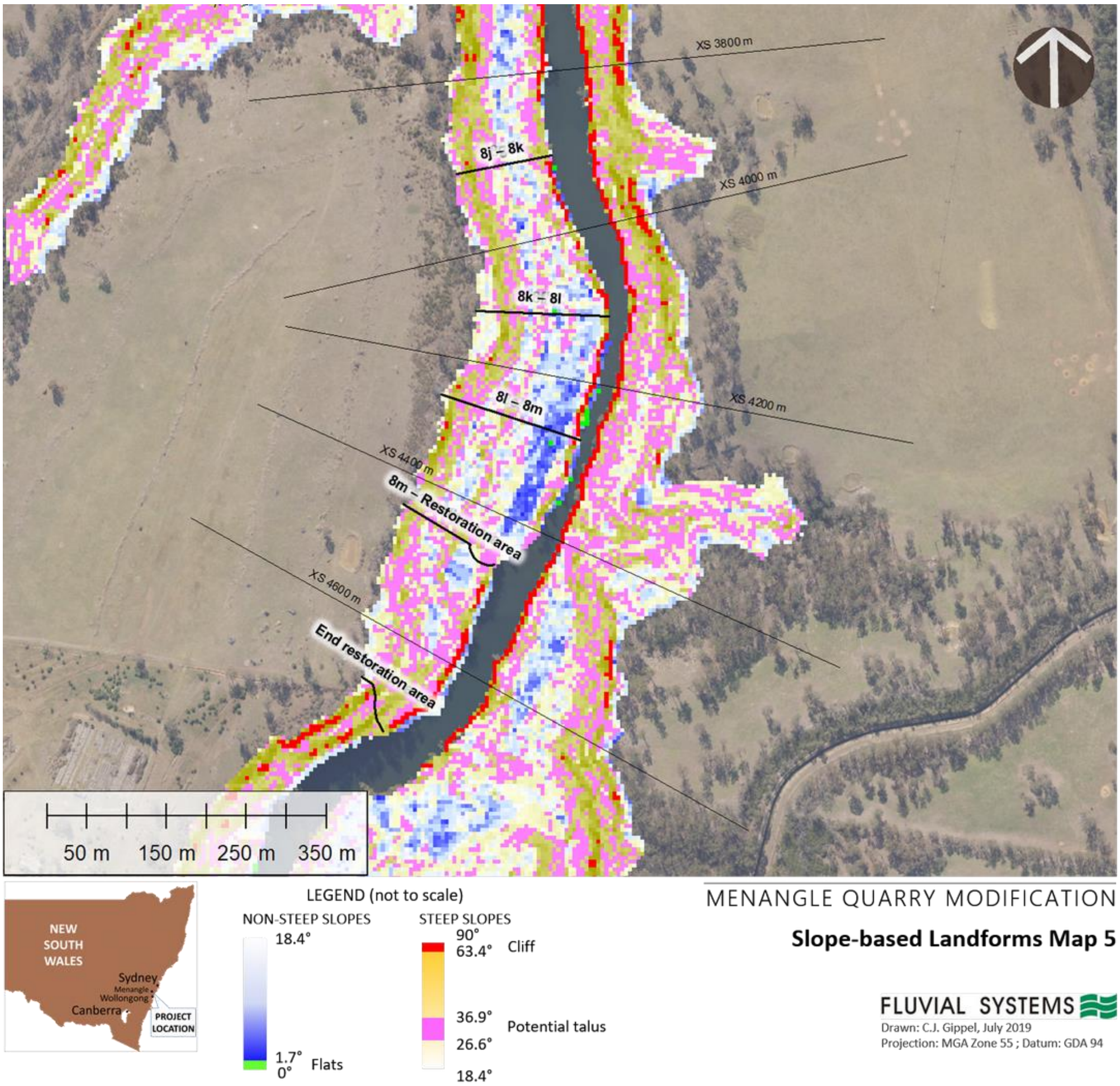


Figure 15. Slope –based landforms Map 5.

7.2 Topographic Position Index (TPI) plain landform class

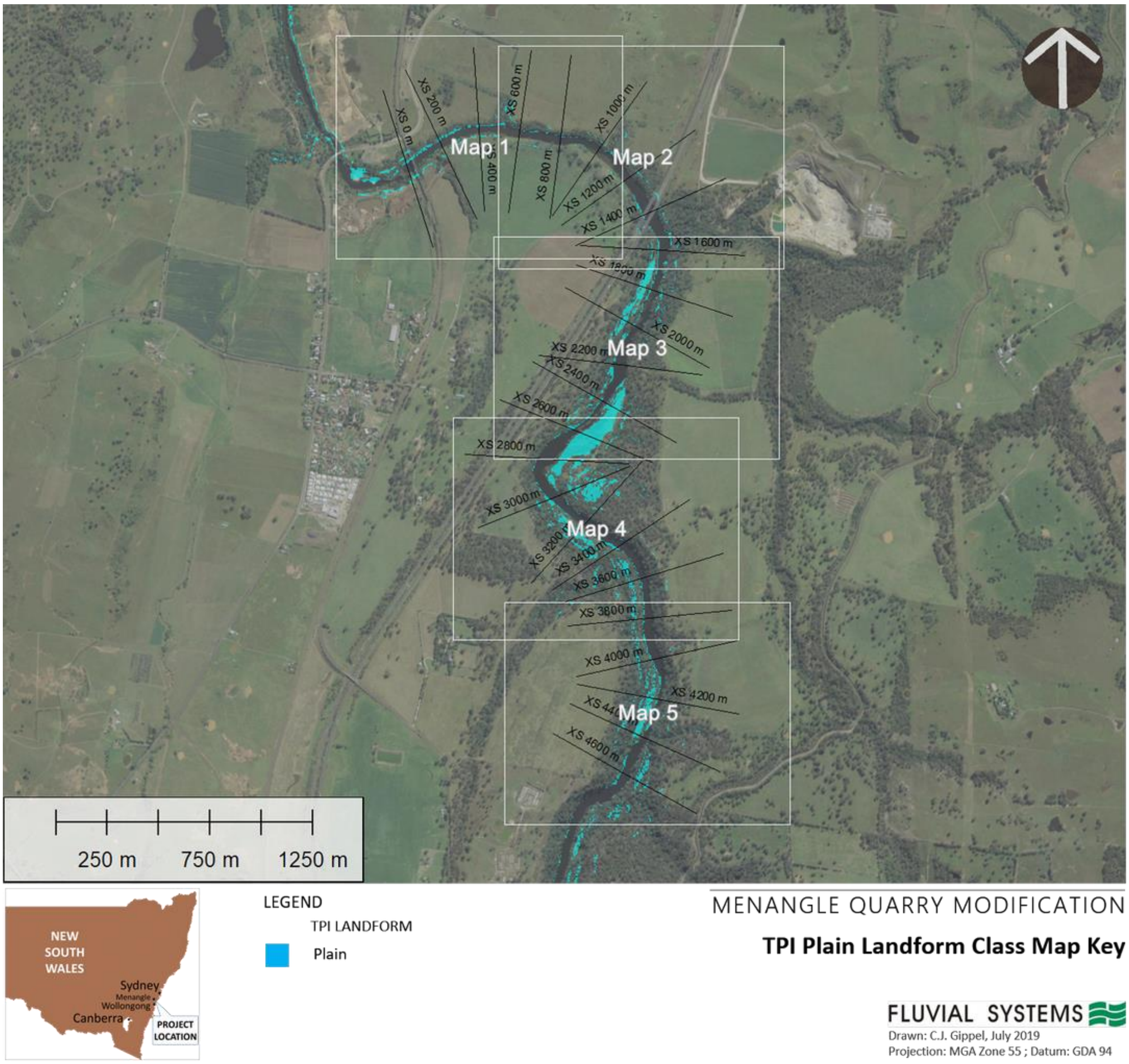


Figure 16. Topographic Position Index (TPI) plain landform class map key.

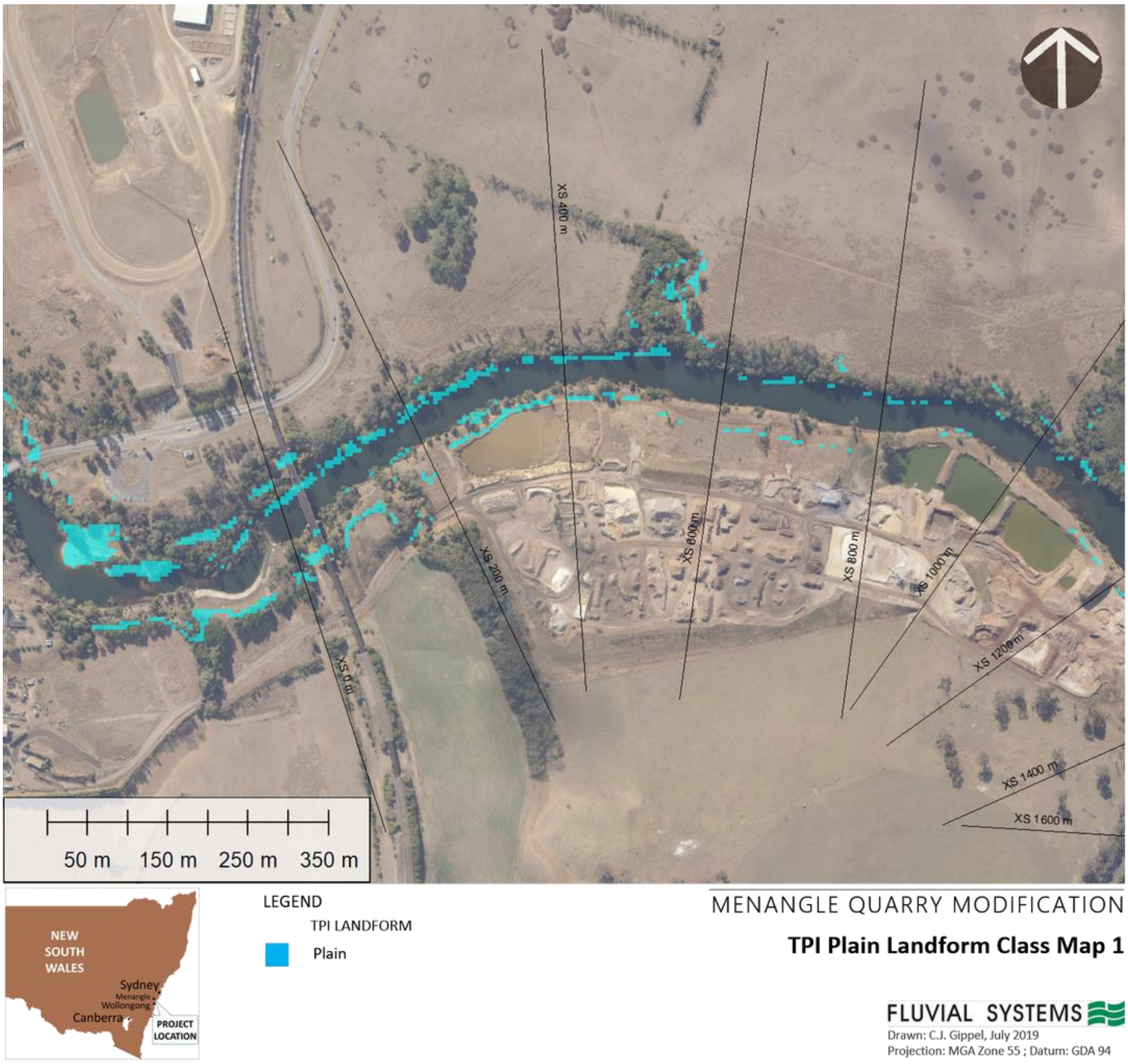


Figure 17. Topographic Position Index (TPI) plain landform class Map 1.

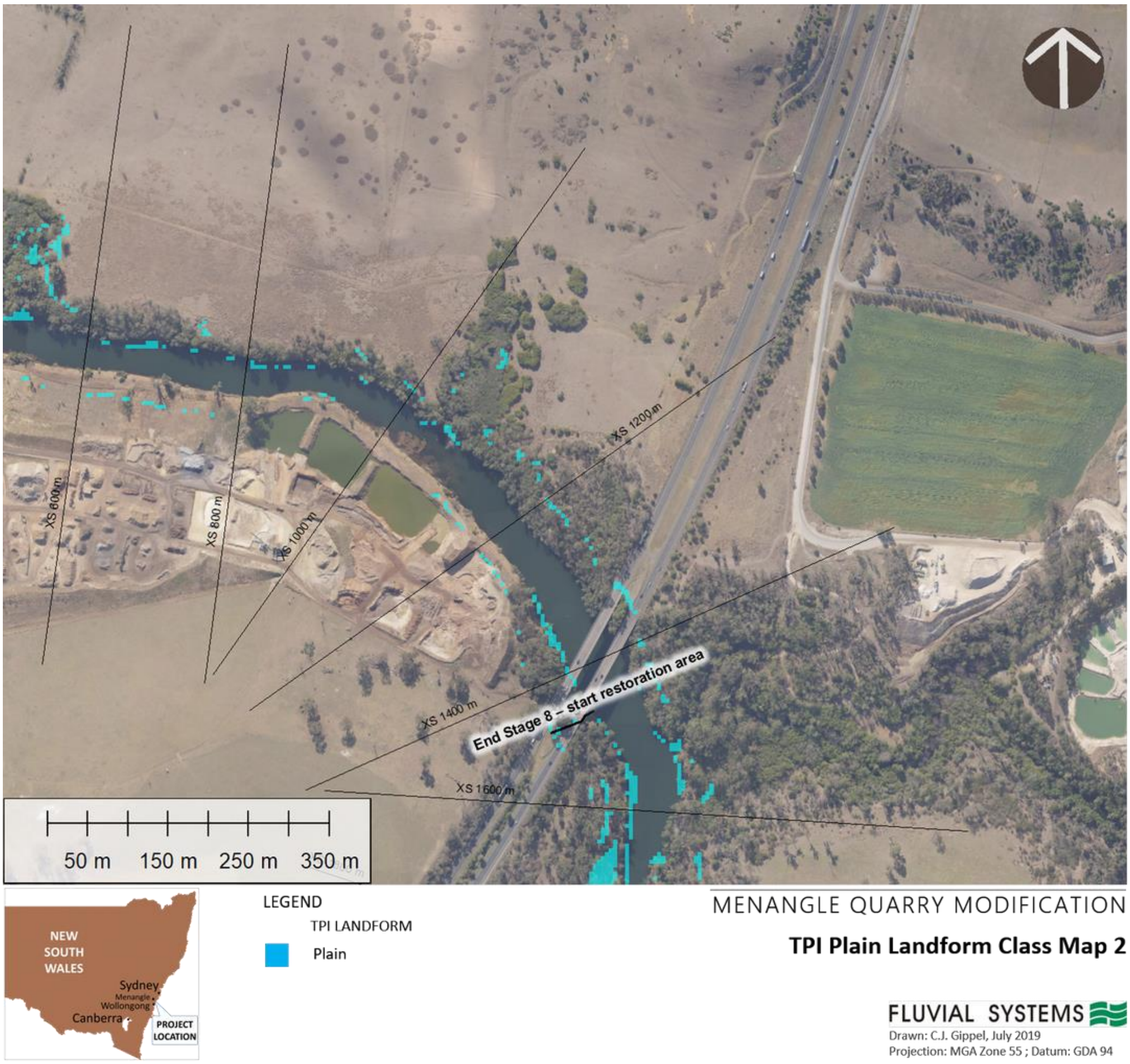


Figure 18. Topographic Position Index (TPI) plain landform class Map 2.

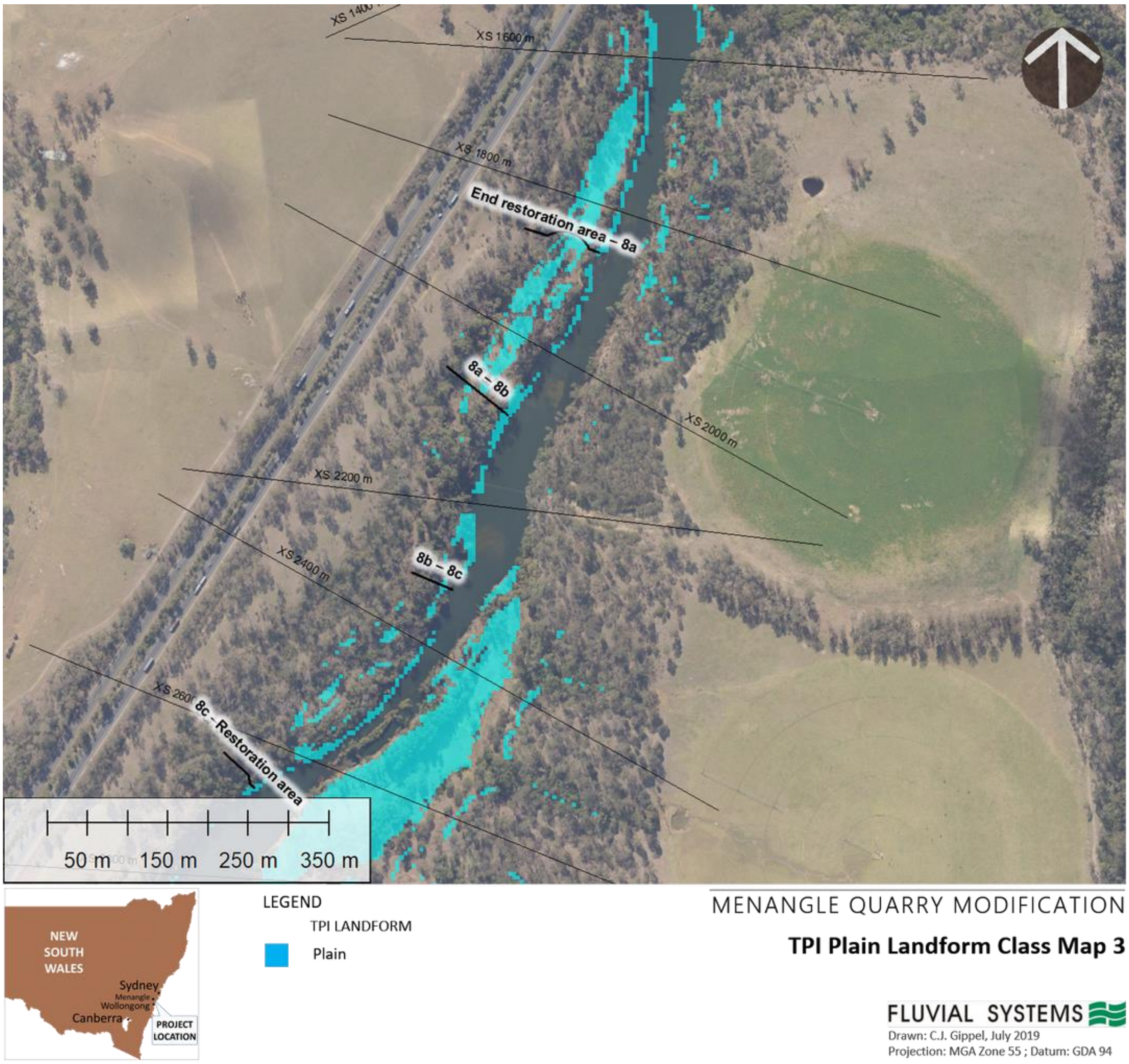


Figure 19. Topographic Position Index (TPI) plain landform class Map 3.

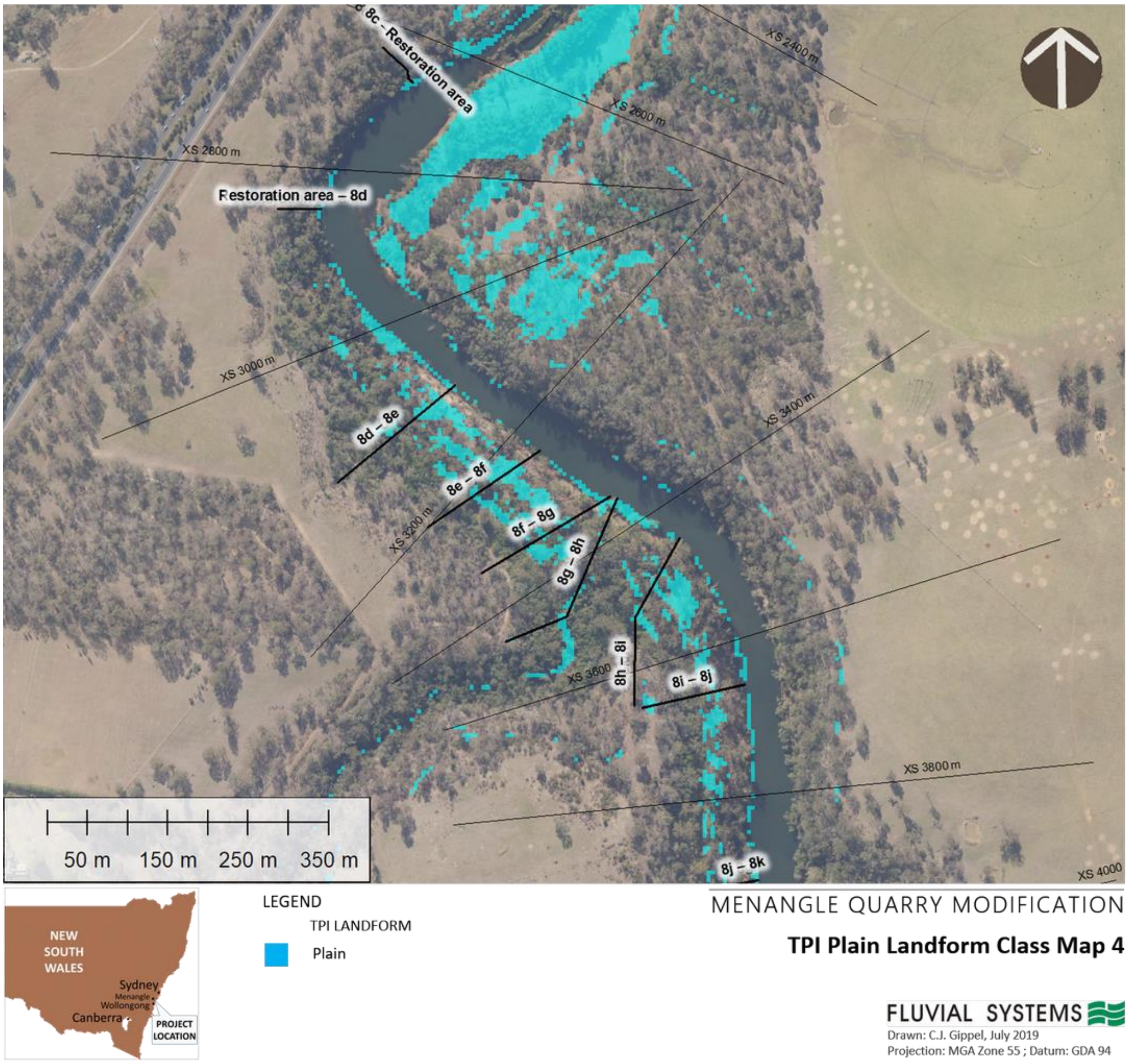


Figure 20. Topographic Position Index (TPI) plain landform class Map 4.

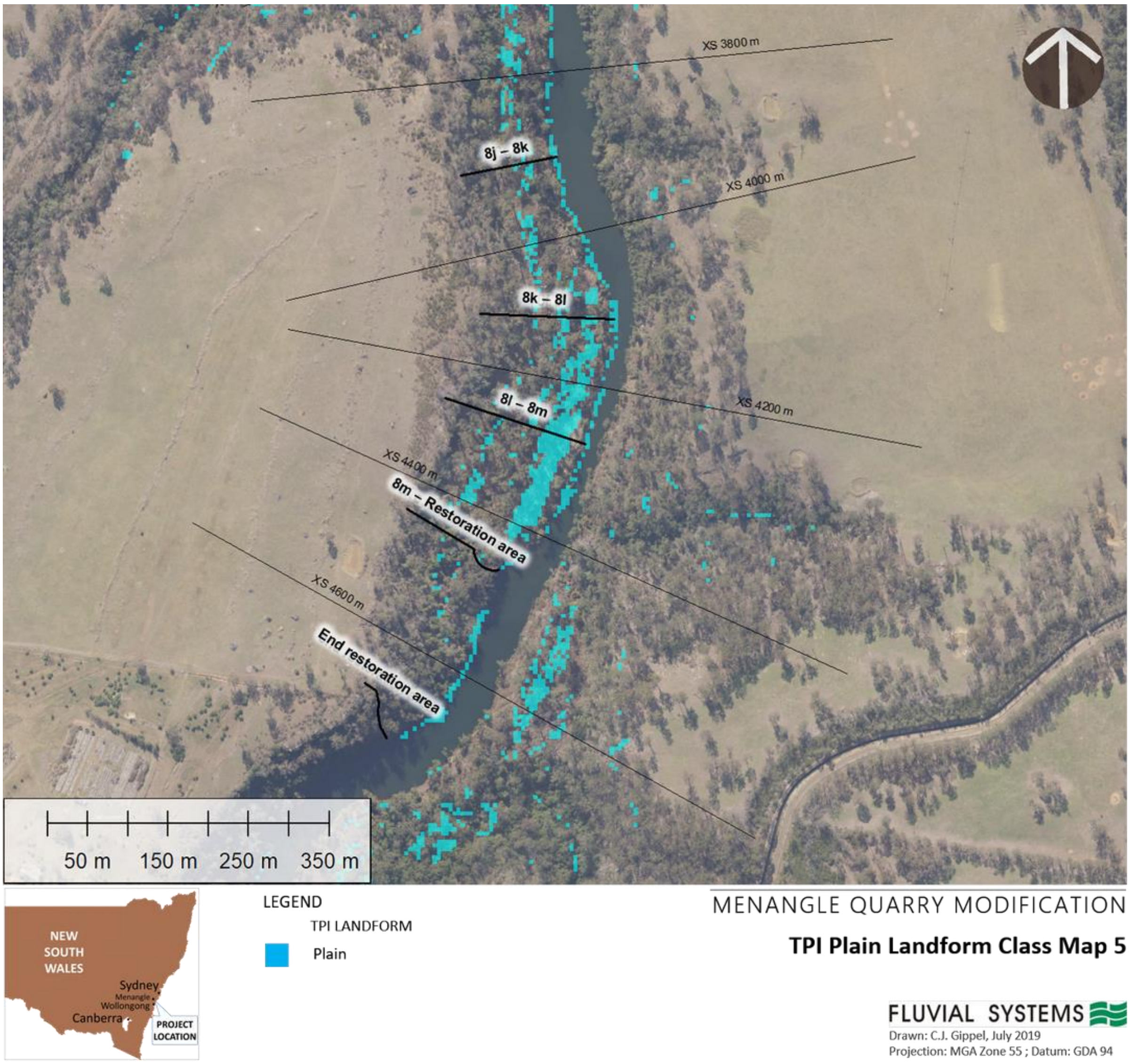


Figure 21. Topographic Position Index (TPI) plain landform class Map 5.

7.3 Terrain Surface Classification (TSC) gentle slope landform class

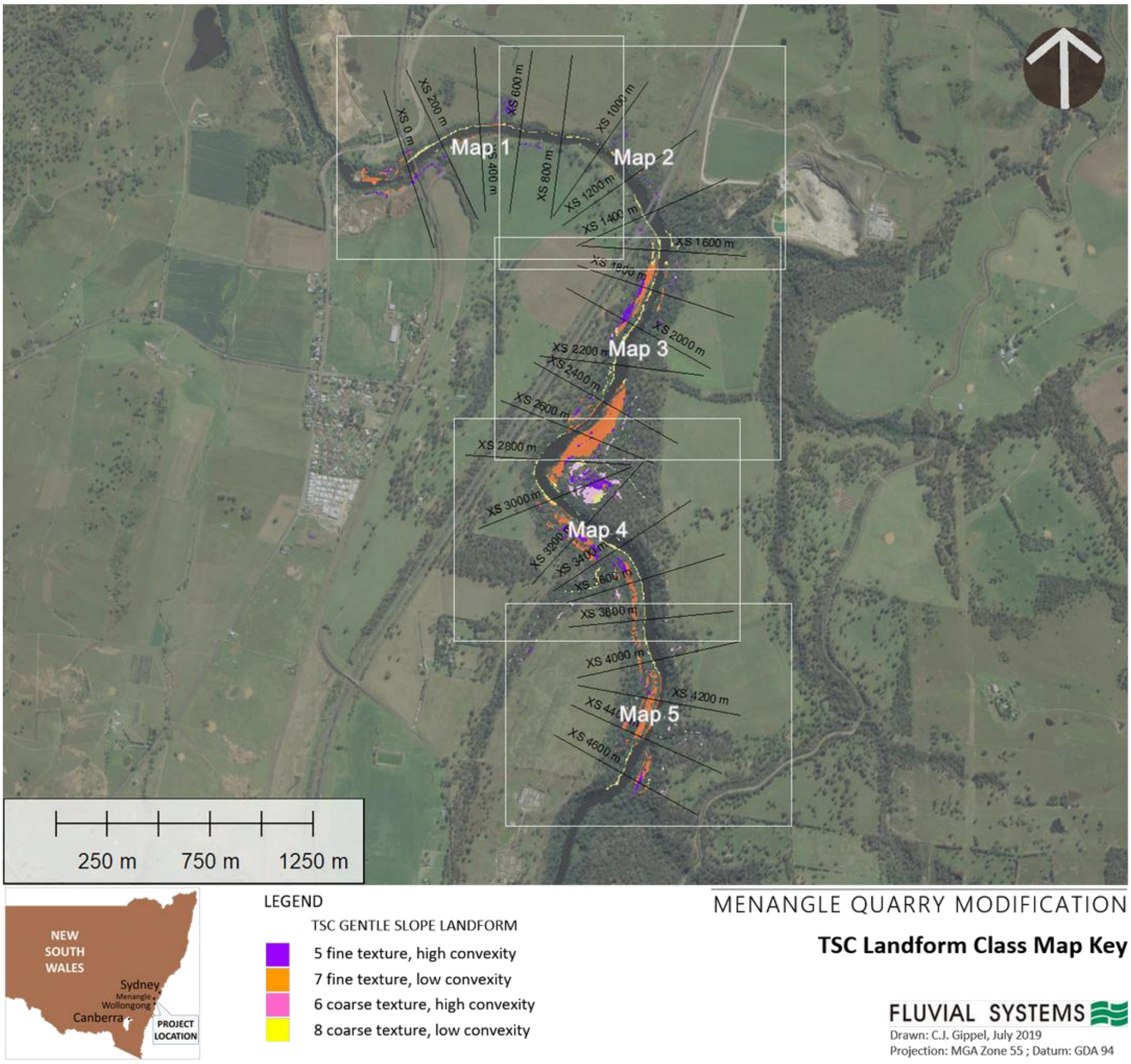


Figure 22. Terrain Surface Classification (TSC) gentle slope landform class map key.

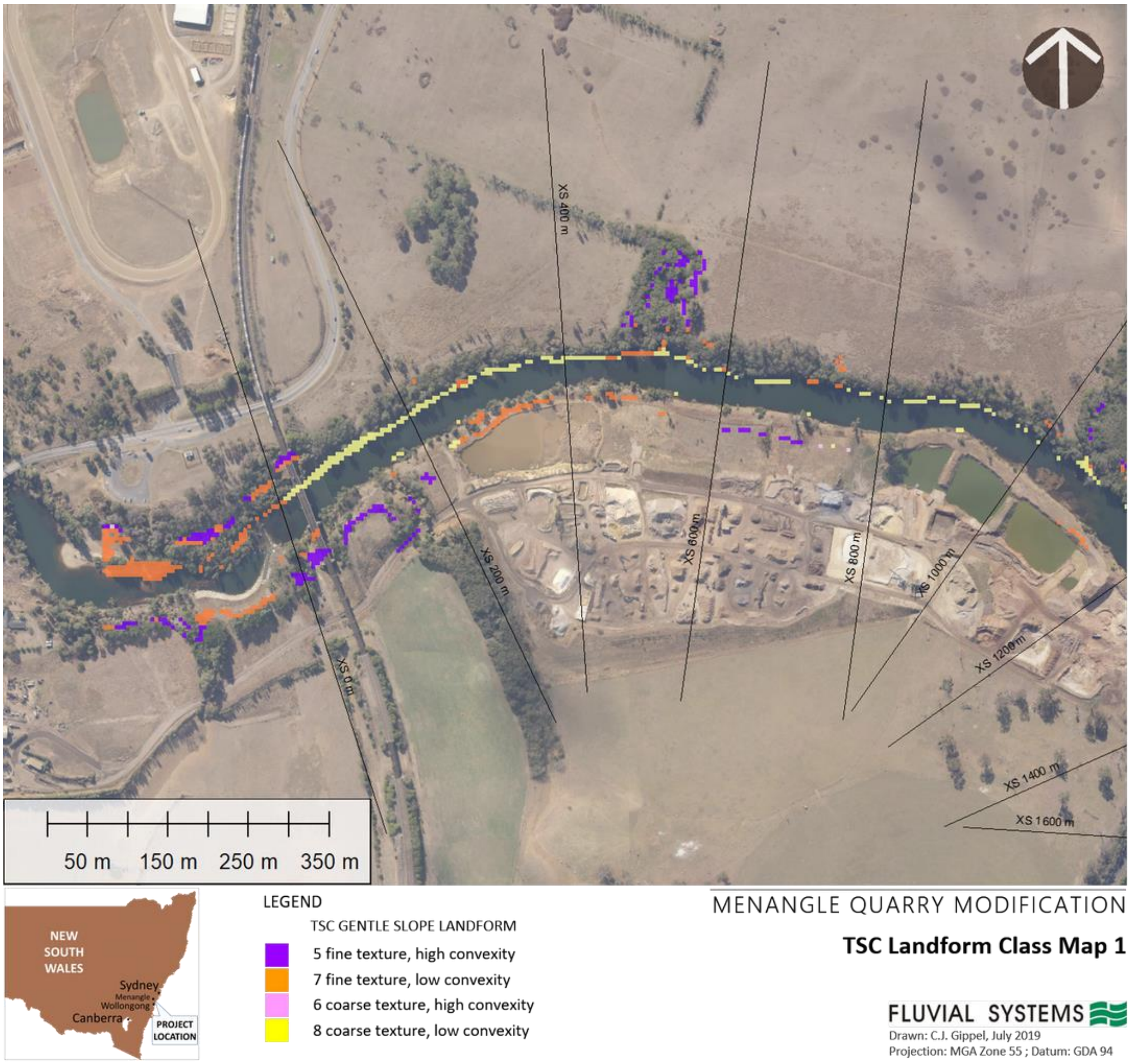


Figure 23. Terrain Surface Classification (TSC) gentle slope landform class Map 1.

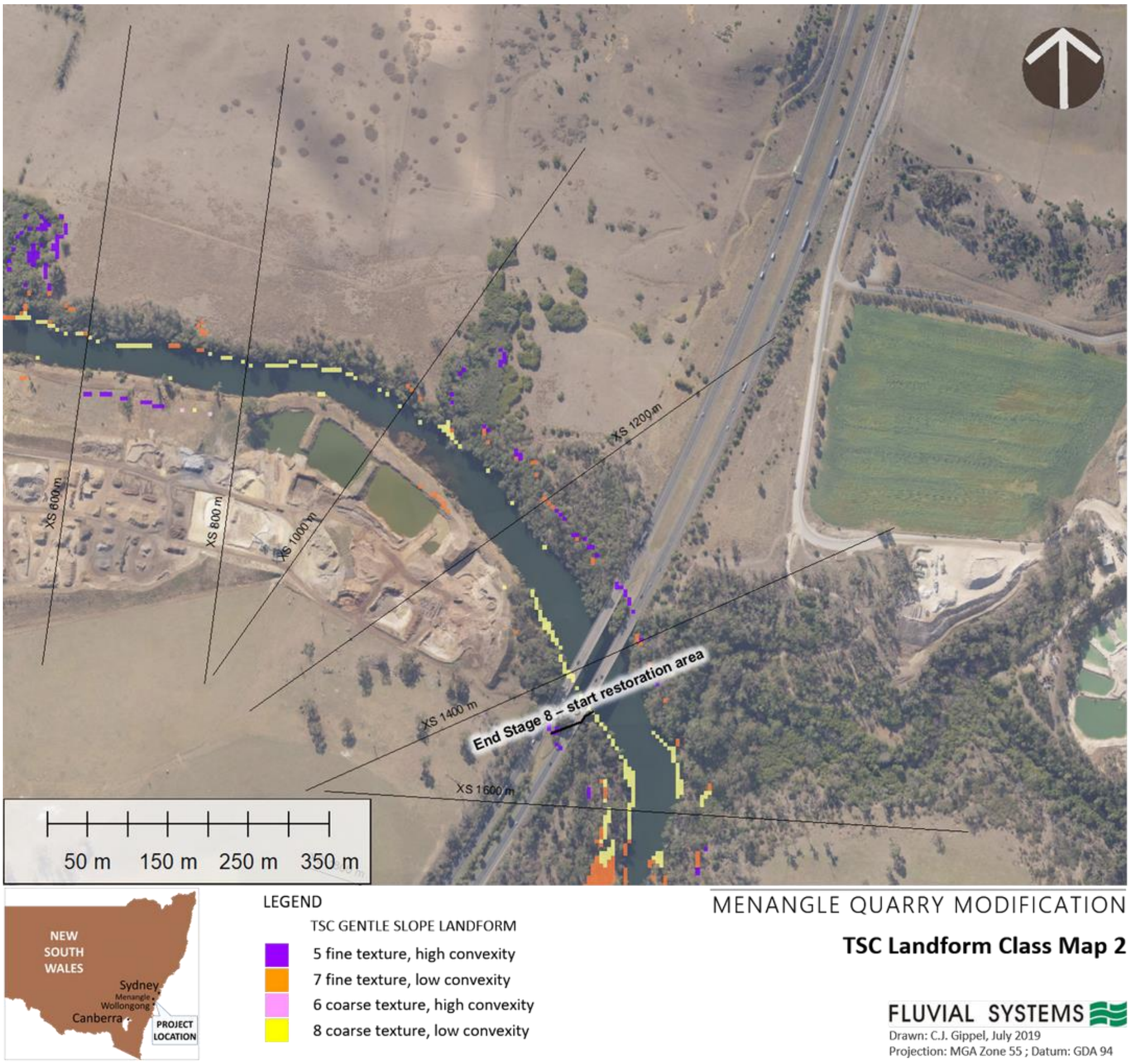


Figure 24. Terrain Surface Classification (TSC) gentle slope landform class Map 2.

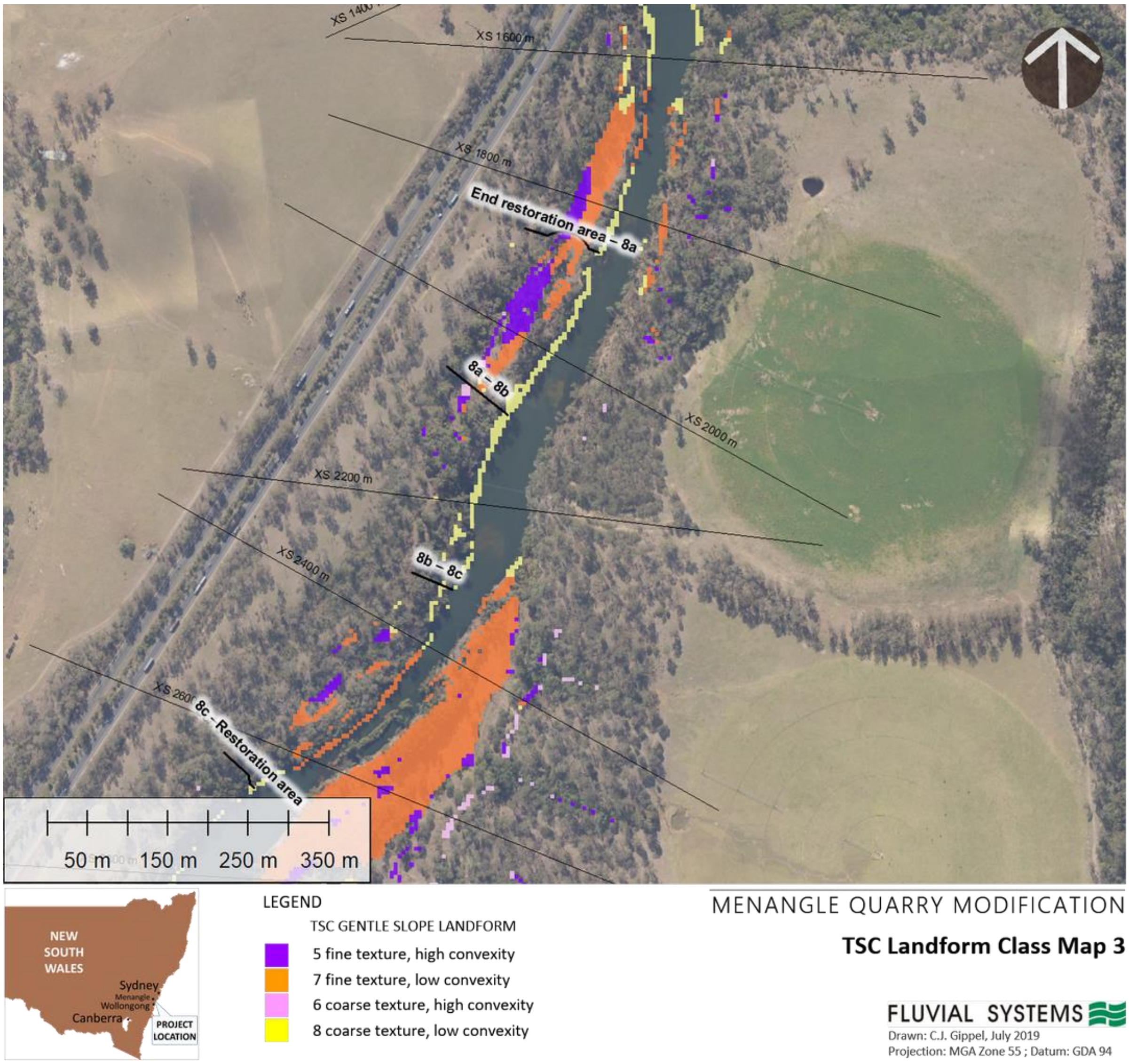


Figure 25. Terrain Surface Classification (TSC) gentle slope landform class Map 3.

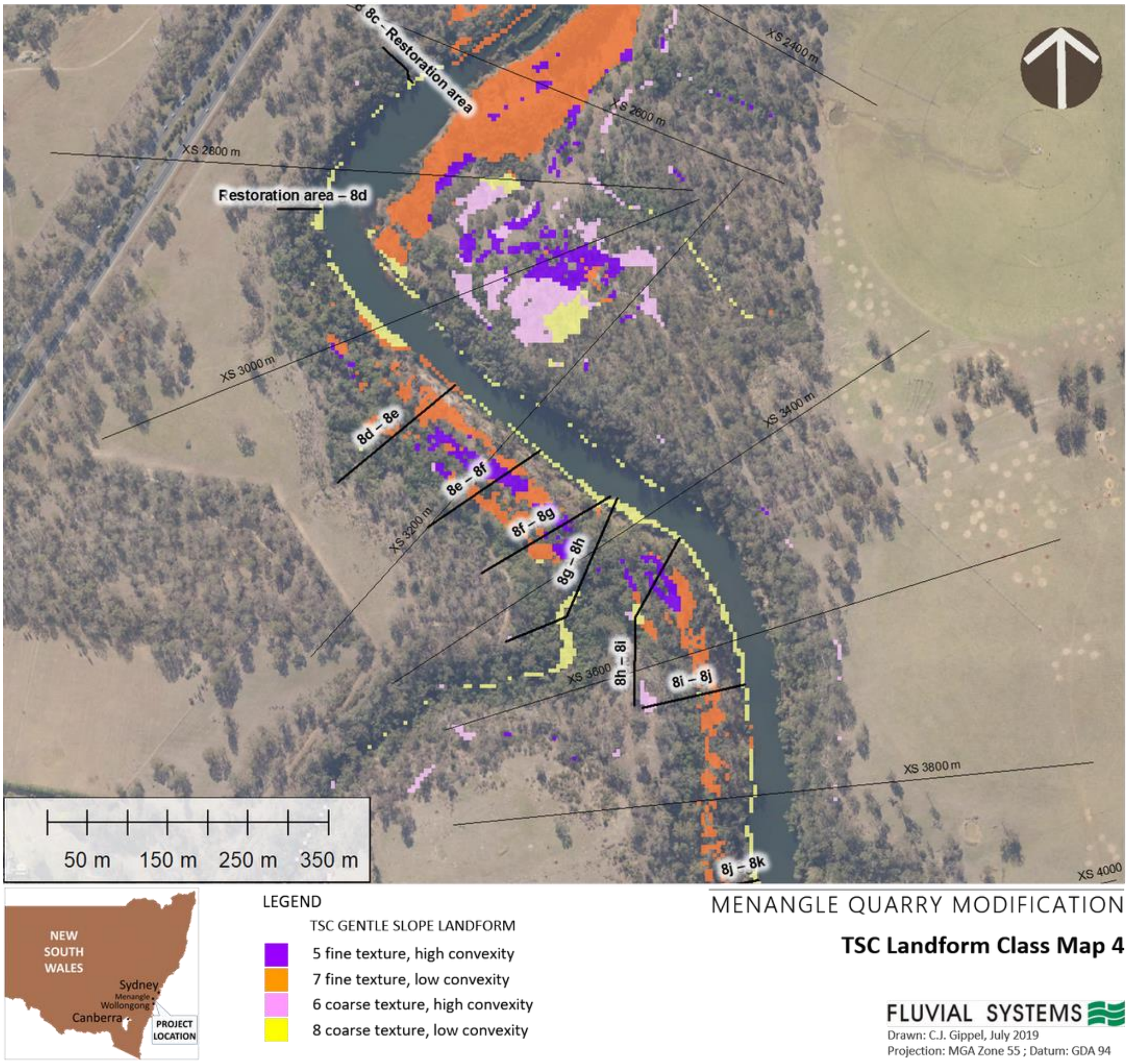


Figure 26. Terrain Surface Classification (TSC) gentle slope landform class Map 4.

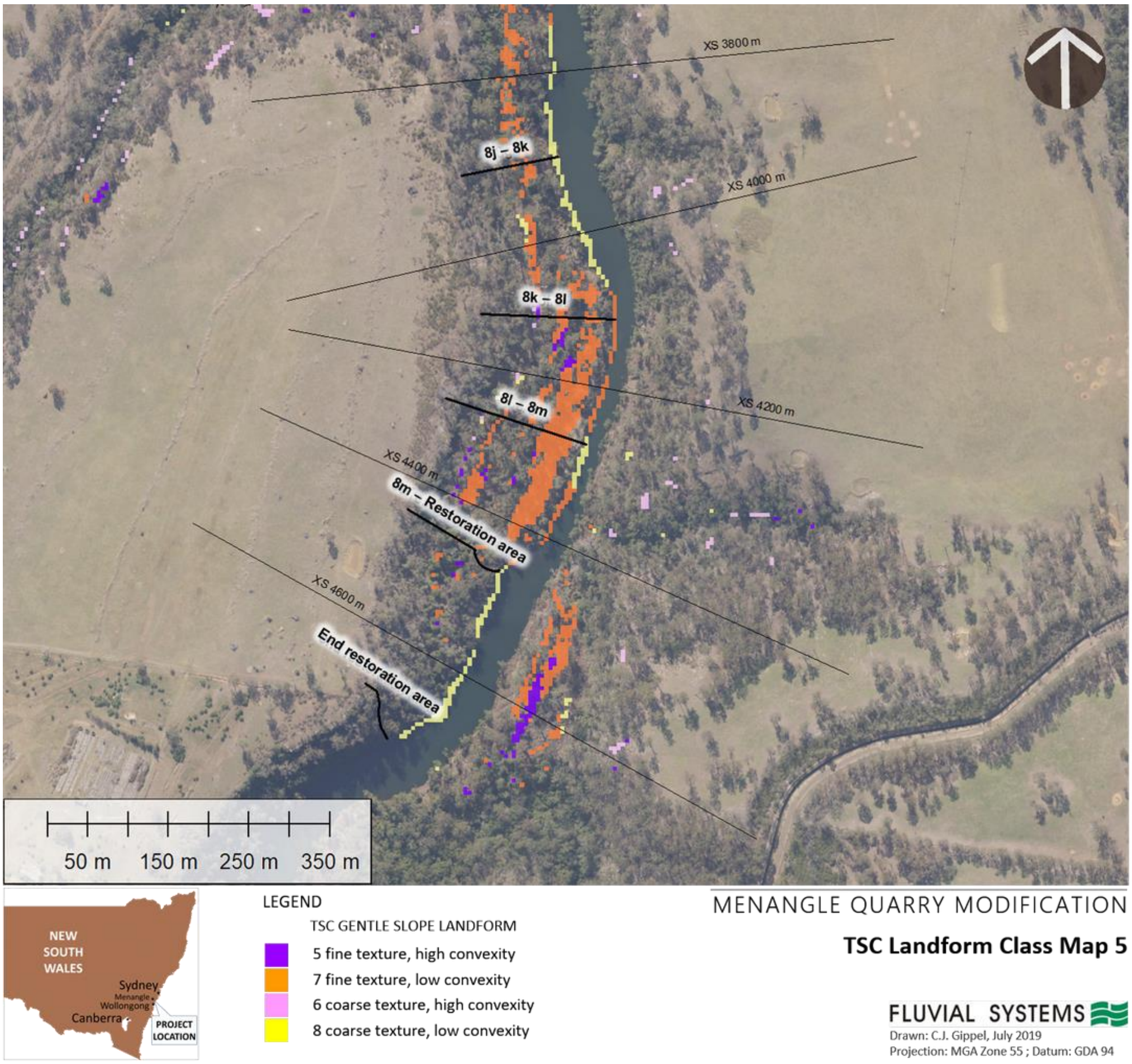


Figure 27. Terrain Surface Classification (TSC) gentle slope landform class Map 5.

7.4 Profile Curvature

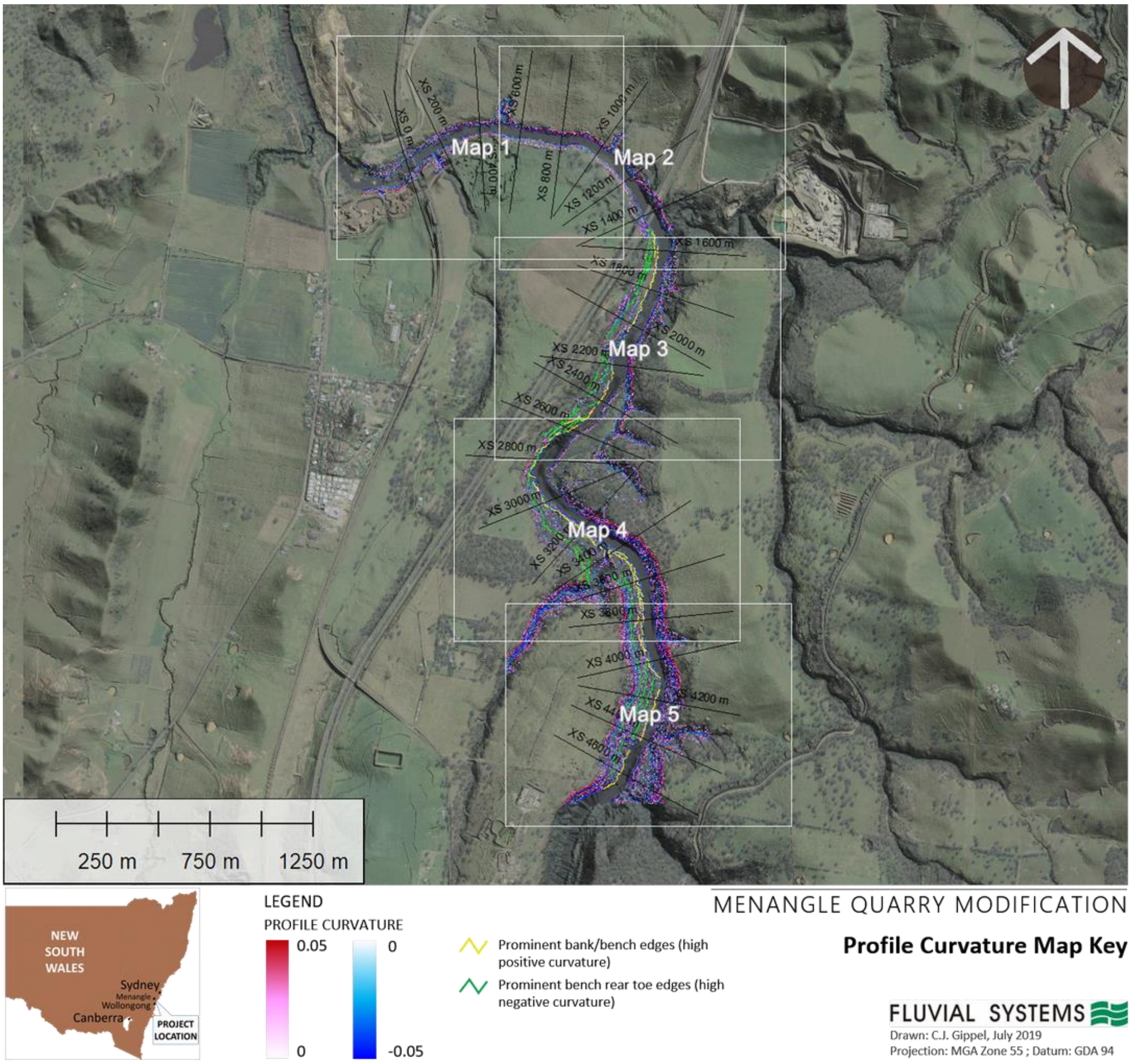


Figure 28. Profile curvature map key.

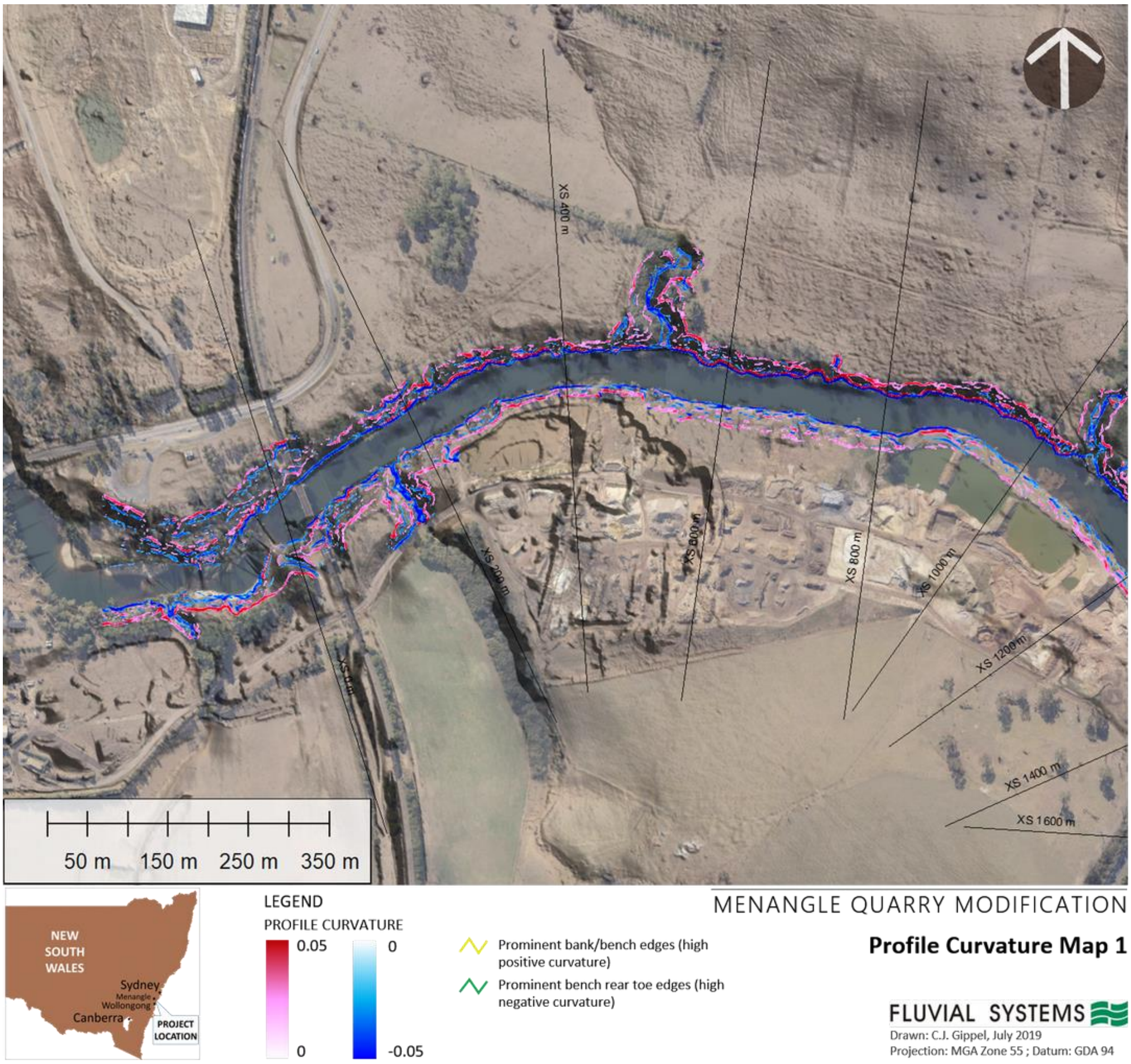


Figure 29. Profile curvature Map 1.

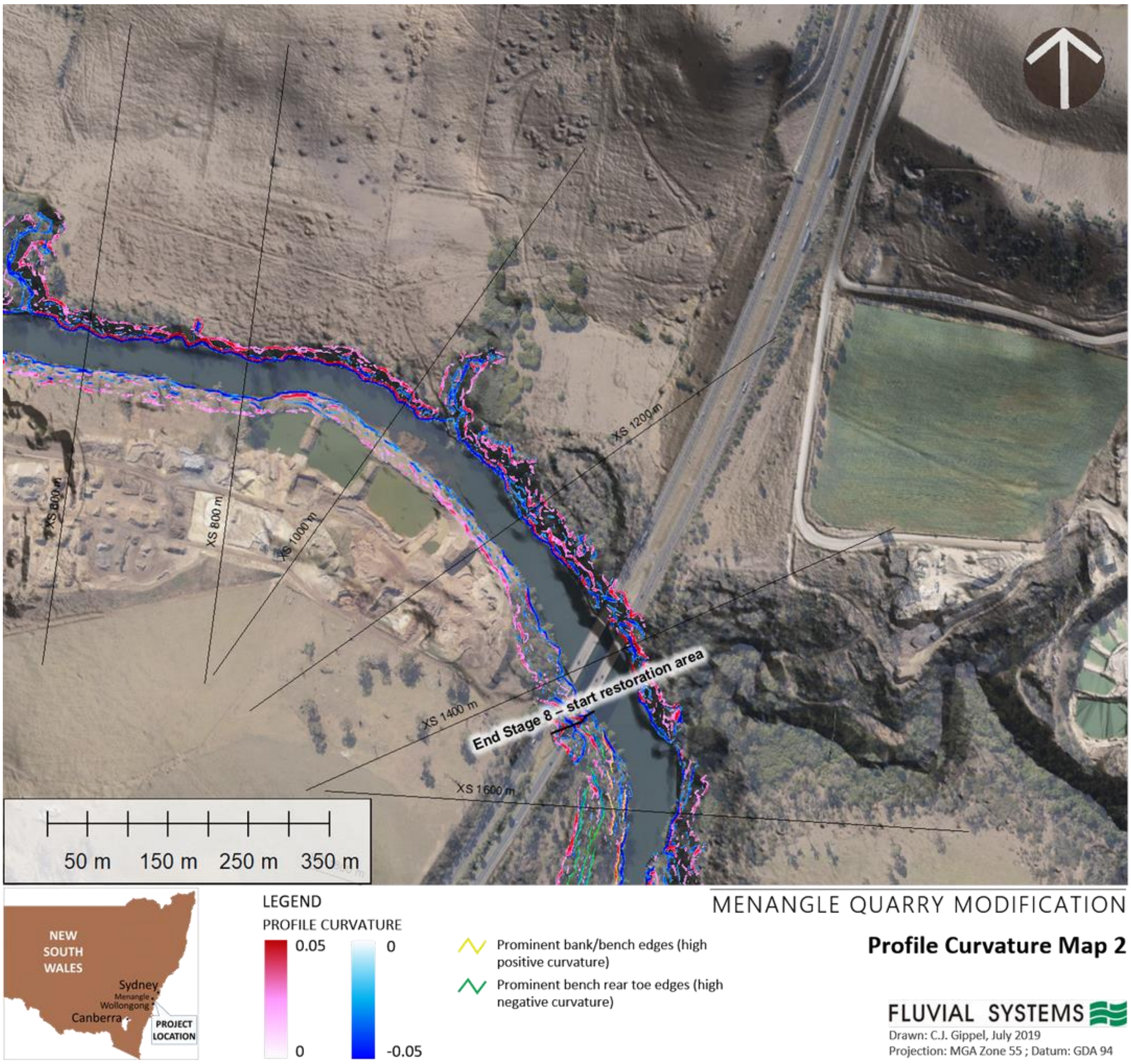


Figure 30. Profile curvature Map 2.

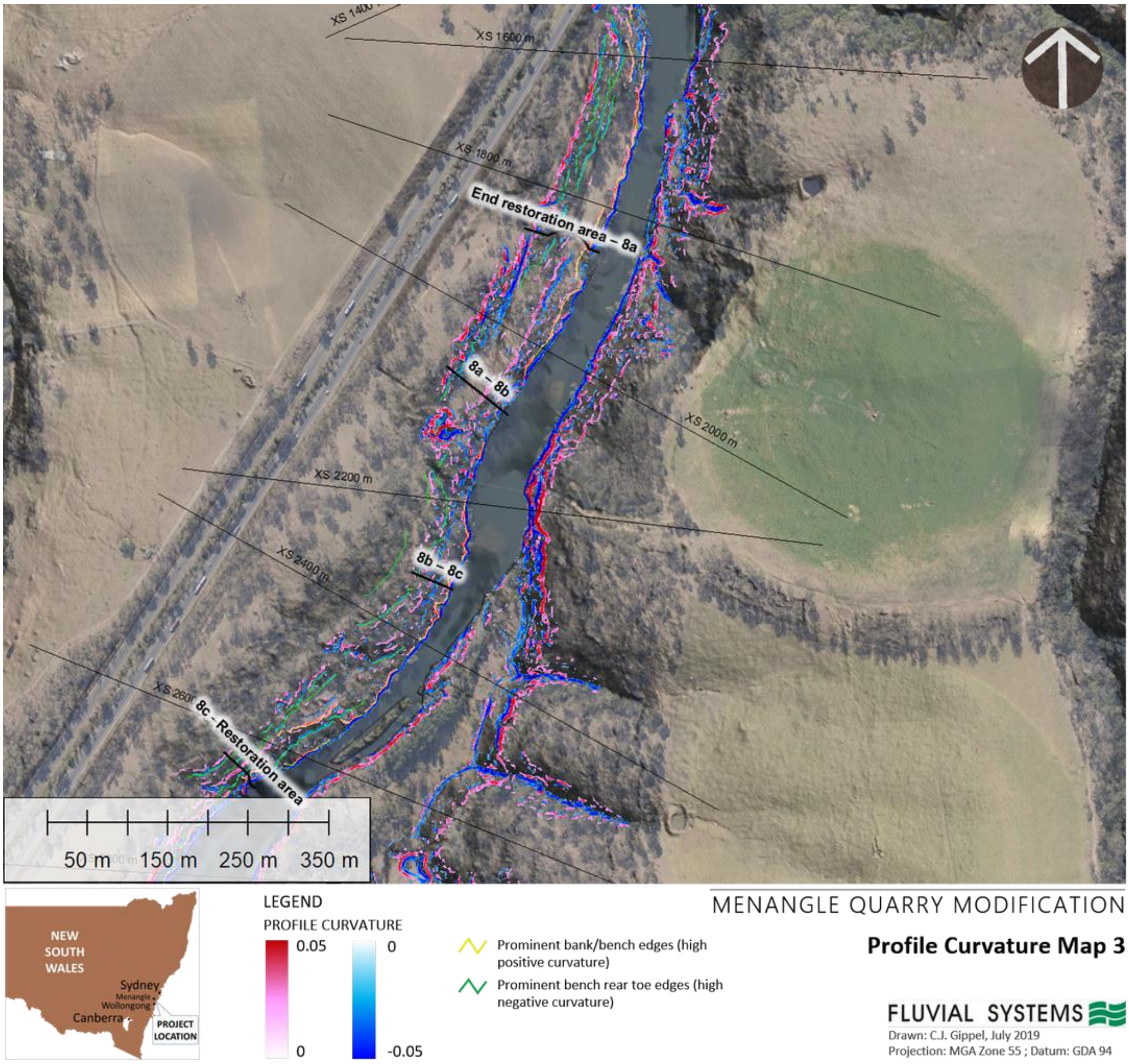


Figure 31. Profile curvature Map 3.

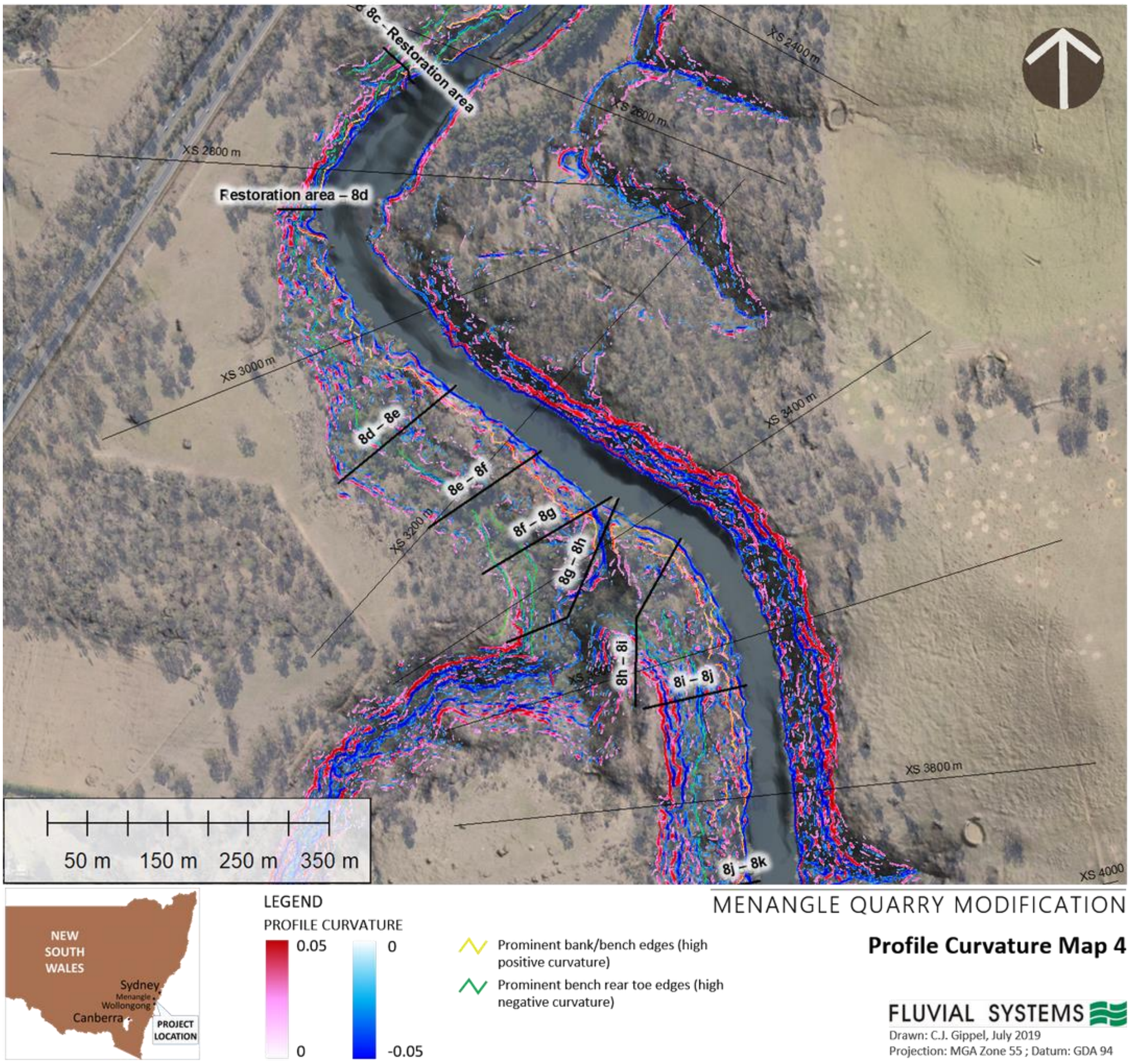


Figure 32. Profile curvature Map 4.

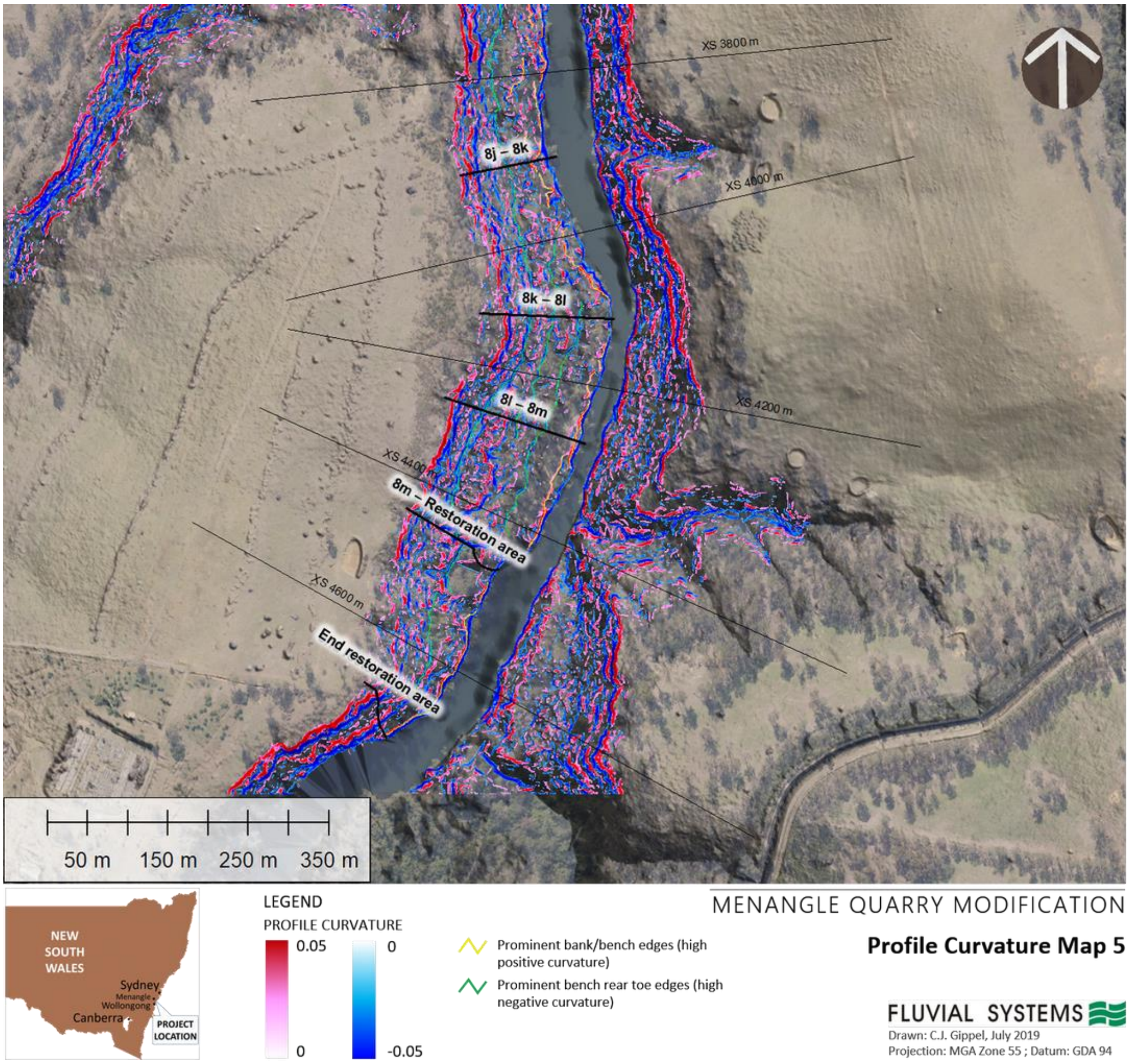


Figure 33. Profile curvature Map 5.

7.5 Peak Bed Shear Stress 50% AEP Event Existing Case

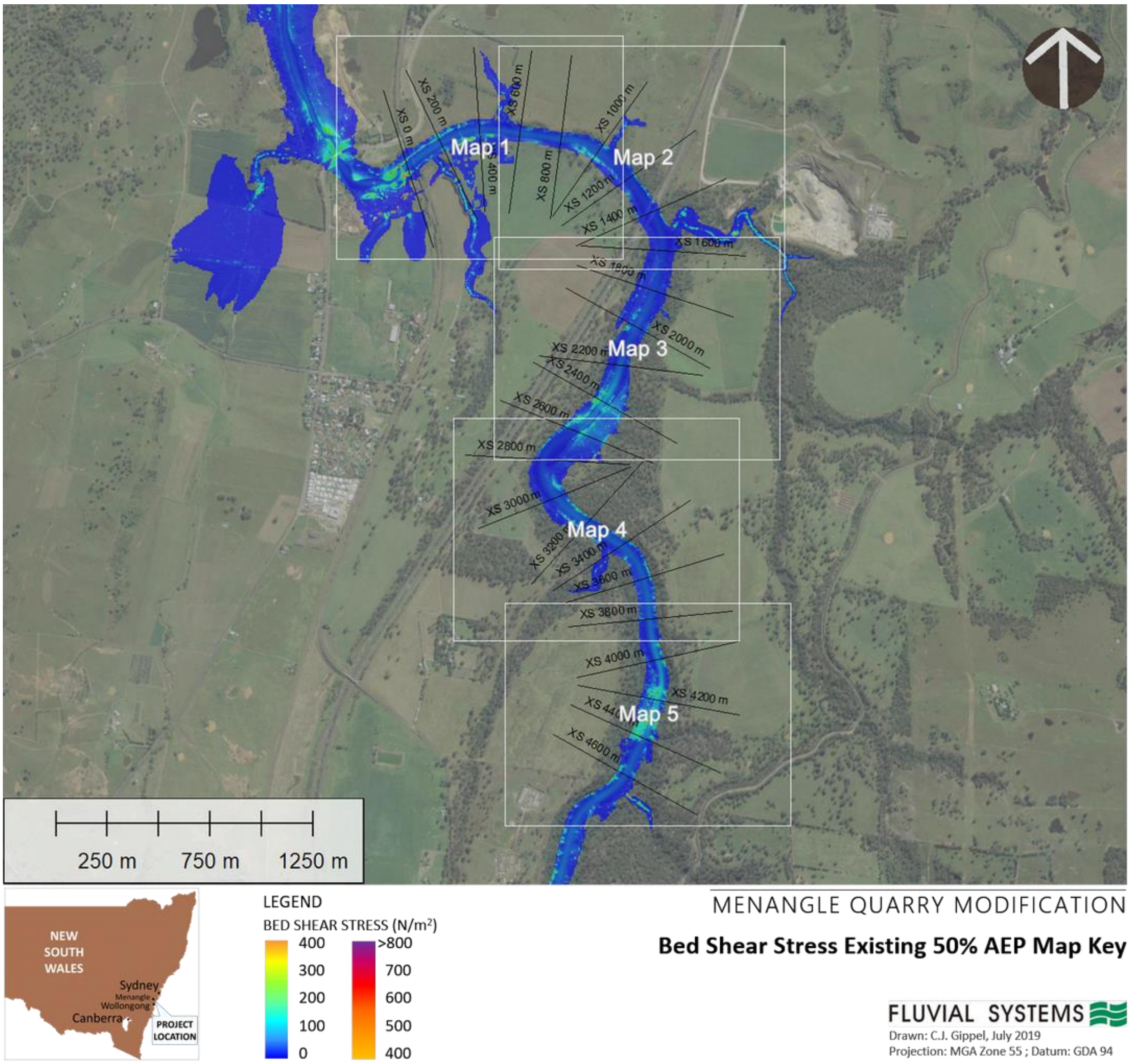


Figure 34. Peak bed shear stress 50% AEP event existing case map key.

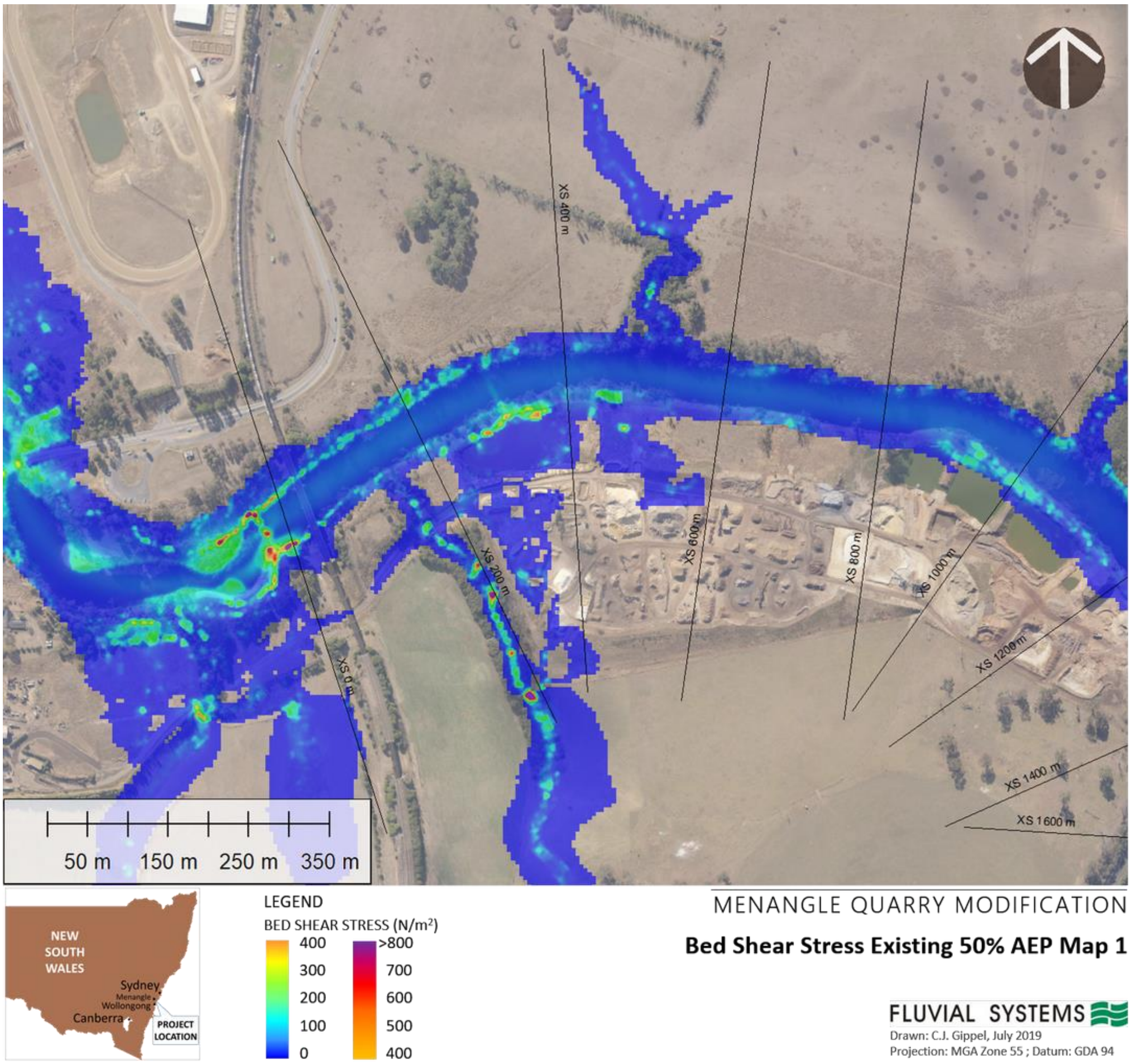


Figure 35. Peak bed shear stress 50% AEP event existing case Map 1.

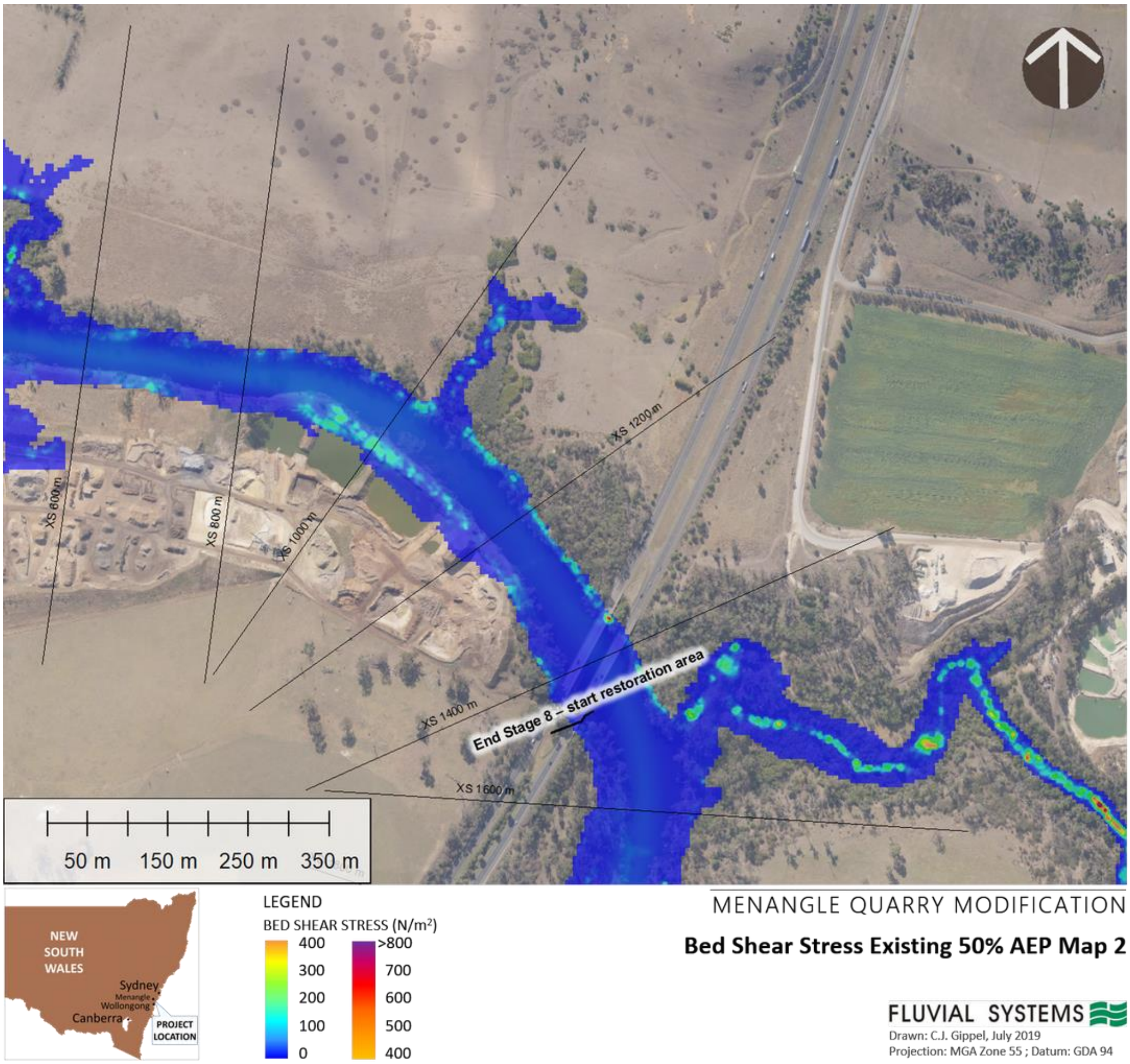


Figure 36. Peak bed shear stress 50% AEP event existing case Map 2.

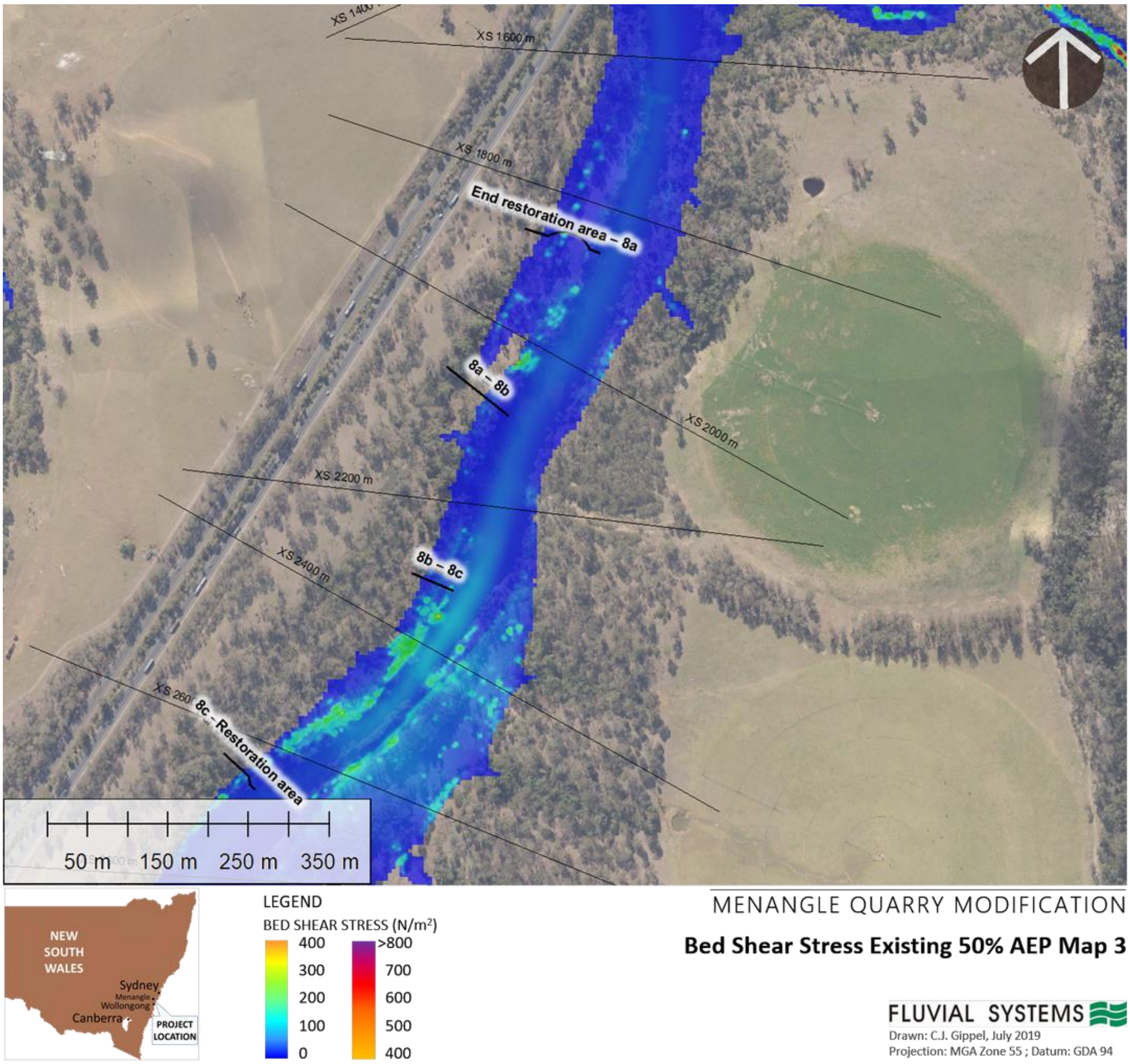


Figure 37. Peak bed shear stress 50% AEP event existing case Map 3.

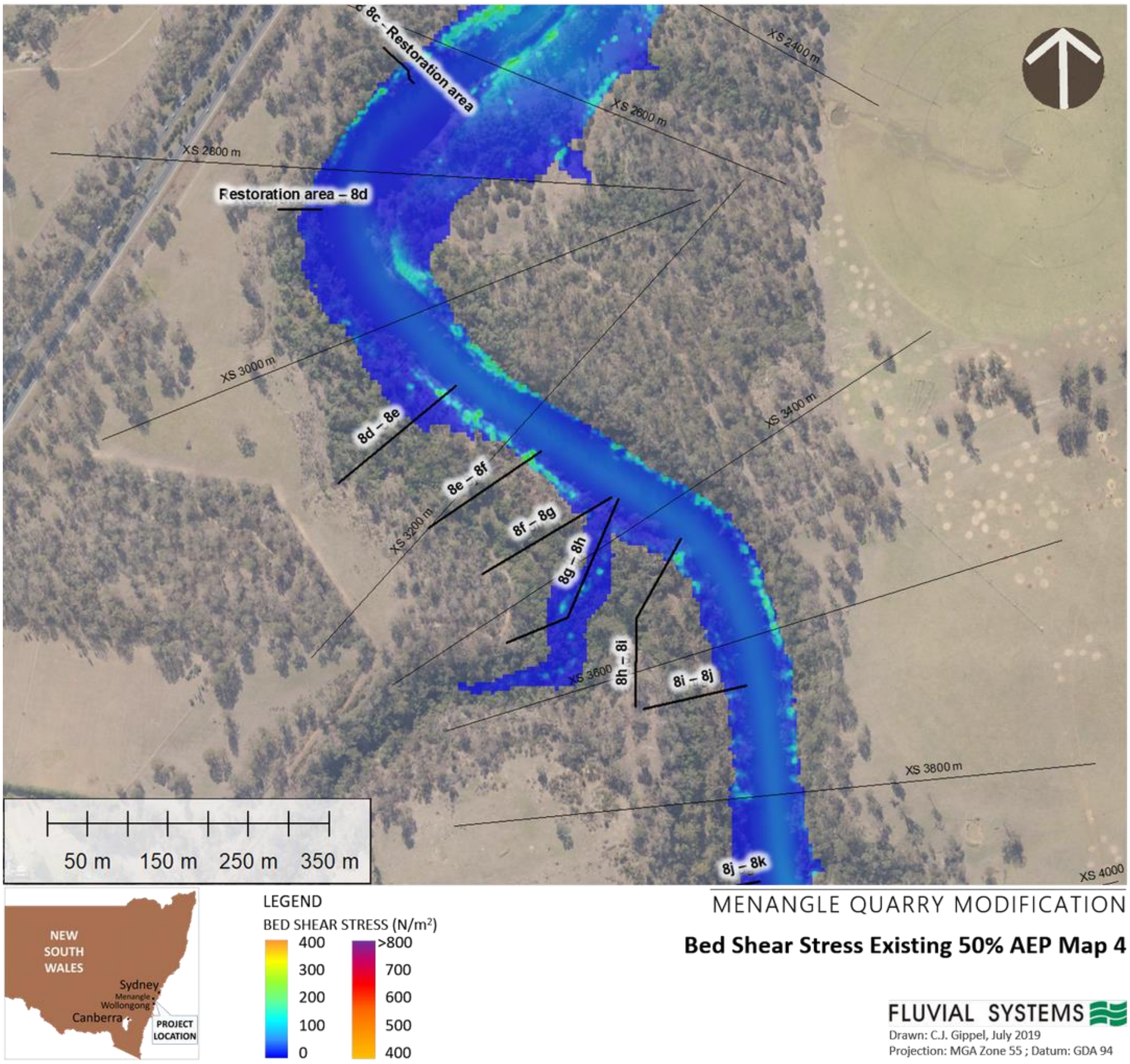


Figure 38. Peak bed shear stress 50% AEP event existing case Map 4.

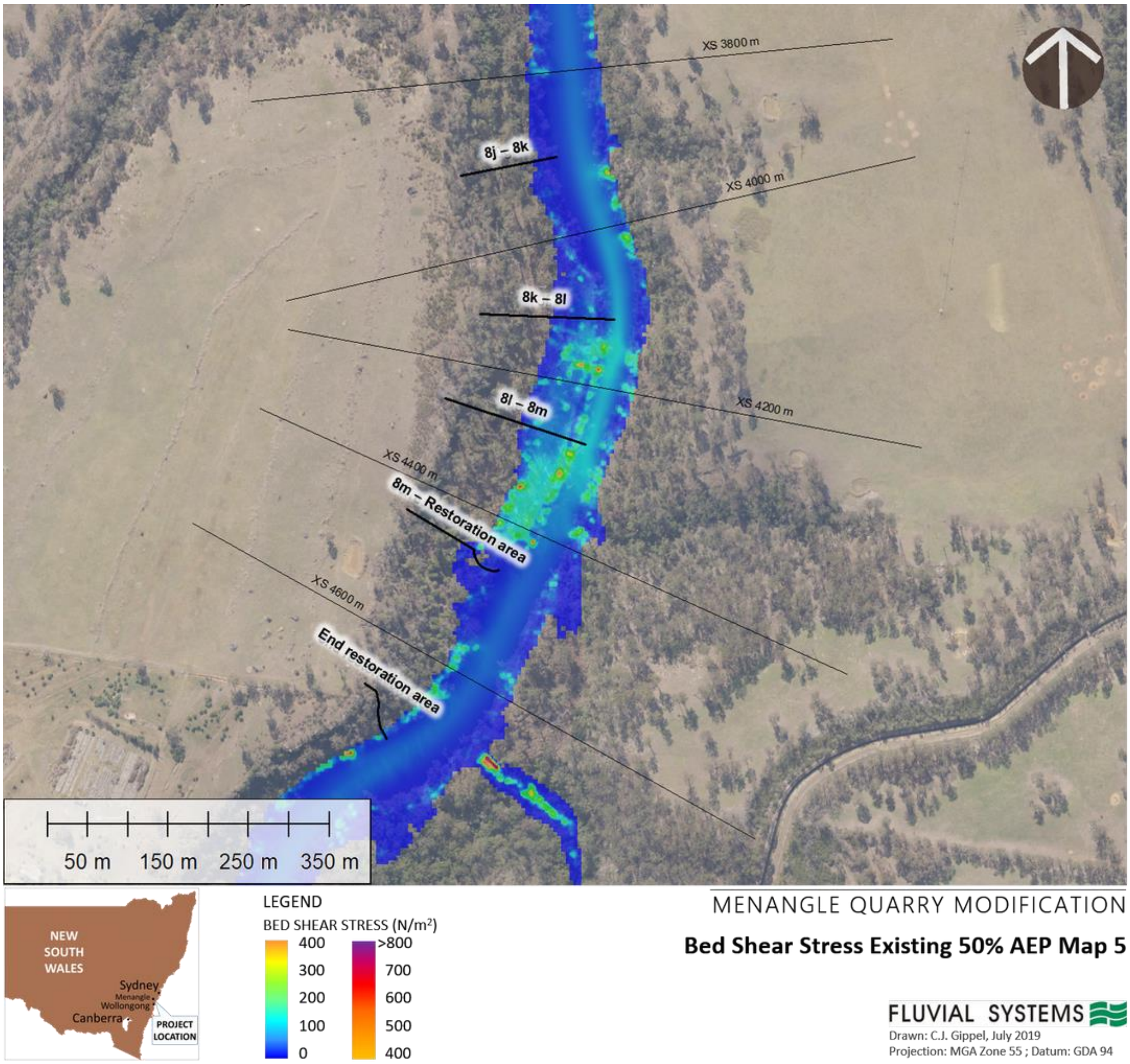


Figure 39. Peak bed shear stress 50% AEP event existing case Map 5.

7.6 Peak Bed Shear Stress 50% AEP Event Mid-Works Scenario

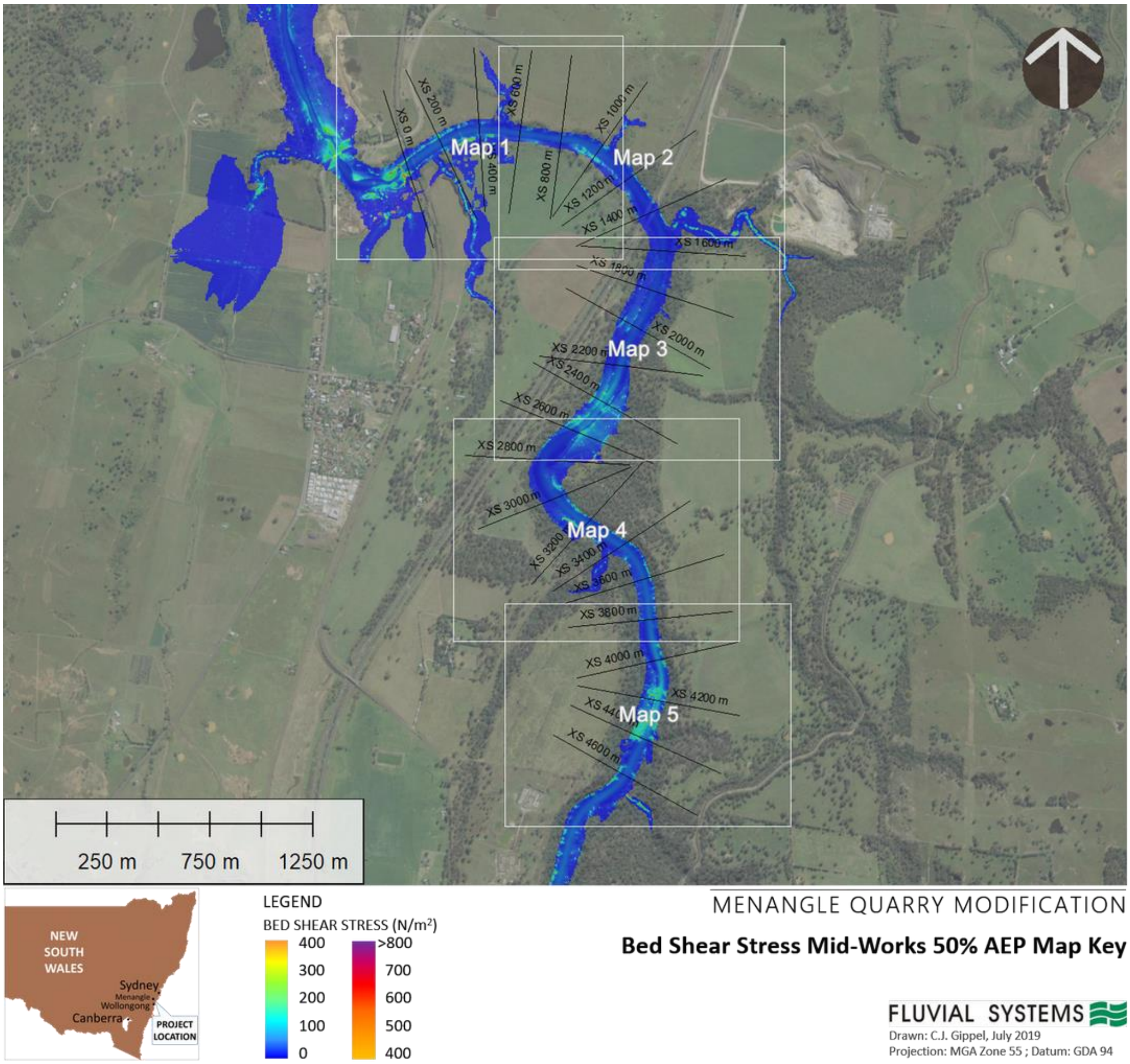


Figure 40. Peak bed shear stress 50% AEP event mid-works scenario map key.

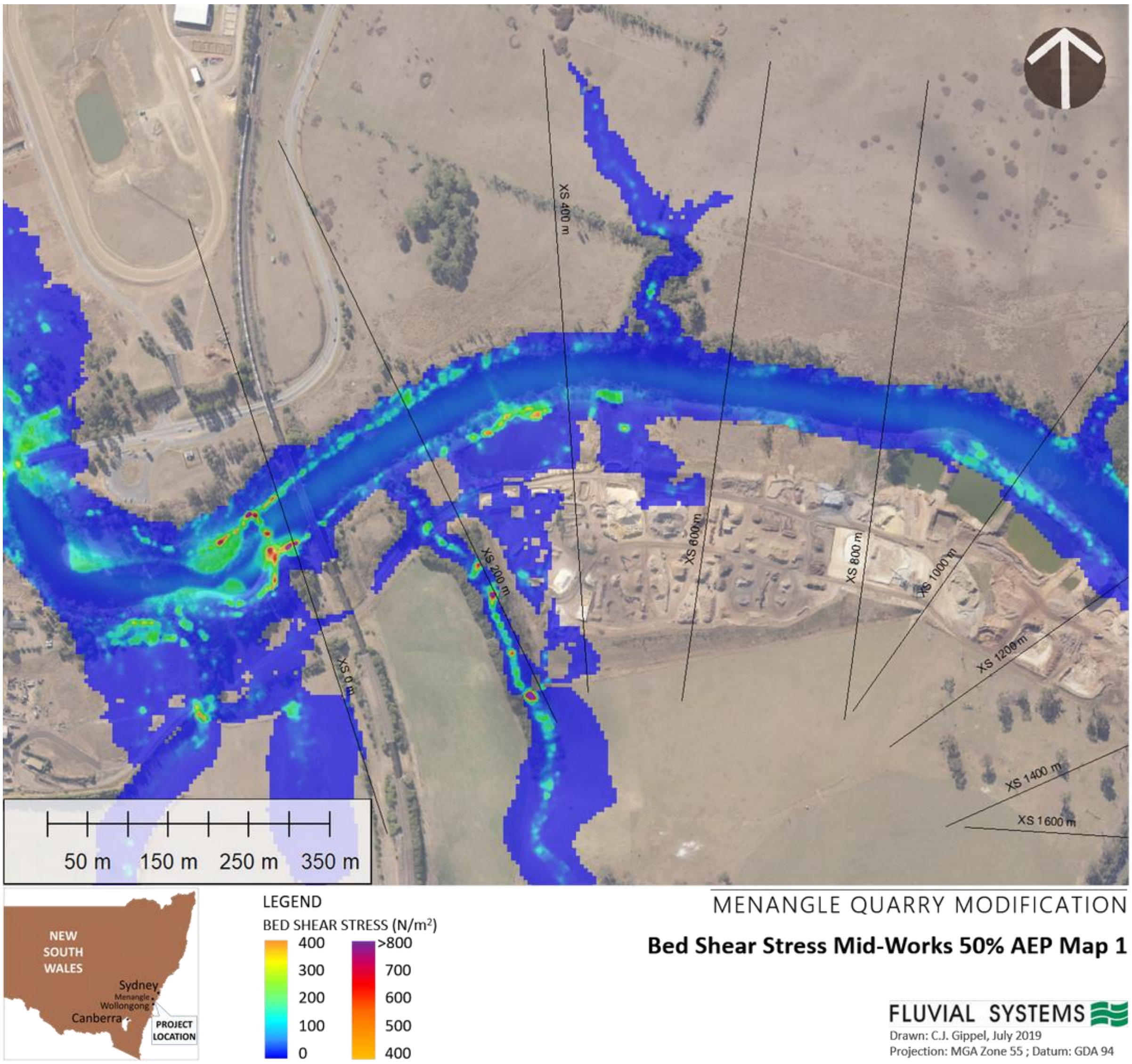


Figure 41. Peak bed shear stress 50% AEP event mid-works scenario Map 1.

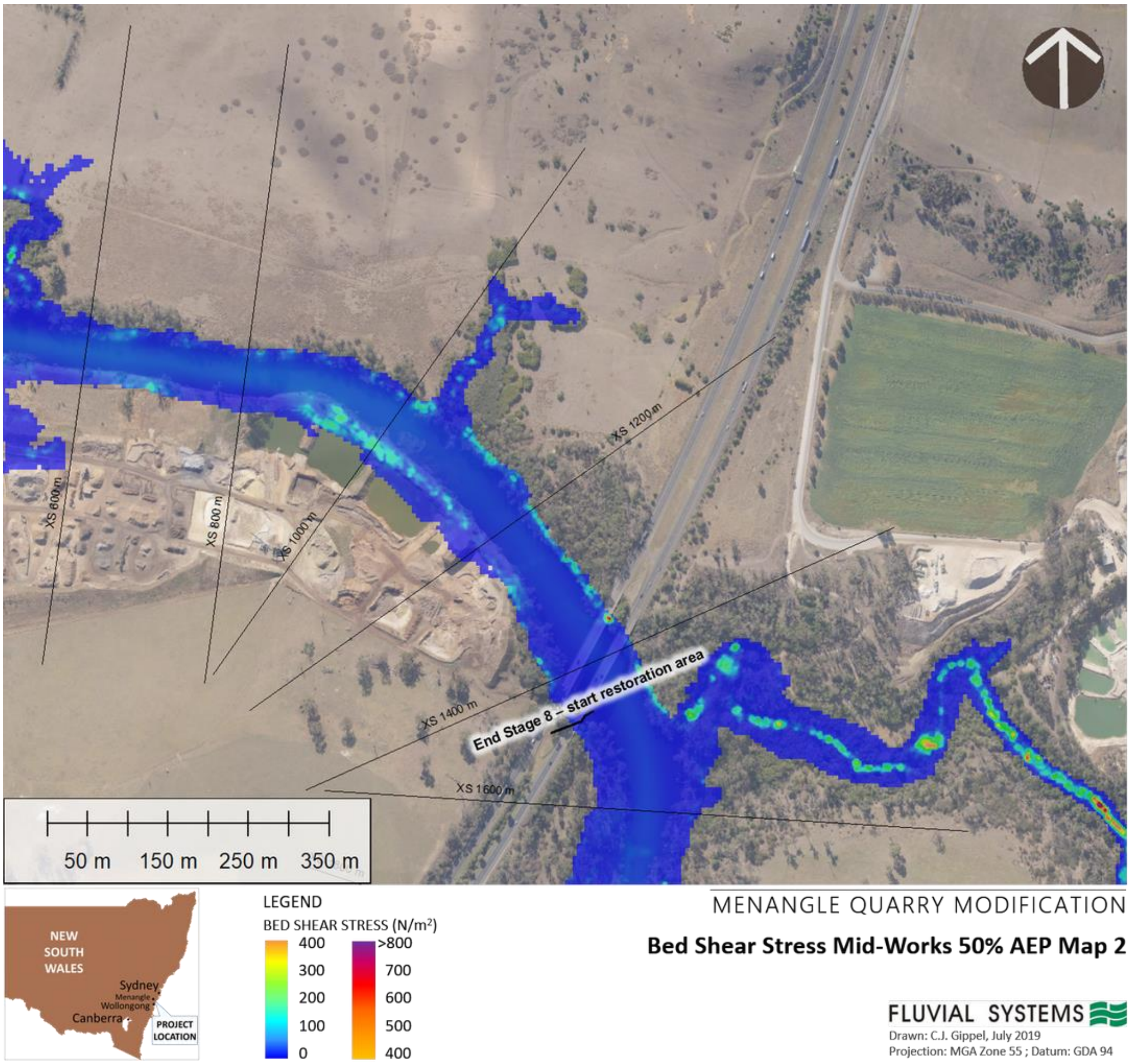


Figure 42. Peak bed shear stress 50% AEP event mid-works scenario Map 2.

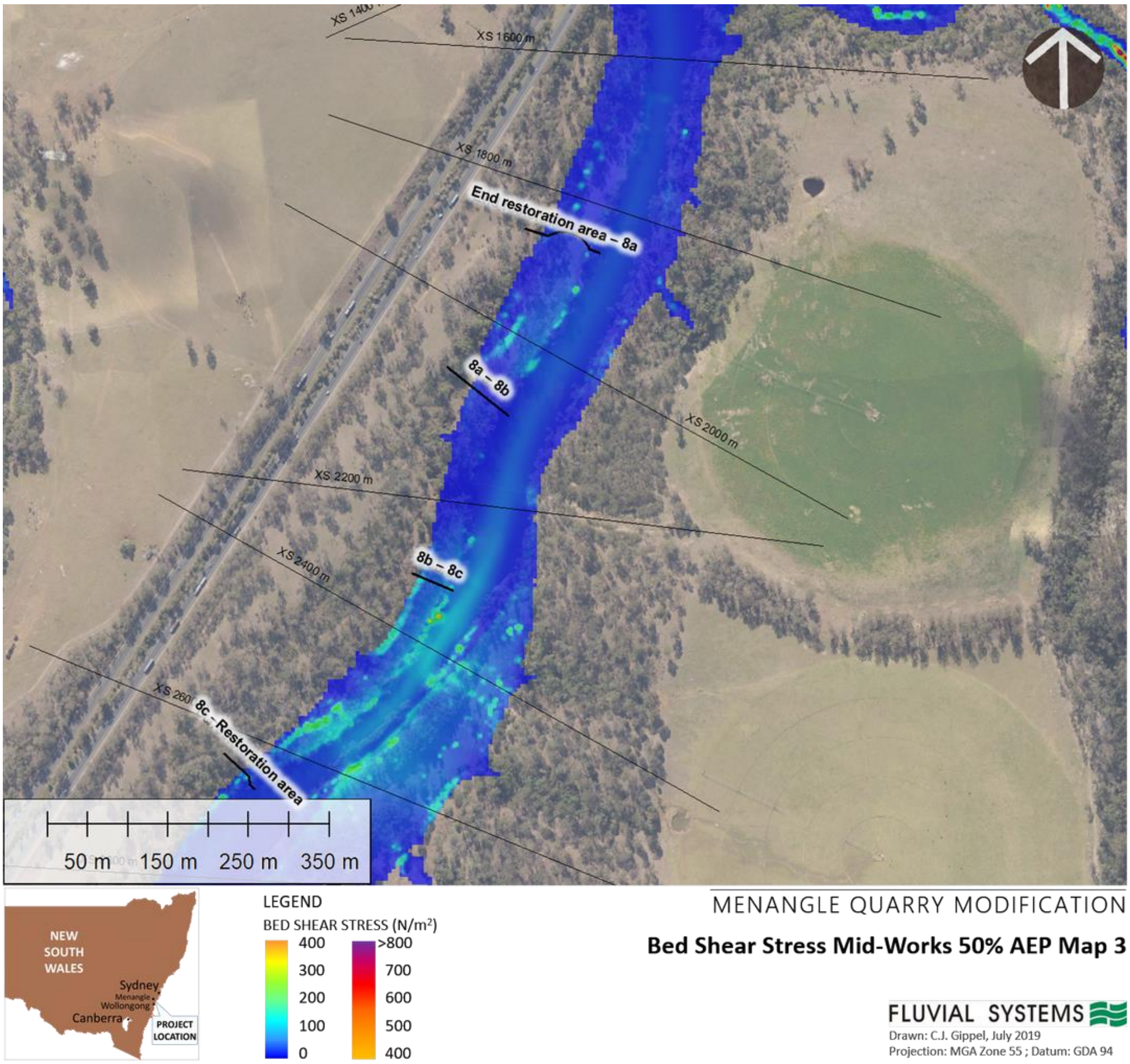


Figure 43. Peak bed shear stress 50% AEP event mid-works scenario Map 3.

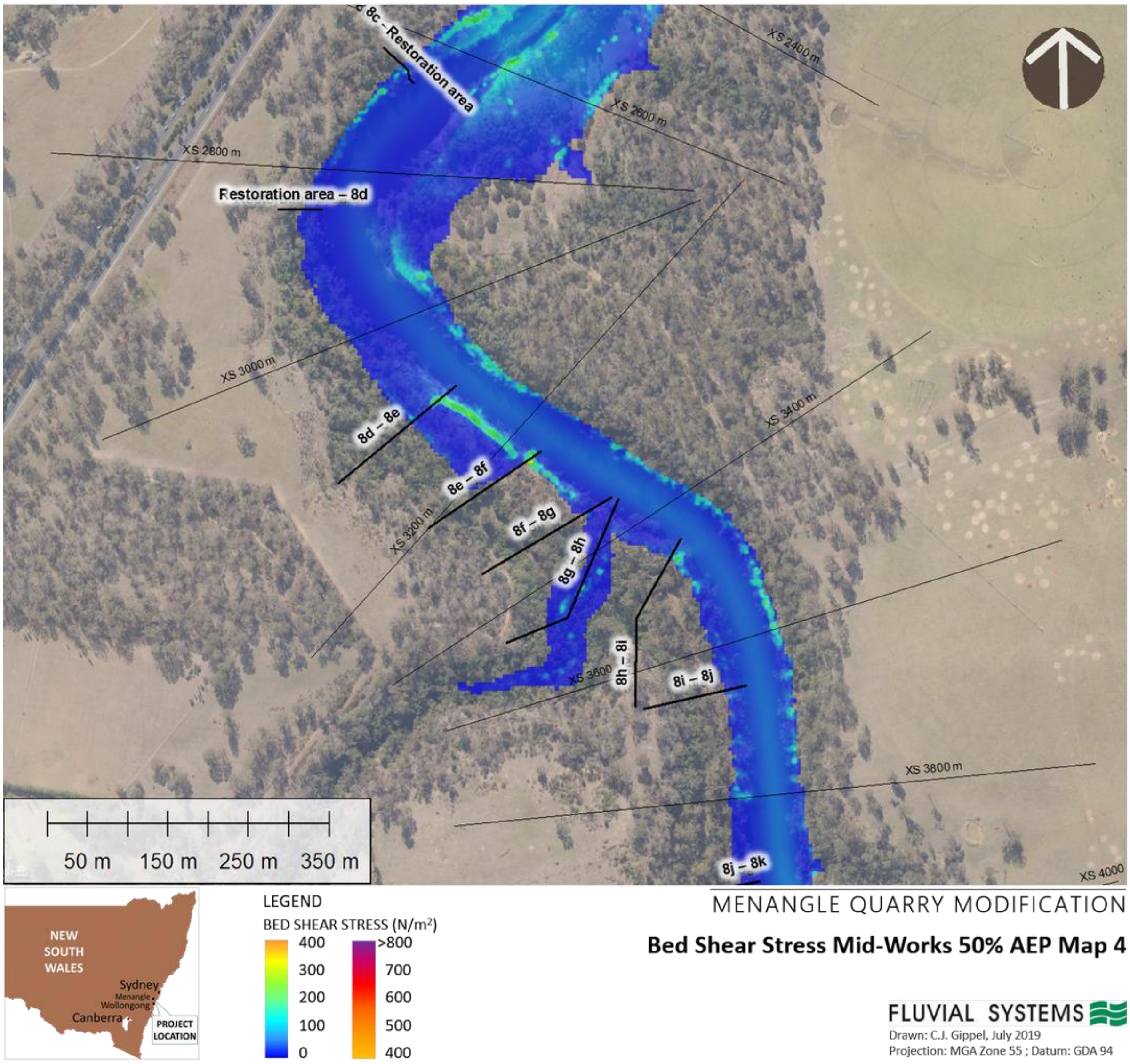


Figure 44. Peak bed shear stress 50% AEP event mid-works scenario Map 4.

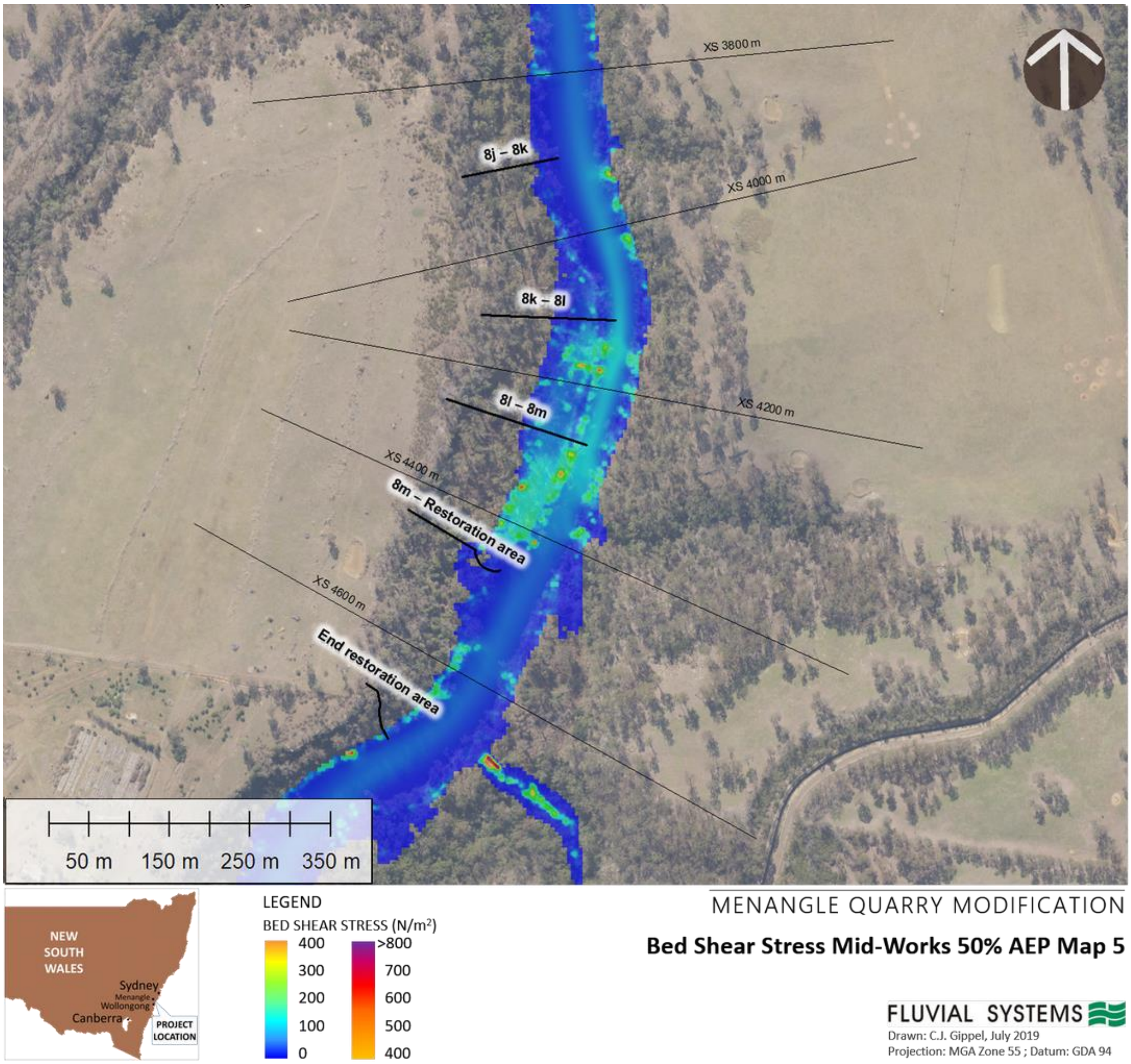


Figure 45. Peak bed shear stress 50% AEP event mid-works scenario Map 5.

7.7 Peak Bed Shear Stress 1% AEP Event Existing Case

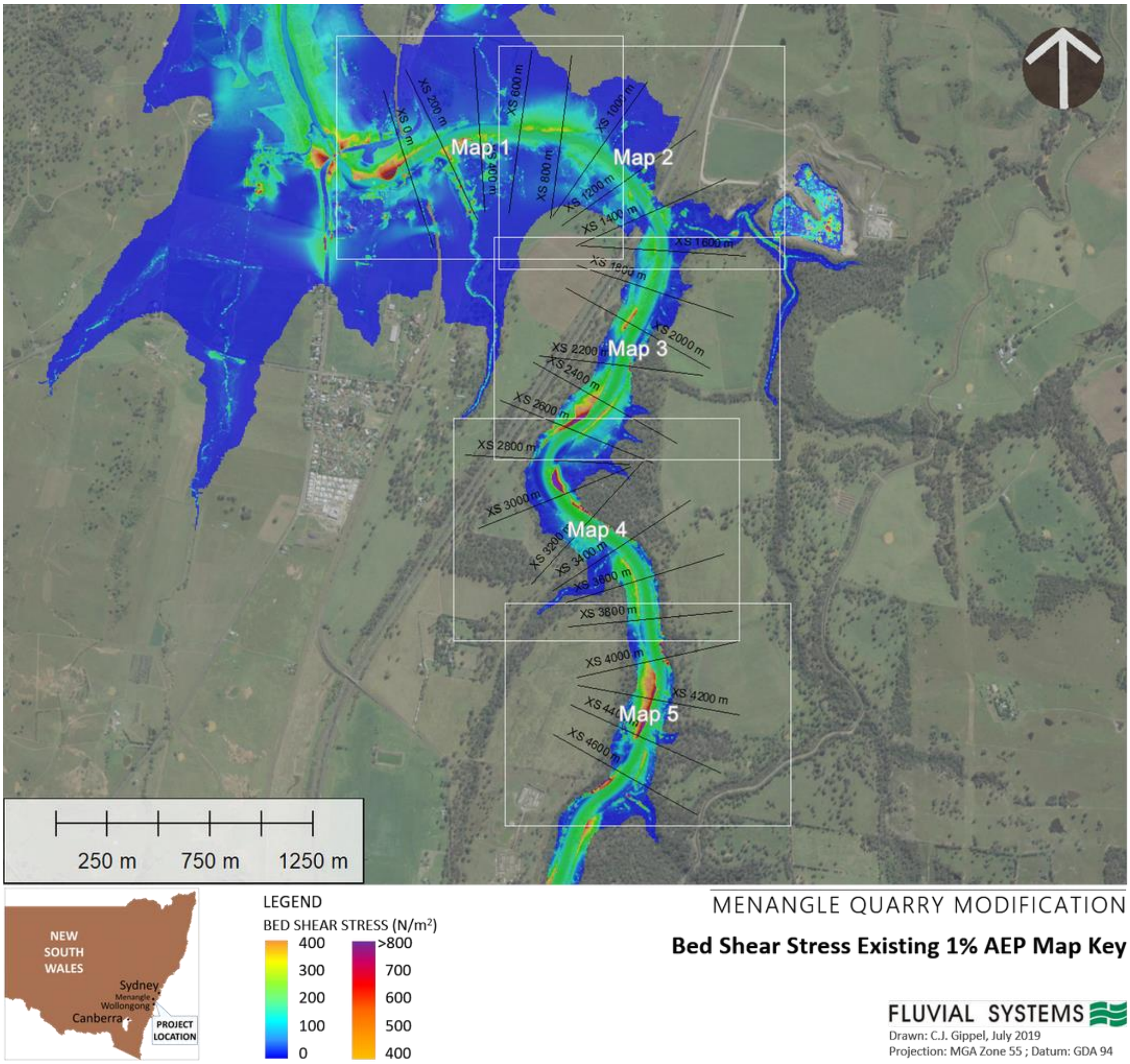


Figure 46. Peak bed shear stress 1% AEP event existing case map key.

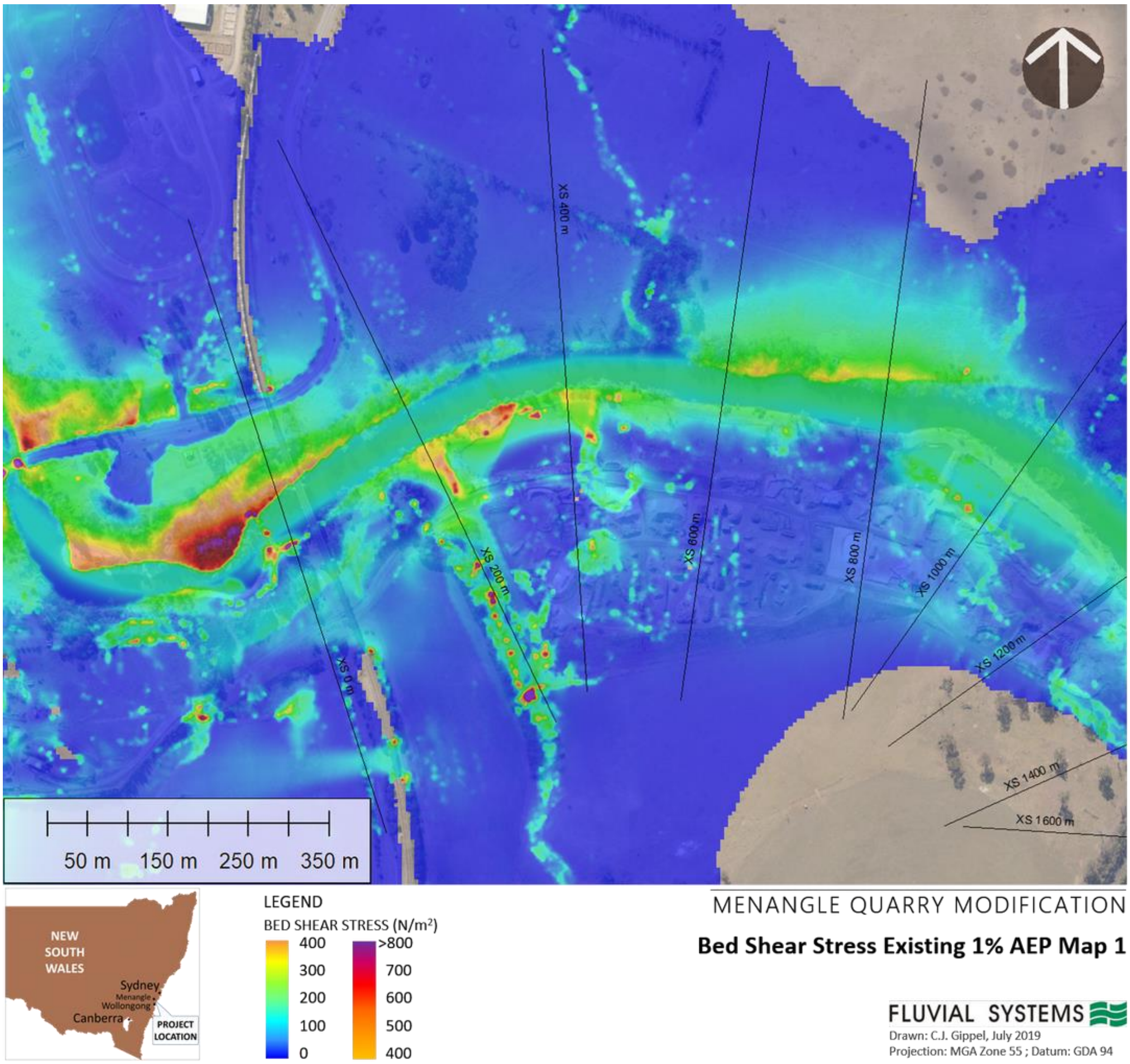


Figure 47. Peak bed shear stress 1% AEP event existing case Map 1.

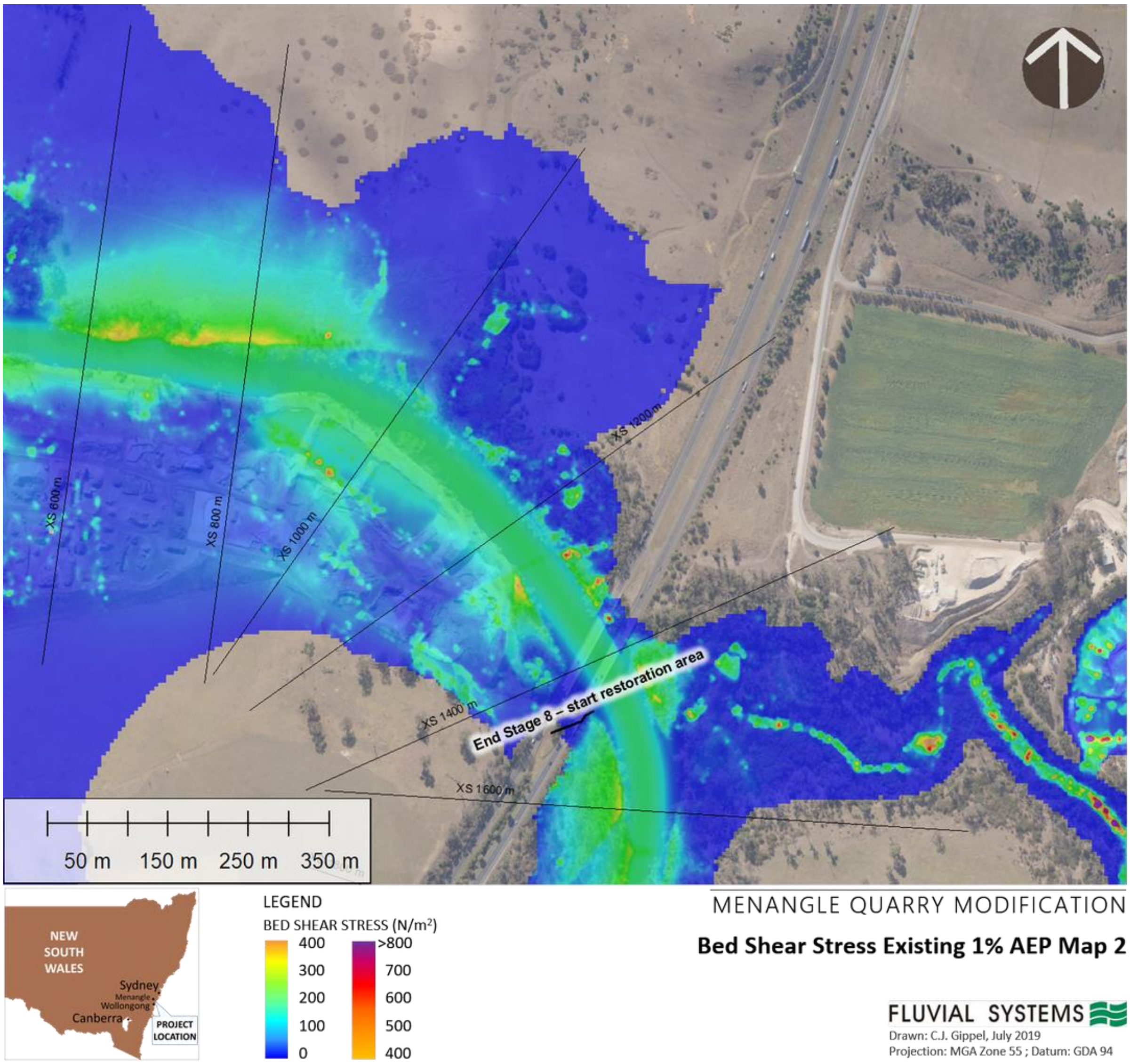


Figure 48. Peak bed shear stress 1% AEP event existing case Map 2.

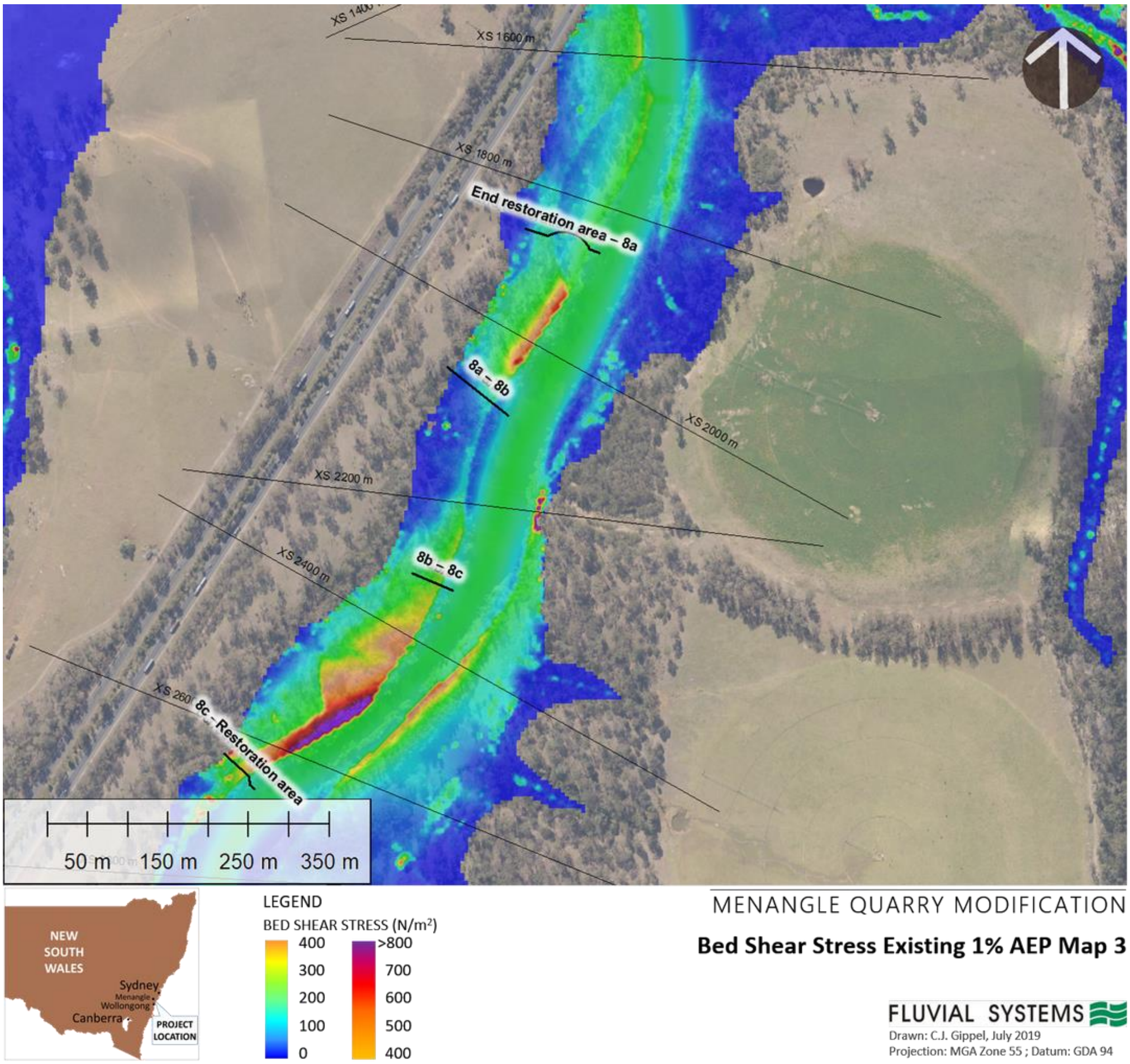


Figure 49. Peak bed shear stress 1% AEP event existing case Map 3.

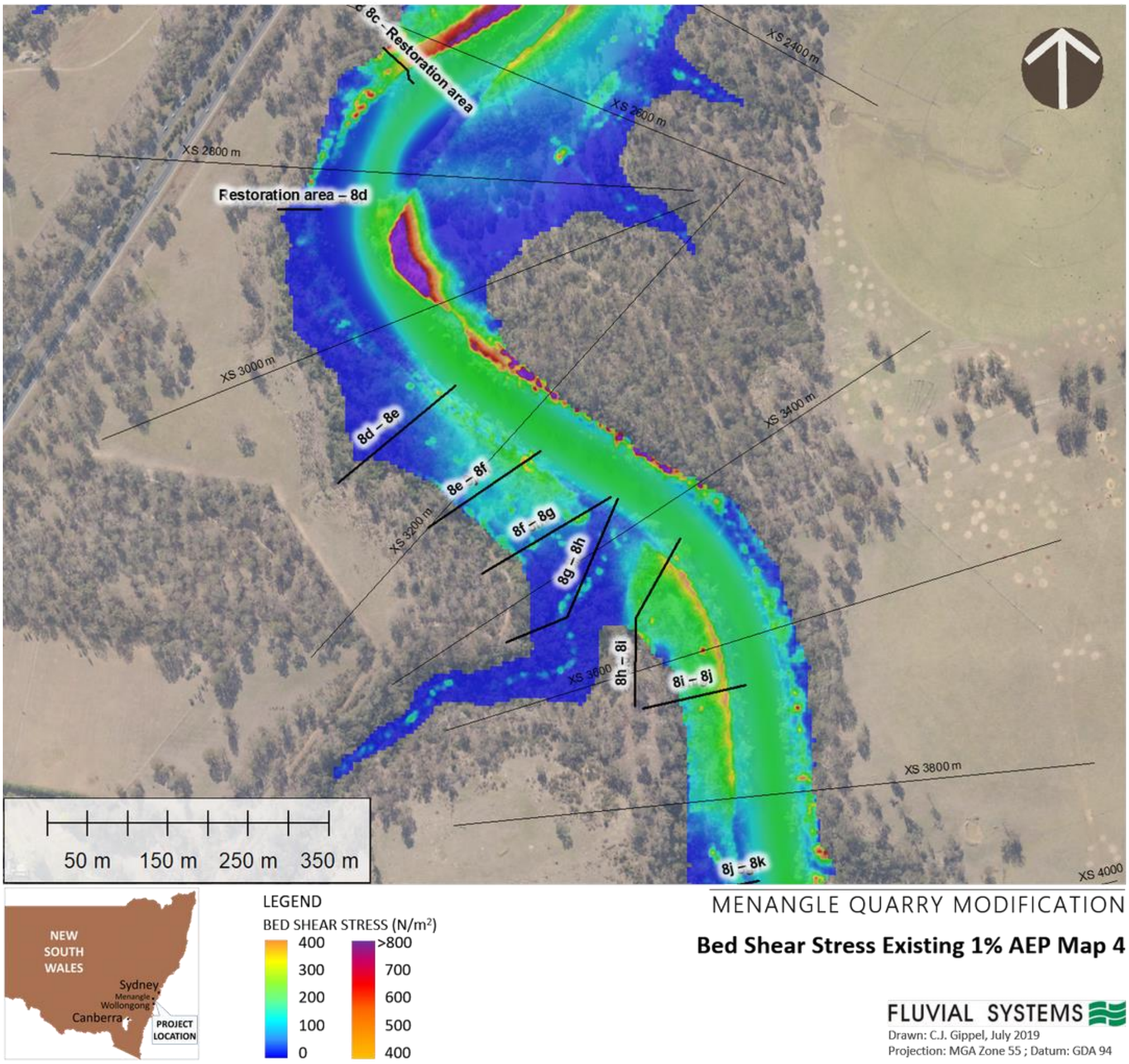


Figure 50. Peak bed shear stress 1% AEP event existing case Map 4.

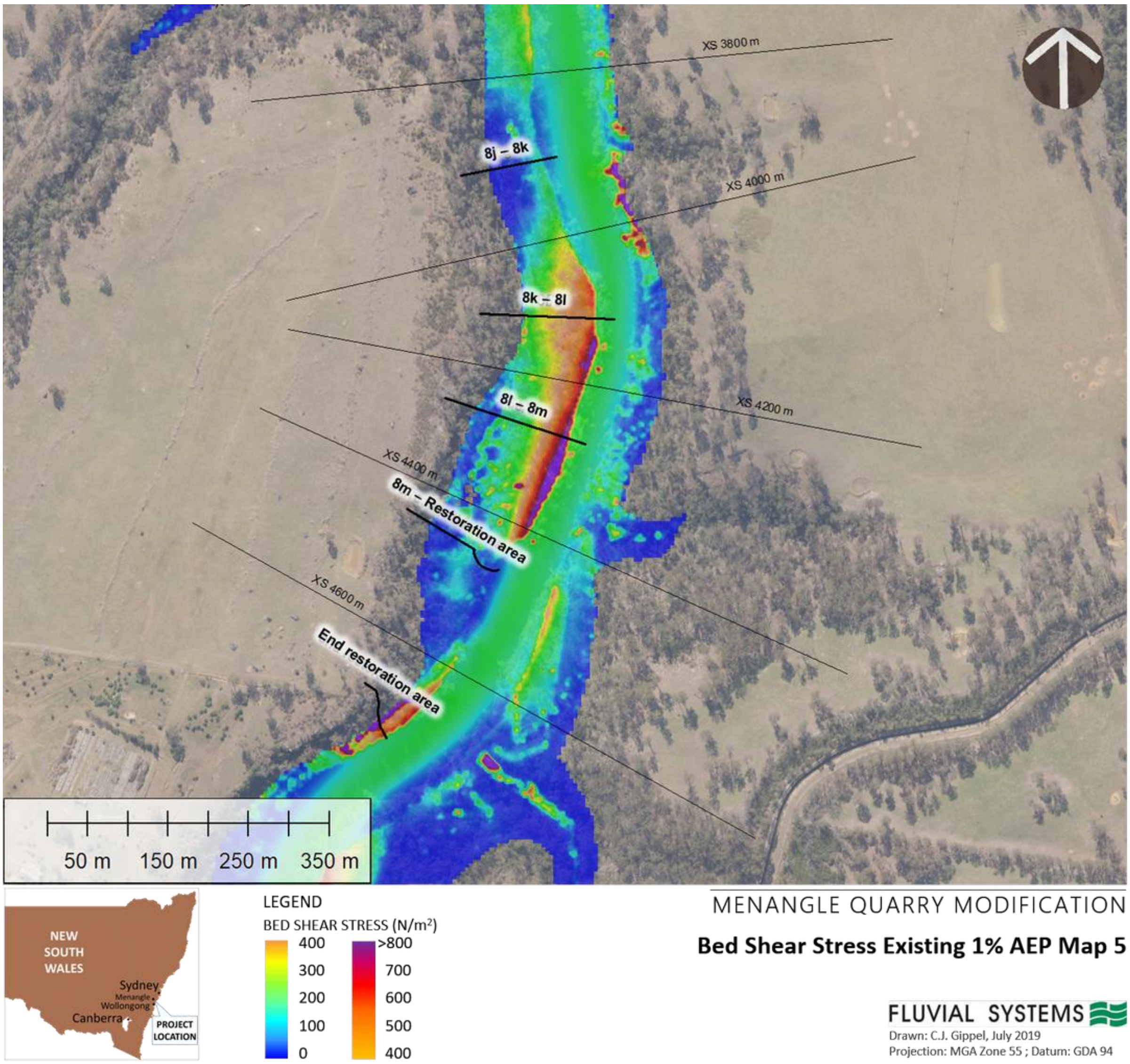


Figure 51. Peak bed shear stress 1% AEP event existing case Map 5.

7.8 Peak Bed Shear Stress 1% AEP Event Mid-Works Scenario

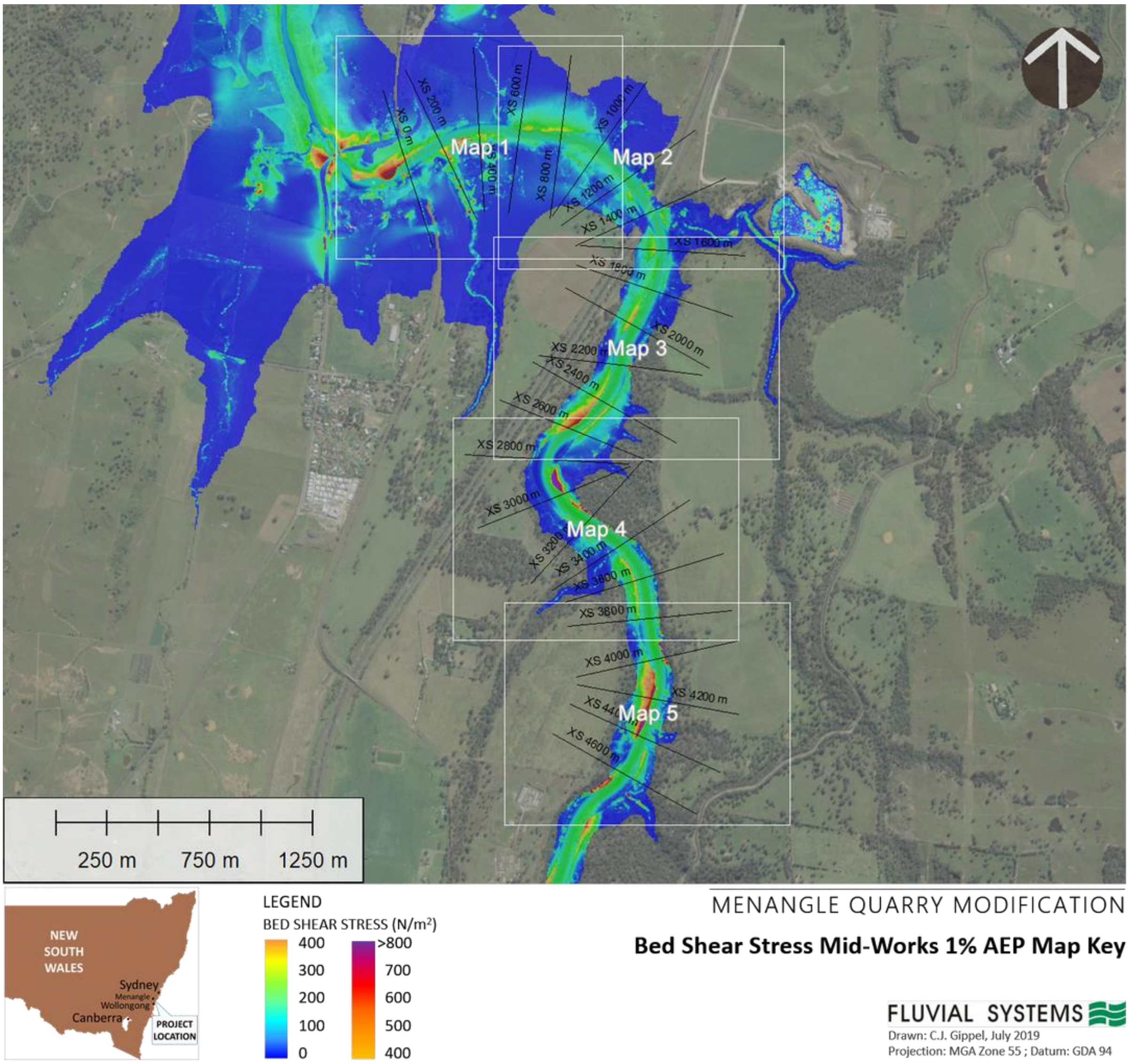


Figure 52. Peak bed shear stress 1% AEP event mid-works scenario map key.

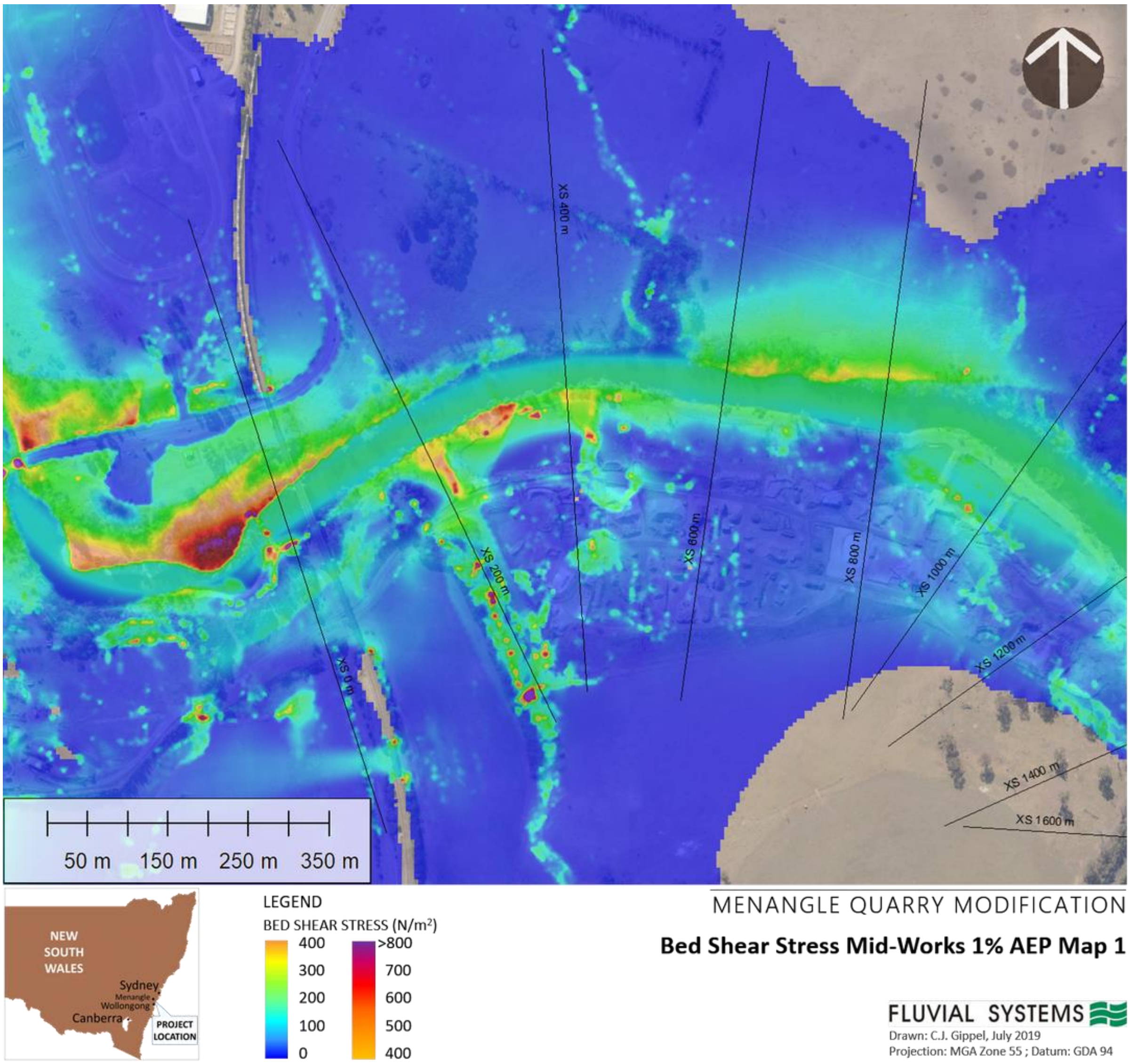


Figure 53. Peak bed shear stress 1% AEP event mid-works scenario Map 1.

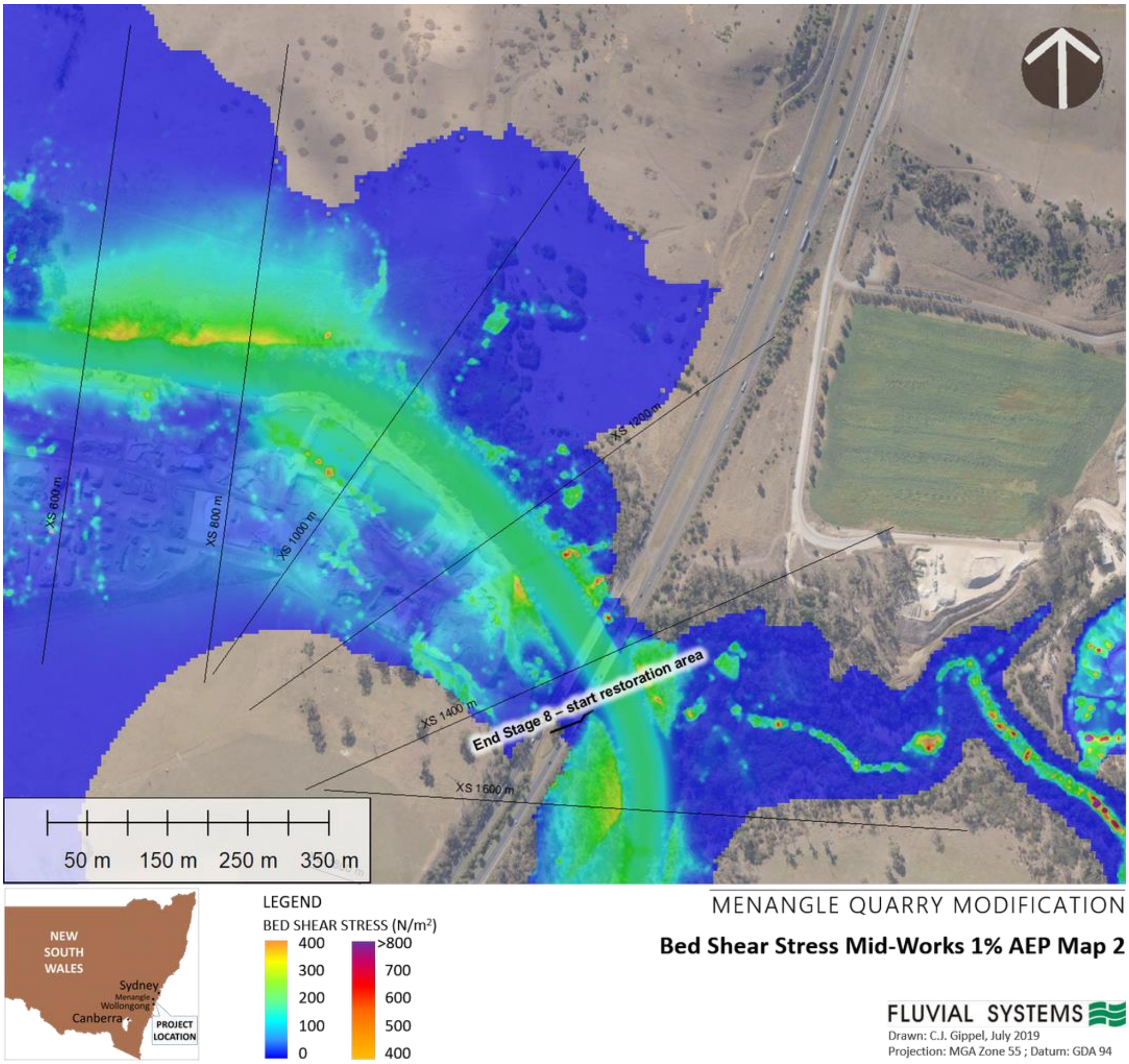


Figure 54. Peak bed shear stress 1% AEP event mid-works scenario Map 2.

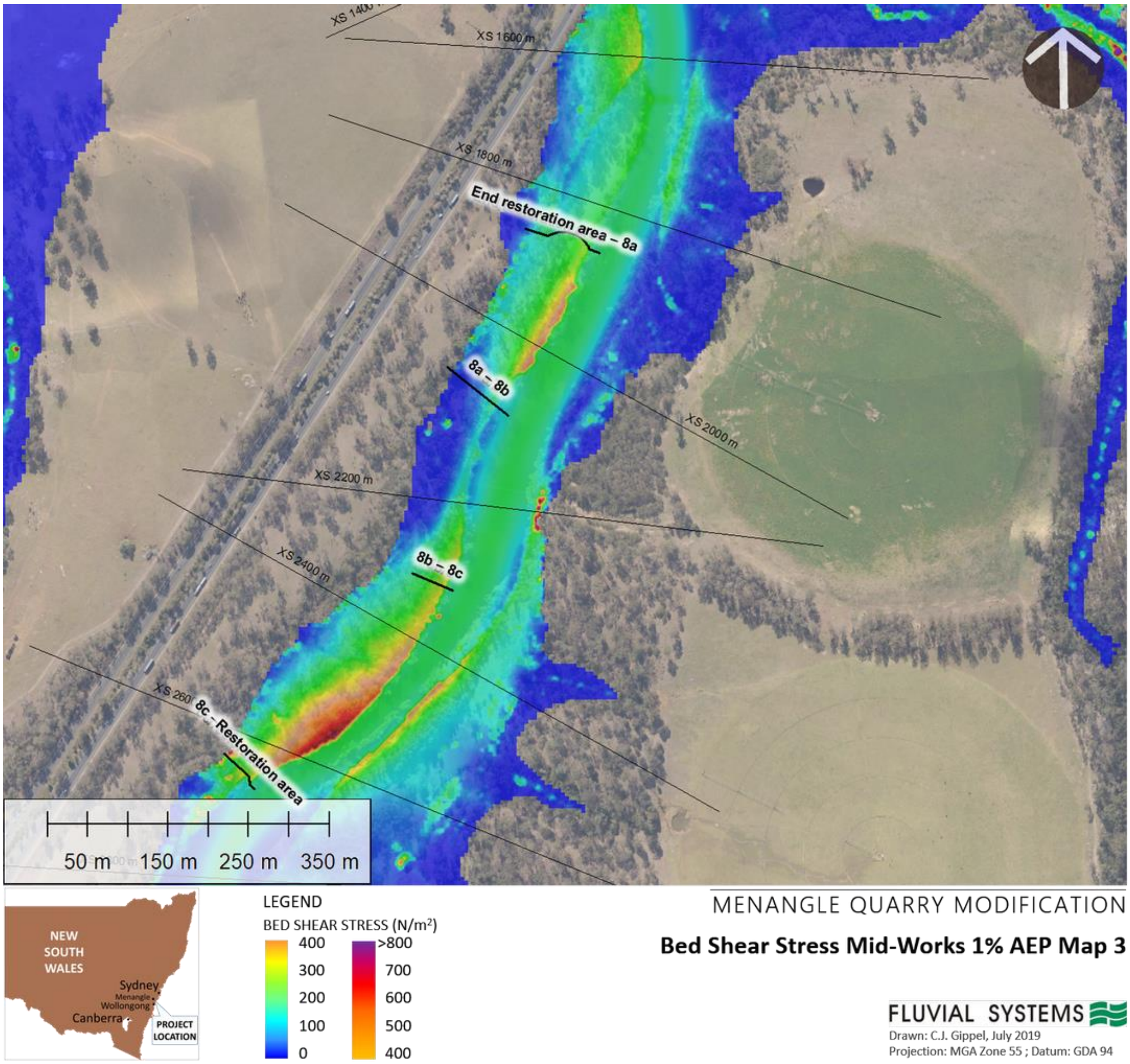


Figure 55. Peak bed shear stress 1% AEP event mid-works scenario Map 3.

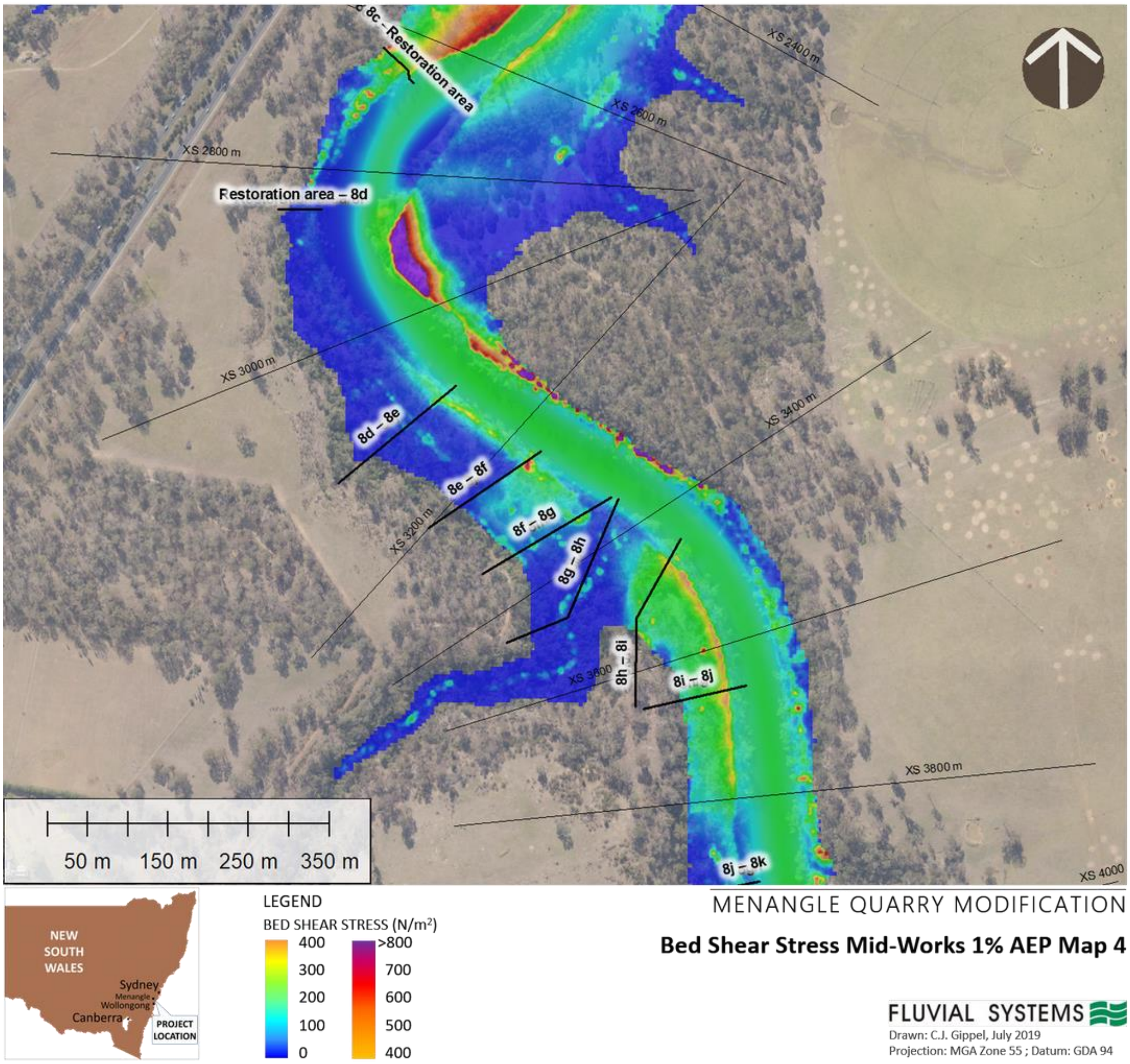


Figure 56. Peak bed shear stress 1% AEP event mid-works scenario Map 4.

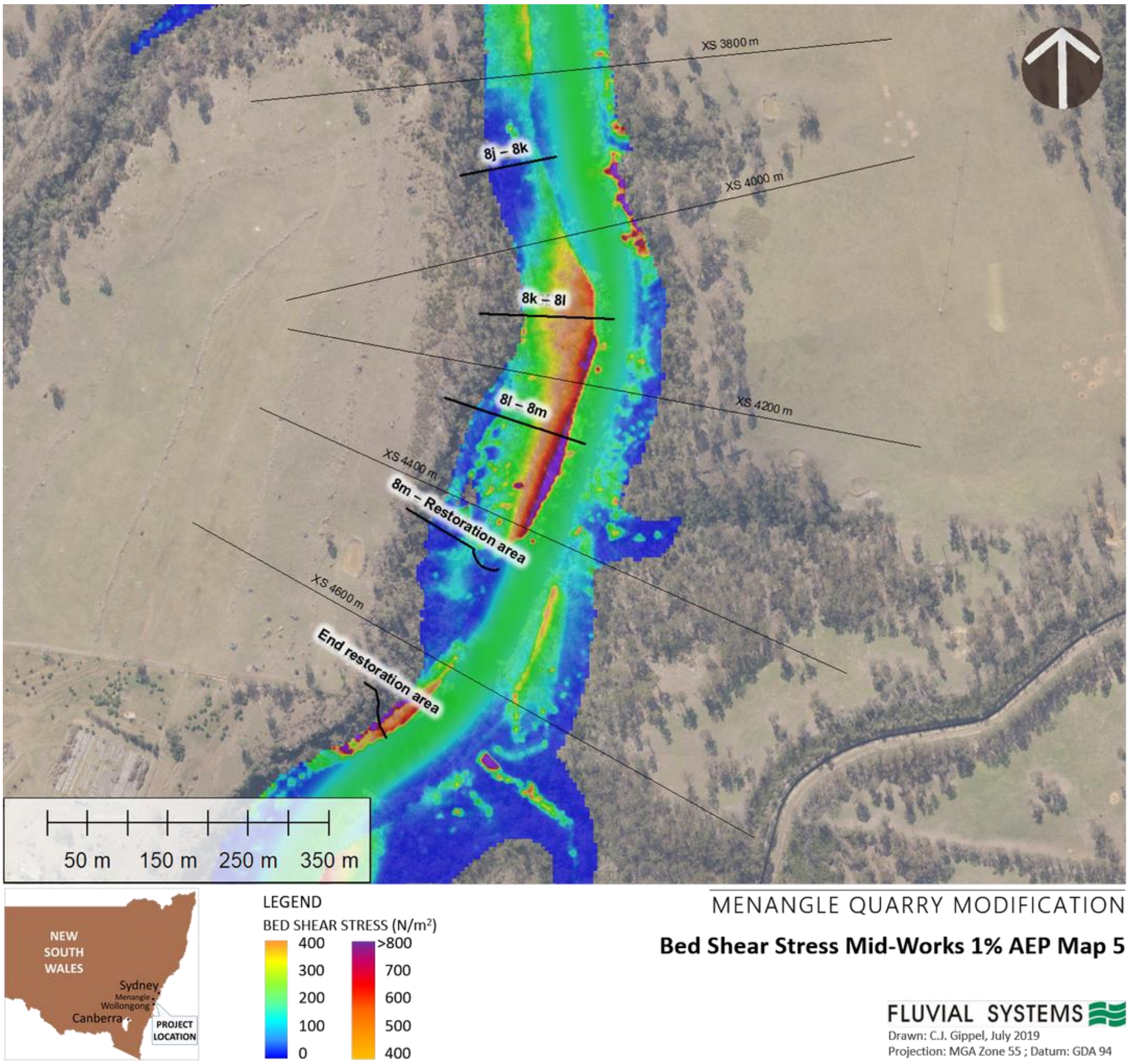


Figure 57. Peak bed shear stress 1% AEP event mid-works scenario Map 5.

7.9 64 m, 67 m, 70 m contours, and 10 m setback from 64 m contour

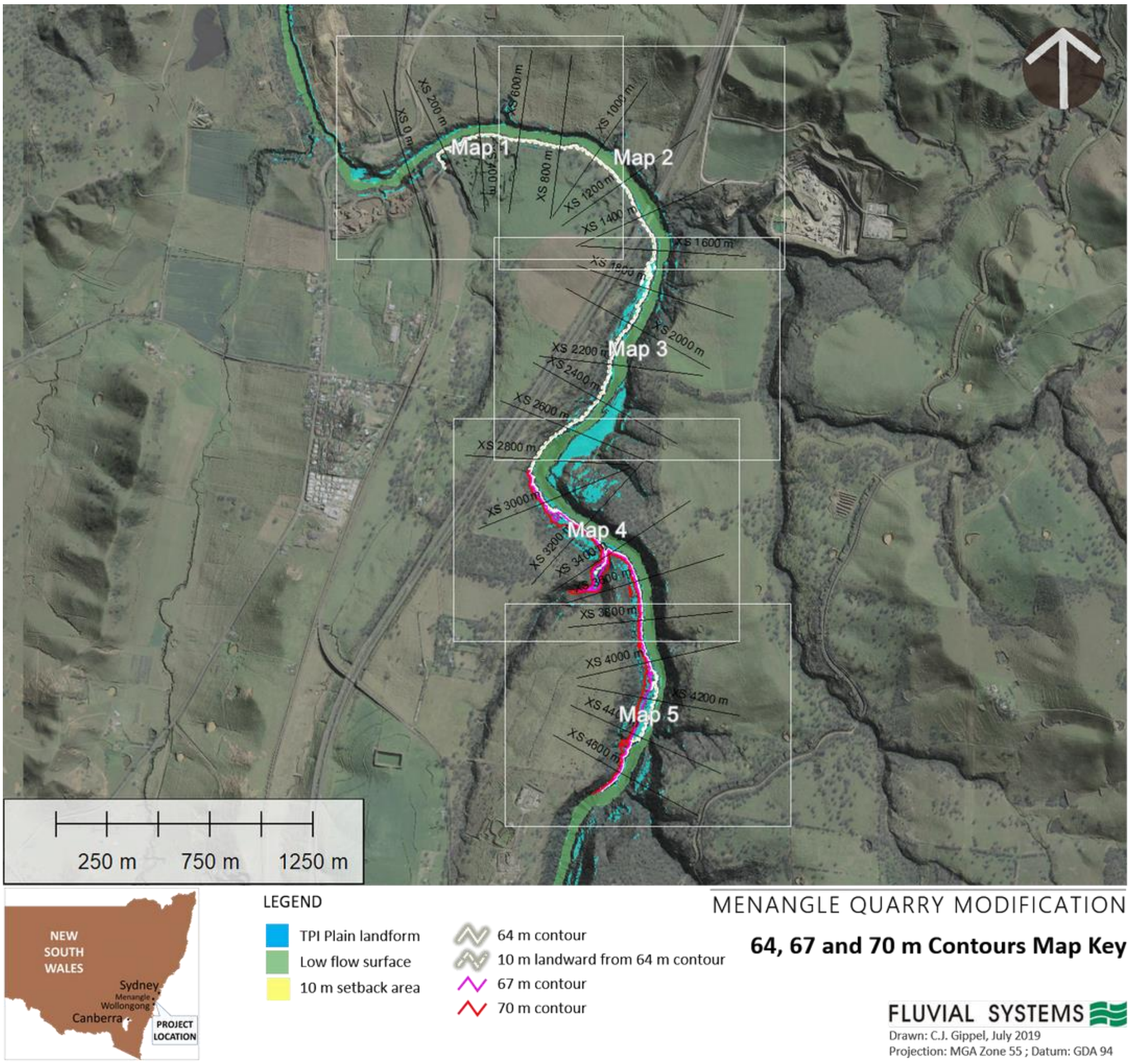


Figure 58. 64 m, 67 m, 70 m contours, and 10 m setback from 64 m contour map key.

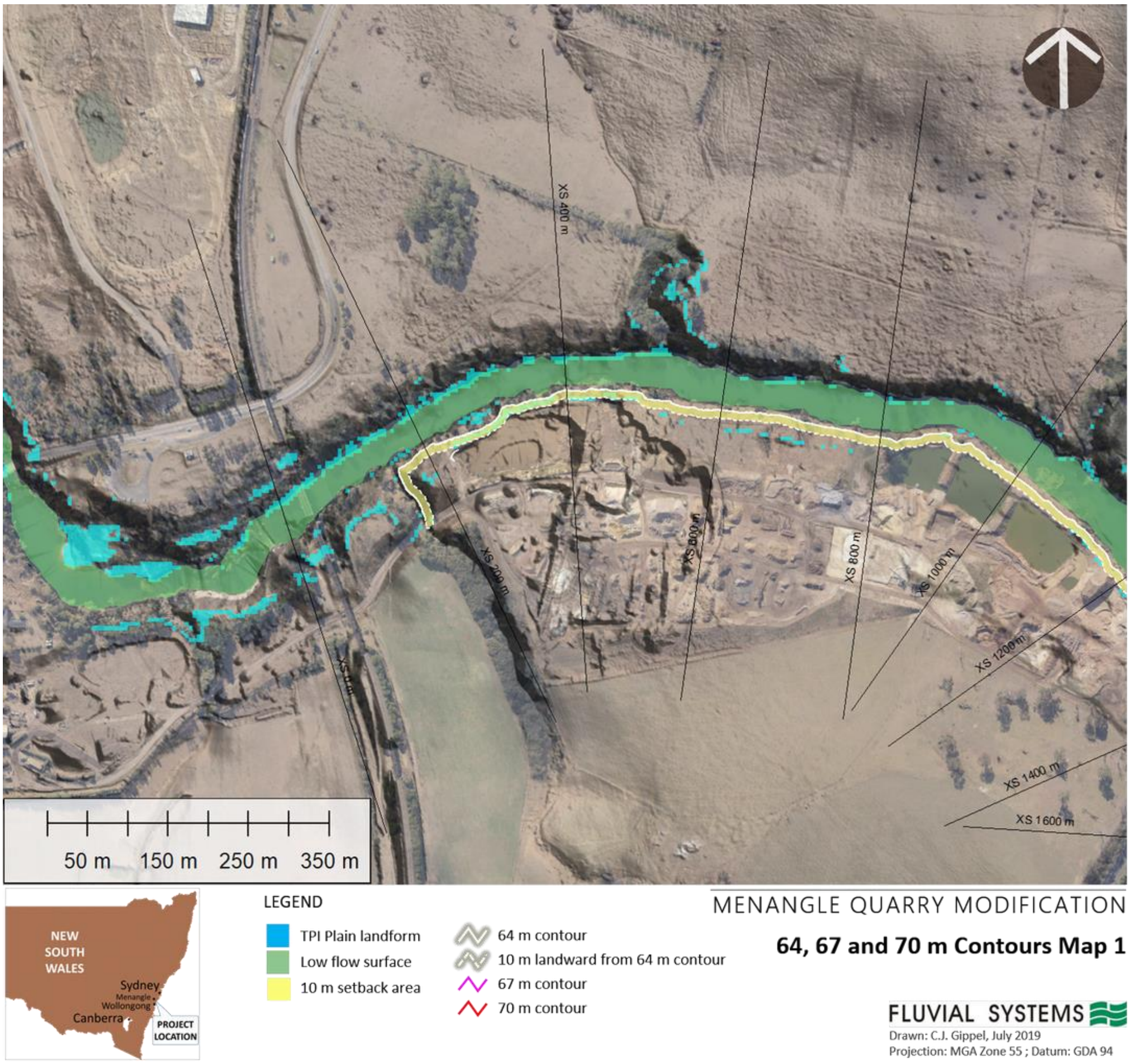


Figure 59. 64 m, 67 m, 70 m contours, and 10 m setback from 64 m contour Map 1.

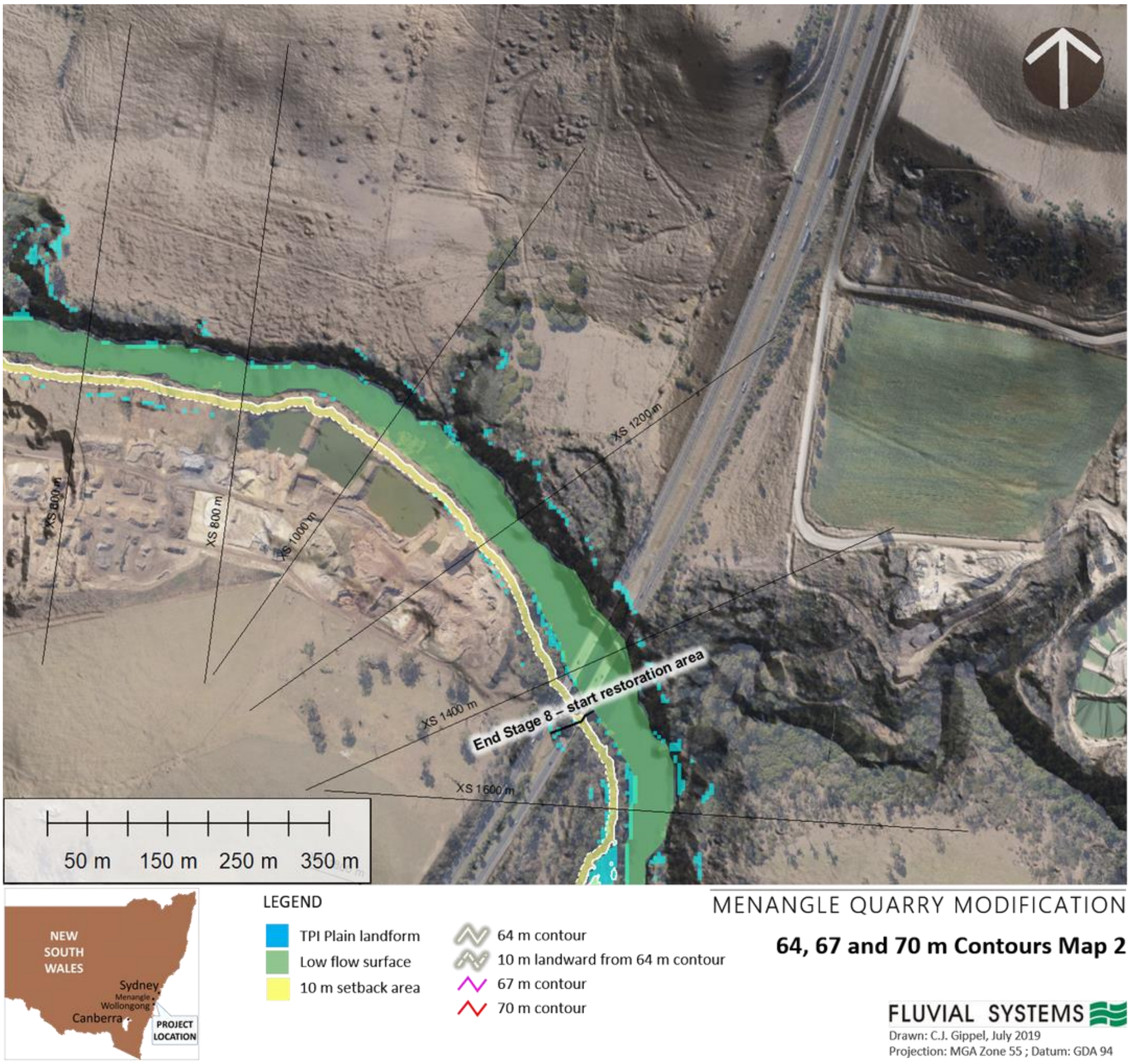


Figure 60. 64 m, 67 m, 70 m contours, and 10 m setback from 64 m contour Map 2.

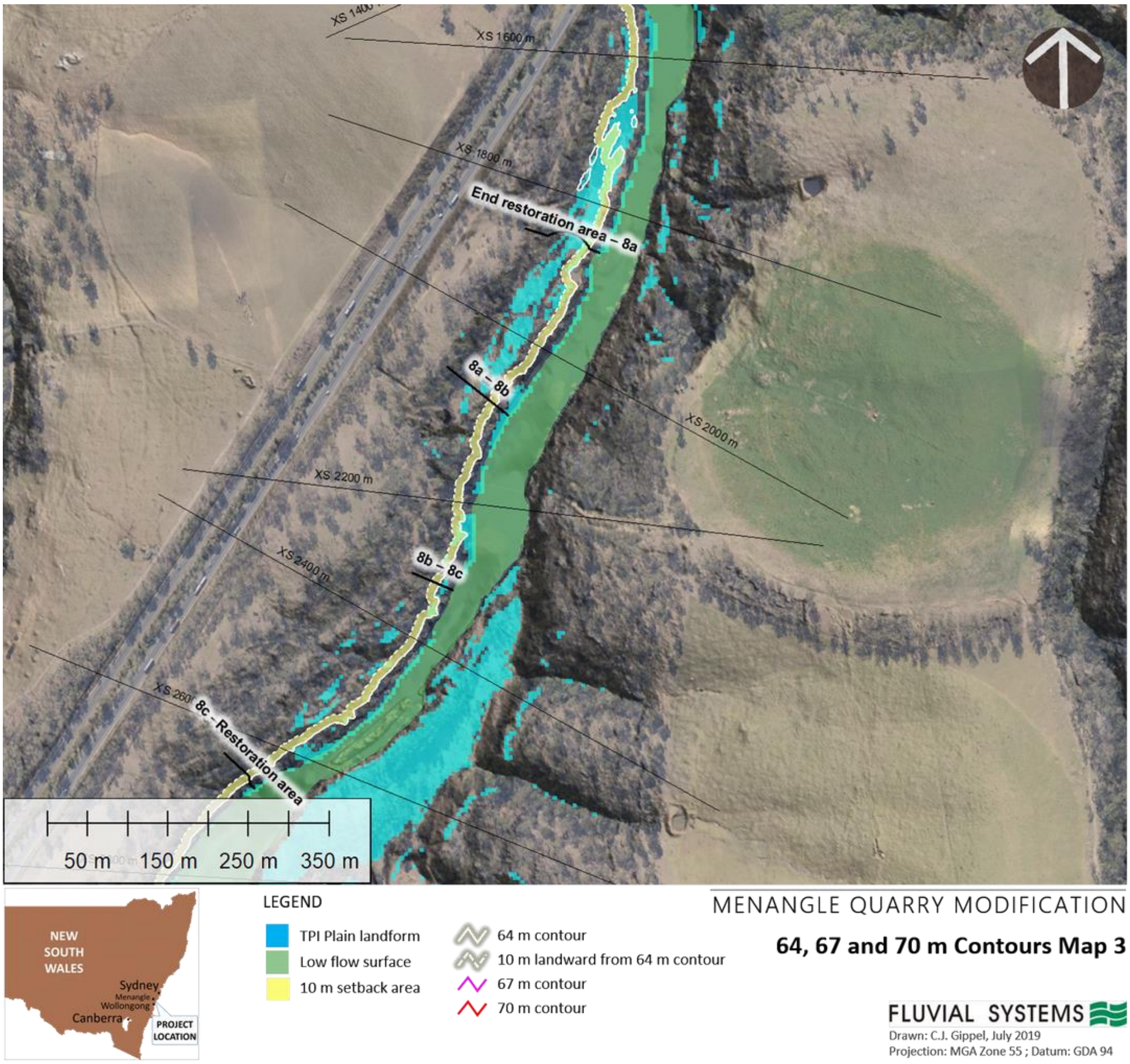


Figure 61. 64 m, 67 m, 70 m contours, and 10 m setback from 64 m contour Map 3.

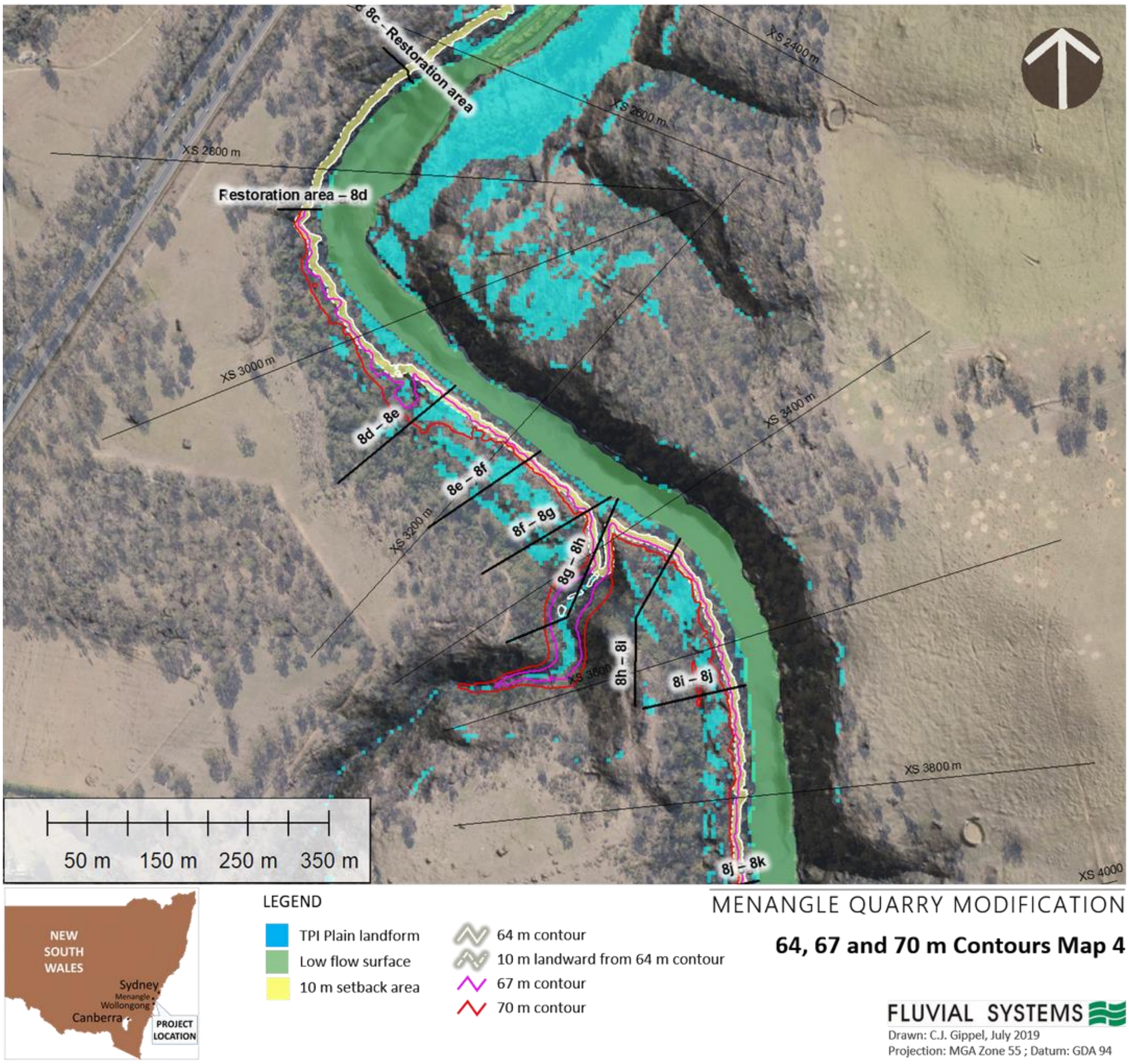


Figure 62. 64 m, 67 m, 70 m contours, and 10 m setback from 64 m contour Map 4.

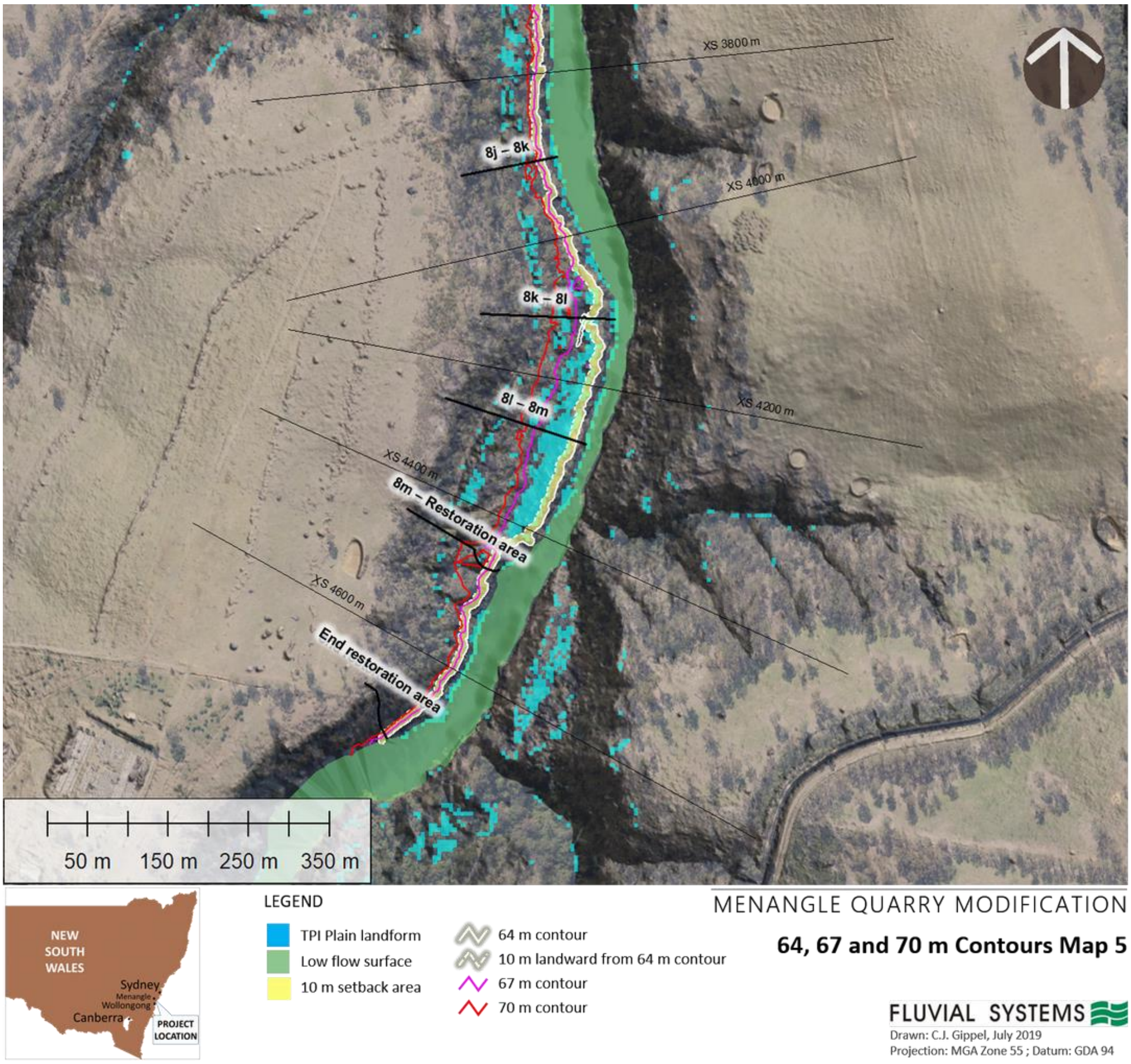
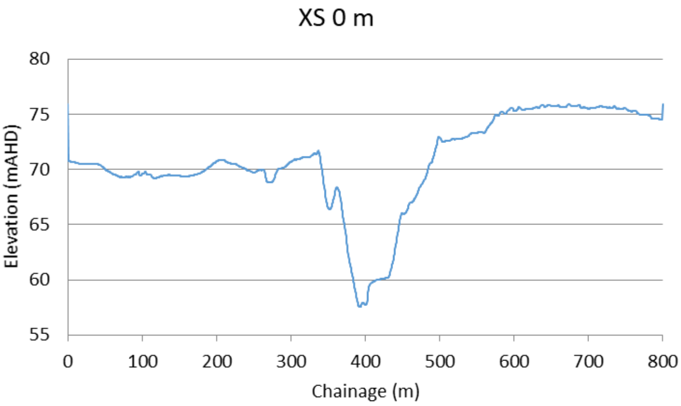
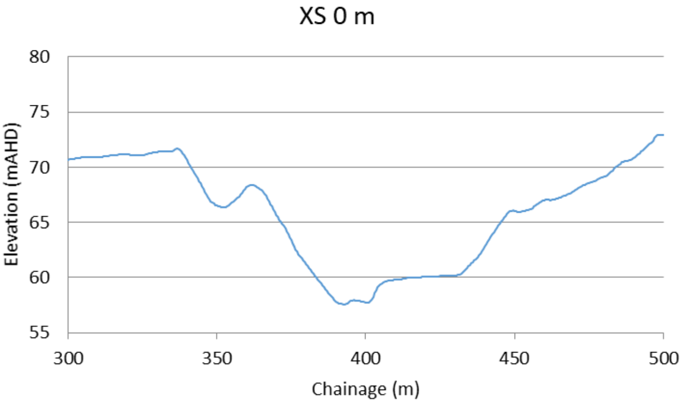
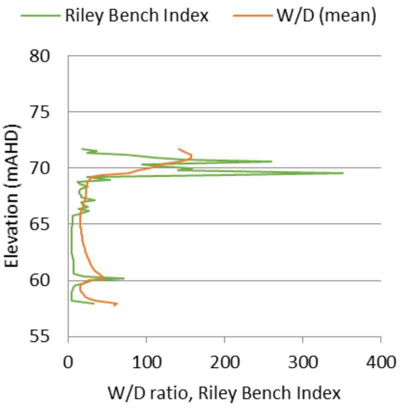


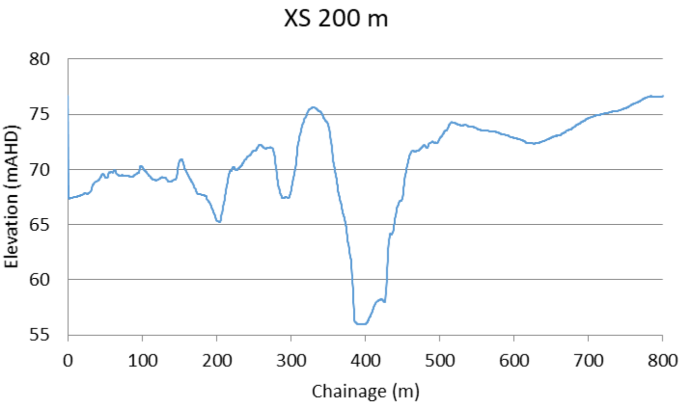
Figure 63. 64 m, 67 m, 70 m contours, and 10 m setback from 64 m contour Map 5.

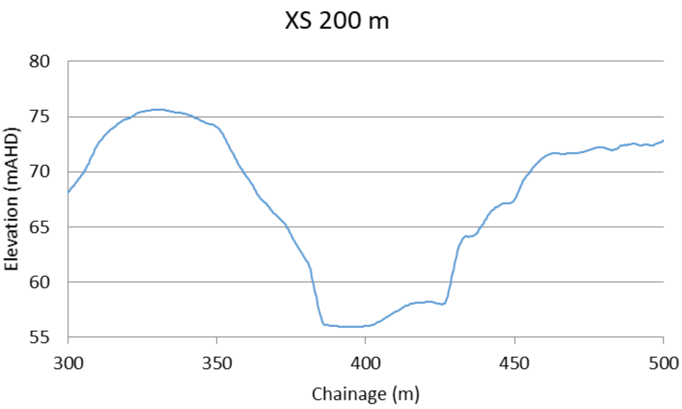
8. Appendix 2. Morphometric Indexes at Cross-sections

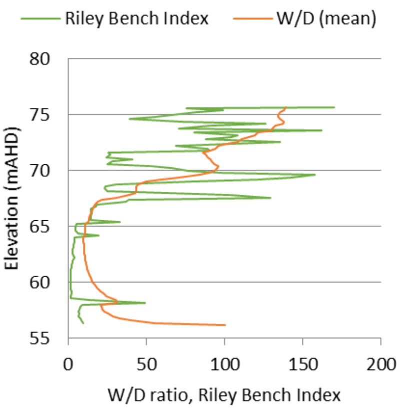

XS 0 m
Elevation (mAHD)
Chainage (m)
80
75
70
65
60
55
0
100
200
300
400
500
600
700
800

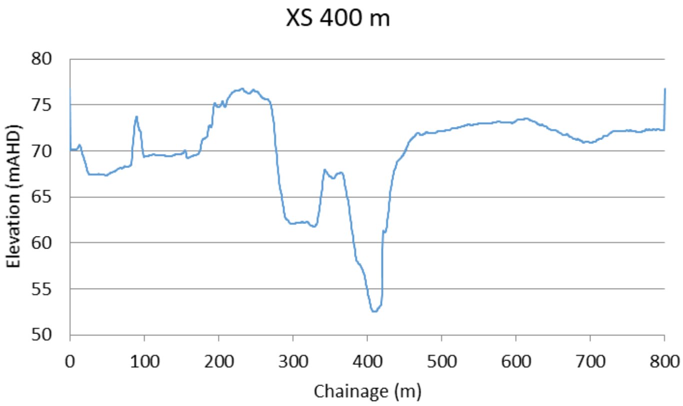

XS 0 m
Elevation (mAHD)
Chainage (m)
80
75
70
65
60
55
300
350
400
450
500

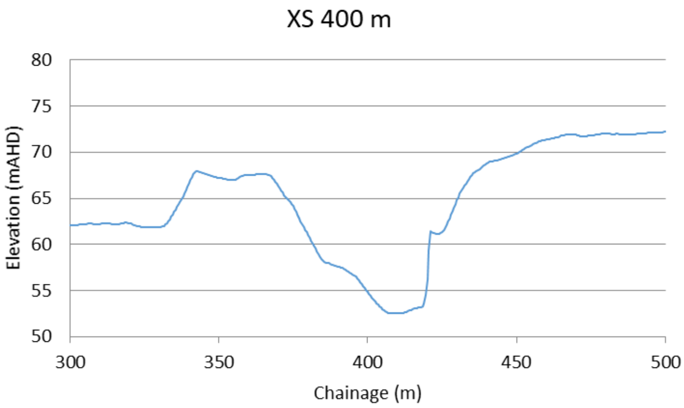

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index
80
75
70
65
60
55
0
100
200
300
400

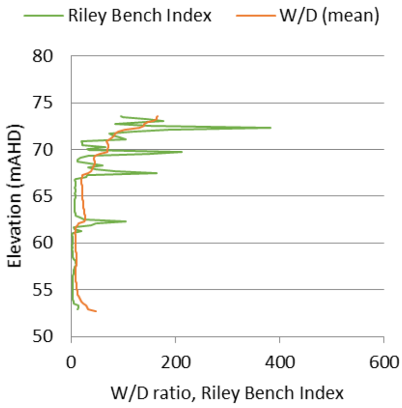

XS 200 m
Elevation (mAHD)
Chainage (m)
80
75
70
65
60
55
0
100
200
300
400
500
600
700
800

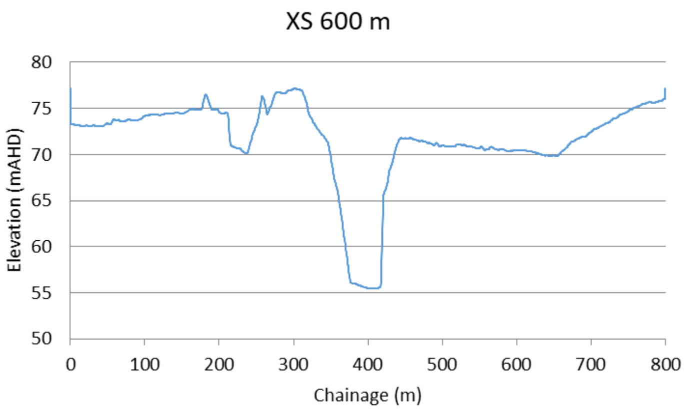

XS 200 m
Elevation (mAHD)
Chainage (m)
80
75
70
65
60
55
300
350
400
450
500

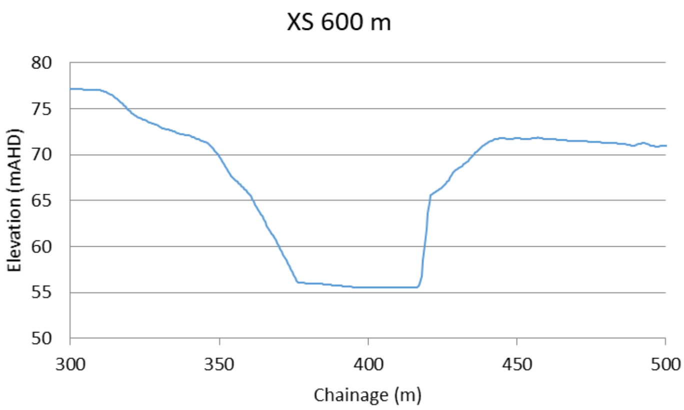

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index
80
75
70
65
60
55
0
50
100
150
200

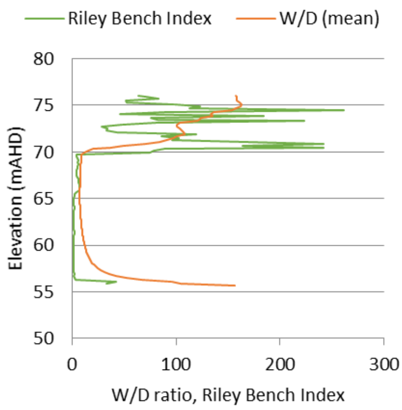

XS 400 m
Elevation (mAHD)
80
75
70
65
60
55
50
0
100
200
300
400
500
600
700
800
Chainage (m)

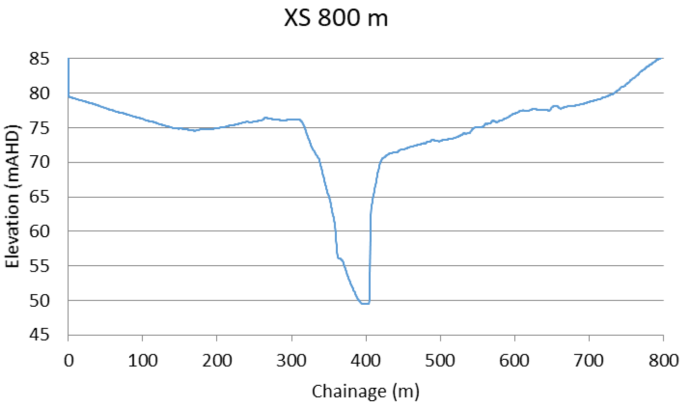

XS 400 m
Elevation (mAHD)
80
75
70
65
60
55
50
300
350
400
450
500
Chainage (m)

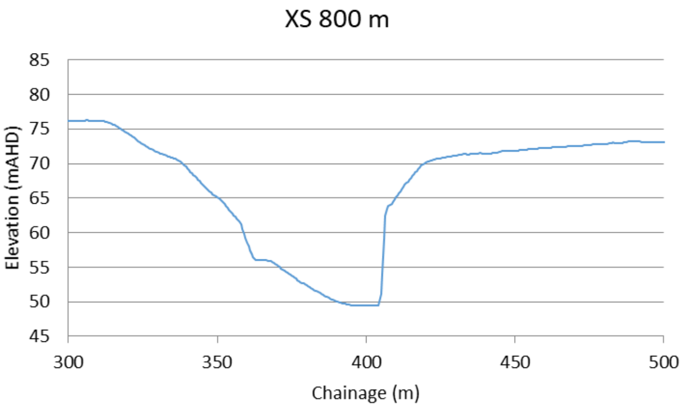

Riley Bench Index
W/D (mean)
Elevation (mAHD)
80
75
70
65
60
55
50
0
200
400
600
W/D ratio, Riley Bench Index

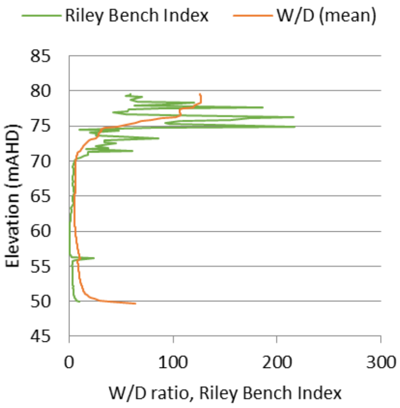

XS 600 m
Elevation (mAHD)
80
75
70
65
60
55
50
0
100
200
300
400
500
600
700
800
Chainage (m)

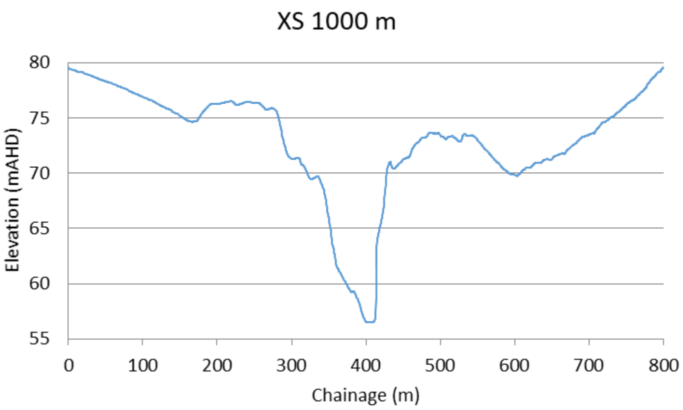

XS 600 m
Elevation (mAHD)
80
75
70
65
60
55
50
300
350
400
450
500
Chainage (m)

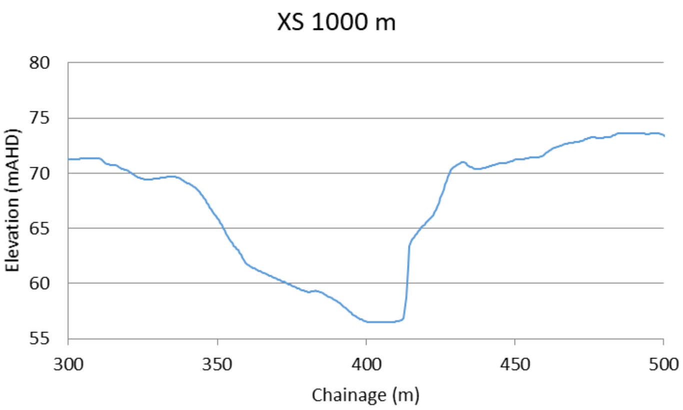

Riley Bench Index
W/D (mean)
Elevation (mAHD)
80
75
70
65
60
55
50
0
100
200
300
W/D ratio, Riley Bench Index

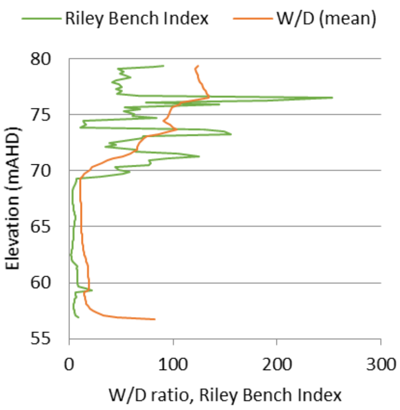

XS 800 m
Elevation (mAHD)
Chainage (m)

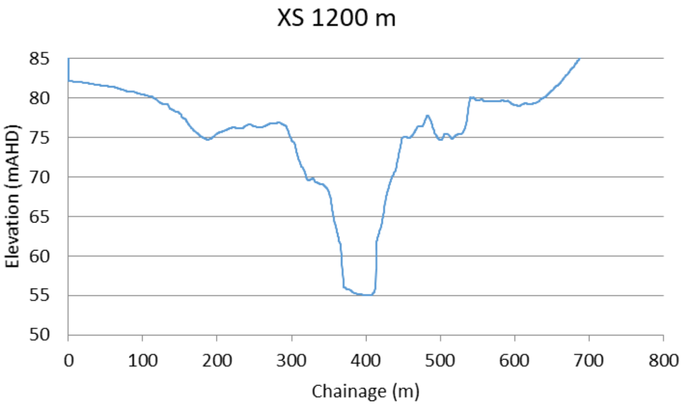

XS 800 m
Elevation (mAHD)
Chainage (m)

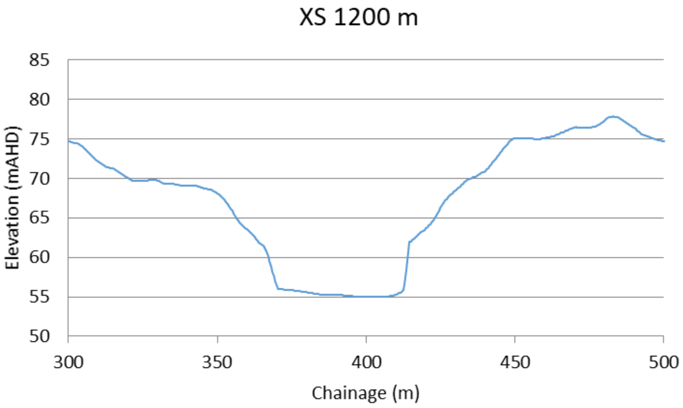

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index

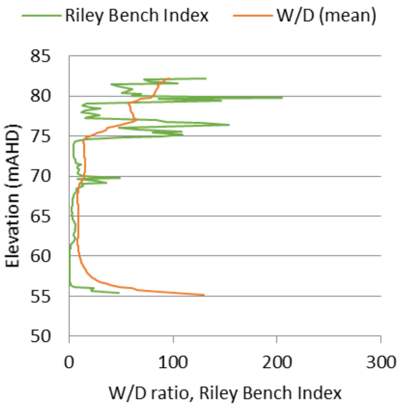

XS 1000 m
Elevation (mAHD)
Chainage (m)

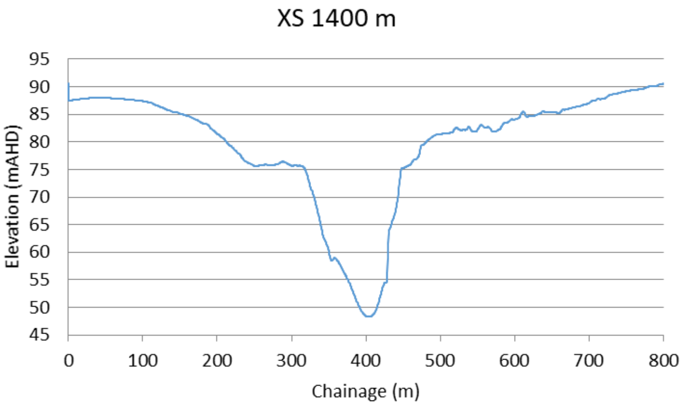

XS 1000 m
Elevation (mAHD)
Chainage (m)

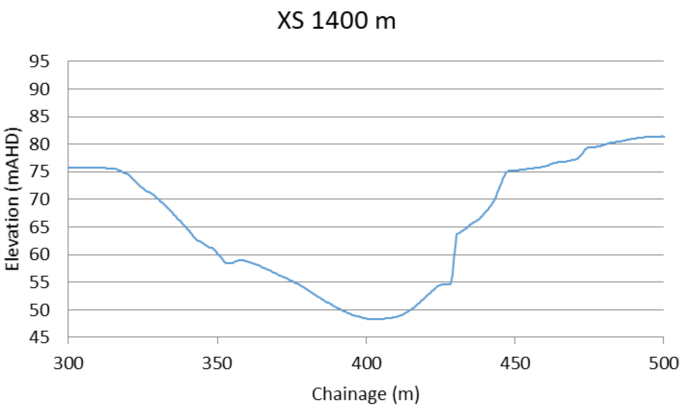

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index

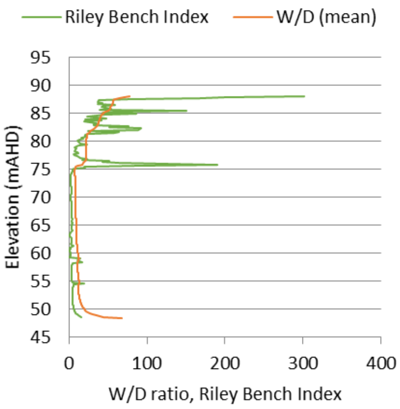

XS 1200 m
Elevation (mAHD)
85
80
75
70
65
60
55
50
0 100 200 300 400 500 600 700 800
Chainage (m)

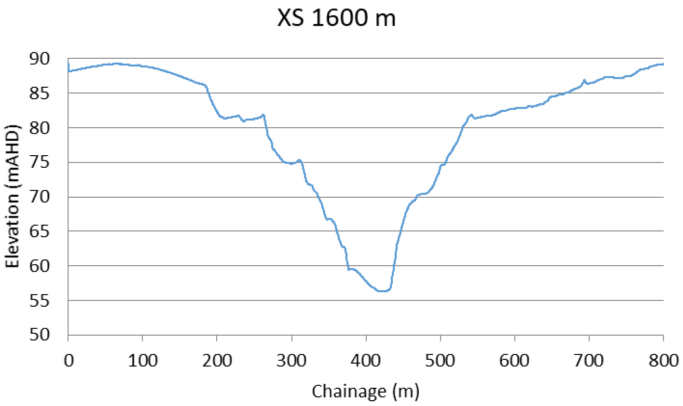

XS 1200 m
Elevation (mAHD)
85
80
75
70
65
60
55
50
300 350 400 450 500
Chainage (m)

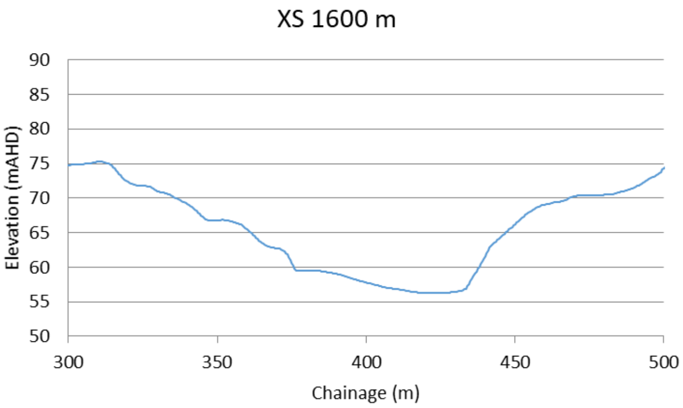

Riley Bench Index
W/D (mean)
Elevation (mAHD)
85
80
75
70
65
60
55
50
0 100 200 300
W/D ratio, Riley Bench Index

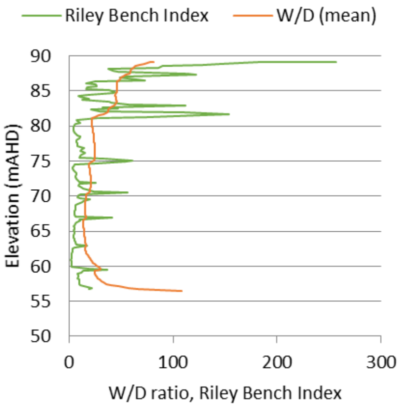

XS 1400 m
Elevation (mAHD)
95
90
85
80
75
70
65
60
55
50
45
0 100 200 300 400 500 600 700 800
Chainage (m)

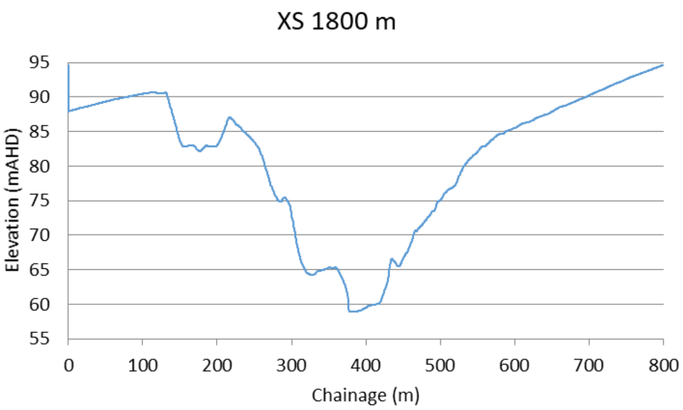

XS 1400 m
Elevation (mAHD)
95
90
85
80
75
70
65
60
55
50
45
300 350 400 450 500
Chainage (m)

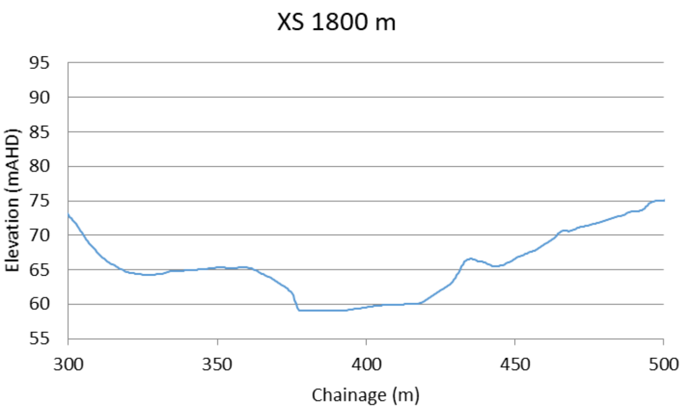

Riley Bench Index
W/D (mean)
Elevation (mAHD)
95
90
85
80
75
70
65
60
55
50
45
0 100 200 300 400
W/D ratio, Riley Bench Index

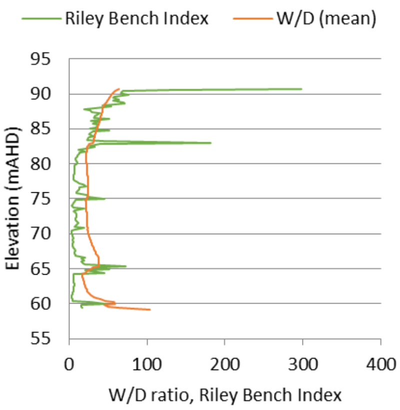

XS 1600 m
Elevation (mAHD)
90
85
80
75
70
65
60
55
50
0
100
200
300
400
500
600
700
800
Chainage (m)

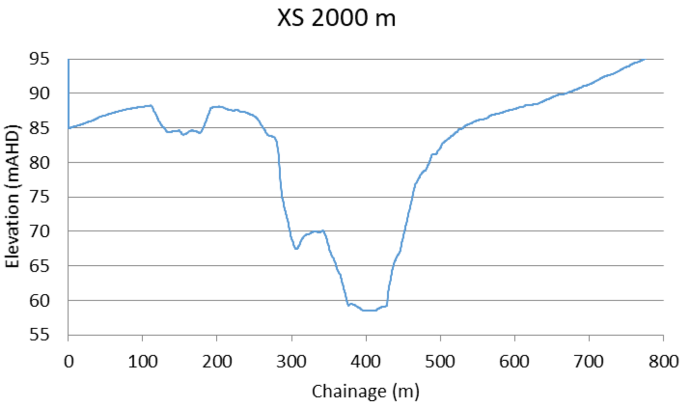

XS 1600 m
Elevation (mAHD)
90
85
80
75
70
65
60
55
50
300
350
400
450
500
Chainage (m)

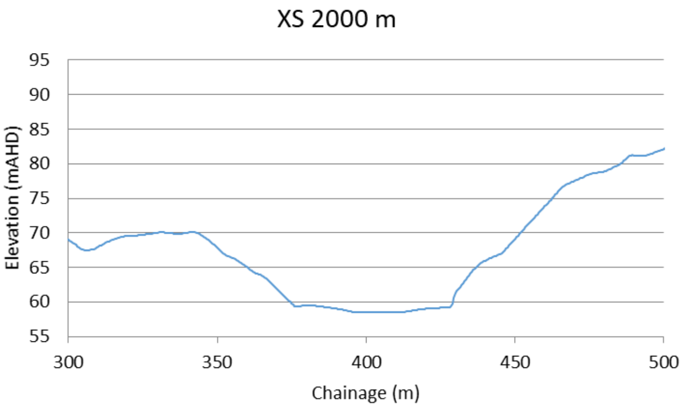

Riley Bench Index
W/D (mean)
Elevation (mAHD)
90
85
80
75
70
65
60
55
50
0
100
200
300
W/D ratio, Riley Bench Index

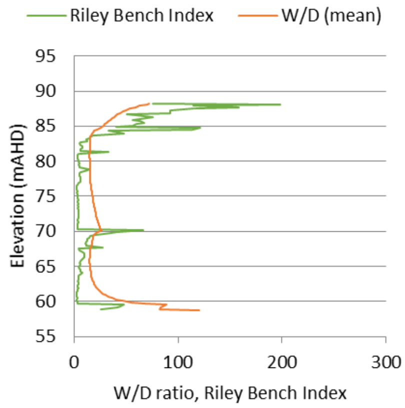

XS 1800 m
Elevation (mAHD)
95
90
85
80
75
70
65
60
55
0
100
200
300
400
500
600
700
800
Chainage (m)

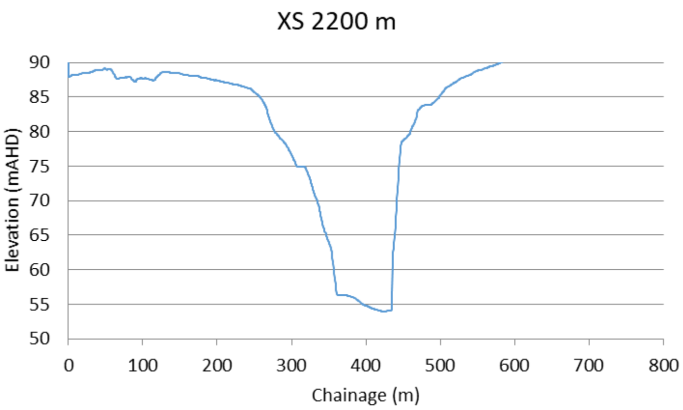

XS 1800 m
Elevation (mAHD)
95
90
85
80
75
70
65
60
55
300
350
400
450
500
Chainage (m)

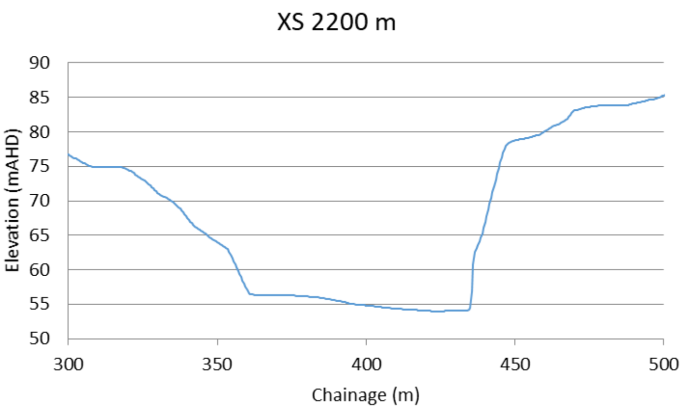

Riley Bench Index
W/D (mean)
Elevation (mAHD)
95
90
85
80
75
70
65
60
55
0
100
200
300
400
W/D ratio, Riley Bench Index

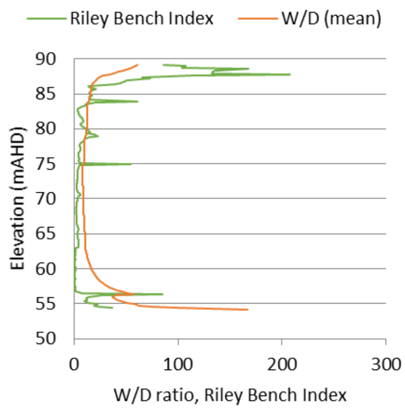

XS 2000 m
Elevation (mAHD)
Chainage (m)

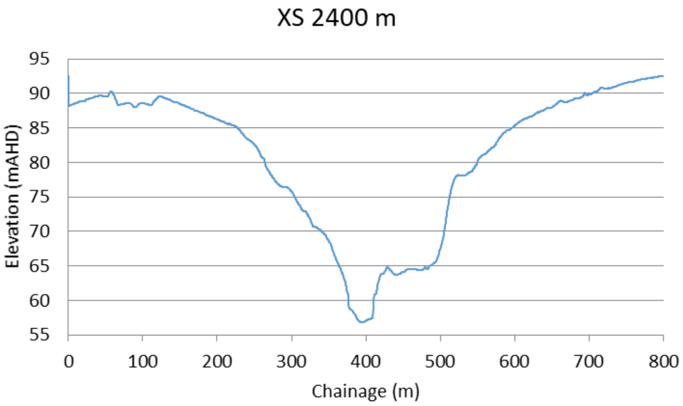

XS 2000 m
Elevation (mAHD)
Chainage (m)

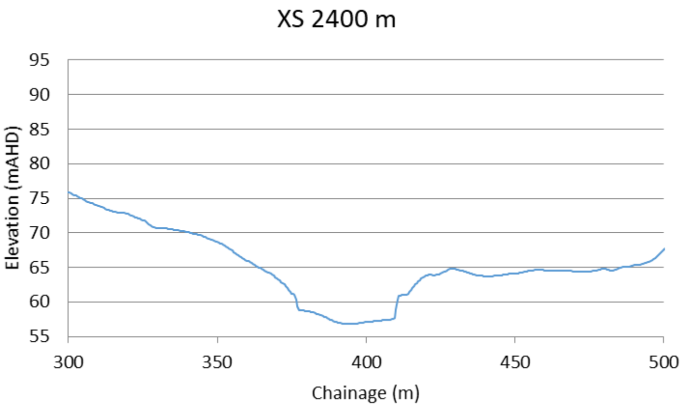

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index

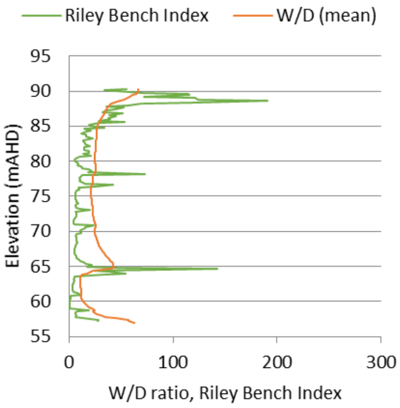

XS 2200 m
Elevation (mAHD)
Chainage (m)

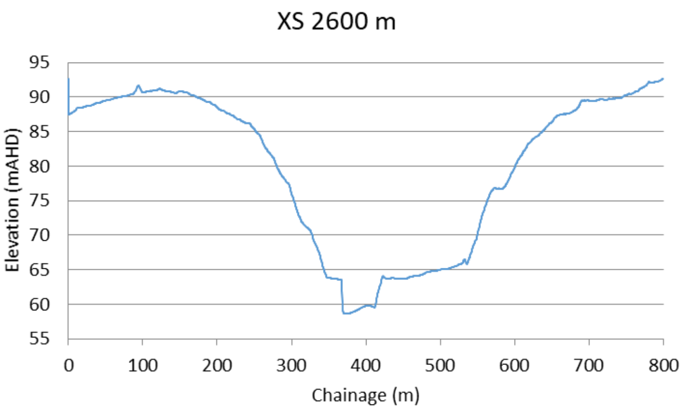

XS 2200 m
Elevation (mAHD)
Chainage (m)

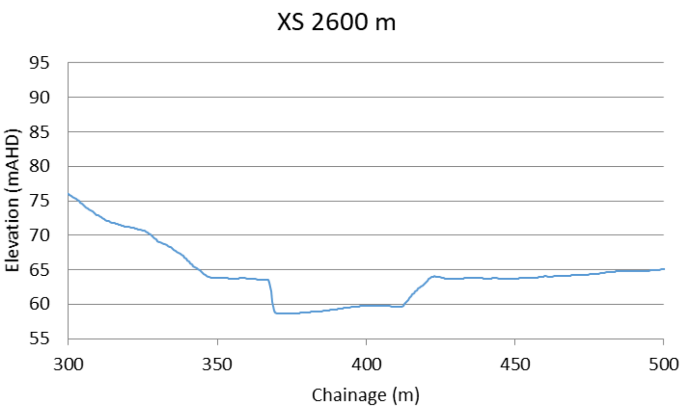

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index

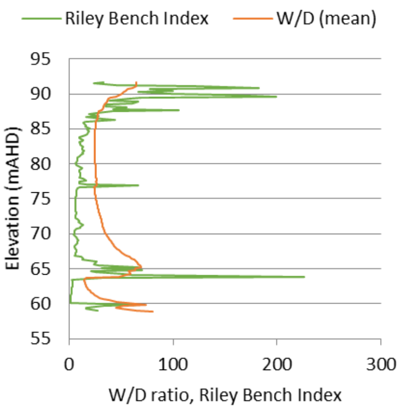

XS 2400 m
Elevation (mAHD)
Chainage (m)

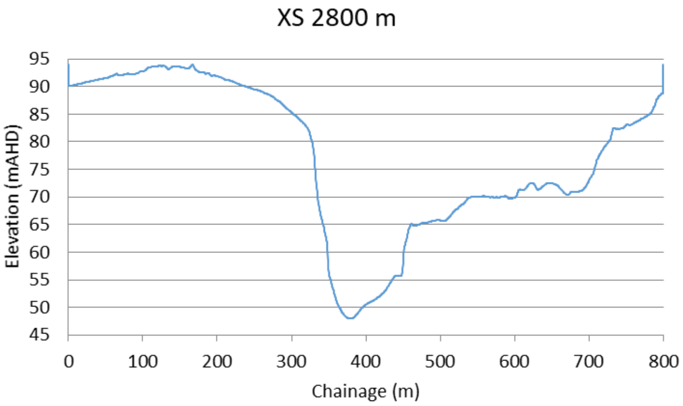

XS 2400 m
Elevation (mAHD)
Chainage (m)

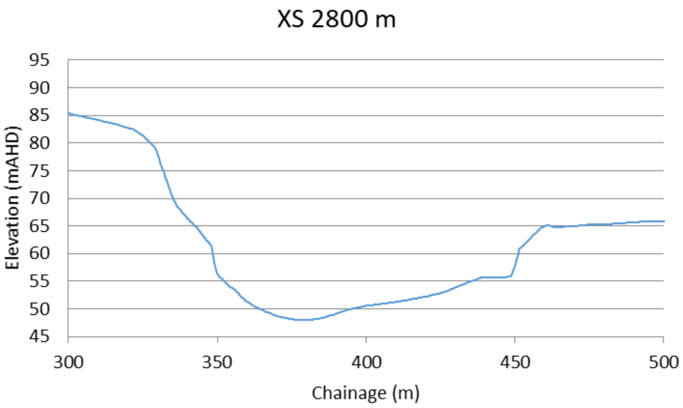

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index

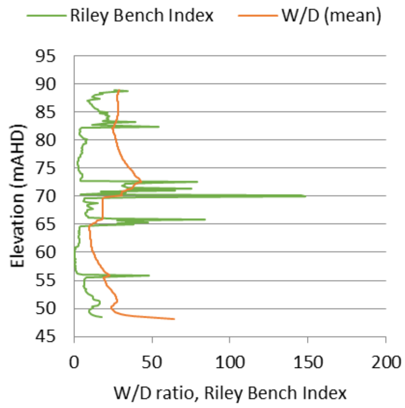

XS 2600 m
Elevation (mAHD)
Chainage (m)

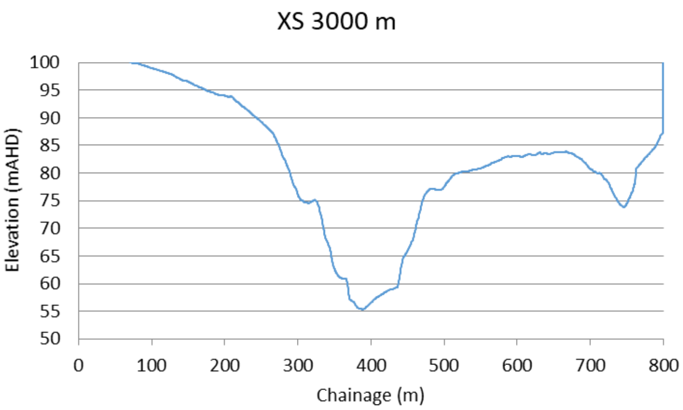

XS 2600 m
Elevation (mAHD)
Chainage (m)

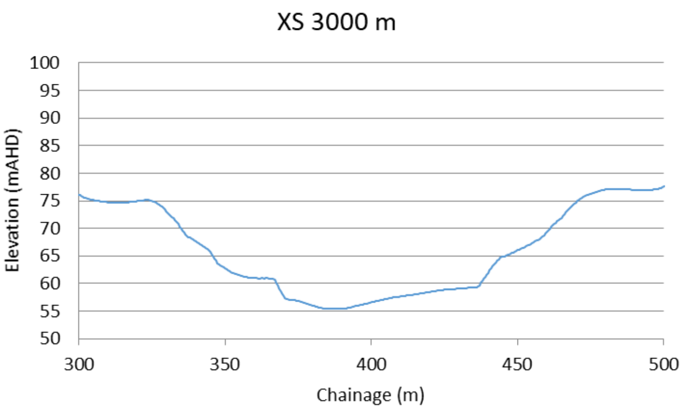

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index

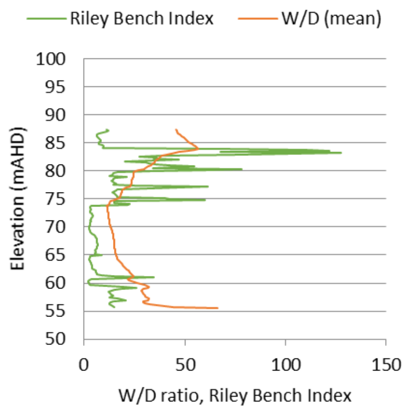

XS 2800 m
Elevation (mAHD)
95
90
85
80
75
70
65
60
55
50
45
0
100
200
300
400
500
600
700
800
Chainage (m)

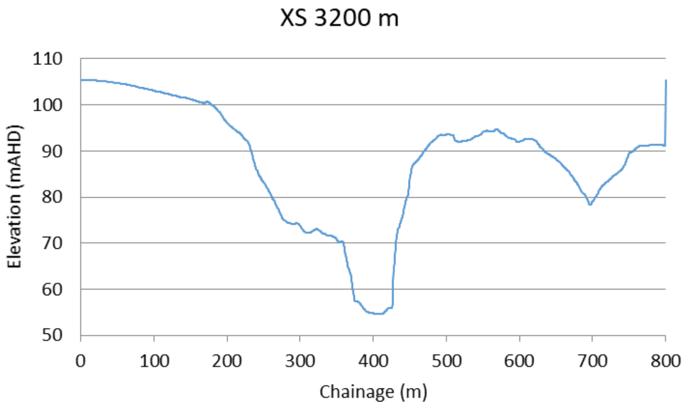

XS 2800 m
Elevation (mAHD)
95
90
85
80
75
70
65
60
55
50
45
300
350
400
450
500
Chainage (m)

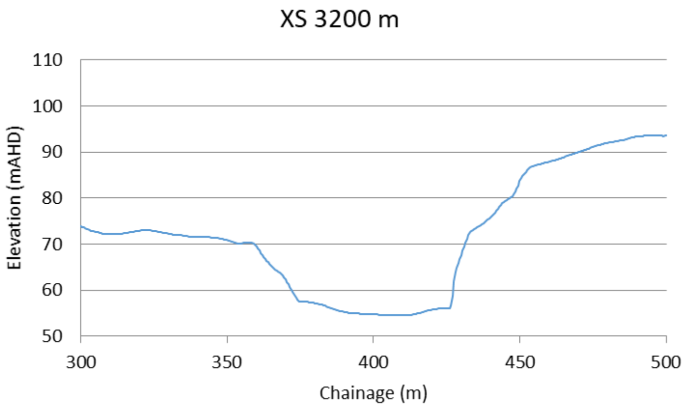

Riley Bench Index
W/D (mean)
Elevation (mAHD)
95
90
85
80
75
70
65
60
55
50
45
0
50
100
150
200
W/D ratio, Riley Bench Index

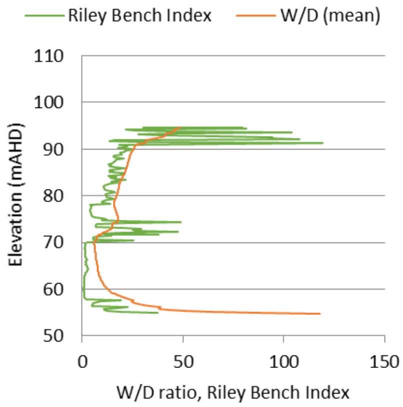

XS 3000 m
Elevation (mAHD)
100
95
90
85
80
75
70
65
60
55
50
0
100
200
300
400
500
600
700
800
Chainage (m)

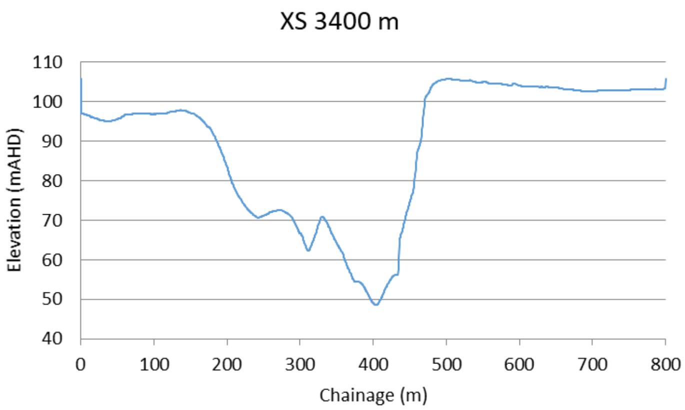

XS 3000 m
Elevation (mAHD)
100
95
90
85
80
75
70
65
60
55
50
300
350
400
450
500
Chainage (m)

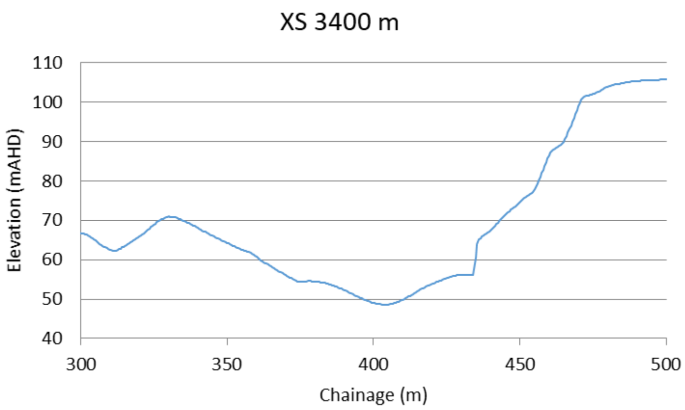

Riley Bench Index
W/D (mean)
Elevation (mAHD)
100
95
90
85
80
75
70
65
60
55
50
0
50
100
150
W/D ratio, Riley Bench Index

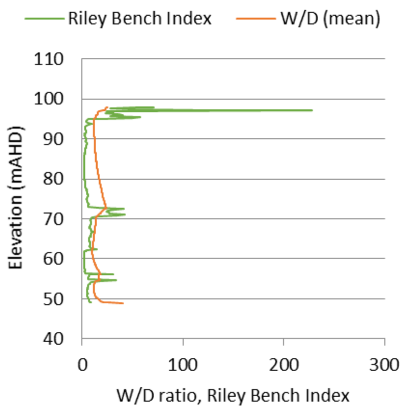

XS 3200 m
Elevation (mAHD)
Chainage (m)

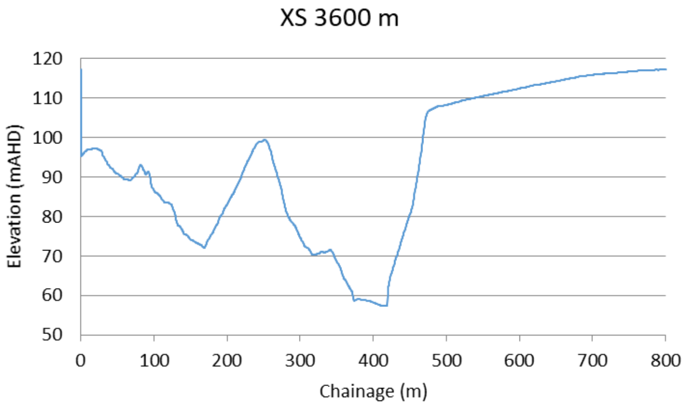

XS 3200 m
Elevation (mAHD)
Chainage (m)

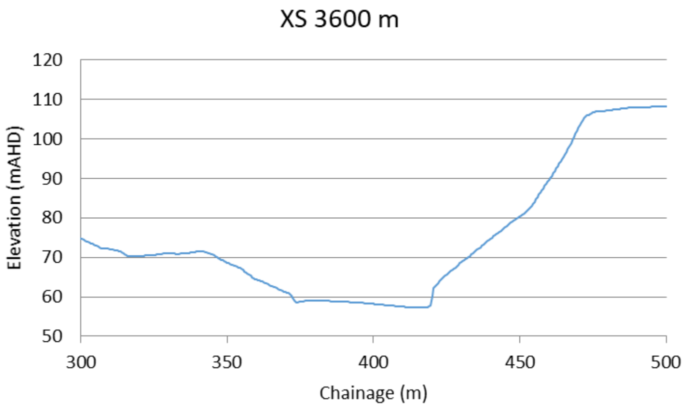

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index

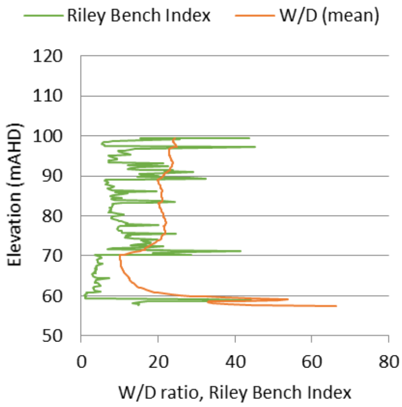

XS 3400 m
Elevation (mAHD)
Chainage (m)

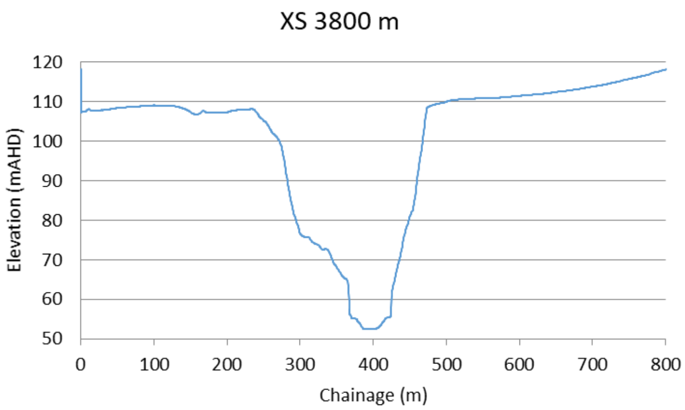

XS 3400 m
Elevation (mAHD)
Chainage (m)

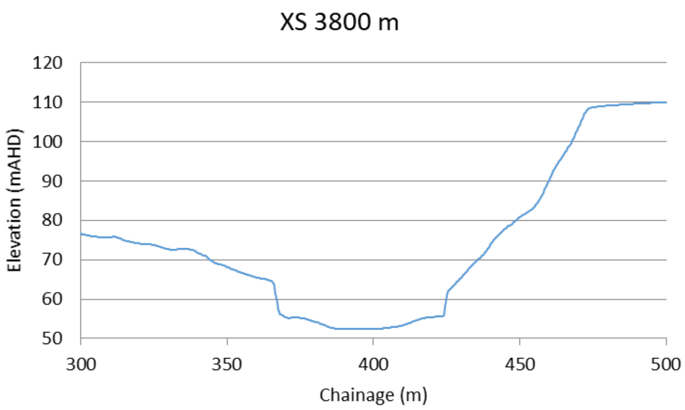

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index

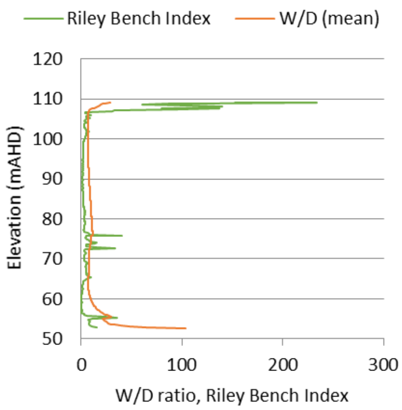

XS 3600 m
Elevation (mAHD)
120
110
100
90
80
70
60
50
0
100
200
300
400
500
600
700
800
Chainage (m)

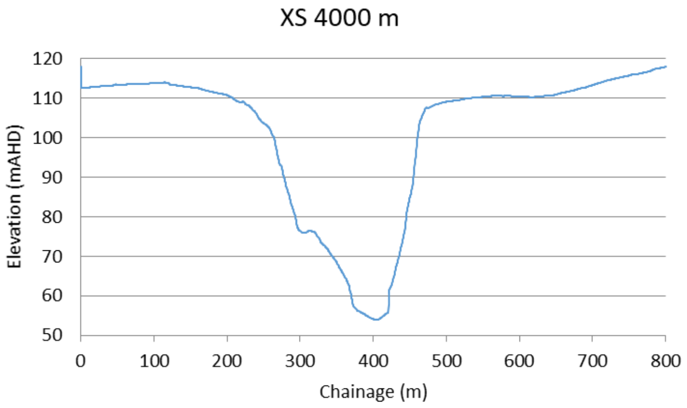

XS 3600 m
Elevation (mAHD)
120
110
100
90
80
70
60
50
300
350
400
450
500
Chainage (m)

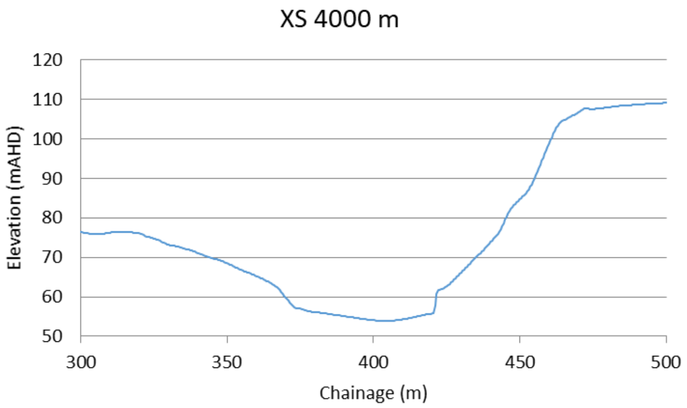

Riley Bench Index
W/D (mean)
Elevation (mAHD)
120
110
100
90
80
70
60
50
0
20
40
60
80
W/D ratio, Riley Bench Index

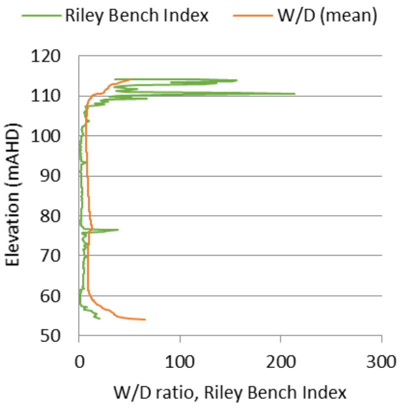

XS 3800 m
Elevation (mAHD)
120
110
100
90
80
70
60
50
0
100
200
300
400
500
600
700
800
Chainage (m)

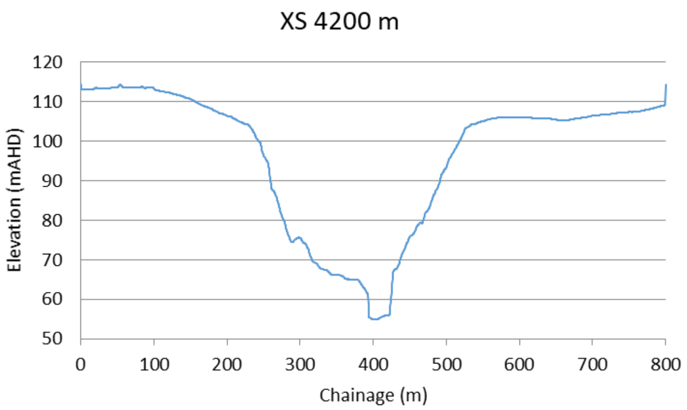

XS 3800 m
Elevation (mAHD)
120
110
100
90
80
70
60
50
300
350
400
450
500
Chainage (m)

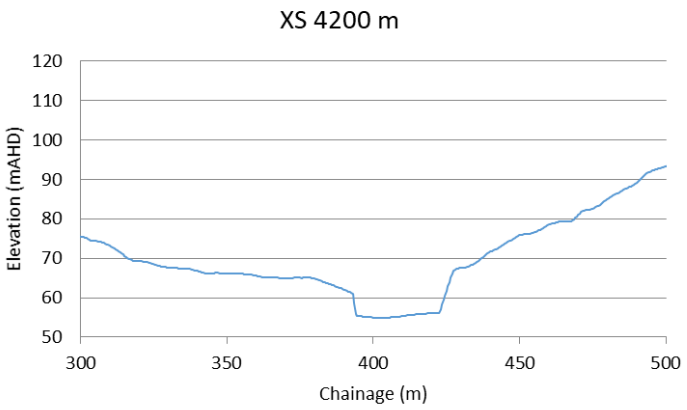

Riley Bench Index
W/D (mean)
Elevation (mAHD)
120
110
100
90
80
70
60
50
0
100
200
300
W/D ratio, Riley Bench Index

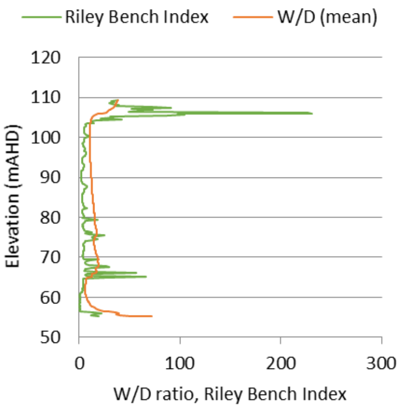

XS 4000 m
Elevation (mAHD)
Chainage (m)
50
60
70
80
90
100
110
120
0
100
200
300
400
500
600
700
800

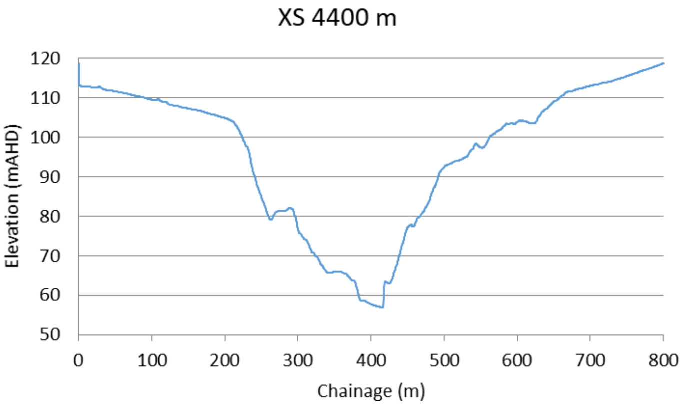

XS 4000 m
Elevation (mAHD)
Chainage (m)
50
60
70
80
90
100
110
120
300
350
400
450
500

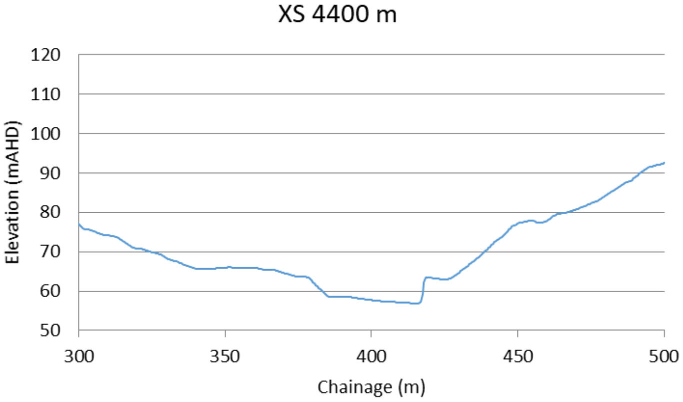

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index
50
60
70
80
90
100
110
120
0
100
200
300

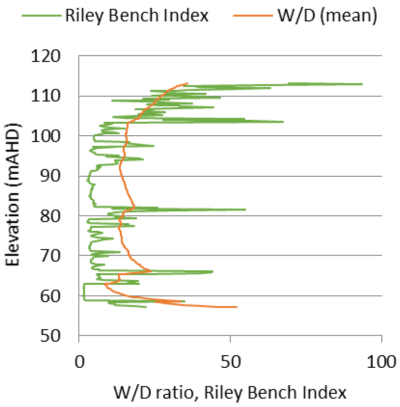

XS 4200 m
Elevation (mAHD)
Chainage (m)
50
60
70
80
90
100
110
120
0
100
200
300
400
500
600
700
800

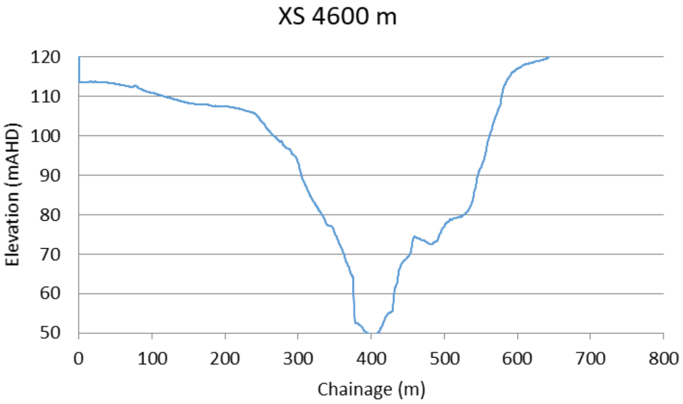

XS 4200 m
Elevation (mAHD)
Chainage (m)
50
60
70
80
90
100
110
120
300
350
400
450
500

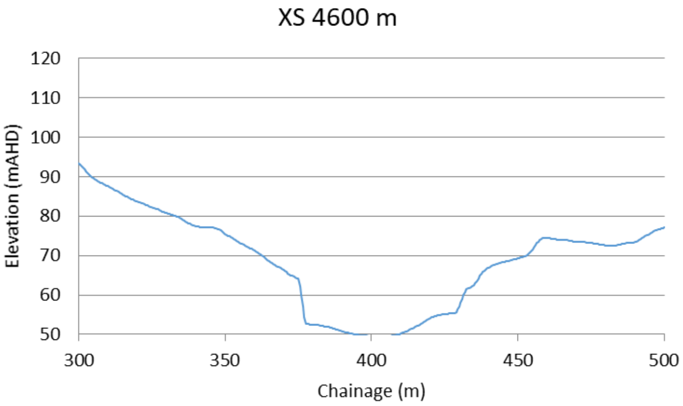

Riley Bench Index
W/D (mean)
Elevation (mAHD)
W/D ratio, Riley Bench Index
50
60
70
80
90
100
110
120
0
100
200
300

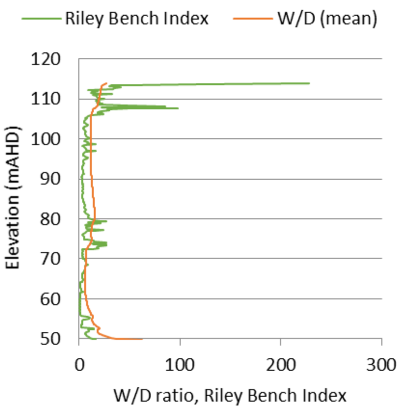

XS 4400 m
Elevation (mAHD)
120
110
100
90
80
70
60
50
0
100
200
300
400
500
600
700
800
Chainage (m)


XS 4400 m
Elevation (mAHD)
120
110
100
90
80
70
60
50
300
350
400
450
500
Chainage (m)


Riley Bench Index
W/D (mean)
Elevation (mAHD)
120
110
100
90
80
70
60
50
0
50
100
W/D ratio, Riley Bench Index


XS 4600 m
Elevation (mAHD)
120
110
100
90
80
70
60
50
0
100
200
300
400
500
600
700
800
Chainage (m)


XS 4600 m
Elevation (mAHD)
120
110
100
90
80
70
60
50
300
350
400
450
500
Chainage (m)


Riley Bench Index
W/D (mean)
Elevation (mAHD)
120
110
100
90
80
70
60
50
0
100
200
300
W/D ratio, Riley Bench Index

9. Appendix 3. Morphometric Indexes Minima and Maxima

XS 0 m	XS 0 m	XS 0 m	XS 0 m	XS 0 m	XS 0 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
15.34	59.37	2	4.25	58.57	8
15.79	59.57	4	4.5	58.77	7
14.89	65.77	1	4.25	62.57	8
15.50	65.97	3	4	63.17	10
			5.25	65.77	6
			16.25	66.97	3
			14	67.97	4
			12.25	68.77	5
			94.25	70.37	1
			24.25	71.37	2

XS 200 m	XS 200 m	XS 200 m	XS 200 m	XS 200 m	XS 200 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
20.60	58.00	4	6.5	57.00	9
9.72	64.00	1	7	57.60	8
10.62	65.20	2	1.5	60.60	11
12.41	65.40	3	4.5	64.80	10
86.12	71.60	5	14.75	66.60	7
90.23	71.80	6	23	68.40	6
134.47	75.00	7	23.75	68.60	5
135.57	75.20	8	25	70.60	4
			68.75	72.20	1
			39.25	74.60	3
			55	74.80	2

XS 400 m	XS 400 m	XS 400 m	XS 400 m	XS 400 m	XS 400 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
8.25	56.70	2	3.25	53.90	13
8.26	56.90	3	2.75	56.10	14
7.32	61.10	1	3.75	61.70	12
11.09	61.90	4	37.5	61.90	4
19.63	66.90	5	6.75	63.70	11
20.76	67.10	6	7	64.30	10
43.57	69.10	7	7.5	66.90	9
44.42	69.30	8	31.5	68.10	5
69.41	70.10	10	11.5	68.70	8
68.46	70.90	9	12.5	68.90	7
73.98	71.10	11	29.75	70.10	6
			72.75	71.70	3
			117.25	71.90	1
			83.5	72.70	2

XS 600 m	XS 600 m	XS 600 m	XS 600 m	XS 600 m	XS 600 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
7.42	65.50	1	2.25	56.70	9
7.48	65.70	2	4.25	67.70	8
101.00	72.90	3	5.25	68.30	6
103.86	73.10	4	5	69.70	7
135.67	74.30	5	96	71.30	1
158.25	75.50	6	33	72.30	5
			48.5	72.90	4
			75.5	73.70	2
			51.75	75.50	3

XS 800 m	XS 800 m	XS 800 m	XS 800 m	XS 800 m	XS 800 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
8.65	55.70	3	5.25	50.50	8
5.44	63.50	1	4.25	51.30	9
5.47	63.70	2	4	51.90	11
34.34	74.70	4	3.5	53.50	15
106.61	77.10	5	0.75	58.90	18
126.62	78.90	6	0.75	59.10	17
			2.5	63.50	16
			3.5	64.50	14
			4.25	65.90	9
			4	66.50	12
			4	69.30	12
			34.5	72.90	6
			26.25	73.70	7
			92.5	75.50	2
			106.5	75.70	1
			42.5	76.90	5
			56.75	77.10	4
			59.5	78.70	3

XS 1000 m	XS 1000 m	XS 1000 m	XS 1000 m	XS 1000 m	XS 1000 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
15.04	59.10	4	4.75	57.70	12
12.07	65.50	3	5.5	58.30	11
10.97	68.50	1	6.75	59.10	10
10.98	68.70	2	8.25	60.10	9
91.09	74.50	5	4.75	64.70	13
94.30	74.70	6	44.25	70.30	5
121.61	79.10	7	63.75	71.70	1
			51.5	72.70	2
			11.25	73.90	8
			14	74.50	7
			46.5	76.90	4
			42	77.90	6
			49.5	78.70	3

XS 1200 m	XS 1200 m	XS 1200 m	XS 1200 m	XS 1200 m	XS 1200 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
8.52	61.60	1	21.5	55.80	3
8.53	61.80	2	1	57.00	16
8.61	67.20	3	1	58.60	16
8.61	67.40	4	0.75	60.80	18
14.24	74.40	5	2	61.40	15
14.54	74.60	6	4.75	62.80	12
59.49	78.20	9	3	65.20	13
57.39	79.00	7	3	65.80	14
58.96	79.20	8	8	69.60	8
89.10	81.60	10	8	70.40	9
			8	71.20	9
			5.5	74.20	11
			48	76.00	1
			15.25	77.20	5
			12	78.00	7
			12.5	78.80	6
			17	79.00	4
			40.25	81.40	2

XS 1400 m	XS 1400 m	XS 1400 m	XS 1400 m	XS 1400 m	XS 1400 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
11.95	54.29	7	5	51.09	9
10.88	58.29	5	4.75	52.09	10
11.65	58.49	6	4	55.29	12
10.56	61.09	4	4	57.89	13
9.32	63.89	3	4.5	58.09	11
7.90	74.49	1	1.75	59.49	18
7.92	74.69	2	1.5	60.49	21
22.01	77.69	10	2.75	61.69	15
21.67	79.09	8	1.75	63.29	20
21.72	79.29	9	1.75	63.49	18
			3.25	68.69	14
			2.75	69.49	15
			2.75	70.49	17
			43.5	76.29	1
			6.25	77.69	8
			7.75	78.29	7
			10.25	79.09	6
			11.5	80.09	5
			20.75	80.89	4
			24	84.49	3
			37.75	87.29	2

XS 1600 m	XS 1600 m	XS 1600 m	XS 1600 m	XS 1600 m	XS 1600 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
24.67	59.10	11	8.75	58.90	7
24.90	59.30	13	12	59.10	1
15.52	62.70	5	2.5	60.30	20
13.97	66.10	1	2.25	60.90	21
14.00	66.30	2	5	64.50	15
15.43	68.70	3	5	65.70	15
15.46	68.90	4	5.25	65.90	13
19.23	74.50	6	5.25	67.30	14
19.85	74.70	7	5.5	67.50	12
24.78	75.90	12	8.25	68.90	9
22.10	80.30	9	8.75	69.90	7
21.91	80.90	8	9.25	70.10	6
22.41	81.10	10	9.5	71.50	5
44.35	84.50	14	6.25	72.70	11
45.13	84.70	15	3.75	74.10	19
46.08	85.50	16	10.5	75.50	4
46.18	86.30	17	11.25	75.70	3
			11.5	76.50	2
			7.5	77.90	10
			4.75	79.30	18
			5	79.90	15

XS 1800 m	XS 1800 m	XS 1800 m	XS 1800 m	XS 1800 m	XS 1800 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
45.42	59.80	13	21.25	64.80	6
17.17	64.20	1	15.75	66.00	8
21.22	64.40	2	7.25	67.20	14
38.18	66.00	11	5.25	68.40	16
23.77	70.60	8	5.25	69.20	16
22.41	73.40	4	3.5	70.20	21
21.47	74.80	3	4	70.40	19
22.95	75.00	7	9.75	71.20	9
24.40	76.00	9	8.5	72.00	12
24.40	76.20	10	6	73.20	15
22.56	80.80	5	4	74.00	20
22.64	81.40	6	4.75	74.20	18
43.09	88.00	12	9.25	76.00	10
			7.75	79.80	13
			8.5	80.60	11
			24	83.40	5
			24.75	83.60	4
			27.5	84.40	3
			34.5	85.20	1
			33.75	86.80	2
			19.25	87.80	7

XS 2000 m	XS 2000 m	XS 2000 m	XS 2000 m	XS 2000 m	XS 2000 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
83.52	59.10	11	2.75	60.10	20
16.49	63.90	9	3.75	62.30	16
15.07	65.70	2	4.25	63.50	14
15.09	65.90	3	4.75	64.90	12
15.42	67.50	5	6.25	65.70	9
16.72	67.70	10	4.5	67.50	13
15.53	78.50	8	11.25	68.30	7
14.83	81.10	1	11.75	68.50	6
15.48	81.70	6	4	73.30	15
15.36	82.70	4	3.75	74.90	16
15.50	82.90	7	3	75.50	19
			6.5	78.50	8
			5	79.50	11
			3.25	80.50	18
			5.25	82.50	10
			15	83.30	5
			33.5	84.30	4
			56	85.10	1
			56	85.90	1
			51	86.70	3

XS 2200 m	XS 2200 m	XS 2200 m	XS 2200 m	XS 2200 m	XS 2200 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
37.22	55.95	10	19.75	54.75	1
8.87	70.15	3	10.25	55.35	7
8.87	70.35	4	14	55.95	4
8.49	74.15	1	1	57.15	21
8.51	74.35	2	2	62.75	20
10.05	75.55	6	3.5	65.95	16
10.03	76.55	5	3.5	70.15	16
10.05	76.75	7	3	71.35	18
12.68	82.95	8	3	71.95	18
12.73	83.15	9	4.75	75.55	12
			4.25	76.15	13
			4.75	76.35	11
			5.5	77.75	10
			6.75	77.95	8
			13	79.35	6
			6.5	80.75	9
			3.75	82.55	15
			4	82.75	14
			15	85.15	3
			16.75	85.35	2
			13.5	86.15	5

XS 2400 m	XS 2400 m	XS 2400 m	XS 2400 m	XS 2400 m	XS 2400 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
23.12	58.60	9	6.25	57.80	15
11.17	60.80	3	6.25	58.40	15
10.74	63.20	1	3.75	61.60	20
10.77	63.40	2	3.5	62.20	21
25.10	70.20	12	25	64.40	2
25.29	70.40	13	18	65.00	4
22.85	72.80	8	5.75	67.60	19
20.91	75.80	4	6.5	69.40	13
21.36	76.40	5	10.75	70.20	8
22.66	77.80	6	15.75	70.40	5
22.71	78.00	7	6.75	72.80	11
24.61	80.60	10	6.25	73.80	15
24.92	80.80	11	6.5	75.60	12
26.87	84.20	14	10.25	77.20	9
			11	77.80	7
			8.75	79.40	10
			5.75	80.20	18
			6.5	80.40	14
			14.5	82.00	6
			19.5	85.20	3
			36.25	87.20	1

XS 2600 m	XS 2600 m	XS 2600 m	XS 2600 m	XS 2600 m	XS 2600 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
44.92	59.46	10	17	59.46	3
14.35	63.46	1	2	60.26	21
16.92	63.66	2	2.5	62.26	20
57.39	64.66	11	21	64.66	2
24.43	76.66	3	24	65.66	1
26.26	77.46	9	5.75	66.86	15
24.69	81.26	5	5.25	68.06	18
24.72	81.46	6	5.75	68.26	15
24.74	83.06	7	5	69.86	19
24.66	83.86	4	5.5	70.46	17
24.75	84.06	8	9.25	71.66	9
			6.25	72.46	13
			6	74.26	14
			8	76.46	10
			10.5	78.06	5
			9.75	79.06	8
			6.5	80.06	12
			7	80.26	11
			10.5	81.06	6
			10	83.86	7
			14.25	85.86	4

XS 2800 m	XS 2800 m	XS 2800 m	XS 2800 m	XS 2800 m	XS 2800 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
24.20	50.00	8	9.75	49.60	3
24.99	50.60	10	10.25	49.80	2
19.19	55.60	6	7.5	53.20	6
10.00	64.60	1	6.25	54.00	11
10.38	64.80	2	6.75	55.20	9
18.28	67.60	3	7.25	55.40	7
18.43	68.40	5	1.75	56.40	20
18.36	69.60	4	0.75	58.60	21
19.47	69.80	7	2.75	63.00	19
30.97	70.60	15	4.25	64.60	17
24.70	82.20	9	7.25	67.00	8
26.37	83.00	11	8.5	68.20	5
28.00	87.20	13	8.75	68.40	4
27.98	88.00	12	6	69.20	13
28.08	88.20	14	6.5	69.40	10
			4	70.40	18
			31	71.80	1
			4.5	73.00	14
			4.5	77.40	14
			6.25	79.20	11
			4.5	82.00	16

XS 3000 m	XS 3000 m	XS 3000 m	XS 3000 m	XS 3000 m	XS 3000 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
29.55	56.77	7	12.5	56.37	10
28.60	58.57	5	12.5	57.37	10
28.80	58.77	6	12	58.37	12
21.50	60.77	4	13.5	58.57	8
15.99	64.77	3	2.25	60.37	21
11.41	73.77	1	4.25	62.57	16
11.92	73.97	2	2.5	64.17	20
			5.75	65.97	15
			3.25	69.17	18
			3.25	73.57	19
			3.5	73.77	17
			16.25	75.37	3
			14.25	76.17	6
			15	76.37	4
			14.75	77.57	5
			13.5	78.17	9
			14	79.37	7
			20.5	81.77	2
			38.5	82.77	1
			9.25	84.17	13
			6.5	86.57	14

XS 3200 m	XS 3200 m	XS 3200 m	XS 3200 m	XS 3200 m	XS 3200 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
38.04	55.98	10	10.75	55.78	7
24.40	57.38	7	7.5	57.18	10
5.98	69.98	1	1	60.98	21
6.24	70.18	2	1.75	65.18	18
14.74	73.98	3	1.75	65.98	16
15.32	74.18	4	1.75	67.18	19
15.65	78.18	5	1.5	69.58	20
15.87	78.38	6	1.75	69.78	16
31.55	91.98	8	24.75	72.78	1
34.29	92.18	9	6.75	73.78	12
47.70	94.38	11	7.25	73.98	11
			9.75	74.78	8
			3.75	76.58	15
			4	76.78	14
			4	78.18	13
			9.5	78.78	9
			10.75	78.98	5
			11.75	80.38	4
			10.75	81.98	5
			14	83.78	2
			13	84.38	3

XS 3400 m	XS 3400 m	XS 3400 m	XS 3400 m	XS 3400 m	XS 3400 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
11.43	52.43	5	6.5	49.63	8
11.33	53.03	3	5	51.83	13
11.38	53.23	4	5.5	53.03	12
15.97	55.83	9	6.25	55.43	9
9.55	62.23	1	2.25	58.23	18
10.02	62.43	2	7.25	63.23	6
11.55	93.43	6	8.75	66.03	3
11.58	94.83	7	7.25	67.63	6
11.76	95.03	8	7.5	68.23	5
			8.5	69.83	4
			23.75	71.83	2
			25.5	72.03	1
			5.75	73.03	11
			6	73.23	10
			4.25	75.03	15
			4.5	76.23	14
			2.25	80.83	18
			2.25	81.83	18
			2	82.63	21
			3.75	88.23	16
			3.5	89.43	17

XS 3600 m	XS 3600 m	XS 3600 m	XS 3600 m	XS 3600 m	XS 3600 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
32.85	58.36	20	14.75	58.36	2
33.17	58.56	21	1	59.56	21
12.54	64.16	5	3.25	61.56	19
10.33	67.76	3	3	64.96	20
10.10	69.36	2	3.5	66.96	17
10.00	70.16	1	4	67.56	15
11.12	70.36	4	4.25	68.36	14
16.51	71.96	6	4	68.96	15
17.02	72.16	7	3.5	70.16	17
21.49	77.36	15	18.75	70.76	1
21.57	77.56	16	8	71.96	8
21.34	80.16	14	12.75	72.76	4
20.21	82.96	10	14.25	72.96	3
20.22	83.16	11	11.25	74.56	5
20.81	85.16	12	9.25	76.76	7
20.81	85.36	13	7.75	79.56	10
19.87	88.96	8	7	80.96	13
19.90	89.16	9	7.25	81.96	12
22.97	95.16	19	7.75	82.16	10
22.90	96.36	17	10.5	83.16	6
22.93	96.56	18	7.75	84.16	9
23.90	98.76				

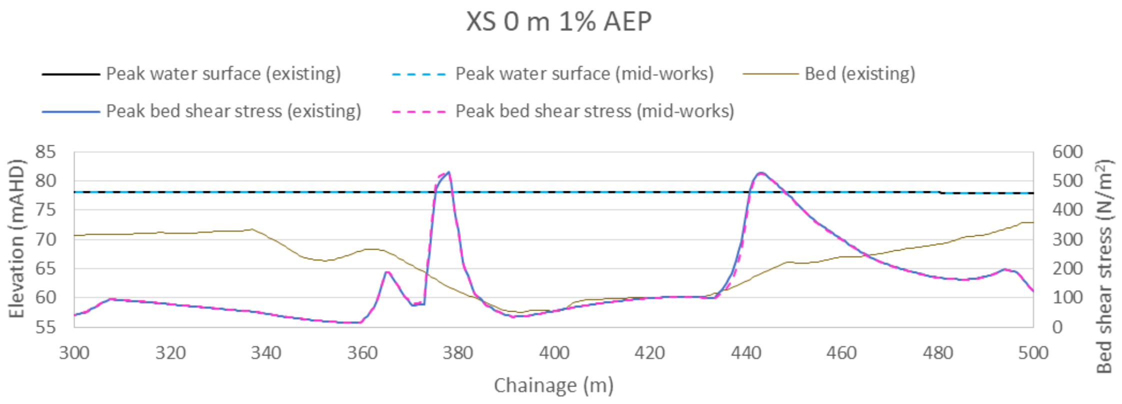
XS 3800 m	XS 3800 m	XS 3800 m	XS 3800 m	XS 3800 m	XS 3800 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
21.69	55.10	13	7.5	53.90	2
6.48	64.50	1	7.25	54.70	3
6.52	64.70	2	8	54.90	1
7.85	70.90	8	2.75	55.90	13
7.83	72.30	6	0.25	56.70	21
7.85	72.50	7	1.5	63.50	16
9.15	73.30	9	5.25	66.10	4
9.15	73.50	10	4.25	68.10	8
10.04	75.70	11	2.75	70.10	12
11.16	75.90	12	3.5	72.10	10
6.58	99.90	3	4.5	73.10	6
6.59	100.10	4	4.5	73.30	5
6.86	103.90	5	4.25	75.30	9
			4.5	75.50	6
			2.5	82.90	14
			2	83.50	15
			1.5	87.30	17
			1.25	89.50	18
			1.25	90.70	18
			1.25	91.30	18
			3.5	104.50	11

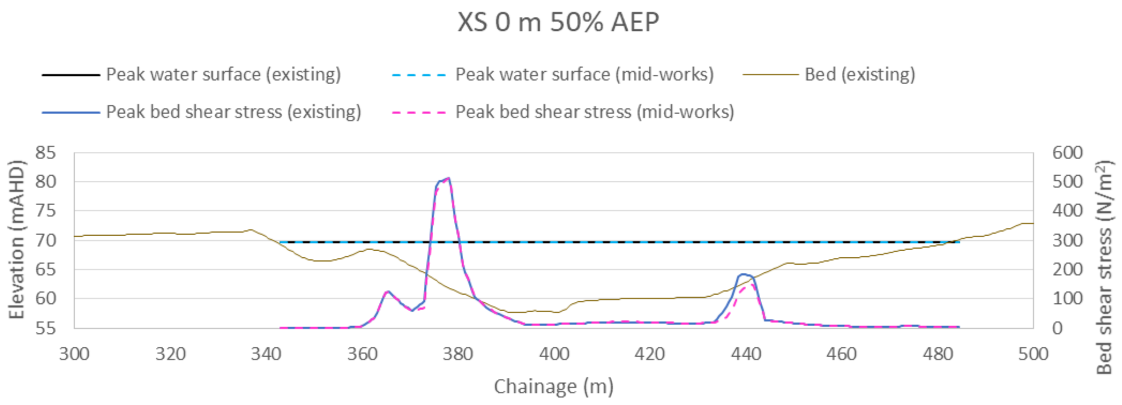
XS 4000 m	XS 4000 m	XS 4000 m	XS 4000 m	XS 4000 m	XS 4000 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
34.19	55.40	18	14.5	54.80	2
9.02	61.60	11	15.25	55.40	1
8.65	65.40	6	12.5	56.00	3
8.66	65.60	7	4.75	56.60	5
8.70	67.80	10	1.25	60.00	21
8.68	68.60	8	1.5	61.60	19
8.69	68.80	9	3.5	62.40	13
9.05	71.60	12	3.75	64.20	12
9.09	71.80	13	4.25	65.20	6
9.45	74.60	14	4.25	66.80	6
9.48	74.80	15	4	67.40	9
9.53	75.80	16	4	68.40	9
10.13	76.00	17	4.25	68.60	6
7.70	93.00	5	4	71.60	9
6.79	100.20	3	5.25	72.60	4
6.80	100.40	4	3.5	74.20	13
6.76	102.20	1	3.25	75.60	16
6.77	102.40	2	3.5	75.80	13
			1.5	77.80	20
			1.75	79.20	18
			2	80.40	17

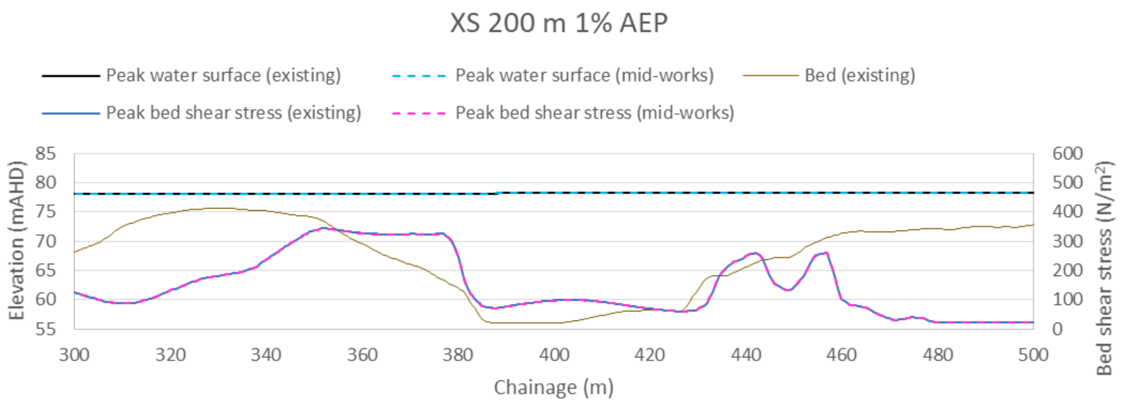
XS 4200 m	XS 4200 m	XS 4200 m	XS 4200 m	XS 4200 m	XS 4200 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
36.58	55.80	20	0.75	56.40	18
5.97	61.40	1	0.5	57.60	20
6.00	61.60	2	0.5	58.40	20
12.46	65.80	10	0.75	60.80	18
16.61	67.20	17	3.25	62.20	15
16.84	67.40	18	4	63.80	10
18.56	69.00	19	5.5	65.60	8
14.56	74.20	14	7.5	65.80	3
14.81	74.40	15	5.25	66.60	9
15.48	79.20	16	5.5	66.80	7
14.45	82.00	13	5.75	68.80	6
12.75	87.20	11	6.5	69.00	4
12.76	87.40	12	12.25	75.00	2
10.88	95.20	7	15.75	75.20	1
10.90	95.40	8	6	76.00	5
10.97	96.80	9	3.5	77.80	13
10.76	99.60	3	3.75	78.40	11
10.76	99.80	4	3.25	80.00	14
10.86	102.60	5	3	81.40	17
10.87	102.80	6	3.75	83.00	11
			3.25	85.60	16

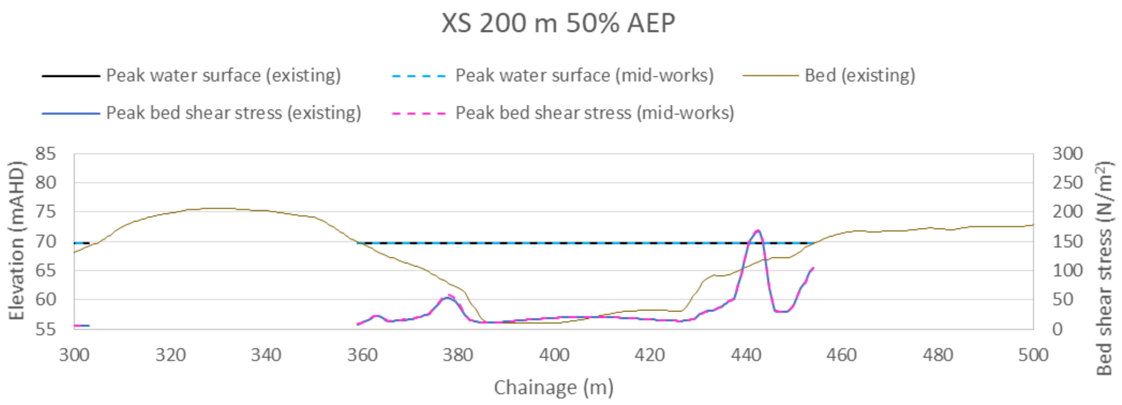
XS 4600 m	XS 4600 m	XS 4600 m	XS 4600 m	XS 4600 m	XS 4600 m
Min W/Depth (mean)	Elevation	Rank	Max Bench Index	Elevation	Rank
18.33	51.70	21	6	51.50	6
12.54	54.90	18	8.75	52.30	4
12.94	55.10	19	2.25	53.10	16
6.17	61.50	5	3	54.50	14
5.54	64.10	1	1	55.90	19
5.56	64.30	2	0.5	57.70	20
5.67	65.90	3	0.5	59.90	20
5.70	66.10	4	1.25	62.70	17
7.29	70.90	8	1	63.30	18
7.28	71.70	7	3	65.30	15
7.27	72.30	6	3.25	70.30	12
7.55	72.50	9	3.25	70.90	12
11.85	76.30	16	3.5	72.30	11
11.85	76.50	17	18.25	73.10	1
13.12	78.70	20	12.5	73.90	2
11.38	94.90	12	4.5	74.90	8
11.41	95.10	13	4	75.70	10
11.34	96.50	10	4.25	76.30	9
11.35	96.70	11	6.75	77.90	5
11.52	98.50	14	5.75	78.50	7
11.70	98.70	15	9	80.30	3
11.76	99.70				

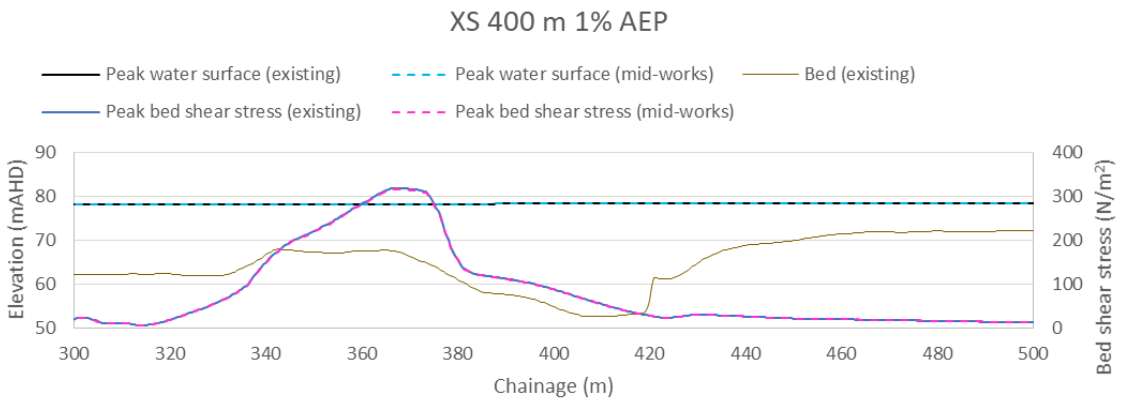
10. Appendix 4. Bed Shear Stress at Cross-sections

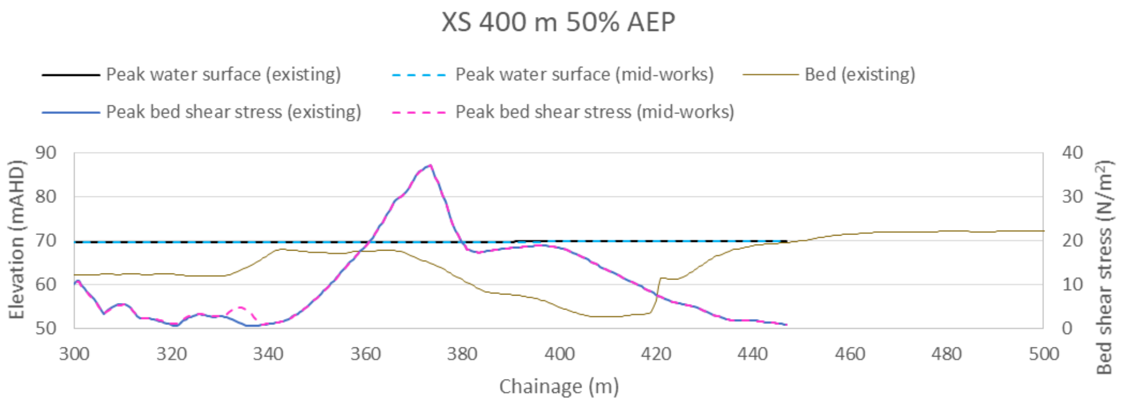

XS 0 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

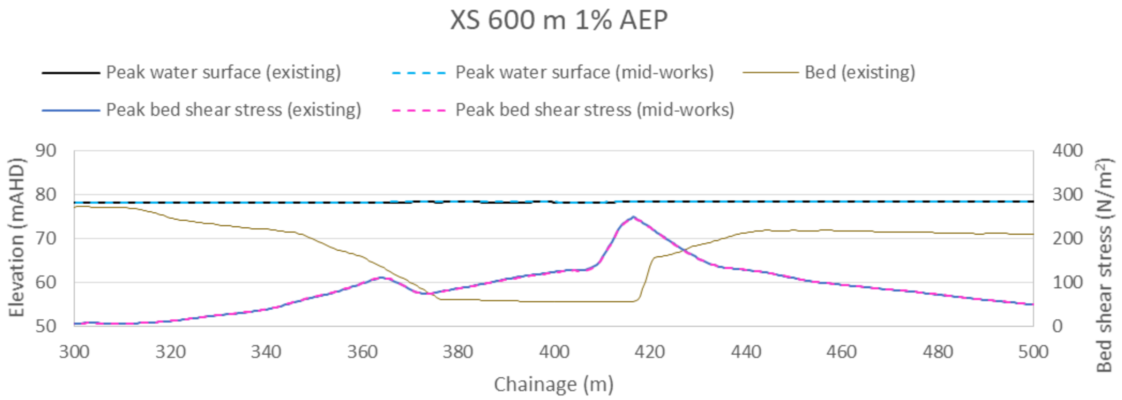

XS 0 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

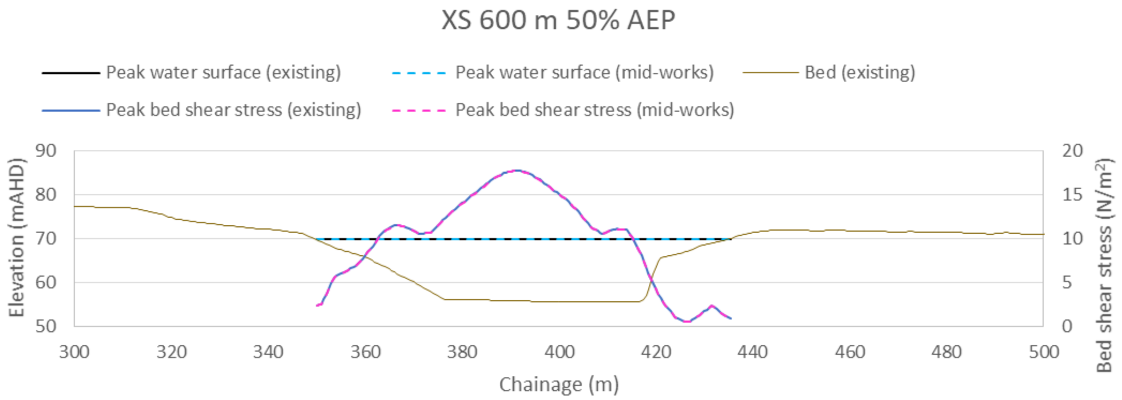

XS 200 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

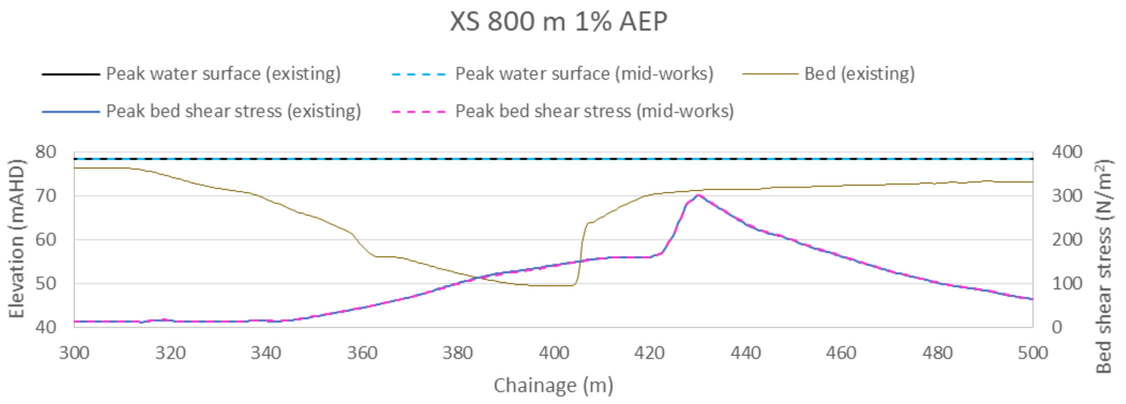

XS 200 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

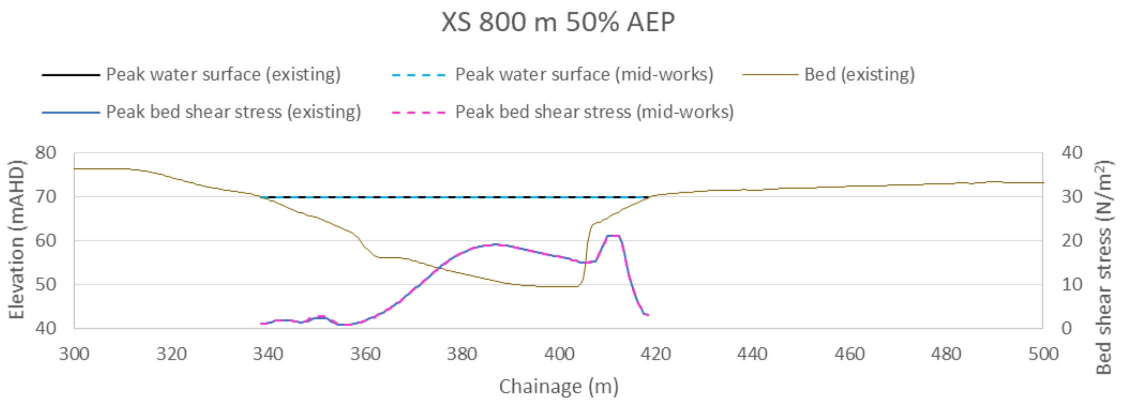

XS 400 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
90
80
70
60
50
400
300
200
100
0
Bed shear stress (N/m²)
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)

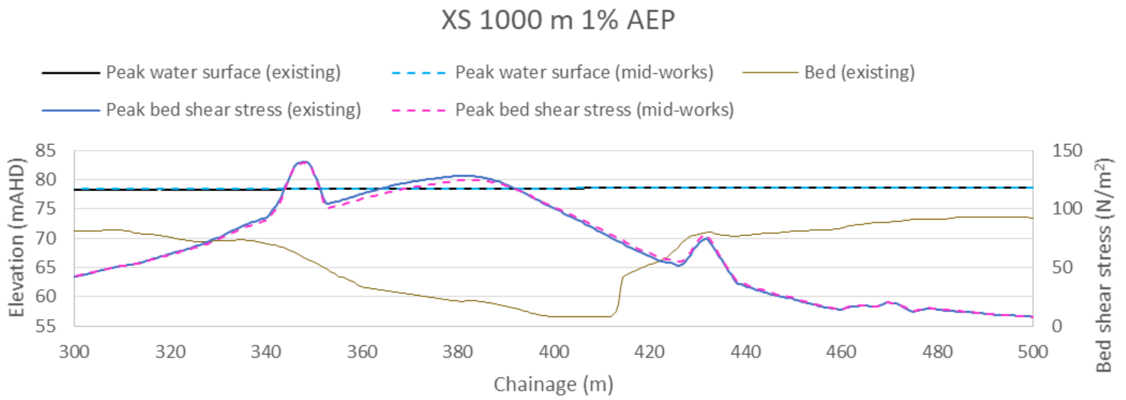

XS 400 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
90
80
70
60
50
40
30
20
10
0
Bed shear stress (N/m²)
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)

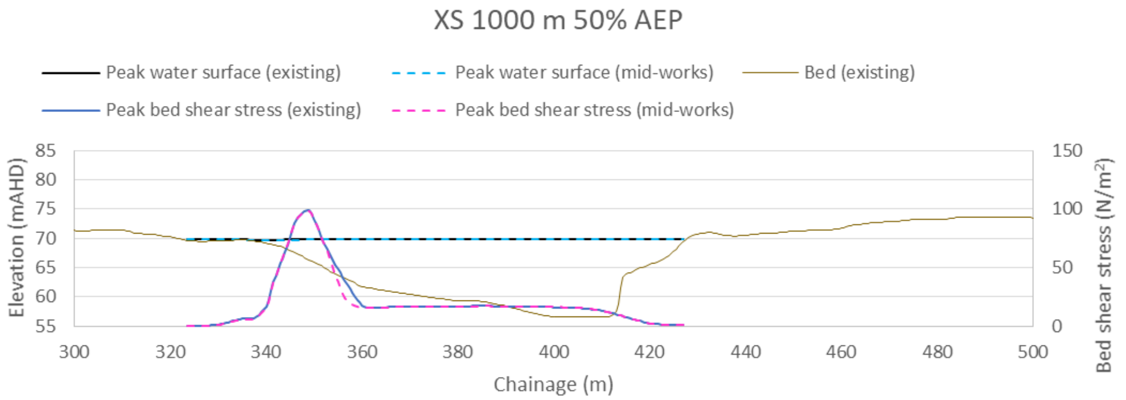

XS 600 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
90
80
70
60
50
400
300
200
100
0
Bed shear stress (N/m²)
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)

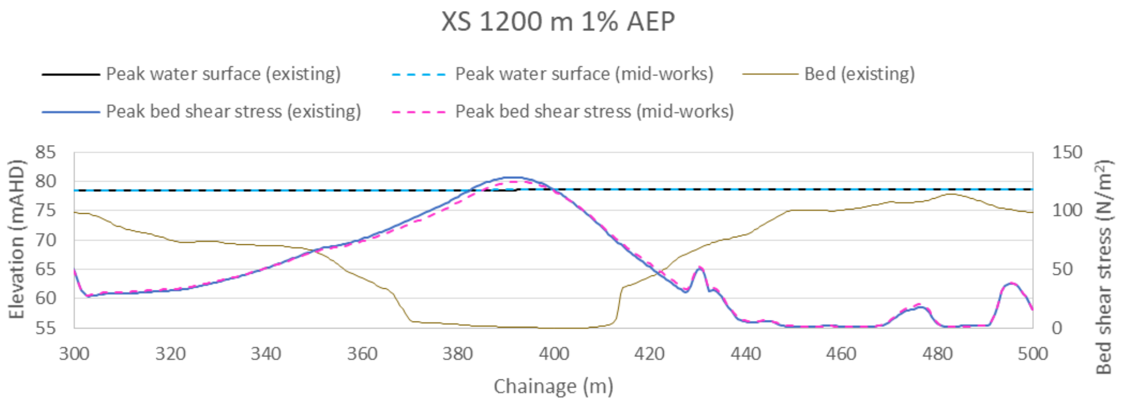

XS 600 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
90
80
70
60
50
20
15
10
5
0
Bed shear stress (N/m²)
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)

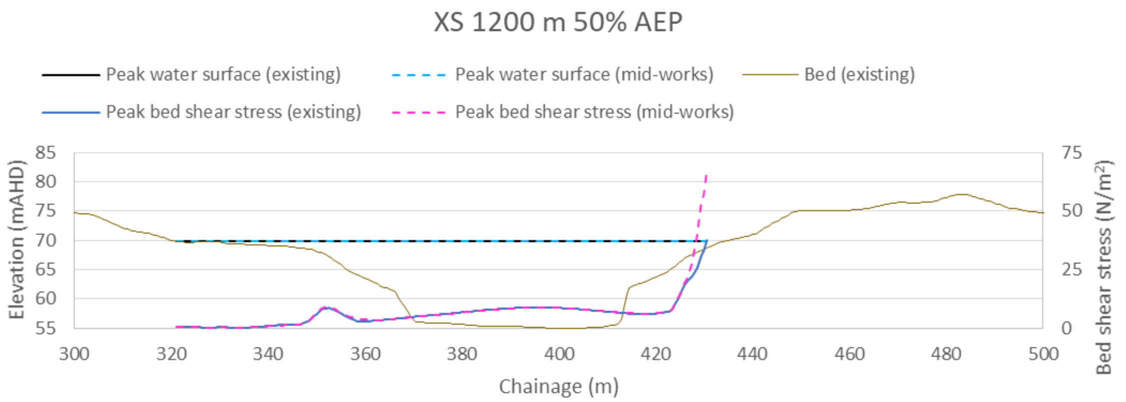

XS 800 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

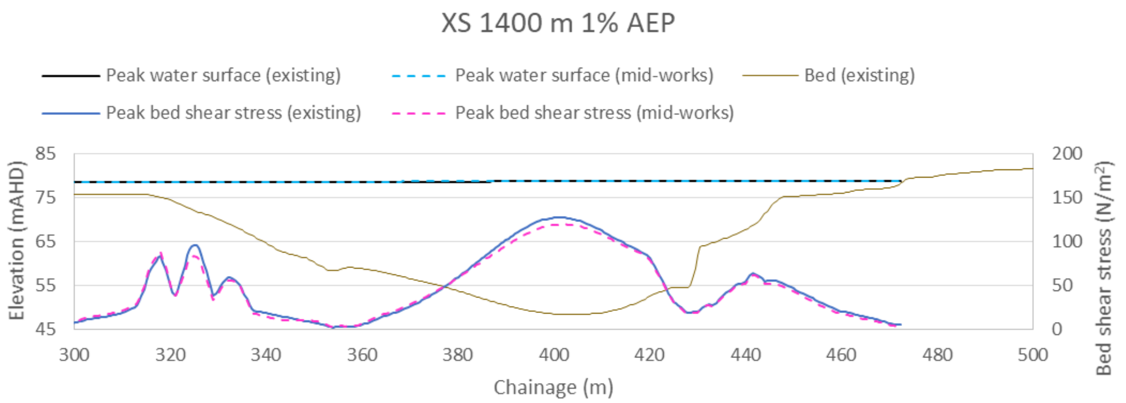

XS 800 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

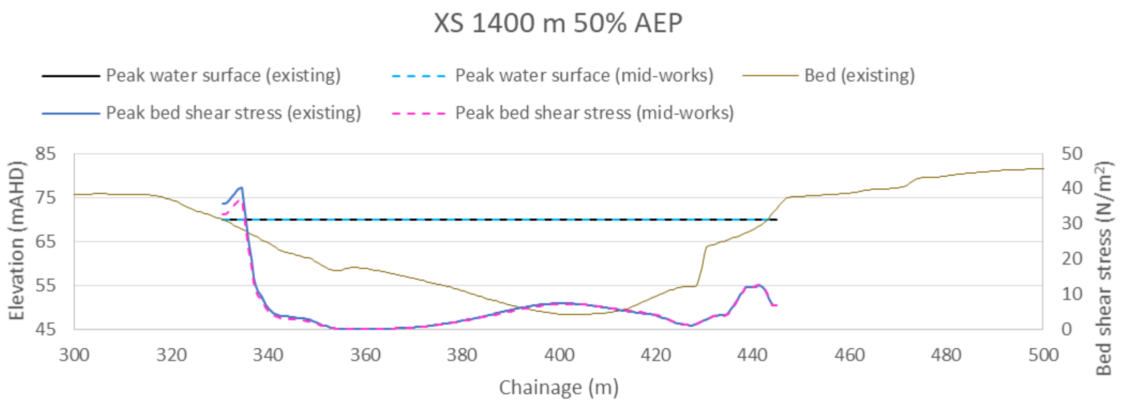

XS 1000 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

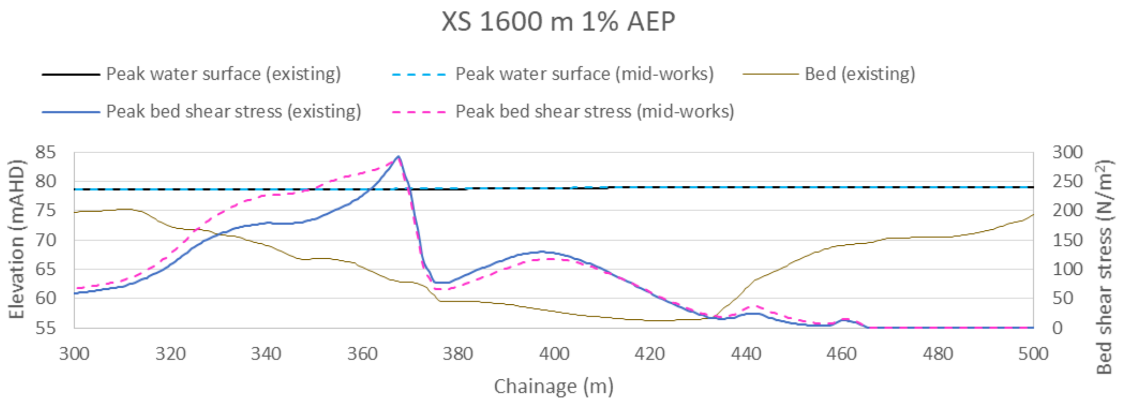

XS 1000 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

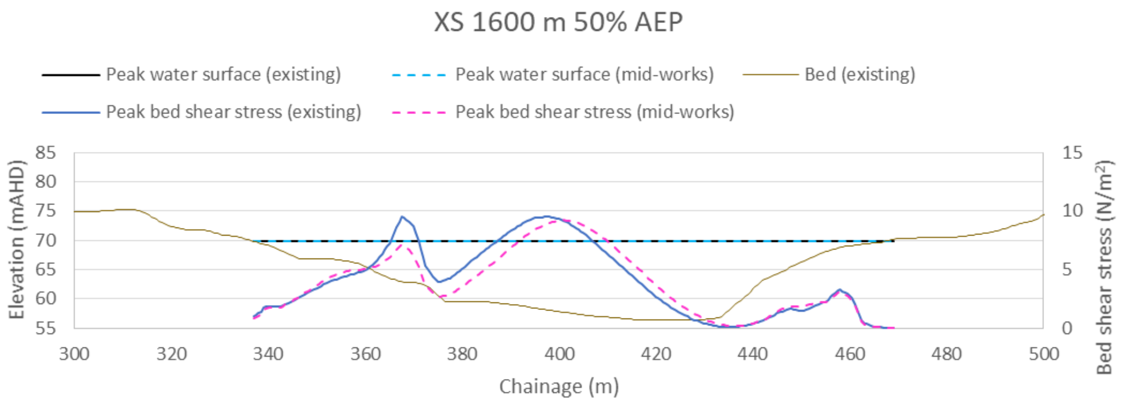

XS 1200 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m^2)
Chainage (m)

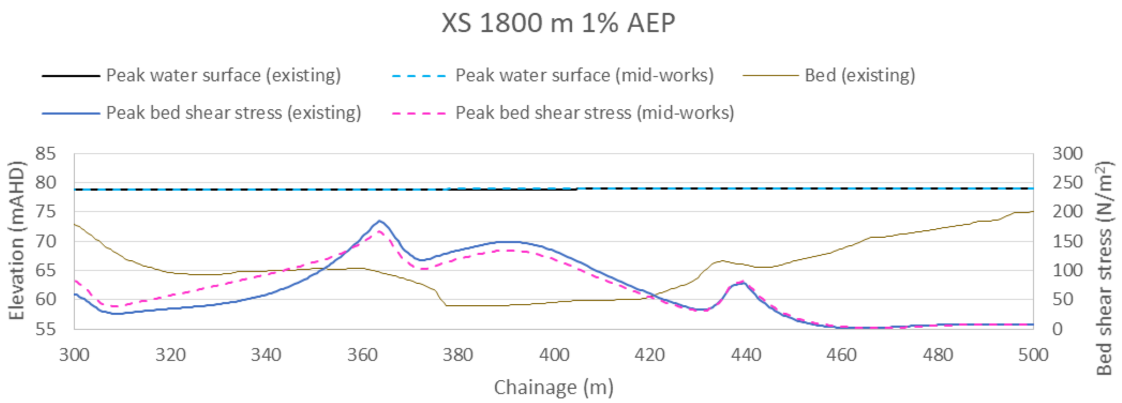

XS 1200 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m^2)
Chainage (m)

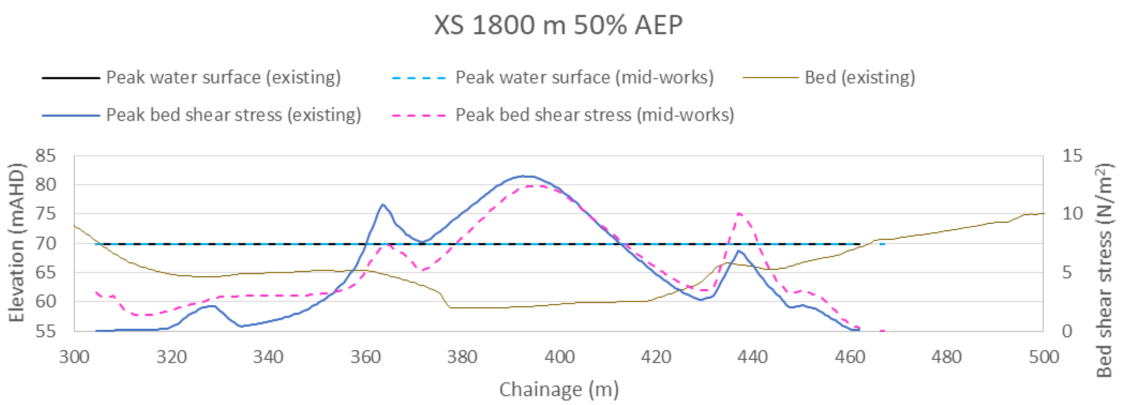

XS 1400 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m^2)
Chainage (m)

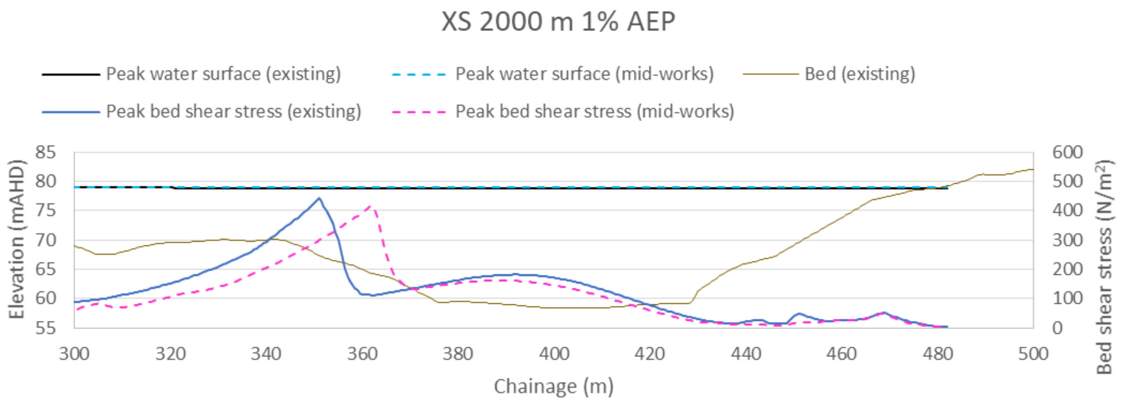

XS 1400 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m^2)
Chainage (m)

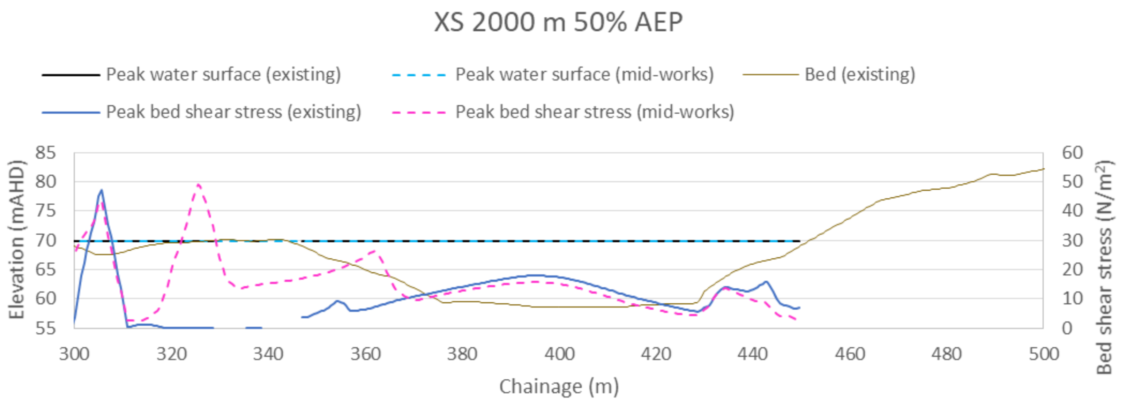

XS 1600 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)
85
80
75
70
65
60
55
300
250
200
150
100
50
0
300
320
340
360
380
400
420
440
460
480
500

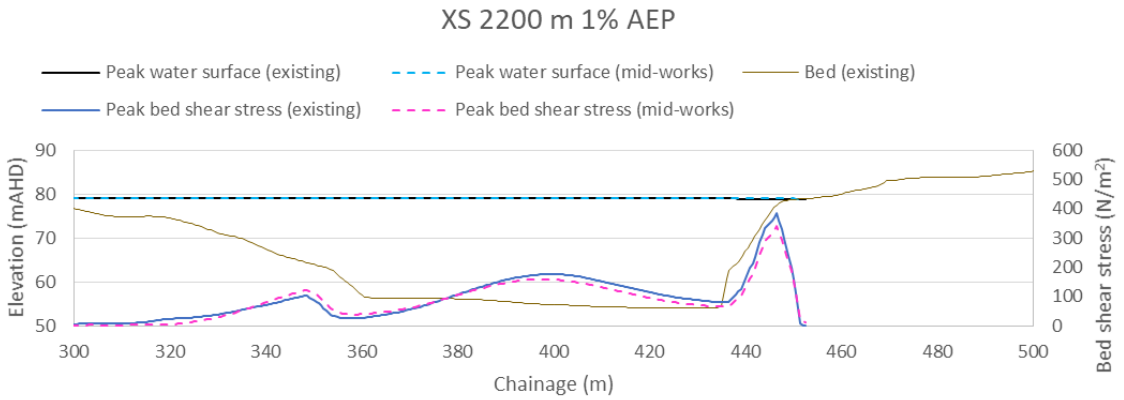

XS 1600 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)
85
80
75
70
65
60
55
15
10
5
0
300
320
340
360
380
400
420
440
460
480
500

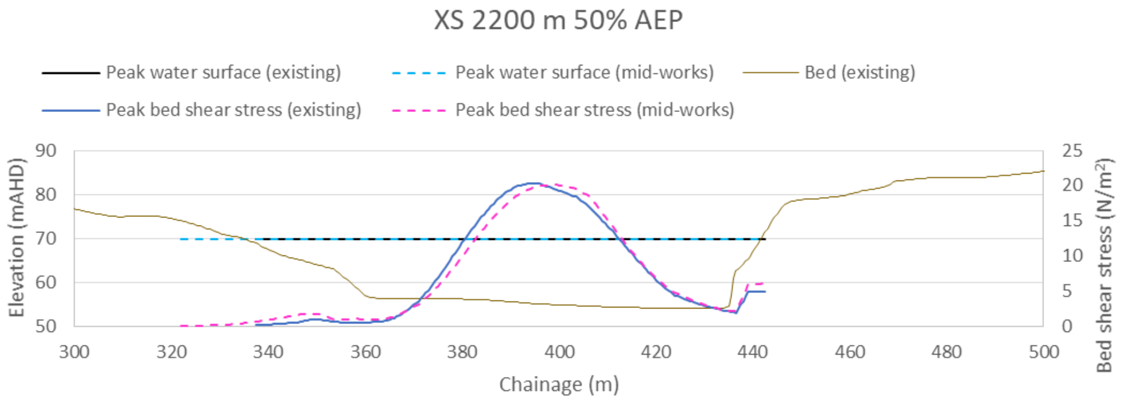

XS 1800 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)
85
80
75
70
65
60
55
300
250
200
150
100
50
0
300
320
340
360
380
400
420
440
460
480
500

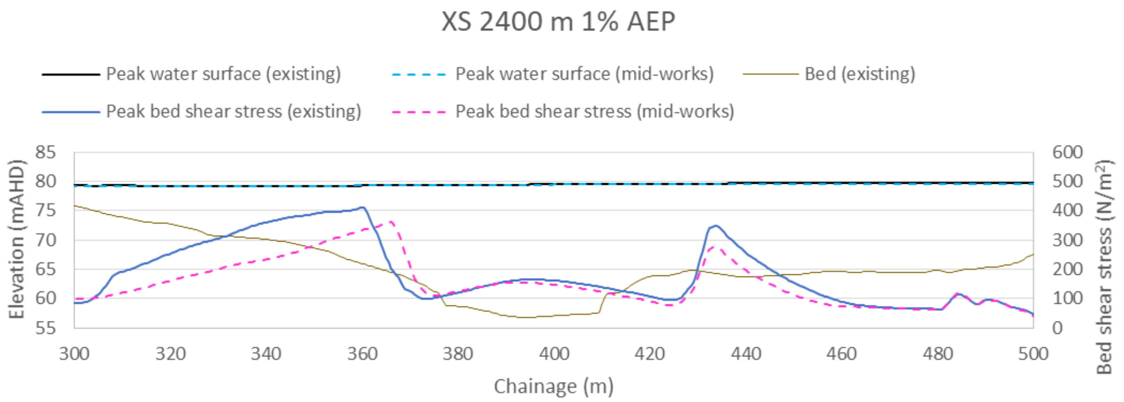

XS 1800 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)
85
80
75
70
65
60
55
15
10
5
0
300
320
340
360
380
400
420
440
460
480
500

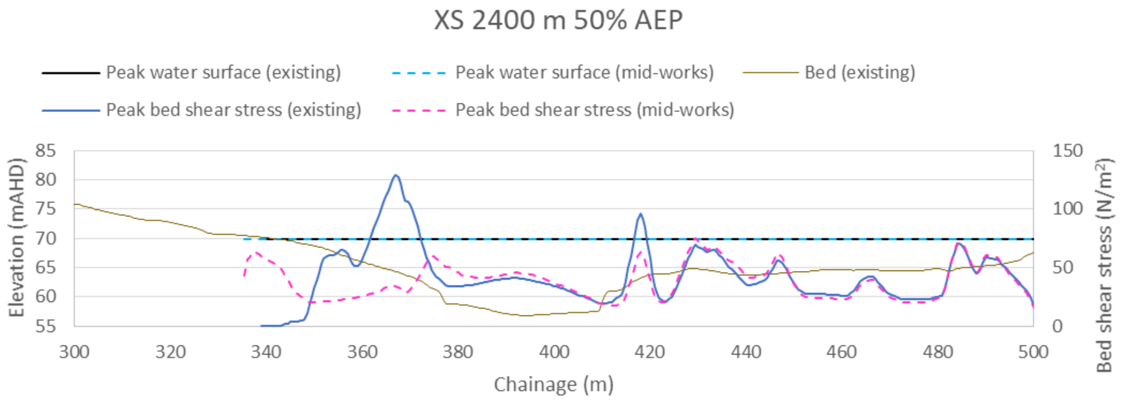

XS 2000 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
85
80
75
70
65
60
55
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)
600
500
400
300
200
100
0
Bed shear stress (N/m²)

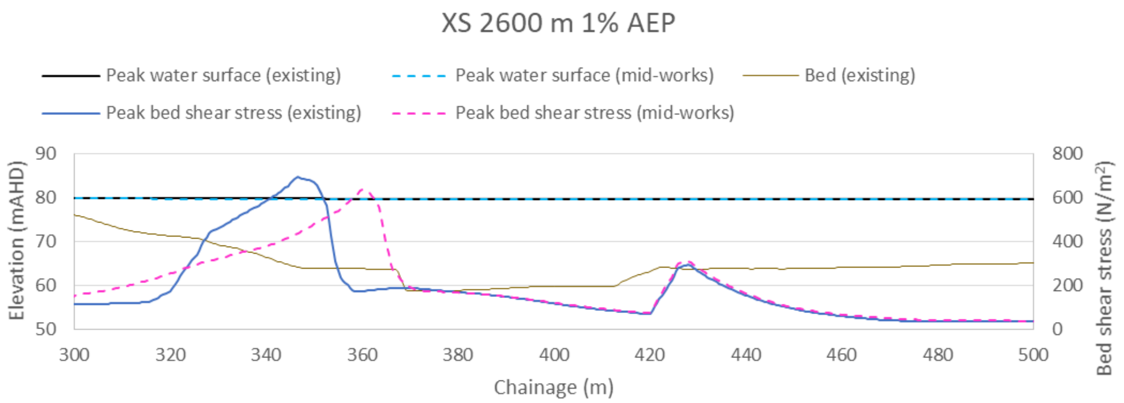

XS 2000 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
85
80
75
70
65
60
55
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)
60
50
40
30
20
10
0
Bed shear stress (N/m²)

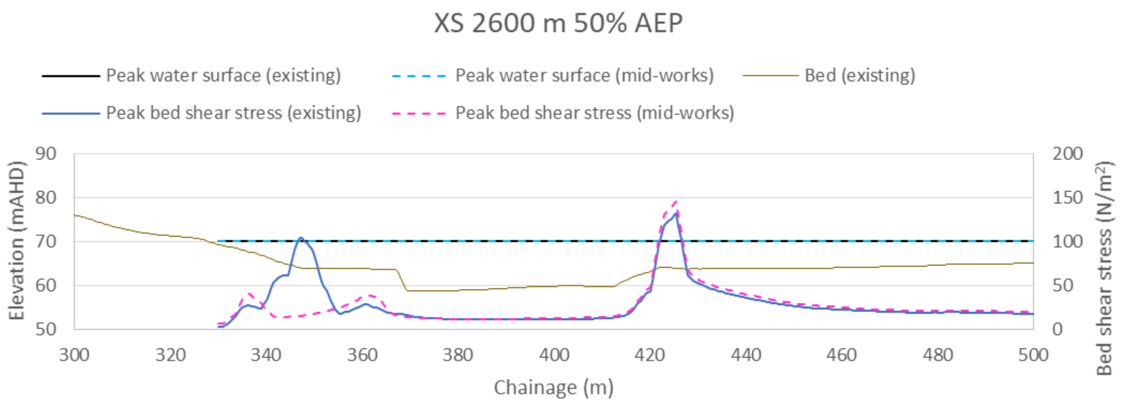

XS 2200 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
90
80
70
60
50
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)
600
500
400
300
200
100
0
Bed shear stress (N/m²)

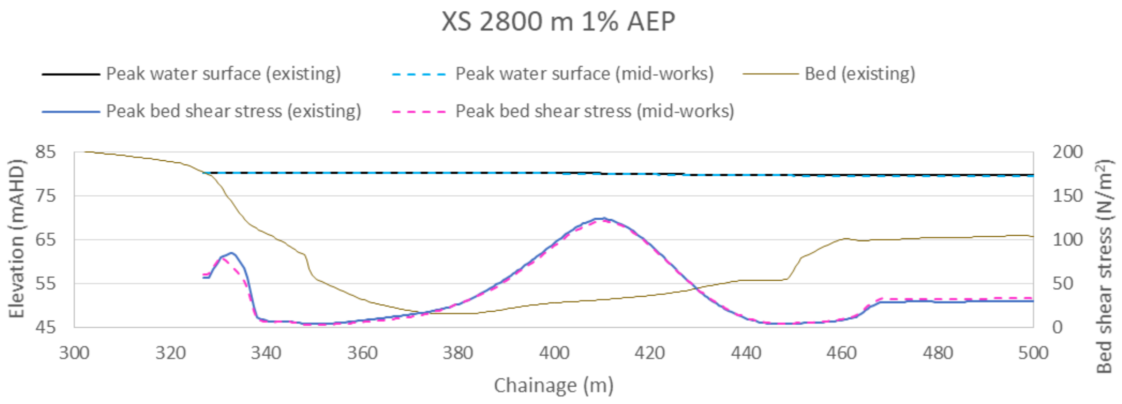

XS 2200 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
90
80
70
60
50
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)
25
20
15
10
5
0
Bed shear stress (N/m²)

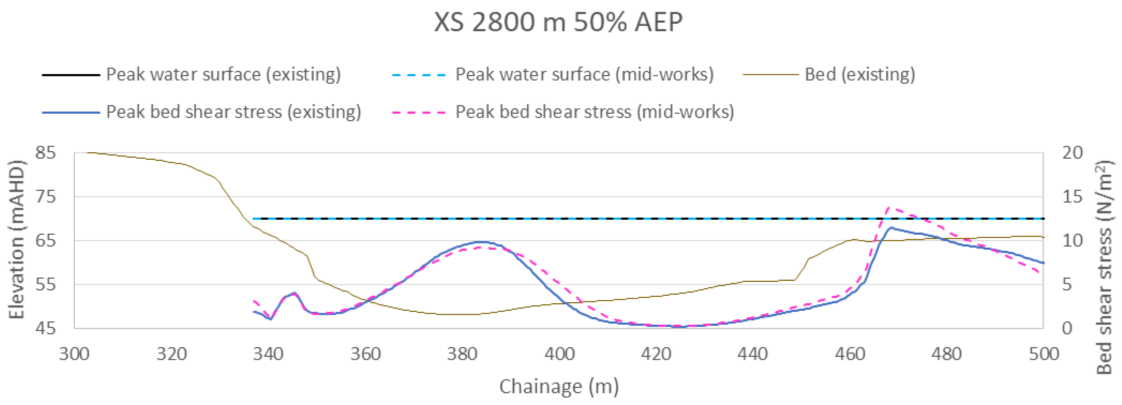

XS 2400 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
85
80
75
70
65
60
55
600
500
400
300
200
100
0
Bed shear stress (N/m²)
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)

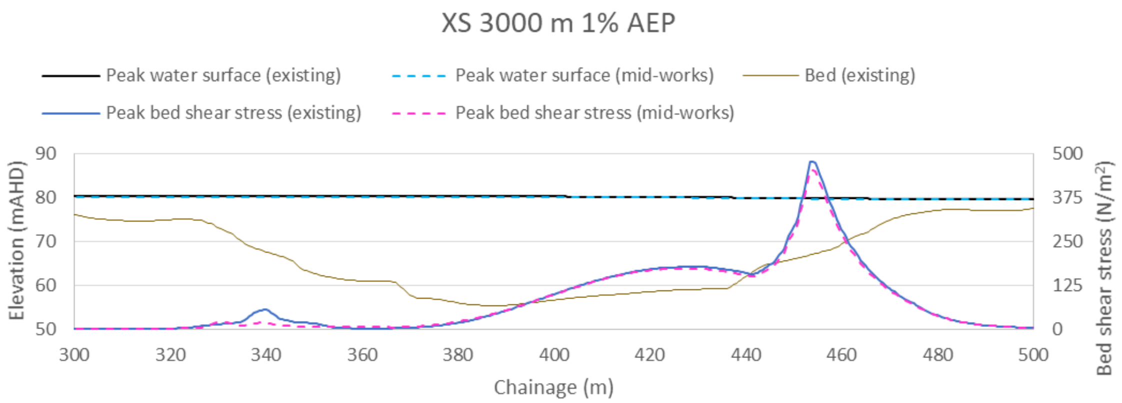

XS 2400 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
85
80
75
70
65
60
55
150
100
50
0
Bed shear stress (N/m²)
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)

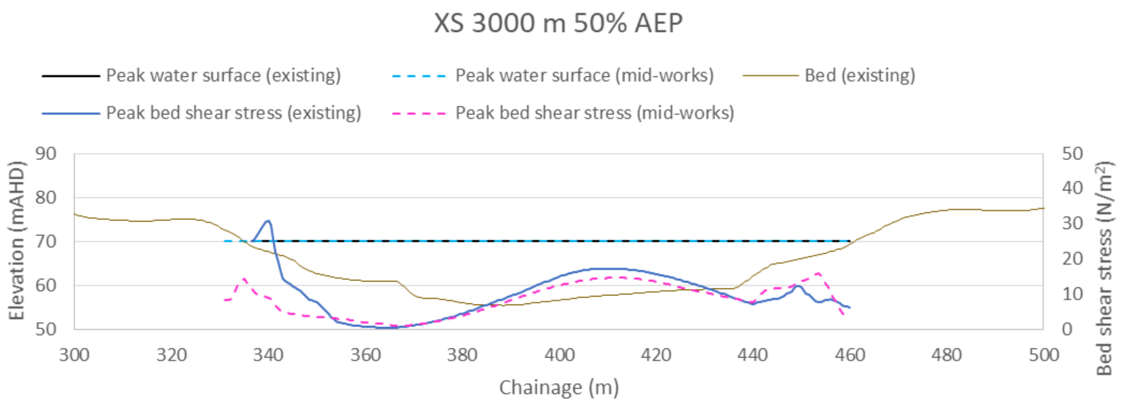

XS 2600 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
90
80
70
60
50
800
600
400
200
0
Bed shear stress (N/m²)
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)

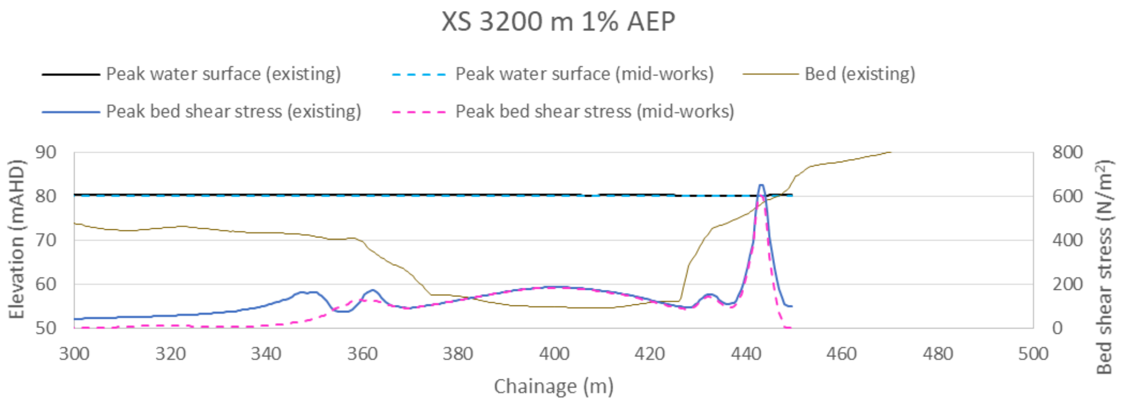

XS 2600 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
90
80
70
60
50
200
150
100
50
0
Bed shear stress (N/m²)
300
320
340
360
380
400
420
440
460
480
500
Chainage (m)

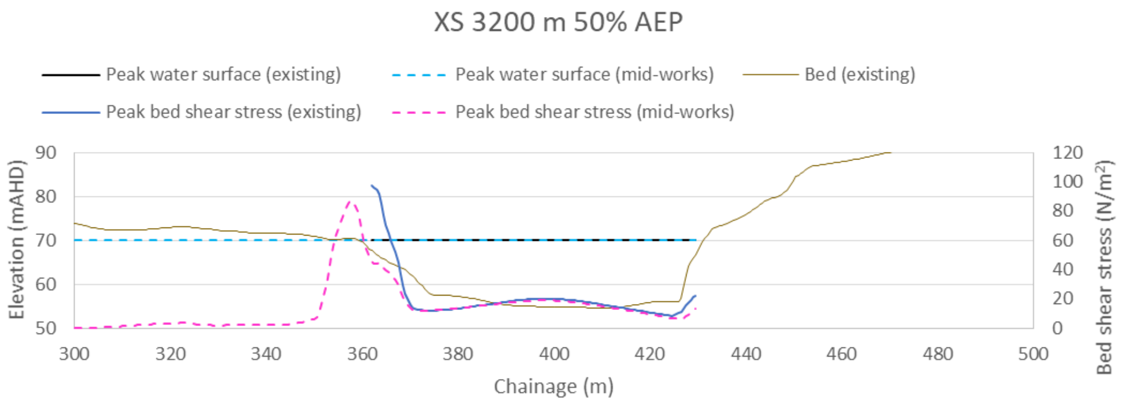

XS 2800 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

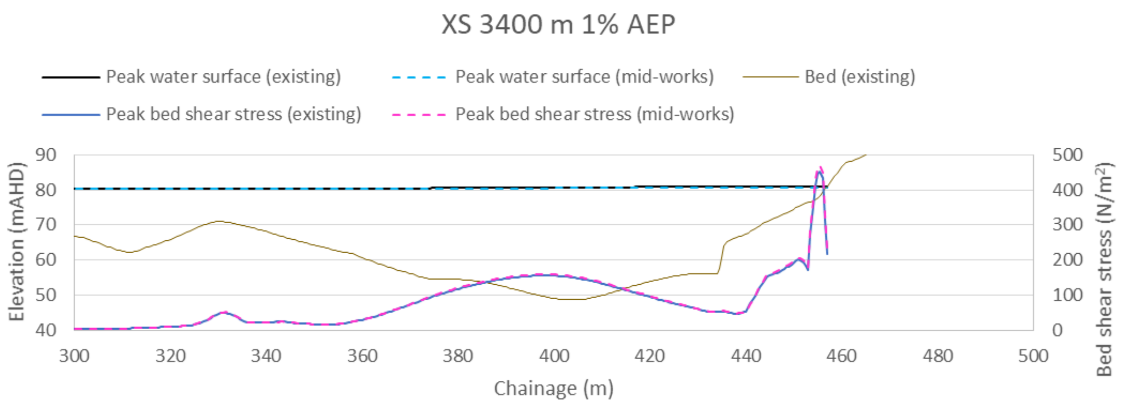

XS 2800 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

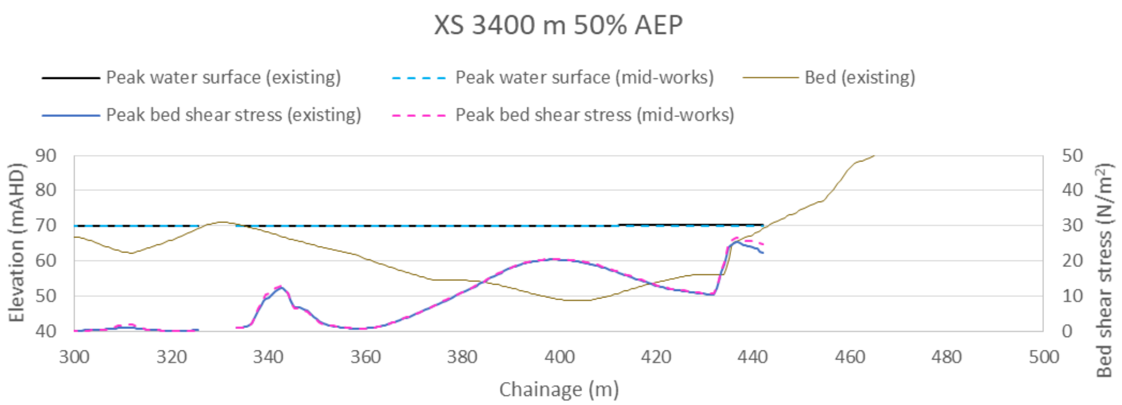

XS 3000 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

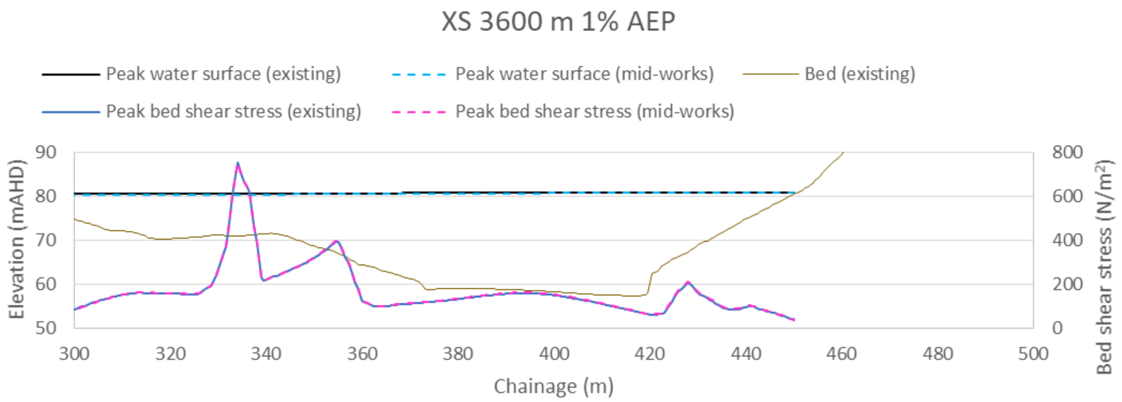

XS 3000 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

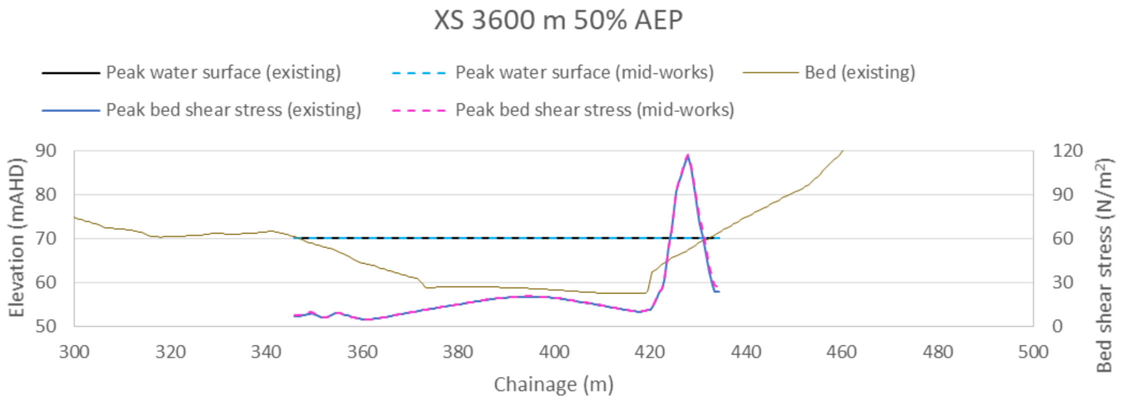

XS 3200 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

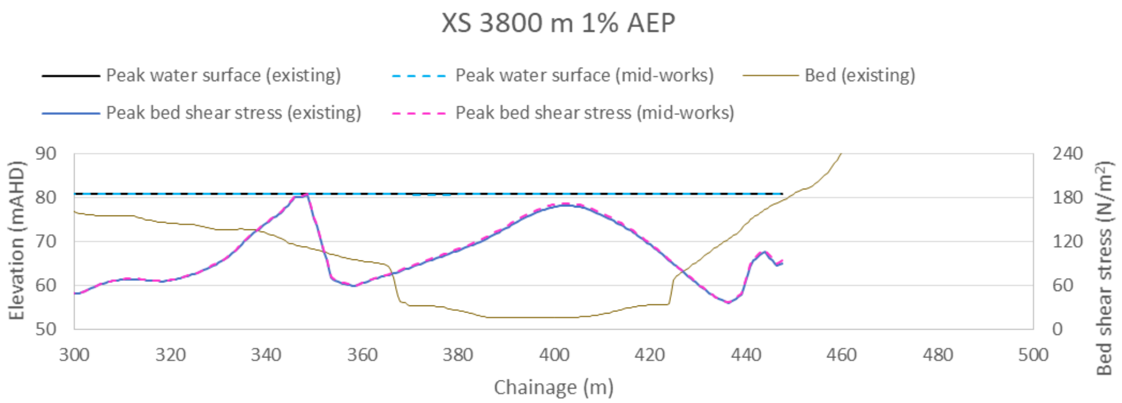

XS 3200 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

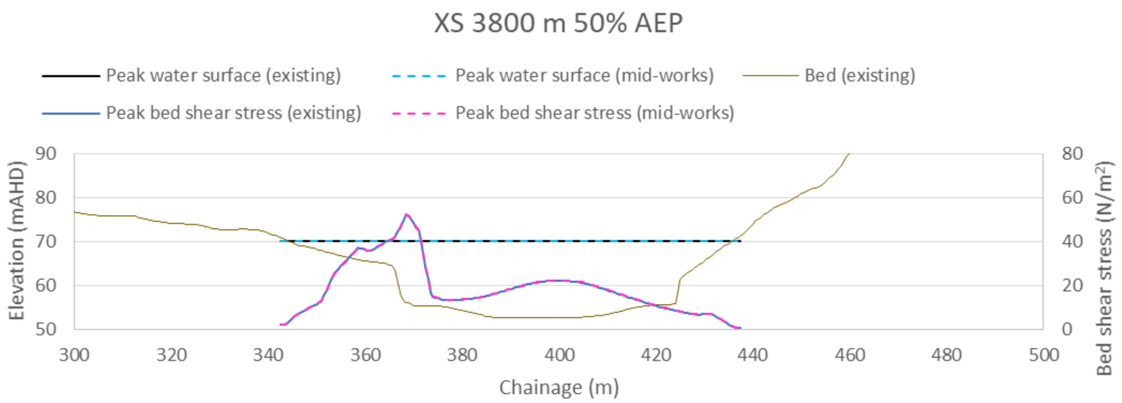

XS 3400 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

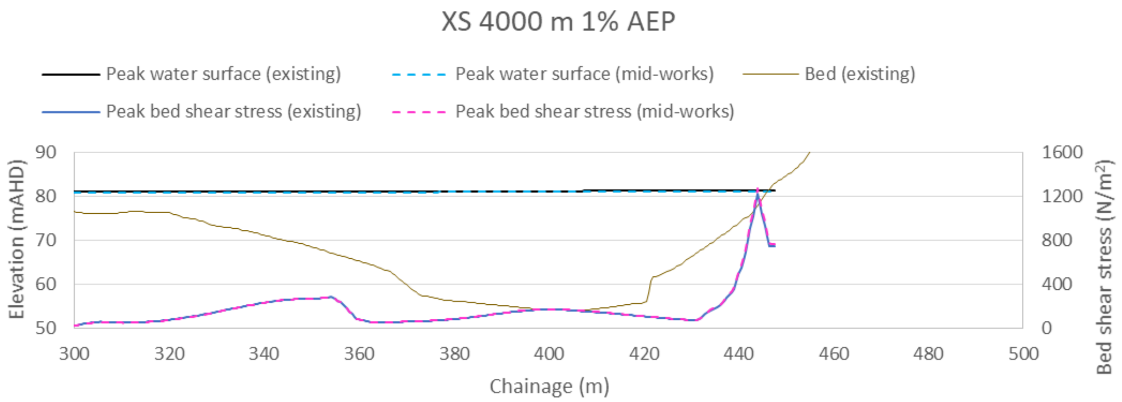

XS 3400 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

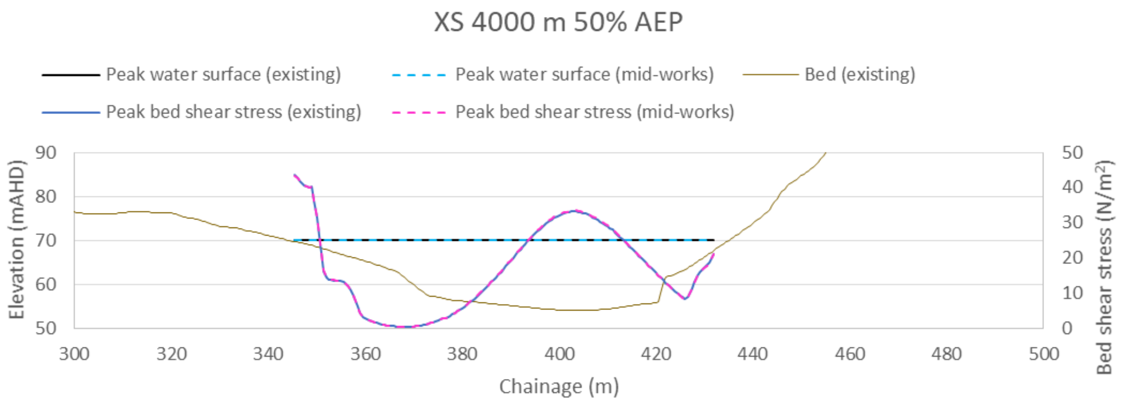

XS 3600 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

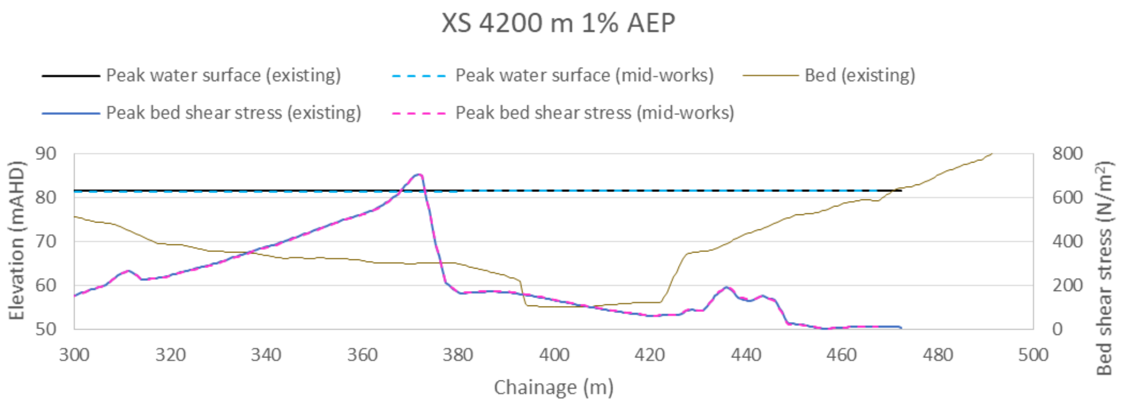

XS 3600 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

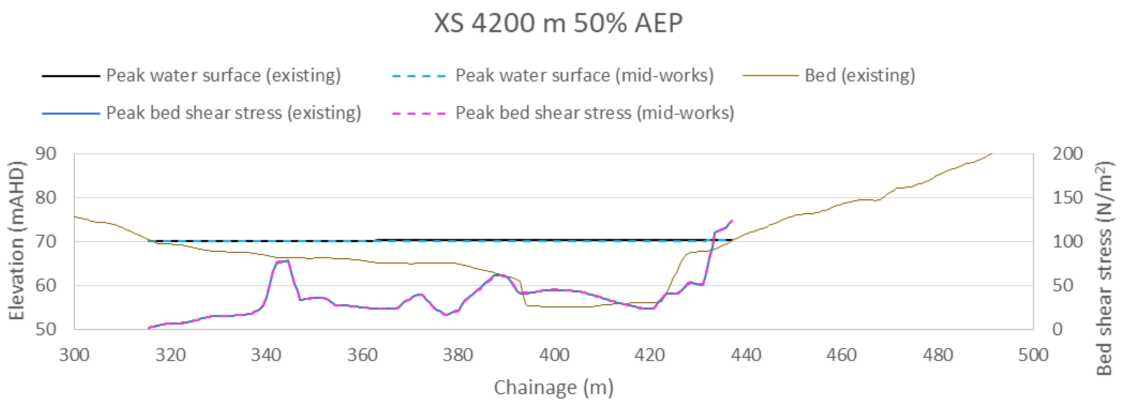

XS 3800 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

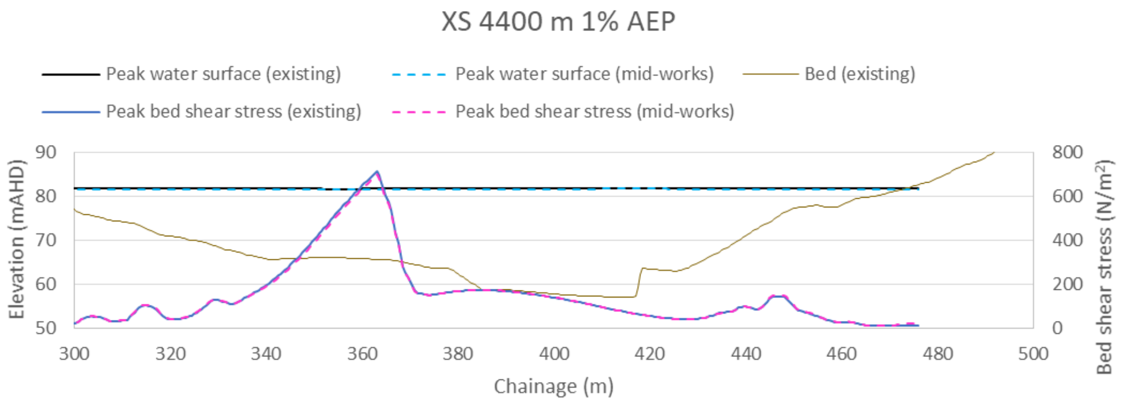

XS 3800 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)

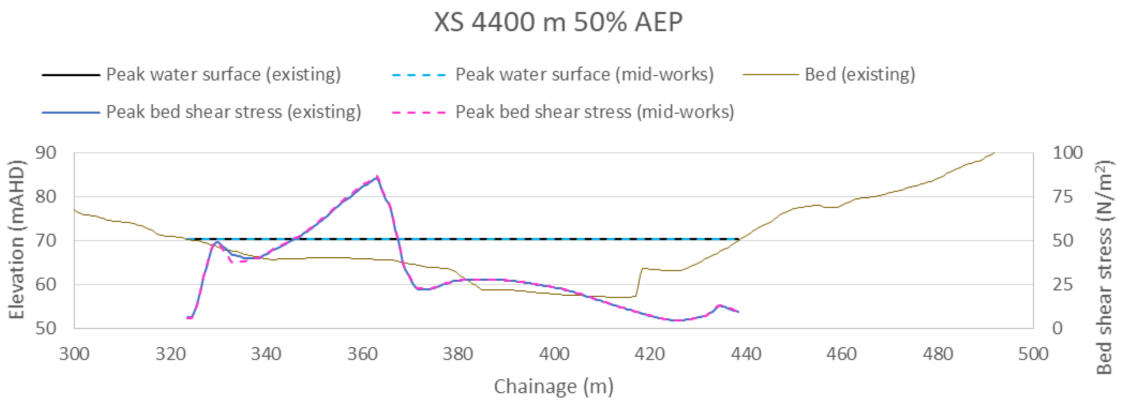

XS 4000 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Chainage (m)
Bed shear stress (N/m²)

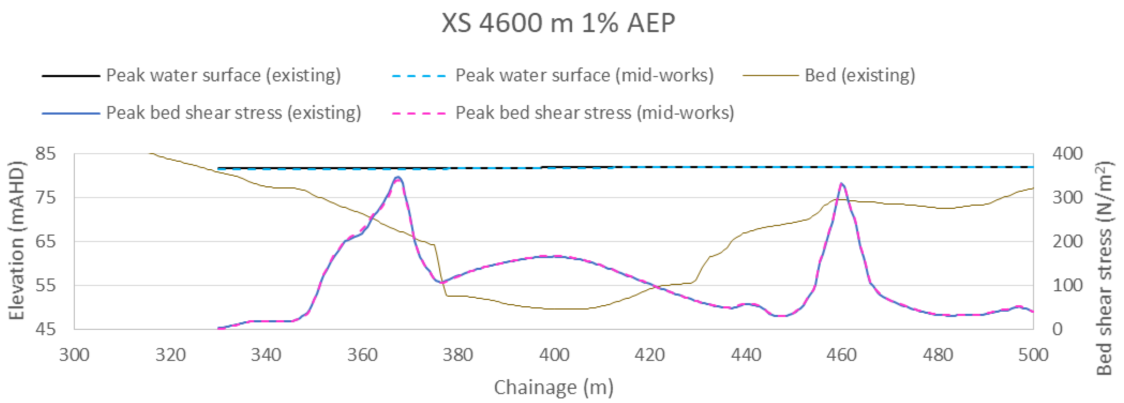

XS 4000 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Chainage (m)
Bed shear stress (N/m²)

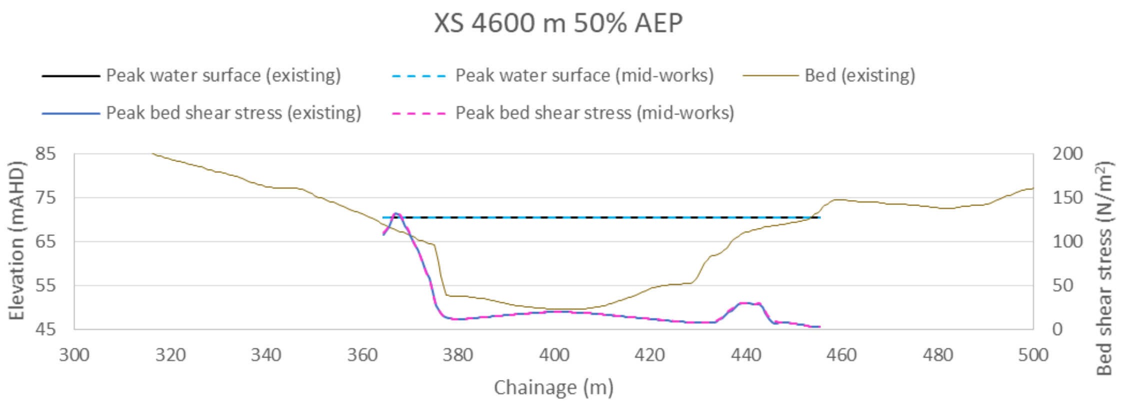

XS 4200 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Chainage (m)
Bed shear stress (N/m²)


XS 4200 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Chainage (m)
Bed shear stress (N/m²)


XS 4400 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)


XS 4400 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)


XS 4600 m 1% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)


XS 4600 m 50% AEP
Peak water surface (existing)
Peak water surface (mid-works)
Bed (existing)
Peak bed shear stress (existing)
Peak bed shear stress (mid-works)
Elevation (mAHD)
Bed shear stress (N/m²)
Chainage (m)