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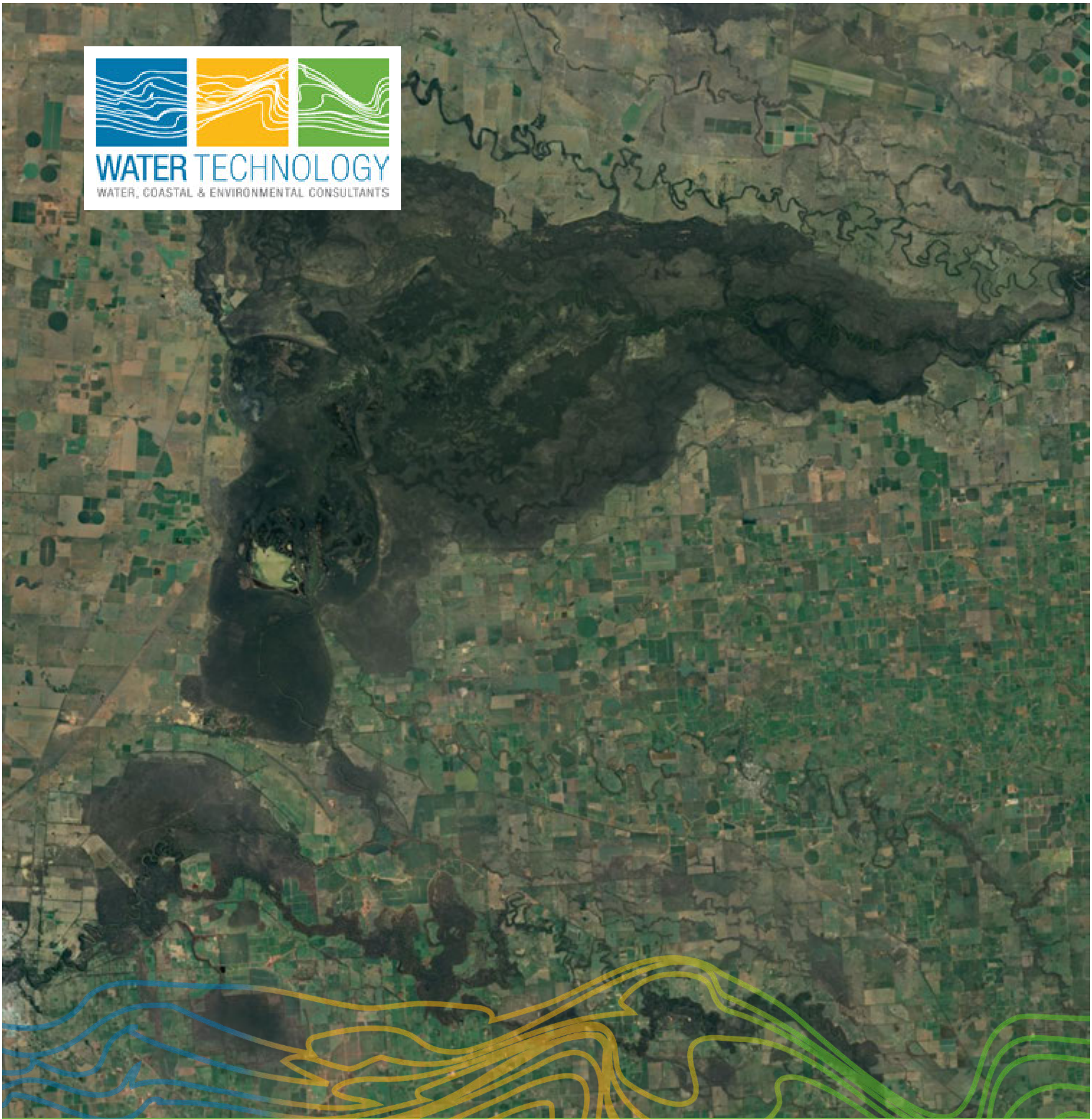

Technical Report

Barmah Choke Channel Capacity and Geomorphic Investigation

Murray Darling Basin Authority

22 April 2020

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EXECUTIVE SUMMARY

Introduction

Water Technology was commissioned by the Murray Darling Basin Authority (MDBA) to undertake a geomorphic and hydraulic investigation into the apparent channel capacity changes and conveyance loss within the Barmah Choke. This report has been prepared by Water Technology on behalf of the MDBA and forms the draft technical reporting for the investigation.

The Barmah Choke represents a unique reach of the River Murray system. As the name implies, the Barmah Choke is a narrow section of the Murray River that passes through the Barmah- Millewa Forest. While it is generally referred to as the Barmah Choke, it comprises three key flow constriction points, namely the Tocumwal Choke, the Barmah Choke and the Edward Choke. Collectively, the Barmah Choke system presents the greatest flow restriction in the Murray River (MDBA, 2019).

The Barmah Choke also presents numerous environmental and operational challenges. The MDBA acknowledge that maintaining the structural integrity of the banks of the River Murray as it flows through the Barmah Choke is a critical component in the ability of MDBA to deliver water in a timely manner to downstream water users in NSW, Victoria and South Australia.

To fulfil irrigation and other downstream demands, regulated flows are often at or close to the operating limit through the Barmah Choke for several months. Any additional water released from Yarrawonga Weir can lead to overbank flow into the Barmah-Millewa forest or require forest regulators to be opened. This can occur following 'rainfall rejections' of irrigation orders from Lake Mulwala. In the past, prolonged flooding has caused waterlogging in parts of the forest, listed as a RAMSAR wetland, to its detriment.

Concerns about the constraints posed by the limited capacity through the Barmah Choke have been compounded by the belief that the capacity has been declining over recent years. It is generally thought that channel capacity of the Choke has reduced from 10,600 ML/day in 1996 to below 9,500 ML/day (downstream from Yarrawonga Weir) at present. This is based on a range of different sources of information, including:

- Specific water surface gauge heights at Picnic Point.
- Periodic flow trials conducted by the MDBA.
- An apparent reduction in commence to flow rates for several small effluent creeks along the Choke into Moira Forest.
- An increased frequency of overbank flow events resulting from releases from Yarrawonga that previously would have been accommodated within the channel.

Recent observations from relevant managers across several stakeholder Authorities and Agencies have also highlighted other associated concerns, including:

- That there is extensive on-going erosion of both riverbanks and levees. In some cases, this has led to breakouts where water escapes into the forest floodplains, often inundating large areas at unseasonal times of the year and causing implications for maintaining the already limited channel capacity.

Potentially increased rates of sediment deposition occurring within the reach, combined with a number of trees that have fallen into the river. There is a concern that these processes can lead to increased rates of bank erosion, increase in hydraulic roughness and potentially a reduction in channel capacity.

With reference to the project context, the overall objective that guided the Barmah Choke Channel Capacity Investigation and Geomorphic Investigation is as follows:

To maintain channel capacity through the Barmah Choke to be able to meet the requirements of downstream water users in NSW, Victoria and South Australia.

The key questions to be answered through the investigation are as follows:

1. What is the current geomorphic condition of the reach?
2. What are the threatening processes occurring within the reach?
3. Are these processes currently affecting channel capacity?
4. What is the magnitude and trajectory of change of these threatening processes?
5. What are the potential management options, opportunities and costs associated with maintaining current channel capacity?

The study area includes the Murray River between the offtake of Bullatale Creek and Barmah.

Method and Data Limitations

A comprehensive review of available data was undertaken in the first phase of this project. This was carried out to assess the comparability between data sets so as to identify sources of error and to better understand the limitations on any interpretation of this data. During this process data manipulation was required to bring data sets together and to assess their comparability. Channel morphology data is the most important data set to answer any channel capacity change questions like those posed for this study. These data sets allow us to measure channel characteristics such as depth, width, channel cross-sectional area and channel slope. Whereas the new bathymetric data (2018) is extremely useful for assessing current condition and channel morphology, many issues were identified when trying to compare this data with previously captured survey cross-sections.

Results

Within the study area, there are two dominant reaches based on fluvial processes. The upstream section (essentially upstream of Picnic Point) is laterally migrating with some long anabranches. That is, the channel network has naturally evolved through the migration of meander bends and development of anabranches. Downstream of this section, between Picnic Point and Barmah, is not laterally migrating. This reach appears to be widening, with continuous erosion along banks on both sides of the channel, typical of boat wash induced erosion.

Anthropogenic pressures are interacting with natural processes to influence erosion rates in this reach of the Murray River. Influences on the physical form of the river are:

- River regulation.
- Floods (the frequency of which has been modified by the presence of regulating structures upstream).
- De-snagging.
- Changes in riparian vegetation.
- Boat wash.

The current bank condition of the reaches observed in this study was poor, largely due to the vertical upper bank scarps, likely induced through a combination of river regulation and boat wash. This vertical scarp often extended behind stands of in-channel vegetation (macrophytes).

The Murray River is, in general, a very low gradient watercourse and the study reach at the Barmah Choke is no different. Only minor variations in bed-grade were observed; with the top three slope-delineated reaches essentially the same grade (±0.00001 m/m). The Narrows are identifiable as steeper than those upstream, however, they would still be classed as low grade.

Due to the very low gradient and cohesive bank material, the Murray River is a very slow-moving system. As such channel planform changes were minor and limited almost entirely to the upstream laterally migrating section, as expected. Changes were assessed between 2001 and 2016. Changes in The Narrows were not observed over this period, whereas some minor lateral migration is noted in the upper reaches. Aerial photographic assessment did not provide any observable changes.

Channel bedform can be an indicator of bed load and hydraulic energy. In the absence of high-resolution data on sediment type distribution within the channel, qualitative assessment of the morphology of bedform features provides us with a proxy for interpretation. It is clear that bedform is very different between the upper laterally migrating reach and The Narrows. The upstream reach is dominated almost entirely by an undulating channel bed composed of large ripples and dunes, indicative of a sandy bed load in a low energy environment, where sands are transported downstream by rolling rather than saltation. Very little submerged woody debris was observed in this reach indicating that this has been buried by sand or removed. In contrast, within The Narrows, the bedform is more complex with irregular bedform consisting of scour pools and ledges with submerged partially buried woody debris and a smooth bed profile indicative of scour and erosion rather than a mobile bedload.

As a general trend, channel width decreases in a downstream direction, with the minimum channel width measured within The Narrows as expected. Channel width then increases rapidly beyond The Narrows towards Barmah. Despite the very minor changes in channel slope, there is some discernible correlation between channel slope and width.

Average channel depth, derived from the 2017 bathymetric data, shows an observable trend of depth decreasing in a downstream direction. The depth then appears to increase slightly within the vicinity of The Narrows which would be expected due to its steeper and narrower morphology. However, the data is distorted in the area where only partial bathymetry is available. Regardless, the data indicates that The Narrows are both narrower and shallower, as expected. These characteristics are in-line with the bedform assessment with a wider lower energy environment in the upstream laterally migrating section and a narrower and relatively higher energy environment in The Narrows.

The data show some trend of channel capacity reduction in the upper reaches. Many of the comparisons show changes below 5% which is likely within the error introduced by manipulating the cross sections and the varying methodologies used to obtain the survey. Furthermore, only two of the 14 cross-sections show a consistent trend across the time periods. It is common for the cross-sectional area to fluctuate between different survey dates.

Bed material sampling was undertaken at a late stage in the project and at the time this report was written no analysis had been carried out. All samples consisted of medium to coarse sand. Whereas it appears that the material within The Narrows is slightly finer than the sediment upstream, no real trend can be discerned without particle size analysis. Bank material where observed consisted of fine sandy silts and clays.

Hydraulic modelling was undertaken under two flow scenarios. The 6000 ML/day scenario is representative of flows that are entirely within the channel (no over bank flow) and the 9500 ML/day approximately represents bank full.

For the 6000 ml/day scenario, within the upper reaches, velocities are consistently around 0.4 m/s, whereas The Narrows experience around 0.6 m/s and up to 1 m/s. Peaks in velocity are also observed at the Edwards River offtake. Bed Shear Stress for this scenario follows a similar trend with very low shear stresses of around 1.6 N/m^2, jumping up to 5 and 6 N/m^2 in The Narrows. Whereas these shear stresses are quite low, the difference does represent a likely threshold change in terms of the entrainment threshold for coarse sands.

The modelling results for the 9500 ML/day scenario show slightly higher velocities within the upper reaches compared to those of the 6000 ML/day scenario with velocities around 0.5 m/s. However, downstream of the Edwards River offtake the velocities are almost identical. This is the same for bed shear stress with values slightly higher than those in the 6000 ML/day scenario upstream of the Edward River offtake and similar values downstream. This may be due to the constriction of The Narrows being the major hydraulic control.

Discussion

The results from this study provide information into the condition of the Murray River in the Barmah Choke area and some insight into the processes occurring within the channel. However, they only provide part of the story and more information is required to confidently answer some of the key questions with regards to channel capacity and conveyance. The key questions are discussed below.

What is the current geomorphic condition of the reach?

The reach upstream of Picnic Point and the Edwards River offtake is in moderate condition. The reach is dominated by lateral migration. This is a very low energy environment with a coarse sandy bedload (likely large volumes), where the channel is slowly moving through the extension of meander bends through erosion, with deposition occurring on the corresponding inside bend. The channel in this reach has gone through and will continue to go through phases of channel lengthening (through the meander extension process) and channel shortening (through the meander cut-off process). Bank erosion throughout this reach is common but for the most part associated with the processes mentioned above. These are likely exacerbated by anthropogenic activities such as boating and river regulation.

The downstream reach between the Edwards River offtake and Barmah is in poor condition. This is a higher energy reach than the reach upstream of the Edwards River offtake, albeit still very low energy when compared to Australian rivers in general. This reach has a slightly finer sandy bedload, however bedform indicates that this reach is less dominated by sand. Bank erosion in this reach is occurring on both sides of the channel, indicating channel widening (although cross section analysis shows only minor widening). The eroded bank profile is typical of boat wash induced erosion. The profile also includes a uniform notch typical of erosion through relatively stable water levels in regulated rivers. Riparian vegetation where present is in good condition albeit sparse. The vegetation is also threatened by the channel widening process, where trees on the bank are undermined and collapse. Like the upstream reach, bank face or/and in channel vegetation in this reach is notably absent, apart from isolated areas of macrophytes.

What are the threatening processes occurring within the reach?

The key geomorphic processes occurring within the study reach are lateral migration and channel widening. Lateral migration is a natural process and not seen as a threatening process to waterway health, whereas channel widening, in this scenario, is largely an anthropogenically forced process. Channel widening could become a problem as it often accompanied by channel capacity reduction through a reduction in energy and subsequent aggradation of the bed, however, such aggradation was not identified in this study. These processes are both exacerbated by the relative stable water levels associated with river regulation.

Erosion of the riverbanks within the study area will contribute fine sediment to the reach with bank materials consisting of fine sandy silts and clays. This suggests that a majority of bed material within both reaches in not locally derived. However, the process that may threaten hydraulic conveyance in the upper reach is the erosion of and breaching of levee features that would have otherwise increased conveyance at high flow.

While there is a general understanding that vessel wash contributes to riverbank erosion, at this stage the precise contribution to erosion in this reach from boating activity remains unknown. Many of the erosional features in the reach are typical of boat wash, indicating that boating activity may play a significant role, at least in localised areas. The presence of these erosional features, in particular elongated ledges rising to vertical scarps, results in a common bank profile often observed in other high boat use areas, such as in the vicinity of Bundalong (MDBA 2017) and indicate an accelerated rate of upper bank retreat.

The combined effects of both river regulation and boating are likely to be compounded through the interaction of both processes. This is particularly true where boating activity is occurring during sustained high flow periods where the water surface intersects with the vertical upper bank profile. Therefore, it is likely that present boating activities or intensities are unsustainable within the project reach particularly where vulnerable banks present a high risk of levee breaches (breakouts) occurring.

The only two viable options for managing the impacts of vessel wash are to regulate vessel operations or to implement measures to armour the banks. Any future management strategies and decisions related to dealing with vessel wash impacts in the reach should be based on sound scientific evidence and advice including collection of site-specific boat usage data.

Are these processes currently affecting channel capacity?

Channel capacity change within the study reach over period in which survey has been captured (1986 to 2017) vary significantly, with some cross-sections indicating capacity reductions and other indicating capacity increases. As discussed in Section 2.3.2, measuring channel capacity changes through cross section analysis, particularly at the resolution of data available for this study is not possible with any accuracy. This is particularly true given the nature of the river in this location and the expected changes to bedform. Despite the limitations associated with this data, there is some indication of minor channel capacity reduction occurring in the upstream reaches; however, only two cross-sections show a consistent trend in reduction over the four data capture dates, with the others simply showing a fluctuating cross-sectional area. This fluctuating channel cross-sectional area is consistent with the process described in Section 2.3.2, whereby the channel bedform is often reconfiguring, meaning that a reduction in channel cross-sectional area at one cross section is not necessarily an indication of reduction in channel cross-sectional area across a reach.

Whereas channel width has increased slightly within The Narrows over the period analysed in this study (LiDAR capture dates 2001 and 2016), channel depth cannot be assessed accurately in this section due to the absence of historic bathymetric data. The bedform assessment completed as part of this study suggests that the channel bed in The Narrows is not accreting and as such channel capacity in this section is not thought to be decreasing. Channel width in the upper reach of the study area has not changed significantly over the period analysed in this study (LiDAR capture dates 2001 and 2016). As such, if channel capacity in the upper reach is decreasing, it must be due to bed aggradation. As discussed above the bed material in this reach consists of coarse sands and differs greatly to any observed material within the riverbanks. As such the drivers that may be affecting channel capacity are not local and are a result of processes occurring outside this study area.

The only process occurring within the reach that could be affecting hydraulic conveyance is the erosion of and breaching of levee features that would have otherwise increased conveyance at high flow as discussed above. This process is the most likely to be a major influence on any loss of hydraulic conveyance.

It is noted that the Barmah Choke Study: Investigation Phase Report (MDBA, 2009), a hydrologically focussed report, concluded that there is no evidence of a general decline in hydraulic capacity within the Barmah Choke Reach that could be expected to continue into the future.

What is the magnitude and trajectory of change of these threatening processes?

The magnitude of bed aggradation in the upper reach cannot be quantified with the data currently available. It can be speculated that, if bed aggradation is occurring due to excess sandy material being slowly transported through the system, this may be a temporary issue (albeit likely long lasting). However, with no knowledge on the depth of this sand, its upstream longitudinal extent or even its source, it is not possible to establish a trajectory for this process. It is also important to note that we cannot even state with any confidence that channel capacity is decreasing to a point which threatens conveyance.

Similarly, the magnitude and impact of levee breaches on high-flow conveyance cannot be accurately assessed with the currently available data. It can be speculated that the trajectory for change from this process is likely to involve worsening as more breaches occur. However, with no high-resolution information on levee extent, levee height or breach regularity, it is not possible to identify a rate of bank retreat, frequency of levee breaches and thus magnitude of impact.

What are the potential management options, opportunities and costs associated with maintaining current channel capacity?

Channel Capacity

More data, analysis and investigation are required to first establish whether channel capacity is decreasing, the degree of reduction in channel capacity (if it's occurring) and the likely trajectory for change based on an investigation of the process. If excess sandy sediment from upstream of the study area is contributing to channel capacity reduction, additional bathymetric survey will be required to map the excess sediment, along with an investigation into potential sediment sources.

There are essentially four methods for managing excess sediment in any channel. These include reducing the sediment supply at the source, promoting sediment storage on the floodplain, accelerating sediment transport through the system or directly extracting sediment from the channel (Sims and Rutherford, 2017). Sims and Rutherford (2017) go on to point out that these are not necessarily mutually exclusive.

However, even with the additional information outlined above, and assuming a sediment source is identified, there will be a significant lag period (decades) between addressing the source of sediment (if it can be found) and any reduction in impacts at the Barmah Choke. Promoting sediment storage on the floodplain in this scenario is unlikely to provide any significant reduction in sediment within the channel due to the magnitude and thus infrequency of floods that would be required to move the sandy bedload out of the channel and onto the floodplain.

Accelerating sediment transport, in this area is not likely possible. As discussed in Section 4.4, bed shear stresses in this reach, even under the 9500 ML/day bank-full scenarios only reach between 1 and 2 N/m^2. As such, it is not likely possible to alter flows to a point where the threshold for entrainment of these sands is crossed (such as in The Narrows). Further hydraulic modelling, including a full calibration of the model used in this study, may see some increase in energy in this area.

This essentially leaves sediment extraction from the channel, which is unlikely to be palatable and will be required on a large scale to make any significant difference. Strategic sediment extraction areas within the study reach could see wide scale bed level lowering occur through the formation of head-cuts into the excess sand deposit. However, undertaking this option would require detailed knowledge on the thickness of the sand deposit and its longitudinal extent to ensure minimum impact to the Murray River. Additionally, such a study should consider the upstream and downstream implications to sediment transport processes and channel stability.

Levee Breaching and Conveyance Loss

More data and analysis are required in order to understand the impacts of such a process in detail. Survey of the entire levee on both sides of the creek would be required to gauge the impact accurately. We can, however, speculate as to the potential management options for such an issue. These management options could include:

- Repair and maintenance of the levee system on both side of the creek, and bank erosion mitigation to prevent further erosion.
- Construction of a new levee system further back from the river.

- Diverting flow around the problematic reach through a pipe or channel.
- Reducing high flow levels and extending their duration to prevent flow through the breaches and maintain conveyance.

The reach in question is long with multiple levee breaches. Erosion in this reach is occurring along very long sections of difficult to access riverbank, through naturally occurring processes. It would be extremely expensive to undertake erosion mitigation along this entire section of the river and would not be in the best interests of waterway health. Even if the breaches are specifically identified and addressed directly and locally, it is likely that more breaches would form as the channel migrates in other locations. Constructing a new levee at a distance from the river that would be less susceptible to future channel migration would allow for maintenance of conveyance albeit at a slightly reduced rate. However, this would be a very large undertaking and would have various detrimental impacts on the Barmah forest.

Piping or diverting flow through a secondary channel and bypassing this section of the Murray River is another option for maintaining flow conveyance to the downstream reaches. This would, again, be a very large undertaking and would have various detrimental impacts on the Barmah Forest. Piping flows would likely be a better option in terms of reducing losses; however, there are many channels (effluents) within the area which could be stabilised (sealed and / or excavated) to serve as a bypass for the required flow volumes. Bypassing the area where breaching is affecting delivery would reduce water escaping through the levee breaches by reduce flows through this. As such, various feasibility studies would be required to determine the optimal flow rate required and the effects of this on the area being bypassed (reduction in flows and impact to sediment transport capacity).

The final option is to reduce high flow levels and extend their duration to prevent flow through the breaches and maintain conveyance. This would have to be tested using a calibrated model and some survey of the existing breaches. This study should also be undertaken in context with the channel capacity and sediment behaviour assessments to ensure that and changes to high flow don't result in deposition or channel capacity reductions.

Summary and Recommendations

The results from this study provide information into the condition of the Murray River in the Barmah Choke area and some insight into the processes occurring within the channel. However, primarily due to the limitations associated with existing monitoring datasets, the key questions can only be partially addressed. As such, more information is required to answer some of the key questions with regards to channel capacity and conveyance.

Recommendations for management with reference to these limitations and the key questions identified in the study are summarised in the following sections.

Repeat Bathymetric Survey

The new bathymetric data (2018) is extremely useful for assessing current condition and channel morphology where it has been captured. Additionally, bathymetric survey will form a key dataset moving forward to quantify changes in bed and bank form, channel capacity and conveyance. It is recommended that additional bathymetric survey be undertaken. Future high-resolution bathymetric survey should include the following:

- Supplementing the existing bathymetric survey to cover the entire width of the channel at the same resolution as the previous survey from Yarrawonga Weir to the Cobb Highway Bridge at Echuca (Figure 6-1). It is important that the survey overlaps the previous full survey for at least 100m on the upstream and downstream extents to ensure accurate stitching of the two datasets.
- Utilising appropriate technology (dual band echo sounder) over the entire bathymetric survey extent (Yarrawonga Weir to the Cobb Highway Bridge at Echuca), measure the sand depth in the riverbed, thus

quantifying both the thickness of the sand deposit and its longitudinal extent across the bathymetric survey reach.

Extending the bathymetric survey extent will:

- Allow full analysis of the current project area and to establish a baseline condition.
- Assist in the identification of potential sediment source reaches and the longitudinal extent of sand deposits upstream of the project area.
- Assist in quantifying changes in bed and bank form, channel capacity and conveyance.

The capture of repeat high-resolution bathymetric survey nominally every five years, or following flood events will provide a more accurate, efficient and comprehensive method of quantifying channel change and area compared to historic monitoring techniques such as the capture of repeat cross sectional surveys at limited locations. Hence, it is not recommended that the capture of cross-sectional surveys be incorporated into any future monitoring.

Hydraulic Analysis

This study has facilitated the development of a 2D in-channel hydraulic model which incorporates the available bathymetric survey data. This hydraulic model forms a valuable tool to assess:

- Baseline conditions.
- Sensitivity to change associated with a number of influential variables.
- The effectiveness and sensitivity of potential management opportunities.

In addition, an existing independent floodplain hydraulic model has previously been established on behalf of the MDBA extending from the Tocumwal Gauge through to Barmah. This model was initially developed in 2002 and has been periodically updated to incorporate technological improvements in modelling software and higher resolution LiDAR. In addition, the model was calibrated against observations associated with the 2010 flood event.

Moving forward it is recommended that:

- The existing hydraulic model be updated to incorporate additional recommended bathymetric survey data from Yarrawonga Weir to Echuca to allow full analysis of the current project area and to establish a baseline condition (outlined in Section 6.2).
- The existing in-channel and floodplain hydraulic models be combined to provide a comprehensive in-channel/floodplain representation of the study area.
- The model be calibrated based on field measurements of water level and velocity to ensure the model accurately reflects existing conditions.

Potential Sediment Sources

This study has found that the bed load through the project area is likely to be derived from upstream sources and not from local sources within the Barmah Forest. As the Yarrawonga Weir likely presents an effective sediment trap it can be assumed that either:

- The potential sediment source reach is situated between the Yarrawonga Weir and the Barmah Forest, or from tributaries that enter the Murray River within the same reach.
- Alternatively, the sediment source is located upstream of the Yarrawonga Weir, but entered the Murray River prior to the construction of the Yarrawonga Weir.

A sediment source and sediment transport investigation could be undertaken to:

- Inform the potential sediment sources and if excess sandy sediment from upstream of the study area is contributing to channel capacity reduction through the Barmah Forest.
- Assess the effectiveness and sensitivity of potential management opportunities.

In undertaking this study, it is important to note:

- That the primary source of sediment may no longer be actively contributing sediment to the channel (e.g. historic mining activities).
- That in low energy river systems such as the Murray River, the sediment transport rates are very low. Resultantly, it may take decades for excess sandy sediment from upstream reaches to enter the Barmah Choke reach.
- Viable options to manage excess in-channel sediment loads are limited.

A sediment source and sediment transport investigation would be informed through:

- The capture of additional bathymetric survey (outlined in Section 6.2).
- Hydraulic modelling (outlined in Section 6.3).
- A particle size and sediment tracing analyses both within and upstream of the study reach.

Levee Breaching

The erosion and breaching of levee features within the Barmah Forest have the potential to reduce flow conveyance through the reach. However, the magnitude and impact of levee breaches on high-flow conveyance cannot be accurately assessed with the currently available data. That is, the LiDAR does not accurately represent either the levees or the breaches accurately.

Survey of the entire levee on both sides of the creek would be required to gauge the impact accurately. The levee survey could then be incorporated into the hydraulic model to determine the implications of the levee breaches. It is noted that it may not be considered feasible to undertake survey over the entire reach due to the substantial extent. However, survey and investigation of known key problem areas could be undertaken as a priority.

Hydrology

The interpretation of flow rates and levels through the Barmah Forest are somewhat compromised by the Picnic Point gauge:

- Capturing water levels only.
- Being positioned between the Edward River and Gulpa River offtakes, which have the potential to influence river profiles.

It is recommended that a formal stream gauge or gauges, measuring both streamflow discharge and water level be established to assist with flow management and monitoring. The establishment of gauges upstream and downstream of the Barmah Choke would provide an accurate assessment of flow loss through the project area. This should be monitored over a whole season at a minimum.

Works Program

SITE BASED EROSION CONTROL WORKS

Large scale site-based management actions specifically aimed at managing flow capacity are not recommended within the study area on the basis that:

- It is not clear if channel capacity is decreasing at all, or to a point which threatens conveyance.
- The processes that may be affecting channel capacity are not local and are a result of processes occurring outside this study area.
- It would be a very large and expensive project to undertake large scale erosion mitigation along this entire section of the river due to:
  - The ubiquitous nature of bank erosion downstream of Picnic Point.
  - Lateral migration (the extension of meander bends through erosion, with deposition occurring on the corresponding inside bend (point bars)) being the dominant erosion process upstream of Picnic Point.
  - Access restrictions throughout the Barmah Forest.

Additionally, widescale intervention across the system may not only be unnecessary but also potentially harmful to river health in the long term.

Small scale bank erosion works may be undertaken where continued bank erosion threatens high value or strategic assets or areas (e.g. cultural heritage values, access tracks, levees, breakouts) and where access permits.

TARGETED SEDIMENT EXTRACTION

Targeted sediment extraction has been identified as the only management solution that is likely to have any immediate or substantial effect on bed aggradation. Sediment extraction activities should only be undertaken if channel capacity is concluded to be occurring to the point which threatens conveyance. Importantly, any sediment extraction activity would require detailed knowledge on the thickness of the sand deposit and its longitudinal extent to ensure minimum impact to the Murray River. Such a study should consider the upstream and downstream implications to sediment transport processes and channel stability.

FLOW DIVERSION

Piping or diverting flow through a secondary channel and bypassing this section of the Murray River is another option for maintaining flow conveyance to the downstream reaches. This would, again, be a very large undertaking and would have various detrimental impacts on the Barmah Forest. Piping flows would likely be a better option in terms of reducing losses; however, there are many channels (effluents) within the area which could be stabilised (sealed and / or excavated) to serve as a bypass for the required flow volumes. Bypassing the area where breaching is affecting delivery would reduce water escaping through the levee breaches by reduce flows through this. As such, various feasibility studies would be required to determine the optimal flow rate required and the effects of this on the area being bypassed (reduction in flows and this impact to sediment transport capacity).

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1 INTRODUCTION

1.1 Overview

Water Technology was commissioned by the Murray Darling Basin Authority (MDBA) to undertake a geomorphic and hydraulic investigation into the apparent channel capacity changes and conveyance loss within the Barmah Choke. This report has been prepared by Water Technology on behalf of the MDBA and forms the technical reporting for the investigation.

1.2 Project Context

The Barmah Choke represents a unique reach of the River Murray system. As the name implies, the Barmah Choke is a narrow section of the Murray River that passes through the Barmah- Millewa Forest. While it is generally referred to as the Barmah Choke, it comprises three key flow constriction points, namely the Tocumwal Choke, the Barmah Choke and the Edward Choke. Collectively, the Barmah Choke system presents the greatest flow restriction in the Murray River (MDBA, 2019).

The Barmah Choke also presents numerous environmental and operational challenges. The MDBA acknowledge that maintaining the structural integrity of the banks of the River Murray as it flows through the Barmah Choke is a critical component in the ability of MDBA to deliver water in a timely manner to downstream water users in NSW, Victoria and South Australia.

To fulfil irrigation and other downstream demands, regulated flows are often at or close to the operating limit through the Barmah Choke for several months. Any additional water released from Yarrawonga Weir can lead to overbank flow into the Barmah-Millewa forest or require forest regulators to be opened. This can occur following ‘rainfall rejections’ of irrigation orders from Lake Mulwala. In the past, prolonged flooding has caused waterlogging in parts of the forest, listed as a RAMSAR wetland, to its detriment.

Concerns about the constraints posed by the limited capacity through the Barmah Choke have been compounded by the belief that the capacity has been declining over recent years. It is generally thought that channel capacity of the Choke has reduced from 10,600 ML/day in 1996 to below 9,500 ML/day (downstream from Yarrawonga Weir) at present. This is based on a range of different sources of information, including:

- Specific water surface gauge heights at Picnic Point.
- Periodic flow trials conducted by the MDBA.
- An apparent reduction in commence to flow rates for several small effluent creeks along the Choke into Moira Forest.
- An increased frequency of overbank flow events resulting from releases from Yarrawonga that previously would have been accommodated within the channel.

Recent observations from relevant managers across several stakeholder Authorities and Agencies have also highlighted other associated concerns, including:

- That there is extensive on-going erosion of both riverbanks and levees. In some cases, this has led to breakouts where water escapes into the forest floodplains, often inundating large areas at unseasonal times of the year and causing implications for maintaining the already limited channel capacity.
- Potentially increased rates of sediment deposition occurring within the reach, combined with a number of trees that have fallen into the river. There is a concern that these processes can lead to increased rates of bank erosion, increase in hydraulic roughness and potentially a reduction in channel capacity.

1.3 Project Objectives and Scope

With reference to the project context, the overall objective that guided the Barmah Choke Channel Capacity and Geomorphic Investigation is as follows:

To maintain channel capacity through the Barmah Choke to be able to meet the requirements of downstream water users in NSW, Victoria and South Australia.

The key questions to be answered through the investigation are as follows:

1. What is the current geomorphic condition of the reach?
2. What are the threatening processes occurring within the reach?
3. Are these processes currently affecting channel capacity?
4. What is the magnitude and trajectory of change of these threatening processes?
5. What are the potential management options, opportunities and costs associated with maintaining current channel capacity?

The study area includes the Murray River between the offtake of Bullatale Creek and Barmah (Figure 1-1), although focuses on the reach downstream of Picnic Point.

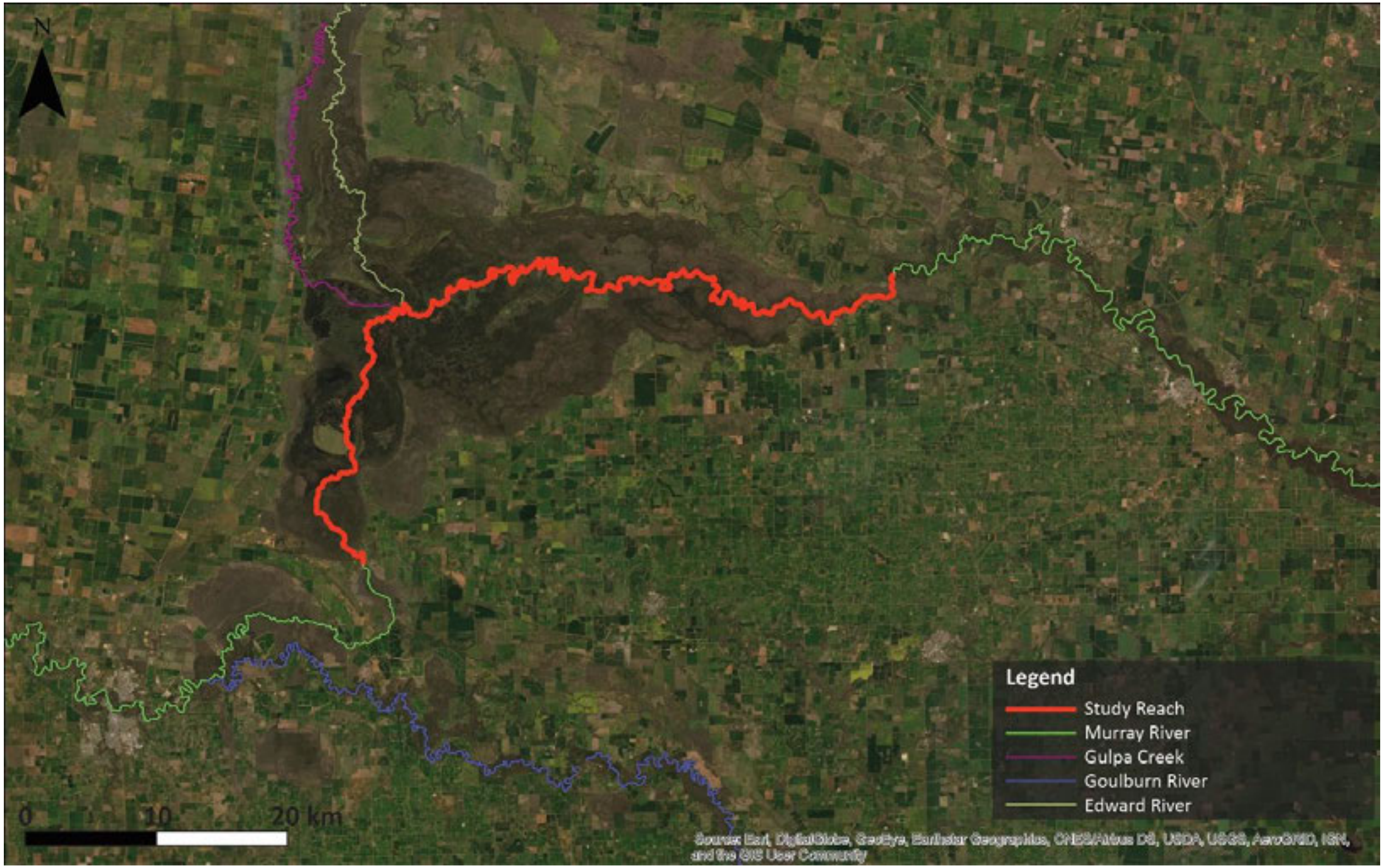

FIGURE 1-1 STUDY AREA.

2 DATA AND LIMITATIONS

A comprehensive review of available data was undertaken in the first phase of this project. This was carried out to assess the comparability between data sets so as to identify sources of error and to better understand the limitations on any interpretation of this data. During this process data manipulation was required to bring data sets together and to assess their comparability. Data sets assessed as part of this study include:

- Topographic Data:
  - 2001 LiDAR (1 m resolution).
  - 2007 LiDAR (5 m resolution).
  - 2017 LiDAR (1 m resolution).
- Aerial Imagery:
  - 2007.
  - 2009.
  - 2013.
  - 2015.
  - 2017.
- Channel Morphology Data:
  - 1986 Channel Cross-Sections.
  - 1996 Channel Cross-Sections.
  - 2006 Channel Cross-Sections.
  - 2018 Bathymetric Survey.

The following sections outline the results of this assessment and lists the limitations associated with each data set.

2.1 Topographic Data

All three LiDAR data sets proved useful for a high-level assessment of channel planform changes over the data capture period. However, the 2007 LiDAR data set was captured at a far lower resolution than the 2001 and 2017 data sets and as such cannot be used to precisely assess top of bank alignment. Topographic data acquired through LiDAR is also unable to capture elevations below the water and as such is not useful for assessing channel morphology.

Despite the 2001 and 2017 LiDAR data sets being of a sufficient resolution to identify the planform top of bank alignment, any such measurement of mapping of these alignments is likely to have an error of ± 0.5 m (due to the 1 m resolution). Systems like the Murray River are very slow moving and therefore in many circumstances any lateral movement measured over the data capture period (16 years) is likely to be within that error. In these circumstances, it is not possible to make any accurate conclusion on the magnitude of lateral movement of the channel.

The resolution of the LiDAR also makes it extremely difficult to map the natural levees along the channel, or the breakouts. These levee features are very subtle features along a somewhat longitudinally variable floodplain surfaces. As such, the resolution of the available LiDAR data sets is not sufficient to map or assess these features remotely.

2.2 Aerial Imagery

Whereas, several aerial imagery data sets are available, using these data sets to quantify any kind of channel changes, other than qualitative observations, is notoriously difficult. There are several reasons for this. Firstly, aerial imagery must be orthorectified (stretched) in order to align images from separate capture dates. This process is not often accurate enough over large areas to measure changes. This is particularly so for changes as minor as we expect in this system. Secondly, even if the orthorectification process did produce a precise image stretch, riparian vegetation often obscures the top of bank, making measurement impossible.

2.3 Channel Morphology Data

Channel morphology data is the most important data set to answer any channel capacity change questions like those posed for this study. These data sets allow us to measure channel characteristics such as depth, width, channel cross-sectional area and channel slope. Whereas the new bathymetric data (2018) is extremely useful for assessing current condition and channel morphology, many issues were identified when trying to compare this data with previously captured survey cross-sections. These issues are identified and discussed below in sections 2.3.1 and 2.3.2.

2.3.1 Bathymetry

The current (2018) bathymetry is incomplete with most of the focus reach (The Narrows) represented only as partial bathymetry (a strip of data down the middle of the channel). This makes it impossible to determine maximum depth (and thus channel slope) or channel cross sectional area. The data set also has gaps where no bathymetry is recorded. A map of bathymetric survey extent is shown in Figure 2-1 with an example of missing and partial data shown in Figure 2-2.

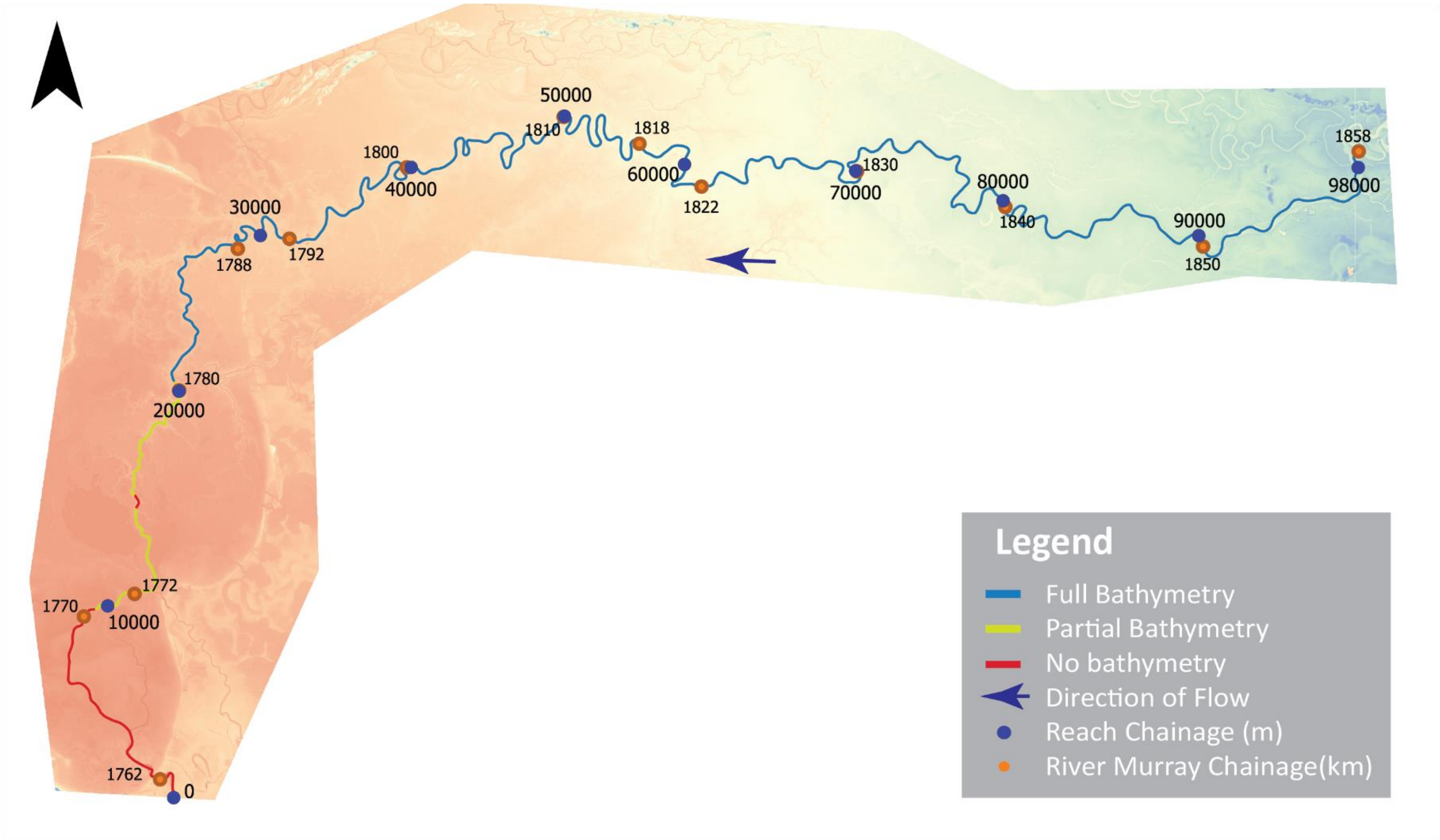

FIGURE 2-1 MAP OF BATHYMETRIC SURVEY EXTENT, RELATIVE TO BOTH REACH CHAINAGE AND RIVER MURRAY CHAINAGE.

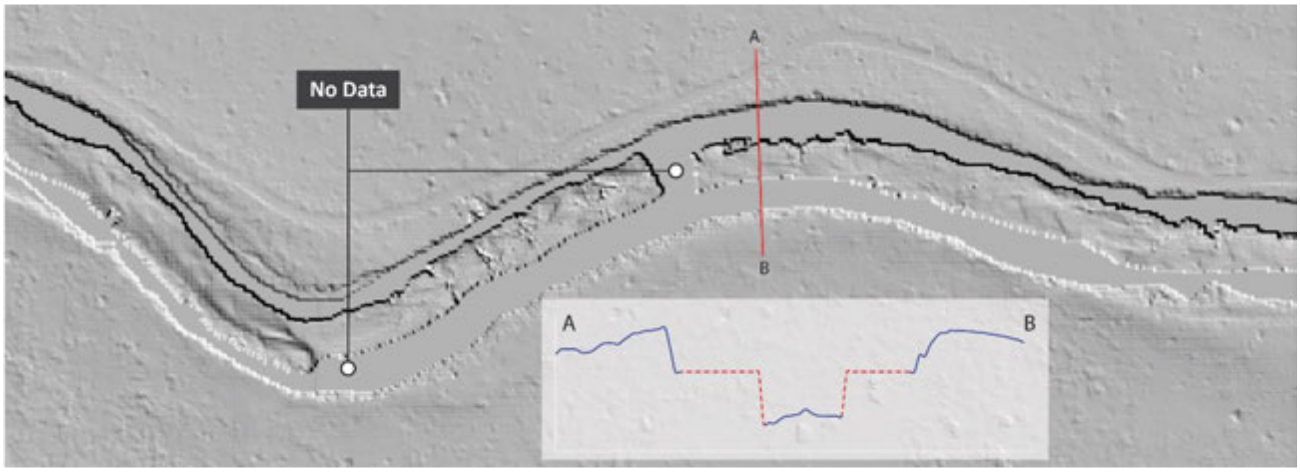

FIGURE 2-2 MISSING AND PARTIAL BATHYMETRY.

2.3.2 Cross Section Data

The methodology used to acquire the historic surveyed cross-section data (1986 and 1996) does not allow for precise comparison to more current data (2006 or LiDAR). On average, cross-sections are taken every 6km. These historical cross sections were taken as distance and height, from a known location (trees[1]), whereas the more recent data consists of coordinates and elevation. Even the 2006 cross-sections are not particularly well aligned and require manual adjustment to align landscape features. These inconsistencies and the need for manual alignment introduce a high degree of error meaning that precise measurement and interpretation is not possible in most circumstances. This is particularly so in such a slow-moving system.

Finally, cross-sectional data has inherent limitations when assessing channel capacity due to the nature of the fluvial system, whereby the channel bedform is often moving and as such reconfiguring. This means that channel expansion, through bed lowering at one cross section is not necessarily an indication of channel expansion across a reach. It may only reflect the crest of a ripple moving past the cross-section location as shown in Figure 2-3.

[1] Benchmarks were not always relocatable and sometimes moved slightly for a range of reasons (including swelling/ shrinking clays, roots, vandals). As such, blazes on trees acted as markers for approximation of benchmarks locations.

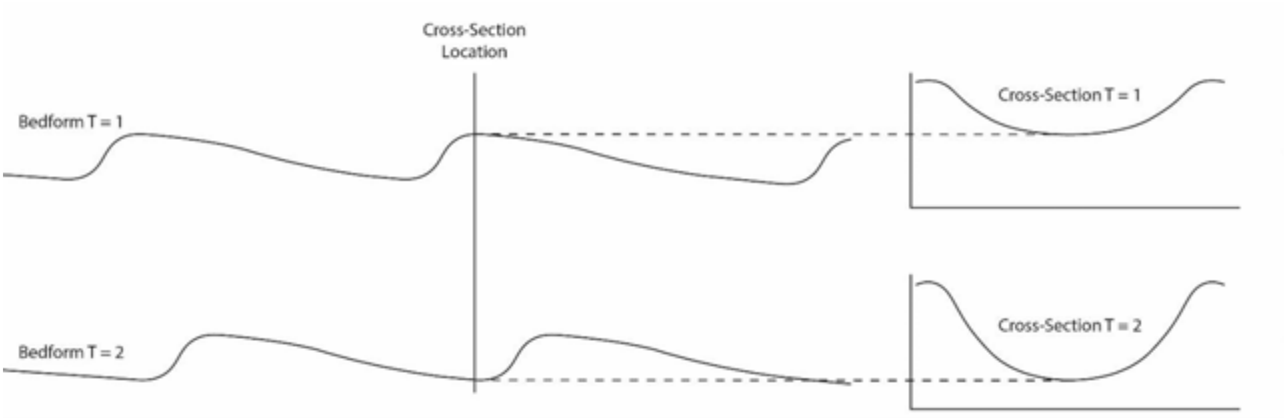

FIGURE 2-3 FALSE BED DEEPENING INFERENCE THROUGH CROSS SECTION ANALYSIS.

2.4 Sediment Data

Sediment samples were collected in the field and visually assessed for classification. At the time this report was written, laboratory analysis of the sediment samples was not possible due to time and budget restrictions. Sediment analysis is recommended in future studies.

3 METHOD

The following key project tasks were undertaken in the development of this technical report.

1. **Project Scoping and Initiation**. This stage involved:
    a. A workshop/steering committee meeting with the MDBA Steering Committee to confirm project scope, timelines and to communicate relevant information and knowledge.
    b. A review of relevant data and documentation with a focus on information pertaining to the history, management, condition, values and threats across the project area.
2. **A field based geomorphic investigation**, undertaken on the 17th – 19th June 2019.
3. **A second Steering Committee meeting** to discuss the preliminary findings of the Project Scoping and Initiation and field based geomorphic investigation and to revisit the project scope relative to these preliminary findings.
4. **Hydraulic modelling**, simulating two in-channel flow events selected by the MDBA (further discussed in Section 4.4.2).
5. **A channel morphology analysis**, informed through LiDAR data, surveyed cross-sections and bathymetric survey (Section 4.2).
6. The preparation of this **technical report**.

4 RESULTS

This assessment consisted of a site investigation in which field observations on channel condition and fluvial processes were made and desktop analysis of various GIS, topographic, bathymetric and survey datasets. The observations and results of these analyses are outlined in the following sections in context of the observations made in the field.

4.1 Channel Condition and Features

The Murray River is a "Type 3: *mixed-load, laterally active anabranching river*", (Nanson & Knighton, 1996). By definition, this means that the Murray River is characteristically a dynamic river system where:

- The meander bends are free to progress across the floodplain surface.
- Meander cut-offs are common (oxbow lakes).
- Multiple river channels can form, where a secondary channel leaves the parent river (in this case the Murray River) to re-join it further downstream (defined as an anabranch).

Within the study area, there are two dominant reaches based on fluvial processes (Figure 4-1). The upstream section (essentially upstream of Picnic Point) is laterally migrating with some long anabranches (Figure 4-1). That is, the channel network has naturally evolved through the migration of meander bends and development of anabranches. Hence, erosion has and always will be a natural process within this reach. Key geomorphic features in this reach include:

- Anabranches.
- Sinuous channel planform.
- Oxbow lakes (semi-permanent water – topography capable of directing overland flow).
- Scroll bars (raised topographic features often seen on the inside of meander bends, formed through mender progression - capable of directing overland flow).

Downstream of the section, between Picnic Point and Barmah, is not laterally migrating (Figure 4-1). Stone (2006) suggests that this section of the Murray River is relatively new, having been formed after tectonic activity when the Cadell Tilt Block shifted upwards. This forced the Murray River to avulse from its previous course through a previously inundated palaeolake south to meet the Goulburn River. Key geomorphic features in this reach include:

- Relatively straight channel planform.
- Relatively narrow channel.
- Some avulsions (channel straightening).

Anthropogenic pressures are also interacting with natural processes to influence erosion rates in this reach of the Murray River. Influences on the physical form of the river are:

- River regulation.
- Floods (the frequency of which has been modified by the presence of upstream regulating structures, in particular Lake Hume).
- De-snagging.
- Changes in riparian vegetation.
- Boat wash.

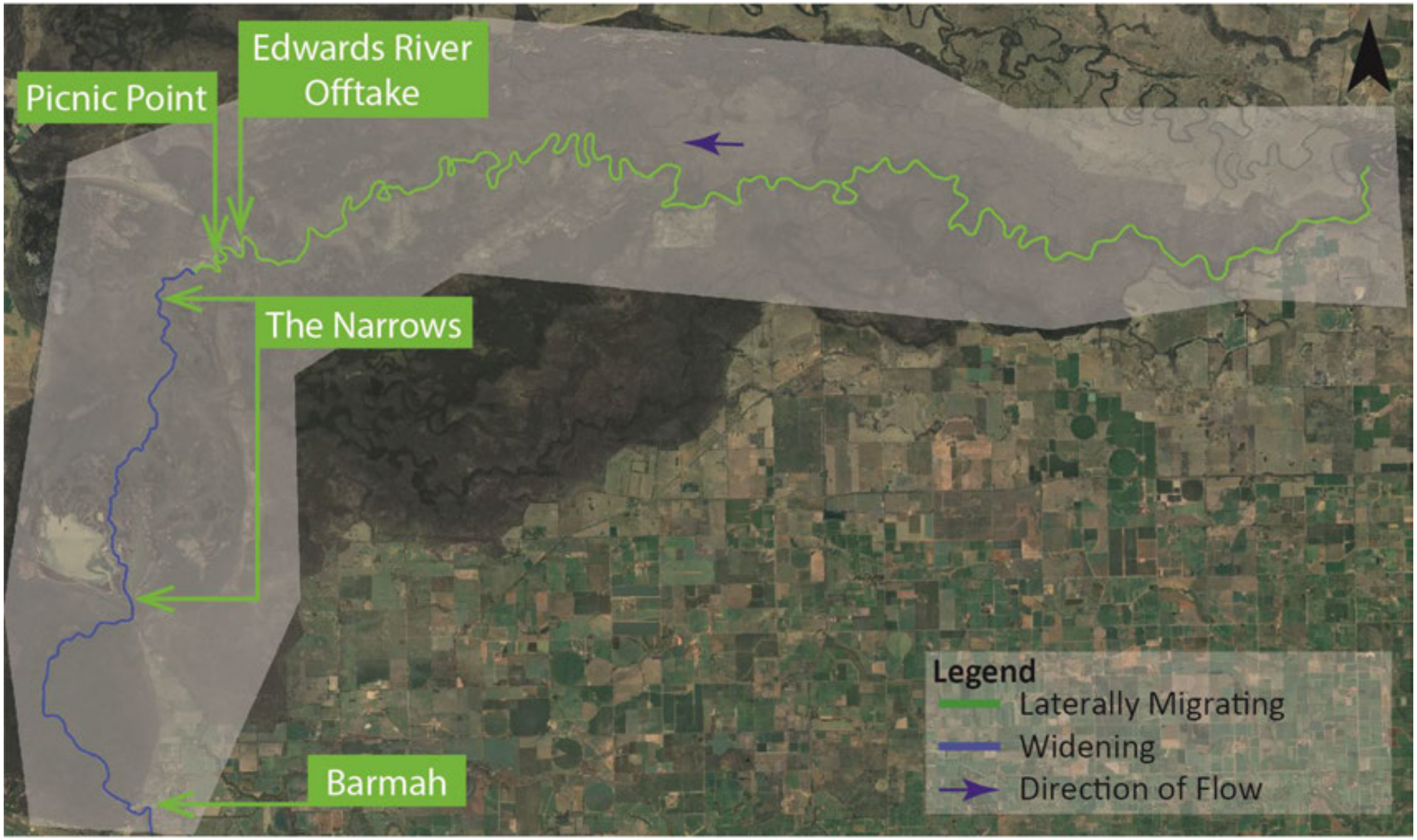

FIGURE 4-1 DOMINANT FLUVIAL PROCESS MAP.

From field observation, the key fluvial processes currently operating in the study reach are lateral migration in the upper reach and apparent channel widening in The Narrows.

- **Lateral migration** is a natural geomorphic process and involves the movement of a meander bend in an outward and downstream direction that results in corresponding deposition on the opposite bank. Evidence of lateral migration can be found in the presence of point bars, scroll bars, floodplain ridges, cut-offs, counter point bars and concave benches on the floodplain.
- **Channel widening** is the erosion of a riverbank that is not restricted to outside bends, without corresponding deposition on the opposite bank. Channel widening is also a natural process but usually occurs discontinuously in a natural setting.

Rutherfurd (1991) notes that in general the plan-form of the River Murray has not significantly changed since the 1860's when the river was first surveyed and that by world standards, the River Murray is one of the most stable rivers of its size described in literature.

The current bank condition of the reaches observed in this study was poor, largely due to the vertical upper bank scarps, likely induced through a combination of river regulation and boat wash (Figure 4-2). This vertical scarp often extended behind stands of in-channel macrophytes (e.g. Phragmites) (Figure 4-3) which indicates either recruitment since erosion or a limited ability for the macrophytes to dissipate erosive energy.

The use of boat wash on inland waters has increased significantly in the last 30 years. It is likely that this trend will continue. The Murray River through Barmah-Millewa forest is a very attractive site for recreational boating partly due to the relatively stable summer and early autumn flows and protection from wind waves due to the presence of dense riparian vegetation.

While there is a general understanding that vessel wash contributes to riverbank erosion, at this stage the precise contribution to erosion in this reach from boating activity remains unknown. Many of the erosional features in the reach are typical of boat wash, indicating that boating activity may play a significant role, at least in localised areas.

The impacts of boat wash are further discussed in Section 5.2.

FIGURE 4-2 VERTICAL BANK FACES TYPICAL OF BOAT WASH INDUCED EROSION (NOTE NOTCH HALFWAY UP THE BANK WHICH IS A RESULT OF RIVER REGULATION AND THE 9000 ML SUMMER FLOW).

FIGURE 4-3 BOAT WASH INDUCED EROSION EXTENDING BEHIND IN CHANNEL VEGETATION.

4.2 Channel Morphology Analysis

LiDAR data, surveyed cross-sections and bathymetric survey were assessed and compared to gain an understanding of changes over time. As the Murray River is a relatively stable system (slow moving) these changes were minor and many changes are likely to be within the error introduced through the issues discussed in Section 2.3. The channel morphology characteristics assessed as part of this study included:

- Channel Slope.
- Channel Planform.
- Bedform (2018 Bathymetry only).
- Channel Width.
- Channel Depth.
- Cross Sectional Area.

This assessment was undertaken in an attempt to identify any recent changes that may have had an effect on channel capacity.

4.2.1 Channel Slope

The initial analysis included a bed grade assessment. This was undertaken to ascertain any high-level bed grade changes occurring in the reach. Bed grade is linked to the length of the channel with higher grade reaches generally narrower with higher energy flows (velocity). The smoothed longitudinal profile is shown in Figure 4-4, along with a delineation based on bed grade and the location of The Narrows.

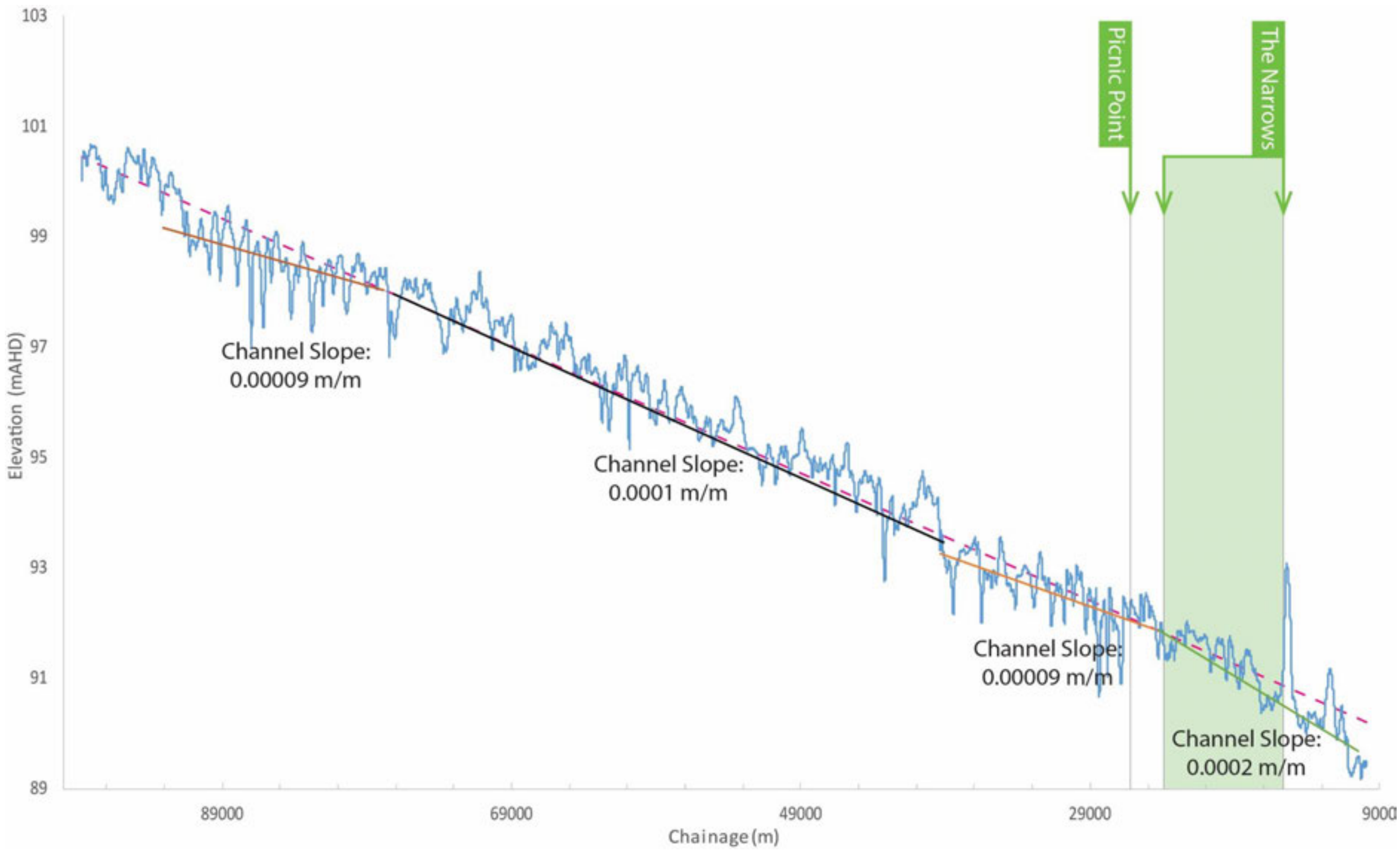

FIGURE 4-4 LONGITUDINAL BED PROFILE SHOWING DELINIATION BY HIGH LEVEL BED GRADE, WHERE CHAINAGE 9000M EQUATES TO RIVER MURRAY CHAINAGE 1770KM.

The Murray River is, in general, a very low-grade watercourse and the study reach at the Barmah Choke is no different. Only minor variations in bed-grade were observed; with the top three slope-delineated reaches essentially the same grade (±0.00001 m/m). The Narrows are identifiable as steeper than those upstream, however, this reach would still be classed as low grade. Bed-grade assessment was not undertaken below the downstream extent of available channel bathymetry. Whereas the partial bathymetry was included in the bed-grade analysis and some error is likely to be introduced due to incomplete data, the grade of the reach when assessed at this resolution is unlikely to be highly inaccurate.

4.2.2 Channel Planform

As discussed above, the Murray River is a very slow-moving system. As such channel planform changes were minor and limited almost entirely to the upstream laterally migrating section, as expected. Changes were assessed between 2001 and 2016 (LiDAR capture dates). Changes in The Narrows were not observed over this period, whereas some minor lateral migration is noted in the upper reaches. Aerial photographic assessment did not provide any observable changes.

As discussed in Section 4.1, various floodplain features were noted in the LiDAR which infer certain processes. Oxbow lakes and scroll bars in the upstream reaches are good indicators of channel migration (Figure 4-5). Cut-offs with no scroll bars in the lower reaches (The Narrow) indicate rapid channel straightening through avulsion (Figure 4-6).

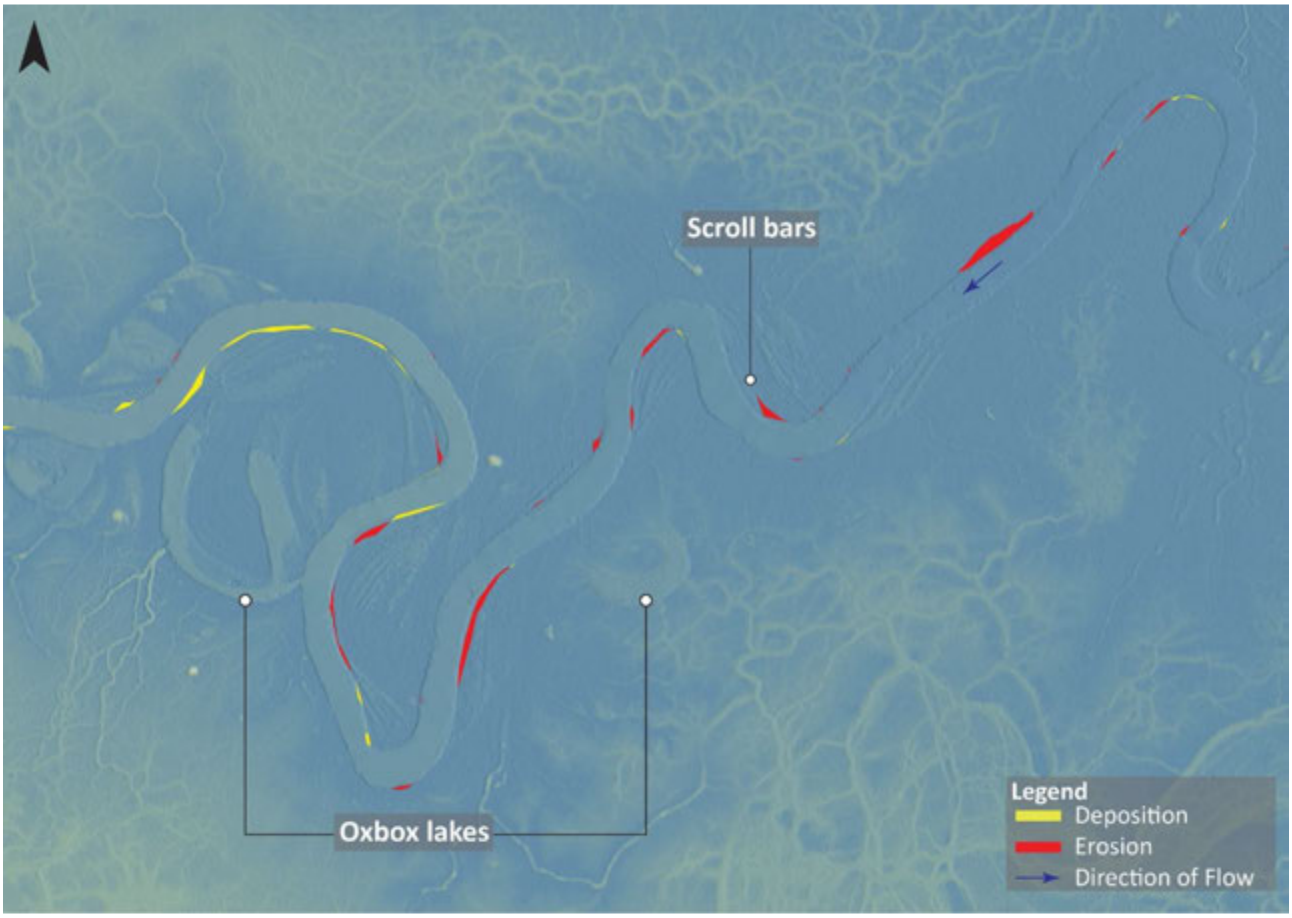

FIGURE 4-5 CHANNEL PLANFORM CHANGE IN THE UPPER REACHES (UPSTREAM OF PICNIC POINT).

FIGURE 4-6 CHANNEL PLANFORM CHANGE IN THE NARROWS (DOWNSTREAM OF PICNIC POINT).

4.2.3 Channel Bedform

Channel bedform can be an indicator of bed load and hydraulic energy. In the absence of high-resolution data on sediment type distribution within the channel this provides us with a proxy for interpretation. Within the study area several observations can be made. It is clear that bedform is very different between the upper laterally migrating reach and The Narrows.

The upstream reach is dominated almost entirely by an undulating channel bed composed of large ripples (metre scale: mega-ripples or dunes) (Figure 4-7). Such features are indicative of a sandy bed load in a low energy environment, where sands are transported downstream by rolling rather than saltation. This bedform type is dominant from the upstream extent of the study reach to approximately picnic point. Other features noted in this area are pools, however these are infrequent, likely due to the large volumes of sand, which is transported downstream and fills the pools. Very little submerged woody debris was observed in the bathymetry in this reach indicating that this has been buried by sand or removed. It is noted that large wood was observed along the channel margins during the field assessment.

In contrast, mega-ripples are essentially absent within The Narrows. Instead, the bedform is more complex with irregular bedform consisting of scour pools and ledges with submerged partially buried woody debris and a smooth bed profile indicative of scour and erosion rather than a mobile bedload (Figure 4-8). Where ripples are observed they are localised and lensoidal in geometry indicating infilled pools (most likely filled with sand). The presence of sand in these pools is significant as it means that sand is travelling through the system.

There is no abrupt boundary between the upper and lower bedform zones. The change happens over approximately four kilometres starting immediately upstream of Picnic Point. An example of this transition zone is shown in Figure 4-9.

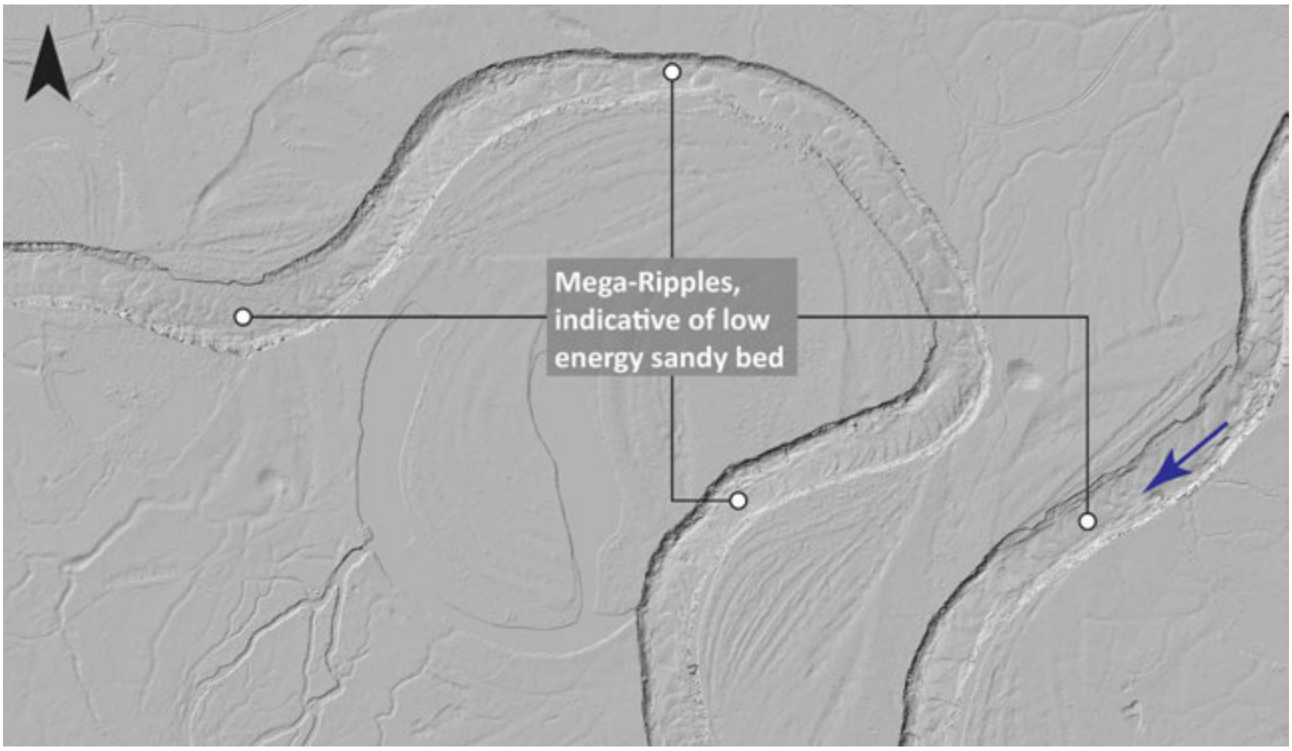

FIGURE 4-7 BEDFORM WITHIN THE UPSTREAM REACHES.

19010125_R01_V03_Barmah Choke

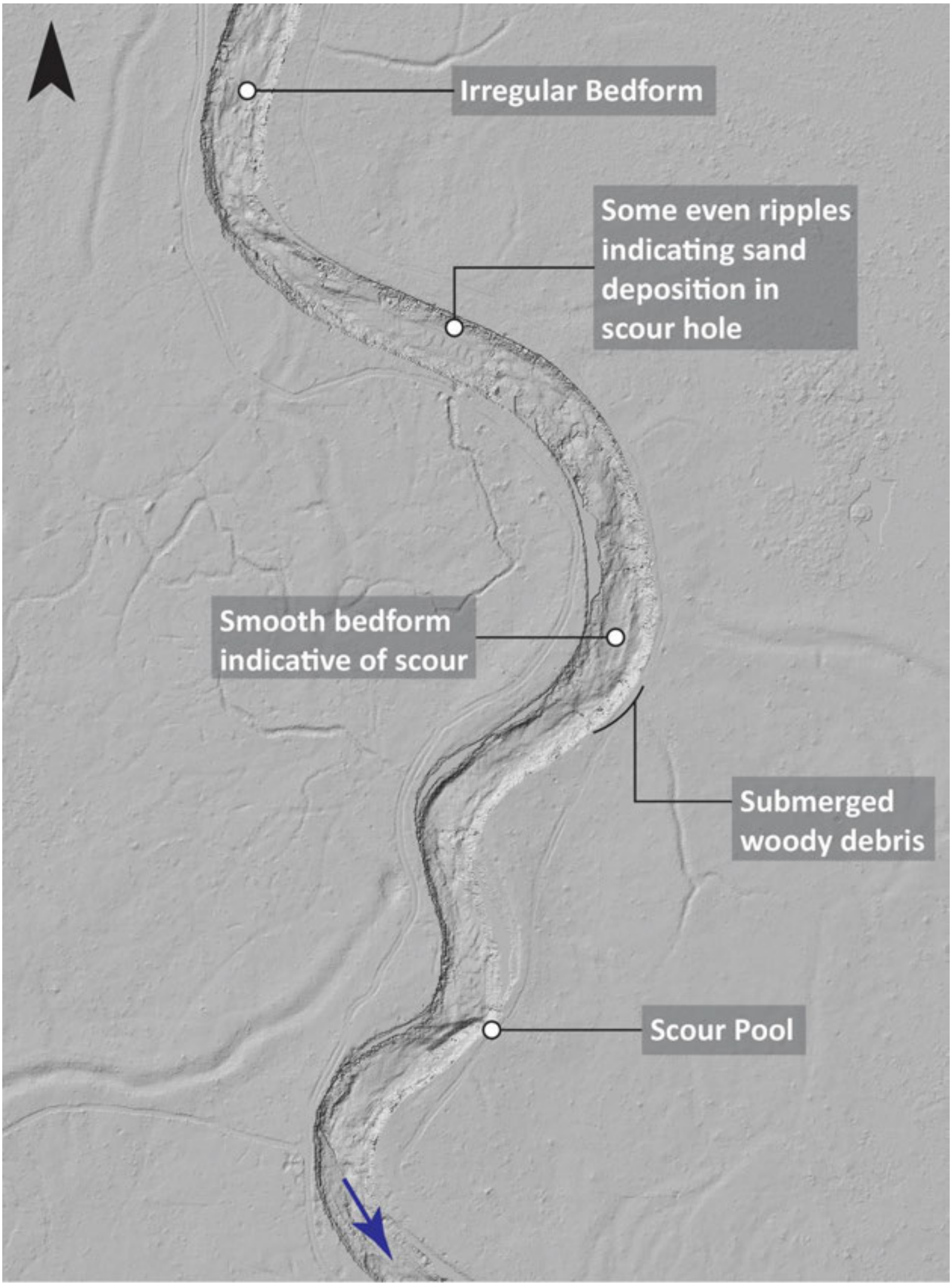

FIGURE 4-8 BEDFORM WITHIN THE DOWNSTREAM REACHES.

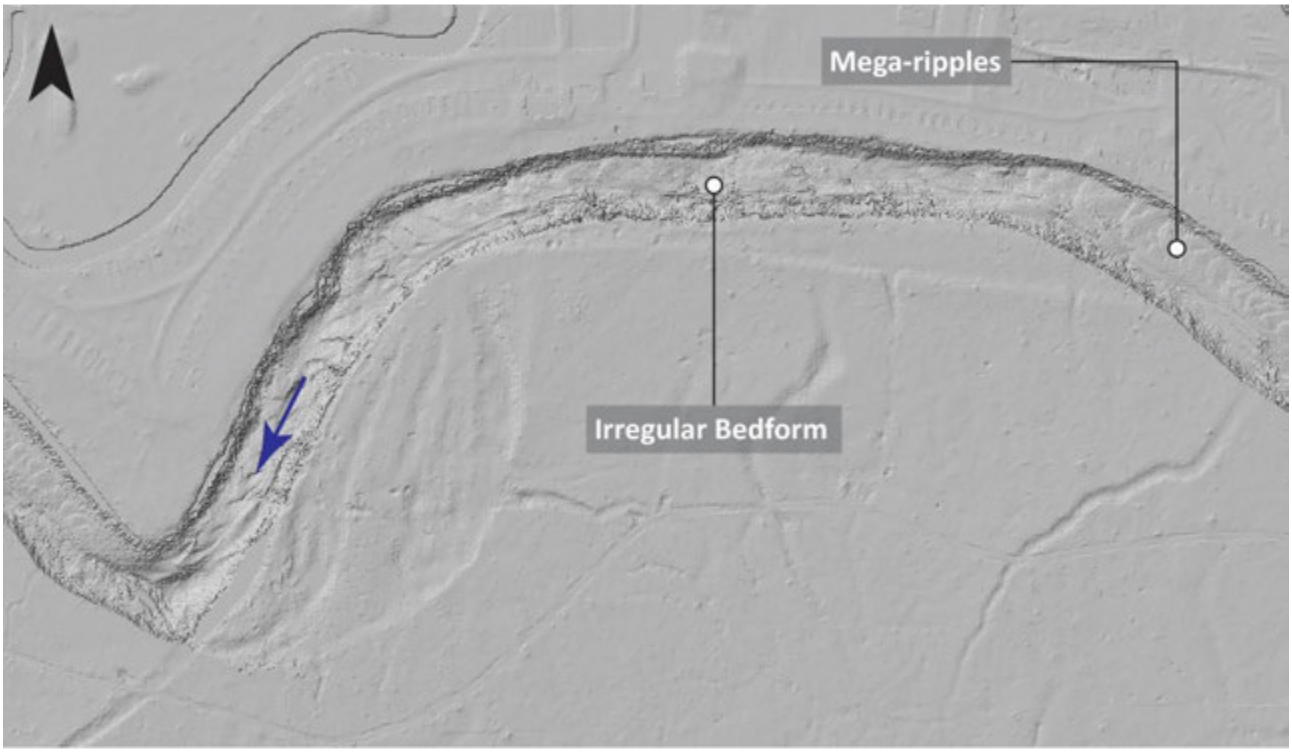

FIGURE 4-9 BEDFORM WITHIN THE TRANSITION ZONE.

4.2.4 Channel Width and Depth

Channel width and depth are inherently related and as such discussed together. Channel width and depth were assessed both as a ratio and against river chainage. They are also assessed in the context of channel slope, planform.

Channel width was measured from the 2001 and 2016 LiDAR data sets and compared against river chainage. Channel depth was only available at a suitable resolution from the 2017 Bathymetric Survey. Channel depth is given as an average. It is important to note that the observable difference in average channel depth within The Narrows are likely a function of the partial bathymetry in this area.

As a general trend, channel width decreases as we move downstream (Figure 4-10), with the minimum channel width measured within The Narrows as expected. Channel width then increases rapidly beyond the Narrows towards Barmah. Despite the very minor changes in channel slope, there is some discernible correlation between channel slope and width.

Average channel depth, derived from the 2017 bathymetric data, shows an observable trend of depth decreasing in a downstream direction (Figure 4-11). The depth then appears to increase slightly for a short distance at the upstream extent of The Narrows which would be expected due to its steeper and narrower morphology. However, the data is distorted in the area where only partial bathymetry is available. Regardless, the majority of the data indicates that The Narrows are both narrower and shallower, as expected.

These characteristics are in-line with the bedform assessment with a wider lower energy environment in the upstream laterally migrating section and a narrower and relatively higher energy environment in The Narrows.

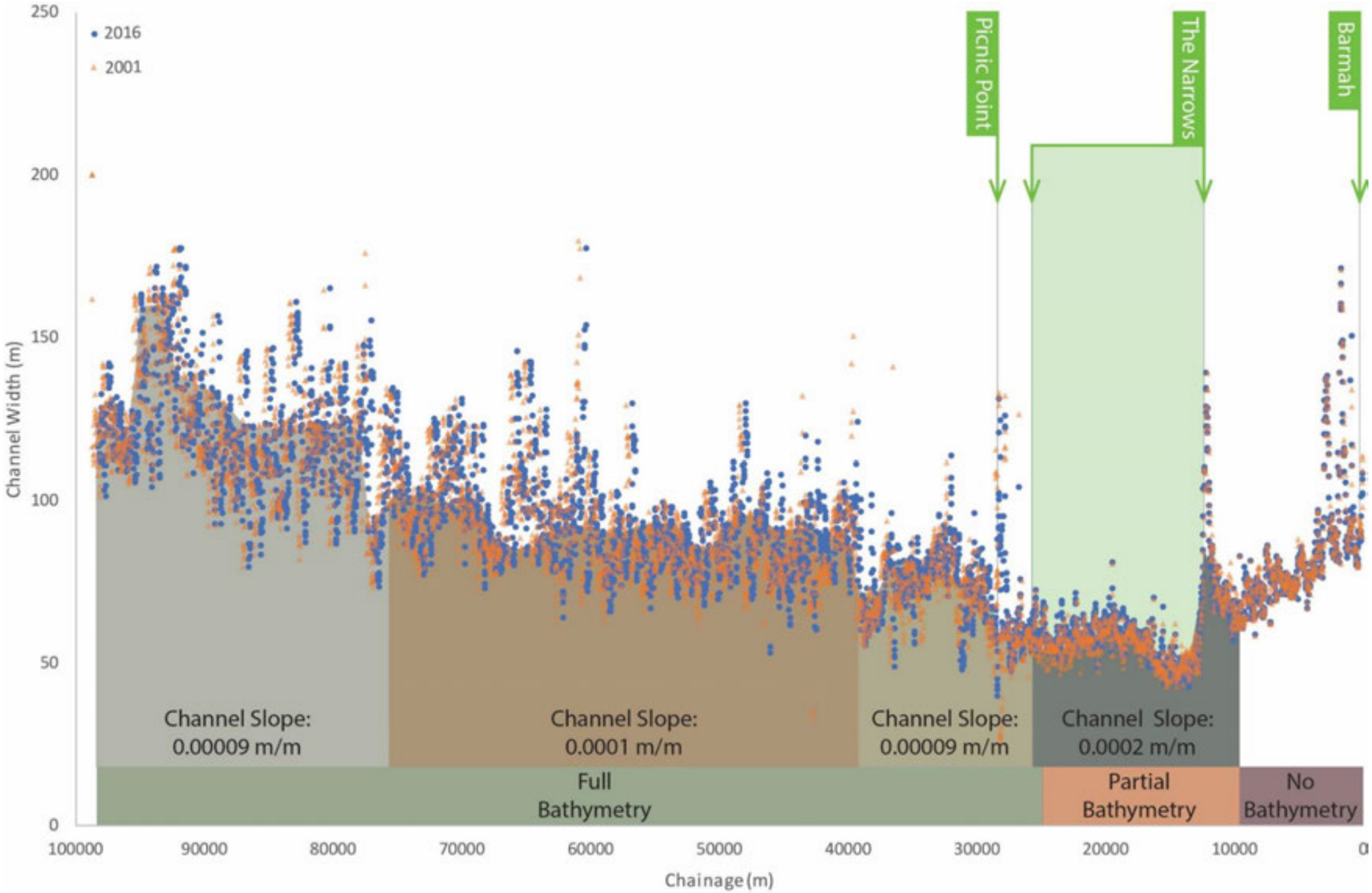

FIGURE 4-10 CHANNEL WIDTH BY STUDY REACH CHAINAGE, SHOWING CHANNEL SLOPE AND THE EXTENT OF BATHYMETRIC DATA, WHERE CHAINAGE 0M EQUATES TO RIVER MURRAY CHAINAGE 1760.6KM.

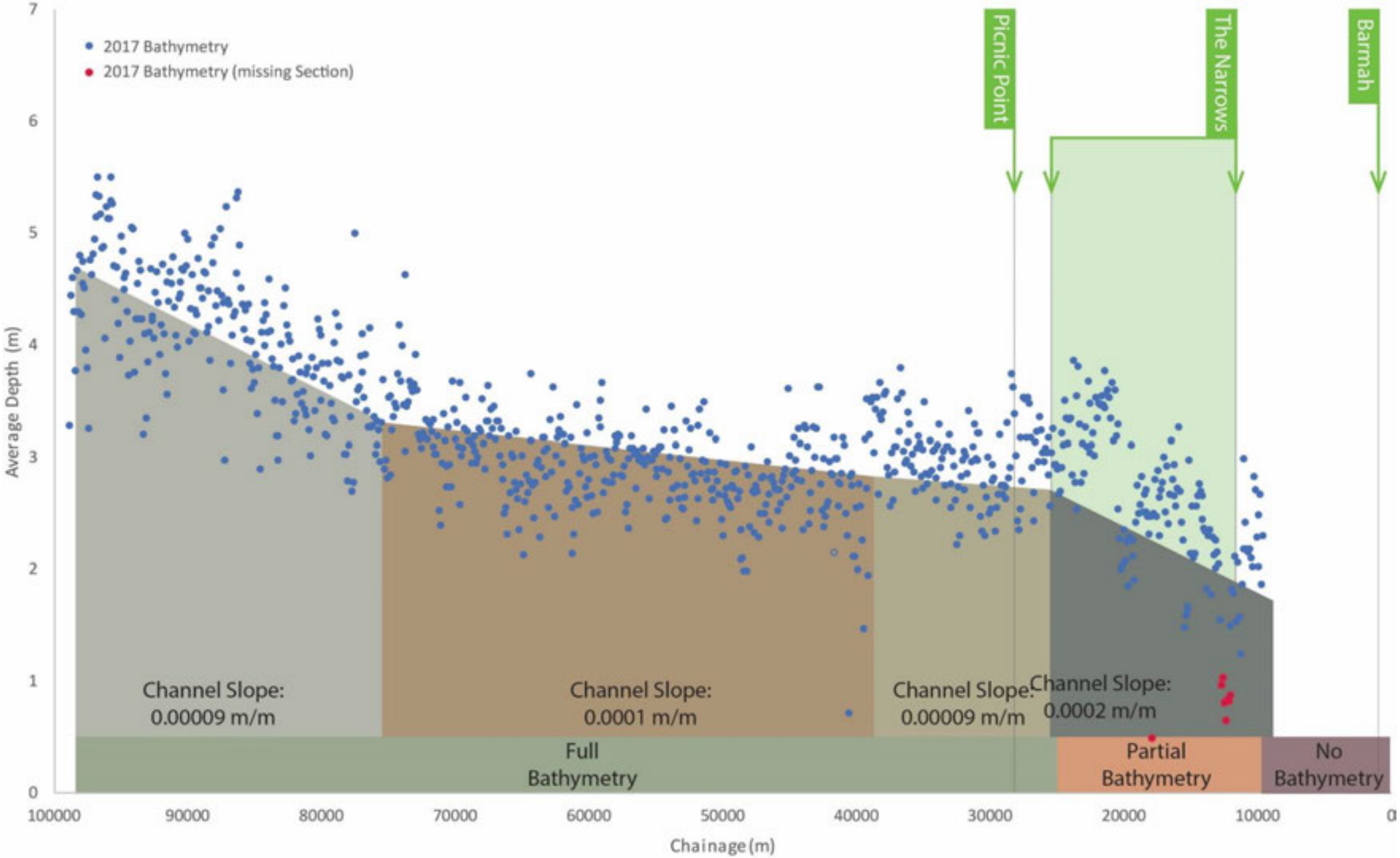

FIGURE 4-11 AVEREAGE CHANNEL DEPTH BY STUDY REACH CHAINAGE, SHOWING CHANNEL SLOPE, , WHERE CHAINAGE 0M EQUATES TO RIVER MURRAY CHAINAGE 1760.6KM.

4.2.5 Channel Cross-Sectional Area

Changes in channel cross-sectional area have been assessed using the historical survey data and the current (2017) bathymetric survey. As discussed in Section 2.3, this data required substantial manipulation to allow comparison and cross section data, as this resolution is not ideal to assess channel capacity over long reaches.

Cross sectional area for each cross section and survey date is given in Table 4-1, with cross-section comparisons shown in Figure 4-12 and Figure 4-13. Figure 4-15 shows cross section locations and chainage. Cross-sectional area (2017) against chainage is shown in Figure 4-15.

The data shows a minor net trend of channel capacity reduction in the upper reaches (>35300 m chainage). The lower three cross sections lack the 2017 bathymetric survey for comparison. Many of the comparisons show changes below 5% which is likely within the error introduced by manipulating the cross sections and the varying methodologies used to obtain the survey. Furthermore, only two of the 14 cross-sections show a consistent trend across the time periods (green cells in Table 4-1). It is more common that cross-sectional area increases and decreases between different survey dates.

Whereas, a direct comparison between these cross-sections and survey capture dates is likely flawed, it does appear that some minor channel contraction is occurring in the upper reaches from 35300 m chainage upstream. This section loosely correlates to the upper, laterally migrating section dominated by coarse sandy bedload and mega-ripple bedform.

TABLE 4-1 CHANNEL CROSS SECTIONAL AREA COMPARISON.

River Murray Chainage (km)	Reach Chainage (m)	1986 (m^2)	1996 (m^2)	2006 (m^2)	Lidar & Bathymetry (m^2)	Net Change	% Change
~1763	2,400	407	421	425	No data	+18	4.4%#
~1771.5	10,520	234	238	234	No data	+0	0.0%#
~1779	19,100	197	213	191	No data	-6	-3.0%#
~1787	26,988	202	195	223	190	-12	-5.9%#
~1790.5	30,468	186	198	195	184	-2	-1.1%#
~1795.3	35,300	275	256	265	205	-70	-25.5%
~1803.5	43,319	238	260	246	307	+69	29.0%
~1811	51,639	231	231	231	191	-40	-17.3%
~1819.5	59,500	272	267	294	261	-11	-4.0%#
~1827.4	67,625	269	354	321	328	+59	21.9%
~1836.4	75,975	357	344	322	337	-20	-5.6%#
~1843.6	83,939	420	420	419	478	+58	13.8%
~1851.4	91,900	827	786	712	729	-98	-11.9%
~1857.7	98,333	517	485	473	446	-71	-13.7%

The degree of change for these comparisons is likely within error.

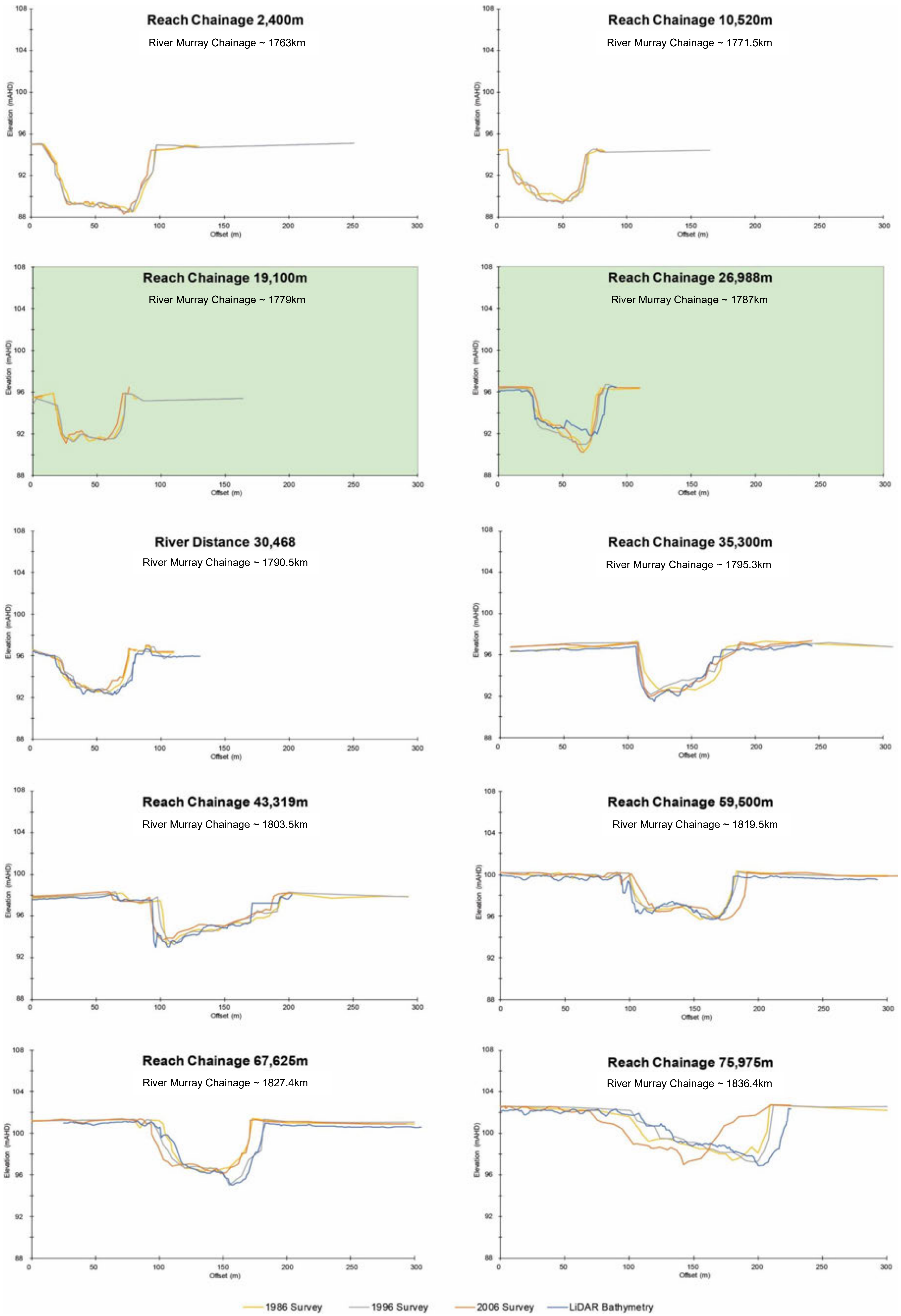

FIGURE 4-12 CROSS-SECTION COMPARISON (ADDITIONAL CROSS-SECTIONS ON NEXT PAGE). NOTE THE TWO CROSS SECTIONS IN GREEN REPRESENT THE CROSS SECTIONS THROUGH THE NARROWS.

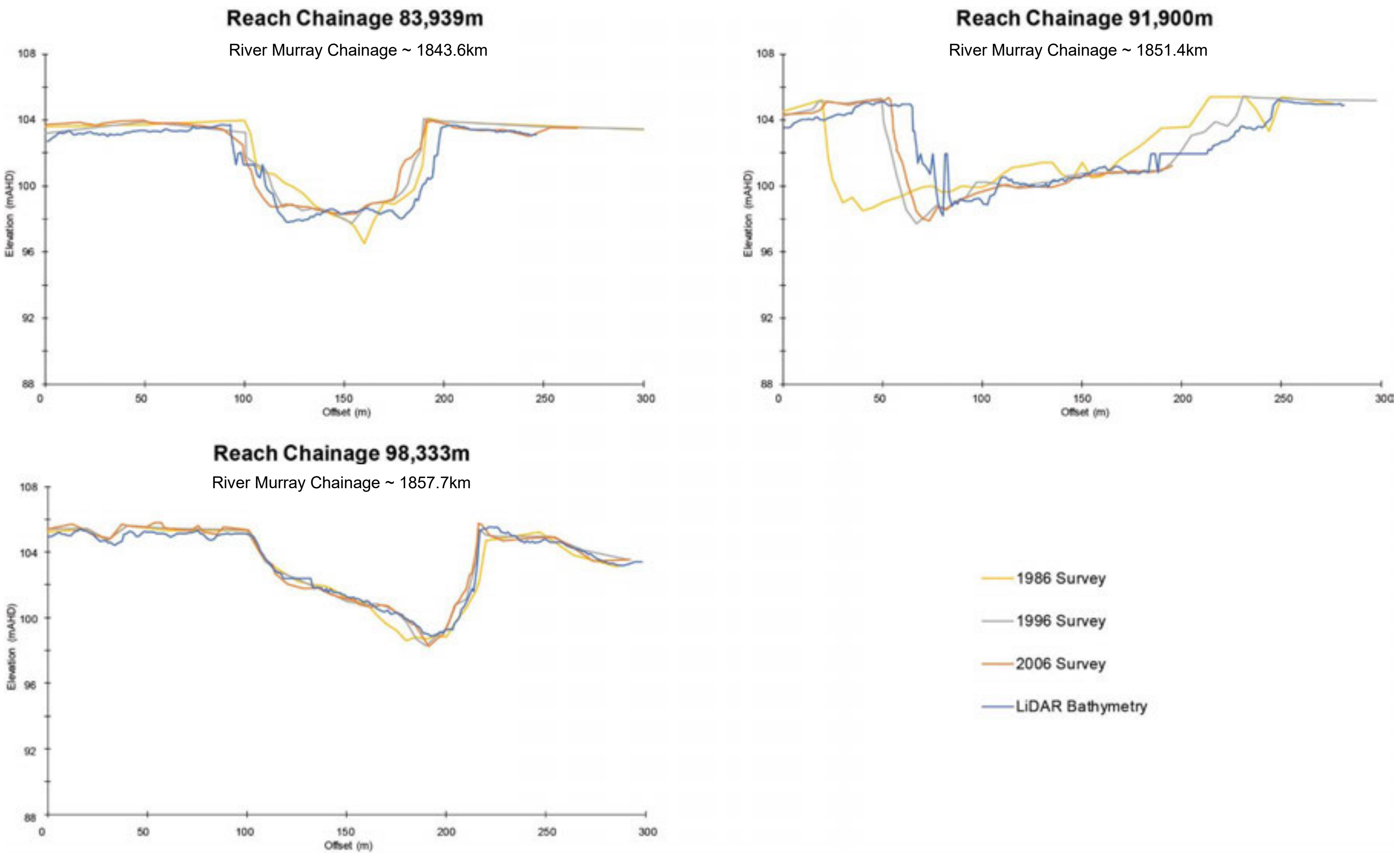

FIGURE 4-13 CROSS-SECTION COMPARISON.

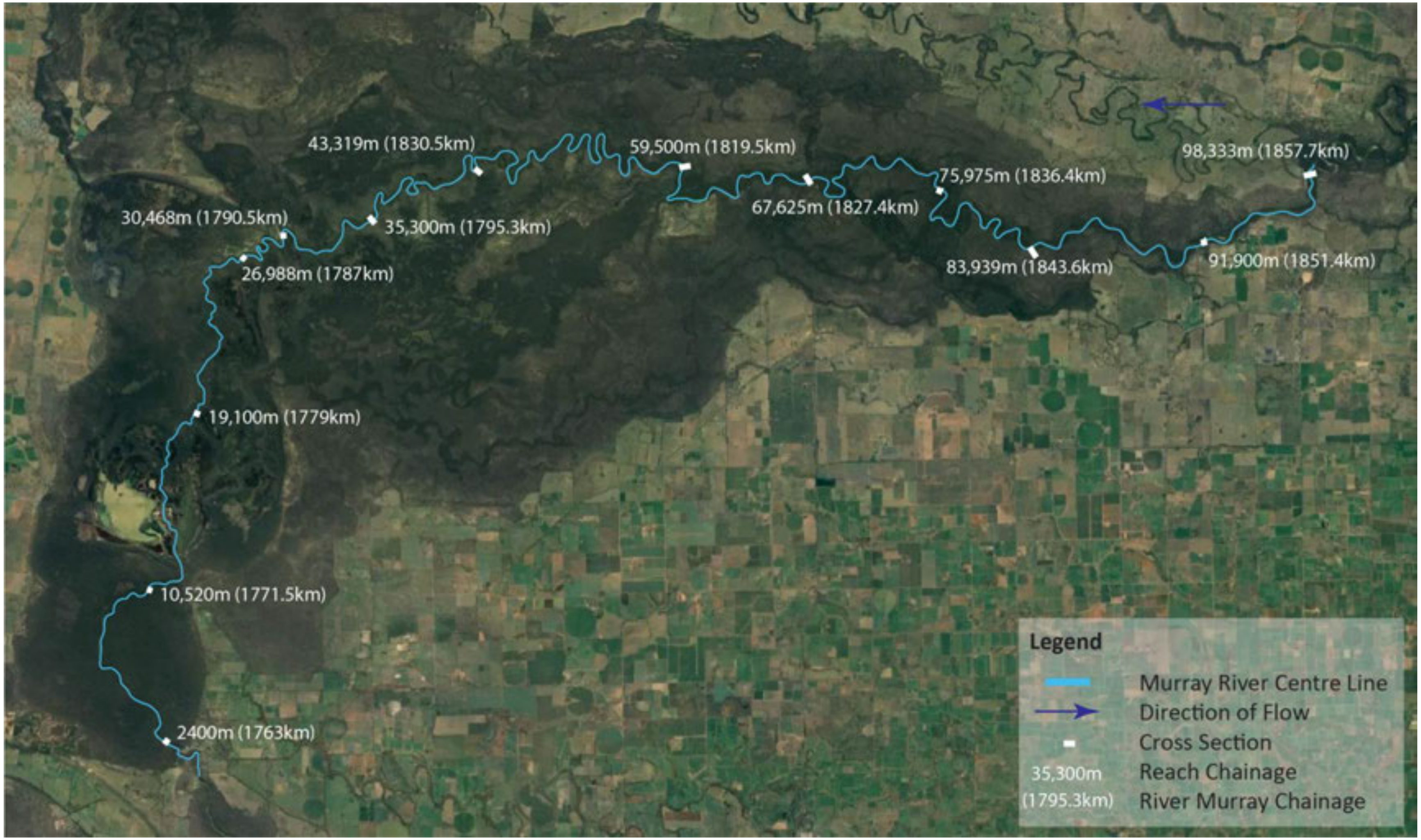

FIGURE 4-14 CROSS SECTION LOCATIONS.

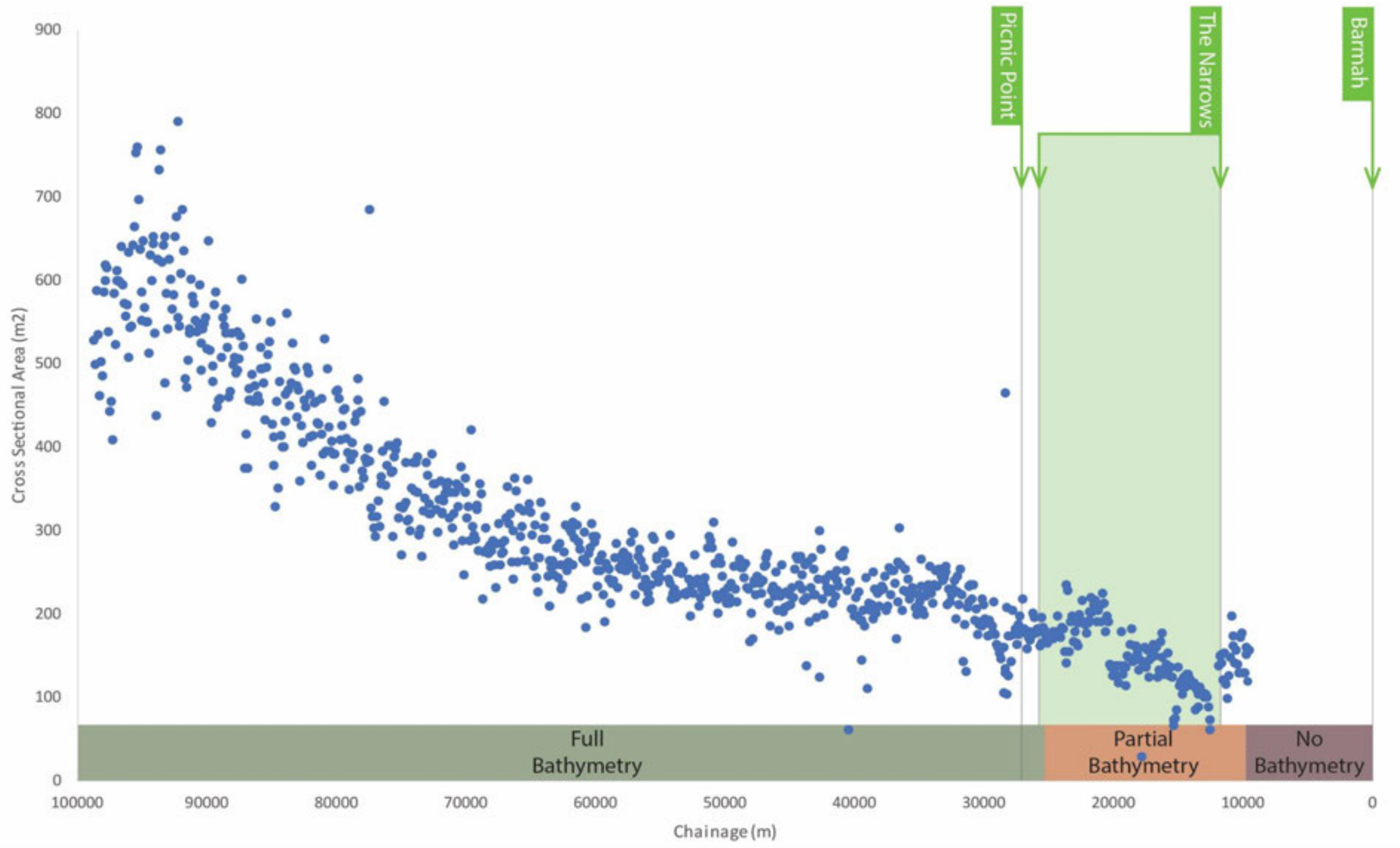

FIGURE 4-15 CROSS-SECTIONAL AREA BY STUDY REACH CHAINAGE, WHERE CHAINAGE 0M EQUATES TO RIVER MURRAY CHAINAGE 1760.6KM.

4.3 Bed Material Assessment

Bed material sampling was undertaken at a late stage in the project and at the time this report was written no analysis had been carried out. Figure 4-16 shows the sampling locations, with the sample information, in order of river chainage, along with a classification based on a visual assessment given in Table 4-2. Whereas it appears that the material within The Narrows is slightly finer than the sediment upstream, no real trend can be discerned without particle size analysis. Of note is the sample from downstream of The Narrows where the sand layer appears to be only a thin layer overlying clay. Bank material, where observed, consisted of fine sandy silts and clays.

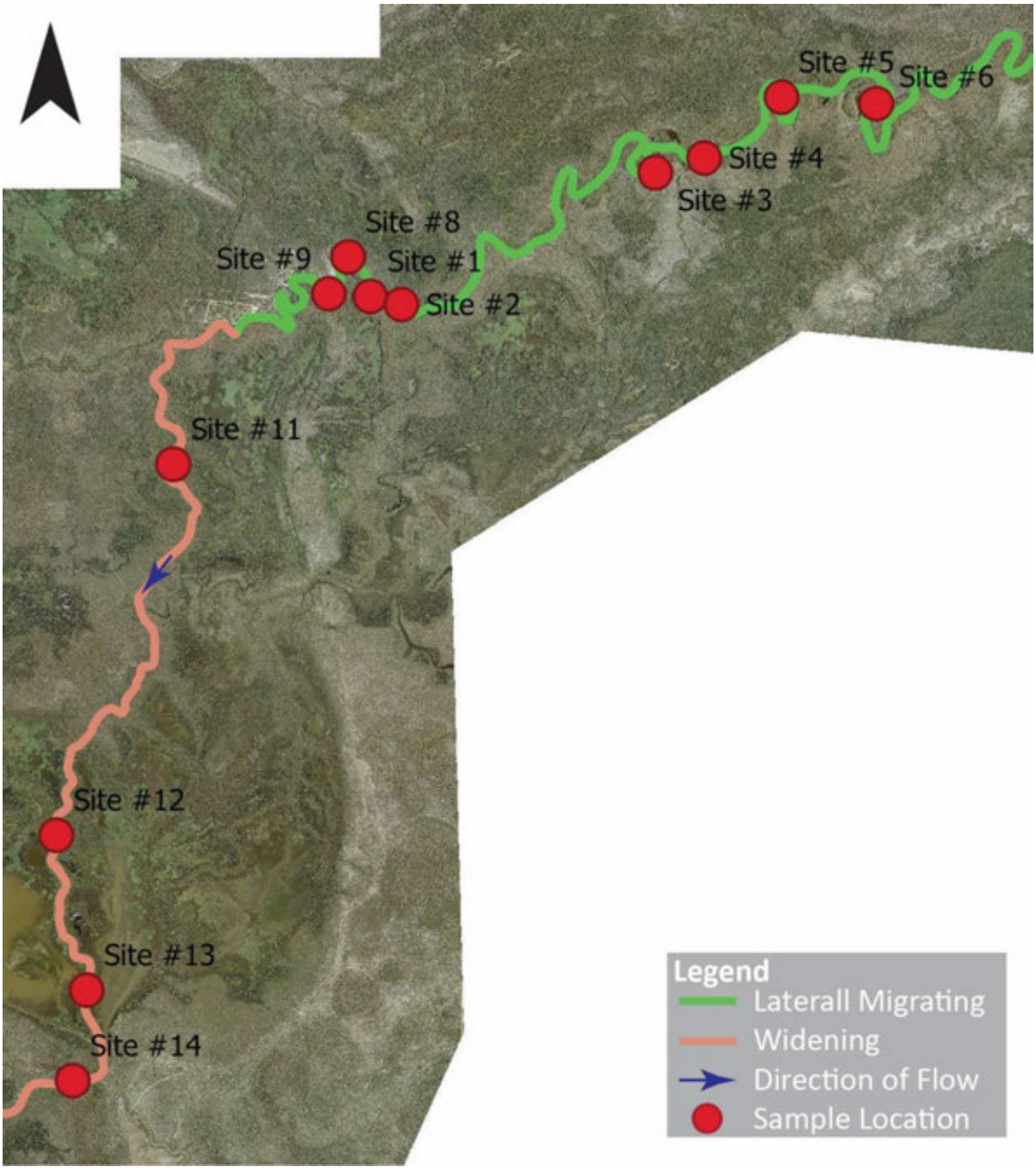

FIGURE 4-16 SEDIMENT SAMPLING LOCATIONS.

TABLE 4-2 VISUAL BED MATERIAL CLASSIFICATION. NOTE THE SAMPLES HIGHLIGHTED IN GREEN REPRESENT THE SAMPLE LOCATIONS WITHIN THE NARROWS.

Reach Chainage (m)	Sample Name	Description
45850	6	Coarse Sand
42800	5	Coarse Sand
40700	4	Medium Sand
39300	3	Coarse Sand
32150	2	Coarse Sand
31550	1	Coarse Sand
30800	8	Coarse Sand
29900	9	Coarse Sand
23300	11	Medium Sand
16050	12	Medium Sand
13250	13	Medium Sand
11400	14	Coarse Sand (Top 100mm) Clay with sandy layers (>100mm)

4.4 Hydraulics

4.4.1 Overview

Hydraulic modelling was undertaken under two flow scenarios. The 6000 ML/day scenario is representative of flows that are entirely within the channel (no over bank flow) and the 9500 ML/day approximately represents a bank full flow. A full set of maps for the hydraulic modelling results (Bed Shear Stress and Velocity) is provided in Appendix A.

4.4.2 Method

A 2D hydraulic model was developed using MIKE21 software for the Murray River from downstream of the Bullatale Creek offtake to the township of Barmah. The 2D hydraulic model used a flexible mesh to represent the bathymetry and banks of the river. To enable fast model run times with a relatively high-resolution topography, Graphical Processing Unit (GPU) hardware was used.

Flexible mesh refers to an unstructured grid, compared to conventional hydraulic models that consist of grid cells (squares) of uniform size. The flexible mesh uses triangular shapes which can vary in size and geometry. This enables modelling with smaller mesh resolutions within the channel and banks of waterways or in areas of interest, and larger mesh elements on the outer floodplain areas, or in deep, flat wetlands for example.

The model domain is presented in Figure 4-17. The model includes a reach of the Murray River just under 100 km long, to optimize run times larger mesh elements were defined in the floodplain and higher resolution was applied within the Murray River channel. The Murray River banks were accurately digitized using GIS software and the available LiDAR data and were incorporated into the model as follows:

- Define the areas of high resolution required in the model, necessary to accurately describe the hydraulic behaviour within the waterway.

- Represent bank crest levels via explicit structures in the 2D model called dike lines. The crest levels are extracted from the LiDAR data set along the digitised polyline and applied directly to the model elements to ensure overtopping to and from the floodplain, and channel capacity, are accurately represented.

Given the purpose of this hydraulic model, the entire floodplain of the Barmah-Millewa Forest wasn't included in the model domain. Mesh elements vary in size from 100 m² within the Murray River banks, providing a minimum of 6 to 8 elements across the channel, to over 10,000 m² in the floodplain. The basis of the hydraulic model, and more particularly the elevation data applied to the flexible mesh, is a DEM (Digital Elevation Model) built from the merging of topographic and bathymetric data. The DEM created for the model development is presented in Figure 4-17. A significant amount of effort went into merging bathymetry and LiDAR but it is noted that some sections of the bathymetry were incomplete at the time of modelling, requiring interpolation between available survey.

To minimize the influence of boundary conditions on the results in the Murray River, outflow boundaries were defined along the edge of the model domain to allow water to flow out and avoid a glass wall effect with excessively high-water levels. Level-discharge relationships (H/Q) based on the topography were applied, with boundary locations as required.

The hydraulic model was used to assess flow conditions under two scenarios where a constant inflow in the Murray River was applied:

- 6,000 ML/d and,
- 9,500 ML/d.

The simulation was run until steady conditions were reached throughout the model domain.

It should be noted that the offtake structures located along the modelled reach were considered closed in the model setup, minimising how the much the floodplain is engaged for the modelled flows. Furthermore, given the low resolution of the mesh out on the floodplain it is likely that the flooding behaviour shown in the model results is not representative of observed flow behaviour. However, the flow conditions within the Murray River channel should be reasonably accurate given the high-resolution, and the results fit for purpose to interpret likely velocities and bed shear stress.

It is noted that the model is uncalibrated, and that improvements could be made to calibrate the model to measured flow velocities and water levels by adjusting the model roughness within the channel. A roughness value of 0.03 was adopted for the modelled river channel.

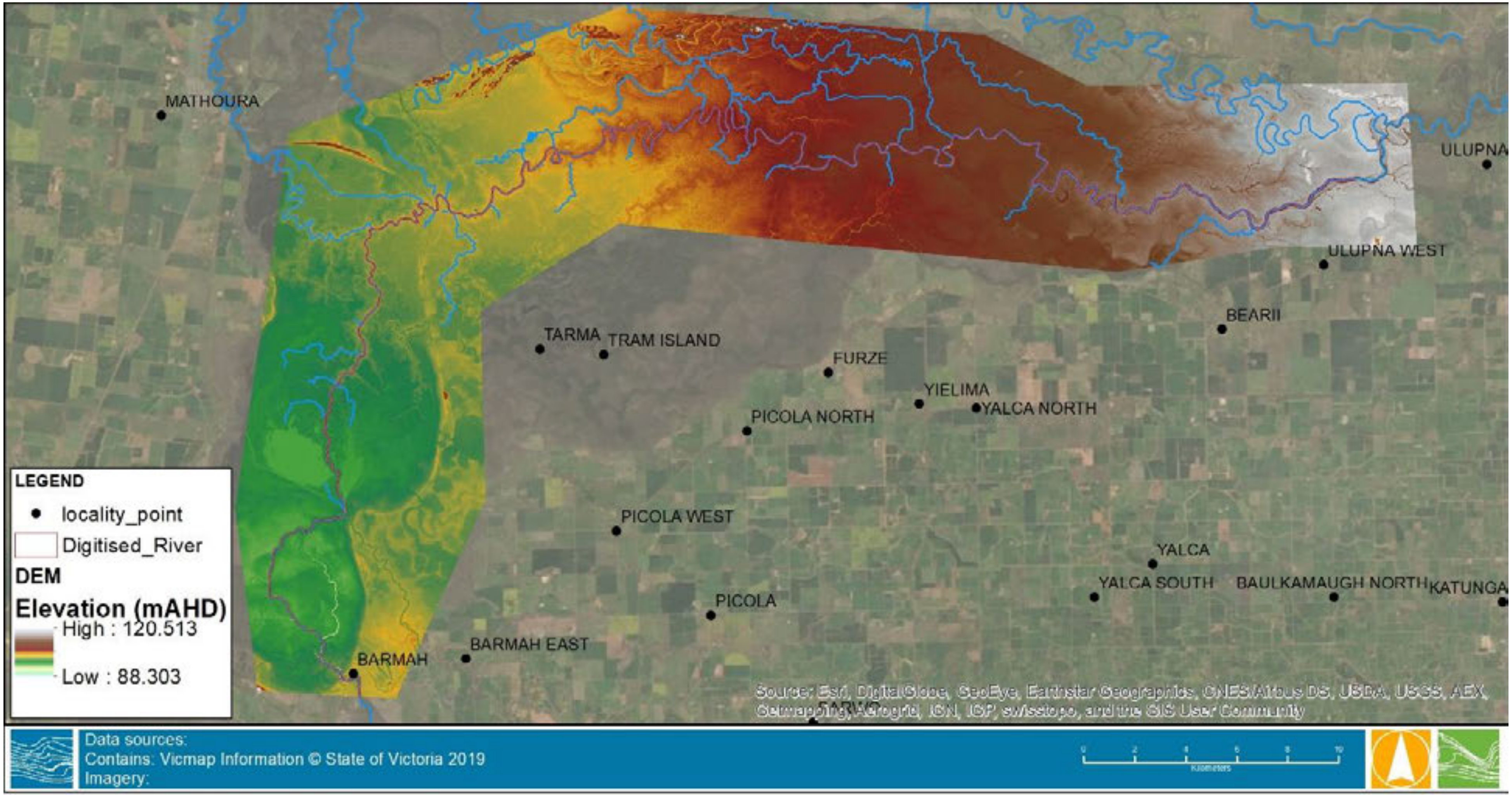

FIGURE 4-17 MODEL DOMAIN AND DEM.

4.4.3 6000 ML per day

The modelling results for the 6000 ML/day scenario show low velocities in general although there is an observable increase in energy beginning at Picnic Point and continuing downstream. Within the upper reaches velocities under this scenario are consistently around 0.4 m/s, whereas The Narrows experience around 0.6 m/s but up to 1 m/s. Peaks in velocity are also observed at the Edwards River offtake.

Bed Shear Stress for this scenario follows a similar trend with very low shear stresses of around 1.6 N/m^2 in the upstream reaches, jumping up to 5 and 6 N/m^2 in The Narrows. Whereas these shear stresses are quite low, the difference does represent a likely threshold change in terms of the entrainment threshold for coarse sands. The permissible shear stress for sands with a D_{75} less than 1.3 mm is 1 N/m^2, with fine gravels with a D_{75} less than 7.5 mm at 5.6 N/m^2 (Kilgore and Cotton, 2005).

TABLE 4-3 TYPICAL PERMISSIBLE SHEAR STRESSES FOR BARE SOIL (FROM KILGORE AND COTTON, 2005)

Category	Material	Permissible Shear Stress (N/m^2)
Bare Soil, Non-cohesive (PI < 10)	Finer than coarse sand D_{75} < 1.3 mm	1.0
	Fine gravel D_{75} = 7.5 mm	5.6
	Gravel D_{75} = 15 mm	11

4.4.4 9500 ML per day

The modelling results for the 9500 ML/day scenario show slightly higher velocities within the upper reaches compared to those of the 6000 ML/day scenario with velocities around 0.5 m/s. However, downstream of the Edwards River offtake the velocities are almost identical to those in the 6000 ML/day. This is the same for bed shear stress with values slightly higher than those in the 6000 ML/day scenario upstream of the Edward River offtake and similar values downstream. This may be due to the constriction of The Narrows being the major hydraulic control, forcing water through levee breaches. A comparison of velocities and bed shear stresses for all scenarios against reach chainage is shown in Figure 4-18.

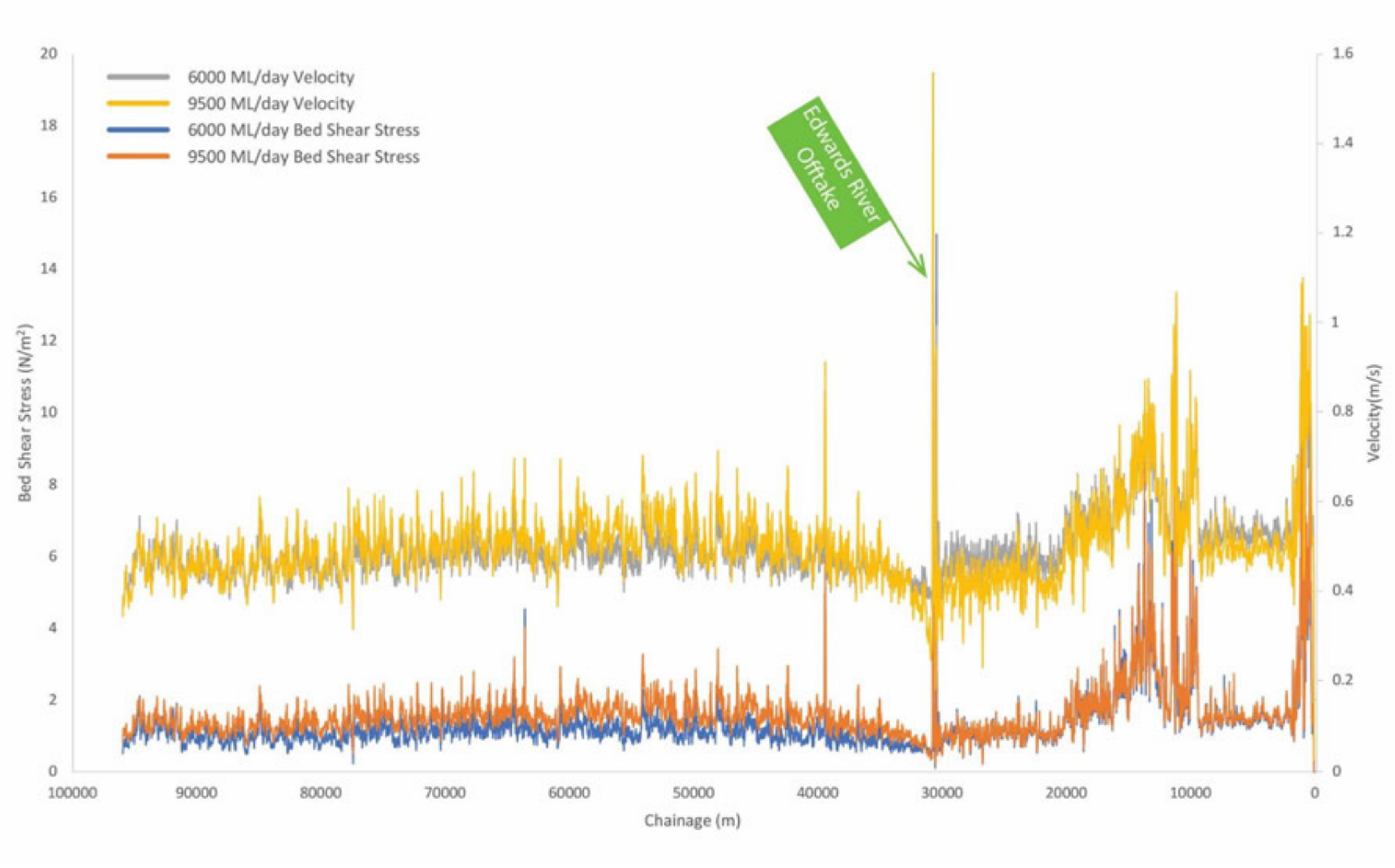

FIGURE 4-18 CENTRELINE, PEAK VELOCITY AND BED SHEAR STRESS FOR THE 9500 ML/DAY AND 6000 ML/DAY MODELLING SCENARIOS AGAINST CHAINAGE, WHERE CHAINAGE 0M EQUATES TO RIVER MURRAY CHAINAGE 1760.6KM.

5 DISCUSSION

The results from this study provide information into the condition of the Murray River in the Barmah Choke area and some insight into the processes occurring within the channel. However, they only provide part of the story and more information is required to confidently answer some of the key questions with regards to channel capacity and conveyance. These key questions are listed below and discussed in the following sections.

1. What is the current geomorphic condition of the reach?
2. What are the threatening processes occurring within the reach?
3. Are these processes currently affecting channel capacity?
4. What is the magnitude and trajectory of change of these threatening processes?
5. What are the potential management options, opportunities and costs associated with maintaining current channel capacity?

5.1 What is the current geomorphic condition of the reach?

Currently the study area can be broadly divided into two reaches based on geomorphic and riparian condition. These reaches correlate well with the two dominant fluvial processes occurring within the study area, along with bedform types and breaks in channel slope.

The reach upstream of Picnic Point and the Edwards River offtake is in moderate condition. The reach is dominated by lateral migration. This is a very low energy environment with a coarse sandy bedload (likely large volumes), where the channel is slowly moving through the extension of meander bends through erosion, with deposition occurring on the corresponding inside bend. The channel in this reach has gone through and will continue to go through phases of channel lengthening (through the meander extension process) and channel shortening (through the meander cut-off process). Bank erosion throughout this reach is common but for the most part associated with the processes mentioned above. These are likely exacerbated by anthropogenic activities such as boating and river regulation. The riparian vegetation adjoining the top of river bank generally comprises a continuous River Red Gum overstorey, however is generally devoid of shrub or native grasses (Figure 4-2 and Figure 4-3). This vegetation is threatened by anthropogenically induced erosion, where trees on the bank are undermined and collapse. Bank face and in channel vegetation in this reach is also notably absent, apart from isolated zones where macrophytes have established (Figure 4-3).

The downstream reach between the Edwards River offtake and Barmah is in poor condition. This is a higher energy reach than the reach upstream of the Edwards River offtake, albeit still very low energy when compared to Australian rivers in general. This reach has a slightly finer sandy bedload, however bedform indicates that this reach is less dominated by sand. Bank erosion in this reach is occurring on both sides of the channel, indicating channel widening (although cross section analysis shows only minor widening). The eroded bank profile is typical of boat wash induced erosion. The profile also includes a uniform notch typical of erosion through relatively stable water levels in regulated rivers. Riparian vegetation where present is in good condition albeit sparse. The vegetation is also threatened by the channel widening process, where trees on the bank are undermined and collapse. Like the upstream reach, bank face or/and in channel vegetation in this reach is notably absent, apart from isolated areas of macrophytes.

5.2 What are the threatening processes occurring within the reach?

As discussed above, the key geomorphic processes occurring within the study reach are lateral migration and channel widening. Lateral migration is a natural process and not seen as a threatening process to waterway health, whereas channel widening, in this scenario, is largely an anthropogenically forced process. Channel widening could become a problem as it often accompanied by channel capacity reduction through a reduction in energy and subsequent aggradation of the bed, however, such aggradation was not identified in this study. These processes are both exacerbated by the relative stable water levels associated with river regulation.

Erosion of the riverbanks within the study area will contribute fine sediment to the reach with bank materials consisting of fine sandy silts and clays. This suggests that a majority of bed material within both reaches in not locally derived. However, the process that may threaten hydraulic conveyance in the upper reach is the erosion of and breaching of levee features that would have otherwise increased conveyance at high flow.

While there is a general understanding that vessel wash contributes to riverbank erosion, at this stage the precise contribution to erosion in this reach from boating activity remains unknown. Many of the erosional features in the reach are typical of boat wash, indicating that boating activity may play a significant role, at least in localised areas. The presence of these erosional features, in particular elongated ledges rising to vertical scarps, results in a common bank profile often observed in other high boat use areas, such as in the vicinity of Bundalong (MDBA 2017) and indicate an accelerated rate of upper bank retreat.

The combined effects of both river regulation and boating are likely to be compounded through the interaction of both processes. This is particularly true where boating activity is occurring during sustained high flow periods where the water surface intersects with the vertical upper bank profile. Therefore, it is likely that present boating activities or intensities are unsustainable within the project reach particularly where vulnerable banks present a high risk of levee breaches (breakouts) occurring.

The only two viable options for managing the impacts of vessel wash are to regulate vessel operations or to implement measures to armour the banks. Any future management strategies and decisions related to dealing with vessel wash impacts in the reach should be based on sound scientific evidence and advice including collection of site-specific boat usage data.

5.3 Are these processes currently affecting channel capacity?

Channel capacity change within the study reach over period in which survey has been captured (1986 to 2017) vary significantly, with some cross-sections indicating capacity reductions and other indicating capacity increases. As discussed in Section 2.3.2, measuring channel capacity changes through cross section analysis, particularly at the resolution of data available for this study is not possible with any accuracy. This is particularly true given the nature of the river in this location and the expected changes to bedform. Despite the limitations associated with this data, there is some indication of minor channel capacity reduction occurring in the upstream reaches; however, only two cross-sections show a consistent trend in reduction over the four data capture dates, with the others simply showing a fluctuating cross-sectional area. This fluctuating channel cross-sectional area is consistent with the process described in Section 2.3.2, whereby the channel bedform is often reconfiguring, meaning that a reduction in channel cross-sectional area at one cross section is not necessarily an indication of reduction in channel cross-sectional area across a reach.

Whereas channel width has increased slightly within The Narrows over the period analysed in this study (LiDAR capture dates 2001 and 2016), channel depth cannot be assessed accurately in this section due to the absence of historic bathymetric data. The bedform assessment completed as part of this study suggests that the channel bed in The Narrows is not accreting and as such channel capacity in this section is not thought to be decreasing. Channel width in the upper reach of the study area has not changed significantly over the period analysed in this study (LiDAR capture dates 2001 and 2016). As such, if channel capacity in the upper reach is decreasing, it must be due to bed aggradation. As discussed above the bed material in this reach consists of coarse sands and differs greatly to any observed material within the riverbanks. As such the drivers that may be affecting channel capacity are not local and are a result of processes occurring outside this study area.

The only process occurring within the reach that could be affecting hydraulic conveyance is the erosion of and breaching of levee features that would have otherwise increased conveyance at high flow as discussed above. This process is the most likely to be a major influence on any loss of hydraulic conveyance.

It is noted that the Barmah Choke Study: Investigation Phase Report (MDBA, 2009), a hydrologically focussed report, concluded that there is no evidence of a general decline in hydraulic capacity within the Barmah Choke Reach that could be expected to continue into the future.

5.4 What is the magnitude and trajectory of change of these threatening processes?

The magnitude of bed aggradation in the upper reach cannot be quantified with the data currently available. It can be speculated that, if bed aggradation is occurring due to excess sandy material being slowly transported through the system, this may be a temporary issue (albeit likely long lasting). However, with no knowledge on the depth of this sand, its upstream longitudinal extent or even its source, it is not possible to establish a trajectory for this process. It is also important to note that we cannot even state with any confidence that channel capacity is decreasing to a point which threatens conveyance.

Similarly, the magnitude and impact of levee breaches on high-flow conveyance cannot be accurately assessed with the currently available data. It can be speculated that the trajectory for change from this process is likely to involve worsening as more breaches occur. However, with no high-resolution information on levee extent, levee height or breach regularity, it is not possible to identify a rate of bank retreat, frequency of levee breaches and thus magnitude of impact.

5.5 What are the potential management options, opportunities and costs associated with maintaining current channel capacity?

5.5.1 Channel Capacity

More data, analysis and investigation are required to first establish whether channel capacity is decreasing, the degree of reduction in channel capacity (if it's occurring) and the likely trajectory for change based on an investigation of the process. If excess sandy sediment from upstream of the study area is contributing to channel capacity reduction, additional bathymetric survey will be required to map the excess sediment, along with an investigation into potential sediment sources.

There are essentially four methods for managing excess sediment in any channel. These include reducing the sediment supply at the source, promoting sediment storage on the floodplain, accelerating sediment transport through the system or directly extracting sediment from the channel (Sims and Rutherford, 2017). Sims and Rutherford (2017) go on to point out that these are not necessarily mutually exclusive.

However, even with the additional information outlined above, and assuming a sediment source is identified, there will be a significant lag period (decades) between addressing the source of sediment (if it can be found) and any reduction in impacts at the Barmah Choke. Promoting sediment storage on the floodplain in this scenario is unlikely to provide any significant reduction in sediment within the channel due to the magnitude and thus infrequency of floods that would be required to move the sandy bedload out of the channel and onto the floodplain.

Accelerating sediment transport, in this area is not likely possible. As discussed in Section 4.4, bed shear stresses in this reach, even under the 9500 ML/day bank-full scenarios only reach between 1 and 2 N/m^2. As such, it is not likely possible to alter flows to a point where the threshold for entrainment of these sands is crossed (such as in The Narrows). Further hydraulic modelling, including a full calibration of the model used in this study, may see some increase in energy in this area.

This essentially leaves sediment extraction from the channel, which is unlikely to be palatable and will be required on a large scale to make any significant difference. Strategic sediment extraction areas within the study reach could see wide scale bed level lowering occur through the formation of head-cuts into the excess sand deposit. However, undertaking this option would require detailed knowledge on the thickness of the sand deposit and its longitudinal extent to ensure minimum impact to the Murray River. Additionally, such a study should consider the upstream and downstream implications to sediment transport processes and channel stability.

5.5.2 Levee Breaching and Conveyance Loss

Again, more data and analysis are required in order to understand the impacts of such a process in detail. Survey of the entire levee on both sides of the creek would be required to gauge the impact accurately. We can, however, speculate as to the potential management options for such an issue. These management options could include:

- Repair and maintenance of the levee system on both side of the creek, and bank erosion mitigation to prevent further erosion.
- Construction of a new levee system further back from the river.
- Diverting flow around the problematic reach through a pipe or channel.
- Reducing high flow levels and extending their duration to prevent flow through the breaches and maintain conveyance.

The reach in question is long with multiple levee breaches. Erosion in this reach is occurring along very long sections of difficult to access riverbank, through naturally occurring processes. It would be extremely expensive to undertake erosion mitigation along this entire section of the river and would not be in the best interests of waterway health. Even if the breaches are specifically identified and addressed directly and locally, it is likely that more breaches would form as the channel migrates in other locations. Constructing a new levee at a distance from the river that would be less susceptible to future channel migration would allow for maintenance of conveyance albeit at a slightly reduced rate. However, this would be a very large undertaking and would have various detrimental impacts on the Barmah forest.

Piping or diverting flow through a secondary channel and bypassing this section of the Murray River is another option for maintaining flow conveyance to the downstream reaches. This would, again, be a very large undertaking and would have various detrimental impacts on the Barmah Forest. Piping flows would likely be a better option in terms of reducing losses; however, there are many channels (effluents) within the area which could be stabilised (sealed and / or excavated) to serve as a bypass for the required flow volumes. Bypassing the area where breaching is affecting delivery would reduce water escaping through the levee breaches by reduce flows through this. As such, various feasibility studies would be required to determine the optimal flow rate required and the effects of this on the area being bypassed (reduction in flows and impact to sediment transport capacity).

The final option is to reduce high flow levels and extend their duration to prevent flow through the breaches and maintain conveyance. This would have to be tested using a calibrated model and some survey of the existing breaches. This study should also be undertaken in context with the channel capacity and sediment behaviour assessments to ensure that and changes to high flow don't result in deposition or channel capacity reductions.

6 RECOMMENDATIONS

6.1 Overview

The results from this study provide information into the condition of the Murray River in the Barmah Choke area and some insight into the processes occurring within the channel. However, primarily due to the limitations associated with existing monitoring datasets, the key questions can only be partially addressed. As such, more information is required to answer some of the key questions with regards to channel capacity and conveyance.

Recommendations for management with reference to these limitations and the key questions identified in the study are summarised in the following sections.

6.2 Repeat Bathymetric Survey

The new bathymetric data (2018) is extremely useful for assessing current condition and channel morphology where it has been captured. Additionally, bathymetric survey will form a key dataset moving forward to quantify changes in bed and bank form, channel capacity and conveyance. It is recommended that additional bathymetric survey be undertaken. Future high-resolution bathymetric survey should include the following:

- Supplementing the existing bathymetric survey to cover the entire width of the channel at the same resolution as the previous survey from Yarrawonga Weir to the Cobb Highway Bridge at Echuca (Figure 6-1). It is important that the survey overlaps the previous full survey for at least 100m on the upstream and downstream extents to ensure accurate stitching of the two datasets.
- Utilising appropriate technology (dual band echo sounder) over the entire bathymetric survey extent (Yarrawonga Weir to the Cobb Highway Bridge at Echuca), measure the sand depth in the riverbed, thus quantifying both the thickness of the sand deposit and its longitudinal extent across the bathymetric survey reach.

Extending the bathymetric survey extent will:

- Allow full analysis of the current project area and to establish a baseline condition.
- Assist in the identification of potential sediment source reaches and the longitudinal extent of sand deposits upstream of the project area.
- Assist in quantifying changes in bed and bank form, channel capacity and conveyance.

The capture of repeat high-resolution bathymetric survey nominally every five years, or following flood events will provide a more accurate, efficient and comprehensive method of quantifying channel change and area compared to historic monitoring techniques such as the capture of repeat cross sectional surveys at limited locations. Hence, it is not recommended that the capture of cross-sectional surveys be incorporated into any future monitoring.

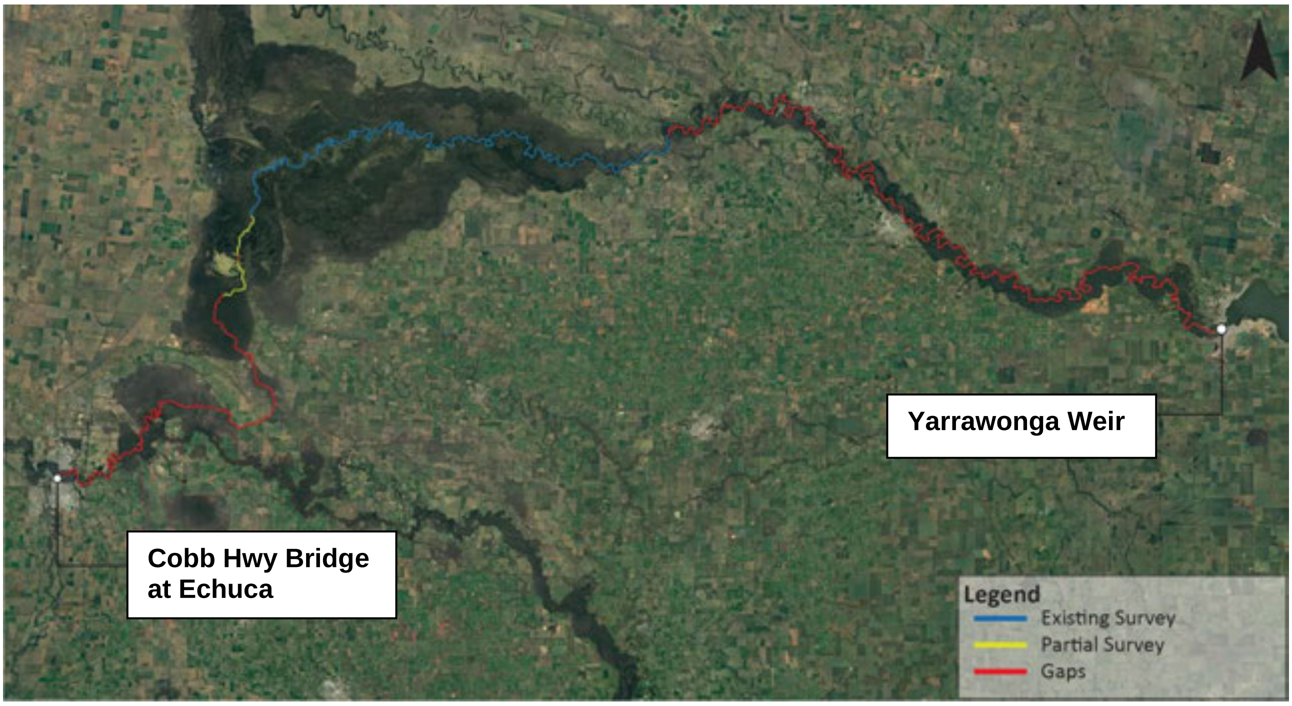

FIGURE 6-1 SURVEY REQUIREMENTS AND EXISTING SURVEY EXTENT.

6.3 Hydraulic Analysis

This study has facilitated the development of a 2D in-channel hydraulic model which incorporates the available bathymetric survey data. This hydraulic model forms a valuable tool to assess:

- Baseline conditions.
- Sensitivity to change associated with a number of influential variables.
- The effectiveness and sensitivity of potential management opportunities.

In addition, an existing independent floodplain hydraulic model has previously been established on behalf of the MDBA extending from the Tocumwal Gauge through to Barmah. This model was initially developed in 2002 and has been periodically updated to incorporate technological improvements in modelling software and higher resolution LiDAR. In addition, the model was calibrated against observations associated with the 2010 flood event.

Moving forward it is recommended that:

- The existing hydraulic model be updated to incorporate additional recommended bathymetric survey data from Yarrawonga Weir to Echuca to allow full analysis of the current project area and to establish a baseline condition (outlined in Section 6.2).
- The existing in-channel and floodplain hydraulic models be combined to provide a comprehensive in-channel/floodplain representation of the study area.
- The model be calibrated based on field measurements of water level and velocity to ensure the model accurately reflects existing conditions.

6.4 Potential Sediment Sources

This study has found that the bed load through the project area is likely to be derived from upstream sources and not from local sources within the Barmah Forest. As the Yarrawonga Weir likely presents an effective sediment trap it can be assumed that either:

- The potential sediment source reach is situated between the Yarrawonga Weir and the Barmah Forest, or from tributaries that enter the Murray River within the same reach.
- Alternatively, the sediment source is located upstream of the Yarrawonga Weir, but entered the Murray River prior to the construction of the Yarrawonga Weir.

A sediment source and sediment transport investigation could be undertaken to:

- Inform the potential sediment sources and if excess sandy sediment from upstream of the study area is contributing to channel capacity reduction through the Barmah Forest.
- Assess the effectiveness and sensitivity of potential management opportunities.

In undertaking this study, it is important to note:

- That the primary source of sediment may no longer be actively contributing sediment to the channel (e.g. historic mining activities).
- That in low energy river systems such as the Murray River, the sediment transport rates are very low. Resultantly, it may take decades for excess sandy sediment from upstream reaches to enter the Barmah Choke reach.
- Viable options to manage excess in-channel sediment loads are limited.

A sediment source and sediment transport investigation would be informed through:

- The capture of additional bathymetric survey (outlined in Section 6.2).
- Hydraulic modelling (outlined in Section 6.3).
- A particle size and sediment tracing analyses both within and upstream of the study reach.

6.5 Levee Breaching

The erosion and breaching of levee features within the Barmah Forest have the potential to reduce flow conveyance through the reach. However, the magnitude and impact of levee breaches on high-flow conveyance cannot be accurately assessed with the currently available data. That is, the LiDAR does not accurately represent either the levees or the breaches accurately.

Survey of the entire levee on both sides of the creek would be required to gauge the impact accurately. The levee survey could then be incorporated into the hydraulic model to determine the implications of the levee breaches. It is noted that it may not be considered feasible to undertake survey over the entire reach due to the substantial extent. However, survey and investigation of known key problem areas could be undertaken as a priority.

6.6 Hydrology

The interpretation of flow rates and levels through the Barmah Forest are somewhat compromised by the Picnic Point gauge:

- Capturing water levels only.
- Being positioned between the Edward River and Gulpa River offtakes, which have the potential to influence river profiles.

It is recommended that a formal stream gauge or gauges, measuring both streamflow discharge and water level be established to assist with flow management and monitoring. The establishment of gauges upstream and downstream of the Barmah Choke would provide an accurate assessment of flow loss through the project area. This should be monitored over a whole season at a minimum.

6.7 Works Program

6.7.1 Site Based Erosion Control Works

Large scale site-based management actions specifically aimed at managing flow capacity are not recommended within the study area on the basis that:

- It is not clear if channel capacity is decreasing at all, or to a point which threatens conveyance.
- The processes that may be affecting channel capacity are not local and are a result of processes occurring outside this study area.
- It would be a very large and expensive project to undertake large scale erosion mitigation along this entire section of the river due to:
  - The ubiquitous nature of bank erosion downstream of Picnic Point.
  - Lateral migration (the extension of meander bends through erosion, with deposition occurring on the corresponding inside bend (point bars)) being the dominant erosion process upstream of Picnic Point.
  - Access restrictions throughout the Barmah Forest.

Additionally, widescale intervention across the system may not only be unnecessary but also potentially harmful to river health in the long term.

Small scale bank erosion works may be undertaken where continued bank erosion threatens high value or strategic assets or areas (e.g. cultural heritage values, access tracks, levees, breakouts) and where access permits.

6.7.2 Targeted Sediment Extraction

Targeted sediment extraction has been identified as the only management solution that is likely to have any immediate or substantial effect on bed aggradation. Sediment extraction activities should only be undertaken if channel capacity is concluded to be occurring to the point which threatens conveyance. Importantly, any sediment extraction activity would require detailed knowledge on the thickness of the sand deposit and its longitudinal extent to ensure minimum impact to the Murray River. Such a study should consider the upstream and downstream implications to sediment transport processes and channel stability.

6.7.3 Flow Diversion

Piping or diverting flow through a secondary channel and bypassing this section of the Murray River is another option for maintaining flow conveyance to the downstream reaches. This would, again, be a very large undertaking and would have various detrimental impacts on the Barmah Forest. Piping flows would likely be a better option in terms of reducing losses; however, there are many channels (effluents) within the area which could be stabilised (sealed and / or excavated) to serve as a bypass for the required flow volumes. Bypassing the area where breaching is affecting delivery would reduce water escaping through the levee breaches by reduce flows through this. As such, various feasibility studies would be required to determine the optimal flow rate required and the effects of this on the area being bypassed (reduction in flows and this impact to sediment transport capacity).

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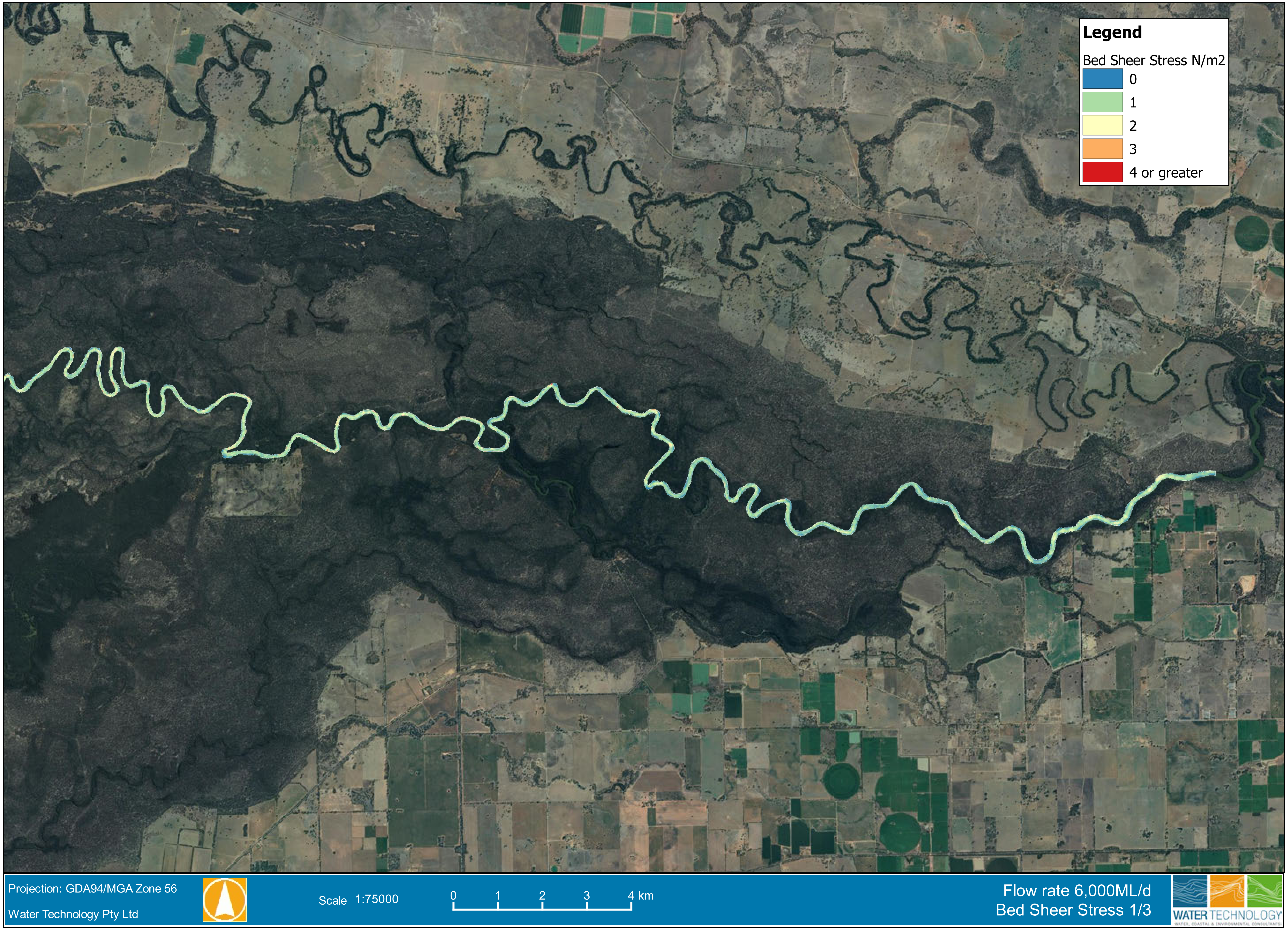
APPENDIX A
HYDRAULIC MODELLING RESULTS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Bed Sheer Stress N/m2
0
1
2
3
4 or greater
Projection: GDA94/MGA Zone 56
Water Technology Pty Ltd
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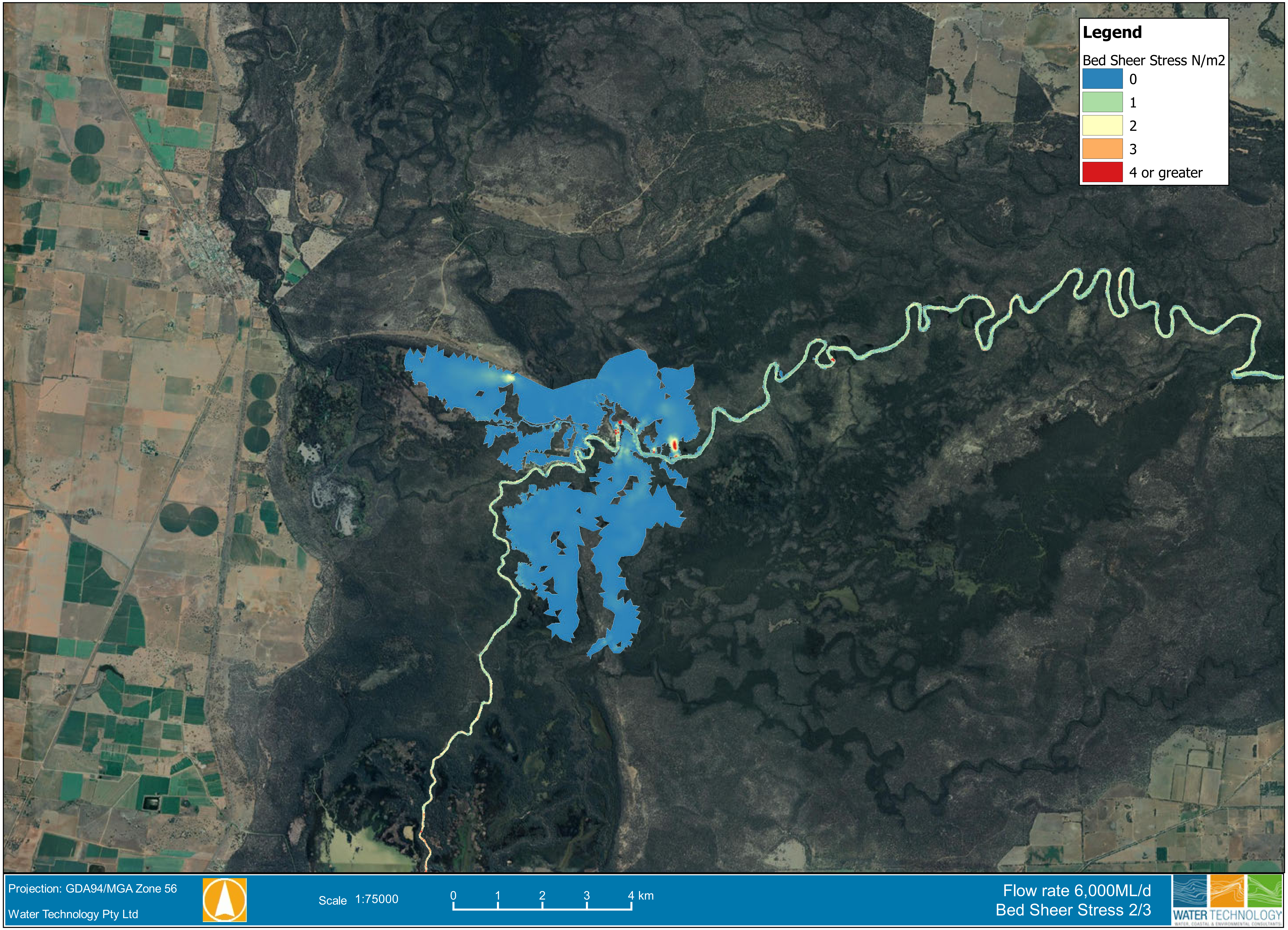
0 1 2 3 4 km
Flow rate 6,000ML/d
Bed Sheer Stress 1/3
WATER TECHNOLOGY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2
3
4 or greater
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Water Technology Pty Ltd
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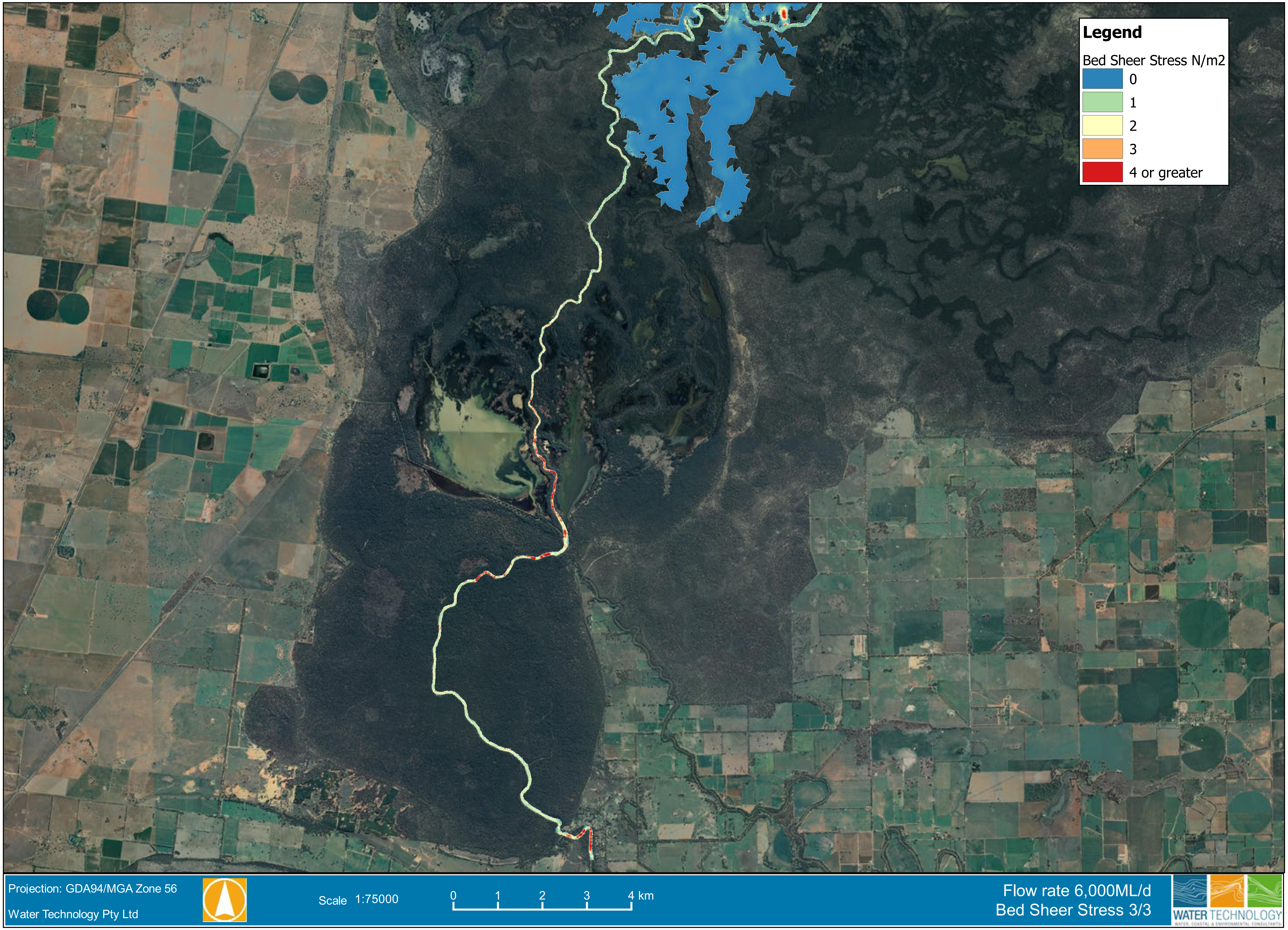
Bed Sheer Stress 2/3
WATER TECHNOLOGY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2
3
4 or greater
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Water Technology Pty Ltd
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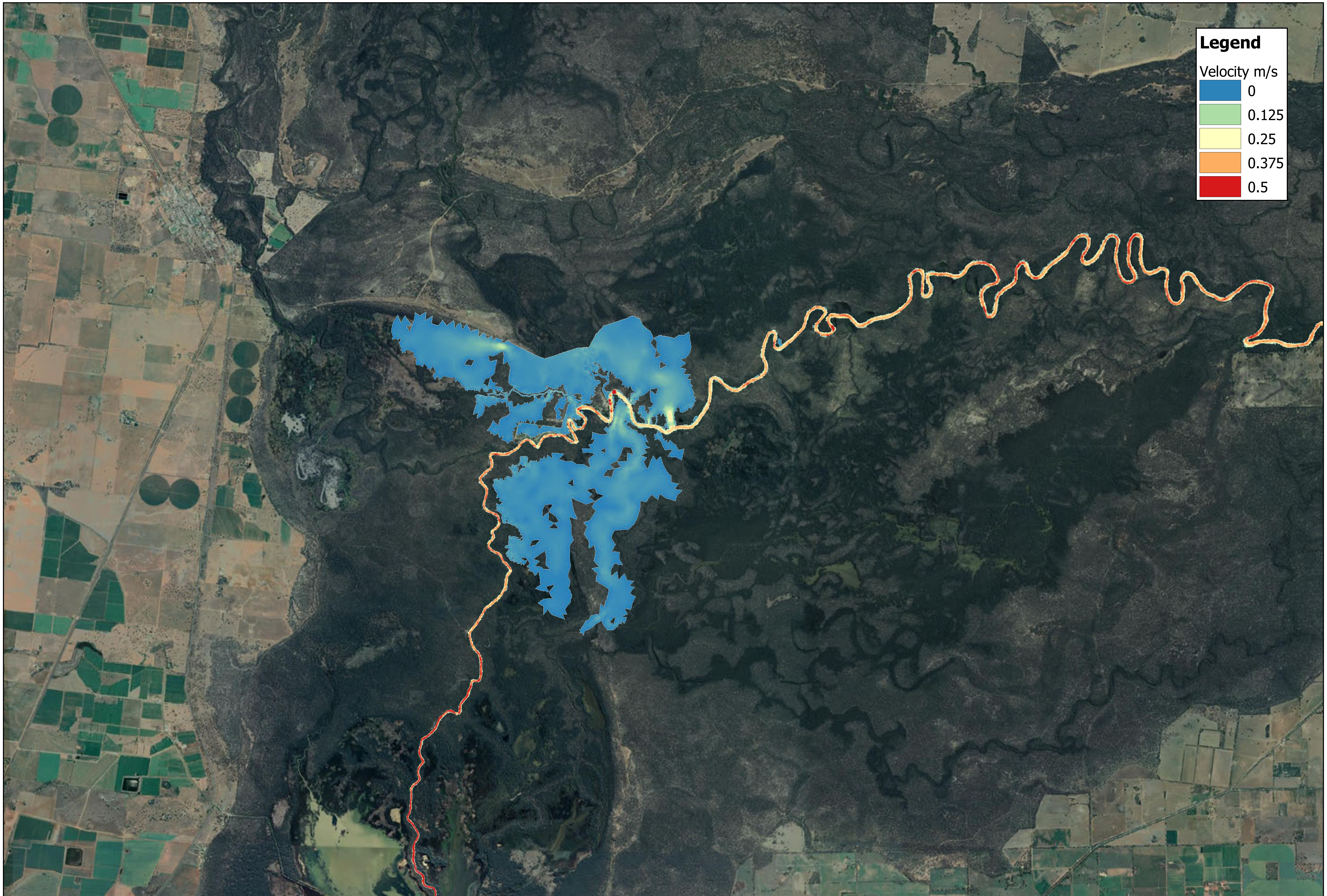
Flow rate 6,000ML/d
Bed Sheer Stress 3/3
WATER TECHNOLOGY


Legend
Velocity m/s
0
0.125
0.25
0.375
0.5
Projection: GDA94/MGA Zone 56
Water Technology Pty Ltd
Scale 1:75000
0 1 2 3 4 km
Flow rate 6,000ML/d
Velocity 1/3
WATER TECHNOLOGY



Projection: GDA94/MGA Zone 56

Water Technology Pty Ltd

Scale 1:75000

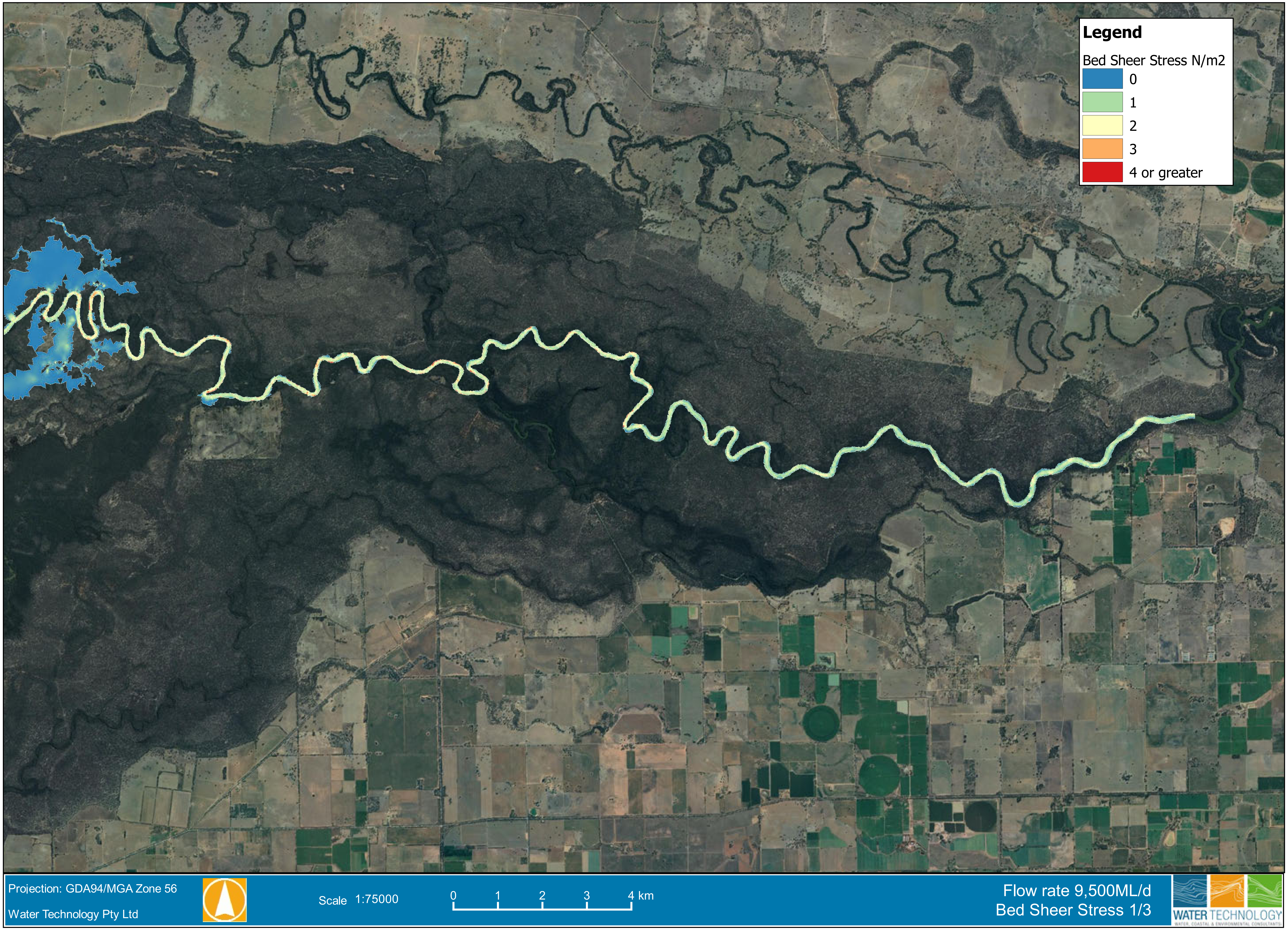
0 1 2 3 4 km

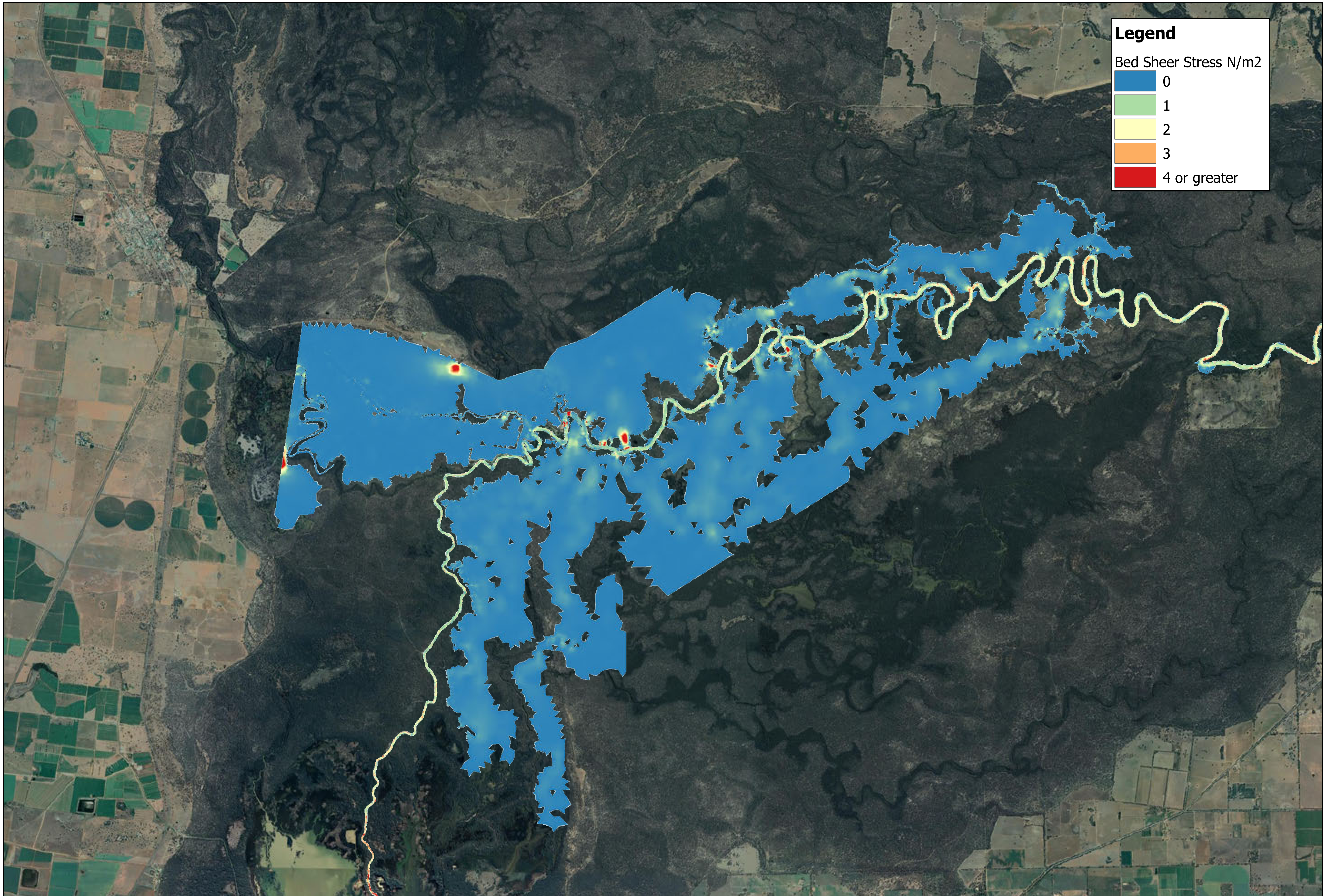
Flow rate 6,000ML/d

Velocity 2/3

WATER TECHNOLOGY

Legend
Velocity m/s
0
0.125
0.25
0.375
0.5
Projection: GDA94/MGA Zone 56
Water Technology Pty Ltd
Scale 1:75000
0 1 2 3 4 km
Flow rate 6,000ML/d
Velocity 3/3
WATER TECHNOLOGY


Legend
Bed Sheer Stress N/m2
0
1
2
3
4 or greater
Projection: GDA94/MGA Zone 56
Water Technology Pty Ltd
Scale 1:75000
0 1 2 3 4 km
Flow rate 9,500ML/d
Bed Sheer Stress 1/3
WATER TECHNOLOGY



Projection: GDA94/MGA Zone 56

Water Technology Pty Ltd

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0 1 2 3 4 km

Flow rate 9,500ML/d

Bed Sheer Stress 2/3

WATER TECHNOLOGY


Legend
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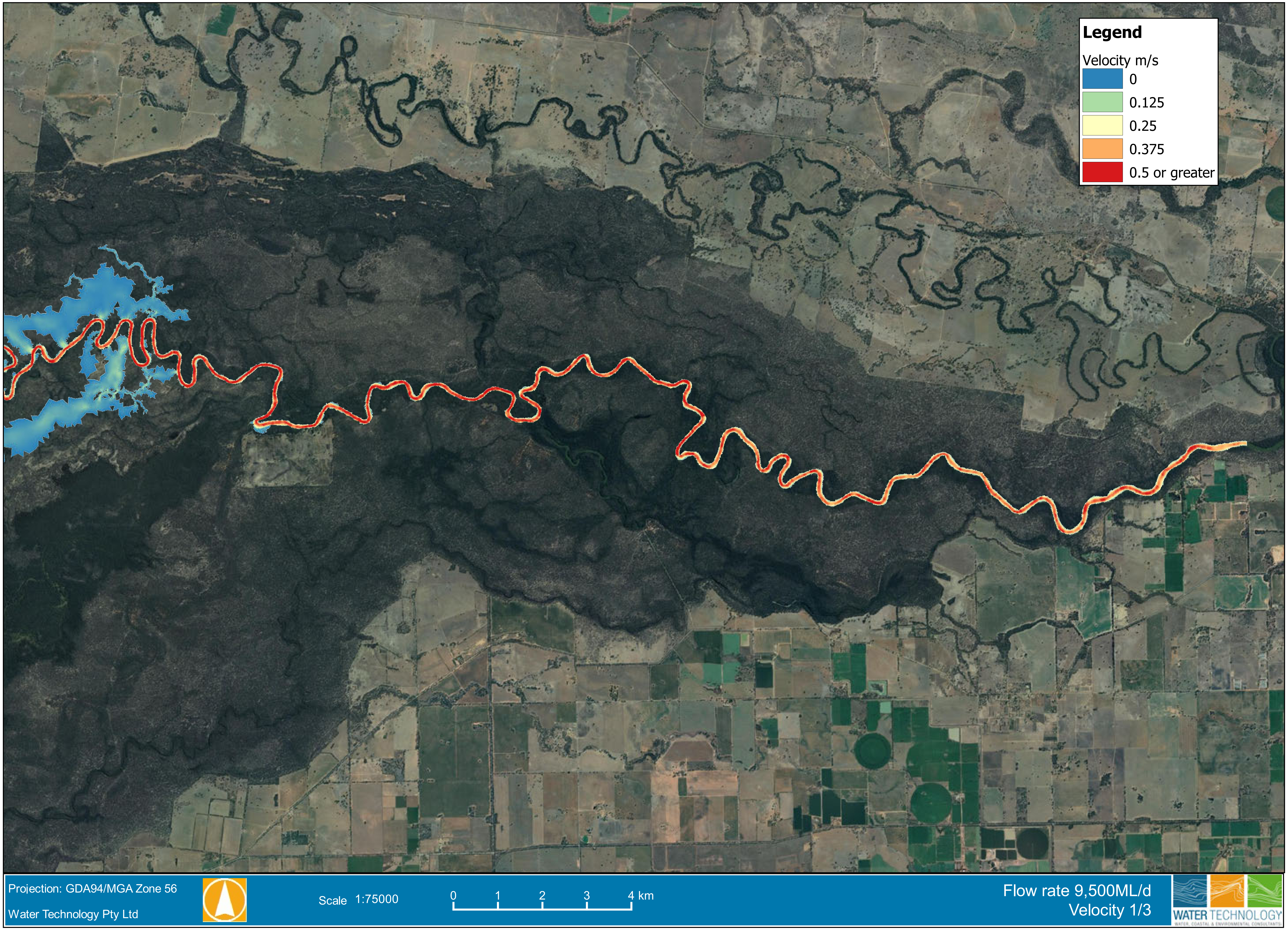
WATER TECHNOLOGY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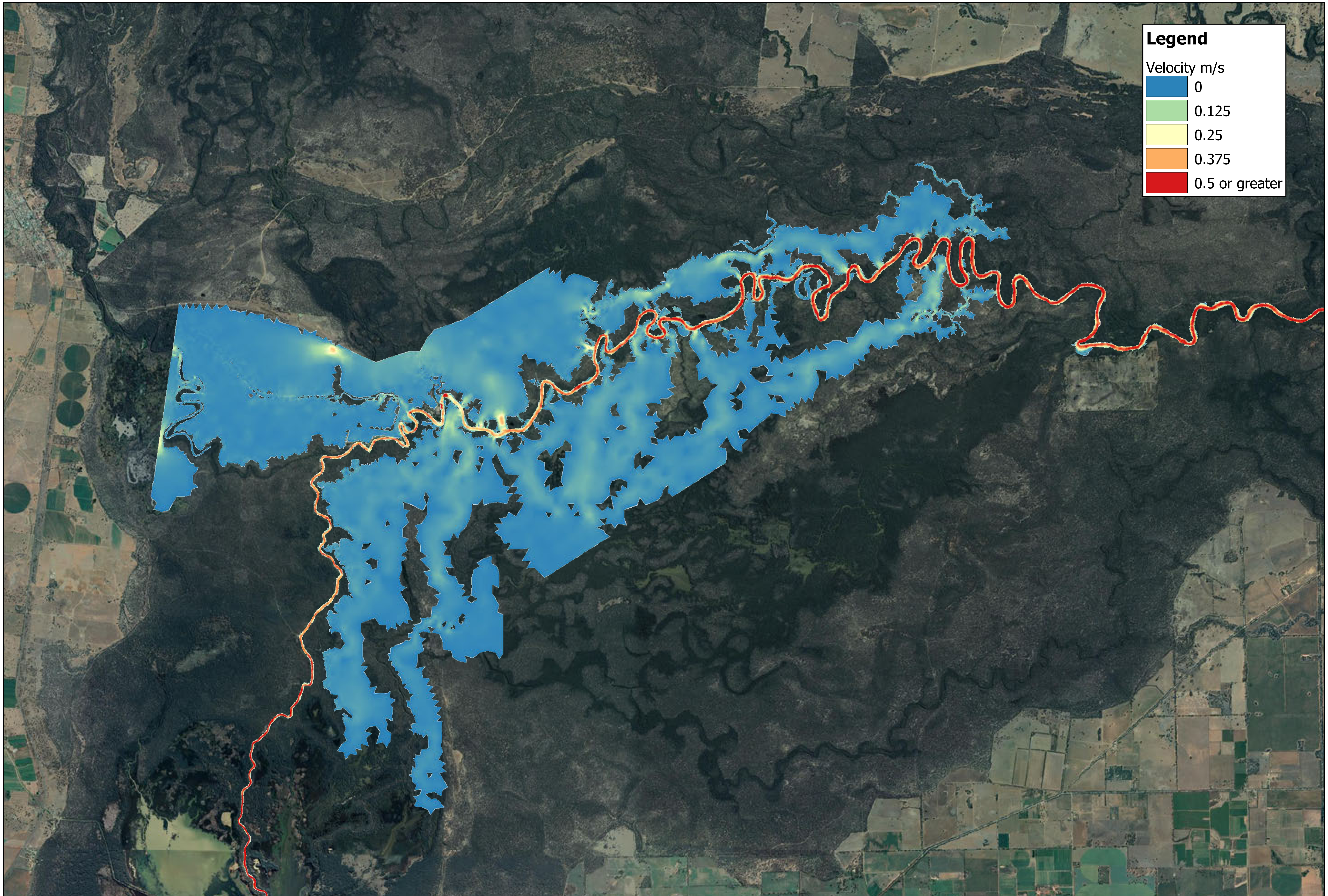

Projection: GDA94/MGA Zone 56

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Scale 1:75000

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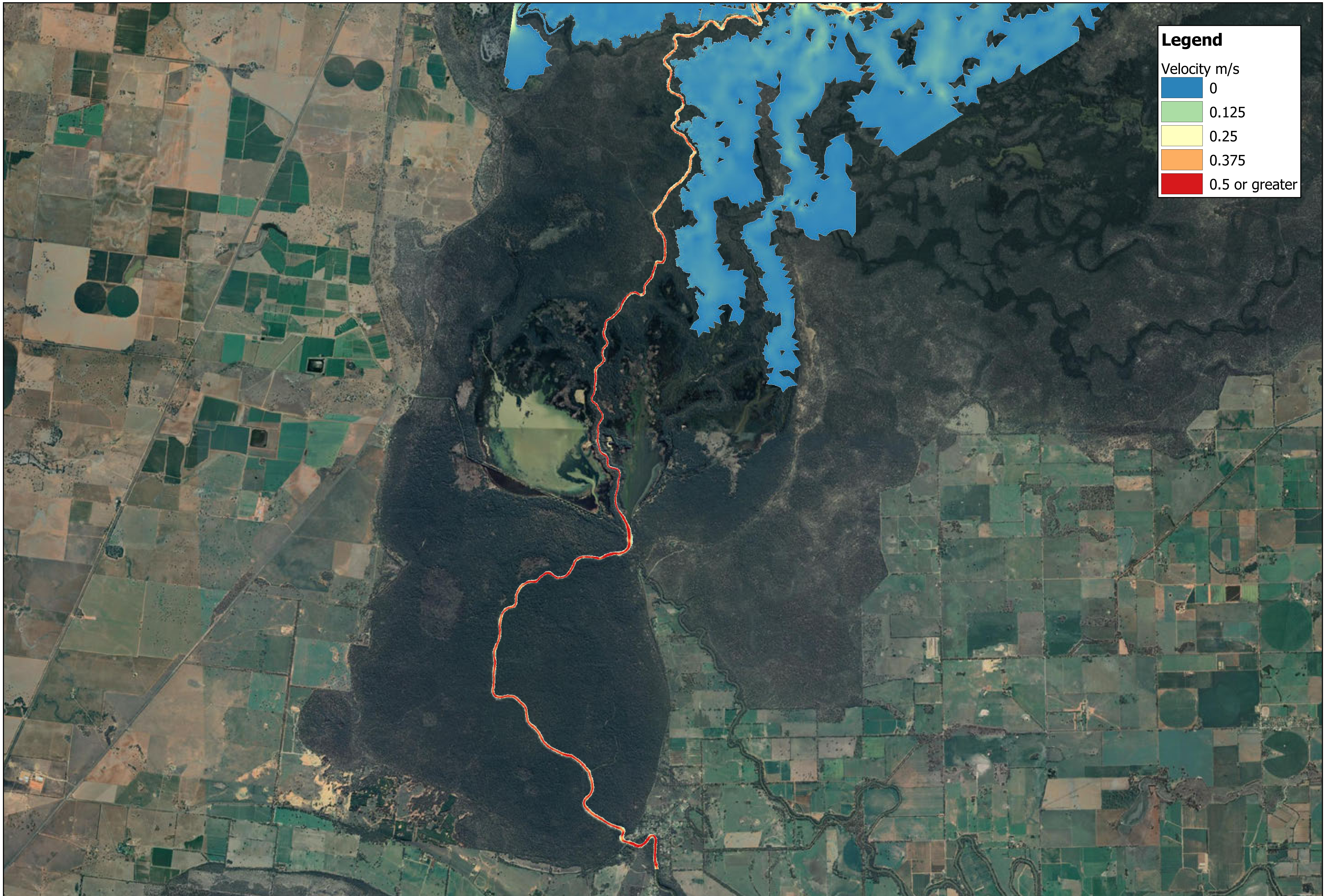
WATER TECHNOLOGY



Projection: GDA94/MGA Zone 56

Water Technology Pty Ltd

Scale 1:75000

0 1 2 3 4 km

Flow rate 9,500ML/d

Velocity 3/3

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