Geomorphic Assessment for the NSW Reconnecting River Country Program In the Murray and Murrumbidgee Rivers

Report for Water Infrastructure NSW, Department of Planning and Environment

July 2022

Prepared by:	Streamology Pty Ltd 3/11 Ireland Street Bright Vic 3741 www.streamology.com.au ACN: 600 641 370
With support from:	Water Technology Wakelin Associates Ian Rutherfurd James Grove
Consultant Contact:	Christine Lauchlan Arrowsmith Christine@streamology.com.au 0448 909 398
Citation:	Lauchlan Arrowsmith, C.S. Vietz, G. Wakelin-King, G. Grove, J. and Rutherfurd, I. Cheetham, M. Martin, J. Gower, T.G. Al Baky, A. Woods, K. Lam, D. (2022). Geomorphic Assessment for the NSW Reconnecting River Country Program in the Murray and Murrumbidgee Rivers, report prepared for Water Infrastructure NSW, Department of Planning and Environment

Document Status

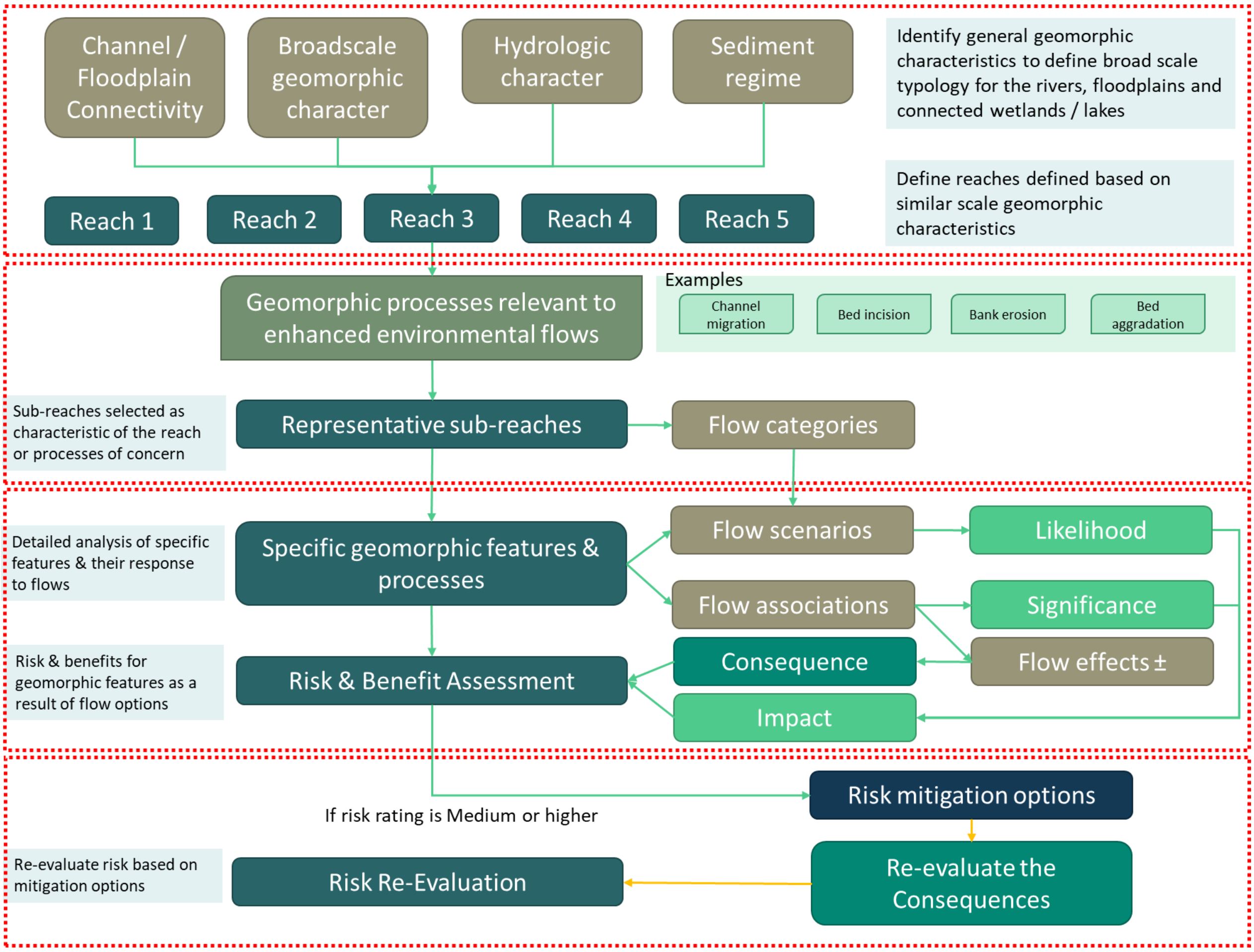
Version	Doc Type	Reviewed By	Approved By	Date Issued
V01	Draft- Part 1	CLA	CLA	07/02/2022
V02	Draft - Part 1 & 2	CLA	CLA	31/03/2022
V03	Draft - Parts 1 to 3	CLA	CLA	29/04/2022
V04	Draft (all parts)	GV	CLA	31/05/2022
V05	Final	Steering Committee	CLA	27/06/2022
V06	Final	DPE	CLA	19/07/2022

Executive Summary

The RRC Program in the Murray and Murrumbidgee catchments aims to improve environmental, social, and cultural outcomes for communities along the River Murray and Murrumbidgee River systems. The program aims to achieve a balance of these outcomes by improving wetland and floodplain connectivity through investigating relaxing or removing some of the constraints or physical barriers that impact delivering water for the environment. It has focussed on the following areas in the southern-connected Murray Darling Basin (the basin), including:

- Hume to Yarrawonga (River Murray)
- Yarrawonga to Wakool (River Murray)
- Murrumbidgee River

Within the RRC program, the objective of the project summarised in this report was to complete a detailed assessment of how delivery of water for the environment, under new flow limit options being considered, will influence the physical form and functioning of these river systems (i.e., their geomorphology), and how this, in turn, might impact on opportunities for water delivery. The following figure summaries the scope of work for the project undertaken in four parts (as defined by the red boxes) to understand the geomorphic risks and benefits of the proposed flow limit options across the rivers and floodplains of the study areas.



Geomorphic Characterisation of the Study Area

The project team undertook a detailed review of the regional geology and geomorphology of the southern Murray-Darling Basin to inform our understanding of the geological context, paleoclimate, landscape evolution, and soils distribution of the waterways in the study area. This information was then combined with elements of various geomorphic classification systems to create a project specific reach-based river channel and floodplain classification system suitable for the River Murray and Murrumbidgee River systems (refer Figure 12). The reaches are typically in the order of tens to hundreds of kilometres in length.

To assess potential flow related risks and benefits within these reaches, it was then necessary to identify sub-reaches which are characteristic of the broader reach type and contained one or more of the dominant geomorphic features of that reach type. They are also typically in the order of a few hundred metres to several kilometres in spatial extent.

Geomorphic features can vary from within-channel features, such as sandbars and riverbanks, to rarely inundated features several kilometres from the main channel, such as floodplain wetlands. All these features have a differing impact on the functions of the river channel.

Geomorphic processes are the way in which features are formed by a range of interactions between flow, sediment, and vegetation. These processes drive the character of the rivers and in turn the value provided by the geomorphic features. Changes in flow can have significant impacts on these processes, such as increases in prolonged bankfull flows driving meander migration and river bend cutoffs.

For each of the 30 representative sub-reaches we analysed the geomorphic features and processes that were present and how they are linked to flow categories, such as freshes, bankfull and overbank flows. From this analysis a 'base case' geomorphic condition and trajectory were developed for each sub-reach which reflected the current (and historic) flow and river management regimes.

Impact Assessment

To understand and quantify the risks and benefits of the flow option scenarios on geomorphic features and conditions we first developed an "impact score" which draws together the various flow categories at a sub-reach level by their frequency of occurrence (likelihood) and the geomorphic features and processes and how they might change (= significance). To do this we have combined the sub-reach assessments of geomorphic forms and processes with the flow categories and frequency of occurrence as calculated from detailed hydrologic modelled (supplied by DPE).

An impact score was then derived for the current constraints flow conditions across each waterway (as provided by the base case scenario) and then for each flow options scenario. The percentage change in impact score was calculated by feature and flow scenario, and then combined for the features within a sub-reach. The resultant changes can then be compared between sub-reaches and then consolidated into the broader geomorphic reach and landscape scales. This provides an indication of the overall sub-reach and reach scale likelihood of geomorphic change because of the flow regime proposed under the flow options scenarios. It does not provide a quantitative measure of actual geomorphic changes that would be realised under the flow options.

Risk and Benefit Assessment

For the risk-benefit assessment we combined the sub-reach change in impact scores (as an indicator of the likelihood of potential geomorphic change), with an understanding of the consequences of geomorphic change occurring (both positive and negative). The risk and benefit analysis produced the following outcomes.

For the River Murray:

- The **River Murray and floodplain from Hume to Yarrawonga** has a medium risk of geomorphic change associated with all the flow options scenarios. Within the medium risk rating the likelihood of change is *unlikely* while the consequence is considered *moderate*. This risk rating is reduced to low if mitigation measures are put in place. Only low geomorphic benefits were identified.
- The **River Murray and floodplain from Yarrawonga to Wakool Junction** has a medium risk of geomorphic change associated with all the flow options scenarios and only low geomorphic benefits were identified. Again, the likelihood of the risk occurring is *unlikely*, but the consequence is *moderate*. This risk rating is reduced to low if mitigation measures are put in place.
- The **River Murray and floodplain from Wakool Junction to Wentworth** has a low risk of geomorphic change associated with all the flow options scenarios and low geomorphic benefits.

For the Edward (Kolety) - Wakool River system:

- The **Edward (Kolety) - Wakool River system and floodplain (within the broader River Murray Yarrawonga to Wakool Junction** has a medium risk of geomorphic change associated with the higher flow options scenarios. Within the medium risk rating the likelihood of change is *unlikely to possible* while the consequence is considered *moderate*. This risk rating is reduced to low for many locations if mitigation measures are put in place.
- There are also medium benefits across many of the waterways.
- Under the lower flow options scenarios risks are generally reduced to low.

For the Murrumbidgee River system, including the Tumut River and Yanco Creek:

- The **Murrumbidgee River and floodplain (from Burrinjuck Dam to the Yanco Creek system)** has a medium risk of geomorphic change associated with the higher flow options scenarios. This reduces to low risk under the lower flow options scenarios. Within the medium risk rating the likelihood of change is *unlikely* while the consequence is considered *moderate*. This risk rating is reduced to low if mitigation measures are put in place.
- The **Murrumbidgee River and floodplain (from the Yanco Creek system to the Murray Junction, including the Lowbidgee floodplain)** has a low risk of geomorphic change for all the flow options scenarios.

- The **Yanco Creek system and floodplain** has a medium risk of geomorphic change associated with the higher flow options scenarios. This reduces to low risk under the lower flow options scenarios. Within the medium risk rating the likelihood of change is *unlikely* while the consequence is considered *moderate*. This risk rating is reduced to low if mitigation measures are put in place.
- The **Tumut River and floodplain (below Blowering Dam to the junction with the Murrumbidgee)** has a low risk all the flow options scenarios.

Whilst the risk of environmental flows on geomorphic features and processes is rated medium for some reaches, it is important to recognise that this is the result of consequences being considered moderate. It is the unlikely, or very unlikely, likelihood of change that should be considered in the context of delivering the benefits of environmental flows in the River Murray and Murrumbidgee River systems.

Mitigation Options and Risk Re-Evaluation

All those sub-reaches with a **Medium** risk rating under one or more of the flow options scenarios were then reviewed to identify potential risk treatments (mitigation opportunities) which would allow the risk to be reduced to a tolerable (**Low**) level through reducing the consequences associated with negative changes to geomorphic feature or processes.

Risk Treatments

- Operational controls and delivery planning are activities that manage the flow regime to minimise geomorphic risks. An example is the "six-inch rule", a constraint on the rate of rise and fall of regulated flows in the River Murray downstream of Hume Dam to minimise potential for bank erosion. Not only will the delivery of environmental flows be managed to maximise benefits and minimise risk, but it will drive improved management of operational flows. This was demonstrated when the Goulburn River, Victoria, moved to a more varied flow regime that minimised geomorphic impacts.

- The typical activities that have been undertaken within previous or existing River Works Programs include riparian/riverbank revegetation, stock exclusion fencing, and physical interventions for erosion control. Physical interventions have included rock or log revetments, timber groynes and avulsion control structures (e.g., pile fields). These programs typically have a specific river management objective which then defines the scope and types of risk treatments that are adopted.

- Other programs or projects that may influence or be influenced by the RRC program and through which actions or activities can be undertaken that would mitigation potential geomorphic risks e.g., the outcomes of the Barmah-Millewa Feasibility Study may include recommendations or actions on managing the excess sand in the reach, which would also address the geomorphic risks identified in this project.

Risk Re-Evaluation

Based on the application of risk mitigation options identified as suitable treatments the geomorphic risks for those sub-reaches with Medium risk ratings were re-evaluated. Overall, the mitigated results indicate that if the proposed risk treatments are applied successfully, all the Medium risk ratings can be reduced to Low throughout the River Murray. This is also the case for the Murrumbidgee River system, including Yanco Creek. Implementation of these treatment may also address current geomorphic risks, such as bank erosion because of prolonged sub-bankfull flows which can occur because of regulation, or bank erosion downstream of flow regulating structures occurring because of the rapid rise and fall of water levels during the structure operations.

Within the Edward (Kolety) - Wakool River system, the risk rating for the mid Wakool and mid Niemur sub-reaches remains at Medium even with the proposed risk treatments. This outcome occurs because the likelihood of change across the flow categories is in the Possible range. However, from a geomorphic perspective these reaches are currently highly impacted by a regulated flow regime and while the reintroduction of a more variable flow regime will result in change through reactivation of geomorphic processes this could be considered as much a benefit as a risk. This remaining risk is best addressed through a Monitoring, Evaluation, Reporting and Improvement Plan (MERI).

Environmental flows cannot be expected to combat a century of change within a few years. In the short term we may see changes that are the river system adjusting to legacy impacts of extensive and ongoing river operations. It is important to recognise that this phase of adjustment, including processes such as bank erosion, is an important step toward a healthy River Murray system.

We note that environmental flows are difficult to distinguish from operational flows in terms of their impacts on riverbanks and river morphology. A good test case for understanding these differences is the Goulburn River in Victoria. A decade of monitoring on this system has highlighted that whilst geomorphic changes such as bank erosion may occur following environmental flows, it is the preparation of the riverbanks by prior operational flows that has been found to be the main cause.

Future work

To further improve the assessment outcomes, verification of the current geomorphic condition of the rivers across the study area through targeted field assessments is recommended. This field work could be completed as part of the baseline monitoring when implementing the proposed flow options and/or mitigation opportunities.

Abbreviations

DPE	NSW Department of Planning and Environment, previously known as the Department of Planning, Industry and Environment (DPIE)
DLWC	Department of Land and Water Conservation
LTWP	Long Term Water Plan
MDBA	Murray-Darling Basin Authority
MERI	Monitoring, evaluation, reporting and improvement
TLM	Living Murray Program
SDLAM	Sustainable Diversion Limit Adjustment Mechanism
SRA	Sustainable Rivers Audit

Glossary

Aggradation	Increase in elevation (e.g., of a riverbed) due to the deposition of sediment carried by a river, stream, or current.
Anabranch	An anabranch is a section of a river or stream that diverts from the main channel and rejoins the main channel downstream.
Avulsion	Reasonably rapid development of a new channel path on the floodplain, and abandonment of the existing channel path.
Bankfull flow	River flows at maximum channel capacity with little overflow to adjacent floodplains. These flows engage the riparian zone, anabranches, flood runners and wetlands located within the meander train. They inundate all in-channel habitats including benches, snags and backwaters.
Breakaway	A low point on the riverbank that allows water to flow away from the River Murray main channel. Some of these flow paths return water to the channel (e.g., meander cut offs) whilst others deliver flows to flood outs (defined below) on the floodplain, but these typically do not return flow to the Murray channel
Constraints	The physical or operational constraints that affect the delivery of water from storages to extraction or diversion points. Constraints may include structures such as bridges that can be affected by higher flows, the volume of water that can be carried through the river channel, or scheduling of downstream water deliveries from storage.
Cutoff	A new, shorter channel abandoning an individual bend, a whole meander loop or multiple loops (Erskine et al 1992a)
Discharge	The volumetric flow rate of water that is transported through a given cross-sectional area of river channel.
Environmental water	Water for the environment. It serves a multitude of benefits to not only the environment, but communities, industry and society. It includes water held in reservoirs (held environmental water) or protected from extraction from waterways (planned environmental water) for the purpose of meeting the water requirements of water-dependent ecosystems.
Flow category	The type of flow in a river defined by its magnitude (e.g. bankfull).
Flow regime	The pattern of flows in a waterway over time
Freshes	Temporary in-channel increased flow in response to rainfall or release from water storages.
Large fresh	High-magnitude flow pulse that remains in-channel. These flows may engage flood runners with the main channel and inundate low-lying wetlands. They connect most in-channel habitats and provide partial longitudinal connectivity, as some low-level weirs and other in-channel barriers may be drowned out.
Lateral connectivity	The flow linking rivers channels and the floodplain.

Levee	A levee can form as a ridge of sediment naturally deposited along the margins of a river channel by overflowing water. Levees can also be artificially constructed along a channel to prevent flooding.
Longitudinal connectivity	The consistent downstream flow along the length of a river
Meander	A meander is one of a series of regular sinuous curves in the channel of a river or other watercourse.
Overbank flow	Flows that spill over the riverbank or extend to floodplain surface flows
Paleochannel	A remnant of an inactive river or stream channel that has been filled or buried by younger sediment.
Paleolake	A remanent of a lake that existed when the climate and hydrological conditions were different than today.
Point bar	Largely unvegetated body of sediment within the river channel against the inside bank of a bend.
Regulator	An artificial structure that regulates flow in or out of a breakaway
Regulated river	A river that is gazetted under the NSW Water Management Act 2000. Flow is largely controlled by major dams, water storages and weirs. River regulation brings more reliability to water supplies but has interrupted the natural flow characteristics and regimes required by native fish and other plant and animal to breed, feed and grow.
Riparian	The part of the landscape adjoining rivers and streams that has a direct influence on the water and aquatic ecosystems within them
Sand slug or sand pulse	A body of sand deposited in a stream channel, often conceptualised as a wave migrating along the bed of the stream. Normally they disperse over time and are often spread over long distances of river.
Scroll bar	A pronounced central ridge running the length of the point bar platform parallel to the curvature of the channel and separated from the bank by a swale (Nanson, 1980)
Sinuosity	The sinuosity of a watercourse is the ratio of the length of the channel to the straight line down-valley distance.
Small fresh	Low-magnitude in-channel flow pulse.

Acknowledgement

The NSW Department of Planning and Environment pays its respect to the Traditional Owners and their Nations of the Murray-Darling Basin. The contributions of earlier generations, including the Elders, who have fought for their rights in natural resource management are valued and respected.

In relation to the Murrumbidgee catchment, the NSW Department of Planning and Environment pays its respects to the Traditional Owners – the Barapa Barapa, Mutthi Mutthi, Nari Nari, Ngarigo, Ngunnawal, Nyeri Nyeri, Wadi Wadi, Wolgalu, Wemba Wemba, Weki Weki and Wiradjuri Nations – past, present and future.

contents

1. Introduction

1.1. Overview

After almost a century of regulation, reconnecting River Murray country is not without challenges, but it has huge potential to transform the future of the landscape for people and the environment

The NSW Department of Planning & Environment (DPE) is undertaking the Reconnecting River Country Program (the RRC Program) in the Murray and Murrumbidgee catchments to improve environmental, social, and cultural outcomes for communities along the Murray and Murrumbidgee River systems. The program aims to achieve a balance of these outcomes by improving wetland and floodplain connectivity.

The program is investigating relaxing or removing some of the constraints or physical barriers that impact delivering water for the environment in the following areas in the southern-connected Murray-Darling Basin (the basin), including:

- Hume to Yarrawonga (River Murray)
- Yarrawonga to Wakool (River Murray)
- Murrumbidgee River

A constraint is any physical, policy or operational barrier limiting the flow of water in river systems. There are a range of flow constraints in the Murray-Darling Basin put into place since the construction of flow structures (Dams, weirs etc.), meaning rivers connect to their floodplains less often than is needed to maintain healthy river, wetland, and floodplain ecosystems. Removing or 'relaxing' constraints allows water for the environment to be delivered at higher levels and at more appropriate times which will enhance ecological outcomes. A range of flow limit options are being analysed to determine the ecological outcome for each scenario. In addition, the development of mitigation measures for affected landholders will be considered.

Within the broader Program, the NSW Department of Planning and Environment (DPE) is undertaking a suite of environmental benefit-risk assessments to inform flow limit options evaluation and development of a strategic business case. These include assessing expected outcomes for native vegetation, native fish, waterbirds, ecosystem functions (productivity), the spread of invasive weed species and carp, water quality and geomorphic processes (this study).

The geographic scope of waterways under consideration in this project is extensive, as detailed in Figure 1.

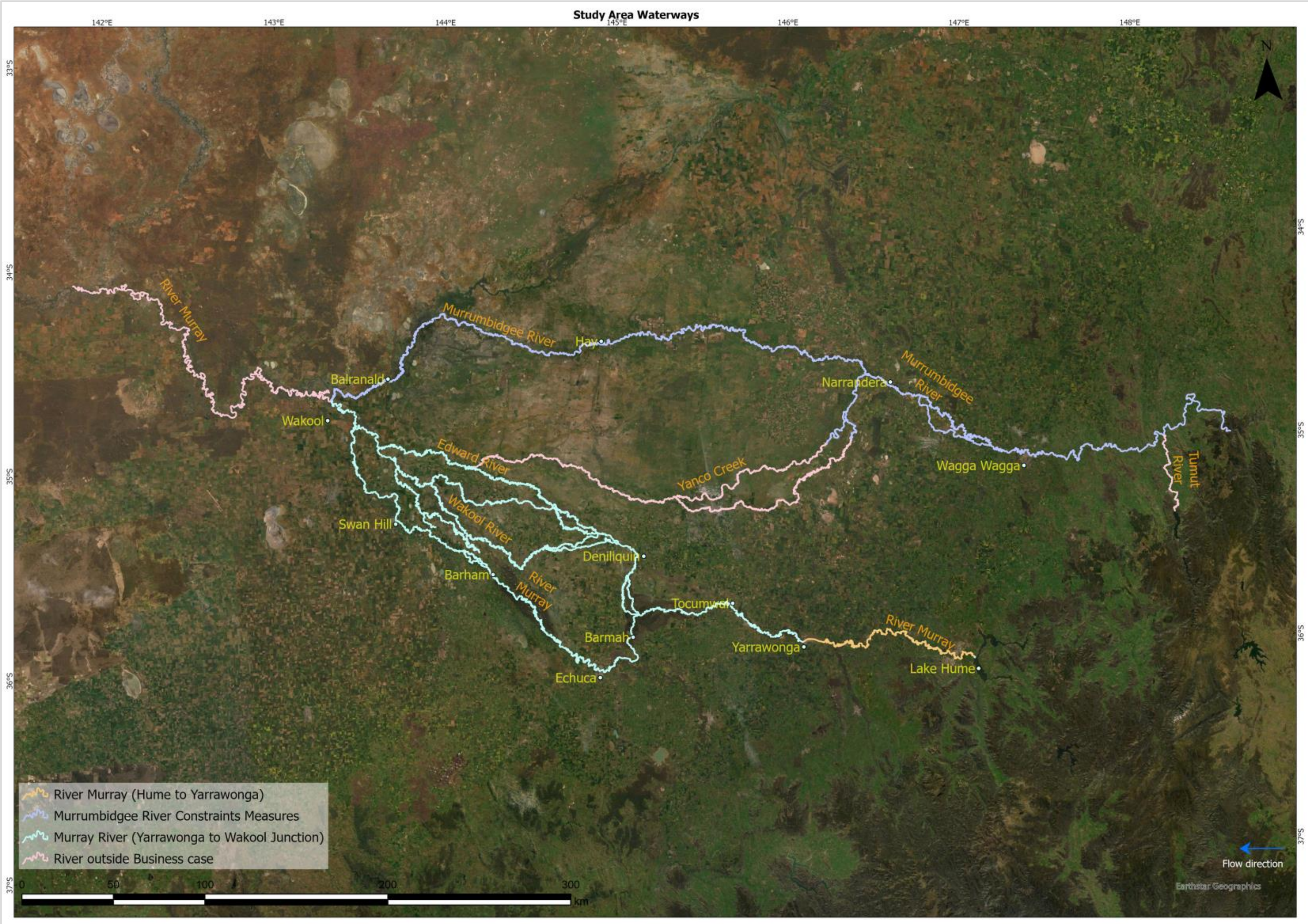


Figure 1 Study area waterways

1.2. **Project Objectives**

The objective of this project is to complete a detailed assessment of how delivery of water for the environment, under new flow limit options being considered under the Program, will influence the physical form and functioning of these river systems, and how this, in turn, might impact on opportunities. Concerns include the likely influence of flow on rates and extent of bank erosion, streambed aggradation (build up) and degradation (erosion), overall changes to channel capacity (flow conveyance) and other geomorphic processes.

The flow limit options, and the spatial extent of the geomorphic assessment are outlined in Table 1.

Table 1 Reconnecting River Country program Project Areas, flow limit options and areas for assessment

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Hume to Yarrawonga	25,000 @ Doctors Point (current flow limit) 30,000 40,000	River Murray and floodplain from Hume Dam to Yarrawonga Weir (NSW and VIC sides)
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 36,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward River at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.
River Murray: Wakool junction to Wentworth	NA - there are no formal flow limits at these locations. The geomorphology project will assess flows associated with flow limit options at d/s Yarrawonga Weir.	River Murray and floodplain, Wakool junction to Lock 10 (Wentworth)

1.3. **Project Outputs**

The overall outcomes from the project will be used to:

- Inform formal evaluation of Program flow limit and mitigation options for the Strategic and Final Business Case
- Address community and landholder concerns about adverse geomorphic events under relaxed flow constraints
- Identify knowledge gaps and potential mitigation measures for reducing potential impacts and maximising benefits, where required.

The key outputs of this project are:

- A broad scale geomorphic characterisation of the waterways in the project area including identification of 'reaches' for each project area, where a reach is defined by relative consistency of geomorphology and/or susceptibility to geomorphic changes
- A selection of sub-reaches which are representative of the geomorphic character of the broader reaches for which a more detailed analysis has assisted in identifying key geomorphic features and flow related impacts.
- Within these sub-reaches we have identified locations where geomorphic processes such as sediment transport, bank erosion, and channel change have been previously recorded or are known to occur and defined the 'base case' in terms of geomorphic impacts associated with the current flow regime.
- An assessment of how the proposed flow option scenarios may affect the flow regime at the sub-reach scale and what this might mean for the geomorphic features and processes in that sub-reach and across the broader river reaches.
- Evaluation of the benefit-risk for each flow option scenario for each sub-reach and broader reaches and an overall evaluation of the risk-benefit outcomes across the project area.
- Identification of mitigation options (where Medium or High risks where identified) and re-evaluation of the risk based on implementation of the proposed mitigation options.
- Identification of knowledge or information gaps where additional study(s) and/or capture would enhance confidence in the risk assessment outcomes.

The following report provides on each element of the projects summarised above.

section two

2. Our Approach

2.1. Overview

This study has been undertaken in four stages; Part 1 Broad Scale Geomorphic Assessment, Part 2 Representative Sub-Reach Assessment, Part 3 Benefit and Risk Assessment, and Part 4 Mitigation Options and Risk Re-evaluation. Given the large geographic context, and the diversity in channel forms, this staged approach has allowed us to categorise the rivers and their reaches with similar behaviour and likely responses to flow, before understanding the risk associated with each. The desktop nature of this study means that all four parts are informed by a preceding data and information review.

The general study approach is broadly summarised in Figure 2. The approach brings together existing knowledge on the broad geomorphic character of the waterways and the channel and floodplain connectivity, together with the flow and sediment regime, to define reaches for each waterway which have a relatively consistent geomorphology and/or susceptibility of flow related change.

We have characterised specific 'reaches' (Part 1) with representative sections within each reach (defined as 'sub-reaches') which have then been analysed in detail to build an understanding of their past and present geomorphic form and processes (Part 2). From this information we then established the base case, which is the current condition and trajectory of the sub-reaches and broader reaches based on current flow constraints for the rivers. The impact of the proposed flow changes on geomorphic features and processes under the flow options was then evaluated against the base case on a sub-reach basis.

Drawing upon Parts 1 and 2 this informs a benefit and risk analysis completed in Part 3. Based on the outcomes of the benefits and risk assessment, mitigation measures that could reduce the risk of potential geomorphic changes were identified and their influence on the benefits and risks evaluated. The overall benefit-risk rating therefore incorporates mitigation measures where relevant (Part 4).

The approach to each stage of the project is further described in the following sections.

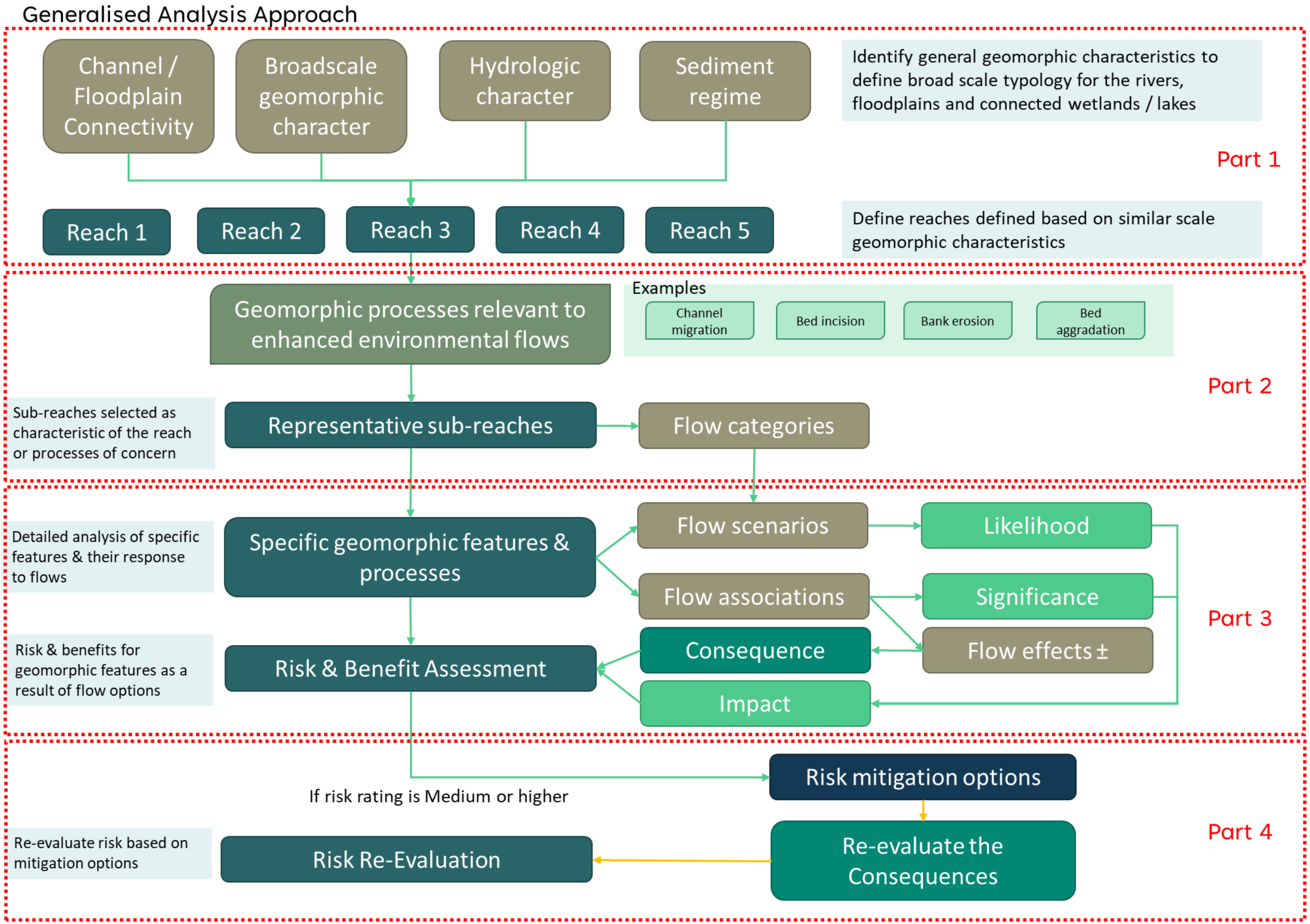


Figure 2 Overview of study approach (main components)

2.2. Data Collation and Review

The types of information sourced for this project can be broadly classified under: Imagery and Survey, Geology and Geomorphology, Locations of Interest, Environmental and Climate, Hydrology and Hydraulic, Cultural, and Assets and Infrastructure.

Once all the data and information were collated, it was reviewed to determine its relevance, any gaps in the information for the purposes of the geomorphic assessment, and its relative importance and impact to the outcomes of such a study.

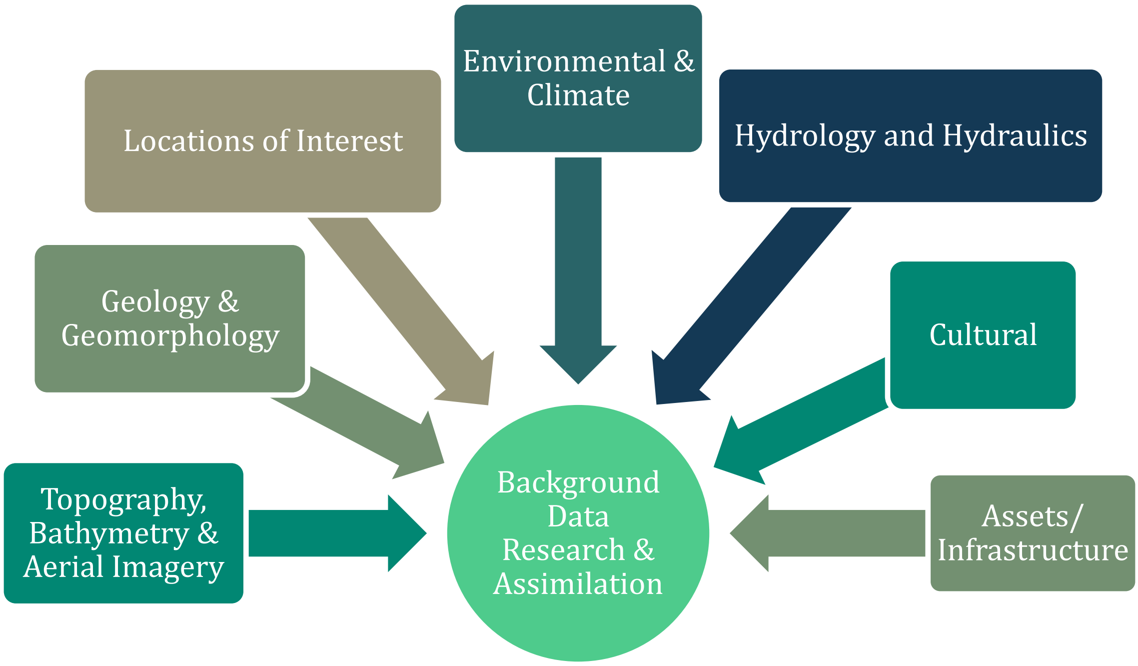


Figure 3 Data and information categories

All datasets, documents and information collated for this project were reviewed for their relative importance and relevance to the project outcomes. A list is provided in Appendix A.

2.3. Analysis Approach

2.3.1. Broad Scale Geomorphic Assessment (Part 1)

Due to the spatial scale and variability of the rivers across the study areas a hierarchical approach (Figure 4) has been developed to categorise reaches and their form and functioning relative to flow.

A river classification system developed for this project (detailed in Section 3) has been used to define morphologically similar reaches across all the study area rivers, which consider the temporal and spatial variability of the broader landscape. These reaches are still in the order of tens to hundreds of kilometres in length.

Within these reaches, sub-reaches have been identified which is characteristic of the broader reach type and contained one or more of the dominant geomorphic features present in that reach type. A sub-reach may extend for a few hundred metres to several kilometres.

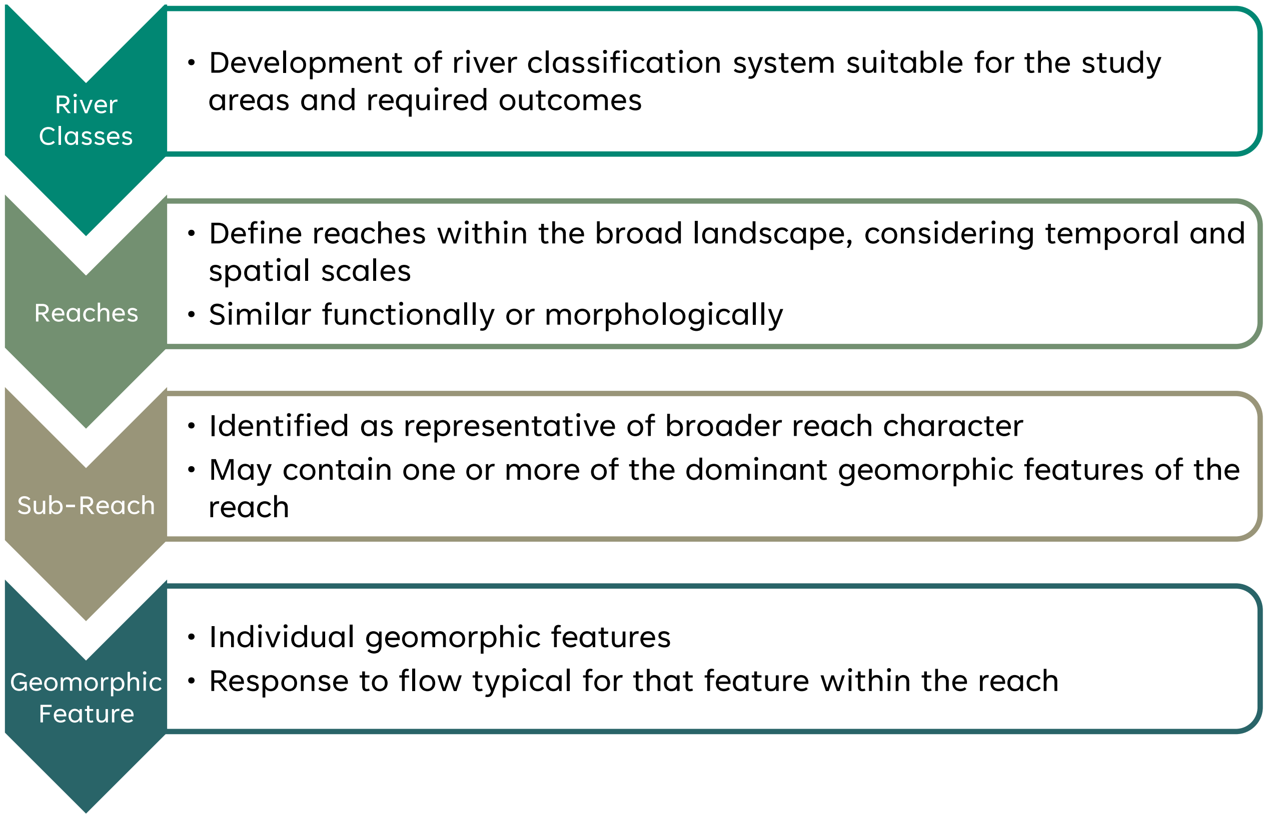


Figure 4 Hierarchical approach to evaluating geomorphic processes

2.3.2. Representative Sub-Reach Assessment (Part 2)

In total 30 sub-reaches were identified and agreed with the project steering committee. These sub-reaches included both representations of the different reach types and areas of interest to stakeholders.

For each sub-reach a detailed geomorphic assessment was completed which identified:

- Channel and floodplain forms and processes - including anthropogenic and historical changes, specific geomorphic features, and their associated processes. This analysis is based on available lidar data, historic imagery, together with available reports, data such as assets layers, and any other assessments that have been collated for this project.
- Hydrological connections have been analysed using the inundation datasets provided by DPE for this project. For each sub-reach maps were produced showing the flow rate corresponding to approximately bankfull conditions, and the inundation extents associated with the different flow option flow ranges relevant to the sub-reach.

Using this information, the current geomorphic condition and key features of the sub-reach have then been described in terms of its 'base case'.

2.3.3. **Linkages to Flow (Part 3)**

Different geomorphic features and processes are affected or driven by different flow conditions. For example, regulated flow conditions where the flow and water level remain relatively constant for prolonged periods of time can lead to riverbank notching, which can then lead to mass failure through bank saturation and rapid drawdown as flow conditions are altered.

For a range of flow conditions, from prolonged regulated flows to flood flows resulting in extensive floodplain inundation, we have linked each flow condition to the geomorphic feature and process through the "strength of association". The strength of association was derived through a review of available literature and expert elicitation within the expert geomorphologists of the project team. Association was assessed as either no association (0), weak association (1), moderate association (2), and strong association (3). Essentially the strength of association tells us how closely linked a specific geomorphic feature, like bank erosion, is linked to a particular flow condition (for example regulated flow conditions).

The flow linkages and strength of association of key geomorphic features in each sub-reach have then been analysed and added to the description of the 'base case' conditions for each sub-reach.

2.3.4. **Impact Analysis (Part 3)**

To understand and quantify the risks and benefits of the flow option scenarios on geomorphic features and conditions we first have developed an "impact score" which draws together the various flow conditions at a sub-reach scale by their frequency of occurrence (likelihood) and the geomorphic features and processes and how they might change (= significance).

To do this we have combined the sub-reach assessments of geomorphic forms and processes with the hydrological connections and inundation mapping as shown in Figure 5.

An impact score is derived for the current constraints flow conditions across each waterway (as provided by the base case scenario in the detailed hydrological modelling outputs provided by DPE) and then for each flow options scenario modelled outputs.

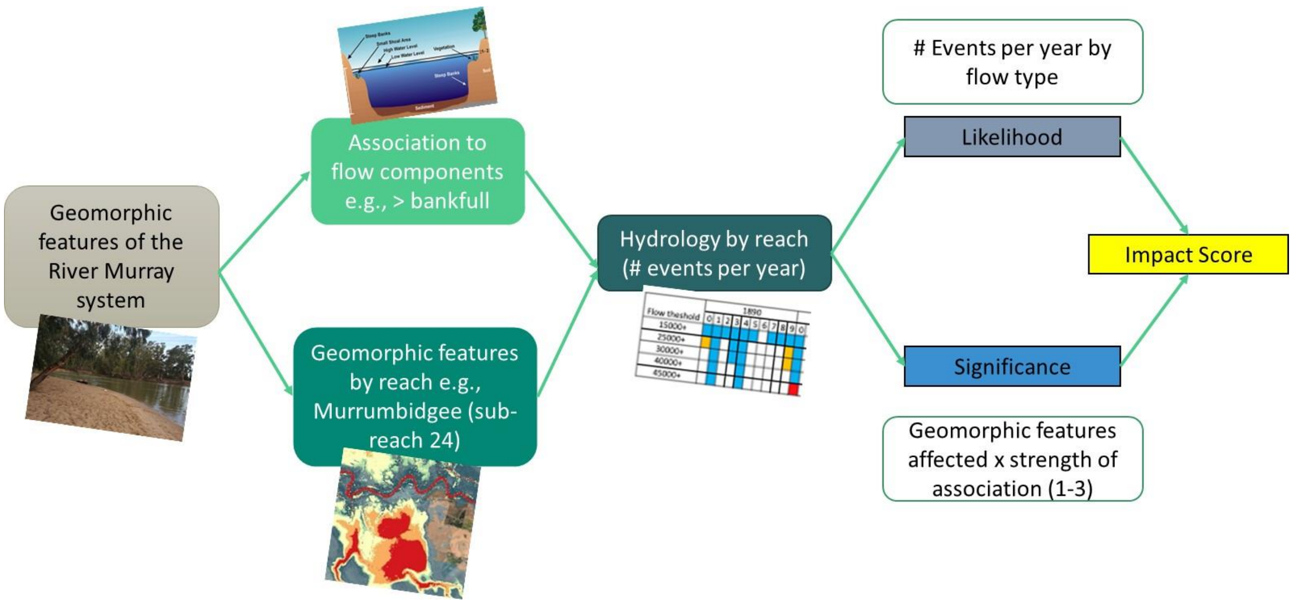


Figure 5 Analysis process used to derive an impact score linking geomorphic features and processes to the current flow and flow options scenarios.

The percentage change in impact score was calculated by feature and flow scenario, and then combined for the features within a sub-reach. The resultant changes can then be compared between sub-reaches and then consolidated into the broader geomorphic reach and landscape scales. This provides an indication of the overall sub-reach and reach scale likelihood of geomorphic change because of the flow regime proposed under the flow options scenarios.

It should be noted that the impact score and the percentage change in impact score are used to compare flow options scenarios to the base case, to indicate the potential for change. The values themselves do not provide a quantitative measure of actual geomorphic changes that would be realised under the flow options.

2.3.5. Risk-Benefit Assessment (Part 3)

Risk-based management is not a new concept in water resource planning. Considerable work has been undertaken by State governments and under Commonwealth-level intergovernmental initiatives to design and implement risk-based water planning. The National Water Initiative Policy Guidelines for Water Planning and Management (NWI, 2010), endorsed by the Council of Australian Governments (COAG), adopts a risk management approach. The standard risk management framework is presented in Figure 6.

NSW has been implementing risk-based water planning processes since implementing water reform in the late 1990s. These approaches have included the initial Stressed Rivers and Aquifer Risk Assessments in 1998 (DLWC, 1998a b). However, to date the assessments have not explicitly incorporated geomorphic risks.

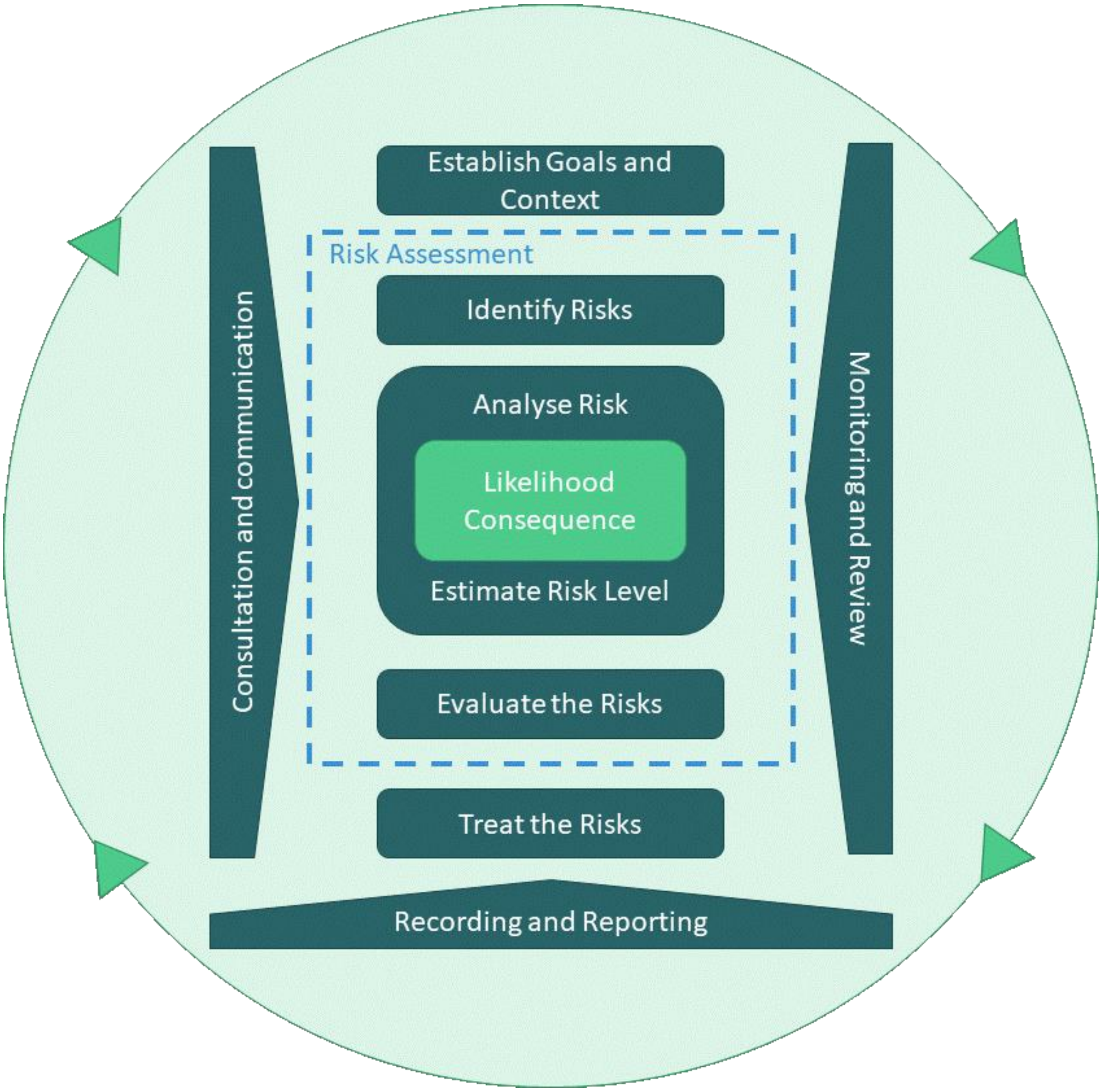


Figure 6 Risk Management Framework (based on AS ISO 31000: 2018)

To complete the risk-benefit assessment we combined the sub-reach percentage change in impact scores as an indicator of the likelihood of potential geomorphic change (defined in Table 2), with the consequences of geomorphic change occurring (as defined in Table 3). This considers the sub-reach, reach and landscape conditions, and the current and potential trajectory under the flow options scenarios.

Table 2 Likelihood of Geomorphic Change Classification

Likelihood	Percentage change in impact score
Very Unlikely	< 5%
Unlikely	5% to 15%
Possible	15% to 25%
Likely	25% to 50%
Almost certain	> 50%

The sensitivity of the selected percentage change in impact score ranges for the likelihood classifications defined above on the overall risk rating has been assessed through sensitivity testing.

Table 3 Consequence Classification for Geomorphic Change

Consequence	Description
Very Low	Insignificant
Low	Localised (< sub-reach scale) short term negative or positive changes
Moderate	Localised (< sub-reach scale) negative or positive changes
High	Sub-reach to reach scale negative or positive changes
Very High	Reach or multi-reach scale negative or positive changes

Negative geomorphic changes represent risks within the context of this project, while positive geomorphic changes are considered benefits. Consequence was assessed based on the trajectory of change relative to the base scale trajectory for each sub-reach (as detailed in Appendix B), and the generalised negative or positive effects of increased flow on geomorphic features (as defined in Section 6).

The risk-benefit rankings were determined using the risk matrix shown in Table 4, which combined the likelihood of change with the severity of the consequences (both positive and negative).

Table 4 Risk-Benefit Assessment Matrix

Likelihood	Consequence				
	Very Low	Low	Moderate	High	Very High
Very Unlikely	Low	Low	Low	Medium	Medium
Unlikely	Low	Low	Medium	Medium	Medium
Possible	Low	Medium	Medium	Medium	High
Likely	Medium	Medium	Medium	High	High
Almost Certain	Medium	Medium	High	High	High

2.3.6. Mitigation Options & Risk Re-evaluation (Part 4)

Part 4 of the project requires a review of medium and high-level risks for each of the reaches across the study area to determine whether they are adequately addressed by existing strategies. Alternatively, modifications of new strategies or mitigation can be identified.

Risk treatments (mitigation) have been generalised and therefore are applicable across the study area, rather than sub-reach or site specific. Treatments range from physical works, targeted flow management, through to monitoring and evaluation planning. The suite of general mitigation measures and treatments will vary in their application across the rivers of the study area.

2.3.7. **Future work**

A ‘best available information’ approach has been used to undertake this risk assessment. However, it should be noted that this work has been completed as a high-level desktop assessment only and no site-specific field work has been undertaken to verify the analysis results.

To further improve the assessment outcomes verification of the current geomorphic condition of the rivers across the study area through targeted field assessments is recommended. This field work could be completed as part of the baseline monitoring when implementing the proposed flow options.

section three

3. Defining Reaches and Sub-Reaches

3.1. Review of River Classification Systems

The classification of waterways is a mechanism that allows order to be created from complex systems. They allow us to organise a waterway network into functional or morphologically similar reaches (as identified by Sear et al. 2003).

Buffington and Montgomery (2013) have described the way that river systems have been classified and how this has changed over time, ranging from stream order and dominant processes through channel-floodplain interactions, to hierarchical and statistical classifications. The types may also change based on the spatial area to which they are applied and the purpose for which they are being used.

For this project a classification system is required which:

- Groups the river networks in the study areas into functionally or morphologically similar reaches, and
- Considers the temporal and spatial variability of the landscape, while
- Readily allowing for the assessment of geomorphic impacts focussed on higher flows at scales relevant to the required study outputs.

Several existing waterway classifications were reviewed for this project including those developed explicitly for application to the Murray-Darling Basin, such as Whittington et al. (2001) and Alluvium (2010), along with others which are commonly applied across NSW such as Brierley et al (2002).

The project team also undertook a detailed review of the regional geology and geomorphology of the southern Murray Darling Basin to inform the project teams understanding of the geological context, paleoclimate, landscape evolution, and soils distribution of the waterways in the study area. A wide range of previous studies, reports and assessments were all collated and reviewed to provide the team with river specific information for the study areas.

These classifications and geomorphic context were then reviewed and workshopped by the project team experts (Prof. Ian Rutherfurd, Dr James Grove, Dr Geoff Vietz, Dr Christine Lauchlan Arrowsmith, Dr Michael Cheetham, Julian Martin, Dr Gresley Wakelin, Dr Daryl Lam, and Dr Abdullah Al Baky) to develop a geomorphic classification which meets the requirements described above.

3.2. River Types and Reach Delineation

3.2.1. Landscape Overview

Literature reviews and analysis of available information has provided the geomorphic context (after Wohl, 2018) for understanding the landscape and river systems of the River Murray and Murrumbidgee catchments from both a spatial and temporal perspective.

The Murray Darling Basin's (MDB) regional geology and geomorphology has been brought together to describe the geological processes, paleoclimate, landscape evolution, and surface soils which has allowed us to define clear landscape zones across the study area. Each of these aspects are briefly discussed below. An expanded summary of this review can be found in Appendix B.

Geologic Processes

Geologic processes that shape the landscape, and our drainage networks happen at different times and through different mechanisms. Over millions of years the Australian mainland has been subject to change through periods of subsidence and uplift. These changes contribute significantly to the variably of the drainage network. For example, uplift or subsidence in the flow path can alter river planform or create conditions favouring sediment deposition or erosion in channels and on floodplains. An example of these processes in the study area is the Cadell Fault which directly altered the course of the River Murray at Barmah.

Paleoclimate Influences

The Australian climate has oscillated through wetter and drier conditions while becoming progressively drier overall. In the geological past the landscape of the MDB contained large lakes and active rivers, but reduced rainfall and increased evaporation have dried out the lakes, depositing sandy lunettes during the process, and resulted in decreased river flows. The landforms relating to these past climates still play an active role in present-day landscapes.

The MDB rivers that flowed during times of wetter climate had greater channel and meander dimensions than the rivers of the present day (Hesse et al, 2018). Traces of these past rivers (often referred to as ancestral channel) are widespread across much of the current study area and can directly impact the form of many sections of the present-day rivers.

For example, some sections of river channel look unconfined (a geomorphic term meaning there are no constraints on the river adjusting to changes in flow or sediment transport) but may be partially confined within a larger ancestral channel. If under the modern flow regime floods occur that are large in comparison to the capacity of the current channel, the flows may still be partially confined within the broader ancestral channel. However, extreme floods may still overtop the ancestral channel and the river becomes unconfined.

The imprint of previous landscapes will contribute to inter-reach variability in a river, such as creating a lesser gradient across a paleolake (Figure 8), in comparison to reaches up- and down-stream.

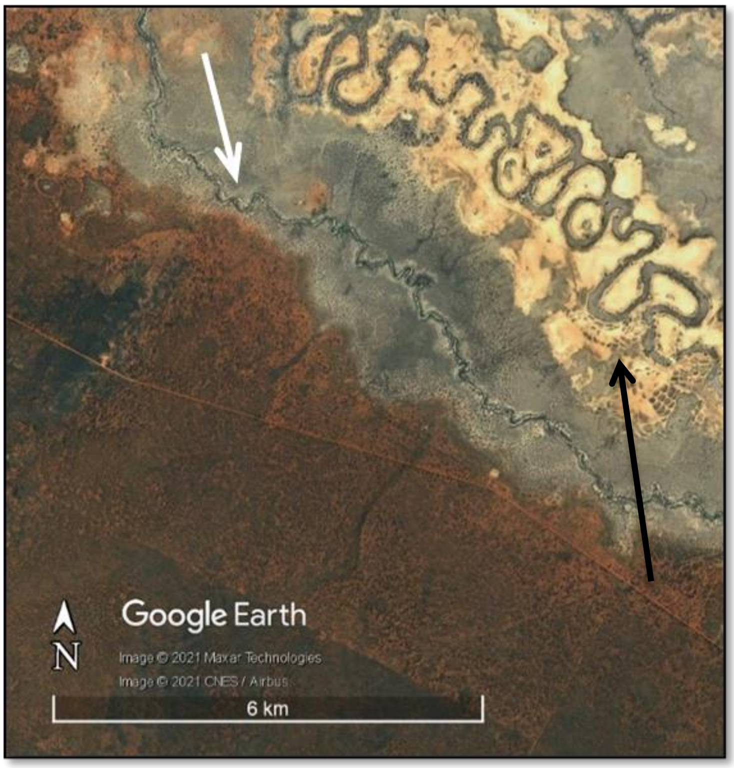


Figure 7 The Bogan River near Brewarrina. The modern river (white arrowed) is smaller, not very sinuous, and lacks significant overbank deposits. The larger scale and greater sinuosity of the ancestral river (black arrow) is outlined by flanking pale silty overbank deposits (figure courtesy of Dr Gresley Wakelin)

Figure 8 Wakool River (flow bottom centre to upper left) and Yarrein Creek (flow right to centre left), between Balranald and Swan Hill. Left, satellite image; right, same image overlaid with outlines of paleolake and ancestral Yarrein channel belt (black lines)

Landscape Evolution

A comprehensive review of the landscape evolution of the southern MBD is provided in McLaren et al (2011). A key feature of this evolution for the current study areas was the formation and retreat of Lake Bungunnia (Figure 9) which controlled the outlet of the River Murray to the sea.

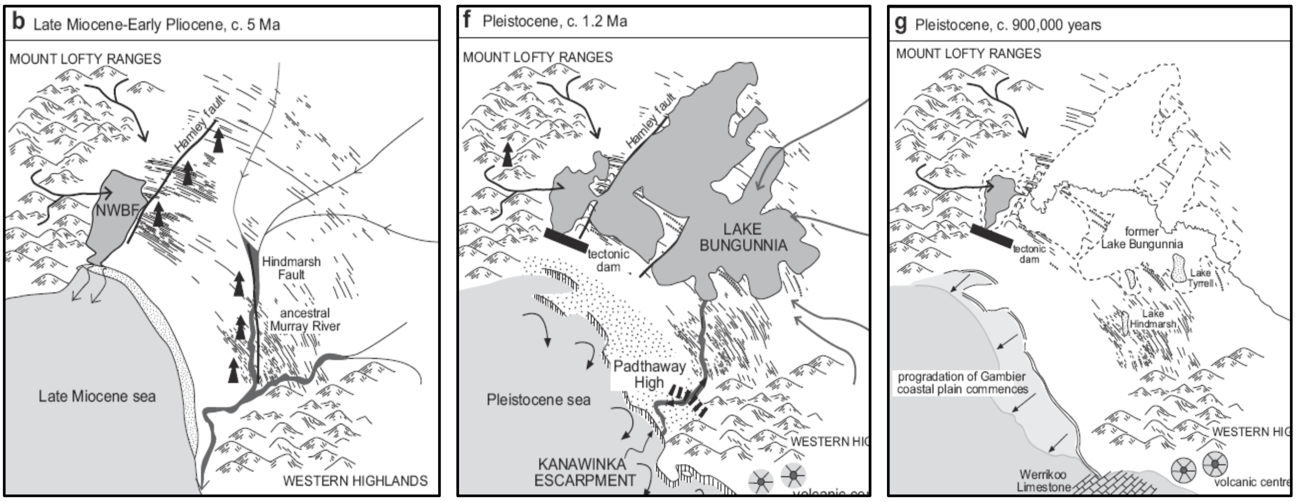


Figure 9 Palaeogeography of the southern MDB (images from McLaren et al., 2011, Figure 14

The footprint of Lake Bungunnia identifies a landscape zone in which the palimpsest landscape formed by the different evolutionary periods of the lake contributes to considerable geomorphic variability. Lake Bungunnia has also influenced the main Murray River channel's setting in the surrounding country, by lowering of base of the channel firstly as the lake dried, and then again as the tectonic dam (see Figure 9, centre) was breached. This has contributed to the present landscape’s red/black soils (discussed below). Finally, the river reaches and drainage network geometry have altered in response to geological processes in the past, and some are still undergoing adjustment in the present day.

Soils - Red Country and Black Country

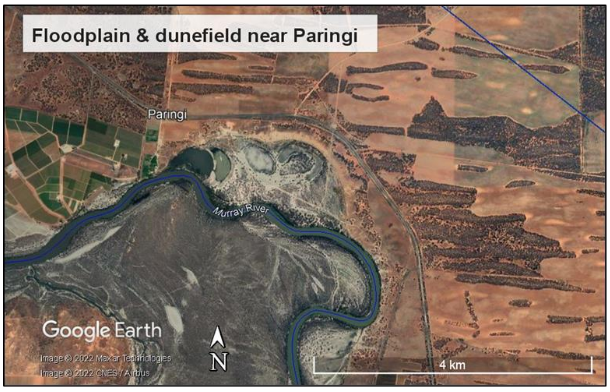
Broadly speaking, a striking feature of drylands Australia is the contrast between 'red' country and ‘black’ country. This is most strongly expressed in the northern MDB but also occurs in the RRC project area.

The red country is (mostly) relatively modern soils and sediments derived from older weathered sediment. Common landforms in the red country include dune fields, lunettes, loamy red-earth plains, and small ephemeral waterways unconnected with the wider MDB drainage network.

The black country is the alluvial plains of the wider drainage network. On satellite images, soil colours range from mid-grey to dark grey or grey-brown, merging into greens in the wetter country of the eastern MDB. These plains are substantially composed of vertic soils, in which clay mineralogy produces strong shrink-swell behaviours. Vertic soils are also known as cracking clay soils or black soils. Australia is one of the few places in the world where vertic soils are common;

they are associated with drylands or moisture-restricted settings. The water-retaining qualities of vertic soils makes them biologically productive and agriculturally valuable.

Landscape evolution has created a sharp juxtaposition of the red country and the black country in parts of the study area (Figure 10) which includes the River Murray from Mildura to Swan Hill, the Murrumbidgee River from Balranald to the River Murray confluence, and parts of Edward River and its anabranches. Upstream from these areas, the red-black variation is less pronounced, although it is still possible to distinguish as far upstream as Narrandera on the Murrumbidgee River.



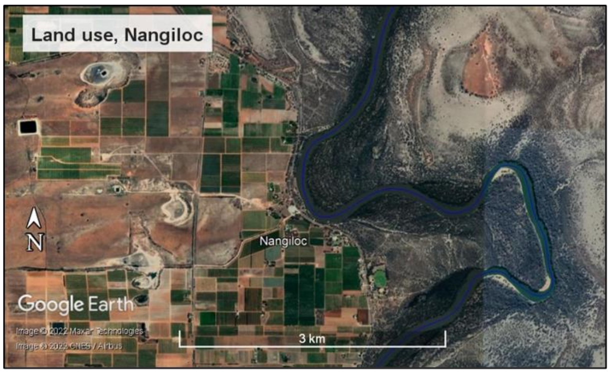


Figure 10 The red/black delineation in the MDB surface soils can be a useful marker for landscape processes and utilisation. Left: At Paringi, the black country defines the extent of fluvial processes. Right: Near Nangiloc, the red country is used for cropping but the floodplain is not. In this area, the Woorinen Sands are good agricultural soils, but presumably the floodplains are too frequently inundated for cropping (images courtesy of Dr Gresley Wakelin)

Landscape Zones

Based on the review of the landscape of the study areas, it has been divided into four landscape zones (Figure 11). The characteristics of these zones are briefly described in Table 5. Note that the Upper and Lower Alluvial Fan zones are sometimes referred to as the 'riverine plain'.

Table 5 Landscape zones defined for the study areas (descriptions provided by Dr Gresley Wakelin)

Landscape Zone	Description
Rocky Hills	This is the hilly upland areas. It comprises relatively narrow and flat valley bottoms between moderately rugged hills. This zone has the greatest relief, probably the steepest gradients, and narrowest valleys of the study areas. The dominantly single channel rivers are semi-confined within the valley margins, and the floodplains are often discontinuous.
Upper Alluvial Fan	This zone contains low-angle alluvial fans punctuated and partially separated by low hills. In terms of gradients, relief, and degree of valley confinement, this area is likely to be intermediate in character between the Rocky Hills and the Lower Alluvial Fan. The drainage network becomes multithreaded in places, with anabranching occurring where the rivers leave the hills. Many of the river channels are meandering and underfit within the remnants of ancestral palaeochannels: although the broadscale landforms suggest unconfined flow, individual channels may be confined or semi-confined. The fan surface is marked with ancestral stream traces, and it is likely that the alluvial fans are developing by channel mobility and avulsion, in combination with vertical accretion during overbank flooding.
Lower Alluvial Fan	This is a broad plain, continuous in the upslope direction with the Upper Alluvial Fan, and laterally continuous. Several large fans from the east and south have coalesced in this lower zone. Gradient and relief are both low. The main-channel drainage network is anabranching in places. The floodplain is widely marked by ancestral streams. It is probable that the fan develops through channel mobility, avulsion, and vertical accretion. Where the downslope toe of the fan was once lapped by the shallow waters of Lake Bungunnia, the landscape is more varied. The Lower Alluvial Fan shows marked effects of geological processes, including chains of lakes and playa lakes, drainage network diversions, and floodouts.
Bungunnia Zone	In the Bungunnia zone, the Murray River cuts down through the flat sediments left behind by Lake Bungunnia. The landscape is a mixture of various generations of palaeolakes, overprinted by dunes, slightly incised by various fluvial networks, and marked by the combined groundwater and wind processes that have created the more recent lakes. These broad plains probably have the lowest gradient overall, but local topography will be more influential in a reach scale. This is the area with the clearest red:black soils distinction.

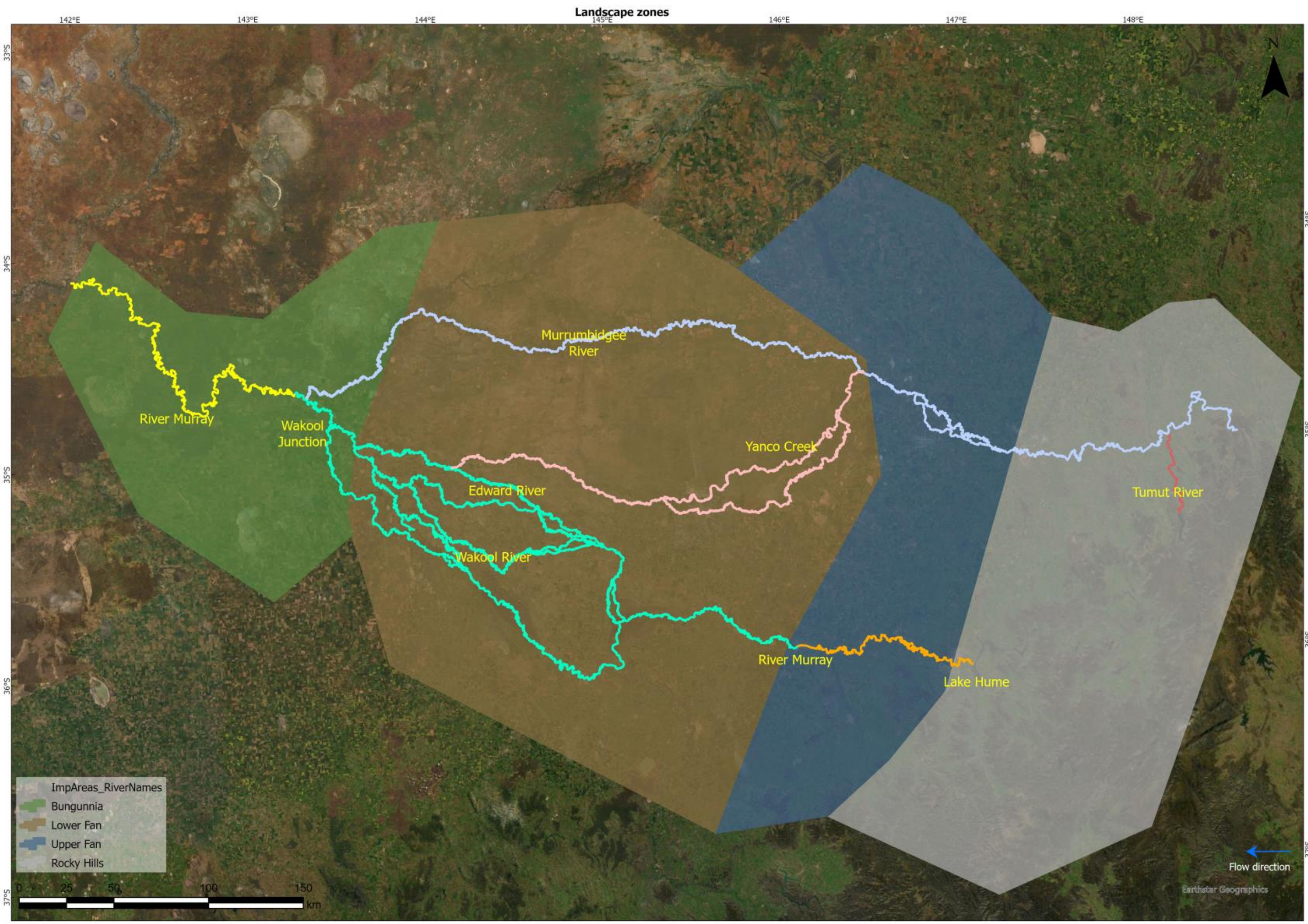


Figure 11 Landscape zones for the RRC study areas

3.2.2. **Reach Types Defined**

As mentioned in Section 3.1, several existing waterway classifications were reviewed for this project including Whittington et al. (2001), Alluvium (2010), and Brierley et al (2002). All the approaches provide information of the character of the rivers in the study areas, but our expert review found that on their own, each classification system did not fully capture the spatial and temporal variability required to assess geomorphic impacts associated with the flow options.

Elements of various classification systems together with information on the landscape evolution of the study area were therefore combined to create a modified reach classification system which is summarised in Figure 12. The classifications clearly link the landscape zones, the level of confinement of the river (i.e., floodplain width), and the dominant geomorphic features you would expect to observe, which will behave differently to changes in flow regime.

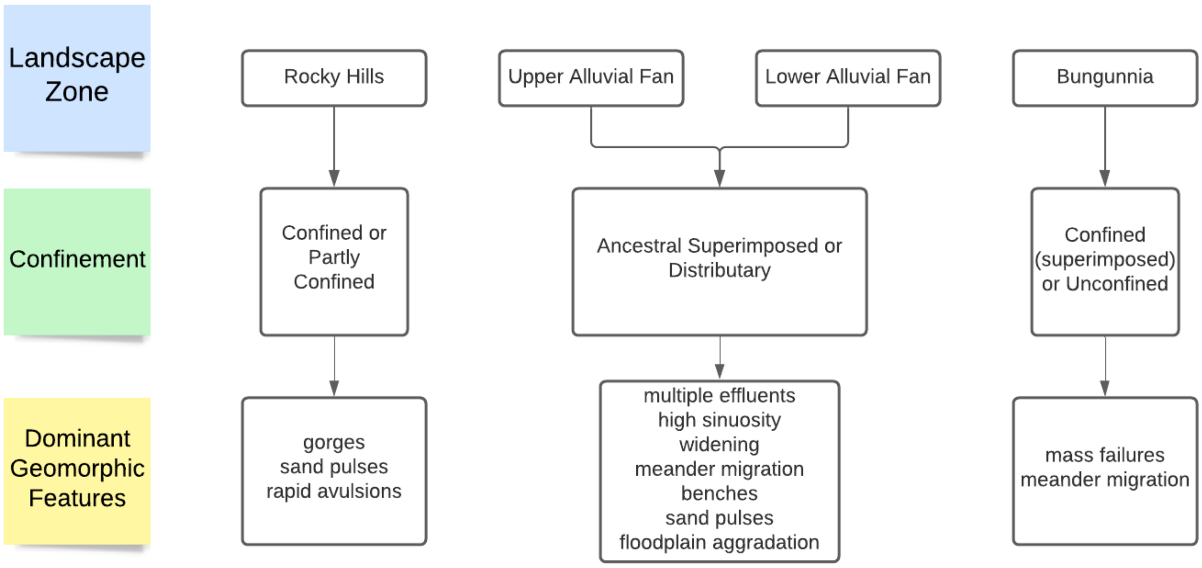


Figure 12 Reach classification system for rivers of the study area

Within the Rocky Hills zone, the confinement of a reach is well characterised within the RiverStyles layer and this therefore has been used to define specific reaches. Across the Upper Alluvial Fan and Lower Alluvial Fan zones (often referred to as the Riverine Plain), the presence and form of ancestral channels and their impacts on the confinement of the rivers allow reaches to be defined. The distributary reaches can also be identified through existing literature and ofttimes are identifiable by their linkages to wetlands complexes such as the Barmah-Millewa Forest. These reaches are unconfined with an anabranching morphology. The Bungunnia zone is also influenced by the past with the ancestral rivers and lakes systems through their imprint on the landscape defining geomorphic reaches.

Previous investigations such as Rutherfurd (1991), Page (1994) and Hesse et al (2018) among others have assessed the delineation of these ancestral channels and their influence on the of the River Murray and Murrumbidgee River systems. Figure 13, Figure 14, and Figure 15 show examples of the previous work. The reach delineation for the study area based on this information and with input from the expert panel members is presented in Figure 16 and summarised in Table 6 and Table 7.

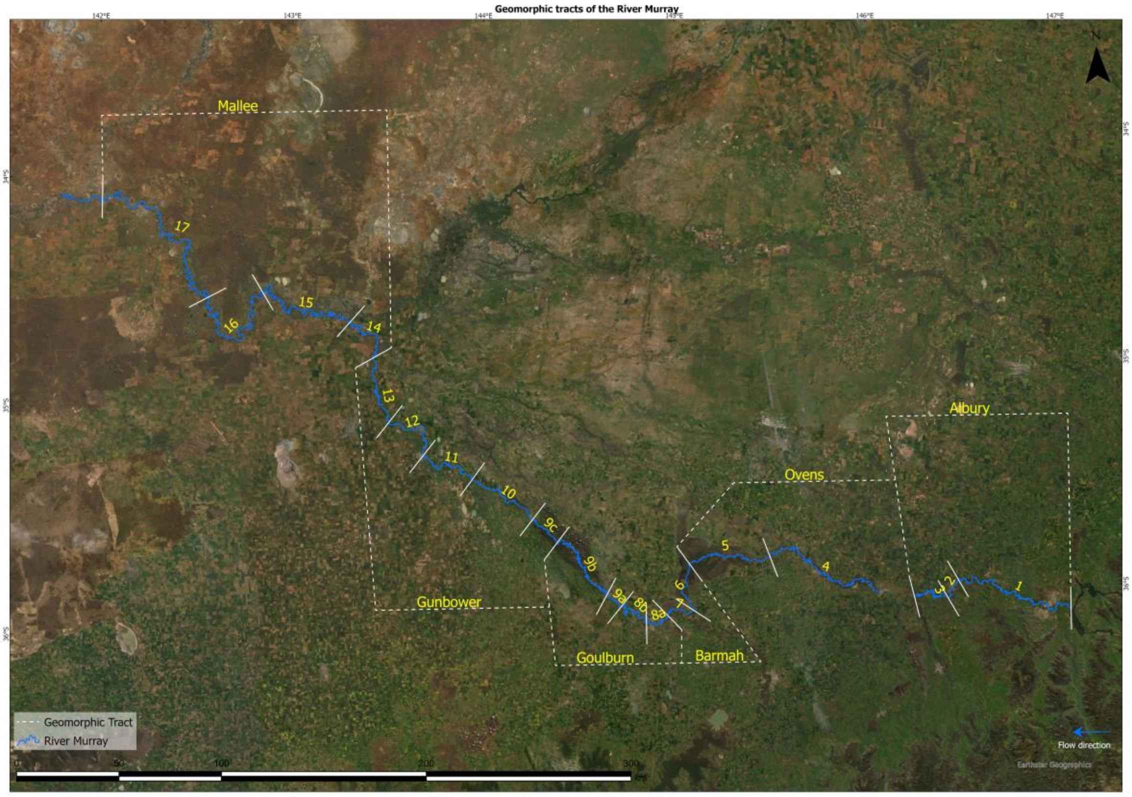


Figure 13 Geomorphic tracts of the River Murray (from Rutherfurd, 1991)

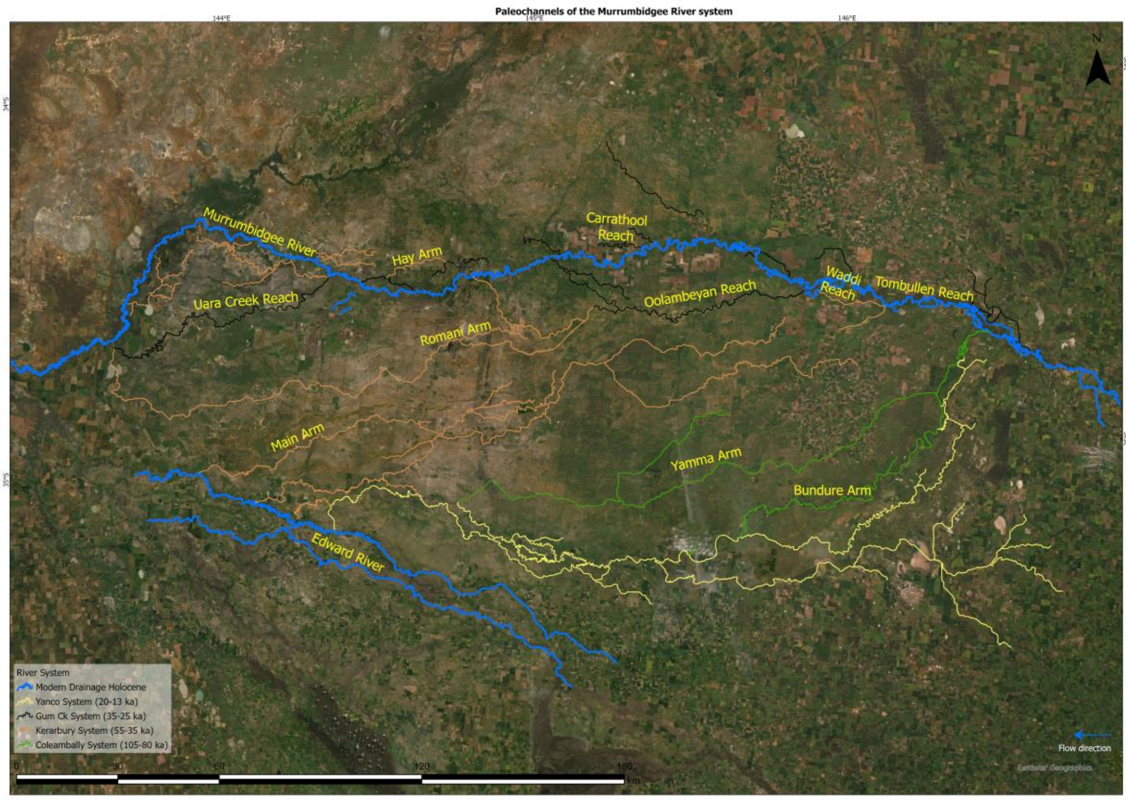


Figure 14 Paleochannels of the Murrumbidgee River system (Figure 6.1 from Page, 1994)

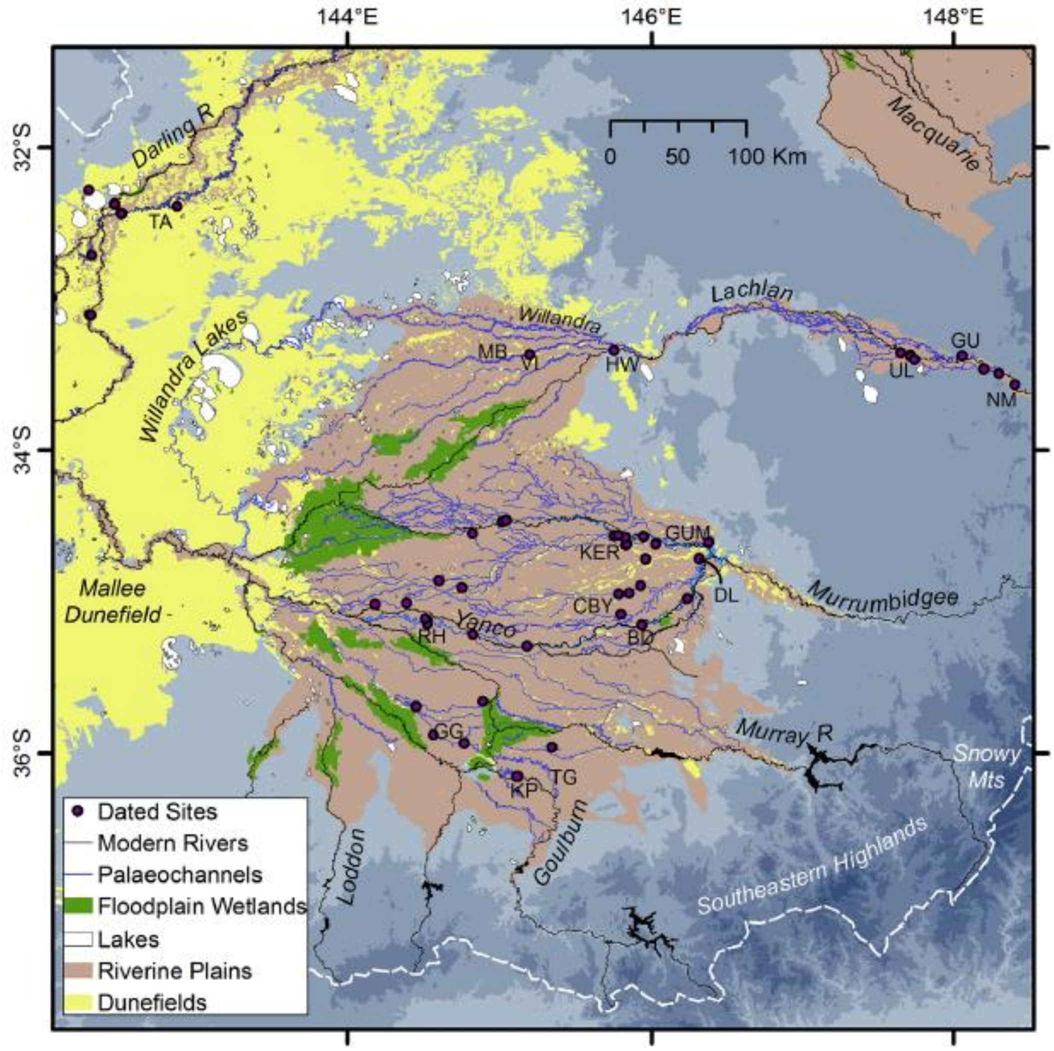


Fig. 5. Southern Riverine Plain of the Murray-Darling Basin. Dated palaeochannel sites from previous work are indicated by dots and selected palaeochannels by blue lines. Shaded topography is the same as for Fig. 1. DFS areas (pink), floodplain wetlands (green), dunefields (yellow) and palaeochannels (blue lines) were interpreted from Esri background satellite imagery. KP – Kotupna, TG – Tallygaroopna, GG – Green Gully, CBY – Coleambally, KER – Kerarbury, GUM – Gum Creek, NM – Nanima, GU – Gulgo, UL – Ulguetherie, HW – Hunthawang, VI – Viela, MB – Middle Billabong; DL – Dry Lake, BD – Bundure, RH – Rhyola; TA – Talyawalka Creek. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Figure 15 Map showing the ancestral channels (termed paleochannels) of the Murray and Murrumbidgee River systems (from Hesse et al. 2018)

Table 6 River Murray Reach Description

River Murray Reaches	Landscape Zone	Description
Albury	Upper Alluvial Fan	Ancestral, medium confined, not underfit, highly anabranching
Howlong	Upper Alluvial Fan	Ancestral, underfit, confined
Corowa	Upper Alluvial Fan	Ancestral, highly confined, straight
Mulwala	Lower Alluvial Fan	Ancestral, underfit, confined, anabranching
Yarrawonga	Lower Alluvial Fan	Ancestral, underfit, confined, anabranching
Tocumwal	Lower Alluvial Fan	Young, highly confined
Barmah 1	Lower Alluvial Fan	Young, unconfined, Distributary
Barmah 2	Lower Alluvial Fan	Young, unconfined, lake floor, distributary
Echuca	Lower Alluvial Fan	Ancestral Goulburn, highly confined, no anabranching (floor of Lake Kanyapella
Perricoota	Lower Alluvial Fan	Young, unconfined, Distributary
Gunbower Tract	Lower Alluvial Fan	Young, confined, avulsive paths
Wakool	Bungunnia	Ancestral confined
Tuppal Creek	Lower Alluvial Fan	Ancestral Murray
Bullatale Creek	Lower Alluvial Fan	Ancestral Murray

Table 7 Murrumbidgee Reach Description

Murrumbidgee Reaches	Landscape Zone	Description
Burrinjuck	Rocky Hills	Confined, bedrock control,
Jugiong	Rocky Hills	Partly confined, low sinuosity
Gundagai	Rocky Hills	Partly confined, low sinuosity
Wagga Wagga	Rocky Hills	Partly confined, anabranching
Mid Murrumbidgee wetlands	Upper Alluvial Fan	Unconfined, distributary
Narrandera	Lower Alluvial Fan	Ancestral, confined, meandering (wide floodplain)
Carrathool	Lower Alluvial Fan	Ancestral, underfit, confined, meandering (narrow floodplain)
Hay	Lower Alluvial Fan	Ancestral, confined
Lowbidgee	Lower Alluvial Fan	Unconfined, distributary, anabranching
Balranald to Wakool Junction	Bungunnia	Ancestral confined
Yanco Creek / Billabong Creek	Lower Alluvial Fan	Ancestral, confined
Tumut River	Rocky Hills	Partly confined, meandering

Note that all reaches of the Murrumbidgee River downstream of the Yanco Creek confluence including Yanco Creek are part of the major Murrumbidgee distributary fan system.

For the Edward (Kolety) – Wakool River systems the reach delineation is preliminary and based on available literature, including hydrologic zones identified by Watts et al (2017). While the broad river class is 'distributary' there are also multiple influences from ancestral channels including those originating from the Murrumbidgee River (e.g., Yanco Creek) and the Murray River (e.g., Barbers Creek, Little Merran Creek). For instance, several ancestral channels cross the current path of the Niemur River and Thule Creek which joins the Wakool system is part of the ancestral Green Gully channel system.

Table 8 Edward (Kolety) – Wakool Reach Description (incomplete)

Edward (Kolety - Wakool Reaches	Landscape Zone	Description
Upper Edward - Gulpa Creek	Lower Alluvial Fan	Distributary, unconfined
Deniliquin to Werai Forest Reach	Lower Alluvial Fan	Distributary, anabranching
Mid Edward	Lower Alluvial Fan	Distributary, anabranching
Lower Edward	Lower Alluvial Fan	Distributary, anabranching
Niemur Reach	Lower Alluvial Fan	Distributary, anabranching
Upper Wakool	Lower Alluvial Fan	Distributary, anabranching
Mid Wakool	Lower Alluvial Fan	Distributary, unconfined
Lower Wakool	Lower Alluvial Fan	Distributary, anabranching

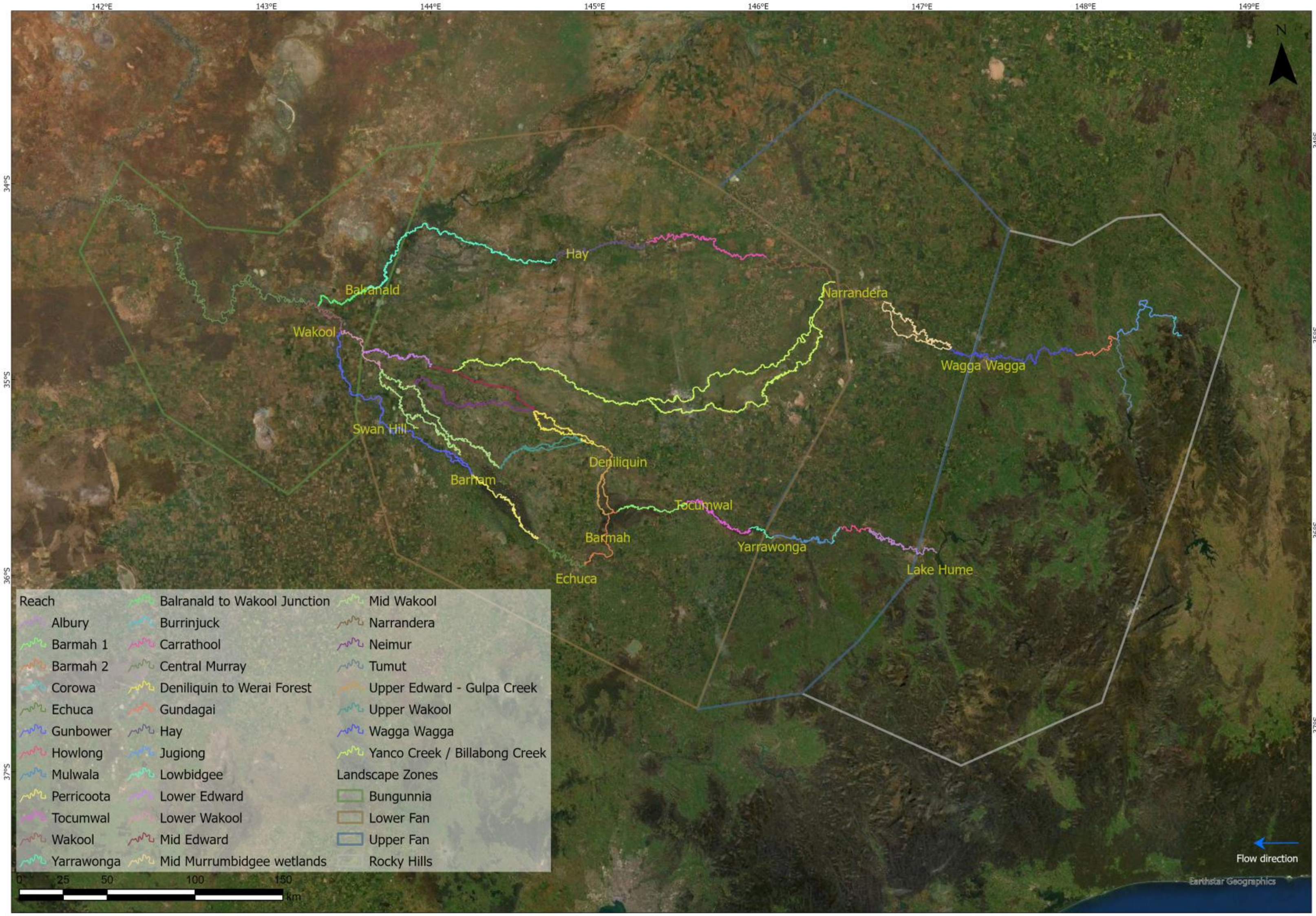


Figure 16 Reach delineation across the rivers of the study areas

3.3. Identifying Sub-Reaches

The river classification system developed for this project along with other geomorphic spatial data (e.g., River Styles database), information obtained from the data review, information on locations of interest, and the extensive knowledge of the study area within the project team was used to develop a list of representative sub-reaches.

Reaches (as defined in the previous section) are in the order of tens to hundreds of kilometres in length. Within these reaches, it is necessary to identify sub-reaches which are characteristic of the broader reach type and contained one or more of the dominant geomorphic features of that reach type. They are also typically in the order of a few hundred metres to several kilometres in spatial extent. This use of sub-reaches has allowed the study team to better analyse the response of these features to flow options and identify any impacts and the associated benefits and risks. The understanding obtained from the analysis of sub-reaches then informs the broader reach and study area assessment.

The sub-reaches identified are summarised by river in Figure 17, Table 9, Table 10, Table 11. The detailed sub-reach summaries are provided in Appendix C.

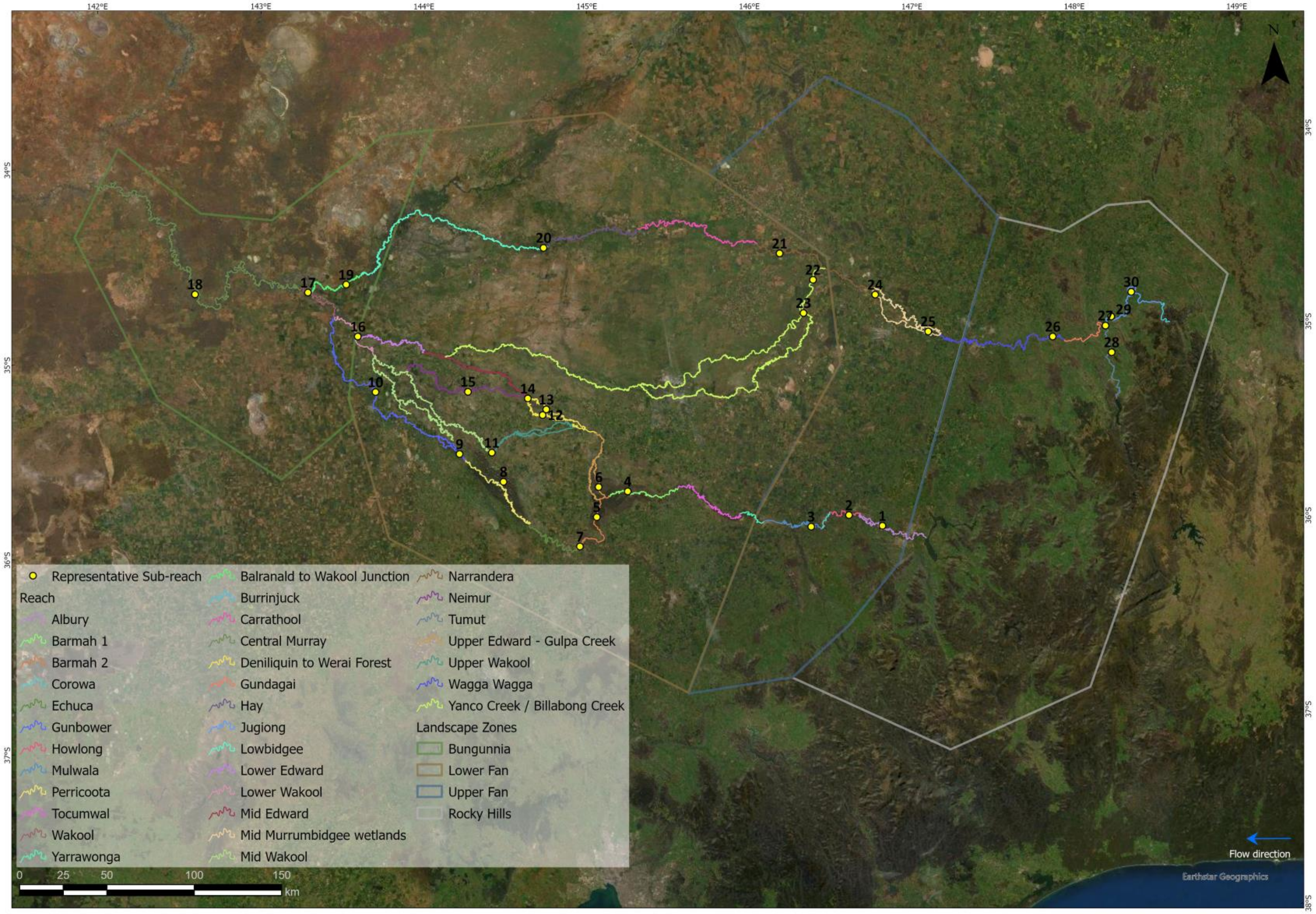


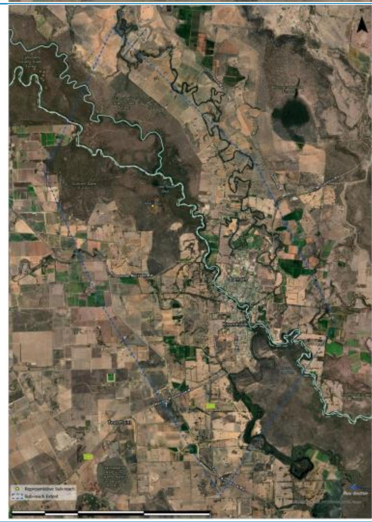
Figure 17 Overview of sub-reaches used for this study, combined with reach delineation

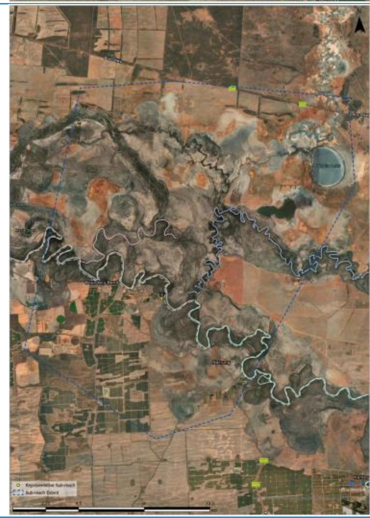
Table 9 Sub-reaches for the River Murray

River System	Reach	Approx. Location	Description / Reasoning	Location
River Murray	Albury Reach, Sub-reach #1	NSW floodplain anabranch complex, approximately 14km upstream of Howlong and 14km downstream of Albury/Wodonga.	The Dights Creek anabranch complex is situated on the NSW floodplain, comprising multiple anabranches including Dights Creek and Yellowbelly Creek. Dights Creek represents a more hydraulically efficient flow path compared to the adjacent section of the Murray River. The anabranch currently captures more than 50% of the flow away from the Murray River. Works aimed at managing anabranch development have been undertaken in Dights Creek. Flooding (including environmental flows) has the potential to influence geomorphic change within the anabranch network through anabranch development and flow capture. Dights Creek is surrounded by freehold agricultural land. River Style is anabranching, low sinuosity fine grained. High suspended load and general low bed load transport. Bed load limited by presence of upstream dam. Soils are predominantly sodasols.	

River System	Reach	Approx. Location	Description / Reasoning	Location
River Murray	Howlong Reach, Sub-reach #2	NSW floodplain anabranch complex	The Little River anabranch complex is situated on the NSW floodplain, comprising two channels, namely Little River and McLeans Creek. The sub reach is situated approximately 12 km downstream of Howlong. The Little River channel extends approximately 2.25km long. The corresponding section of the Murray River extends 4.86km. River Style is anabranching, low sinuosity fine grained. High suspended load and general low bed load transport. Bed load limited by presence of upstream dam. Soils are predominantly sodasols.	
River Murray	Mulwala Reach, Sub-reach #3	NSW floodplain anabranch complex, approximately 6km downstream of Corowa.	The Boiling Downs anabranch complex is situated on the NSW floodplain, comprising Boiling Downs and Hans Creek. The anabranch network represents a more hydraulically efficient flow path compared to the adjacent section of the Murray River. Recent monitoring suggests that Hans Creek in particular is developing through channel widening. Aggradation is evident in the adjacent section of the Murray River. River Style is meandering, fine grained. High suspended load and general low bed load transport. Bed load limited by presence of upstream dam but aggregation observed (see comment above) Soils are predominantly sodasols.	

River System	Reach	Approx. Location	Description / Reasoning	Location
River Murray	Barmah 1 and 2 Reaches, sub-reaches 4 and 5	Barmah-Millewa reach from Bullatale Creek to Barmah township	The Barmah distributary fan feature which is a significant flow constraint along the River Murray. The adjacent map shows the river sections which are experiencing significant aggradation due the presence of a sand slug, which is also exacerbating bank erosion processes.	
River Murray	Echuca Reach, sub-reach 7	Confluence of Goulburn River and River Murray	Influence of major tributary with high suspended sediment load. River Style of the reach itself is fine grained, low sinuosity, within paleolake system. High suspended load in Goulburn and Murray rivers and increasing bed load transport in the Murray (potentially). Soils are predominantly sodasols	

River System	Reach	Approx. Location	Description / Reasoning	Location
River Murray	Perricoota Reach, sub-reach 8	Upstream and downstream of Torrumbarry Weir where flows flood out across the Koondrook-Perricoota forest system	Example of a large distributary system that would have delivered significant flows pre-regulation to the Wakool system. River Style of the reach itself is fine grained, meandering High suspended load and general low bed load transport. Bedload transport from Barmah reach limited by weir. Soils are predominantly vertosol, and the reach is the transition from sodosol to vertosol dominant soils.	
River Murray	Perricoota Reach, sub-reach 9	Upstream and downstream of Barham	This sub-reach extends from just upstream of Barham to the upstream extent of Campbells Island State Forest.	

River System	Reach	Approx. Location	Description / Reasoning	Location
River Murray	Gunbower Reach, sub-reach 10	Downstream of Swan Hill in the old lake zone	Example of a paleolake systems with current river inset into the previous lakebed. River Style of the reach itself is fine grained, low sinuosity. High suspended load and general low bed load transport. Soils are predominantly vertosol with Calcarosols as represented by the previous lake margins.	
River Murray	Wakool Reach, sub-reach 17	Murray River at Boundary Bend	Within the Bungunnia landscape zone, just downstream of confluence with the Murrumbidgee River. Affected by flows from both systems. River Style of the reach itself is fine grained, meandering with a wide riparian zone. High suspended load and general low bed load transport from both the Murray and Murrumbidgee river and moderate bed load through the reach. Soils within the floodplain are predominantly vertosol with calcarosols present outside this.	

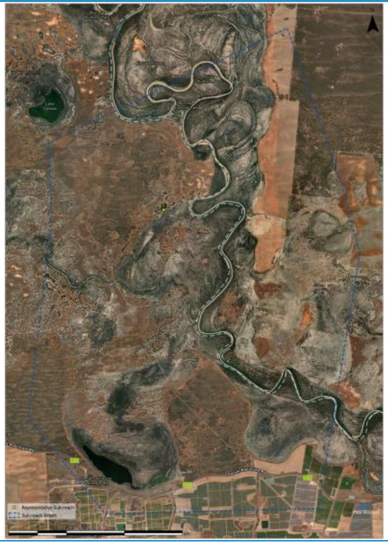
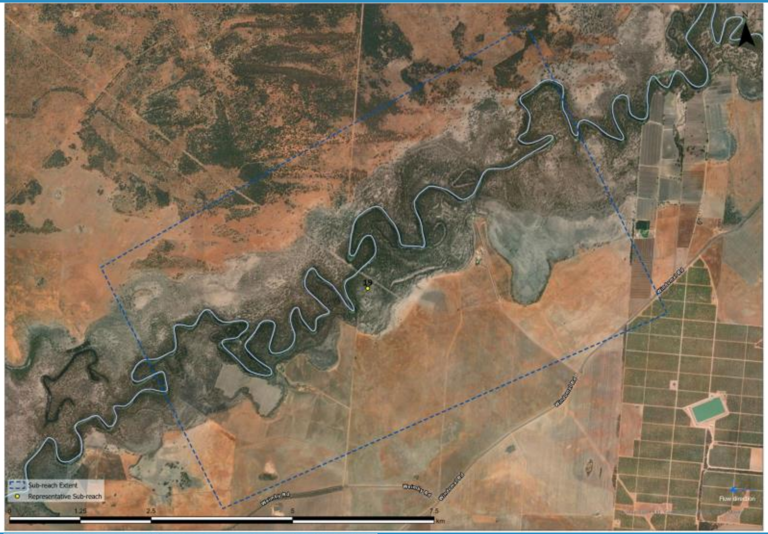
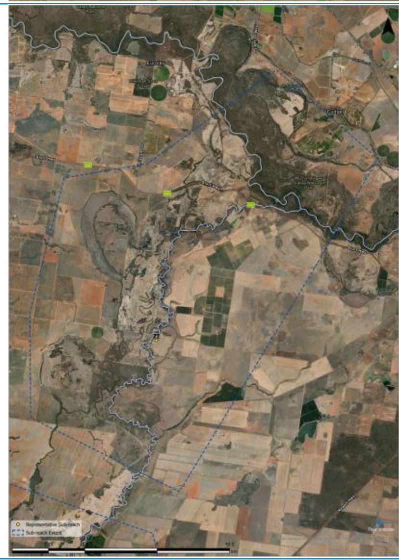
River System	Reach	Approx. Location	Description / Reasoning	Location
River Murray	Wakool Reach, sub-reach 18	Murray River at Jinker Bend	Representative of river and floodplain along this reach, example of different floodplain landforms and soils types. River Style of the reach itself is fine grained, meandering with a wide riparian zone. Adjacent to large floodplain wetland complex. High suspended load and bed load transport. Potential area of bed aggradation. Soils within the floodplain are predominantly vertosol with calcarosols present outside this and across the wetland complex.	

Table 10 Sub-reaches for the Murrumbidgee River

River System	Reach	Approx. Location	Description / Reasoning	Location
Murrumbidgee	Balranald to Wakool Junction, sub-reach 19	Balranald to Murray	Downstream of Balranald, where distributary system recombines and a meandering pattern typical upstream of Maude is again produced. River Style of the reach itself is meandering fine grained. High suspended load and low bed load transport. Soils typically vertosols in the floodplain with calcarosols beyond.	
Murrumbidgee	Carrathool Reach, sub-reach 20	Downstream of Hay, including the Hay Weir	Floodplain is narrow (< 1.5km). Flows and water levels are controlled by the Hay Weir at the upstream. River Style of the reach itself is meandering fine grained. High suspended load and low bed load transport. Soils typically vertosols in this reach.	

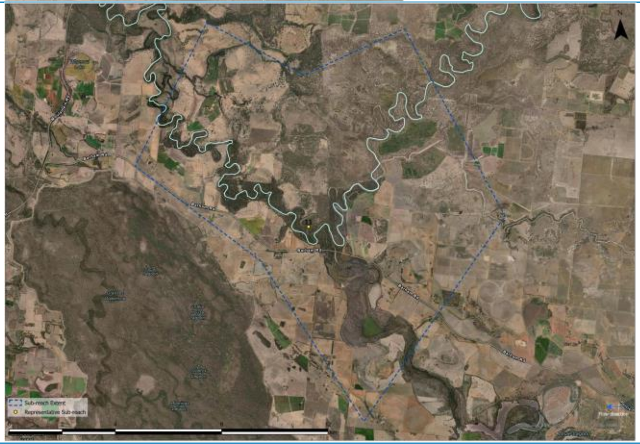
River System	Reach	Approx. Location	Description / Reasoning	Location
Murrumbidgee	Narrandera Reach, sub-reach 21	Murrumbidgee Valley National Park	Extensive floodplain around 2-6km wide, low sinuosity, fine grained system. Murrumbidgee Valley National Park / McCaugheys Lagoon High suspended load and low bed load transport.	
Murrumbidgee	Yanco Creek / Billabong Creek, sub-reaches 22 and 23	Upper Yanco Creek	Yanco Creek bifurcates from the Murrumbidgee River (sub-reach 22) and then slightly further downstream where Colombo Creek branches off from the main channel. The River Style of the reaches are low sinuosity / meandering fine grained, although anabranches and meandering sections visible in floodplain (paleo features?) Moderate suspended load and low bed load transport. May be some bedload accumulation. Soils typically sodasols.	 

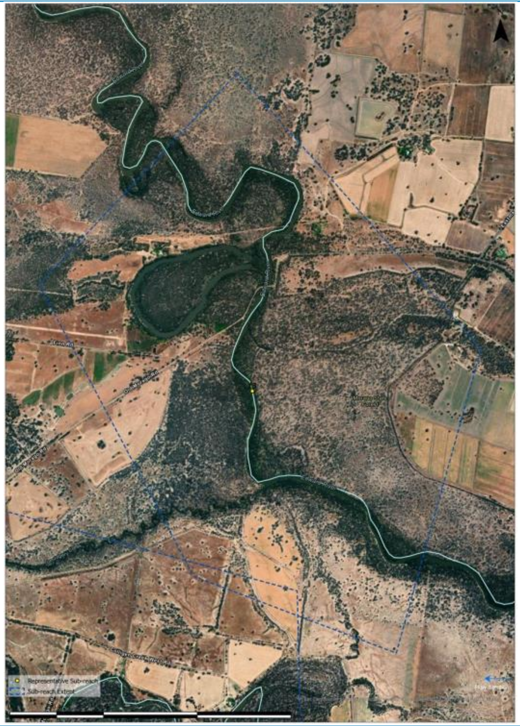
River System	Reach	Approx. Location	Description / Reasoning	Location
Murrumbidgee	Mid-Murrumbidgee wetlands Reach, sub-reaches 24 & 25	Old Man Creek / Beavers Creek	Both reaches are part of the Murrumbidgee - Old Man Creek Anabranch complex. Mixed fragility section with Murrumbidgee having a high fragility index while potential anabranch along Beavers Creek is moderate. Murrumbidgee is meandering fined grained, while Beavers Creek is low sinuosity	 
Murrumbidgee	Wagga Wagga Reach, sub-reach 26	Approx. 25km downstream of Gundagai	Within the anabranch deposition zone, downstream of the meandering transport zone River Style of the reach itself is low sinuosity gravel bed. Although anabranches are visible along with cutoffs (developing?). High suspended load and low? bed load transport. Sand slugs mapped in several tributaries which enter the river through this reach. Soils vary.	

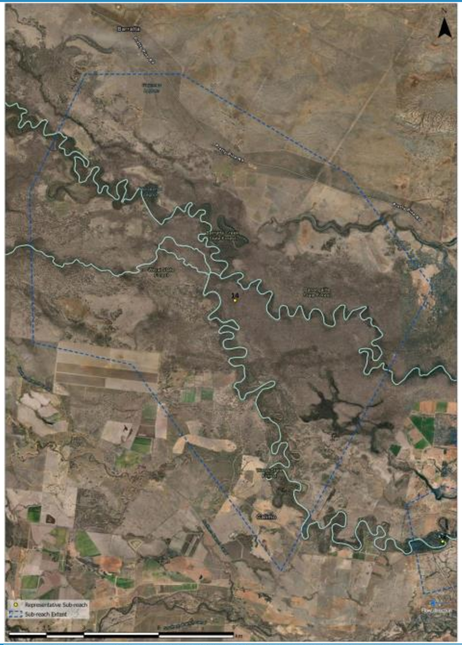
River System	Reach	Approx. Location	Description / Reasoning	Location
Murrumbidgee	Gundagai and Jugiong Reaches, sub-reach 27 & 29	Murrumbidgee and Tumut River confluence	Within the mobile transport zone (valley process zones). River Style of the reach itself is planform controlled, low sinuosity sand bed., High suspended load and low? bed load transport. Downstream of identified sand slugs within tributaries. Soils vary – presence of chromosol, kurosol and kandosols mapped.	 
Tumut River	Tumut Reach	Nimbo Creek to Brungle Bridge	The potential for a complete avulsion of the main channel into Nimbo Creek is the greatest single issue in this reach. Potentially this could occur at the entrance point to the anabranch, or to a lesser degree at several locations where the anabranch and main channel are within tens of metres of each other. The main channel is perched above the anabranch. Low sinuosity, sand? Moderate suspended load and low bed load transport. Soils typically sodasols in the floodplain with chromosols beyond	

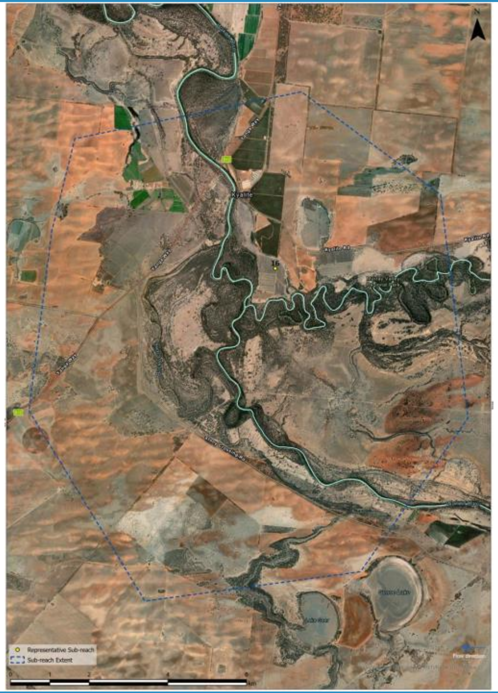
River System	Reach	Approx. Location	Description / Reasoning	Location
Murrumbidgee	Jugiong Reach, sub-reach 30	Jugiong		

Table 11 Sub-reaches the Edward (Kolety) - Wakool River system

River System	Reach	Approx. Location	Description / Reasoning	Location
Edward-Kolety Wakool	Lower Alluvial Fan – Upper Edward, sub-reach 6	Approx. 8.5 km downstream of Murray confluence	The sub-reach is on the Upper Edward River, approx 9km downstream the Edward River offtake. From the confluence to Deniliquin the river style is defined as low sinuosity, fined grained. Moderate suspended load and low bed load transport. Soils type is predominantly sodosol and there is anecdotal evidence of increasing bank erosion along this reach. The river along this reach is within the broader distributary river system.	
Edward-Kolety Wakool	Mid Wakool Reach, sub-reach 11	Located where the Wakool meets Thule Creek		

River System	Reach	Approx. Location	Description / Reasoning	Location
Edward-Kolety Wakool	Lower Alluvial Fan, Deniliquin to Werai, sub-reach 12	Upstream of Stevens Weir	This site is on Colligen Creek downstream of Stevens Weir and is also impacted by flows from the Weir. The river style is defined as low sinuosity, fined grained. Moderate to low suspended load and low bed load transport. Soils type is predominantly vertosol.	
Edward-Kolety Wakool	Lower Alluvial Fan, Deniliquin to Werai, sub-reach 13	Downstream of Stevens Weir	This site is on the Edward River downstream of Stevens Weir, prior to entering the Werai Forest section. The river style is defined as low sinuosity, fined grained. Moderate to low suspended load and low bed load transport. Soils type is predominantly vertosol	

River System	Reach	Approx. Location	Description / Reasoning	Location
Edward-Kolety Wakool	Mid Edward Reach, sub-reach #14	Werai Forest	The Werai forest section covers the Edward River, Colligen Creek and Niemur River. Depending on the flow conditions these flows can be independent or highly interactive. Soil type is predominantly vertosols The river style is defined as meandering low sinuosity, fined grained. Medium suspended load and low bed load transport This is a clearly defined distributary reach.	
Edward-Kolety Wakool	Niemur Reach, sub-reach #15	Located downstream of Cockrans Creek confluence	This site on the Niemur River is downstream of the Werai Forest and includes inflows from several sources. The sub-reach includes a complex network of current and ancestral stream forms. The river style is defined as low sinuosity, fined grained. Low to medium suspended load and low bed load transport Soil type is predominantly vertosols	

River System	Reach	Approx. Location	Description / Reasoning	Location
Edward (Kolety) Wakool	Gunbower - Wakool and Lower Wakool Reaches, sub-reach #16	Edward Wakool Junction	This site is at the confluence with the Wakool River and is within the hydrologic zone from Moulamein to the Junction. It provides representative flow and geomorphic conditions in the lower reaches of both river systems. The river style is defined as meandering, fined grained. Medium to high suspended load and low bed load transport Soil types include calcarosols and vertosols Within the broader distributary system but with strong ancestral channel influences.	

section four

4. **Geomorphic Features and Processes**

4.1. **Overview**

Geomorphic features have been derived from the earlier Functional Process Zone descriptions (Whittington et al, 2001), as well as numerous projects investigating geomorphic features throughout the River Murray system.

Geomorphic features can vary from within-channel features, such as sandbars and riverbanks, to rarely inundated features several kilometres from the main channel, such as floodplain wetlands, Figure 18. All these features have a differing impact on the social, cultural, ecological, and economic functions of the river channel.

Figure 18 Sandbars, wetlands and riverbanks are all geomorphic features that all have processes of formation and destruction linked to various aspects of the flow and sediment regime.

Geomorphic processes are the way in which features are formed by a range of interactions between primarily flow, sediment, and vegetation. These processes drive the character of the rivers and in turn the value provided by the geomorphic features. Changes in flow can have significant impacts on these processes, such as increases in prolonged bankfull flows driving meander migration and river bend cutoffs, as shown in Figure 19.

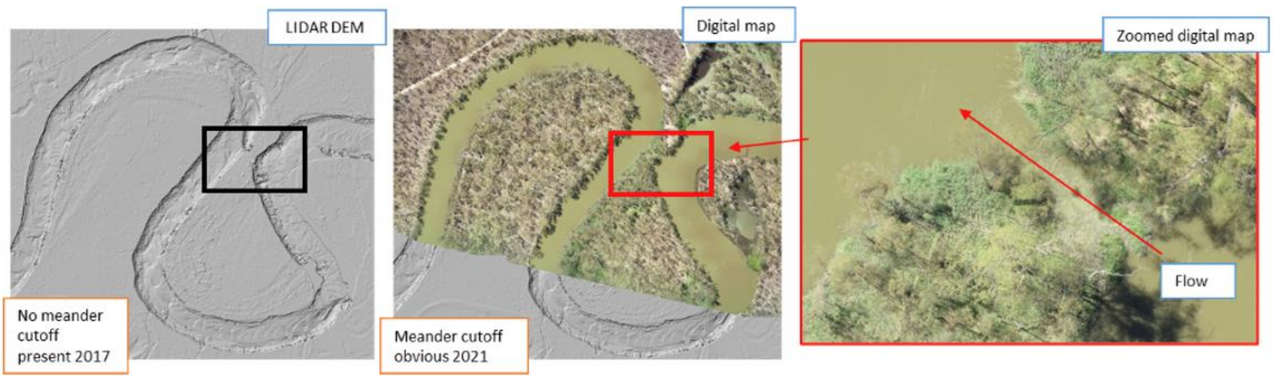


Figure 19 An example of a geomorphic process in the River Murray: Meander cutoffs through channel migration.

Geomorphic features and processes vary significantly depending on the landscape zone and reach types across the waterways. The sub-reach descriptions described in the following section aim to characterise these features and processes.

4.2. Sub-Reach Assessments

As detailed in Section 3, sub-reaches have been identified across the waterways within the study area to allow for a more focussed analysis of geomorphic features, flow linkages and potential impacts of different flows on the various features. Detailed summaries for each sub-reach are provided in Appendix C.

4.3. Linkages to Flows

Waterway form and processes are a function of their flow conditions. There are a range of flows from small freshes to large overbank flows that have differing effects on the geomorphic processes that shape geomorphic features. These processes can be either erosional (degradation) or depositional (aggradation). The likelihood of each is also highly dependent on the sediment availability, i.e., the greater the sediment load the more likely depositional processes may be.

We have considered consistent and prolonged, as well as variable within-channel flows such as freshes up to bankfull flows, and then flows that are larger than bankfull and inundate the floodplain. Each flow plays a differing role in the in the influence on geomorphic processes and features, as outlined in Table 12. We have included a prolonged sub-bankfull flow category as under regulated conditions the flows are maintained at a consistent (typically at around half to two-thirds bankfull) rather than variable level and persist over a prolonged period. This category of flow would not have typically occurred in the River Murray and Murrumbidgee River systems prior to regulation and has been recognised as a significant contributor to geomorphic change particularly erosion.

Table 12 Geomorphic features, processes of formation/destruction and related flows

Channel / Floodplain	Geomorphic features	Processes	Prolonged sub-bankfull flows[1]	Sub-bankfull flows (freshes)	Bankfull and greater
Channel	**Sand bars**	Lateral accretion: Whereby bars are formed by bed sediments (sands/gravels) elevated by transport of coarse sediments	Rarely lead to bar formation unless abrupt bends or obstruction present	Freshes up to bankfull flows are often attributed to the formation of bars	Can cause dramatic changes and modify locations of bars
		Erosion: Removal or reduction in size of bar commonly through fluvial scour	Depending on levels often decrease presence of bars and create homogenous bed formations	Can lead to some bar erosion but more commonly formative	In alluvial settings may not be significantly more effective than bankfull flows
Channel	**Benches**	Vertical accretion: Formed by deposition of fine-grained sediments (silts/clays)	Unlikely to form benches	Often form benches where adequate sediment is available	Will lead to bench formation in some locations where velocities are lower
		Bench edge erosion: Fluvial scour of benches and reduction in bench size.	Known to erode benches (with numerous examples in the River Murray)	Can cause some erosion but more so formative	Likely to cause both erosion and deposition depending on locations
Channel	**Pools (bed depth diversity)**	Bed sediment scour: At high flow stages, when flow converges through pools, greater bed shear stresses induce scour of sediments stored on the bed. Can lead to scour to *in situ* clays.	Not formative	Can lead to formation of pools, particularly bankfull flows	Higher flows will maintain pool depth and diversity
		Infilling: Deposition of sediments within pools leading to loss of depth diversity and bed homogenisation. Requires sediment availability.	Commonly leads to infilling of pools where sediment is mobilised to these areas of the bed.	Can lead to infilling but higher flows (up to bankfull) more formative.	Unlikely to lead to infilling.

[1] Consistent and prolonged flows at around two-thirds bankfull to bankfull

Channel / Floodplain	Geomorphic features	Processes	Prolonged sub-bankfull flows[1]	Sub-bankfull flows (freshes)	Bankfull and greater
Channel	**Mobile bed sediments (non-pools)**	Bed erosion: Removal of sediments from runs, riffles or glide sections of the bed.	Mostly only local bed sediment movement.	Most commonly attributed to bed sediment movement.	Will mobilise bed sediments throughout the channel.
		Bed deposition: Processes of aggradation including bed armouring (whereby sediments form a barrier to erosion)	Likely to lead to localised bed sediment deposition.	Highly likely to lead to bed sediment deposition.	Most effective flows for redistributing bed sediments.
Channel	**Sand slug or pulse**	Aggradation: Sediment supply and transport: Formed when transport capacity is exceeded due to oversupply of sediments. Can lead to translocation of sediment wave or elongation of the bed (long flat bed).	Will contribute to slow migration of bed sediments, sand slugs or pulses.	Common driver of the movement of sand slugs and pulses.	Highly effective at mobilising and transporting sand slugs and pulses.
Channel	**Riverbank**	Erosion: Processes such as fluvial entrainment, notching and mass failure. Increased rate and/or extent of erosion.	Dependent on event pattern but can lead to riverbank notching (prolonged flows), and mass failure (bank saturation and rapid drawdown which then causes part of the bank to collapse).	Can lead to fluvial scour and mass failure (bank saturation and rapid drawdown).	Likely to lead to riverbank disturbance but similar processes to bankfull flows.
		Bank aggradation: Lateral accretion and bank building with fine-grained sediments (silts/clays).	Unlikely to build or aggrade riverbanks.	Most commonly attributed to riverbank building given adequate sediment supply.	Unlikely to significantly contribute to riverbank building.
Channel	**Channel capacity**	Incision: Increase in channel capacity through erosion, namely	Commonly leads to channel incision where all 'work' by fluvial scour is done	Can lead to channel incision, but flows often less common than regulated, so	Can lead to channel incision, but due to infrequent nature, is less likely than

Channel / Floodplain	Geomorphic features	Processes	Prolonged sub-bankfull flows[1]	Sub-bankfull flows (freshes)	Bankfull and greater
		deepening and widening of a river channel's bed and banks.	on the river channel, particularly where sediment supply limited.	therefore less work done.	more frequent, smaller events.
		Aggradation: Building up or infilling of a channel through shallowing and contracting width.	Regulated flows are unlikely to contribute unless excess sediments imported to reach.	Unlikely to contribute.	Highly dependent on location and sediment supply.
Channel	**Levees**	Erosion (levee narrowing by fluvial entrainment): Levees are produced primarily from suspended load deposition.	Unlikely to be at levee height.	Only near-bankfull flows will be near levee height, and these are most likely to cause erosion if prolonged action at the levee. Erosion enhanced by wave action.	Can lead to erosion of levees through fluvial entrainment.
		Erosion (levee breach): Localised erosion failure commonly associated with overtopping (or piping erosion)	Unlikely to be at levee height.	Unlikely to cause levee breach unless piping or undermining failure.	Commonly leads to levee breach where overtopping occurs.
		Aggradation (levee building): Deposition of fine-grained sediment when velocities reduce (requires sediment availability)	Unlikely.	Unlikely.	Levees are formed (aggraded) naturally by overlapping and overtopping where fine-grained sediment is deposited.
Channel / Floodplain	**Sub-bankfull connections (interface channel to floodplain)**	Erosion: Sill levels control flow into anabranches and floodrunners and erosion can lead to increased capacity	If regulated flows of adequate elevation.	Commonly linked to sill level erosion.	No significant increase likely under higher flows.
		Aggradation: Sill level reduced capacity	If regulated flows of adequate elevation.	Likely to contribute to aggradation of sill levels if sediment available.	Most likely on falling limb.

Channel / Floodplain	Geomorphic features	Processes	Prolonged sub-bankfull flows[1]	Sub-bankfull flows (freshes)	Bankfull and greater
Floodplain	**Cutoffs (one bend)**	Erosion of cutoffs at higher discharges can lead to short circuiting of river channels via a direct channel linkage (shorter path)	Less likely to be of adequate flow level to induce scour of cutoffs.	Likely to increase erosion of cut off channels.	Highly likely to increase rates of erosion of cutoffs.
		Meander migration at different rates can lead to joining of two channels and short circuiting of river bends (shorter path)	Highly likely to lead to channel migration that leads to short circuiting.	Can contribute to meander migration but often not of adequate frequency.	Likely to induce final connection if meander migration has progressed.
		Infilling of short circuit paths.	Unlikely to be at flow stage to contribute.	If adequate sediment available can increase infilling via sediment deposition.	If adequate sediment available can increase infilling via sediment deposition though velocities may be too high.
Floodplain	**Anabranches/ Floodrunners**	Avulsion: Development of anabranches (across multiple meander bends).	If adequately low-level prolonged, regulated flow conditions often encourage the development of anabranches (but will not initiate them).	For sub-bankfull connections, these flows will marginally increase development of anabranches but are commonly not frequent or prolonged flows.	These flows often initiate anabranch development (cross-floodplain connections and flow paths) and in developing anabranches can lead to tipping points and further channel incision.
		Infilling: Of anabranches through sediment deposition.	If adequately low-level flows and adequate sediment supply these flows can infill anabranches, but this is not common.	As with regulated flows.	Unlikely to infill anabranches given higher velocities, unless excess sediment available.
Floodplain	**Wetlands / Billabongs / Distributary channel**	Inundation and flow and sediment connectivity	Unlikely to be of adequate levels to connect.	If adequate discharges these may connect but are unlikely to spend significant time to completely fill features or	These flows will connect to a range of features but require adequate duration of flows, and may transport and deposit

Channel / Floodplain	Geomorphic features	Processes	Prolonged sub-bankfull flows[1]	Sub-bankfull flows (freshes)	Bankfull and greater
				transport significant sediments.	sediments if supply adequate.
Floodplain	**Floodplain (>Bankfull connection)**	Inundation of the floodplain and deposition of sediments (where available)	Not of adequate levels.	Not of adequate levels.	These flows will readily inundate floodplains and transport and deposit sediments.
Floodplain	**Rill-like floodplain channel**	Erosion of the floodplain through fluvial entrainment to develop multiple channels.	Not of adequate levels.	Not of adequate levels.	Events greater than bankfull can produce these conditions in high-energy floodplain environments.

For each feature and process in the table above, the ‘strength of association’ between the feature and each flow type has been developed. The strength of association was derived through a review of available literature and expert elicitation within the expert geomorphologists of the project team. Association was assessed as either no association (0), weak association (1), moderate association (2), and strong association (3). The agreed flow associations for the geomorphic features are presented in Table 13.

For each sub-reach the geomorphic features and processes currently present have been identified (refer to the sub-reach assessments in Appendix C) and the strength of association with different flow categories as detailed in Table 13 have been applied. For example, the resultant table for Sub-Reach 1 in the Albury Reach is shown in Figure 20.

A limitation of this approach is that new geomorphic features that may result from a flow type are not explicitly captured.

Table 13 Geomorphic Feature and Strength of Association for each Flow Category

Channel / Floodplain	Geomorphic features	Processes	Flow Categories					
			Prolonged sub-bankfull flows	Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Channel	**Sand bars**	Lateral accretion	0	1	2	3	3	3
		Erosion	2	2	3	3	3	3
Channel	**Benches**	Vertical accretion	0	2	3	3	1	1
		Bench edge erosion	2	2	2	2	1	1
Channel	**Pools (bed depth diversity)**	Bed sediment scour	1	1	2	3	3	3
		Infilling	2	2	1	1	1	1
Channel	**Mobile bed sediments (non-pools)**	Bed erosion	1	2	3	3	2	2
		Bed deposition	2	3	2	2	1	1
Channel	**Sand slug or pulse**	Sediment supply and transport	2	1	2	2	2	2
Channel	**Riverbank**	Erosion	3	3	2	1	1	1
		Bank aggradation	1	3	2	1	1	1
Channel	**Channel capacity**	Incision	3	1	2	2	2	2
		Aggradation	2	3	2	1	1	1

Channel / Floodplain	Geomorphic features	Processes	Flow Categories					
			Prolonged sub-bankfull flows	Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Channel	**Levees**	Erosion (levee narrowing by fluvial entrainment)	0	0	0	2	3	3
		Erosion (levee breach)	0	0	0	2	3	3
		Aggradation (levee building)	0	0	0	2	3	3
Channel / Floodplain	**Sub-bankfull connections (interface channel to floodplain)**	Erosion	0	0	3	3	3	2
		Aggradation	0	0	3	3	3	2
Floodplain	**Cutoffs (one bend)**	Erosion of cutoffs	1	1	2	3	3	3
		Meander migration	1	1	2	3	3	3
		Infilling of short circuit paths.	0	1	2	3	3	3
Floodplain	**Anabranches/ Floodrunners**	Avulsion	1	0	2	3	3	3
		Infilling	0	0	3	3	2	2
Floodplain	**Wetlands / Billabongs / Distributary channel**	Inundation and flow and sediment connectivity	0	0	0	3	3	3
Floodplain	**Floodplain (>Bankfull connection)**	Inundation of, and deposition of sediments	0	0	0	0	3	3
Floodplain	**Rill-like floodplain channel**	Erosion through fluvial entrainment	0	0	0	0	3	3

Figure 20 Example of geomorphic features and processes and the flow associations for each flow category for Sub-reach 1

Geomorphic Feature and Process		Flow Associations					
		Prolong Sub-bankfull flows	Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	3	2	1	1	1
Cutoffs	Avulsion / meander migration	1	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	1	0	2	3	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	0	3	3
Floodplain (> bankfull)	Sediment desposition	0	0	0	0	3	3

4.4. Effects of Flow Changes

The flow options scenarios are aimed at creating a more variable flow regime through removing constraints which will allow water for the environment to be delivered at higher levels and more appropriate times to enhance ecological objectives. From a geomorphic perspective, a more variable flow regime may assist in addressing erosions effects resulting from the current constraints flow regime.

The broad negative and positive geomorphic changes associated with increased and/or more frequent flows are summarised in Table 14 for specific geomorphic features and processes. These changes assume that the geomorphic process is actively occurring under current flow conditions. Only those features and processes identified across the sub-reaches have been included for discussion and the potential changes will vary by sub-reach and by how active the processes that are currently occurring are. In some instances, a change can be both negative and positive.

Table 14 Overview of negative and positive changes associated with geomorphic features and processes identified in the study area

Geomorphic Feature & Process		Potential changes associated with increased and/or more frequent flows	
		Negative	Positive
Riverbanks	Erosion	Enhanced rate of bank erosion	Supplying sediment downstream to support bench and point bar development
		Excessive loss of bank and riparian vegetation	Increasing instream wood load
		Supplying sediment downstream	Bench development
Cutoffs	Avulsion / meander migration / meander extension	Erosion triggered upstream; deposition downstream	Creation of new wetlands (deeper, more diverse, more connected)
			More hydraulically efficient main channel
Anabranches / Floodrunners (sub-bankfull)	Avulsion	Greater rate of development	Increased instream wood load
		Loss of land and riparian vegetation	
		More sediment delivery downstream (major)	
Anabranches / Floodrunners (> bankfull)	Avulsion	More sediment delivery downstream (minor)	Geomorphic diversity increases on floodplain
Floodplain (> bankfull)	Sediment deposition	Flows delivered with no sediment	Sediment depositing on the floodplain
Sand Slugs	Aggradation / Transport	Increased transport into and rates of deposition within Barmah reaches	
		Eroding the ends of point bars	
Benches	Deposition	Increased flow without corresponding sediment load limits deposition	Evolution of bars into benches

Geomorphic Feature & Process		Potential changes associated with increased and/or more frequent flows: Negative	Positive
Bars	Deposition / Erosion	Overstabilisation of instream bar	Recreate bars
		Erosion of bars	Maintain bars
Capacity	Aggradation	Increased rate of capacity reduction	Increased floodplain inundation
		Reduced geomorphic diversity	
		Increased unseasonal floodplain inundation	
		Enhanced bank erosion	
Levee	Deposition / Erosion	Increased number of breakouts	Increased fine sediment movement onto the floodplain
		Increased erosion	
		Increased rates of fine sediment movement onto the floodplain (smothering vegetation)	
Wetlands, billabongs, distributary channels	Sediment Deposition	Increased infilling of features	Increased formation and maintenance of features

4.5. **Other Causes of Geomorphic Change**

4.5.1. **General**

The geomorphic features and processes described in the preceding section highlight that these rivers are not static, and can alter their slope, depth, width, bed form, and planform in response to changes in the balance between sediment supply and the flows capacity to transport the sediment. However, flows are not the only trigger for these changes.

Natural triggers of geomorphic change to river channels and floodplains include (Erskine et. al. 1993):

- Long term trends in the rainfall-runoff or sediment supply of the catchment. For example, the ancestral river channels in the study area were formed during a period of much higher rainfall across the catchment.
- Large floods or a series of floods, bushfires, or landslips.
- Crossing an internal geomorphic threshold, whereby an on-going natural process reaches a stage where a major change is initiated.
- The ongoing complex response of the river system to some previous natural change.

Since European settlement, there has also been direct alteration of channels and floodplain throughout these river systems. Common examples include:

- Removal of vegetation from banks, and the riparian zone which can make the channel more susceptible to bed and bank erosion.
- Removal of floodplain vegetation, which can alter the flood flow split and hence flow energy between the channel and the floodplain.
- De-snagging whereby large wood is removed from the channel, predominantly to improve navigation and decrease flood levels; however, the result can be increased flow velocities resulting in erosion and deepening of the riverbed.
- River realignment or bank stabilisation works, which can change the flow or sediment availability and distribution.
- River regulation through the presence of dams, weirs and regulating structures. They can trap coarser sediments upstream and limit downstream sediment supply as well as rapidly altering the water levels upstream and downstream during their operation, triggering bank erosion. These structures also regulate the broader flow rates and water levels along the rivers.
- Waves generated by vessels which can increase the rate of bank erosion.
- Land use change and historic gold mining, which have been found to have contributed large volumes of sediment to the River Murray, with a large volume of sand now present in the river channel between Tocumwal and Barmah Township. Other sand slugs as a result of the same or similar processes are present in lesser volumes in other rivers across the Murray-Darling Basin.

For this assessment, the focus is only on the flows that drive geomorphic processes and hence channel change. Other drivers of change such as those described above will have influenced the current (baseline) geomorphic trajectory of all the sub-reaches analysed (see Table 24 to Table 14, and Appendix C) but how they continue to do so in the future is highly uncertain in both timing and spatial extent.

4.5.2. Effects of Flow Regulation

It is important to recognise when considering the impacts of environmental flows the legacy impacts from long-running operational management of the River Murray flow regime. A significant outcome of flow regulation across the River Murray and Murrumbidgee River systems are the frequent, consistent, and prolonged high sub-bankfull flows that occur along some waterways. The frequency of flows within this flow category has been identified as an important factor driving channel change beyond that which would naturally be expected. This occurs because an increasing amount of flow energy is concentrated within the channel rather than being dissipated across the floodplain during overbanks flows. For example, Erskine et al (1993) found that the flow energy available to drive in-channel erosion processes had increased by up to 25% over a 30-year period due to the increased frequency of these regulated flow conditions.

The effects of flow regulation on channel change have been studied on the River Murray between Hume Dam and Lake Mulwala as under current constraints these reaches are presently dominated by long-duration high regulated flows between October and March. A visible impact of such flow regulation on this part of the river is channel widening through continued bank erosion. Comparison of historic and contemporary cross sectional surveys indicates that channel widening has accelerated since regulation began (Tilleard et al., 1994). The mechanisms of bank erosion are not fully understood, with several processes influencing erosion rates including flow velocity, water level, rates of rise and fall, bank profile shape, soil properties, bank orientation, and weather. The role of each process relative to flow regulation is currently under investigation.

Studies to date have found that bank erosion is commonly the result of multiple drivers acting in concert, such as:

- Drying and desiccation of soil caused by exposure to air and high temperatures[2].
- Expansion and breakup of soil on wetting, in particular dispersion and slaking[3] due to the types of soil in these reaches.
- Removal of soil particles by flow (fluvial erosion), for which velocity is important.
- Notching caused by prolonged water levels focussed on a point, which results in an overhanging upper bank (Figure 21).
- Upper bank block collapse.

In addition to erosional drivers, soil properties – e.g., clay content and the presence of organic matter - affect the extent to which erosion will occur (especially related to dispersion and slaking).

[2] Soil drying and desiccation prepares riverbanks for erosion. Drying of previously saturated soil, especially that with high clay content, causes shrinking and desiccation, or cracking. Desiccated soils are less cohesive and more prone to both subaerial and fluvial erosion (erosion by heavy rain and stream flow).
[3] Banks with high clay content are prone to breaking up into smaller particles on rewetting, a process known as slaking. Certain clay rich soils are also prone to dispersion, a chemical process in which individual clay particles separate and disperse into solution. Such soils are also referred to as sodic.

Figure 21 Example of notch development on the Edward River (Watts et al, 2020)

Monitoring of bank condition along the Edward (Kolety) - Wakool System (Watts et al, 2020) found that regulated flows that produce prolonged constant periods of inundation to the riverbanks appeared to be the main driver of notching on riverbanks in the Edward (Kolety) River downstream of Stevens Weir. The sequence of flows - those which inundated the bank and created the notches, followed by flows that saturated the bank above the notch, could cause extensive mass-failure of the banks and result in widening of the channel. Channel widening because of bank erosion is the most visible outcome of regulated flow conditions.

Figure 22 Mass failure of the bank on the Edward River (Watts et al, 2020)

section five

5. Impact Assessment

5.1. Overview

As detailed in Section 2.3.4, the assessment of flow impacts on geomorphic features and how this might change with the flow option scenarios has been undertaken on a sub-reach basis. Example outcomes are provided in this section, while the results for each sub-reach are included in Appendix C.

5.2. Flow Categories and their Frequency

5.2.1. Thresholds

The flow categories used for the impact assessment were defined previously in Table 13 and have been selected due to their links to geomorphic features and processes. For the impact assessment we need to assign each flow category to a particular flow magnitude threshold to quantify how often such flow conditions occur both under current constraints conditions and for the flow options scenarios.

Initially for the sub-reach assessment, the available inundation mapping was used to determine what flow category (e.g., flows from small freshes to large overbank flows) corresponds a given flow range and channel or floodplain feature. For example, the inundation mapping for sub-reach 1 is presented in Figure 23. The flow ranges were then compared to the flow threshold estimates within the Long-Term Water Plans (LTWP) for the Murray and Edward Wakool Rivers (DPIE, 2020a and b), and for the Murrumbidgee (DPIE, 2020c and d). The finalised flow thresholds adopted for each of the river systems were detailed in the following section.

As noted in Section 4, prolonged sub-bankfull flows are not a flow category that would have occurred prior to regulation. This flow category is likely to occur less frequently under the flow options scenarios due to the ability to deliver more variable flow conditions reflective of a more natural flow regime. As there is no generalised definition of this flow category it has not been explicitly analysed in the impact assessment, however changes to flows within this range are captured within the results for the low and high freshes.

Representative Sub-reach: 1 Inundation Map

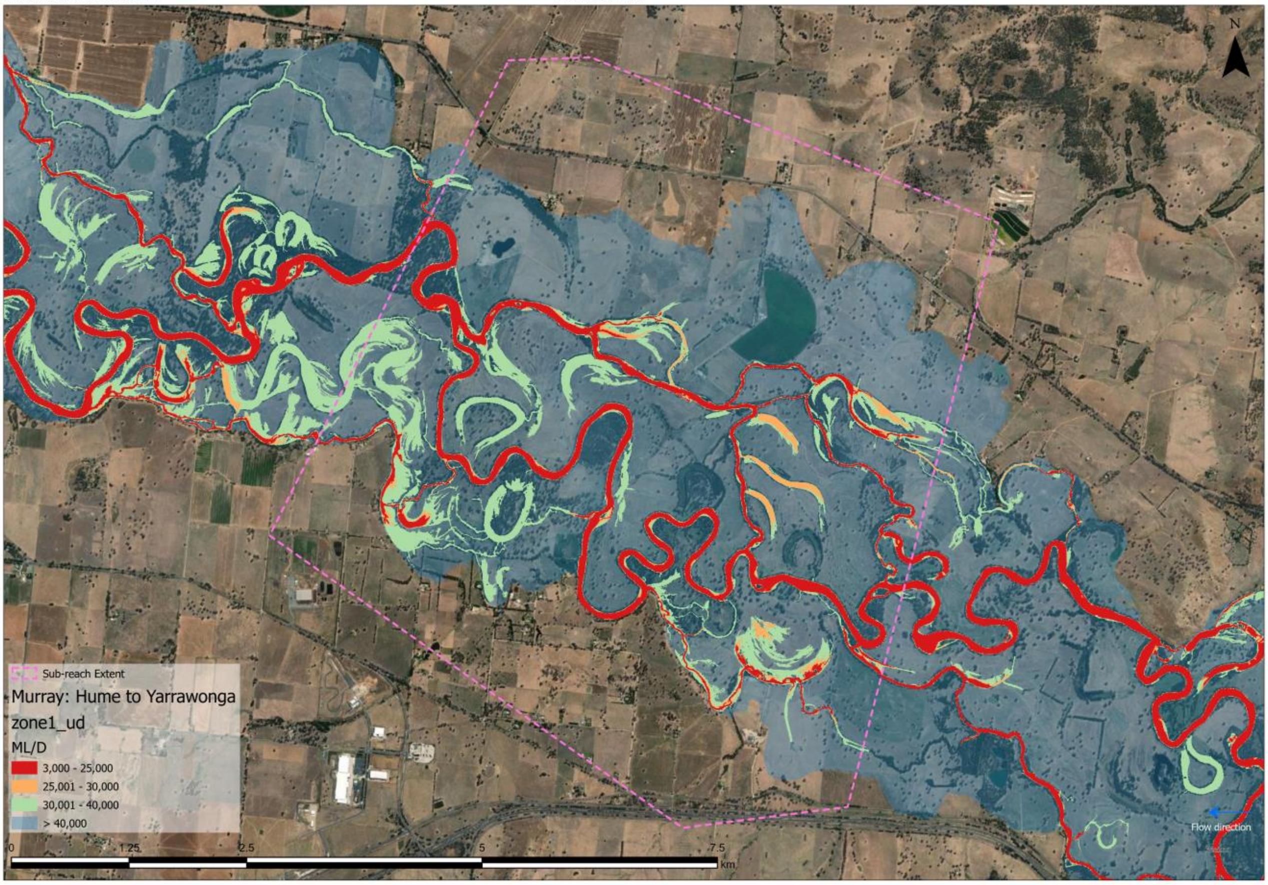


Figure 23 Inundation mapping for sub-reach 1 categorised by flow ranges

5.2.2. Frequency of Flow Categories

A summary of the frequency of different flow categories under the base case (current constraints) and the flow options scenarios was provided by DPE at a selection of locations throughout the study area in Table 15 to Table 17. We have calculated the percentage change in frequency of each flow category in terms of the number (#) of events per year. This allows us to compare the change in event frequency for the flow options scenarios compared to the current constraints' scenario.

The specific flow options scenarios assessed were:

- **Y45D40:** Flow limit at Yarrawonga raised to 45,000 ML/d and at Doctors Point raised to 40,000 ML/d.
- **Y30D30:** Flow limit at Yarrawonga and Doctors Point raised to 30,000 ML/d.
- **W40:** Flow limit at Wagga Wagga raised to 40,000 ML/d.
- **W32:** Flow limit at Wagga Wagga raised to 32,000 ML/d.

Only events of 7 days or more are considered within the analysis.

Table 15 Overview of the frequency (# of events of 7 days of more per year) of different flow magnitude along the River Murray system under current constraints and flow options scenarios (Y45D40, Y30D30)

Flow Type	Flow Increment	Doctors Point (# events / year)		
		Current	Y45D40	Y30D30
Small fresh	>8,000	1.01	1.00	1.00
Large Fresh	>18,000	0.82	0.87	0.92
Bankfull	>28,000	0.39	0.67	0.60
Moderate Overbank	>45,000	0.22	0.19	0.21
Large Overbank	>70,000	0.08	0.07	0.08

Flow Type	Flow Increment	Yarrawonga (# events / year)		
		Current	Y45D40	Y30D30
Small fresh	>10,000	1.00	0.99	0.99
Large Fresh	>20,000	0.72	0.84	0.84
Bankfull	>37,000	0.41	0.60	0.40
Moderate Overbank	>50,000	0.32	0.26	0.29
Large Overbank	>80,000	0.15	0.13	0.14

Flow Type	Flow Increment	Torrumbarry (# events / year)		
		Current	Y45D40	Y30D30
Small fresh	>10,000	1.00	0.99	0.99
Large Fresh	>17,000	0.82	0.90	0.90
Bankfull	>25,000	0.58	0.63	0.62
Moderate Overbank	>40,000	0.34	0.35	0.35
Large Overbank	>55,000	0.12	0.12	0.12

Flow Type	Flow Increment	Wakool Junction (# events / year)		
		Current	Y45D40	Y30D30
Small fresh	>9,000	1.01	1.01	1.01
Large Fresh	>15,000	0.91	0.93	0.95
Bankfull	>22,000	0.76	0.84	0.82
Moderate Overbank	>40,000	0.37	0.39	0.38
Large Overbank	>50,000	0.33	0.31	0.32

Flow Type	Flow Increment	Euston (# events / year)		
		Current	Y45D40	Y30D30
Small fresh	>12,000	1.00	1.00	1.00
Large Fresh	>22,000	0.88	0.89	0.91
Bankfull	>46,000	0.43	0.41	0.41
Moderate Overbank	>60,000	0.31	0.31	0.31
Large Overbank	>80,000	0.23	0.20	0.21

Table 16 Overview of the frequency (# of events of 7 days or more per year) of different flow magnitude along the Murrumbidgee River system under current constraints and for two flow options scenarios (W40 and W32)

Flow Type	Flow Increment	Gundagai (# events / year)		
		Current	W40	W32
Small fresh	>5,000	1.00	1.00	1.00
Large Fresh	>20,000	0.53	0.62	0.61
Bankfull	>48,000	0.13	0.12	0.12
Moderate Overbank	>52,000	0.11	0.11	0.10
Large Overbank	>90,000	0.00	0.00	0.00

Flow Type	Flow Increment	Wagga Wagga (# events / year)		
		Current	W40	W32
Small fresh	>4,000	1.00	1.00	1.00
Large Fresh	>14,000	0.83	0.80	0.81
Bankfull	>48,000	0.23	0.21	0.22
Moderate Overbank	>52,000	0.19	0.17	0.18
Large Overbank	>90,000	0.06	0.05	0.05

Flow Type	Flow Increment	Hay (# events / year)		
		Current	W40	W32
Small fresh	>4,000	0.92	0.92	0.89
Large Fresh	>12,000	0.70	0.69	0.71
Bankfull	>15,000	0.58	0.63	0.66
Moderate Overbank	>30,000	0.33	0.31	0.32
Large Overbank	>40,000	0.21	0.21	0.21

Flow Type	Flow Increment	Balranald (# events / year)		
		Current	W40	W32
Small fresh	>3,000	0.82	0.81	0.79
Large Fresh	>6,000	0.74	0.72	0.73
Bankfull	>9,000	0.44	0.55	0.49
Moderate Overbank	>12,000	0.35	0.36	0.34
Large Overbank	>15,000	0.31	0.31	0.31

Flow Type	Flow Increment	Old Man Creek at Kwong (# events / year)		
		Current	W40	W32
Small fresh	>500	1.00	1.00	1.00
Large Fresh	>2,500	0.73	0.73	0.73
Bankfull	>6,500	0.52	0.61	0.54
Moderate Overbank	>8,500	0.48	0.59	0.50
Large Overbank	>9,500	0.00	0.00	0.00

Flow Type	Flow Increment	Yanco Creek at Yanco Offtake (# events / year)		
		Current	W40	W32
Small fresh	>1,000	0.80	0.77	0.76
Large Fresh	>1,500	0.63	0.66	0.67
Bankfull	>2,500	0.49	0.60	0.56
Moderate Overbank	>4,000	0.35	0.36	0.34
Large Overbank	>7,000	0.15	0.15	0.15

Flow Type	Flow Increment	Tumut River at Tumut (# events / year)		
		Current	W40	W32
Small fresh	>1,000	1.00	1.00	1.00
Large Fresh	>1,500	0.99	1.00	1.00
Bankfull	>2,500	0.27	0.26	0.27
Moderate Overbank	>4,000	0.05	0.04	0.05
Large Overbank	>7,000	0.00	0.00	0.00

Table 17 Overview of the frequency (# of events of 7 days or more per year) of different flow magnitude along the Edward-Kolety / Wakool system under current constraints and for two flow options scenarios (Y45D40, Y30D30)

Flow Type	Flow Increment	Edward River at Deniliquin (# events / year)		
		Current	Y45D40	Y30D30
Small fresh	>6,000	0.72	0.85	0.85
Large Fresh	>9000	0.59	0.76	0.76
Bankfull	>15000	0.39	0.52	0.38
Moderate Overbank	>20000	0.33	0.29	0.31
Large Overbank	>28000	0.26	0.24	0.26

Flow Type	Flow Increment	Edward River at Stevens Weir (# events / year)		
		Current	Y45D40	Y30D30
Small fresh	>2,400	0.98	0.99	0.98
Large Fresh	>4,600	0.69	0.85	0.85
Bankfull	>8,000	0.49	0.66	0.46
Moderate Overbank	>17,000	0.29	0.26	0.28
Large Overbank	>28,000	0.16	0.15	0.15

Flow Type	Flow Increment	Niemur River at Moulamein Road (# events / year)		
		Current	Y45D40	Y30D30
Small fresh	>800	0.91	0.93	0.93
Large Fresh	>1,000	0.88	0.93	0.89
Bankfull	>2,000	0.67	0.84	0.83
Moderate Overbank	>4,000	0.55	0.71	0.63
Large Overbank	>15,000	0.25	0.23	0.24

Flow Type	Flow Increment	Wakool River at Stoney Crossing (# events / year)		
		Current	Y45D40	Y30D30
Small fresh	>3,000	0.67	0.83	0.82
Large Fresh	>6,000	0.52	0.67	0.56
Bankfull	>9,000	0.46	0.57	0.48
Moderate Overbank	>12,000	0.37	0.41	0.38
Large Overbank	>15,000	0.36	0.37	0.36

5.3. **Impact Scores**

The impact score (see Figure 5) is derived from the likelihood of a flow category occurring combined with the level of association of that flow category for a given geomorphic feature and process. The numbers can be compared between different geomorphic features, with a higher score indicting features and processes that are more strongly linked to the flow regime within a specific sub-reach. The impact score is used to compare changes to the base case and therefore the risks and benefits of the flow options, which are detailed in Section 6.

An impact score is calculated for the current constraints' scenario as well as a score for each of the flow options scenarios. The following section steps through the process of calculating the impact score, while the resultant scores for each sub-reach are provided in Appendix C.

5.3.1. **Geomorphic Features, Association and Likelihood Ranking**

For each sub-reach the specific geomorphic features present have been identified along with the level of association of those features to specific flow categories (based on Table 13). This is then combined with the likelihood ranking of that flow category in the reach under current constraints and for the flow options scenarios.

Table 18 provides an example of this analysis. In this instance the small fresh flow category has a frequency of 1 event per year under current constraints and this is only reduced marginally to 0.99 events per year under both flow options scenarios modelled. The large fresh category shows a greater change in frequency, with the number of events increasing from 0.82 times per year for current constraints to 0.90 times per year under the flow options scenarios.

Where a geomorphic feature has a stronger association with a particular flow category (e.g., riverbank erosion has the highest association with small freshes) but there is little change in frequency of this flow category under the flow options we would not expect to see much (if any) change in the impact score.

Table 18 Example of geomorphic features, flow associations and likelihood of occurrence for a sub-reach

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Wetlands, billabongs, distributary channels	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.82**	**0.58**	**0.34**	**0.12**
Likelihood (Y45D40 events per year)		0.99	0.90	0.63	0.35	0.12
Likelihood (Y30D30 events per year)		0.99	0.90	0.62	0.35	0.12

5.3.2. **Defining the Impact Score**

An impact score for each geomorphic feature identified is then calculated based on the likelihood ranking for the flow x the flow association, then summed across the different flow categories. In the example shown in Table 19 under current constraints, the highest impact score is associated with bank erosion which is driven predominantly bankfull and sub-bankfull flows which occur regularly. Avulsions, which develop as flows enlarge anabranches or floodrunners, have the next most significant score, as the processes are driven by flow around bankfull which occur approximately 0.6 times per year (which equates to approx. once every 1.5 to 2 years) and above.

The resultant sub-reach impact score combines the impacts score for the different geomorphic features within the sub-reach.

Table 19 Example impact score for current constraints – sub-reach 8

Geomorphic Feature & Process		Impact Score by Scenario Current Constraints
Riverbanks	Erosion	5.7
Anabranches / Floodrunners (sub-bankfull)	Avulsion	4.8
Floodplain (> bankfull)	Sediment Deposition	1.4
Anabranches / Floodrunners (> bankfull)	Avulsion	1.4
Wetlands, billabongs, distributary channels	Sediment Deposition	3.1
Average		**3.3**

The example in Table 19 is expanded in Table 20 to include the flow options scenarios. The results show limited change in the overall impact score between current constraints and the flow options, as the change in likelihood of the different flow categories is minimal except for the large fresh and bankfull flow categories. There is no change in overbank flow frequency, which have a strong association with geomorphic features and processes in this sub-reach.

We have averaged the impact score for each feature to give an overall impact score for the sub-reach, which allows for comparison between sub-reaches.

Table 20 Example of Impact Scores for Current Constraints and Flow Options Scenarios

Geomorphic Feature & Process		Impact Score by Scenario				
		Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	Erosion	5.7	5.9	4%	5.9	3%
Anabranches / Floodrunners (sub-bankfull)	Avulsion	4.8	5.1	8%	5.1	6%
Floodplain (> bankfull)	Sediment Deposition	1.4	1.4	2%	1.4	2%
Anabranches / Floodrunners (> bankfull)	Avulsion	1.4	1.4	2%	1.4	2%
Wetlands, billabongs, distributary channels	Sediment Deposition	3.1	3.3	6%	3.3	5%
Average		**3.3**	**3.4**	**5%**	**3.4**	**4%**

The impacts scores for all the sub-reaches are presented in Appendix C, while a summary of the percentage change for the two flow options scenarios by reach and then sub-reach is given in Table 21, Table 22 and Table 23 . The sub-reaches are presented from upstream (top) to downstream (bottom). The implications of the changes in impact scores for different reaches and sub-reaches is discussed further in the following sections.

An interesting outcome of the analysis is that the lower of the two flow options scenarios can result in higher impact scores. For instance, in sub-reaches 1, 2 and 3 the Y30D30 option shows an increased change in frequency of flows in the large fresh range compared to Y45D40 and this is an important flow category for geomorphic processes in these sub-reaches.

Table 21 Summary of the percentage change in impact score for the two flow options scenarios for the River Murray sub-reaches

Sub Reach #	Reach	% Change in Impact Score	
		Y45D40	Y30D30
1	Albury	9%	12%
2	Howlong	8%	12%
3	Mulwala	11%	14%
4	Barmah (Bullatale to Picnic Point)	7%	1%
5	Barmah (Picnic Point to Barmah)	7%	1%
7	Echuca	5%	5%
8	Perricoota (Koondrook Perricoota)	5%	4%
9	Perricoota (Barham)	5%	5%
10	Gunbower (Swan Hill)	3%	3%
17	Wakool (Boundary Bend)	-3%	-1%
18	Wakool (Jinker Bend/Hattah)	-4%	0%

Table 22 Summary of the percentage change in impact score for the two flow options scenarios for the Edward (Kolety)-Wakool sub-reaches

Sub Reach #	Reach	% Change in Impact Score	
		Y45D40	Y30D30
6	Upper Edward	11%	2%
12	Werai	10%	3%
13	Werai	10%	3%
14	Mid Edward	10%	2%
11	Mid Wakool	17%	6%
15	Mid Niemur	16%	11%
16	Gunbower Wakool / Lower Wakool	15%	4%

Table 23 Summary of the percentage change in impact score for the two flow options scenarios for the Murrumbidgee River sub-reaches

Sub Reach #	Reach	% Change in Impact Score	
		W40	W32
30	Jugiong	5%	4%
29	Gundagai / Jugiong	6%	4%
28	Tumut	0%	0%
27	Gundagai	5%	3%
26	Wagga Wagga	5%	3%
25	Mid Murrumbidgee (Beavers Creek)	11%	2%
24	Mid Murrumbidgee (Old Man Creek)	12%	2%
23	Yanco	5%	3%
22	Yanco	5%	3%
21	Narrandera	-5%	-3%
20	Carrathool (Hay)	0%	1%
19	Balranald	4%	0%

5.4. Results and Trajectory of Change

The impact scores provide an indication of the potential for geomorphic change to occur because of the proposed changes to the flow regimes. These scores must be viewed in the context of the current (baseline) trajectory of change for each sub-reach and the broader reaches to allow negative and positive consequences of these changes to be assessed. Table 24 to Table 26 present the analysis results by sub-reach along with a summary of current and flow options trajectories based on the more detailed sub-reach assessments in Appendix C.

The tables provide results by river from upstream to downstream. The interpretation of the likely trajectory under the different flow options scenarios is based on the analysis of past and current geomorphic changes within each sub-reach by experienced geomorphologists, considering the drivers of change and the flow category changes predicted for each sub-reach. The results have then been reviewed by the experts within the project team.

Note that negative impact scores are possible and reflect a reduction in the frequency of events within a particular flow category for a given flow options scenario.

Overall, across the various waterways the results indicate there is unlikely to be significant change to the baseline trajectory for geomorphic processes and features because of the change in frequency of different flow categories.

Table 24 Summary of Impact Assessment Results for the River Murray Reaches and Sub-Reaches under Current Constraints and Flow Options Scenarios

Sub-reach	Landscape Zone	Reach	Type	Baseline (Current) Trajectory	Y45D40[4]	Changes to trajectory under Y45D40 flow option scenario	Y30D30[5]	Changes to trajectory under Y30D30 flow option scenario
1	Upper Alluvial Fan	Albury	Ancestral, medium confined, not underfit, highly anabranching	On-going anabranch development On-going bank erosion (due to constant prolonged sub-bankfull flows, vessel wash)	9%	Unlikely to enhance localised erosion and enlargement of the anabranch system or change rates of meander migration and bank erosion.	12%	Unlikely to enhance localised erosion and enlargement of the anabranch system or change rates of meander migration and bank erosion.
2	Upper Alluvial Fan	Howlong	Ancestral, underfit, confined	Locally stable anabranch system. On-going bank erosion (due to constant, prolonged flows, vessel wash)	8%	Unlikely to reactivate anabranch development processes.	12%	Unlikely to reactivate anabranch development processes.
3	Upper Alluvial Fan	Mulwala	Ancestral, underfit, confined, anabranching	On-going anabranch development. On-going bank erosion (due to constant, prolonged flows, vessel wash)	11%	Unlikely to enhance localised erosion and enlargement of the anabranch system or change rates of meander migration and bank erosion.	14%	Unlikely to enhance localised erosion and enlargement of the anabranch system or change rates of meander migration and bank erosion.
4	Lower Alluvial Fan	Barmah 1	Young, unconfined, Distributary	Aggradation due to excess sand. On-going bank erosion (due to constant, prolonged flows, aggradation, vessel wash)	7%	Unlikely to increase the rate of sand delivery into the reach or change the rate of bank erosion.	1%	Very unlikely to increase the rate of sand delivery into the reach or change the rate of bank erosion.
5	Lower Alluvial Fan	Barmah 2	Young, unconfined, lake floor, distributary	Aggradation due to excess sand. On-going bank erosion (due to constant, prolonged flows, aggradation, vessel wash)	7%	Unlikely to increase rate of delivery of sand into the reach or change the rate of bank erosion.	1%	Very unlikely to change baseline trajectory or change the rate of bank erosion.

[4] This column provides the % change in the sub-reach averaged impact score under the Y45D40 flow options scenario

[5] This column provides the % change in the sub-reach averaged impact score under the Y30D30 flow options scenario

Sub-reach	Landscape Zone	Reach	Type	Baseline (Current) Trajectory	Y45D40[4]	Changes to trajectory under Y45D40 flow option scenario	Y30D30[5]	Changes to trajectory under Y30D30 flow option scenario
7	Lower Alluvial Fan	Echuca	Ancestral Goulburn, highly confined, no anabranching	Bank erosion and on-going avulsion development.	5%	Unlikely to increase bank erosion rates or the rate of fine sediment delivery and deposition onto bars and benches, and into connected wetlands.	5%	Unlikely to increase bank erosion rates or the rate of fine sediment delivery and deposition onto bars and benches, and into connected wetlands.
8	Lower Alluvial Fan	Perricoota (Koondrook Perricoota)	Young, unconfined, Distributary	Bank erosion through lateral bend migration, on-going bank erosion (due to constant prolonged flows, and vessel wash).	5%	Unlikely to increase bank erosion rates or the rate of fine sediment delivery and deposition onto bars and benches, and into connected wetlands.	4%	Very unlikely to change baseline trajectory.
9	Lower Alluvial Fan	Perricoota (Barham)	Young, unconfined, Distributary	Bank erosion through lateral bend migration and continued effluent channel development, on-going bank erosion (due to constant prolonged flows).	5%	Unlikely to increase rates of bend migration or effluent channel/avulsion development.	5%	Unlikely to change baseline trajectory.
10	Lower Alluvial Fan	Gunbower (Swan Hill)	Young, confined, avulsive paths	On-going bank erosion (due to constant, prolonged flows, vessel wash)	3%	Negligible flow changes and a low energy environment means it is very unlikely to change baseline trajectory.	3%	Minimal flow changes and a low energy environment means it is very unlikely to change baseline trajectory.
17	Bungunnia	Wakool (Boundary Bend)	Ancestral confined	Low energy, few active geomorphic processes	-3%	No expected change baseline trajectory.	-1%	No expected change baseline trajectory.
18	Bungunnia	Wakool (Jinker Bend/Hattah)	Ancestral confined	Low energy, few active active processes	-4%	No expected change baseline trajectory.	-1%	No expected change baseline trajectory.

Table 25 Summary of Impact Assessment Results for the Edward (Kolety) – Wakool River system Reaches and Sub-Reaches under Current Constraints and Flow Options Scenarios

Sub-reach	Landscape Zone	Reach	Type	Baseline (Current) Trajectory	Y45D40[6]	Trajectory under Y45D40 flow option scenario	Y30D30[7]	Trajectory under Y30D30 flow option scenario
6	Lower Alluvial Fan	Upper Edward	Distributary, unconfined	On-going bank erosion (due to constant, prolonged flows), avulsion development	11%	Unlikely to enhance rates of avulsion development or change the rate of bank erosion.	2%	Very unlikely to change baseline trajectory.
11	Lower Alluvial Fan	Mid Wakool	Transition between Distributary unconfined to anabranching	On-going bank erosion (due to constant, prolonged flows) but low rates of all geomorphic processes	17%	Possible for enhanced rates of change above existing low rates for geomorphic processes. Possible change to the rate of bank erosion depending on the flow delivery pattern.	6%	Unlikely to change baseline trajectory.
12	Lower Alluvial Fan	Werai	Distributary, anabranching	On-going bank erosion (due to constant, prolonged flows & regulator operation) but low rates of all geomorphic processes	10%	Unlikely to change baseline trajectory. Unlikely to change the rate of bank erosion depending on the flow delivery pattern.	3%	Very unlikely to change baseline trajectory.
13	Lower Alluvial Fan	Werai	Distributary, anabranching	On-going bank erosion (due to constant, prolonged flows and regulator operation) but low rates of all geomorphic processes	10%	Potential for enhanced bank erosion close to regulators due to the potential rapid rates of change when flows are delivered. No change to rates of other geomorphic processes	3%	Very unlikely to change baseline trajectory
14	Lower Alluvial Fan	Mid Edward	Distributary, anabranching	On-going bank erosion (due to constant, prolonged flows) but low rates of all geomorphic processes	10%	Potential for enhanced bank erosion close to regulators due to the potential rapid rates of change when flows are delivered. No change to rates of other processes	2%	Very unlikely to change baseline trajectory

[6] This column provides the % change in the sub-reach averaged impact score under the Y45D40 flow options scenario
[7] This column provides the % change in the sub-reach averaged impact score under the Y30D30 flow options scenario

Sub-reach	Landscape Zone	Reach	Type	Baseline (Current) Trajectory	Y45D40[6]	Trajectory under Y45D40 flow option scenario	Y30D30[7]	Trajectory under Y30D30 flow option scenario
15	Lower Alluvial Fan	Mid Niemur	Distributary, anabranching	Low energy system, few active geomorphic processes.	16%	Potential for increased rates of cutoff and anabranch development but still at a slow rate.	11%	Potential for increased rates of cutoff and anabranch development but still at a slow rate.
16	Lower Alluvial Fan	Gunbower Wakool / Lower Wakool	Distributary, anabranching	Low energy system, few active geomorphic processes.	15%	Potential for increased rates of cutoff and anabranch development but still at a slow rate.	4%	Very unlikely to change baseline trajectory.

Table 26 Summary of Impact Assessment Results for the Murrumbidgee River Reaches and Sub-Reaches under Current Constraints and Flow Options Scenarios

Sub-reach	Landscape Zone	Reach	Type	Baseline (Current) Trajectory	W40[8]	Trajectory under W40 flow option scenario	W32[9]	Trajectory under W30 flow option scenario
30	Rocky Hills	Jugiong	Partly confined, low sinuosity	On-going lateral migration (bank erosion) and potential avulsion and (sand mining) pit capture.	5%	Unlikely to increase the potential for pit capture (avulsion development)	4%	Very unlikely to increase the potential for pit capture (avulsion development)
29	Rocky Hills	Gundagai / Jugiong	Partly confined, low sinuosity	On-going avulsion development, sand transport and deposition.	6%	Unlikely to increase the rate of these processes occurring	4%	Very unlikely to increase the rate of current processes
28	Rocky Hills	Tumut	Partly confined, low sinuosity	On-going bank erosion (due to prolonged constant flows), meander cutoffs, avulsion development	0%	Very unlikely to change baseline trajectory.	0%	Very unlikely to change baseline trajectory.
27	Rocky Hills	Gundagai	Partly confined, low sinuosity	On-going meander and avulsion development development	5%	Unlikely increase the rate of the current processes occurring	3%	Very unlikely to increase the rates of current processes
26	Rocky Hills	Wagga Wagga	Partly confined, anabranching	On-going lateral migration (bank erosion), meander cutoffs	5%	Unlikely to increase the rate of the current processes occurring	3%	Very unlikely to increase the rates of current processes
25	Upper Alluvial Fan	Mid Murrumbidgee (Beavers Creek)	Unconfined, distributary	On-going lateral migration (bank erosion), meander cutoffs. Bank erosion near regulating structures due to rapid flow changes	11%	Unlikely to increase the rate of the current processes occurring. Unlikely to change the rate of bank erosion depending on the flow delivery pattern.	2%	Very unlikely to increase the rates of current processes
24	Upper Alluvial Fan	Mid Murrumbidgee (Old Man Creek)	Unconfined, distributary	On-going lateral migration (bank erosion), meander and anabranch development. Bank erosion near regulating structures due to rapid flow changes	12%	Unlikely to increase the rate of these processes occurring. Unlikely to change the rate of bank erosion depending on the flow delivery pattern.	2%	Very unlikely to increase the rates of current processes

[8] This column provides the % change in the sub-reach averaged impact score under the W40 flow options scenario
[9] This column provides the % change in the sub-reach averaged impact score under the W32 flow options scenario

Sub-reach	Landscape Zone	Reach	Type	Baseline (Current) Trajectory	W40[8]	Trajectory under W40 flow option scenario	W32[9]	Trajectory under W30 flow option scenario
23	Lower Alluvial Fan	Yanco	Ancestral, confined, meandering	Low rates of geomorphic processes due to regulation of flows into the reach.	5%	Unlikely to increase the rate of these processes occurring	3%	Very unlikely to increase the rates of current processes
22	Lower Alluvial Fan	Yanco	Ancestral, confined, meandering	Low rates of geomorphic processes due to regulation of flows into the reach.	5%	Unlikely to increase the rate of these processes occurring	3%	Very unlikely to increase the rates of current processes
21	Lower Alluvial Fan	Narrandera	Ancestral, confined, meandering (wide floodplain)	Bank erosion through notching because of regulated flow conditions or rapid drawdown close to regulating structures	-5%	No expected changes to baseline trajectory	-3%	No expected changes to baseline trajectory
20	Lower Alluvial Fan	Carrathool (Hay)	Ancestral, confined	Bank erosion through notching because of regulated flow conditions or rapid drawdown close to regulating structures	0%	Very unlikely to increase the rates of current processes	1%	Very unlikely to increase the rates of current processes
19	Bungunnia	Balranald	Ancestral confined	Low energy, limit active processes	4%	Very unlikely to increase the rates of current processes	0%	Very unlikely to increase the rates of current processes

5.5. Consequences of Change

The consequences of any changes to channel or floodplain geomorphic features and/or process because of flow changes are summarised in Table 27, Table 28, and Table 29 using the consequence rating previously detailed in Table 3 and our understanding of the effects of change from Table 14. Both negative and positive changes are included. The main processes effected were analysed from the sub-reach assessments to identify those processes with the highest impact score under current constraints.

Table 27 Overview of consequences of geomorphic change across the River Murray sub-reaches

Sub-reach #	Main process affected by flow options changes	Consequences of Change	
		Negative	Positive
1	Meander migration Avulsion	Moderate	Low
2	Aggradation Avulsion	Moderate	Very Low
3	Meander migration Avulsion	Moderate	Low
4	Aggradation Avulsion Deposition	High	Low
5	Aggradation Avulsion Deposition	High	Low
7	Avulsion Deposition	Moderate	Low
8	Avulsion Deposition	Moderate	Moderate
9	Meander migration Erosion Deposition Avulsion	Moderate	Low
10	Deposition	Low	Moderate
17	No process changes identified	Very Low	Very Low
18	No process changes identified	Very Low	Very Low

Table 28 Overview of consequences of geomorphic change across the Edward (Kolety) – Wakool River sub-reaches

Sub-reach #	Main process affected by flow options changes	Consequences of Change	
		Negative	Positive
6	Avulsion Erosion Deposition	Moderate	Moderate
11	Meander migration Erosion Avulsion Deposition	Moderate	Moderate
12	Avulsion Meander migration Deposition	Moderate	Low

Sub-reach #	Main process affected by flow options changes	Consequences of Change	
		Negative	Positive
13	Avulsion Meander migration Deposition	Moderate	Low
14	Avulsion Meander migration Deposition	Moderate	Moderate
15	Avulsion Meander migration Deposition	Moderate	High
16	Avulsion Meander migration Deposition	Moderate	Low

Table 29 Overview of consequences of geomorphic change across the Murrumbidgee River sub-reaches

Sub-reach #	Main process affected by flow options changes	Consequences of Change	
		Negative	Positive
19	Meander migration	Low	Very Low
20	Meander migration Avulsion	Low	Very Low
21	No process changes identified	Moderate	Very Low
22	Avulsion Meander migration	Moderate	Low
23	Avulsion Meander migration	Moderate	Low
24	Avulsion Deposition Meander migration	Moderate	Moderate
25	Avulsion Deposition Meander migration	Moderate	Moderate
26	Avulsion Deposition Meander migration	Moderate	Low
27	Avulsion Deposition Meander migration	Moderate	Low
28	No process changes identified	Very Low	Very Low
29	Avulsion Aggradation Deposition	Moderate	Very Low
30	Avulsion Aggradation Meander migration	Moderate	Very Low

section six

6. Risk-Benefit Assessment

6.1. Geomorphic Objective

To assess the risks and benefits of the flow options scenarios on geomorphic features and processes across the River Murray and Murrumbidgee River systems we have defined the base case geomorphic objective as:

Geomorphic processes continue the same trajectory under the current constraints scenario as presently observed

This allows us to evaluate the potential negative and positive changes and the associated risks and benefits of the flow options scenarios more readily using the changes in impact score by sub-reach and reach and considering their current and predicted potential trajectory (Section 5 and Appendix C), and the potential consequences of changes for different geomorphic features and processes (Section 5.5).

6.2. Assessment Results

6.2.1. River Murray Sub-Reaches and Reaches

The results of the risk assessment for the River Murray sub-reaches is presented in Table 30, from upstream to downstream.

Risks
The results show the risk generally ranging from **Medium** to **Low** for the flow options scenarios, with risks reducing in the downstream direction. Sub-reaches 1 to 3 are within the Upper Alluvial Fan (Hume to Yarrawonga) and show more active current geomorphic processes to those reaches further downstream with greater consequences if these processes are enhanced by increased flows.

The **Medium** risk rating for the Barmah reaches reflects the potential for increased sediment delivery into these reaches with increased flows, which would exacerbate the on-going aggradation which is occurring because of excessive sand deposition. Within the Echuca and Perricoota reaches the risks are predominantly associated the consequences of meander migration and avulsion.

Benefits
The **Low** benefit rating across the sub-reaches reflects the that increased deposition on banks and bars is the main benefit associated with the flow options scenarios.

Table 30 Risk Assessment Results for the River Murray Sub-Reaches and Reaches

Sub-reach	Reach	Likelihood		Consequences		Risk		Benefit	
		Y45D30	Y30D30	Negative	Positive	Y45D30	Y30D30	Y45D30	Y30D30
1	Albury	Unlikely	Unlikely	Moderate	Low	Medium	Medium	Low	Low
2	Howlong	Unlikely	Unlikely	Moderate	Very Low	Medium	Medium	Low	Low
3	Mulwala	Unlikely	Unlikely	Moderate	Low	Medium	Medium	Low	Low
4	Barmah 1	Unlikely	Very Unlikely	High	Very Low	Medium	Medium	Low	Low
5	Barmah 2	Unlikely	Very Unlikely	High	Very Low	Medium	Medium	Low	Low
7	Echuca	Unlikely	Unlikely	Moderate	Low	Medium	Medium	Low	Low
8	Perricoota (Koondrook Perricoota)	Unlikely	Very Unlikely	Moderate	Moderate	Medium	Low	Medium	Low
9	Perricoota (Barham)	Unlikely	Unlikely	Moderate	Low	Medium	Medium	Low	Low
10	Gunbower (Swan Hill)	Very Unlikely	Unlikely	Low	Moderate	Low	Low	Low	Low
17	Wakool (Boundary Bend)	Very Unlikely	Very Unlikely	Very Low	Very Low	Low	Low	Low	Low
18	Wakool (Jinker Bend / Hattah)	Very Unlikely	Very Unlikely	Very Low	Very Low	Low	Low	Low	Low

Overall, in line with the RRC project areas:

- The **River Murray and floodplain from Hume to Yarrawonga** has a medium risk of geomorphic change associated with the flow options scenarios. Only low geomorphic benefits were identified.
- The **River Murray and floodplain from Yarrawonga to Wakool Junction** has a medium risk of geomorphic change associated with the flow options scenarios and only low geomorphic benefits were identified
- The **River Murray and floodplain from Wakool Junction to Wentworth** has a low risk of geomorphic change associated with the flow options scenarios and low geomorphic benefits.

6.2.2. Edward (Kolety) - Wakool River System

The results of the risk assessment for the Edward (Kolety) - Wakool River system sub-reaches are presented in Table 31 from upstream to downstream. The results show risks are **Medium** across the rivers in this system under the higher flow options scenario (Y45D40) which is due to the increased frequency of large freshes and bankfull flows. Conversely, these flows also drive depositional processes which are beneficial to the river channels and so the benefits are also **Medium** for many of the waterways.

The **Medium** risk rating under the lower flow scenarios (Y30D30) for the Niemur River and Mid Wakool River again reflects the substantial change in frequency of many of the flow categories in these sub-reaches, and the varied geomorphic processes occurring. There is likely to be a reactivation of geomorphic processes in this reach in response to the more varied flow regime, which while identified as a risk are also a **Medium** benefit as many of these processes have been restricted by the regulated flow conditions and lack of flow variability in the reach.

Across the Edward (Kolety) - Wakool River system it was noted in the sub-reach assessments that the existing consistent and prolonged flow conditions, and particularly the rate of change of flows and water levels at regulators and weirs has a significant impact on bank erosion processes. As these structures will continue to be used for flow deliveries under the proposed flow options scenarios there may be an increase in the rate of these erosion processes depending on how the operation is managed. This is discussed further in the mitigation section (Section 7).

Overall, in line with the RRC project areas:

- The **Edward (Kolety) - Wakool River system and floodplain (within the broader River Murray Yarrawonga to Wakool Junction** has a <u>medium</u> risk of geomorphic change associated with the higher flow options scenarios. There are also <u>medium benefits</u> across many of the waterways.
- Under the lower flow options scenarios risks are generally reduced to <u>low</u>.

Table 31 Risk Assessment Results for the Edward (Kolety) – Wakool River System Sub-Reaches and Reaches

Sub-reach	Reach	Likelihood		Consequences		Risk		Benefit	
		Y45D30	Y30D30	Negative	Positive	Y45D30	Y30D30	Y45D30	Y30D30
6	Upper Edward	Unlikely	Very Unlikely	Moderate	Moderate	Medium	Low	Medium	Low
11	Mid Wakool	Possible	Unlikely	Moderate	Moderate	Medium	Medium	Medium	Medium
12	Werai	Unlikely	Very Unlikely	Moderate	Low	Medium	Low	Low	Low
13	Werai	Unlikely	Very Unlikely	Moderate	Low	Medium	Low	Low	Low
14	Mid Edward	Unlikely	Very Unlikely	Moderate	Moderate	Medium	Low	Medium	Low
15	Mid Niemur	Possible	Unlikely	Moderate	High	Medium	Medium	Medium	Medium
16	Gunbower Wakool / Lower Wakool	Possible	Very Unlikely	Moderate	Low	Medium	Low	Medium	Low

6.2.3. Murrumbidgee River

The results of the risk assessment for the Murrumbidgee River sub-reaches are presented in Table 32 from upstream to downstream. The results show risks are generally **Medium** in the Rocky Hills and Upper Alluvial Fan landscape zones, and as it transitions into the Lower Alluvial Fan system (Beavers Creek / Old Man Creek). These results reflect the more active geomorphic processes than occur in these upper reaches. The Tumut River is **Low** risk due to the negligible change in the flow frequency of the various flow categories under both flow options scenarios.

For the Murrumbidgee reaches downstream of the Yanco Creek bifurcation, the risk assessment found **Low** risk under both flow scenario options, due to the low rates of change expected under current constraints as well as for future scenarios.

Benefits to geomorphic features and processes are **Low** across all the reaches, with the exception of the Mid Murrumbidgee (Old Man Creek / Beavers Creek) where an increase in frequency of moderate overbank flows would increase deposition into the floodplain, which provides a **Medium** geomorphic benefit.

Overall, in line with the RRC project areas:

- The **Murrumbidgee River and floodplain (from Burrinjuck Dam to the Yanco Creek system)** has a <u>medium</u> risk of geomorphic change associated with the higher flow options scenarios. This reduces to <u>low</u> risk under the lower flow options scenarios.
- The **Murrumbidgee River and floodplain (from the Yanco Creek system to the Murray Junction, including the Lowbidgee floodplain)** has a <u>low</u> risk of geomorphic change for all the flow options scenarios.
- The **Yanco Creek system and floodplain** has a <u>medium</u> risk of geomorphic change associated with the higher flow options scenarios. This reduces to <u>low</u> risk under the lower flow options scenarios.
- The **Tumut River and floodplain (below Blowering Dam to the junction with the Murrumbidgee)** has a <u>low</u> risk all the flow options scenarios.

Table 32 Risk Assessment Results for Murrumbidgee River Sub-Reaches and Reaches

Sub-reach	Reach	Likelihood		Consequences		Risk		Benefit	
		W40	W32	Negative	Positive	W40	W32	W40	W32
30	Jugiong	Unlikely	Very Unlikely	Moderate	Very Low	Medium	Low	Low	Low
29	Gundagai / Jugiong	Unlikely	Very Unlikely	Moderate	Very Low	Medium	Low	Low	Low
28	Tumut	Very Unlikely	Very Unlikely	Low	Low	Low	Low	Low	Low
27	Gundagai	Unlikely	Very Unlikely	Moderate	Moderate	Medium	Low	Low	Low
26	Wagga Wagga	Unlikely	Very Unlikely	Moderate	Moderate	Medium	Low	Low	Low
25	Mid Murrumbidgee (Beavers Creek)	Unlikely	Very Unlikely	Moderate	Moderate	Medium	Low	Medium	Low
24	Mid Murrumbidgee (Old Man Creek)	Unlikely	Very Unlikely	Moderate	Moderate	Medium	Low	Medium	Low
23	Yanco (upper)	Unlikely	Very Unlikely	Moderate	Low	Medium	Low	Low	Low
22	Yanco (upper)	Unlikely	Very Unlikely	Moderate	Low	Medium	Low	Low	Low
21	Narrandera	Very Unlikely	Very Unlikely	Moderate	Low	Low	Low	Low	Low
20	Carrathool (Hay)	Very Unlikely	Very Unlikely	Low	Very Low	Low	Low	Low	Low
19	Balranald	Very Unlikely	Very Unlikely	Low	Very Low	Low	Low	Low	Low

section seven

7. **Risk Treatment (Mitigation)**

7.1. **Potential Opportunities**

All those sub-reaches with a **Medium** risk rating under any of the flow options scenarios have been reviewed to identify potential risk treatments (mitigation opportunities) which would allow the risk to be reduced to a tolerable (**Low**) level through reducing the consequences associated with negative changes to geomorphic feature or processes.

Generalised mitigation opportunities to address negative changes to different geomorphic features and processes have been summarised in Table 33 together with an indication of how these opportunities may be realised.

Table 33 Overview of potential mitigation opportunities and implementation approaches

Geomorphic Feature & Process		Potential negative change associated with increased flows	Mitigation Opportunities	Implementation
Riverbanks	Erosion	Enhanced rate of bank erosion	Active management of the flow patterns – increased variability, rates of rise and fall suitable for bank materials (e.g., 6-inch rule)	Operational controls, delivery planning processes
		Excessive loss of bank and riparian vegetation	Timing of events (natural sequence – higher flows in winter, lower flows in summer)	River Works Programs
		Supplying sediment downstream	Manage other pressures – boating, excess sand removal through flow management or physical extraction, vegetation removal	Use controls (e.g., boat speed or other limits)
Cutoffs	Avulsion / meander migration / meander extension	Erosion triggered upstream, deposition downstream	Physical intervention[10]	River Works Programs

[10] Physical interventions can involve revegetation, stock exclusion and fencing, together with engineered structures such as rock or timber revetments, pile fields, and hybrid structures.

Geomorphic Feature & Process		Potential negative change associated with increased flows	Mitigation Opportunities	Implementation
Anabranches / Floodrunners (sub-bankfull)	Avulsion	Increased rate of development	Active management of the flow patterns – increased variability, rates of rise and fall suitable for bank materials (e.g., 6-inch rule)	Operational controls, delivery planning processes
		Loss of land and riparian vegetation	Physical intervention[10]	River Works Programs
		More sediment delivery downstream (major)	Active management of the flow patterns – increased variability, rates of rise and fall suitable for bank materials (e.g., 6-inch rule)	Operational controls, delivery planning processes
Anabranches / Floodrunners (> bankfull)	Avulsion	More sediment delivery downstream (minor)	Active management of the flow patterns – increased variability, rates of rise and fall suitable for bank materials (e.g., 6-inch rule)	Operational controls, delivery planning processes
Floodplain (> bankfull)	Sediment deposition	Flows delivered with no sediment	Increased flow deliveries to be generally made in conjunction with natural tributary inflows with typically higher sediment loads	Operations and delivery planning processes
Sand Slugs	Aggradation / Transport	Increased transport into and rates of deposition within Barmah reaches	Physical intervention[11]	River Works Program
		Eroding the ends of point bars	Flow regime changes to increase transport rates in the flow ranges that allow efficient downstream sediment movement to occur (not suitable for the Barmah-Millewa reach)	Operational controls, delivery planning processes
			Encouraging sediment storage in floodplain channels through flow regime changes to increase overbank flows (not suitable for coarse sediments)	
Benches	Deposition	Increased flow without corresponding sediment load limits deposition	Increased flow deliveries to be generally made in conjunction with natural tributary inflows with typically higher sediment loads	Operational controls, delivery planning processes Other flow delivery programs (e.g., Enhanced

[11] Investigations are underway as to the options to manage the excess sediment in the reach (see Streamology, 2021)

Geomorphic Feature & Process		Potential negative change associated with increased flows	Mitigation Opportunities	Implementation
				Environmental Water Delivery)
Bars	Deposition / Erosion	Overstabilisation of instream bars	None	
		Erosion of bars	None	
Capacity	Aggradation	Increased rate of capacity reduction	Physical intervention[10]	River Works Programs
		Reduced geomorphic diversity	Flow regime changes to increase transport rates in the flow ranges that allow efficient downstream sediment movement to occur (not suitable for the Barmah-Millewa reach)	Operational controls, delivery planning processes
		Increased unseasonal floodplain inundation	None	
		Enhanced bank erosion	None	
Levee	Deposition / Erosion	Increased number of breakouts	Physical intervention	River Works Programs
		Increased erosion	None	
		Increased rates of fine sediment movement onto the floodplain (smothering vegetation)	None	
Wetlands, billabongs, distributary channels	Sediment Deposition	Increased infilling of features	Physical intervention (i.e., regulators)	River Works Program Other flow delivery programs (e.g., Enhanced Environmental Water Delivery)

The implementation of various mitigation options, as relevant to specific reaches or sub-reaches is discussed further in the following sections.

7.1.1. Operational Controls and Delivery Planning

Current Controls

The rate of rise and fall of water levels over time as a result of river regulation, such as releases from reservoirs or regulars, has been identified as a potential driver of bank erosion and controls or rules have been put in place to protect riverbanks along the River Murray from slumping as a result of rapid decreases in water level.

Current rules on rates of fall below the Hume Dam are set out in the *Objectives and outcomes for river operations in the River Murray System* (MDBA, 2020) and allow for a maximum average rate of fall (over six days) of:

- 0.15 m at Doctors Point
- 0.2 m at Heywoods

In addition, the maximum rate of fall (at either Doctors Point or Heywoods) in any single day is 0.225 m. Similar controls also exist on the Mitta Mitta River below Dartmouth Pondage Weir. The potential geomorphic impacts of changes to the current rule on rate of fall on the Hume to Yarrawonga reach was investigated in Gower et al (2021).

For other locations along the River Murray and Edward (Kolety) - Wakool River system the rates of fall associated with operation of offtakes or regulators is "within the operational discretion of the Authority" (MDBA, 2020).

There are currently no rules on the maximum rate of rise for river reaches below the Hume Dam. However, Lake Victoria has a maximum target rate of rise of lake level of 0.05m/day to protect the integrity of the lake embankments, particularly after sustained periods of extended drawdown (MDBA, 2020).

Other controls that affect geomorphic processes relate to speed limits and wash generation rules for vessels. These can be reviewed at Transport for NSW and signage identifying specific limits or restrictions are provided along the waterways in specific areas.

Delivery Planning
Delivery planning relates to the management of releases from storages or regulators to meet the requirements of the controls mentioned above or to address geomorphic issues identified through monitoring.

7.1.2. River Works Programs

There are currently four river works programs relevant to the study area rivers and floodplains, which are briefly summarised below:

Upper Murray (above Lake Hume) and Tumut River Works Programs
The River Works Program focusses on bank stability and maintenance of channel capacity. Works delivered under the program include[12]:

- Bank condition monitoring
- Log and rock revetments
- Remediation of breakaway flows
- Weed control and stock control fencing
- Installation of off-stream watering points

[12] River Murray joint programs

- Protection of First Nations cultural heritage sites

Hume to Yarrawonga River Works Program
The Hume to Yarrawonga Works Program (H2Y Program) has similar objectives to the Upper Murray program. The typical activities that have been undertaken within the program include riparian/riverbank revegetation, stock exclusion fencing, and physical interventions for erosion control. Physical interventions have included rock or log revetments, timber groynes and avulsion control structures (e.g., pile fields).

Yarrawonga to Torrumbarry Interim River Works Program
In the Yarrawonga to Torrumbarry section of the River Murray an interim river works program (Y2T IRWP) is currently being developed. This program is based around maintaining the existing River Murray operational threshold water level at the Picnic Point gauge of 2.6 m. It aims to reduce the loss of water from the River Murray channel through a range of actions including protecting levees by reducing bank erosion directly, blocking breakaway channels, and other complementary works to reduce breakaway flows. The program is currently only planned to extend over a 5-year period, while options to manage capacity through the Barmah-Millewa reach are investigated further.

7.1.3. Other Programs or Projects

The following programs or projects have been identified which may influence or be influenced by geomorphic risks identified in this project. Activities or actions that have or could be undertaken through these programs or projects could mitigation these potential geomorphic risks. Ad-hoc or reactive works to treat site specific geomorphic risks are not considered unless they form part of a broader program.

The Living Murray Program
The Living Murray Program (TLM) is coordinated by the Murray-Darling Basin Authority and focusses on maintaining the health of six icon sites along the River Murray. Works undertaken through the program to enable the return of water to the environment have included built infrastructure such as regulators, channels, fishways and levee banks.

Sustainable Diversion Limit Adjustment Mechanism (SDLAM) Program
The Sustainable Diversion Limit Adjustment Mechanism (SDLAM) is a way to achieve similar or even better environmental outcomes for rivers, wetlands and wildlife using less water as part of the Murray-Darling Basin Plan. The Reconnecting River Country program itself is part of the SDLAM.

A package of 36 SDLAM projects have been agreed across the southern connected Murray-Darling Basin. Other SDLAM projects that could mitigate geomorphic risks identified within this project include:

- Murrumbidgee and Murray National Parks Projects - these projects will provide improved environmental watering regimes within these national parks.

- Mid-Murray Anabranches Project - a project to improve connectivity between the River Murray and the Edward (Kolety) river system and other surrounding creeks including Tuppal, Native Dog and Bullatale creeks.
- Koondrook-Perricoota Forest Project - a project to mitigate third-party impacts on landholders adjacent to the forest whose properties are inundated as water releases into the forest. This will enable the inundation of greater areas of river red gum forest.
- Yanco Creek Modernisation Project[13] - an investigation of infrastructure to enable smarter use of water in the Yanco Creek system.

Enhanced Environmental Water Delivery Project

Enhanced Environmental Water Delivery Project (EEWD) is a multijurisdictional project aimed at improving the outcomes and efficiency of delivery of water for the environment. It has several aims including[14]:

- To coordinate environmental water releases across the tributaries of the River Murray to maximise outcomes.
- Align the release of held environmental water with regulated and unregulated flows to achieve a desired peak and/or duration for a flow event, to create a stronger biological stimulus in sync with environmental water requirements and climate signals.
- Efficiently use increased delivery capacity to improve in-channel, floodplain/wetland connectivity and end-of-system outcomes.
- Develop a framework including low flows, regulated flow, unregulated flows, as well as the use of works and measures to maximise long-term environmental outcomes.

Operational controls developed as part of the EEWD project could assist in managing risks associated with, for example, sediment loads and contributions from tributary inflows.

Barmah-Millewa Feasibility Study

The Barmah–Millewa Feasibility Study Project is exploring the merits of a variety of options to maintain, and where possible reinstate, the regulated flow capacity through the Barmah–Millewa Forest. This Study builds on multiple pieces of work being undertaken, or in development, by Governments as part of management of the River Murray through the Barmah–Millewa reach. The options being investigated in the study are:

- Potential River works within the Barmah–Millewa reach
- Sediment management (see below)
- Timing of transfers to Lake Victoria – Tar-Ru
- Optimisation of the existing Murrumbidgee Irrigation Limited (MIL) system
- Options for Delivery through the Goulburn Murray Irrigation District area of operations
- Use of Snowy Hydro to transfer Murray Release to the Murrumbidgee

Barmah-Millewa Reach Sediment Management Project

This project is investigating feasible ways to manage the large amount of sediment (sand slug) in the Barmah-Millewa reach of the River Murray. It is exploring targeted sand removal in locations

[13] Yanco Creek Modernisation Project
[14] Enhanced Environmental Water Delivery Project

near the upstream end of the forest around Bearii to stop further sand entering the reach, and near Picnic Point where the river is one third full of sand. The Sediment Management Project is one component of the Barmah-Millewa Feasibility Study (above). The project is currently in Stage 2, the Options Development phase.

7.2. Mitigation Options by Sub-Reach and Reach

Suitable mitigations options that could be applied to specific reaches and sub-reaches within the study area are presented by river system in Table 34, Table 35 and Table 36. There are existing successful examples of these approaches being applied to manage geomorphic changes; for instance, to reduce the risk of avulsion a range of physical interventions have been undertaken in the Hume to Yarrawonga reach and these actions remain applicable in continuing to reduce risks of avulsion development in this reach under the flow options scenarios.

Table 34 Summary of potential mitigation options along the River Murray reaches and sub-reaches with Medium risk ratings

Reach (sub-reaches)	Significant processes resulting in negative changes	Mitigation Opportunity	Description
Hume to Yarrawonga			
Albury, Howlong and Mulwala (1, 2 and 3)	Meander migration, avulsion	Active flow management, physical intervention	For these sub-reaches means active flow management would ensure appropriate rates of rise and fall are implemented for all regulated or environmental flow releases. Physical interventions relate to works such as revegetation, log or rock revetments or pile fields such as those currently used in the H2Y Works Program.
Yarrawonga to Wakool Junction			
Barmah 1 & 2 (4 and 5)	Aggradation, avulsion	Physical intervention	Based on the preliminary outcomes of the Barmah-Millewa Feasibility Study, it is likely that physical management of the excess sand within these reaches will be required to maintain current capacity through the reaches, manage bank erosion, and reduce unseasonal flooding of the wetlands. Specific bank protection works such as those under the Y2T IRWP could also be applicable.
Echuca, Perricoota (Koondrook Perricoota) (7 and 8)	Avulsion, deposition	Active flow management	Active flow management would ensure appropriate rates of rise and fall are implemented for all regulated or environmental flow releases and coordination of releases from tributaries such as the Goulburn River. This could be facilitated by existing flow regulators and structures or new works as part of the Koondrook-Perricoota Forest SDLAM project. Flow management may also provide opportunities to increase sediment transport rates.
Perricoota (Barham) (9)	Meander migration, avulsion, erosion	Active flow management, physical intervention	Active flow management would ensure appropriate rates of rise and fall are implemented for all regulated or environmental flow releases. Physical interventions relate to works such as revegetation, log or rock revetments or pile fields such as those currently used in the H2Y Works Program.

There are no Medium risk reaches along the Murray River downstream of Wakool Junction.

Table 35 Summary of potential mitigation options along the Edward (Kolety) – Wakool River reaches and sub-reaches with Medium risk ratings

Reach	Significant processes resulting in negative changes	Mitigation Opportunity	Description
Edward (Kolety) - Wakool Rivers			
Mid Wakool, Werai, Mid Edward, Mid Niemur, Gunbower Wakool / Lower Wakool	Meander migration, avulsion, erosion	Active flow management, physical intervention	For these sub-reaches mitigation opportunities mean active flow management would ensure appropriate rates of rise and fall are implemented for all regulated or environmental flow releases (e.g., as described in Watts et al 2020 for Stevens Weir). Physical interventions relate to works such as revegetation, log or rock revetments or pile fields such as those currently used in the H2Y Works Program.

Table 36 Summary of potential mitigation options along the Murrumbidgee River reaches and sub-reaches with Medium risk ratings

Reach	Significant processes resulting in negative changes	Mitigation Opportunity	Description
Murrumbidgee River (Burrinjuck Dam to Yanco Creek system)			
Gundagai, Jugialong (29, 30)	Meander migration, aggradation, avulsion	Active flow management, physical intervention	Active flow management would ensure appropriate rates of rise and fall are implemented for all regulated or environmental flow releases, including flows through the Beavers Creek Weir. Physical interventions relate to works such as revegetation, log or rock revetments or pile fields such as those currently used in the H2Y Works Program.
Mid Murrumbidgee, Tumut (24, 25, 26, 27)	Meander migration, avulsion		
Yanco Creek system			
Yanco (upper) (22, 23)	Meander migration, avulsion	Active flow management, physical intervention	Much of the flow regime in the Yanco Creek system can be controlled through regulators or weirs and therefore active flow management to ensure appropriate rates of rise and fall can be implemented for all regulated or environmental flow releases. Works undertaken within the Yanco Creek Modernisation Project would facilitate opportunities for improved mitigation of geomorphic risks. Physical interventions relate to works such as revegetation, log or rock revetments or pile fields such as those currently used in the H2Y Works Program.

7.3. **Risk Re-evaluation**

Based on the application of risk mitigation options identified as suitable treatments the geomorphic risks for those sub-reaches with Medium risk ratings under either one or more of the flow options have been re-evaluated (Table 37, Table 38, and Table 39).

Overall, the results indicate that if these treatments are applied successfully, all the Medium risk ratings can be reduced to Low throughout the River Murray. This is also the case for the Murrumbidgee River system, including Yanco Creek. Implementation of these treatment may also address current geomorphic risks, such as bank erosion because of prolonged sub-bankfull flows which can occur because of regulation, or bank erosion downstream of flow regulating structures occurring because of the rapid rise and fall of water levels during the structure operations.

Within the Edward (Kolety) - Wakool River system, the risk rating for the mid Wakool and mid Niemur sub-reaches remains at Medium even with the proposed risk treatments. This outcome occurs because the changes in the likelihood of change across the flow categories is in the Possible range. However, from a geomorphic perspective these reaches are currently highly impacted by a regulated flow regime and while the reintroduction of a more variable flow regime will result in change through reactivation of geomorphic processes this could be considered as much a benefit as a risk. This remaining risk is best addressed through a Monitoring, Evaluation, Reporting and Improvement Plan, as discussed in Section 7.4.

Table 37 Risk re-evaluation for all Medium risk sub-reaches along the River Murray

Reach	Sub-reaches	Likelihood	Consequence	Risk Rating [15]	Significant processes resulting in negative changes	Mitigation Opportunity	Revised Consequence	Revised Risk Rating
Albury	1	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Howlong	2	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Mulwala	3	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Barmah 1	4	Unlikely	High	Medium	Aggradation, avulsion	Physical intervention	Low	Low
Barmah 2	5	Unlikely	High	Medium	Aggradation, avulsion	Physical intervention	Low	Low
Echuca	7	Unlikely	Moderate	Medium	Avulsion, deposition	Active flow management	Low	Low
Perricoota (Koondrook Perricoota)	8	Unlikely	Moderate	Medium	Avulsion, deposition	Active flow management	Low	Low
Perricoota (Barham)	9	Unlikely	Moderate	Medium	Meander migration, avulsion, erosion	Active flow management, physical intervention	Low	Low

Table 38 Risk re-evaluation for all Medium risk sub-reaches along the Edward (Kolety) – Wakool River system

Reach	Sub-reaches	Likelihood	Consequence	Risk Rating[15]	Significant processes resulting in negative changes	Mitigation Opportunity	Revised Consequence	Revised Risk Rating
Upper Edward	6	Unlikely	Moderate	Medium	Avulsion, erosion	Active flow management	Low	Low
Mid Wakool	11	Possible	Moderate	Medium	Meander migration, avulsion, erosion	Active flow management, physical intervention	Low	Medium
Werai	12	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Werai	13	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Mid Edward	14	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low

[15] The risk rating refers to the worst-case risk rating for each sub-reach. This risk rating may apply to one or all the flow options scenarios.

Reach	Sub-reaches	Likelihood	Consequence	Risk Rating[15]	Significant processes resulting in negative changes	Mitigation Opportunity	Revised Consequence	Revised Risk Rating
Mid Niemur	15	Possible	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Medium
Gunbower Wakool / Lower Wakool	16	Possible	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Medium

Table 39 Risk re-evaluation for all Medium risk sub-reaches along the Murrumbidgee River system

Reach	Sub-reaches	Likelihood	Consequence	Risk Rating[15]	Significant processes resulting in negative changes	Mitigation Opportunity	Revised Consequence	Revised Risk Rating
Yanco	22	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Yanco	23	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Mid Murrumbidgee (Old Man Creek)	24	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Mid Murrumbidgee (Beavers Creek)	25	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Wagga Wagga	26	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Gundagai	27	Unlikely	Moderate	Medium	Meander migration, avulsion	Active flow management, physical intervention	Low	Low
Gundagai / Jugiong	29	Unlikely	Moderate	Medium	Meander migration, aggradation, avulsion	Active flow management, physical intervention	Low	Low
Jugiong	30	Unlikely	Moderate	Medium	Meander migration, aggradation, avulsion	Active flow management, physical intervention	Low	Low

7.4. **Monitoring and Evaluation**

The implementation of the risk treatments identified in the preceding sections will require monitoring, evaluation, reporting and improvement (MERI) plans to manage the risks and particularly for adaptive management where the scale or timing of risks being realised are uncertain, such as under the flow options scenarios.

At its core, adaptive management involves flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood (National Research Council, 2004). This allows responsible agencies and the community to alter management approaches and decisions as new knowledge is gained.

For instance, the Goulburn River example below highlights how MERI and adaptive management can successfully reduce geomorphic risks associated with different types of flow conditions and changing flow regimes.

Adaptative Flow Management to Manage Risks - the Goulburn River example

A current example of adaptive flow response management can be seen in the Goulburn River and management of the impacts of Intervalley Transfer (IVT) flows. This monitoring program has origins dating back to 2010 and covers physical form (geomorphology), vegetation, fish and macroinvertebrates. More recently the program has begun to incorporate platypus and social and cultural values. The annual results of the program link these values to specific characteristics of the IVT flow regime for the season, including overall volumes of IVTs and the pattern with which it is delivered. By monitoring response to flows, and statistically testing relationships, the program has continuously led to modifications to operating rules with a view to minimise impacts. These flow changes include not only overall reduction in IVT volumes but also rules, many of which are related to physical form. The most recent set of rules (soon to be released by DEWLP) include, for example, required variability in flow (to reduce erosional 'notching' of the riverbank), acceptable rates of fall (to reduce bank slumping) and considerations for maximum periods of peak flows (to reduce wholesale channel erosion). These rules are increasingly minimising the impacts of IVTs on river values, whilst also enabling operational transfer of flows through the Goulburn River.

Whilst the damaging impacts of IVTs on the Goulburn River are the focus of current monitoring there is also continued monitoring of environmental flows. It has been important to recognise in the Lower Goulburn River that environmental flows can be perceived to instigate negative changes such as erosion, yet it is the preparation of the banks by IVTs that often leads to this circumstance. Nevertheless, changes to environmental flow rules aimed at achieving objectives must also consider minimising impacts in the context of a highly regulated river system.

section eight

8. **Summary**

The RRC Program in the Murray and Murrumbidgee catchments aims to improve environmental, social, and cultural outcomes for communities along the Murray and Murrumbidgee River systems. The program aims to achieve a balance of these outcomes by improving wetland and floodplain connectivity through investigating relaxing or removing some of the constraints or physical barriers that impact delivering water for the environment. It has focussed on the following areas in the southern-connected Murray-Darling Basin (the basin), including:

- Hume to Yarrawonga (River Murray)
- Yarrawonga to Wakool (River Murray)
- Murrumbidgee River

Within the RRC program, the objective of this project was to complete a detailed assessment of how delivery of water for the environment, under new flow limit options being considered, will influence the physical form and functioning of these river systems (i.e., their geomorphology), and how this, in turn, might impact on opportunities to deliver this water. Concerns included the likely influence of flow on rates and extent of bank erosion, streambed aggradation (build up) and degradation (erosion), overall changes to channel capacity (flow conveyance) and other geomorphic processes.

The following summary outlines the various elements of work completed for this project and the outcomes of the analysis in terms of the geomorphic risks and benefits of the proposed flow limit options across the rivers and floodplains of the study areas. A broad overview of the project tasks and approach is also provided in Figure 2.

8.1. **Geomorphic Characterisation of the Study Area**

The project team undertook a detailed review of the regional geology and geomorphology of the southern Murray-Darling Basin to inform our understanding of the geological context, paleoclimate, landscape evolution, and soils distribution of the waterways in the study area. A wide range of previous studies, reports and assessments were collated and reviewed to provide the team with river specific information for the study areas.

This information was then combined with elements of various geomorphic classification systems to create a project specific reach-based river and floodplain classification system which was summarised in Figure 12. The classifications clearly link the landscape, the level of confinement of the river (i.e., floodplain width), and the dominant geomorphic features you would expect to observe, and which will behave differently to changes in flow regime. The reaches defined across the study area rivers are typically in the order of tens to hundreds of kilometres in length.

Within these reaches, it was necessary to identify sub-reaches which are characteristic of the broader reach type and contained one or more of the dominant geomorphic features of that reach type. They are also typically in the order of a few hundred metres to several kilometres in spatial extent.

8.2. Geomorphic Features and Processes

Geomorphic features can vary from within-channel features, such as sandbars and riverbanks, to rarely inundated features several kilometres from the main channel, such as floodplain wetlands. All these features have a differing impact the functions of the river channel.

Geomorphic processes are the way in which features are formed by a range of interactions between flow, sediment, and vegetation. These processes drive the character of the rivers and in turn the value provided by the geomorphic features. Changes in flow can have significant impacts on these processes, such as increases in prolonged bankfull flows driving meander migration and river bend cutoffs.

For each of the 30 representative sub-reaches we analysed the geomorphic features and processes that were present and how they are linked to flow categories, such as freshes, bankfull and overbank flows. From this analysis a 'base case' geomorphic condition and trajectory were developed for each sub-reach which reflected the current (and historic) flow and river management regimes (Appendix C).

8.3. Impact Assessment

To understand and quantify the risks and benefits of the flow option scenarios on geomorphic features and conditions we first developed an "impact score" which draws together the various flow categories at a sub-reach level by their frequency of occurrence (likelihood) and the geomorphic features and processes and how they might change (= significance). To do this we have combined the sub-reach assessments of geomorphic forms and processes with the flow categories and frequency of occurrence as calculated from detailed hydrologic modelled (supplied by DPE).

An impact score was then derived for the current constraints flow conditions across each waterway (as provided by the base case scenario) and then for each flow options scenario. The percentage change in impact score was calculated by feature and flow scenario, and then combined for the features within a sub-reach. The resultant changes can then be compared between sub-reaches and then consolidated into the broader geomorphic reach and landscape scales. This provides an indication of the overall sub-reach and reach scale likelihood of geomorphic change because of the flow regime proposed under the flow options scenarios. It does not provide a quantitative measure of actual geomorphic changes that would be realised under the flow options.

8.4. **Risk and Benefit Assessment**

For the risk-benefit assessment we combined the sub-reach change in impact scores as an indicator of the likelihood of potential geomorphic change, with an understanding of the consequences of geomorphic change occurring (both positive and negative).

8.4.1. **Outcomes across the Study Area**

The risk and benefit analysis produced the following outcomes.

For the River Murray:

- The **River Murray and floodplain from Hume to Yarrawonga** has a medium risk of geomorphic change associated with all the flow options scenarios. Medium risk is associated with an *unlikely* likelihood but moderate consequence. Only low geomorphic benefits were identified.
- The **River Murray and floodplain from Yarrawonga to Wakool Junction** has a medium risk of geomorphic change associated with all the flow options scenarios and only low geomorphic benefits were identified. Again, the likelihood of the risk occurring is *unlikely*, but the consequence is *moderate.*
- The **River Murray and floodplain from Wakool Junction to Wentworth** has a low risk of geomorphic change associated with all the flow options scenarios and low geomorphic benefits.

For the Edward (Kolety) - Wakool River system:

- The **Edward (Kolety) - Wakool River system and floodplain (within the broader River Murray Yarrawonga to Wakool Junction** has a medium risk of geomorphic change associated with the higher flow options scenarios. Within the medium risk rating the likelihood of change is *unlikely to possible* while the consequence is considered *moderate*.
- There are also medium benefits across many of the waterways.
- Under the lower flow options scenarios risks are generally reduced to low.

For the Murrumbidgee River system, including the Tumut River and Yanco Creek:

- The **Murrumbidgee River and floodplain (from Burrinjuck Dam to the Yanco Creek system)** has a medium risk of geomorphic change associated with the higher flow options scenarios. This reduces to low risk under the lower flow options scenarios. Within the medium risk rating the likelihood of change is *unlikely* while the consequence is considered *moderate*.
- The **Murrumbidgee River and floodplain (from the Yanco Creek system to the Murray Junction, including the Lowbidgee floodplain)** has a low risk of geomorphic change for all the flow options scenarios.
- The **Yanco Creek system and floodplain** has a medium risk of geomorphic change associated with the higher flow options scenarios. This reduces to low risk under the lower flow options scenarios. Within the medium risk rating the likelihood of change is *unlikely* while the consequence is considered *moderate*. This reduces to low risk under the lower flow options scenarios.

- The **Tumut River and floodplain (below Blowering Dam to the junction with the Murrumbidgee)** has a low risk for all the flow options scenarios.

Whilst the risk of environmental flows on geomorphic features and processes is rated medium for some reaches, it is important to recognise that this is the result of consequences being considered moderate. It is the unlikely, or very unlikely, likelihood of change that should be considered in the context of delivering the benefits of environmental flows in the River Murray and Murrumbidgee River systems.

8.4.2. Mitigation Options and Risk Re-Evaluation

All those sub-reaches with a **Medium** risk rating under one or more of the flow options scenarios were reviewed to identify potential risk treatments (mitigation opportunities) which would allow the risk to be reduced to a tolerable (**Low**) level through reducing the consequences associated with negative changes to geomorphic feature or processes.

Risk Treatments

- Operational controls and delivery planning are activities that manage the flow regime to minimise geomorphic risks. An example is the "six-inch rule", a constraint on the rate of rise and fall of regulated flows in the River Murray downstream of Hume Dam to minimise potential for bank erosion.

- The typical activities that have been undertaken within previous or existing River Works Programs include riparian/riverbank revegetation, stock exclusion fencing, and physical interventions for erosion control. Physical interventions have included rock or log revetments, timber groynes and avulsion control structures (e.g., pile fields). These programs typically have a specific river management objective which then defines the scope and types of risk treatments that are adopted.

- Other programs or projects that may influence or be influenced by the RRC program and through which actions or activities can be undertaken that would mitigation potential geomorphic risks e.g., the outcomes of the Barmah-Millewa Feasibility Study may include recommendations or actions on managing the excess sand in the reach, which would also address the geomorphic risks identified in this project.

Risk Re-Evaluation

Based on the application of risk mitigation options identified as suitable treatments the geomorphic risks for those sub-reaches with Medium risk ratings under only some or all of the flow options scenarios were re-evaluated.

Overall, the mitigated results indicate that if the proposed risk treatments are applied successfully, all the Medium risk ratings can be reduced to Low throughout the River Murray. This is also the case for the Murrumbidgee River system, including Yanco Creek. Implementation of these treatment may also address current geomorphic risks, such as bank erosion because of prolonged sub-bankfull flows which can occur because of regulation, or bank erosion downstream of flow regulating structures occurring because of the rapid rise and fall of water levels during the structure operations.

Within the Edward (Kolety) - Wakool River system, the risk rating for the mid Wakool and mid Niemur sub-reaches remains at Medium even with the proposed risk treatments. This outcome occurs because the changes in the likelihood of change across the flow categories is in the Possible range. However, from a geomorphic perspective these reaches are currently highly impacted by a regulated flow regime and while the reintroduction of a more variable flow regime will result in change through reactivation of geomorphic processes this could be considered as much a benefit as a risk. This remaining risk is best addressed through a Monitoring, Evaluation, Reporting and Improvement Plan (MERI).

Environmental flows cannot be expected to combat a century of change within a few years. In the short term we may see changes that are the river system adjusting to legacy impacts of extensive and ongoing river operations. It is important to recognise that this phase of adjustment, including processes such as bank erosion, is an important step toward a healthy River Murray system.

We note that environmental flows are difficult to distinguish from operational flows in terms of their impacts on riverbanks and river morphology. A good test case for understanding these differences is the Goulburn River in Victoria. A decade of monitoring on this system has highlighted that whilst geomorphic changes such as bank erosion may occur following environmental flows, it is the preparation of the riverbanks by prior operational flows that has been found to be the main cause.

8.5. **Future work**

To further improve the assessment outcomes verification of the current geomorphic condition of the rivers across the study area through targeted field assessments is recommended. This field work could be completed as part of the baseline monitoring when implementing the proposed flow options.

section nine

9. **References**

Alluvium (2010). Key ecosystem functions and their environmental water requirements, Report P109093-R05V01 by Alluvium for the Murray-Darling Basin Authority, Canberra

Buffington, J.M., Montgomery, D.R., 2013. Geomorphic classification of rivers. In: Shroder, J. (Editor in Chief), Wohl, E. (Ed.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 9, Fluvial Geomorphology, pp. 730–767.

Brierley, G.J., Fryirs, K., Outhet, D., Massey, C., 2002. Application of the river styles framework as a basis for river management in New South Wales, Australia. Applied Geography 22, 91–122

DeRose, R.C. Prosser, I.P. Weisse, M. and Hughes, A.O. (2003). Patterns of Erosion and Sediment and Nutrient Transport in the Murray-Darling Basin, Technical Report 32/03, CSIRO Land and Water, Canberra

DPIE (2020a). Murray-Lower Darling Long-Term Water Plan Part A: Murray-Lower Darling Catchment, Department of Planning, Industry and Environment, State of NSW

DPIE (2020b). Murray-Lower Darling Long-Term Water Plan Part B: Murray-Lower Darling Planning Units, Department of Planning, Industry and Environment, State of NSW

DPIE (2020c). Murrumbidgee Long-Term Water Plan Part A: Murrumbidgee Catchment, Department of Planning, Industry and Environment, State of NSW

DPIE (2020d). Murrumbidgee Long-Term Water Plan Part A: Murrumbidgee Planning Units, Department of Planning, Industry and Environment, State of NSW

DLWC (1998a). Aquifer Risk Assessment Report, Department of Land and Water Conservation, Sydney.

DLWC (1998b). Stressed Rivers Assessment Report, NSW State Summary, Department of Land and Water Conservation, Sydney

Erskine, W.D. Rutherfurd, I.D. Sherrard, J.J. and Tilleard, J.W. (1993). Investigation of River Channel Changes, Report prepared for the Murray-Darling Basin Commission

Gower, T., Lauchlan Arrowsmith, C., Vietz, G., 2021. River Murray intraday variability trial review (phase 1). Report by Streamology to the Soil Conservation Service of NSW, 2021

Hesse, P.P. Williams, R. Ralph, T.J. Fryirs, K.A. Larkin, T. Westaway, K.E. and Farebrother, W. (2018). Paleohydrology of lowland rivers in the Murray-Darling Basin, Australia, Quaternary Science Reviews, volume 200, pp 85-105

ISO 31000: 2018 Risk Management - Guidelines, International Organisation for Standardisation

Lauchlan Arrowsmith, C. Vietz, G., Gower, T. Woods, K. (2021). Options for Managing Sediment in the Barmah-Millewa Reach of the River Murray – Preliminary Investigations, Report prepared for the Murray-Darling Basin Authority

McLaren, S., Wallace, M. W., Gallagher, S. J., Miranda, J. A., Holdgate, G. R., Gow, L. J., ... & Sandgren, P. (2011). Palaeogeographic, climatic and tectonic change in southeastern Australia: the Late Neogene evolution of the Murray Basin. Quaternary Science Reviews, 30(9-10), 1086-1111

MDBA. (2017). Bank erosion along the River Murray between Hume Dam and the Ovens Junction

MDBA. (2020). Objectives and outcomes for river operations in the River Murray System.

National Research Council, (2004). Adaptive Management for Water Resources Project Planning, Washington, DC: The National Academies Press.

NWI (2010). Policy Guidelines for Water Planning and Management, https://www.awe.gov.au/water/policy/policy/nwi/guidelines-water

Page, K.J. (1994). Late quaternary stratigraphy and chronology of the Riverine Plain, Southeastern Australia, Unpublished PhD Thesis, University of Wollongong

Rutherfurd, I.R. (1991). Channel form and stability in the River Murray: a large, low energy river system in south eastern Australia, Unpublished PhD Thesis, Monash University

Sear, D. A., M. D. Newson and C. R. Thorne (2003). Guidebook of applied fluvial geomorphology, R&D Technical Report FD1914, Defra, Flood Management Division

Streamology (2021). Options for Managing Sediment in the Barmah-Millewa Reach of the River Murray – Preliminary Investigations, Report prepared for the Murray-Darling Basin Authority

Streamology (2022). River Murray Vessel Wash Impacts: Review and Field Experiment. Report by Streamology for the NSW Soil Conservation Service, 2022

Tilleard, J. W., Erskine, W. D., & Rutherfurd, I. D. (1994). Impacts of River Murray flow regulation on downstream channel morphology. National Conference Publication - Institution of Engineers, Australia, 3(94 /15), 409–415

Watts, R.J., McCasker, N., Howitt, J.A., Thiem, J., Grace, M., Kopf, R.K., Healy, S., Bond, N. (2017). Commonwealth Environmental Water Office Long Term Intervention Monitoring Project: Edward-

Wakool River System Selected Area Evaluation Report, 2016-17â€™. Report prepared for Commonwealth Environmental Water Office. Commonwealth of Australia.

Watts R.J., Bond N.R, Healy S., Liu X., McCasker N.G., Siebers A., Sutton N., Thiem J.D., Trethewie J.A., Vietz G., Wright D.W. (2020). 'Commonwealth Environmental Water Office Monitoring, Evaluation and Research Project: Edward/Kolety-Wakool River System Selected Area Technical Report, 2019-20'. Report prepared for Commonwealth Environmental Water Office. Commonwealth of Australia

Whittington, J., Coysh, J., Davies, P., Dyer, F., Gawne, B., Lawrence, I., Liston, P., Norris, R., Robinson, W., Thoms, M. (2001). Development of a framework for the sustainable rivers audit. A report prepared by the CRC for Freshwater Ecology for the Murray Darling Basin Authority. Technical Report no. 8/2001.

Wohl, E. (2018). Geomorphic context in rivers, Progress in Physical Geography: Earth and Environment, Vol 42, Issue 6, p841-857

Appendix A Summary of Datasets and Information Sources

Table A1: List of references for this project

Filename	Type	Format	Location	Category	Year	Creator / Reference	Relevance
MurrayDarlingBasinAssets-Morse-28April2011	Report	pdf	MDB	Assets and Infrastructure	2011	Tony Morse	Low
20-Year-Infrastructure-Options-Study-June-2018	Report	pdf	MDB	Assets and Infrastructure	2018	WaterNSW	Low
07 Koondrook-Perricoota EA - Main Report Chapter 6.pdf	Report	pdf	Murray	Assets and Infrastructure	2021	Koondrook-Perricoota Forest Flood Enhancement Project	Medium
Fenner_1934_Murray River	Journal article	pdf	Murray	Environmental and Climate	1934	Charles Fenner	Low
Bowler (1978)_Quaternary climate and tectonics in the evolution of the Riverine Plain, southeastern Australia	Journal article	pdf	MDB	Environmental and Climate	1978	Bowler	Medium
Bren, L. J. (1988)_Effects of river regulation on flooding of a riparian red gum forest on the River Murray, Australia	Journal article	pdf	Murray	Environmental and Climate	1988	Bren, L.J.	Medium
kenyon and Rutherfurd_1999_Aggradation rate_Barmah region	Journal article	pdf	Murray	Environmental and Climate	1999	Christine Kenyon and Ian D. Rutherford	Medium
edward-wakool-system-river-regulation-and-environmental-flows	Report	pdf	MDB	Environmental and Climate	2000	Damian Green	Medium
Whittington et al. (2001)_Sustainable Rivers Audit Framework	Report	pdf	MDB	Environmental and Climate	2001	Whittington, J., Coysh, J., Davies, P., Dyer, F., Gawne, B., Lawrence, I., Liston, P., Norris, R., Robinson, W. and Thoms, M.	Medium
Bennett et al. (2002)_Guidelines for Protecting Australian Waterways	Report	pdf	General	Environmental and Climate	2002	Bennett, J., Sanders, N., Moulton, D., Phillips, N., Lukacs, G., Walker, K. and Redfern, F.	High

Parsons, Thoms & Norris (2002)_Physical River Assessment Methods	Report	pdf	General	Environmental and Climate	2002	Parsons, M., Thoms, M. and Norris, R.	Medium
Gippel (2003)_MDBC River Murray Environmental Flow Outcomes Review	Report	pdf	MDB	Environmental and Climate	2003	Gippel, C. J.	Medium
The_effects_of_Balranald_Weir_on_spatial_and_tempo	Report	pdf	Murrumbidgee	Environmental and Climate	2004	Lee J. Baumgartner	Low
472_Sediments_nutrients_in_rivers_of_the_MDB	Report	pdf	MDB	Environmental and Climate	2005	Chris Moran, Ian Prosser, Ron DeRose, Hua Lu, Barry Croke, Andrew Hughes, Jon Olley, Greg Cannon	Low
GBCMA_2005_Lower Goulburn Floodplain rehabilitation project	Report	pdf	Murray	Environmental and Climate	2005	Dr John Tilleard, Dr Jane Roberts, Professor Barry Hart, Dr Terry Hillman, Assoc Prof Ian Rutherfurd, Mr Peter Cottingham	High
Conf&#20;PID7388	Conference Paper	pdf	Murrumbidgee	Environmental and Climate	2006	Iain Taylor, Pat Murray and Sarah Taylor + multiple Authers	Medium
DPI (2007)_Threat Abatement Plan Desnagging	Report	pdf	MDB	Environmental and Climate	2007	NSW Department of Primary Industries	Low
Alluvium (2010)_Key Ecosystem Functions_Final Report	Report	pdf	MDB	Environmental and Climate	2010	Alluvium	High
Murrumbidgee-region	Report	pdf	Murrumbidgee	Environmental and Climate	2010	Murrumbidgee Catchment Management Authority	Medium
Environmental water delivery_Edward-Wakool	Report	pdf	MDB	Environmental and Climate	2011	Hale, J and SKM	Low
NSW_Ecological Description_Ramser site forest	Report	pdf	MDB	Environmental and Climate	2011	Harrington, B. and Hale, J.	Low
BarmahMillewa Forest_icon_site_annual_report_2010-2011_final_june_2012	Report	pdf	Murray	Environmental and Climate	2011	Goulburn Broken Catchment Management Authority	Medium

ewater-delivery-yarrawonga	Report	docx	Murray	Environmental and Climate	2011	Michael Jensz (Victorian Department of Sustainability and Environment), Keith Ward (Goulburn Broken Catchment Management Authority), Rick Webster (NSW Office of Environment and Heritage), Garry Smith (DG Consulting), Ben Gawne (Murray-Darling Freshwater Research Centre), Daren Barma (Barma Water Resources), NSW Office of Water, NSW State Water, Murray-Darling Basin Authority	Medium
EWR-EdwardWakool-Final	Report	docx	MDB	Environmental and Climate	2012	Murray-Darling Basin Authority	Low
GBCMA_2012_Kanyapella_Basin_Environmental Water Management Plan	Report	pdf	Murray	Environmental and Climate	2012	Goulburn Broken Catchment Management Authority	Medium
Development_of_a_Reference_Mode_for_Characterizati	Journal article	pdf	MDB	Environmental and Climate	2014	Naeem Khan, Alan McLucas and Keith Linard	Low
Yarrawonga-to-Wakool-reach-report	Report	pdf	Murray	Environmental and Climate	2015	Murray–Darling Basin Authority	Medium
Caveat-murrumbidgee-reach-report-July-2015	Report	docx	Murrumbidgee	Environmental and Climate	2015	Murray–Darling Basin Authority	High
2016014DeniliquinSouthWEB	Report	pdf	MDB	Environmental and Climate	2016	Skyla Birch, Abbie Blake, Jarrah Fitzpatrick, Phoebe Jefferies, Emily Marshall,	Low

						Mia Parks, Grayce Pratt, Jace Collins, Hayden Doncon, Eddie Dudley, Angus Hillman, Cooper King, Logan Leiper, Ben Monro, Tyson Willis, Cameron Wills, Cormac Witty, Lilly Davies-Wilson, Jade Trencher, Connor Clayton, Will Croker, Jonathan Dover, Joe Fenton, Thomas Grange, Lachlan Holloway, Zack Liu, Zac Mills and Joshua Reeves Teacher: Jenna Purtill School: Deniliquin South Public School	
WMO (2019) Guidance on Environmental Flows	Book	pdf	General	Environmental and Climate	2019	World Meteorological Organization	High
murray-lower-darling-long-term-water-plan-part-a-catchment-200080	Report	pdf	MDB	Environmental and Climate	2020	State of NSW and Department of Planning, Industry and Environment	Medium
murray-lower-darling-long-term-water-plan-part-b-planning-units-200081	Report	pdf	MDB	Environmental and Climate	2020	State of NSW and Department of Planning, Industry and Environment	Medium
ANAE-classification-of-the-Murray-Darling-Basin-v3.0-User-Guide	Book	pdf	MDB	Environmental and Climate	2021	Brooks, S.	Medium
Rutherfurd_1994_Inherited controls on the form of a large_MurrayR	Journal article	pdf	Murray	Geology and Geomorphology	1894	Rutherfurd, I.D.	Low
Pels-1964-Ancestral Murray	Journal article	pdf	Murray	Geology and Geomorphology	1964	S. PELS	Low

Bowler and Harford_1965_Quarternary tectoonics and evolution of the riverine plan_Echuca	Journal article	pdf	Murray	Geology and Geomorpholo gy	1965	Bowler and Harford	Low
Currey_1978_Geomorphology of the Barmah-Millewa forests environment	Journal article	pdf	Murray	Geology and Geomorpholo gy	1978	D.T. Curry and D.J. Dole	Medium
Bowler_1986_Quaternary Landform Evolution	Book	pdf	MDB	Geology and Geomorpholo gy	1986	Bowler	High
Butler et al. (1991) Geomorphic Map of Riverine Plain SE Aus	Book	pdf	MDB	Geology and Geomorpholo gy	1991	Butler, B. E., Blackburn, G., Bowler, J. M., Lawrence, C. R., Newell, J. W. and Pels, S.	Medium
Nanson ad Price_1991_Thermoluminescence chronology_SE Australia	Journal article	pdf	MDB	Geology and Geomorpholo gy	1991	K. J. PAGE, G. C. NANSON AND D. M. PRICE	Low
Thoms and Walker (1993)-1993_channel changes_MurrayR	Journal article	pdf	Murray	Geology and Geomorpholo gy	1993	M. C. THOMS AND K. F. WALKER	High
Walker&Thoms_1993_Environmental effects of flow regulation in the lower Murray	Journal article	pdf	Murray	Geology and Geomorpholo gy	1993	K. F. WALKER AND M. C. THOMS	High
Tilleardetal1994	Journal article	pdf	Murray	Geology and Geomorpholo gy	1994	Tilleard J.W., Erskine W.D., and Rutherfurd I.D	Medium
Page Thesis (1994)_Late quaternary stratigraphy and chronology of the Riverine Plain	Thesis	pdf	MDB	Geology and Geomorpholo gy	1994	Page, K. J.	Low

9968.275-284-226-Olive	Report	pdf	Murrumbidgee	Geology and Geomorphology	1995	L. J. OLIVE, J. M. OLLEY, A. S. MURRAY & P. J. WALLBRINK	Medium
Prosser et al. (2001)_Large-scale Erosion and Sediment Transport Patterns_Aus	Conference Paper	pdf	General	Geology and Geomorphology	2001	Prosser, I. P., Rutherfurd, I. D., Olley, J. M., Young, W. J., Wallbrink, P. J., Moran, C. J.	Low
65882_00000241_01_Tilleard	Thesis	pdf	General	Geology and Geomorphology	2001	John W. Tilleard	Low
Kemp Thesis 2001	Thesis	pdf	Murray	Geology and Geomorphology	2001	Justine Kemp	High
Ogden et al_2001_Sediments dates_Murray Tri	Journal article	pdf	Murray	Geology and Geomorphology	2001	Ralph Ogden, Nigel Spooner, Michael Reid, John Head	Low
Prosser et al_2001_Erosion and transportation_MurrayR	Journal article	pdf	Murray	Geology and Geomorphology	2001	Ian P. Prosser A,B , Ian D. Rutherfurd B,C , Jon M. Olley A,B , William J. Young A,B , Peter J. Wallbrink A,B, and Chris J. Moran A	Low
Page (2003)_Murrumbidgee Floodplain Formation and Sedument Stratigraphy	Journal article	pdf	Murrumbidgee	Geology and Geomorphology	2003	K.J. PAGE, G.C. NANSON, AND P.S. FRAZIER	Medium
Lloyd et al. (2005)_ Responses to Flow Modification Review	Report	pdf	General	Geology and Geomorphology	2005	Lloyd, N., Quinn, G., Thoms, M., Arthington, A., Gawne, B., Humphries, P. and Walker, K.	Medium
Rutherfurd_2005_BarmahRutherfurdKenyonRoyalSocVic2005	Journal article	pdf	Murray	Geology and Geomorphology	2005	Rutherfurd, I.D.	Medium
Rayburg et al. (2006)_Review of Geomorphic Classification Schemes	Report	pdf	General	Geology and Geomorphology	2006	Rayburg, S. C., Nanson, R. A., Thoms, M. C., Neave, M. R., Breen, T. P., Lenon, E.	High

Stone_2006_Holocene orogin_Murray R	Journal article	pdf	Murray	Geology and Geomorphology	2006	Tim Stone	Low
Parsons et al. (2007)_ SRA Physical Form_Namoi River_Final Report	Report	pdf	MDB	Geology and Geomorphology	2007	Parsons, M., Thoms, M., Harris, C. and Rayburg, S.	High
Rayburg et al. (2007)_Quantiative River Classification_Namoi River	Report	pdf	MDB	Geology and Geomorphology	2007	Rayburg, S. C., Thoms, M. C., Harris, C. and Neave, M.	High
McGinness (2007)_PhD_Macintyre River	Thesis	pdf	General	Geology and Geomorphology	2007	McGinness, H. M.	Medium
Outhet & Young (2007)_Geomorphic Targets Stream Rehabilitation	Conference Paper	pdf	General	Geology and Geomorphology	2007	Outhet, D. and Young, C.	High
Parsons (2007)_SRA Methods for Reference Geomorpholgy of Rivers	Report	pdf	General	Geology and Geomorphology	2007	Parsons, M.	Medium
Rutherfurd, Anderson & Ladson (2007)_Effects of Riparian Vegetation on Flooding	Book Chapter	pdf	General	Geology and Geomorphology	2007	Rutherfurd, I., Anderson, B. and Ladson, A.	Low
2007_Judd_A_case_study_of_the_processes_displacing_flow_from_Anabrnach	Journal article	pdf	MDB	Geology and Geomorphology	2007	Dean A. Judd, Ian D. Rutherfurd, John W. Tilleard and Robert J. Keller	Medium
Gippel et al. (2008)_NCCMA Fluvial Geomorphic Investigation	Report	pdf	MDB	Geology and Geomorphology	2008	Gippel, C. J., Anderson, B. A., Doeg, T., Wealands, S. and MacLaren, G.	High
Barmah_Choke_factsheet	Report	pdf	Murray	Geology and Geomorphology	2008	Murray-Darling Basin Commission	Medium
MDBA_2009_Barmah-Choke-Study-Investigations-Phase-Report	Report	pdf	Murray	Geology and Geomorphology	2009	Murray-Darling Basin Authority	Medium

Hufschmidt & Glade (2010)_Geomorphic Risk Assessment Vulnerability Analysis	Book Chapter	pdf	General	Geology and Geomorphology	2010	Hufschmidt, G. and Glade, T.	Medium
Outhet (2011)_Lachlan Valley River Styles_Draft	Report	docx	Murrumbidgee	Geology and Geomorphology	2011	Outhet, D.	Medium
2011-02-24-Overbank-Flow-Recommendations-for-the-Lower-Goulburn-Final-reduced-size…	Report	pdf	Murray	Geology and Geomorphology	2011	Department of Sustainability and Environment	High
Hughes_thesis_Hydraulic habitat in the River Murray the influence of geomorohology and large wood	Thesis	pdf	Murray	Geology and Geomorphology	2011	Hughes, A. O.	Low
Buffington & Montgomery (2013)_Geomorphic Classification of Rivers	Book Chapter	pdf	General	Geology and Geomorphology	2013	Buffington, J. M. and Montgomery, D. R.	High
edward-wakool-channel-system-distribution-sulfidic-channel-sediments-130311	Report	pdf	MDB	Geology and Geomorphology	2013	State of NSW and Office of Environment and Heritage	High
Murray_2014_Cause-and-effect-in-geomorphic-systems-Complex-systems-perspectives	Journal article	pdf	General	Geology and Geomorphology	2014	A. Brad Murray, Giovanni Coco, Evan B. Goldstein	Low
Mulwala Weir to Torrumbarry Weir Murray River Bank Profile Analysis 2015 - 2018	Report	pdf	Murray	Geology and Geomorphology	2015	Soil Conservation Service River Murray Works Unit, Murray Darling Basin Authority	Medium
Cullum et al. (2016)_Landscape archetypes	Journal article	pdf	General	Geology and Geomorphology	2017	Cullum, C., Brierley, G., Perry, G. L. W. and Witkowski, E. T. F.	Low
Moore et al. (2017)_Hydrogeological Landscape Framework	Journal article	pdf	General	Geology and Geomorphology	2017	Moore, C. L., Jenkins, B. R., Cowood, A. L., Nicholson, A., Muller, R., Wooldridge, A., Cook, W., Wilford, J. R., Littleboy, M., Winkler, M. and Harvey, K.	Low

Fryirs_Brierley_2016_RiverRecoveryWiRESWater	Journal article	pdf	General	Geology and Geomorphology	2017	Kirstie A. Fryirs and Gary J. Brierley	Medium
Thoms 2017_Bank instability along a weir pool of the River Murray	Journal article	pdf	Murray	Geology and Geomorphology	2017	Martin Thoms	Low
Mallen-Cooper & Zampatti (2018)_Hydrology and Hydraulics	Journal article	pdf	General	Geology and Geomorphology	2018	Mallen-Cooper, M. and Zampatti, B. P.	Low
McManamay et al. (2018)_Physical Habitat Diversity Classification_USA	Journal article	pdf	General	Geology and Geomorphology	2018	McManamay, R. A., Troia, M. J., DeRolph, C. R., Sheldon, A. O., Barnett, A. R., Kao, S-C. and Anderson, M. G.	High
Wohl (2018)_Geomorphic Context in Rivers	Journal article	pdf	General	Geology and Geomorphology	2018	Wohl, E.	Medium
Davies et al. (2018)_Riverine Sediment Production Reconstruction Vic	Journal article	pdf	MDB	Geology and Geomorphology	2018	Peter Davies, Susan Lawrence, Jodi Turnbull, Ian Rutherfurd, James Grove, Ewen Silvester, Darren Baldwin, Mark Macklin	Medium
Streamology_Barmah_Choke_Sediment_Report_Final_29NOV2020	Report	pdf	Murray	Geology and Geomorphology	2020	Streamology, Prof. Ian Rutherfurd, Dr. Alex Sims	Medium
ZhangRutherfurd2020erosionandlargewood	Journal article	pdf	Murray	Geology and Geomorphology	2020	Nuosha Zhang and Ian D. Rutherfurd	Low
Water Tech_Barmah choke channel capacity	Report	pdf	Murray	Geology and Geomorphology	2020	Water Technology Pty Ltd Murray Darling Basin Authority	Medium
Adams (2021)_Morphodynamics Erodible Channel	Journal article	pdf	General	Geology and Geomorphology	2021	Adams, D.	Low

Currey and Dole_1978_Flood flow pattern_Murray	Journal article	pdf	Murray	Hydrology and Hydraulic	1978	D.T. Curry and D.J. Dole	Medium
Kennett-Smith et al. 1994. Factors affecting groundwater recharge following clearing in the south western Murray Basin	Journal article	pdf	Murray	Hydrology and Hydraulic	1994	Kennett-Smith et al.	Low
Maheshwari_et_al-1995_Flow regime of the MurrayR	Journal article	pdf	Murray	Hydrology and Hydraulic	1995		Medium
Stewart et al_2002_Barmah_Millewa forest environmental water allocation	Journal article	pdf	Murray	Hydrology and Hydraulic	2002	G. Stewart and B. Harper	Medium
Chong_et_al-2003-Analysis and management of Unseasonal flooding in the Barmah-Millewa Forest	Journal article	pdf	Murray	Hydrology and Hydraulic	2003	Chong	Medium
WT (2005) LGFloodplainRehabilitationScheme-HydraulicModellingReport	Report	pdf	Murray	Hydrology and Hydraulic	2005	Water Technology PtyLtd - Goulburn CMA	High
CSIRO_River Murray Floodplain Inundation Model (RiM-FIM)	Report	pdf	Murray	Hydrology and Hydraulic	2006	Overton, IC, McEwan, K, Gabrovsek, C, and Sherrah, JR	High
Howitt_2077_Modelling-blackwater--Predicting-water-quality-during-flo_2007_Ecological-Mo	Report	pdf	Murray	Hydrology and Hydraulic	2007	Howitt	Low
Rayburg & Thoms (2008)_Flooding and Surface Sediments_Narran Lakes	Conference Paper	pdf	MDB	Hydrology and Hydraulic	2008	Rayburg, S. C. and Thoms, M. C.	Medium
Kennard et al. (2009)_Ecohydrological Classification Flow Regimes	Report	pdf	General	Hydrology and Hydraulic	2009	Kennard, M. J., Pusey, B. J., Olden, J. D., Mackay, S., Stein, J. and Marsh, N.	High
Barmah-Millewa_hydrodynamic_modelling_report_optimized	Report	pdf	Murray	Hydrology and Hydraulic	2009	Water Technology - Goulburn Broken Catchment Management Authority	High
DPIE (2011)_Murrumbidgee Map 2011	Spatial	pdf	Murrumbidgee	Hydrology and Hydraulic	2011	DPIE	High

Vanags & Vervoort (2013)_MDB Implications of Geomorphological Stratification	Journal article	pdf	MDB	Hydrology and Hydraulic	2013	Vanags, C. P. and Vervoort, R. W.	Low
Gippel (2013)_Little Murray River Weir Pool Hydraulics	Report	pdf	Murray	Hydrology and Hydraulic	2013	Gippel, C. J.	Medium
RiM-FIM Floodplain Inundation Modelling for the Edward-Wakool, Lower Murrumbidgee and Lower Darling RiverSystems	Report	pdf	MDB	Hydrology and Hydraulic	2014	Sims, N.C., Warren, G., Overton, I.C., Austin, J., Gallant, J., King, D. J., Merrin, L.E., Donohue, R., McVicar, T.R., Hodgen, M.J., Penton D.J., Chen, Y., Huang, C. & Cuddy, S.	High
Flood mapping of the Murray_SA	Report	pdf	Murray	Hydrology and Hydraulic	2015	DEWNR	Low
Stewardson & Guarino (2018)_MBD EW Delivery	Journal article	pdf	MDB	Hydrology and Hydraulic	2018	Stewardson. M. J. and Guarino, F.	Medium
Hesse et al (2018)_Palaeohydrology of lowland rivers in the Murray-Darling Basin	Journal article	pdf	MDB	Hydrology and Hydraulic	2018	Paul P. Hesse, Rory Williams, Timothy J. Ralph, Kirstie A. Fryirs, Zacchary T. Larkin, Kira E. Westaway, Will Farebrother	Medium
Goulburn Broken Regional Floodplain Management strategy	Report	pdf	Murray	Hydrology and Hydraulic	2018	Goulburn Broken Catchment Management Authority	Medium
MDBA_2018_River flows and connectivity	Report	pdf	MDB	Hydrology and Hydraulic	2018	Murray–Darling Basin Authority	High

Rutherfurd, I.D. et al2020. Human impacts on suspended sediment and turbidity in the River Murray, South Eastern Australia Multiple lines of evid	Journal article	pdf	Murray	Hydrology and Hydraulic	2020	Rutherfurd, I.D.	Low
Schumm (1968)_Murrumbidgee River Adjustment to Altered Hydrologic Regimen	Book	pdf	Murrumbidgee	Locations of Concern	1968	Schumm, S. A.	Medium
Gill (1973)_Murray River Geology and Geomorphology	Book Chapter	pdf	Murray	Locations of Concern	1973	Gill., E. D.	High
RSV (1978)_Proceedings Royal Society Victoria_Vol90_Part1	Book	pdf	MDB	Locations of Concern	1978	Royal Society of Victoria	Medium
Erskine & Melville (1982)_Cuttoff and Oxbow Lake	Journal article	pdf	Murrumbidgee	Locations of Concern	1982	Erskine, W. and Melville, M.	Medium
Dexter et al_2018_River regulation and associated forest management proble	Journal article	pdf	Murray	Locations of Concern	1986	B. D. Dexter, H. J. Rose and N. Davies	Medium
Thoms & Walker (1992)_Murray Sediment Transport	Book Chapter	pdf	Murray	Locations of Concern	1992	Thoms, M. C. and Walker, K. F.	Medium
Olive et al. (1994) Murrumbidgee SS Transport Spatial Variation	Conference Paper	pdf	Murrumbidgee	Locations of Concern	1994	Olive, L. J., Olley, J. M., Murray, A. S. and Wallbrink, P. J.	Medium
Page (1994)_Late Quaternary Stratigraphy and Chronology Riverine Plain_SE Aus	Thesis	pdf	Murrumbidgee	Locations of Concern	1994	Page, K. J.	Medium
Olive et al. (1995)_Murrumbidgee Sediment Transport	Conference Paper	pdf	Murrumbidgee	Locations of Concern	1995	Olive, L. J., Olley, J. M., Murray, A. S. and Wallbrink, P. J.	Medium
Olive & Olley (1997)_Murrumbidgee Regulation and Sediment Transport	Conference Paper	pdf	Murrumbidgee	Locations of Concern	1997	Olive, L. J. and Olley, J. M.	Medium
Thoms et al. (2000)_MBDC Murray Dartmouth-Wellington and Lower Darling	Report	pdf	Murray	Locations of Concern	2000	Thoms, M., Suter, P., Roberts, J., Koehn, J., Jones, G., Hillman, T. and Close, A.	Low
Gippel & Blackham (2002)_Murray and Lower Darling Flow Regulation Environmental Impacts	Report	pdf	Murray	Locations of Concern	2002	Gippel, C. and Blackham, D.	Medium
Olley & Scott (2002)_Murrumbidgee and Namoi Sediment_Technical Report	Report	pdf	Murrumbidgee	Locations of Concern	2002	Olley, J. and Scott, A.	Medium

Vietz & Hardie (2002)_Murray Wetland Water Regime Requirements_Hume Dam-Murray Mouth	Conference Paper	pdf	Murray	Locations of Concern	2002	Vietz, G. and Hardie, R.	Medium
DeRose et al. (2003)_Goulburn & Broken Erosion, Sediment and Nutrient Transport Patterns	Report	pdf	Murray	Locations of Concern	2003	DeRose, R. C., Prosser, I. P., Wilkinson, L. J., Hughes, A. O. and Young, W. J.	Medium
DeRose et al. (2003)_MDB Erosion, Sediment and Nutrient Transport Patterns	Report	pdf	Murray	Locations of Concern	2003	DeRose, R. C., Prosser, I. P., Weisse, M. and Hughes, A. O.	Medium
Olley & Wasson (2003)_Upper Murrumbidgee Sediment Changes	Journal article	pdf	Murrumbidgee	Locations of Concern	2003	Olley, J.. M. and Wasson, R. J.	Medium
Hughes & Prosser (2003)_MDB Gully and Riverbank Erosion Mapping	Report	pdf	MDB	Locations of Concern	2003	Hughes, A. O. and Prosser, I. P.	Medium
MDBC (2004)_ SRA Physical Habitat Technical Report	Report	pdf	MDB	Locations of Concern	2004	Murray-Darling Basin Commission	Medium
MDBC (2004)_SRA Technical Report Physical Habitat	Report	pdf	MDB	Locations of Concern	2004	Murray-Darling Basin Commission	High
Kingsford & Thomas (2004)_Murrumbidgee Dams and Irrigation Threats Wetlands Waterbirds	Journal article	pdf	Murrumbidgee	Locations of Concern	2004	Kingsford, R. T. and Thomas, R. F.	Medium
Loweer Goulburn Floodplain Rehabilitation	Report	pdf	Murray	Locations of Concern	2005	Dr John Tilleard, Dr Jane Roberts, Professor Barry Hart, Dr Terry Hillman, Assoc Prof Ian Rutherfurd, Mr Peter Cottingham	High
Stone (2006)_Murray River Course Origin	Journal article	pdf	Murray	Locations of Concern	2006	Stone, T.	Medium
Stone (2006)_Murray River Course Origin	Journal article	pdf	Murray	Locations of Concern	2006	Stone, T.	Medium
Martin & Judd (2007)_Murray River Anabranch Management	Conference Paper	pdf	Murray	Locations of Concern	2007	Martin, J. and Judd, D.	Medium
Clarke et al. (2008)_Murray Geomorphology Robinvale-Boundary Bend	Report	pdf	Murray	Locations of Concern	2008	Clarke, J., Wong, V., Pain, C., Apps, H., Gibson, D., Luckman, J. and Lawrie, K.	Medium

Clarke et al. (2008)_Murray Geomorphology_Liparoo-Robinvale	Report	pdf	Murray	Locations of Concern	2008	Clarke, J., Wong, V., Pain, C., Apps, H., Gibson, D., Luckman, J. and Lawrie, K.	Medium
CSIRO (2008)_Murrumbidgee Water Availability	Report	pdf	Murrumbidgee	Locations of Concern	2008	CSRIO	High
Williams (2010)_MDB and its Dynamics	Book Chapter	pdf	MDB	Locations of Concern	2010	Williams, J.	Medium
Harrington & Hale (2011)_Central Murray Forests Ramar Site Ecological Description	Report	pdf	Murray	Locations of Concern	2011	Harrington, B. and Hale, J.	High
Edward-and-Niemur-Rivers-Stage-3	Report	pdf	MDB	Locations of Concern	2011	Department of Environment, Climate Change and Water NSW	Medium
MDBA (2012)_Edward-Wakool EW Requirements	Report	pdf	MDB	Locations of Concern	2012	Murray-Darling Basin Authority	Medium
MDBA (2012)_Gunbower-Koondrook-Perricotta Forest Environmental Water Requirements	Report	docx	Murray	Locations of Concern	2012	Murray-Darling Basin Authority	Medium
Hardwick et al. (2012)_Murrumbidgee Burrinjuck Dam EW	Report	pdf	Murrumbidgee	Locations of Concern	2012	Hardwick. L., Chessman, B., Westhorpe, D. and Mitrovic, S.	Low
MDBA (2012)_Lower Murrumbidgee Floodplain EWR	Report	pdf	Murrumbidgee	Locations of Concern	2012	Murray-Darling Basin Authority	High
MDBA (2012)_Lower Murrumbidgee In-channel flows EWR	Report	pdf	Murrumbidgee	Locations of Concern	2012	Murray-Darling Basin Authority	Medium
MDBA (2012)_Mid Murrumbidgee Wetlands EWR	Report	pdf	Murrumbidgee	Locations of Concern	2012	Murray-Darling Basin Authority	Medium
OEH (2012)_Yanga National Park Wetland Ecological Characteristics	Report	pdf	Murrumbidgee	Locations of Concern	2012	NSW Office of Environment and Heritage	Low
Edward-and-Wakool-Rivers-stage-1-fmp	Report	pdf	MDB	Locations of Concern	2012	Department of Environment, Climate Change and Water NSW	Medium

EWR-Lower-Murrumbidgee-River	Report	pdf	Murrumbidgee	Locations of Concern	2012	Murray-Darling Basin Authority	Medium
Tulau & Morand (2013)_Edward-Wakool Sulfidic Sediments	Report	pdf	MDB	Locations of Concern	2013	Tulau, M. and Morand, D.	Medium
Rogers et al. (2013)_Murrumbidgee Wetlands Thresholds and Limits	Journal article	pdf	Murrumbidgee	Locations of Concern	2013	Rogers, K., Saintilan, N., Colloff, M. J. and Wen, L.	Medium
Burns & Gawne (2014)_MDB EW_Final Report	Report	pdf	MDB	Locations of Concern	2014	Burns, I. and Gawne, B.	High
Wassens et al. (2014)_Murrumbidgee Selected Area Monitoring and Evaluation Plan	Report	pdf	Murrumbidgee	Locations of Concern	2014	Wassens, S., Jenkins, K., Spenser, J., Thiem, J., Bino, G., Lenon, E., Thomas, R., Kobyashi, T., Baumgartner, L., Brandis, K., Wolfenden, B., Hall, A., Watson, M. and Scott, N.	High
Watts & Healy (2015)_Edward-Wakool LTIM Progress Report No.5_Final_2015-16	Report	pdf	MDB	Locations of Concern	2015	Watts, R. J. and Healy, S.	Low
MDBA (2015)_Murray Yarrawonga Weir to Wakool Junction_Final Report	Report	pdf	Murray	Locations of Concern	2015	Murray-Darling Basin Authority	High
Smith, Croke & Newham (2015)_Murrumbidgee Suspended Sediment Loads	Conference Paper	pdf	Murray	Locations of Concern	2015	Smith, C. J., Croke, B. G. W. and Newham, L. T. H.	Low
Wassens et al. (2016)_CEWO LTIM Murrumbidgee Evaluation Report 2014-16	Report	pdf	Murrumbidgee	Locations of Concern	2016	Wassens, S., Spencer, J., Thiem, J., Wolfenden, B., Jenkins, K., Hall, A., Ocock, J., Kobayashi, T. Thomas, R., Bino, G., Heath, J. and Lenon, E.	High
Watts et al. (2017)_Edward-Wakool LTIM Evaluation Report 2016-17	Report	pdf	MDB	Locations of Concern	2017	Watts, R. J., McCasker, N., Howitt, J. A., Thiem, J., Grace, M., Kopf, R. K., Healy, S. and Bond, N.	Low
MDBA (2017)_River Murray Bank Erosion Vessel Wash	Report	pdf	Murray	Locations of Concern	2017	Murray-Darling Basin Authority	Low

DPI (2017)_Murrumbidgee Water Resource Plan_Surface Water	Report	pdf	Murrumbidgee	Locations of Concern	2017	DPI	High
Wassens et al. (2017)_CEWO LTIM Murrumbidgee Evaluation Report 2014-17	Report	pdf	Murrumbidgee	Locations of Concern	2017	Wassens, S., Spencer, J., Wolfenden, B., Thiem, J., Thomas, R., Jenkins, K., Brandis, K., Lenon, E., Hall, A., Ocock, J., Kobayashi, T., Bino, G., Heath, J. and Callaghan, D.	High
21480640_published_report	Report	pdf	Murray	Locations of Concern	2017	Watts RJ, Wolfenden B, Howitt JA, Jenkins K, McCasker N, Blakey R	High
Watts et al. (2019)_CEWO Edward-Wakool Evaluation and Research Plan 2019-22	Report	pdf	MDB	Locations of Concern	2019	Watts, R. J., McCasker, N., Howitt, J., Liu, X., Trethewie, J., Allan, C., Thiem, J., Duncan, M., Healy, S., Bond, N., Van Dyke, J., Vietz, G. and Donges, M.	Low
DPI (2019)_Murrumbidgee Water Resource Plan Area Risk Assessment_Part1	Report	pdf	Murrumbidgee	Locations of Concern	2019	DPI	High
Wassens et al. (2019)_Murrumbidgee MER Plan 2019	Report	pdf	Murrumbidgee	Locations of Concern	2019	Wassens, S., Michael, D. R., Spencer, J., Thiem, J., Kobayashi, T., Bino, G., Thomas, R., Brandis, K., Hall, A. and Amos, C.	High
Watts et al. (2020)_CEWO Research_EdwardKolety-Wakool Technical Report	Report	docx	MDB	Locations of Concern	2020	Watts, R. J., Bond, N. R., Duncan, M. Healy, S., Liu, X., McCasker, N. G., Siebers, A., Sutton, N., Thiem, J. D., Threthewie, J. A., Vietz, G. and Wright, D. W.	Medium
DPIE (2020)_Murrumbidgee Water Quality Technical Report_SW9	Report	pdf	Murrumbidgee	Locations of Concern	2020	DPIE	Medium

DPIE (2021)_Murrumbidgee Long-Term Water Plan PartA	Report	pdf	Murrumbidgee	Locations of Concern	2021	DPIE	High
Fryirs et al. (2021)_NSW River Styles Database	Journal article	pdf	Murrumbidgee	Locations of Concern	2021	Fryirs, K., Hancock, F., Healey, M., Mould, S., Dobbs, L., Riches, M., Raine, A. and Brierley, G.	Medium
2019-20-goulburn-mer-annual-summary-report	Report	pdf	Murray	Locations of Concern	2021	Simon Treadwell, Angus Webb, Xue Hou, Ben Baker, Simon Casanelia, Michael Grace, Joe Greet, Claudette Kellar, Wayne Koster, Daniel Lovell, Daniel McMahon, Kay Morris, Jackie Myers, Vin Pettigrove, Neil Sutton, Geoff Vietz	Medium
Olley et al. (n.d.)_Murrumbidgee Sources of SS and Phosphorus	Report	pdf	Murrumbidgee	Locations of Concern	n.d.	Olley, J., Caitcheon, G., Donnelly, T., Hancock, G., Olive, L., Murray, A., Short, D., Wallbrink, P. and Wasson, R.	Medium
Edward River Characterisation	Report	pdf	MDB	Locations of Concern			Medium

Spatial data

Filename	Type	Format	General	Category	Year	Creator / Reference	Relevance
211220_DPIE_Assets/RRC_AssetDB_Env_Exp.gdb	Spatial	shp	MDB	Assets and Infrastructure	N/A	DPIE	Medium
220114_DPIE_InunMap	Spatial	shp	MDB	Hydrology and Hydraulic	2014	CSIRO	High

220121_DPIE_RIMFIM	Spatial	shp	MDB	Hydrology and Hydraulic	2012	CSIRO	High
220204_JG_IR_reaches	Spatial	shp	MDB	Geology and Geomorphology	N/A	JG & IR	Medium
ESRI - World Imagery	Spatial	shp	MDB	Imagery and Survey	2022	ESRI	Medium
LiDAR DEM	Spatial		MDB	Imagery and Survey	2022	Geoscience Australia	High
Historical Imagery - NSW	Spatial		MDB	Imagery and Survey	2022	NSW Government	Medium
Historical Imagery - Historical Aerial Photography	Spatial		MDB	Imagery and Survey	2021	Geoscience Australia	Medium

Appendix B Hydrologic Assessment

Catchment characteristics

The Murray and Murrumbidgee River catchments extend from the Snowy Mountain ranges on the eastern boundary and drains towards the west of NSW. The Murrumbidgee River has its headwaters in the Snowy mountains, drains through Wagga Wagga and passes 30km south of Griffith. The Murray River passes through major townships of Albury and Echuca as it meanders along the NSW/VIC border. The Murrumbidgee-Murray rivers connect at Boundary Bend before passing through Robinvale.

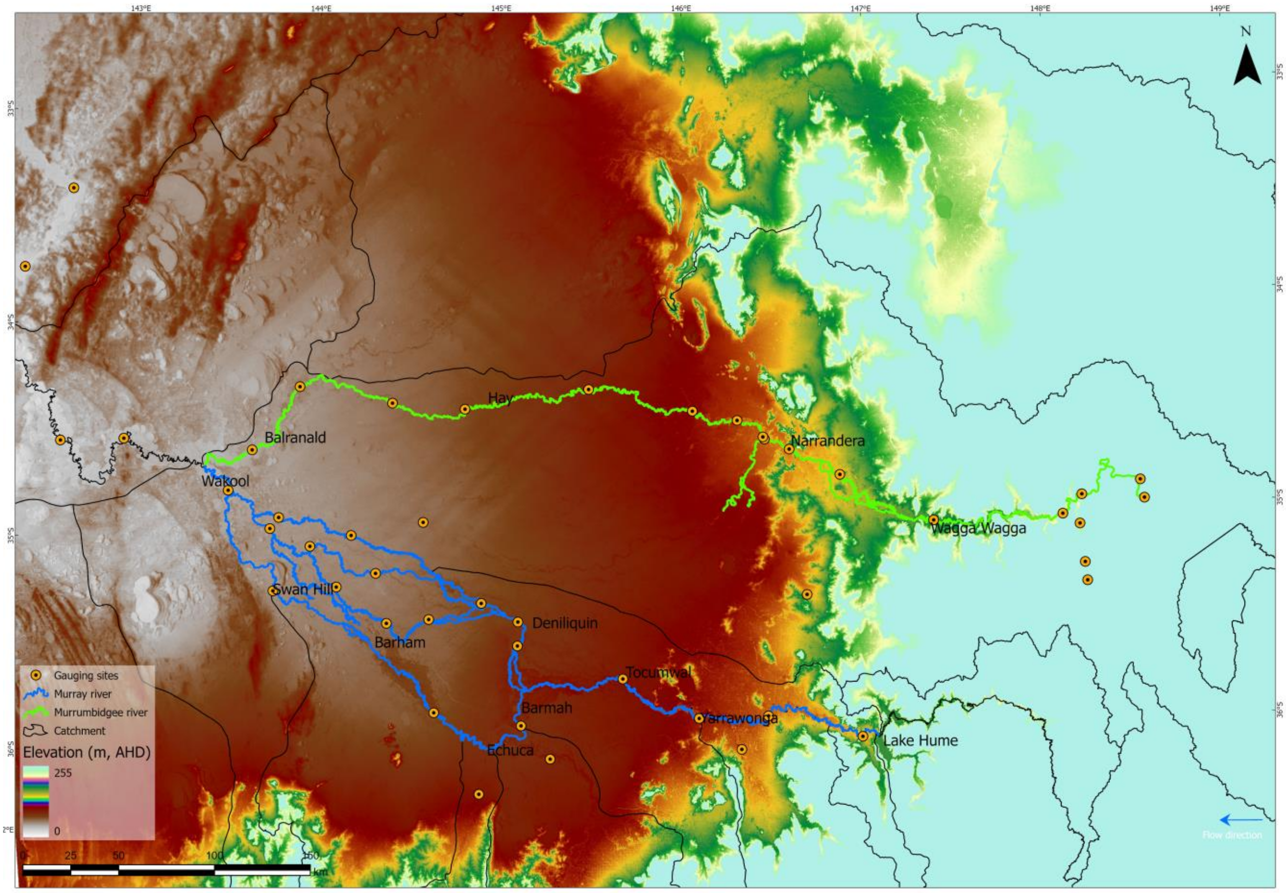


Figure 24 Catchment overview and river network

Current hydrologic conditions

The topography and geographical distribution of the Murray Murrumbidgee region results in large spatial variations in climatic conditions. It is relatively wet towards the Snowy Mountains (average annual rainfall of approximately 1600–2400mm) on the eastern boundary of the region, and dry in the west of the region (average annual rainfall of approximately 300mm at Robinvale).

Across the Murray Darling Basin there has been extended drought conditions since the mid-1990s, comprising the Millennium Drought (1997–2009); and the 2017–2019 drought.

Precipitation in southeast Australia, where the Murrumbidgee and Murray River catchment is located, is typically highest in winter. The lowest precipitation is typically witnessed in Summer and early autumn. Climate projections are in agreeance that the precipitation will decrease in spring and increase in autumn.

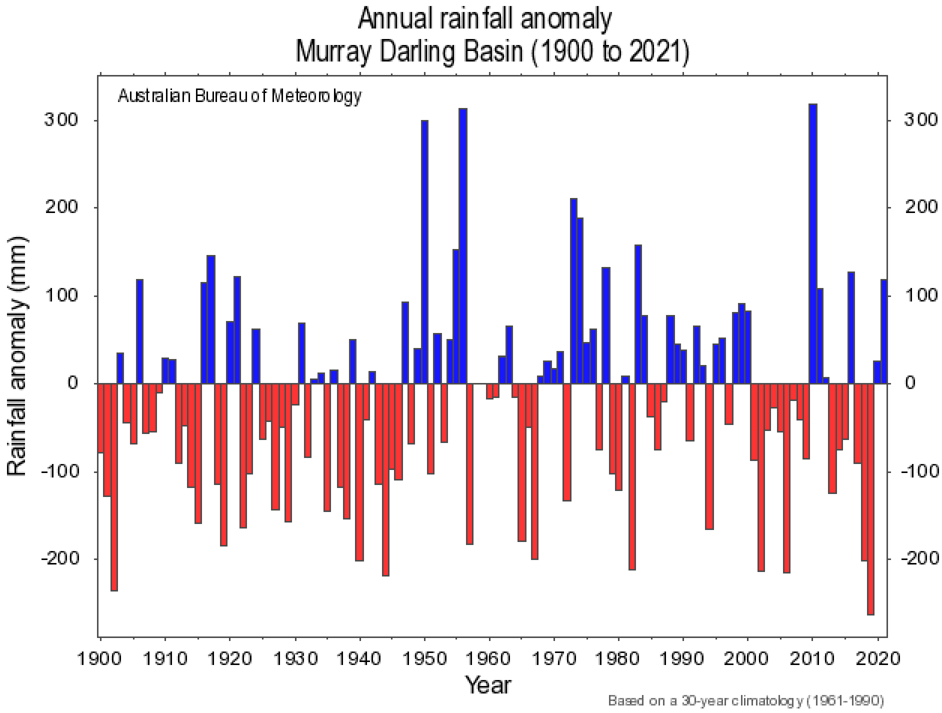


Figure 25 Annual rainfall anomaly

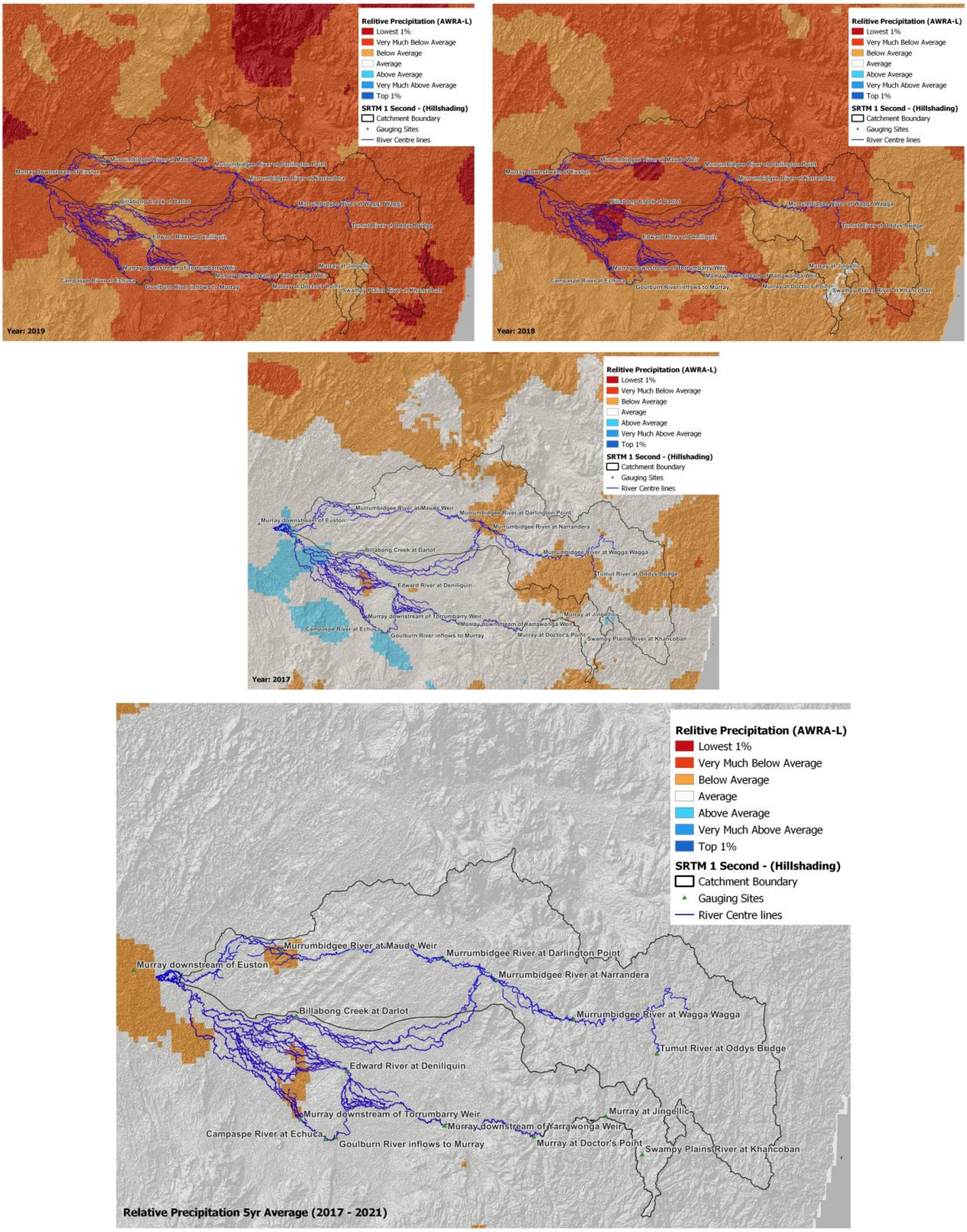
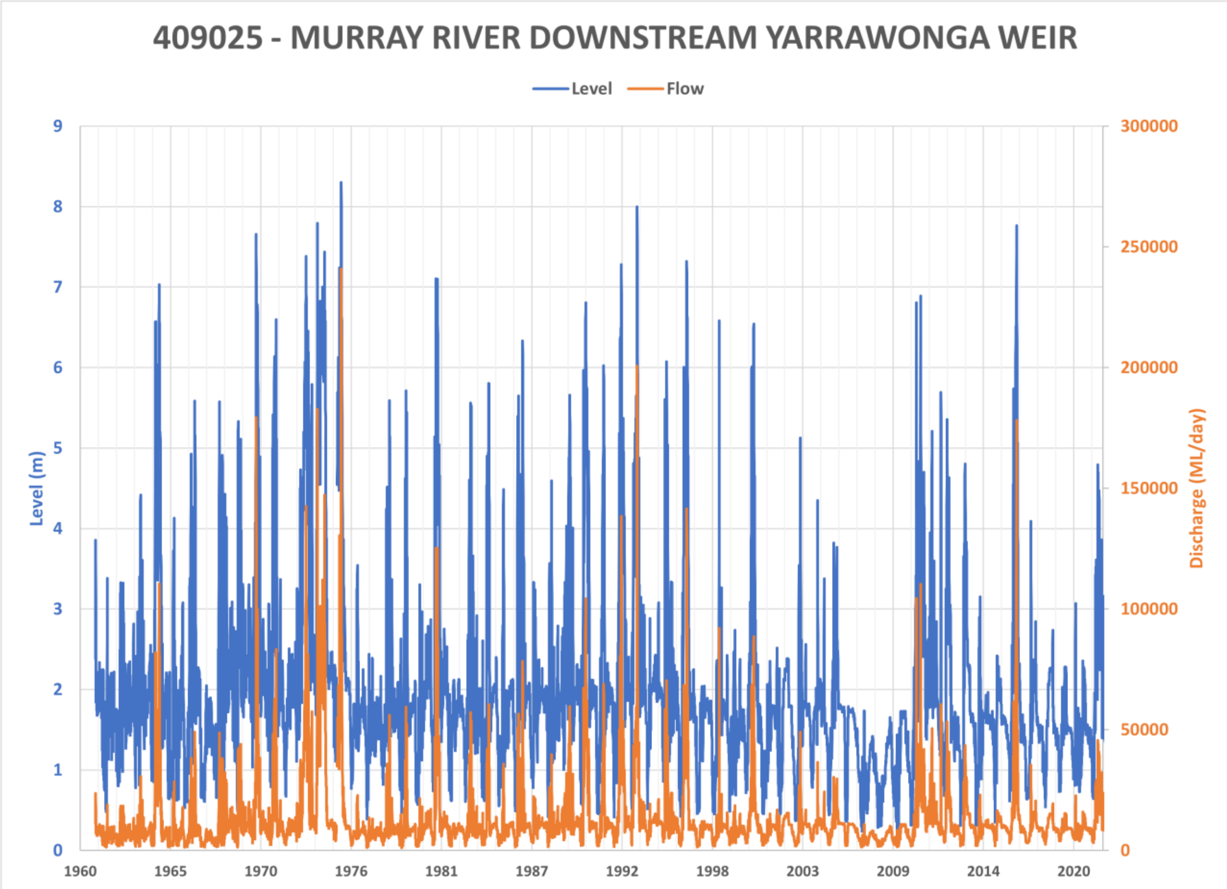


Figure 26 Relative Precipitation – AWRA-L (Australia Land and Water Model, BoM, 2022)



Flow options hydrology

The Source hydrological (river system) model was used to represent potential environmental water delivery in the Murray River under Reconnecting River Country Program flow limit options. In the Source model, environmental water Orders are placed at Yarrawonga as flows to provide outcomes upstream and downstream. Orders are aimed to achieve at Yarrawonga Environmental Water Requirements (EWRs) for the Murray River d/s Yarrawonga Weir published in the in Murray-Lower Darling Long Term Water Plan (LTWP) (DPIE 2020).

The Source modelling for the Reconnecting River Country Program represents historic climate for the 1/7/1895-30/6/2019 period, with water regulating infrastructure, water sharing policies and water recovery for the environment as it exists on 1 January 2021 with all environmental water managed as a single portfolio. The model considers combined inflows from the Murray and Goulburn Rivers and delivery strategy is not to deliver in summer months to limit blackwater risks (MDBA 2022). The modelling tries to represent appropriate environmental water delivery options, either on the back of existing flows (to extend duration of natural high flow and medium flow events) or to create new events, with the focus on small and medium overbank events (MDBA 2022).

Appendix C – Sub-Reach Assessments