FINAL REPORT:

UPPER MURRUMBIDGEE HABITAT REVIEW

May 2022

streamology
waterway science and management

Acknowledgements

Streamology acknowledges and respects the Traditional Owners as First Peoples of the lands and waters of this Country. We recognise their unique ability to care for Country and their deep spiritual connection to it. We honour Elders past and present and whose knowledge and wisdom has ensured the continuation of culture and traditional practices. We are committed to genuinely partner, and meaningfully engage, with Traditional Owners and Aboriginal communities to support the protection of Country, the maintenance of spiritual and cultural practices and their broader aspirations in the 21st century and beyond.

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This report was commissioned by the Upper Murrumbidgee Demonstration Reach and funded by the Native Fish Recovery Strategy. The Native Fish Recovery Strategy is funded under the joint programs and coordinated by the Murray-Darling Basin Authority. The views expressed in this document are those of the authors and may not reflect the views of the Upper Murrumbidgee Demonstration Reach or the Murray-Darling Basin Authority.

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Cover image: Murrumbidgee River at Tharwa. Hugh Allen.

Contents

Acronyms

ARI	Arthur Rylah Institute
DEPI	Department of Environment and Primary Industries
DSE	Department of Sustainability and Environment
EGCMA	East Gippsland Catchment Management Authority
ELJ	Engineered Log Jam
NCCMA	North Central Catchment Management Authority
MDBA	Murray Darling Basin Authority
OEH	Office of Environment and Heritage
SSC	Snowy Scientific Committee
UMDR	Upper Murrumbidgee Demonstration Reach
UMRR	Upper Murrumbidgee Recovery Reach
USDA	United States Department of Agriculture

1 Introduction

Streamology Pty Ltd. (Streamology) has been engaged by Bush Heritage Australia on behalf of the Upper Murrumbidgee Demonstration Reach (UMDR) to conduct a review of fish habitat restoration options for sand affected river reaches that are applicable to the Upper Murrumbidgee River. The project also makes recommendations about which habitat restoration options may be most suitable for the study reach given the aquatic fauna found within the river. The habitat improvement options investigated as part of this project are required to reduce the impact on instream sedimentation and/or improve habitat complexity with a focus on fish and the ecological functions on which they depend. It is also important that proposed options do not reduce other important values. The objectives for this project are:

- To provide the UMDR with a review of the current state of knowledge of options to improve ecological functioning and habitat complexity in sand affected streams.

- To provide recommendations on the habitat improvement options that would be most suitable for the Upper Murrumbidgee River.

This work will form Stage 1 of the 'Improving habitat complexity in sand affected streams' project, the outcomes of which will be used to inform Stage 2 of the project that will work to trial the most suitable options as identified through this scope of work. This project was funded by the Native Fish Recovery Strategy as part of the Upper Murrumbidgee Recovery Reach (UMRR).

1.1 Project background

The Murrumbidgee River is a major tributary of the Murray River. The focus of this project is the Upper Murrumbidgee Recovery Reach (Figure 1), which stretches approximately 320 km from Tantangara Dam to Burrinjuck Dam. This reach is the focus area of the UMDR partnership which aims to work with all catchment stakeholders to improve river health for the benefit of native fish and community well-being. The UMDR is a collaborative partnership between Bush Heritage Australia, the ACT Government, Upper Murrumbidgee Waterwatch, the Australian River Restoration Centre, the University of Canberra, South-East Local Land Services, NSW Department of Primary Industries, and local communities. The reach lies within a highly modified catchment which has resulted in both aquatic and riparian habitat loss. The UMDR has recently obtained a grant from the Murray Darling Basin Authority (MDBA) under the Native Fish Recovery Strategy to implement the UMRR project, the focus of which is to support native fish recovery and community engagement in the upper Murrumbidgee catchment. The Native Fish Recovery Strategy is funded under the joint programs and coordinated by the MDBA. The joint programs promote and coordinate effective planning, management and sharing of the water and other natural resources of the Murray-Darling Basin.

Threats to river health and native fish populations within the catchment include the clearing of riparian vegetation, erosion and sedimentation, invasion by pest plant and animal species and significant flow diversion which have altered both the hydrology and transport capacity of the river. The study reach has been significantly affected by in-channel sand deposition which has smothered structural fish habitat, created instream barriers to fish movement, increased water temperature and simplified trophic food webs. These impacts have had follow on consequences for the ecological functioning of the river and reduced ecosystem resilience.

Despite significant change and ongoing environmental threats, the Upper Murrumbidgee is a significant riverine ecosystem, providing habitat for nationally listed species such as Macquarie Perch and Murray Cod and contains large areas of intact riparian vegetation. The Upper Murrumbidgee is also listed on the Register of the National Estate due to the presence of Trout Cod and the critical habitat required to support the species.

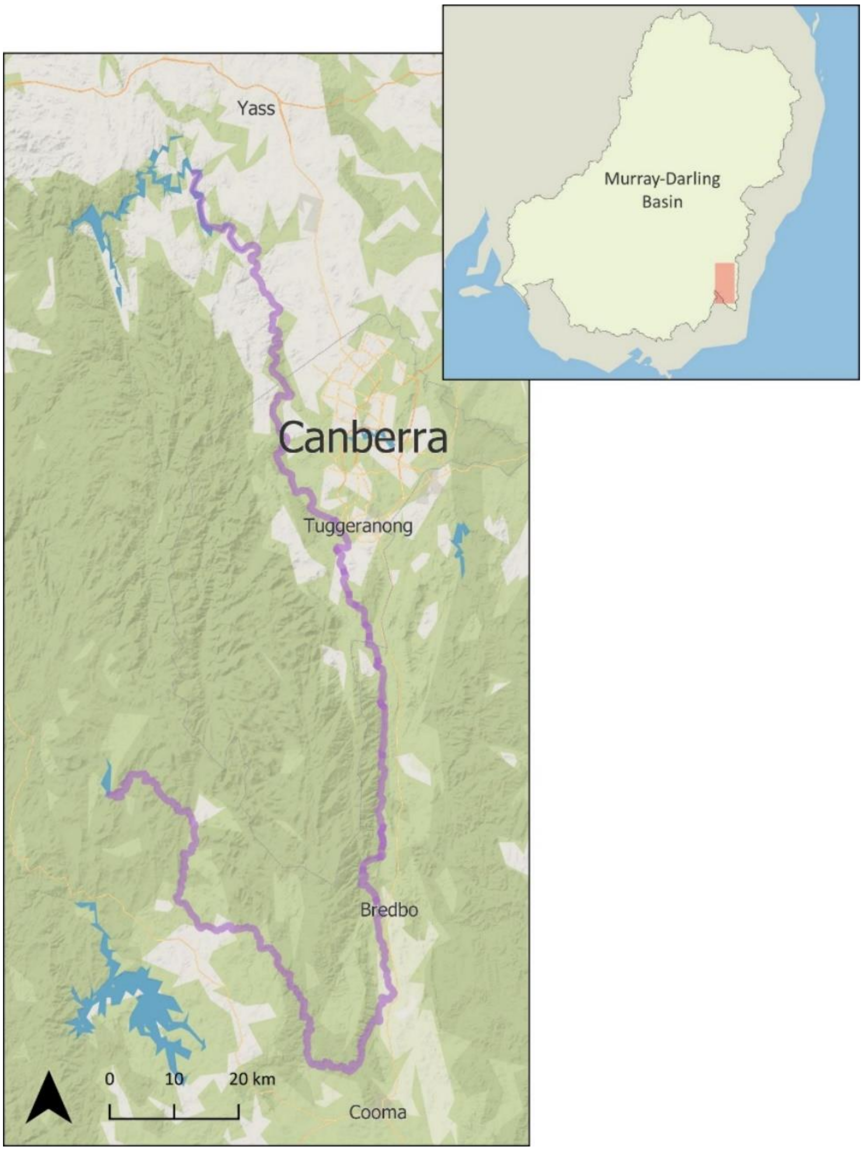


Figure 1. Location of the study reach for this project - highlighted in purple

Previous work carried out by the UMDR investigated options to improve channel connectivity for fish habitat and recommended the use of engineered log jams (ELJs) in the worst affected areas of the Murrumbidgee River. These have been implemented at Tharwa where a series of rock groynes and two groups of paired log jams were installed and at Bumbalong where woody weed control, installation of bank habitat structures and riparian and instream planting has occurred.

These interventions have had varying degrees of success. It has been observed that the most successful interventions were costly and required a high level of constructor expertise, making it difficult to implement the program over a large area with the involvement of the local community. Additionally, intervention options have been specifically focussed on channel forming, however monitoring of structures over time has seen that there have been a number of associated instream responses such as establishment of reed beds which have provided additional ecological benefit in target reaches.

In response to this, this project will review the current evidence around improving fish habitat and ecological functioning in sand affected streams. A key consideration will be to look at options that are low cost and low tech, potentially allowing local communities to be involved in their implementation.

1.2 Project scope

The aim of this project is to conduct a review of lower-cost and lower-tech fish habitat restoration options for sand affected river reaches that are applicable to the Upper Murrumbidgee River. As outlined in the Statement of Requirements for this project, the literature review considers:

- channel deepening and instream connectivity to facilitate fish passage,
- improved habitat availability and complexity,
- reduced water temperatures, and
- improved aquatic productivity and ecological functioning.

As a desired outcome of this project is to support and improve native fish populations present in the Upper Murrumbidgee River, the review also focuses on reviewing evidence to understand how different intervention options may impact on key fish species. Additionally, there is an emphasis on intervention options that have the most applicability to upland river conditions and to consider the differing scale and extent of the sand deposits to ensure that options are suitable for a range of conditions across the UMDR's focus reach of the Upper Murrumbidgee River. The potential to include community groups in river restoration activities is also highly desirable.

2 Biophysical setting and processes

2.1 Catchment setting

The Murrumbidgee is a major tributary of the Murray River and is the second longest river in Australia. It rises in the Snowy Mountains and flows over 1400 km through NSW and the ACT to its confluence with the Murray River between Swan Hill and Mildura. The catchment of the Murrumbidgee covers an area of approximately 84,000 km² or around 8% of the Murray Darling Basin (MDBA, 2021) and is divided into three distinct geomorphic zones. The upper catchment, and subject of this review, is characterised by mountainous terrain with cleared valley bottoms that are deeply incised. In this upper part of the catchment, the river is mostly confined between steep hillslopes and floodplains that are less than 500m wide. The predominant land use in the upper catchment is grazing although the steepest areas still maintain a good cover of native vegetation (Olley and Scott 2002).

The geology of the Murrumbidgee is complex, and the river crosses many different geologic units along its length (Figure 2). The river rises in the upper catchment on sedimentary and extrusive deposits of the Silurian and Devonian rock before flowing in a south-easterly direction across the shales and sandstone of the Ordovician and granitic intrusions of the Devonian. As the river turns northward, it flows across sedimentary and volcanic deposits of the Silurian before turning west. Flowing to the west, the river crosses both sedimentary and volcanic deposits of the Devonian, Silurian and Ordovician periods. Downstream from Wagga Wagga, the Murrumbidgee flows through quaternary alluvium with Devonian granite and Ordovician sedimentary outcrops before it enters the riverine plain. During the Pliocene, uplift in the eastern part of the catchment changed the nature of sediments delivered to the lower catchment from marine and lacustrine to fluvial (Schumm, 1968).

The geology of the Upper Murrumbidgee River catchment is principally Ordovician-Lower Devonian volcanics. Much of the rock is granite, which typically produces sand-sized bedload in river systems. From Bredbo, the river runs north along a straight course as it flows close to the Murrumbidgee fault. To the east lie the Ordovician sedimentary and acid volcanic rocks of the Monaro Slope and Basin. From Tharwa to Burrinjuck the river flows through the Silurian acid volcanics of the Yass-Canberra Rise (Lintermans, 2001).

The climate varies greatly across the catchment with hot, dry summers and cool, moist winters on the plains downstream of Narrandera where average annual rainfall is around 300 mm, and cool summer with cold, wet winters in the alps of the Snowy Mountains, where average annual rainfall is approximately 1600 mm (Olley and Scott 2002; Schumm 1968). Despite significant annual rainfall in the upper catchment, the hydrology of the system has been greatly altered through flow regulation as part of the Snowy Mountains Scheme where 96% of the headwaters of the Upper Murrumbidgee River are diverted at Tantangara Dam. As a result, the average period between high flow events having doubled and the maximum period between events having tripled (GHD, 2011a).

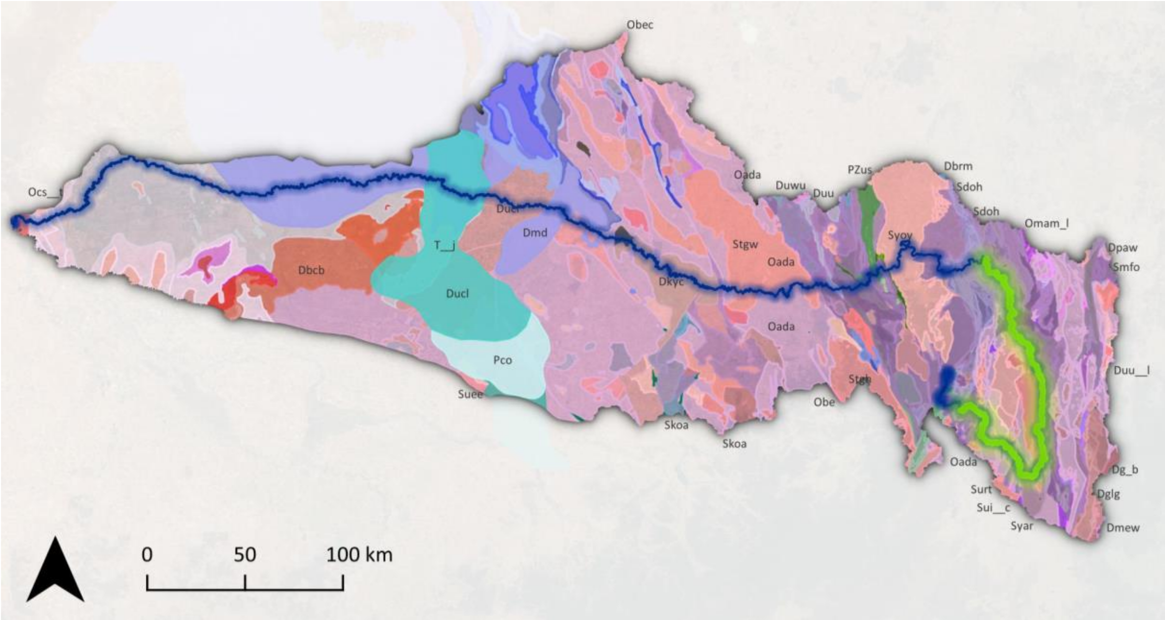


Figure 2. Geology of the Murrumbidgee catchment. Pinks and purples show the various geological units of the Lachlan Orogen (210 to 1800 Ma), blues show the geological units of the Western Devonian Basins and aqua shows the geological units of the Permian-Triassic Basins. The study reach for this project is highlight in green.

2.2 Catchment history

The physical characteristics of the Murrumbidgee catchment have changed significantly since European settlement. Historical accounts describe heavily vegetated hills, headwater reaches with deep alluvium and well vegetated shallow valley floor depressions in the upper catchment, a pebble and gravel bed river with sandy well vegetated banks between Yass and Wagga Wagga and a sandy river with clear water downstream of Wagga Wagga (GHD, 2011a). The first Europeans arrived in the catchment in the 1820s and began dramatically changing the landscape. Before the end of the 1820s sheep and cattle grazing were occurring in the catchment as well as cereal cropping and horticulture. The early years of settlement in the catchment saw a drastic increase in stock numbers which led to significant clearing of native vegetation (Olley and Scott 2002).

Considerable landscape degradation is thought to have occurred in the period between 1830 and 1850 as clearing for agriculture and an extended dry period contributed to increases in rates of hillslope erosion as a result of the loss in vegetative cover (Olley and Scott 2002). The first records of gullying in the catchment were recorded by the 1870s and by the 1900s many gully networks were already well established, although aerial photography reveals little change in gully dimensions since the 1940s. It is believed that large flood events in 1852 and 1860 contributed to channel incision and the initiation of many gully networks (Olley and Scott 2002; Olley and Wasson, 2003). More recently patterns of fire and flood, notably the 2019-2020 bushfires and storms, have provided a significant sources of fine sediment and sand through runoff and erosion from fire affected catchments.

2.3 Catchment hydrology

The upper Murrumbidgee catchment covers an area of 10,500 km² upstream of Burrinjuck Reservoir (Olly and Wasson, 2003; GHD, 2011a). The hydrology of the Upper Murrumbidgee River has changed over the last 180 years in three main ways; multi-decadal changes in rainfall, changes in land use, affecting runoff patterns and river flows being altered by the presence of dams (Olley and Wasson 2003). Tantangara Dam, located in the headwaters of the Murrumbidgee was constructed in the 1960s and has a substantial impact on the hydrology of the UMDR. Tantangara Dam at one time diverted

99.6% of the average natural flows from the catchment to Lake Eucumbene and the Snowy Hydro Scheme (Pendlebury *et al.*, 1997), although this is now reportedly 96% of the average natural flows (Antia Brademann pers comm.). Passing base flows of up to 32ML/d are provided at Mittigang Crossing, however when this is provided by tributary inflows, releases are ceased. The Snowy Montane Rivers Increased Flows Initiative has been implemented to reduce these effects and returns up to 1,026 GL annually into the Murrumbidgee system although return flows are constrained by the outlet capacity of the dam (1500ML/d), the availability of water and the requirement to set releases in advance of the water year (CSIRO, 2008; Office of Environment and Heritage, 2018).

The Snowy Hydro Scheme (SHS) has meant major changes in hydrology for the Upper Murrumbidgee. The main characteristics of the post-SHS flow regime as inferred for the Murrumbidgee River at Mittagang Crossing by comparing flow analyses for 1926-1960 with 1961-1995 (Pendlebury *et al.*, 1997) are:

- Retention of seasonal pattern with winter-spring peak but considerably reduced.
- A four-fold reduction in the occurrence of higher flows; flows exceeding 2000 ML/day occur approximately 5% of the time (compared with approximately 20% of the time pre-SHS).
- Fewer flow events of all sizes, but particularly the largest events (volumes greater than 60 GL) which occurred 9 times in 1961-1995 compared with 39 times in 1926-1960; for this, an event is defined as a peak of 2500 ML/day lasting at least 2 days and a minimum of 1250 ML/day.
- Very few flood events with sustained duration: only 5 events lasting 30 days and 20 events lasting 10 days (compared with over 30 and over 70 such events pre-SHS).
- Reduced base-flows in all seasons but particularly in winter, with 95%iles for August and September being only 190 and 280 ML/day (compared with 420 and 520 ML/day pre-SHS).

2.4 Geomorphology

Evidence for the pre-disturbance geomorphic condition of the Upper Murrumbidgee River is limited to anecdotal accounts of early settlers which described the reach around Lanyon as consisting of “large, deep holes, between which the stream flowed gently over gravel bed during normal summer flow” (Lintermans, 2004a). Reports suggest that significant change in geomorphic form occurred in this reach after a large flood event in 1852 which saw the channel double in width, banks steepen, riparian vegetation wash away and the gravel bed disappear. This period was reportedly the beginning of excess sand deposits in the reach which continued with subsequent flood events (Lintermans, 2004a).

A geomorphic investigation of the study reach was undertaken in 1999 (AWT and Fluvial Systems, 1999). The investigation was undertaken along the reach in the Upper Murrumbidgee River between Bredbo (in NSW) and Casuarina Sands (in the ACT). In 2018 the UMDR focus reach was established to include the Upper Murrumbidgee River between Tantangara and Burrinjuck dams. The investigation divided the river into two main geomorphic reaches; the Tharwa Reach from just upstream of the Tharwa Bridge to the upper end of a bedrock rapid upstream of Lanyon and the Lanyon to Point Hut Crossing Reach. Geomorphic descriptions at the time of the investigation are summarised below.

Tharwa Reach

The Tharwa Reach, particularly between Tharwa and Lanyon was found to be sand affected with a flat, featureless, sandy bed. In this reach the river was described as between 30 and 60 m wide, straight with a flat, sandy channel which is crossed by a shallow, sinuous thalweg. This reach was described as a depositional zone, receiving sand from the Billilingra Gorge, and as such, bed slope decreases, and sandy bars have developed filling in pools. Banks have been known to be susceptible to undercutting and slumping resulting in channel widening. Aerial imagery analysis, using photos from as early as 1944 has shown that there has been little planform change in this reach however the low flow channel has been observed to migrate across the flat, sandy bed. An analysis of sediment depths and volumes was also undertaken which found that the greatest depth of sediment occurred between Tharwa and Lanyon where the average depth was between 2.3 and 2.9 m. The analysis also demonstrated that the volume of sand within the reach had increased with 0.71 million m^3 calculated in 1971 and 1.1 million m^3 calculated in 1999 (Lintermans, 2004a).

Lanyon to Point Hut Crossing Reach

At the time of the investigation, the Lanyon to Point Hut Crossing Reach was characterised by steep, rocky rapids and sandbars with deep pools. The channel was described as sinuous and wide (up to 130 m) which has been attributed to broad, sandy point bars. The reach has also been characterised by rock outcrops which form rapids and break up sandy sections of the reach. Deep pools (2-4 m) were common at the time of the investigation in the section downstream of Lambrigg (Lintermans, 2004a).

The UMDR focus reach has also previously been classified according to the RiverStyles Framework (Brierley and Fryirs, 2005) and largely comprises three RiverStyles (Figure 3) GHD (2011a) described the three key River Styles as follows:

- Gorge - Gorges are characterised by a single, symmetrical channel in bedrock confined, irregular V or U-shaped valley. Channel geometry and sinuosity is valley controlled. Bed and banks are dominantly composed of bedrock and boulders and floodplains are absent. These are geomorphically stable reaches that are subject to very slow rates of change due to the high degree of bedrock confinement. The relatively steep gradients and high degree of valley confinement generate high-energy flows which throughput sediment over short to moderate timeframes.
- Floodplain Pockets, Sand - This style occurs in confined valleys and the channel is not free to migrate laterally. The channel may slowly erode the valley wall if it is not composed of bedrock. Occasional floodplain pockets are associated with tributary confluences or short reaches of localised valley widening. The relatively steep gradients and high degree of valley confinement generate high-energy flows which throughput sediment over short to moderate timeframes.
- Bedrock Controlled Sand Bed River with Discontinuous Floodplains - This type of river is associated with a relatively high degree of bedrock control that imparts considerable lateral and vertical stability on the channel. Hence, in response to disturbance, the channel is largely limited to expansion and contraction processes. Sediments are generally throughput over the long term with temporal storage in floodplain deposits. Sediments may accumulate if upstream reaches are disturbed, resulting in pool infilling and a less diverse bed character.

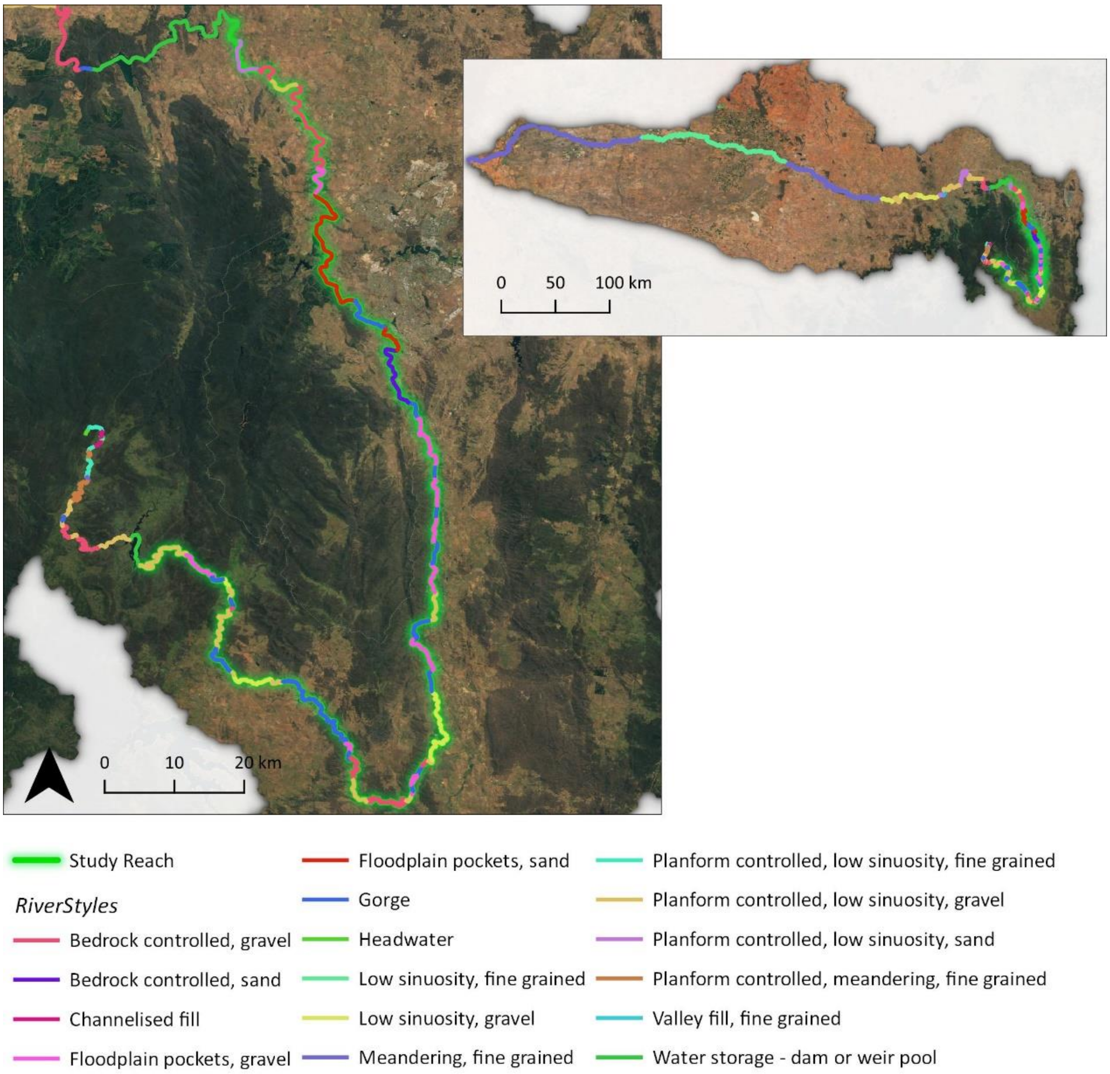


Figure 3. Mapped RiverStyles for the UMDR (left) and the entire Murrumbidgee River (right)

GHD (2011a) undertook a qualitative assessment of sand affected reaches in the UMDR (as per the focus reach area prior to 2018). The assessment used aerial imagery to divide the UMDR into reaches based on the observable amount of instream sediment storage (Figure 4). Reaches were classified according to the following categories:

- Negligible – reach exhibits none or limited mobile deposits (e.g., small bank attached bars) and the impact of sedimentation on channel form is negligible.
- Minor – reach exhibits occasional mobile deposits, however, significant fish habitat in the form of deep linked pools is still maintained throughout the reach.
- Moderate – pools are still maintained; however, the degree of sedimentation means that fish passage between pools at low flows is restricted.
- Major – the entire channel bed is essentially a sand sheet such that no deep pools are present.

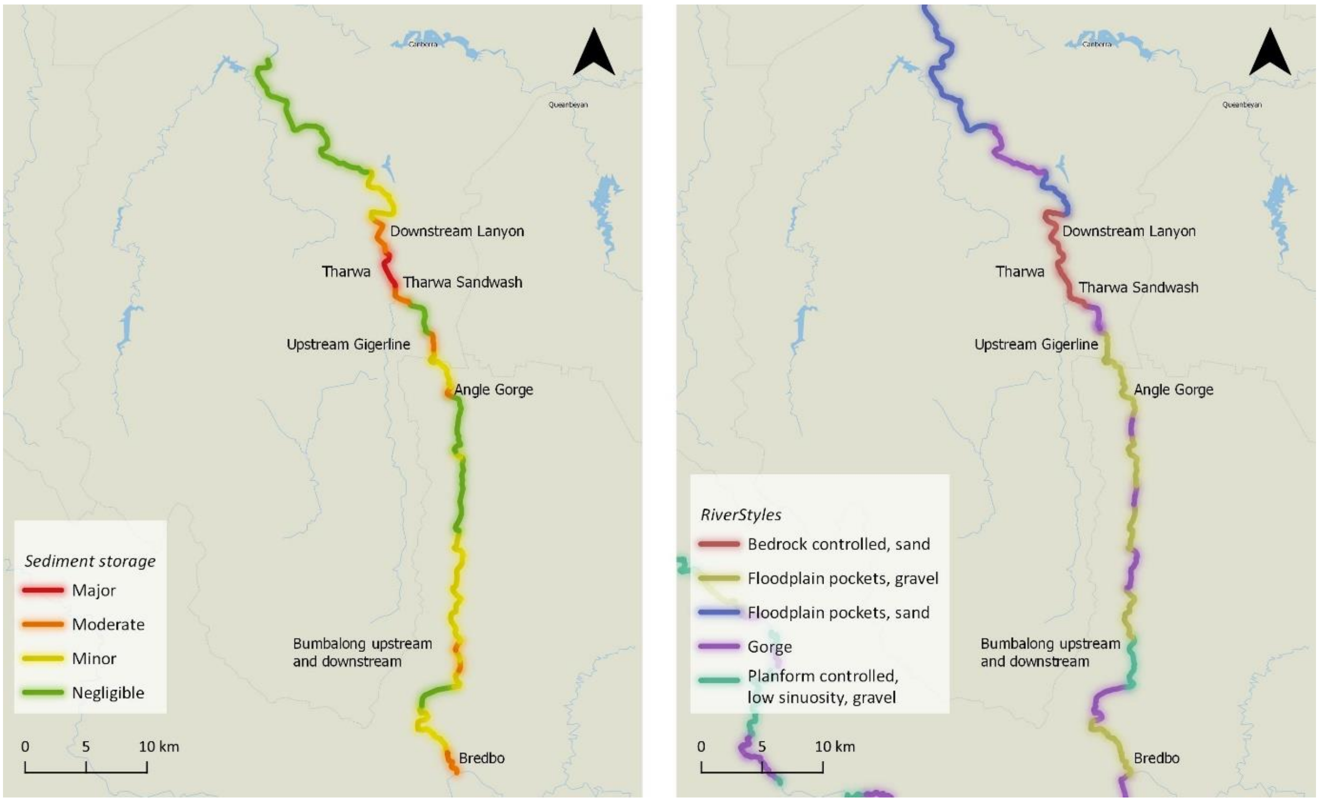


Figure 4. Sediment storage within the UMDR (adapted from GHD 2011a -left) compared with mapped RiverStyles (right)

Based on this assessment, the majority of the UMDR was found to have a negligible or minor degree of sediment storage, seven separate reaches totalling 15 km had a moderate degree of sediment storage while one reach totalling 4.3 km was considered to exhibit a high degree of sediment storage (GHD, 2011a). Of the reaches assessed in the UMDR, the reach at Tharwa was found to be the most sand affected with the greatest opportunity for rehabilitation activities. The reaches with the highest volume of sediment storage are correlated with less confined RiverStyles, with the most sand affected reaches found in the bedrock controlled, sand reach and other significant sediment storage reaches found in the floodplain pockets, gravel reaches.

Site inspections 2021

In October 2021, a site inspection was undertaken at selected locations along the UMDR to understand the current condition of the study reach. Sites were visited at the confluence of the Bredbo River and the Murrumbidgee, around Bumbalong, at Gigerline and Tharwa (Figure 5). Key observations from the site visits are summarised below.

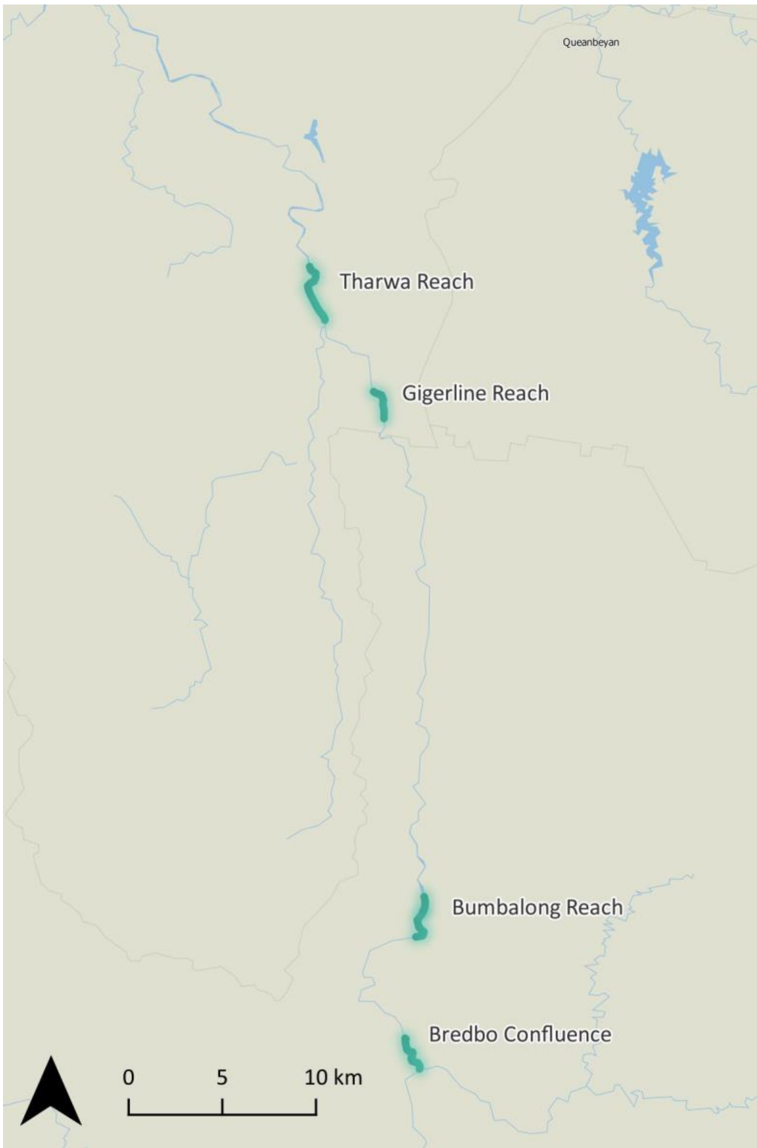


Figure 5. Locations visited during site inspections in October 2021 are highlighted in green

Key tributary source of sand: Bredbo River

The Bredbo River is one of the key tributary sources of sediment in the UMDR. Inputs from the Bredbo River tend to be dominated by larger sand and smaller gravel substrate types (

Figure 7). Upstream of the confluence with the Bredbo River, the Murrumbidgee River is relatively narrow (<50m), but immediately downstream of the confluence the channel widens to ~90m. Riparian cover is lacking, and mostly in the form of sparse shrubs and some willows. Under low flows, it is likely that this section would act as a barrier to upstream fish movement, because of its lack of depth or flow refuge. Impacts of the sedimentation are seen for the next 4 km, with much of that reach heavily sand affected. There is an absence of riparian vegetation in many areas along the reach and instream wood loads are low.

Figure 6. Drone image of the confluence of the Murrumbidgee River (top of image) and the Bredbo River, showing the abundance of sand being delivered by the Bredbo River to the Murrumbidgee River. The white arrow shows the direction of the flow (Photo: Hugh Allen)

Figure 7. Typical composition of the bedload of the Bredbo River at the confluence with the Murrumbidgee River (Photo: Ben Broadhurst)

Key sand affected reach: Tharwa

The 4.3 km Tharwa reach is the most sand affected reach in the UMDR (GHD 2011a). The Murrumbidgee River here is between 40 - 90 m wide and has varying riparian condition, though generally at least some vegetation present. Sediments here are typically sand to small gravel (Figure 9). Despite the high level of sedimentation, the channel still shows some depth diversity with shallow, uniform areas over sand waves and with a deeper thalweg and deeper areas adjacent to constructed features such as the engineered log jams, and the rock groynes. There is a general lack of hard substrate and very little in the way of edge cover for fish. During low and moderate flow, the channel in this reach diverges into several shallow braids and would present a significant barrier to upstream fish movement because of its extremely shallow and featureless nature, and general lack of cover from predation or refugee from warmer water temperatures in summer.

Figure 8. Tharwa reach of the Murrumbidgee River looking downstream towards the engineered log jams. (Photo: Hugh Allen)

Figure 9. Typical composition of the bed load of the Tharwa reach of the Murrumbidgee River (Photo: Ben Broadhurst)

Less-sand affected reaches

The reaches at Bumbalong and Gigerline are less sand affected than those at Tharwa. The reach at Bumbalong is much deeper than other reaches and there is some diversity with deeper pools and a deep thalweg (Figures 10). There are intermittent sand bars within the channel that are starting to be colonised with vegetation. Although the reach is much less sand affected than others such as the Tharwa reach, there still remains a lack of habitat diversity. Riparian vegetation along the reach is very limited with little overhanging or instream vegetation. There is also an absence on large wood within the reach.

Figures 10a and b. The Bumbalong Reach which has some depth diversity with deeper pools and some instream sand bars. There is little habitat diversity through this reach however, with no riparian zone and no large, instream wood.

The Gigerline Reach is mapped as gorge using the RiverStyles Framework and like the Bumbalong Reach shows minor impacts of sedimentation compared with other reaches. Through this reach, there is some depth diversity with deeper areas as well as some shallow areas where sand has been deposited however, overall, large sand bars and benches are not present. Bed load sediments in this reach are also different than in sand affected reaches. In the Tharwa Reach for example, bed load sediments range from sand to small gravel while in the Gigerline Reach, bed load sediments are predominately coarse gravel with most sand sediments likely to have been transported downstream due the higher energy environment within the gorge. (Figure 11). As with other reaches, riparian vegetation and instream large wood are lacking.

Figure 12. Aerial view of the Gigerline reach. A small sandbar can be seen in the mid-ground but in general the reach has few sand bars and benches.

Figure 11. Bed load sediments from the Gigerline Reach which are predominately coarse gravels.

2.5 Ecology

The Upper Murrumbidgee River and tributaries are home to 10 species of native fish (Lintermans 2002; GHD 2011; University of Canberra Unpublished data). Of conservation concern are Macquarie Perch (*Macquaria australasica*), Trout Cod (*Maccullochella macquariensis*), Murray Cod (*Maccullochella peelii peelii*), Stocky Galaxias *(Galaxias tantangara)* and Silver Perch (*Bidyanus*

bidyanus) species which are nationally threatened, and Two-spined Blackfish (*Gadopsis bispinosus*) which is threatened at the state/territory level. The population of Macquarie Perch in the upper Murrumbidgee is of utmost importance, as it represents one of the strongest remnant riverine populations of this species remaining. Although vagrants appear further downstream, the current strong hold of this population in the upper Murrumbidgee is between Tantangara Dam and the ACT border. There are historical records of Two-spined Blackfish in the Murrumbidgee River, but this species is now suspected to be largely confined to the Cotter River Catchment (a tributary of the Murrumbidgee River), apart from a small population in the headwaters of the Murrumbidgee River above Cooma (Lintermans, 2002). Historical records suggest that Trout Cod were present in the upper Murrumbidgee, but this population now is likely supported by a stocking program. Silver Perch were once common in the lower upper Murrumbidgee but are now extremely rare and are likely stocked individuals. Murray Cod are common and widespread throughout the lower end of the upper Murrumbidgee, though recent expansion past Gigerline Gorge (near the ACT / NSW border) is suspected to be attributed to translocations and stocking upstream. Mountain Galaxias (*Galaxias olidus*) is a small bodied species that would likely have been prolific and widespread through the upper Murrumbidgee but is now restricted to stretches of river with low abundances of introduced trout (either above barriers, or areas where thermal tolerances are exceeded for trout). Golden Perch (*Macquaria ambigua*), Australian Smelt (*Retropinna semoni*) and Western Carp Gudgeon (*Hypseleotris klunzingeri*) are common and widespread in the upper Murrumbidgee, particularly in the lower reaches.

The Upper Murrumbidgee River is also home to two species of native aquatic mammals, Platypus (*Ornithorhynchus anatinus*) and Rakali or Water Rat (*Hydromys chrysogaster*), which are both commonly sighted along the reach. Other large-bodied aquatic animals present in the upper Murrumbidgee are the Eastern Long-necked Turtle (*Chelodina longicollis*), and several species of decapod crustaceans including Murray Crayfish (*Euastacus armatus*) which is listed as threatened in the ACT and Yabbies (*Cherax destructor*).

The upper Murrumbidgee is also home to seven species of alien fish. European Carp (*Cyrpinus carpio*), Eastern Gambusia (*Gambusia holbrooki*), Oriental Weatherloach (*Misgurnus anguillicaudatus*) and Goldfish (Carassius auratus) are common and widespread throughout the UMDR. Once more widespread, the two salmonid species (Rainbow Trout *Onchorhynchus mykiss* and Brown Trout *Salmo trutta*) are largely restricted to the upper section of the upper Murrumbidgee, where river temperatures are cooler. Redfin Perch (*Perca fluviatis*) are currently restricted to the lower section of Upper Murrumbidgee River, though, some upstream expansion of this species has recently been detected (ACT Government unpublished data).

Table 1 summarises the key habitat requirements of specific fish species present in the Upper Murrumbidgee River along with threats to these species. Most species require depth diversity in the channel with deep pools between shallower sections and sufficient depth to allow connectivity between these deep pools at specific life stages. The presence of wood in the channel assists in providing cover and habitat for spawning.

Table 1. Conservation status, distribution, key habitat requirements and key threats of threatened native fish species in the Upper Murrumbidgee River

Species	Conservation status and current distribution in the UMDR	Key habitat / life history requirements relevant to UMDR	Key threats in UMDR
Macquarie Perch ***Macqauria australasica***	Endangered (EPBC, IUCN, NSW, ACT) Once widespread through the UMDR. Population stronghold currently between Tantangara Dam and ACT Border, though some rare captures in the ACT. Strong population in the Cotter River.	Access to clean cobble riffles for spawning Deep holes (> 2 m) with cover (predation refuge, staging for spawning) Connectivity for spawning migrations Good water quality for visual feeding	Sedimentation Disease (EHNV) River regulation Interactions with alien species Habitat modification (clearing of riparian vegetation, loss of instream structure)
Trout Cod ***Maccullochella macquariensis***	Endangered (EPBC NSW, ACT), vulnerable (IUCN) Historically present throughout, rare captures along the reach, with stocking likely contributing to the bulk of recent recruitment in the upper Murrumbidgee. Stocked Trout Cod have been found to interbreed with Murray Cod in the reach.	Deep holes (> 2 m) with cover (structural woody habitat, rock, undercut banks) Connectivity (depth > 0.5m, some flow refuge and cover) Hard substrate to spawn on (e.g., wood, rock)	Sedimentation River regulation Habitat modification (clearing of riparian vegetation)
Murray Cod ***Maccullochella peelii peelii***	Vulnerable (EPBC), Formerly restricted to the Murrumbidgee downstream of Gigerline gorge. Stocking suspected to have expanded the range upstream to at least Cooma.	Deep holes (> 2 m) with cover structural woody habitat, rock, undercut banks Connectivity (depth > 0.5m, some flow refuge and cover) Hard substrate to spawn on (e.g. wood, rock)	Sedimentation River regulation Overfishing Habitat modification (clearing of riparian vegetation)

Silver Perch ***Bidyanus bidyanus***	Critically endangered (EPBC), Endangered (ACT), Vulnerable (NSW) Currently extremely rare. Previously (before the 1990s) an upstream extension of the Burrinjuck reservoir population.	Deep holes (> 2 m) with cover structural woody habitat, rock, undercut banks) Connectivity for spawning migrations High spring \ summer flows to promote spawning activity	River regulation (disruption of migration and spawning behaviour) Introduced diseases
Two-spined Blackfish ***Gadopsis bispinosus***	Vulnerable (ACT) Likely historically present right along the upper Murrumbidgee and its tributaries. now confined to the Cotter River catchment and a small population in the Murrumbidgee River above Cooma.	Clear cobble boulder substrate with interstitial spaces for cover	Sedimentation Interactions with alien fish (trout / redfin)

2.6 Previous works

Previous general stream rehabilitation works have been undertaken within the upper Murrumbidgee, particularly within the Tharwa reach. In the early 2000s 15 rock deflectors were constructed downstream of the Tharwa bridge. The deflectors were constructed in three groups, spaced 50 metres apart with one group of 6 placed on the left bank at the upstream extent of the reach, another group of 5 placed on the right bank in middle of the reach and a final group of 6 placed on the left bank at the downstream end of the reach. In addition to these works, a pool was excavated on the outside of a river bend, and snags were re-introduced downstream of the third group of deflectors. The expectation was that the extracted pool would remain open due to secondary circulation in the bend. This proved not to be the case.

Post-construction monitoring of the interventions was undertaken and found that:

- Permanent scour holes developed and were maintained at the tip of the deflectors however, deflector spacing along the banks was too great because individual scour holes did not link up.
- Snags that were re-instated between deflectors were buried in sand because they were placed too far from the tip of the deflectors.
- Deflectors at the upstream end of the group were prone to become swamped with sand because of shifts in the position of the thalweg.
- The excavated pool was completely infilled with sand.

Figure 13. Previously installed engineered log jams (part of the 2011 GHD work) and an enlarged and realigned rock groyne (originally part of the early 2000s work) within the Tharwa Reach. (Photo: Hugh Allen).

In 2011, GHD (2011b) reviewed the feasibility of sand management options and proposed concepts for the reach at Tharwa. The investigation recommended the construction of two small, engineered log jams with rock abutments to be placed on the right bank in the upstream extent of the reach and tied in with the realigned and enlarged rock deflectors on the left bank. It also recommended the construction of a large, woody debris log jam to be placed on the right bank in the upstream extent of the reach which was complemented by additional logs and rock work to protect the existing deflectors. The implementation of these structures has had success however the limitations include the need for a high level of constructor expertise during construction and their expense and their limited spatial effect.

The installation of waterway structures in the Tharwa reach in 2000, 2013 and 2018 have had some definite positive impacts on channel heterogeneity by forming deeper sections of river, with slower flow velocities, and enough so to promote the inhabitancy of adult and juvenile Murray Cod at this site (Lintermans 2004; ACT Government unpublished data). Aerial imagery of the site from February 2021 shows that the impacts of these structures a relatively spatially restricted (< 150 m), with homogenous shallow sand habitat above and below the influences of these structures (Figure 14).

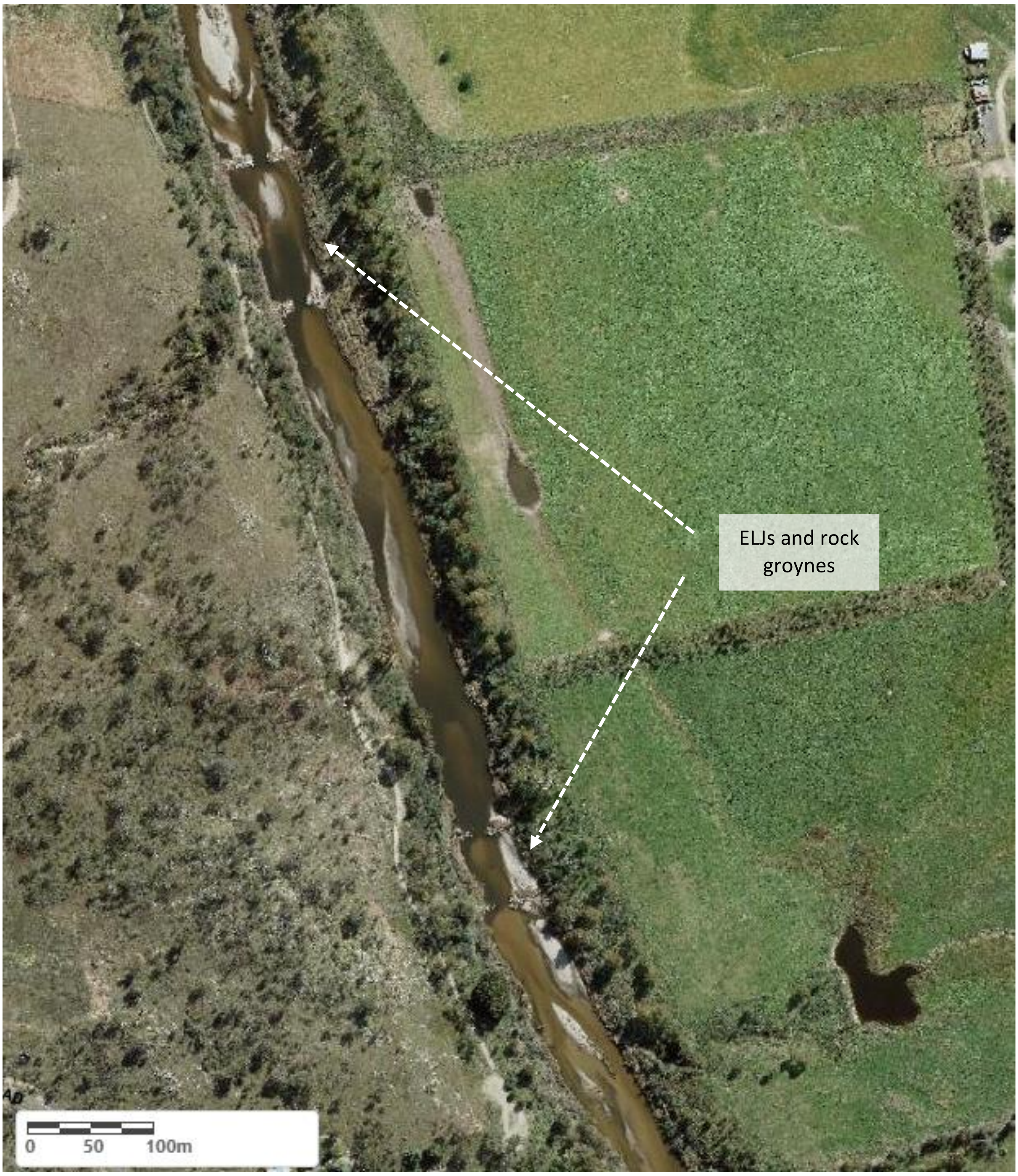


Figure 14. Aerial imagery of the Tharwa reach showing the 2013 engineered log jams, paired to enlarged rock groynes (bottom pair of structures) and the 2018 engineered log jams (top pair of structures) in February 2021 (Photo: ACT Government)

3 Sand slugs and sedimentation

3.1 Sources of excess sand

Excess sediment is delivered to the river channel from a variety of different anthropogenic activities and natural processes. Catchment disturbance is common to all these activities and processes and a primary driver is a change in land cover – i.e. a change in the cover of vegetation – which precipitates a geomorphic response (Fuller and Rutherfurd, 2010). Processes and activities associated with the delivery of excess sediment to waterways include gullying within the catchment and tributaries (Fuller and Rutherfurd, 2010), bushfires which increase sediment runoff and the likelihood of debris flows (Potter, 2005), increased rates of bank erosion (James, 2018), the removal of dams (Pizzuto, 2002) and mining activities (Bartley and Rutherfurd, 2005).

Within the upper Murrumbidgee system, the delivery of excess sediment to the river channel has been the result of three key factors; the introduction of grazing stock, historical variations in climate, and dam construction (Olley and Wasson 2003). The biggest contributor of excess sediment was the land cover changes associated with the introduction of grazing stock, which has altered sediment fluxes by a factor of more than 150 (Olley and Wasson 2003). Prior to European settlement, the headwaters of the Murrumbidgee consisted of well vegetated, valley floors which had a low susceptibility to erosion, even in 1-in-100-year flood events (Prosser and Slade, 1994). With the dramatic increase in stock numbers between from the 1820s – 1900s, much of the valley-floor vegetation cover was degraded making it susceptible to erosion (Olley and Wasson 2003). This early period of grazing within the catchment coincided with a period of lower than average rainfall that spanned the decades between 1830 and 1850 and is thought to have contributed to the degradation in land cover.

Changes in land cover led to extensive gullying within the catchment which was reported to be widespread by the 1870s, although gully dimensions have remained relatively consistent since the mid-1940s, indicating that sediment delivery through this means is largely an historical process (Olley and Scott 2002). In addition the development of gullies across the catchment, there are reports that channel widening has a occurred in larger tributaries as a result of local clearing and changes in the catchment discharge resulting from channelisation of the headwaters (Olley and Wasson 2003). Using gully density and assuming the present-day sediment delivery ratio at Burrinjuck, Olley and Wasson (2003) calculated a sediment delivery rate for the peak period of sediment delivery of 480,000 t $year^{-1}$ or 200 times the pre-European rate of sediment delivery.

Another factor which has contributed to the current sediment loads in the Murrumbidgee is changing channel discharge which has been altered in several ways. There have been three primary changes in discharge within the catchment; there have been multi-decadal changes in annual rainfall with mean annual rainfall since the mid-1940s higher than during the 45 years prior, there has been alterations to the patterns and volumes of catchment runoff because of channel extension and land cover degradation and there has been a significant change in river flows as a result of the construction of dams along the river totalling 500 GL of storage (Olley and Wasson 2003). After the initiation of gullies and extension of the channel network, sediment transport capacity varied with shifts between wet and dry periods. During wet periods, sediment transport capacity increased, however channel incision is also likely to have occurred with increased flow velocities, contributing even more sediment from incision, and widening processes. During dry periods, as discharge decreased so did transport capacity and instream sediment storage occurred which in some locations has been exacerbated by the construction of dams (Olley and Wasson 2003).

3.2 The effects of excess sand

There are several impacts associated with excess sand in a river system, which are briefly described below.

Loss of channel capacity and increased flooding

A major impact of sediment slugs is that they can reduce flow capacity of the channel. Once excess sediment is delivered to the river channel, it may be deposited instream in instances where flow is insufficient to transport the additional material (James 2010). As excess sediment is deposited, channel cross-sectional area decreases leading to a reduction in capacity and an increase overbank flood frequency and duration. This increase in flood risk is a common reason for active management of sand slugs in rivers (Sims and Rutherfurd, 2017).

Accelerated bank erosion

Streams with less resistant banks commonly widen in response to rapid bed aggradation which occurs because of excessive sediment inputs (i.e., sand slugs). Bartley (2001) summarises the large-scale impacts of sand slugs and found that in general, channels aggrade and widen, have a change in bed material, pools infill and channel roughness decreases.

Changes that occur to the morphology of a river when there is an increase in sediment load were first described by Schumm (1969). The analysis found that an increase in sediment load (without an increase in discharge) will result in channel widening, increase in meander wavelength and channel slope and a decrease in depth and sinuosity. If there is an increase in the percentage of bed material load and a subsequent decrease in mean annual discharge the channel depth and sinuosity will decrease and the gradient and width to depth ratio will increase.

Jackson and Beschta (1984) outlined how increased sand delivery alters the morphologic response and roughness of channels. Based on flume studies, they found that channel widening, combined with decreased average channel depth (from sand build-up) meant that overall channel stability is reduced.

Sims and Rutherfurd (2017) documented the following examples of this process occurring:

- When mining sediments filled the Ringarooma River in Tasmania, the channel widened by between 15 and 65% in upstream reaches (Bartley and Rutherfurd, 2005b), and by over 300% in downstream reaches (Knighton, 1987).
- A slug of sediment into Creightons Creek in SE Australia led to a 25% increase in channel width (Bartley and Rutherfurd, 2005a)

This process is also thought to be occurring in the Barmah-Millewa reach of the River Murray where a large-scale sand slug is present in the reach and bank erosion rates are increasing. An outcome of this accelerated bank erosion is the increasing loss of riparian vegetation and increased connection of flows with the floodplain as natural levees are eroded.

Loss of diversity and habitat

A more varied, or more complex, bed suggests an environment less dominated by mobile bed sediment. Sand is preferentially deposited in pools and shallow depressions on the streambed. As sand supply increases and pools and depressions are infilled, bed relief decreases, and the channel bed is smoothed. Sims and Rutherfurd (2017) found that excess sediment in a river will fill pools and smother bed features such as large wood and channel vegetation.

Hogg and Norris (1991) investigated the impact of sediment loads from land clearing and urban development on the macroinvertebrate pool fauna of the Murrumbidgee River. They found that sediment deposition on the bed was the major cause of reduced macroinvertebrate abundance.

Lintermans (2004b) noted that in the Upper Murrumbidgee River between Tharwa and Lanyon "sand has filled in the majority of holes with the consequent loss of former pool/riffle sequence. Sediment addition is a major threatening process for fish, particularly species which lay demersal eggs on substrate."

Gippel et al (2007) provides a useful summary of the relationships between geomorphic conditions and biodiversity. Key learnings included:

- Good geomorphic condition is associated with increased biological assemblages.
- Physical diversity and heterogeneity in streams correlate well with biological diversity, while streams impacted by sand slugs were less diverse than unimpacted reaches (Bartley and Rutherfurd, 2005).
- Reduced surface roughness and heterogeneity can in turn reduce species diversity, population abundance and recruitment. Primary producers such as periphyton and aquatic macrophytes are affected which is then reflected in the reduction in invertebrate and fish communities (Waters, 1995; Wood and Armitage, 1997).
- Covering the surface of coarse substrate by fine sediment deposition can lead to increased mortality of fish eggs, larvae and juveniles in gravel spawning species (Cordone and Kelley, 1961).
- Loss of pool habitat through sedimentation is also likely to have a detrimental effect on fish fauna because pools provide rearing habitat for many fish species (Waters, 1995).
- There are known strong links between the distribution and loading of large woody debris in streams and aspects of stream health (Gippel, 1995).

In a more recent discussion, Wohl (2015) also notes that:

- Enhanced sedimentation can result in lower channel and floodplain habitat diversity and stability, along with lower abundance and diversity of stream organisms.
- Excess sediment can alter water temperature, water chemistry, turbidity, and nutrient supply.
- A channel can have lower retention and resilience if sediment accumulation limits features such as riparian vegetation, hyporheic exchange, and physically complex channel boundaries.
- Excess sediment can also create effects that extend from the channel into the riparian zone and from the riparian zone into the terrestrial zone because of disruption of ecosystem subsidies such as emergent insects.

Large scale channel change (avulsion)

An avulsion is the term used to describe when a river changes its course and forms a new main channel on a floodplain. An avulsion occurs where the bed of the river tends to naturally fill up, until it is higher than some of the effluent channels. At this point a connection between the main channel and the new channel forms and most of the flow is captured by the new channel. The process is described in Figure 15 below, where the new channel is the 'daughter' channel. In sand affected rivers, the excess sand accelerates this natural process, leading to more rapid avulsions as the old channel infills more rapidly and diverts more flow out.

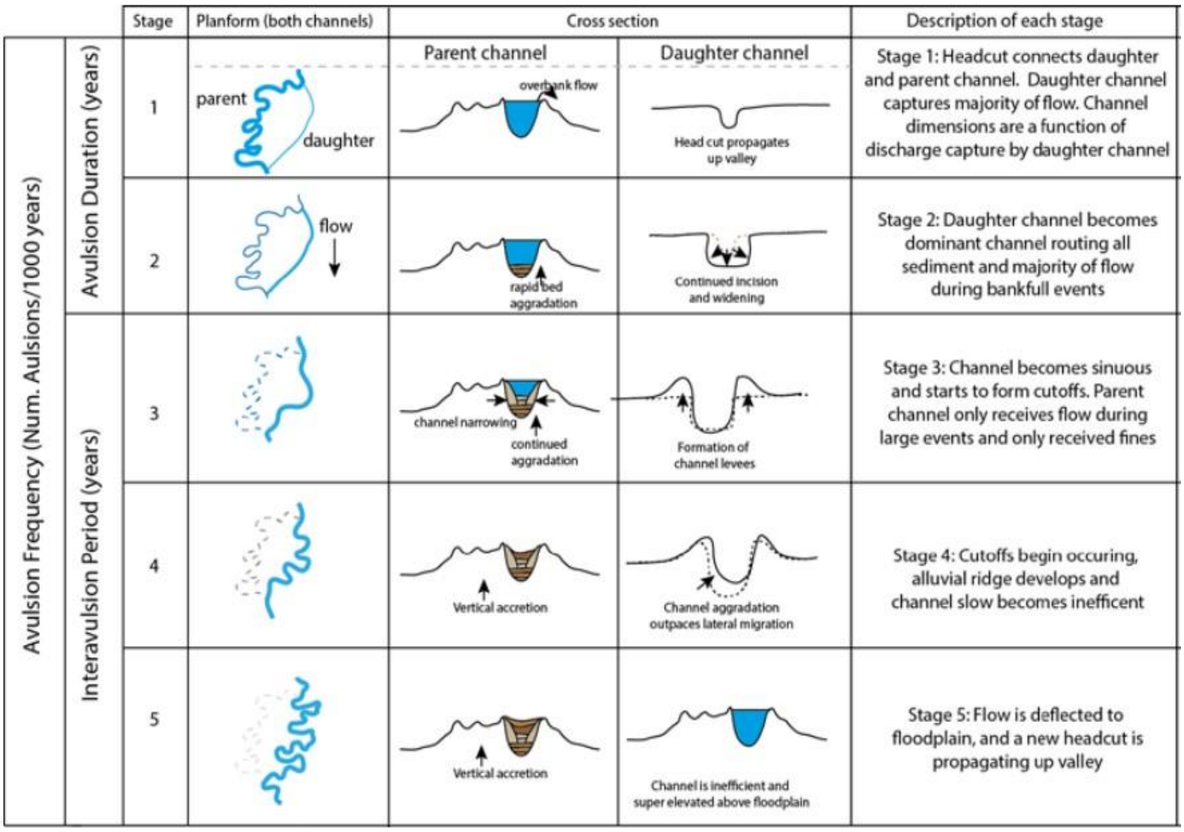


Figure 15. An adaptation of the five-stage model by Schumm et al. (1996) of avulsion development by Stout (2017).

Tributary Interactions

Sediment moving down a main channel or a tributary can have various impacts on the river system. If the sediment moves down the main channel it can block the tributary, resulting in a backwater lake which occurred in the lower Ringarooma River in Tasmania (Sims and Rutherfurd, 2017). Sediment slugs moving down a tributary can also block the main channel. There are several examples of this process occurring on the Glenelg River in Western Victoria (Brizga *et al.*, 2003; Sims and Rutherfurd, 2021).

4 Options for managing sand and enhance habitat values for fish

4.1 Overview

Options for managing excess sediment in affected waterways are commonly limited to four main categories within the literature: controlling the source, flushing sediment through a reach, storing it in a reach, and physically removing it. Interventions from these categories have been used in isolation but are commonly used in conjunction with each other. There are other waterway management options such as the installation of large wood and riparian or instream revegetation which are not necessarily used for managing excess sand but are used for habitat improvement.

The suitability of different options is dependent on the specific processes and morphology of the river as well as the specific goal of the intervention. For the UMDR the focus is on enhancing fish habitat through:

- Channel deepening and instream connectivity to facilitate fish passage,
- Improved habitat availability and complexity,
- Reduced water temperatures through deeper water sections,
- Improved aquatic productivity.

A summary of the options for managing sand identified in this review and their ability to influence fish habitat is provided in Table 2 and a more detailed description of these different options is outlined in the following sections.

Table 2. Summary of the intervention categories outlined in the literature and their links to habitat enhancement

Category	Description	Links to enhancing fish habitat
Controlling the source	Options that reduce or eliminate sediment supply at the source – either within the main channel, within tributaries, or from the catchment itself. It could also be controlling sediment inputs from one reach to another. This can include stabilising of streambank erosion sites or catchment sediment control works.	Reducing fine sediment inputs which limits smothering and infilling of substrates. Reduced further build-up of sand in depositional reaches. Provision of additional wood or structures to provide habitat areas.
Flush the sediment through the system	Options that encourage the increased transport of sediment through the system. This could comprise: - Implementing changes to the flow regime to enhance sediment transport through the reach. - Increasing overbank flows to move coarse sediment onto the floodplain for storage.	Assists in reducing the volume of sediment in a reach, with an overall deepening the channel to create better instream connectivity. Depending on how the sediment moves, there may be the formation of deep pools. Can provide flow triggers for spawning.
Storing the sediment	Trapping the excess sediment in the channel, which protects downstream reaches from high sediment loads. Includes use of in-channel structures, such as pile fields or revegetation of bars and benches, to stabilise and trap sediment in the reach and limit further transport downstream.	Limits excess sand moving into habitat areas downstream. Reduces mobile channel bed extent, allowing a deeper main channel(s) to form and improving instream connectivity.

	Preventing sediment entering the channel through catchment sediment control works.	
Hybrid interventions	This includes installation of large wood and revegetation of riparian areas.	Provides structural habitat for cover. Hard substrate for spawning. Reduction in water temperatures through shading, improvement in trophic inputs.
Physically removing the sand	Options that physically remove some or all the sediment from the bed of the channel. This can include local removal to create deeper water or removal at a large scale to progressively remove the excess sand from a reach.	Creates deeper pools or reaches. Can improve longitudinal connectivity. Reduces/controls sediment inputs/transfer between reaches.

4.2 Source control

Excess sediment in a river system can be associated with a point source (such as a landslide deposit, or specific sites of active bank erosion) or diffuse sources (such as the removal of vegetation because of land use change, or broader scale bank erosion). If the source of the sediment or the process driving the input stops then the sediment already in the waterway may migrate downstream and the process of recovery can commence. Sediment already within the channel (i.e., sand slugs) can be considered a 'source' for downstream reaches.

Diffuse source control

The current condition of the study reach is the result of a variety of historical factors including grazing during dry periods and droughts (Snowy Scientific Committee 2010). The contribution of sediment from gullying, headward erosion and channel incision has exceeded contributions arising because of climate variability and regulation. However, the formation and development of gullies within the Upper Murrumbidgee is historic, with little change in gully dimensions recorded since the mid-1940s (Olley and Scott 2002). While extension of most channels has ceased, there are reports that some channels continue to widen and migrate laterally, contributing ongoing sediment to the system (Olley and Scott 2002).

Diffuse sources of sediment such as those resulting from catchment clearing or bank and gully erosion can be addressed successfully through revegetation programs. For example, reforestation of gullies in the Waipaoa River in New Zealand reduced annual sediment yield from treated gullies by up to 62% (Sims and Rutherfurd, 2017). Riparian restoration has also been implemented in the Murrumbidgee catchment, at the downstream end of the study reach and including major and minor tributaries. The Riparian Restoration Program was implemented between 2000 and 2004 and included "one-off" restoration activities using one of four methods; fencing only, fencing and direct seeding, fencing and tube stock, fencing, direct seeding and tube stock (Higgisson *et al*., 2019). A 10-year evaluation of the works found that treated sites had better riparian vegetation condition than untreated sites and geomorphic condition of treated sites was significantly better than at untreated sites. The evaluation highlighted the benefits and key role stock exclusion played on geomorphic condition of sites (Higgisson *et al*., 2019) indicating that traditional waterway management activities have a role to play in reducing instream sediment loads. However, no instream recovery has been documented in the upper Murrumbidgee.

Potential locations for targeting diffuse sources of sediment in the upper Murrumbidgee have previously been identified by Wilkinson et al. (2004) who undertook a SedNet assessment of sediment budgets and vegetation in the upper catchment. With the objective of reducing sediment supply as the primary objective, reaches were mapped in three priority levels based on erosion hazard which incorporated stream power and the amount of erodible soil along the reach (Figure 16). Many of the reaches that are included in the current study area are prioritised high or moderate.

The benefits for fish of controlling diffuse sources of sediment inputs in reducing the volumes of sand being transported through the river, as well as capturing the finer sediment before it enters the waterways. These finer sediments tend to infill between coarser material and reduce spawning habitat.

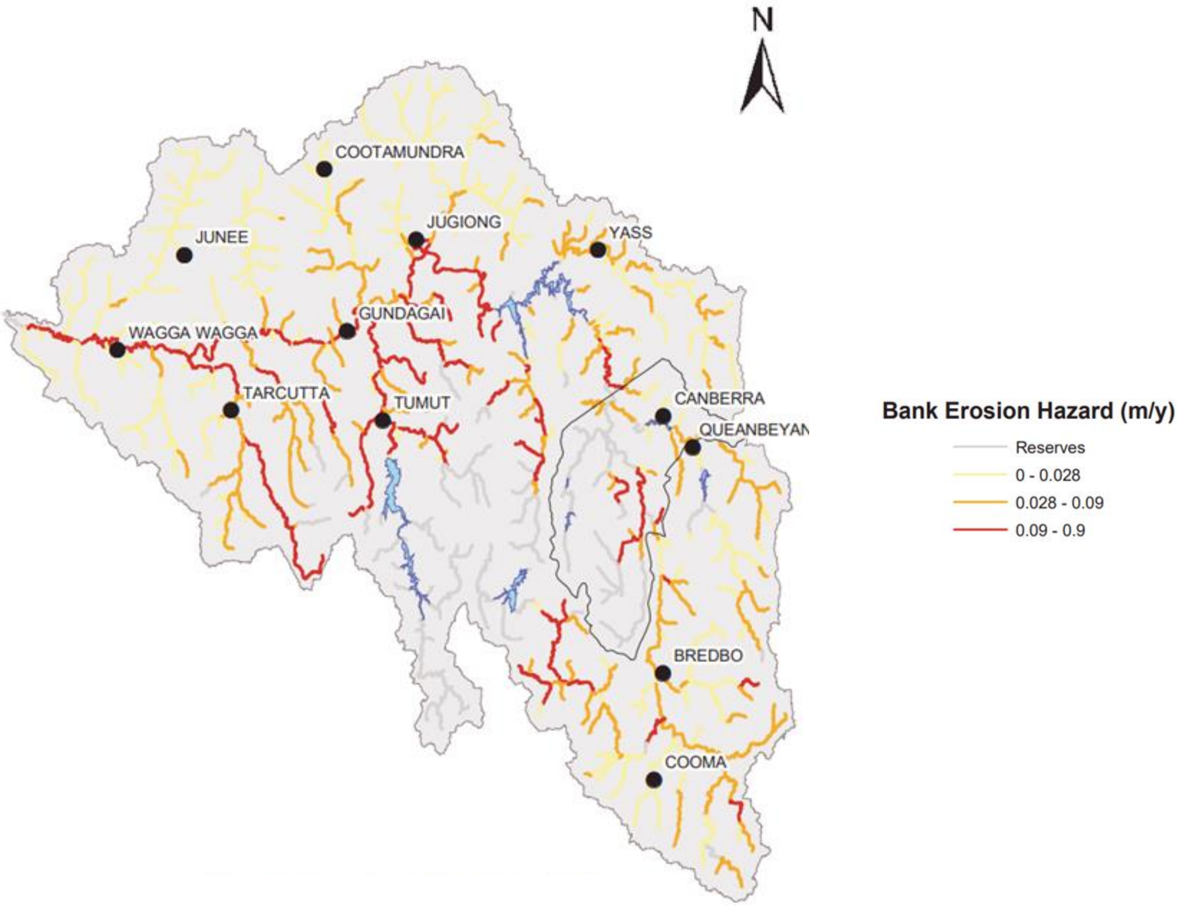


Figure 16. Priority levels for bank erosion control using bank erosion hazard (m/yr). Source: Wilkinson et al. (2004).

Point source control

Point sediment sources generally include things such as the sediment generated from dam removal or tailings deposition from mining (Sims and Rutherfurd, 2017), or sometimes localised erosion processes such as bank, gully or hillslope erosion associated with a specific location. The Actions for Clean Water Plan (Murrumbidgee Catchment Management Authority, 2012) report identified several sites of bank, gully, and bed erosion across the study reach.

In addition, bushfires within the catchment may also initiate the delivery of sediment to the channel, for example bushfires in 2019-2020 followed by a series of storm events led to the deposition of significant quantities of sediment in tributary gullies of the Murrumbidgee River at Bumbalong (Antia Brademann*, pers. comm*.). Common across south-eastern Australia, post-fire debris flows pose a significant threat to water quality and have serious implications for the supply of sediment to affected waterways. Debris flows are a hazard in catchments with a low, post-burn infiltration capacity, where there is widespread sheet erosion and rills on steep upper slopes and is correlated with fire severity (Nyman *et al.*, 2011, 2015). For this report, bushfires are considered a point source of sediment but due to the widespread extent of some fires they are sometimes considered a diffuse source of sediment.

The upper Murrumbidgee catchment was severely affected by bushfires in the 2019/20 summer, which was then followed by several rainfall events. The rainfall flushed ash, sand, and soil from the fresh fire ground into the waterways. The 2020 Catchment Health Indicator Program (CHIP) report includes a special fire report, describing the impact on the waterways and water quality in the Upper Murrumbidgee River following the bush fires. The fine ash can be particularly detrimental to fish habitat as it clogs the interstitial spaces between sediment on the bed of the river as well as smothering any instream vegetation.

Increasing frequency and severity of bushfires, associated with climate change will increase the risk of post-fire sediment delivery to waterways and options to mitigate this risk should be considered in the event of bushfire within the upper Murrumbidgee catchment. Options to limit the delivery of sediment to the channel post fire include:

- Hillslope treatments such as wood mulch, straw mulch and coir logs or bales. These methods add roughness resulting in more ponding of water and reducing the quantity and velocity of overland flow, reduce soil water repellence and increase surface cover reducing raindrop impact (Robichaud, Lewis, *et al.*, 2013; Robichaud, Wagenbrenner, *et al.*, 2013; (Morris, et al., 2008)).
- Sediment trapping interventions such as silt fencing, constructed log jams, debris barriers, road embankments and check dams which allow for sediment to be deposited prior to reaching the stream and reduce flow velocity (Verstraeten and Poesen, 2000).

Silt fencing (for both Diffuse and Point Source Sediment Control)

Silt fences are temporary, permeable geotextile barriers installed between star pickets or wooden posts. They are a common management intervention in the construction industry to prevent environmental damage and also in burnt landscapes to minimise the impacts of post-burn debris flows. Silt fencing works to prevent the transport of sediment in two ways (Melbourne Water, 2017);

1. Run-off velocity is slowed decreasing the ability for sediment to be transported in suspension which occurs through a damming effect behind the fencing.
2. Filtration of sediment from runoff as it passes through the silt fence.

Advantages of silt fencing include the low cost and ease of installation as well as their ability to treat large areas. In flume and controlled field studies, silt fencing has been shown to be quite effective at removing sediment from runoff and the USA EPA has shown that the following percentage fragments will be removed by well installed and maintained silt fences (Melbourne Water, 2017).

Table 3. Percentage sediment removal by silt fencing based on sediment size

Soil type	Percentage removal
Total suspended solids	70%
Sand	80-90%
Silt-loam	50-80%
Silt-clay-loam	0-20%

It is important to note that silt fencing is not considered an appropriate management option for areas where concentrated flow is a problem or in fine or dispersive soils where fences have no filtering capacity (Melbourne Water, 2017). Despite the findings of flume experiments, there remains little scientific basis for the efficacy of silt fencing in real world conditions – which have many variables including soil type and size, precipitation, slope and vegetation type – as demonstrated by the failure of many of these interventions to prevent sediment inputs to freshwater ecosystems (Cooke, *et al.* , 2015). Cooke et al. (2015) attributed most silt fence failures to either a lack of correct installation and the absence of regular monitoring and maintenance. They found a range of common issues with failed silt fencing which included mesh tearing, broken or bent support posts, material piled against fencing and insufficient fencing area.

Literature and case studies on the effectiveness of silt fencing in applied settings is sparse. Case studies examining the effectiveness of silt fencing have largely been assessed in the context of post-fire debris flow management. SA Water, SA Forestry and the South Australian Department of Environment and Heritage installed and evaluated the effectiveness of different types of sediment management techniques following a bushfire within the Mount Bold Reservoir in January 2007. Among the mitigation methods tested was a silt fence which was constructed with posts placed 3 m apart with jute matting and 1 cm galvanised bird netting. The fence was reinforced at each end and each post was attached to an additional upstream post. Evaluation of the fencing found that despite trapping up to 22 m^3, the fence failed in the mid-section and allowed a 15 m wide wash of water and material to be transported downslope of the fence. The agencies involved concluded that silt fencing may have been more successful if multiple fences were utilised, if finer mesh were installed and if fences were stronger, to withstand the volume and water and sediment washed from the hillslope (Morris *et al.*, 2008).

In the United States, Best Management Practices (BMPs) for forestry operations, which included silt fencing were evaluated by Wear et al. (2013). They examined three types of BMPs, adjacent to streams which included 1. Using logging slash, 2. Using straw mulch and grass seeding, 3. using straw mulch, grass seeding and installing a silt fence. Daily samples were collected both up and downstream of the interventions for a year and evaluated for total suspended solids (TSS). The results indicated that option 3 which included silt fencing resulted in an increase in TSS due the disturbance associated with installed the fence and they concluded that this option should not be considered adjacent to streambanks if alternatives exist.

In their Burned Area Emergency Response Catalog, the USDA Forest Service (2006) includes silt fences as an effective management intervention. However, it cautions that this technique is infrequently deployed by the Service because they need to be carefully installed, with the bottom on the fence properly anchored, require significant installation effort and constant maintenance to be effective.

Silt fencing can be an effective sediment control measure if deployed in the correct context. Silt fences would have the greatest impact in catchments where there is a significant source of hillslope generated runoff and erosion. They are only suited to treating erosion resulting from sheet flow and have not proven successful in instances where flow is concentrated. Silt fences have the highest level of effectiveness where sediments are coarse and provide little to no benefit in instances where soils are fine grained or dispersive. As already noted, care and attention must be paid to correct installation, monitoring and maintenance for silt fences to remain effective. Other considerations for successful deployment of silt fencing include post placement (maximum of 1 m spacing), reinforcement with wire mesh, tapering the ends of the fence in the upslope direction and maximum upstream slope length (guidance provided in Table 4) (Melbourne Water, 2017).

Table 4. Maximum slope length recommended above silt fencing based on slope gradient

Slope (V:H)	Maximum slope length (m)
1:2	15
1:3	25
1:4	40
1:5	50
Flatter than 1:5	60

4.3 Flushing sediment through

Increasing the sediment transport rate by increasing the flow velocities is an option to accelerate the movement of sediment through the system and reduce recovery time (Sims and Rutherfurd, 2017). This can be achieved through manipulation of the flow regime or through changing the in-channel flow conditions via the use of waterway structures to encourage an increase in sediment transport. However, an important consideration with this option is whether flushing sediment through will adversely impact downstream reaches.

Flow regime change

Using the flow regime to flush sediment through a river requires an increase in the flows above the critical threshold for sediment movement. Once this threshold is exceeded the sediment will be moved by the flow either in suspension or as bedload depending on the flow magnitude. Different types of sediment movement have different thresholds.

The use of flow regime change in the form of targeted environmental flows has previously been implemented in Australia to manage sand affected reaches of the Snowy River. Flow recommendations were made to reinstate channel forming flows which had been absent due to the regulation associated with the operation of SHS. A modest mean annual flood of 139 m^3/s was recommended to initiate scour and reverse the trend of channel contraction. While not sufficient to restore the system to a pre-disturbance state the flows allow for bedform maintenance the destratification of pools (Erskine *et al.*, 2017).

As outlined above in Section 2.3, the hydrology of the Upper Murrumbidgee has been significantly impacted by the development and operation of the SHS. During the environmental flow investigation for the Murrumbidgee, the Expert Panel found the Upper Murrumbidgee "was showing classic symptoms of chronic flow reduction with sediment in-filling, channel contraction, reduced habitat volume and diversity, and the development of a littoral and fringing perennial vegetation associated with stable flows. These symptoms were particularly well-developed in the river between Tantangara Dam and Murrell's Crossing" (Pendlebury *et al.*, 1997). A review of the adequacy of environmental flow deliveries compared with the recommendations for the system was undertaken and 2010 and found that both the maximum volume allocated to the environment and the rate of delivery has been less than recommended resulting in the compromising of some flow components; for example no summer baseflows were provided (Snowy Scientific Committee, 2010). The delivery of environmental flows has been limited by a variety of resource constraints including a number of dry years but at the time of the review was found to be inadequate for the maintenance and protection of environmental values (Snowy Scientific Committee, 2010).

Given the scale of sedimentation within the Upper Murrumbidgee and existing resource constraints, it is uncertain if a change to the flow regime alone would be sufficient to manage the sand affected reaches and improve habitat for fish. The reduction in flows associated the construction of instream storages such as the Tantangara Dam, has led to a significant reduction in channel forming flows which would need to be reinstated through environmental flow deliveries if sand is to be managed. Constraints on these deliveries were already noted in the 2010 review by the Snowy Scientific Committee who flagged the dry conditions as a risk to the delivery of the required level of environmental flows. Without the appropriate allocation to meet these recommendations and with expected climate related changes in rainfall and runoff, it is unlikely that there will be sufficient volumes of water to regularly implement channel forming flows although the report does not define what elements of the channel or bed material this relates to. In terms of bedload management for native fish, this would mean riffle maintenance (removal of fine sediment) for Macquarie Perch spawning (targeting the reach between Tantangara Dam and Numeralla River confluence), refuge pool maintenance and channel deepening for connectivity (throughout entire UMDR, but especially in the shallow sandy reaches from Bredbo River confluence to Burrinjuck Reservoir headwaters).

Furthermore, the location of the sand affected reaches in the Upper Murrumbidgee mean there are few options for increasing flows other than releases from Tantangara Dam, although releases from the dam could be used to supplement higher flows in tributaries to achieve higher flows in the Murrumbidgee.

If flow releases are to be used to attempt to move sediment in the UMDR, consideration of critical life stages of native fish must be made and any potential impacts on fish within the downstream reaches. Of particular concern would be spawning timing of Macquarie Perch, who lay demersal sticky eggs in riffles usually October - November (Cadwallader and Rogan, 1977; Tonkin *et al.*, 2010; Broadhurst et al. unpublished data). Although there would be some benefit from a pre-spawning scour of potential spawning sites as well as increased connectivity between individuals and habitats for Macquarie Perch, timing of any planned releases would have to be outside the key nursery time. Tonkin et al., (2017) found that recruitment of Macquarie Perch was lower during years with high discharge during the key egg development and early recruitment timing of Macquarie Perch. The mechanisms by which high discharge could affect recruitment include dislodging of eggs (e.g., Smith *et al.*, 2005) smothering of egg incubation sites with sediment (Milner *et al.*, 2003), displacement of early larvae (e.g., Simonson and Swenson, 1990), loss of critical nursery habitat (Freeman *et al.*, 2001) and high turbidity and water velocity which can impact negatively on early foraging success and survival of larvae (Piccolo *et al.*, 2008). These mechanisms are relevant to the early life-history characteristics of Macquarie Perch who deposit fertilised eggs in riffles to ensure maximum aeration and minimise the risk of eggs being smothered in sediment (Cadwallader and Rogan, 1977; Ingram *et al.*, 2000). A similar risk is posed to other nesting species Murray Cod and Trout Cod, which deposit eggs on a hard substrate (wood or rock), which is then guarded and maintained by the male until the larvae leave the nest and drift downstream. In lowland rivers, high water velocities associated with peaks in discharge during Murray Cod nesting (September – December) have been linked to low larval abundances, likely related to eggs being displaced from nests (Humphries *et al.,* 1999).

Waterway structures

In-stream structures that modify the flow conditions and enhance local sediment transport can take a variety of forms. GHD (2011a) have previously reviewed the use of deflectors and instream elements that can be used to provide local scour, create deeper pools and thereby improve instream habitat for aquatic fauna. A summary of the options to initiate local scour in sand affected streams is provided below.

Bank attached deflectors

Bank attached deflectors are structures that are constructed of either rock or timber and protrude outwards from the bank with the aim of generating local scour (GHD, 2011a).

Post-construction monitoring of the interventions was undertaken (Lintermans, 2004b) and found that:

- Permanent scour holes developed and were maintained at the tip of the deflectors however, deflector spacing along the banks was too great because individual scour holes did not link up. This impacted on one of the key objectives of the rehabilitation strategy – to improve connectivity for fish through the sand affected reach.
- Snags that were included between deflectors were buried in sand because they were placed too far from the tip of the deflectors.
- Deflectors at the upstream end of the group were prone to become swamped with sand because of shifts in the position of the thalweg.
- The excavated pool was completely infilled with sand.

Following on from the above works, a second rehabilitation effort along the Tharwa sand affected reach was undertaken in 2013, focussing on two engineered log jams (ELJs) and two large rock groynes, along with riparian planting (Figure 17). Bathymetry surveys after construction found that the new deflectors had increased depth in the vicinity of the structures from ~ 0.35 m - up to 2 m (ACT Government unpublished data). Fish surveys conducted prior to the 2013 installation found some juvenile Murray Cod present, mostly associated with the existing rock groynes structures built in 2000. Monitoring following the 2013 installation found approximately twice as many Murray Cod present compared to earlier surveys (ACT Government unpublished data).

Figure 17. Aerial image of the engineered log jams at the Tharwa sand affected reach (Photo: ACT Government).

The use of bank attached deflectors was also trialled within sand affected reaches of Hughes Creek in Victoria. A number of different types of deflectors were trialled in this case including downstream angled, timber groynes placed 20cm above the bed of the channel to encourage scour beneath the structure and log jams extending from both banks into the channel to constrict flow and encourage bed scour through the middle of the channel (Glassford *et al.*, 2016). Instream works varied in how they were installed with some large wood anchored to the bank and other structures consisting of multiple pieces of overlapping wood to achieve the desired length, and secured in place with rock on either side. Immediately post-construction, localised scour was evident around structures however in early 2016, the catchment recorded a significant flood event which tested the performance of the structures. As a result of the flood event, several the instream structures were damaged or washed away and only those that had been anchored into the bank were still in place. Repairs were made to structures which included the use of more complex timber and anchoring all structures into the bank. Evaluation of the trial found that the structures which were undamaged maintained some scour depth around them post-flood although not as great as in the immediate post-installation phase. They also found that the timber used in the initial construction of the deflectors and log jams was not ideal for this use being too light and simple. Timber used in repairs was larger and more branching which were successfully anchored in place and found to provide more diverse habitat (Glassford *et al.*, 2016).

Instream deflectors

Instream deflectors are structures (e.g. submerged vanes) placed in the channel which generate secondary forces that alter the magnitude and direction of bed shear stresses and cause a change in the distribution of the velocity, depth and sediment in the area influenced by the vanes (Odgaard and Wang, 1991). Locally, sediment is directed away from a specific area by the orientation of the vanes. Vanes are typically made of reinforced concrete but there are also instances of the use of wood and sheet piling to construct vanes. The effectiveness of sheet pile vanes has been compared with that of traditional vanes in experimental settings which found that sheet pile vanes show similar results as traditional vanes, except when the angle of attack is increased. In this scenario, traditional vanes outperformed sheet piles vanes in terms of scour depth (Boniforti *et al*., 2015). The design of submerged vanes also requires the careful consideration of a number of variables including river height, velocity, discharge, bank material and bed-load transport and while design guidelines are available, their effectiveness depends on design being tailored to site conditions (Odgaard, 2009).

The use of sheet piling, or concrete vanes limits the opportunity to provide additional instream habitat which could be provided by using wood, although longevity is an issue for wood installations. A laboratory experiment has investigated the effectiveness of two types of timber vanes with standard concrete vanes. The experiment tested that the effectiveness of sediment distribution around vanes made of stacked logs and single large trunks placed on the stream bed. The experiment showed that all the wood structures were successful in redistributing sediment however, the single logs were the least effective, thought to be the result of a stronger decrease in the streamwise velocity then either the standard vanes or the timber screens (Poelman *et al*., 2019). The authors concluded that wood logs could be used as vanes to alter sediment transport and provide a nature-based alternative. However, in practice such structures have limited longevity of 5-8 years (Ian Rutherfurd, *pers comm*).

Various configurations of rock have also been used as vanes in laboratory experiments including a traditional vane constructed of rock, a j-hook rock vane and a cross vane constructed of rock that spanned the full stream width. Flume testing showed that all three types of rock vane resulted in a scour hole in the immediate vicinity of the structure and a downstream depositional bar. In all three cases, the depositional bar was found to migrate downstream and dramatically change bed morphology because of its larger size in comparison to normal bed forms. As a result, the investigation recommended caution using these structures in meandering stream to protect the concave bank due to the risk of creating downstream bank instabilities (Khosronejad *et al.*, 2013).

Boulder seeding/clusters

Boulder seeding or clusters are large rock or groups of rocks that can be placed instream to encourage scour and improve habitat. The separation of flow around boulders creates conditions that both generate scour, leading to the development of deeper water and increasing physical diversity and create overhead cover for fish through the creation of eddies and vortices (Fischenich and Seal, 1999). Design considerations for the implementation of boulder seeding/clusters include the number, configuration and location of the structures, the size of the boulders required for stability and the hydraulic impacts of the boulders. The use of this intervention is most successful in locations where there is limited geomorphic diversity, there is sufficient velocity (i.e., not in large, slow pools) and in reaches where the banks are stable. The use of boulder seeding is not generally recommended in sand bed streams or braided rivers because of their tendency to be quickly buried (Fischenich and Seal, 1999).

Summary

Installation of waterway structures to rehabilitate the stream channel and assist in sediment transport have varying success, and success is not usually static through time. Furthermore, adequate assessment of these types of structures on fish assemblages is often lacking.

Carline and Klosiewski (1985) found that sections of an Ohio creek with rock deflectors had significantly more species and higher numbers and biomass of fish than did sections without structures. This was largely due to the rock deflectors creating the only deep pool habitat in the reach. Champoux et al. (2003) found that success of deflectors varied over time, with best results observed three years after installation (compared to 30 years later), largely as the result of structure degradation over time.

4.4 Storing sediment

Another option for managing sand affected stream is to increase the storage of sediment within the affected reach and reduce the movement of the sand pulse through the system. Revegetation of instream bars and benches or the construction of instream structures such as pile fields stores sediment in part of the channel and can promote the formation of a narrower, deeper, more defined main inset channel. The increased deposition and retention of sediment on bars and benches, prevent the downstream migration of excess sediment loads (Sims and Rutherfurd, 2017) and the narrower and deeper main channel promotes connectivity for fish.

Revegetation

Instream bars and benches can be revegetated by waterway managers which will encourage the deposition and trapping of sediment as the sand deposits are protected from erosion by increase in roughness and a slowing of the flow velocity (Sims and Rutherfurd, 2017). Allowing for these features to be colonised or planted with vegetation results in a contraction of the channel and reduces the transport capacity of river allowing for sediment to be maintained in place. Additionally, the contraction of the channel through these means focuses flow into a smaller main section of the channel, increasing velocities here which create a deeper mid-channel and increase the capacity to move sediment (Gurnell, 2014).

Revegetation of bars, benches and the riparian zone of sand affected reaches is a low-tech and relatively low-cost solution which has proved successful in a number of different sand affected streams. In Bryan Creek in western Victoria, Sims and Rutherfurd (2021) found that revegetation was significant in terms of improving geomorphic complexity within sand affected reaches of the creek and this benefit was further increased if stock were also excluded from the waterway. *Phragmites* was found to be particularly successful in trapping and storing sediment and reintroducing geomorphic complexity in the form of pools. The physiological characteristics of *Phragmites* (being drought, waterlogging and salt tolerant, as well as being rhizomatous) was found to result in increased sediment cohesion and storage (Sims and Rutherfurd, 2021). Importantly, the study highlighted the value of local scale interventions in contributing to reach scale improvements.

Revegetation has also been successful in storing sediment and improving complexity in eastern Victoria. Over many years, revegetation, stock exclusion and pile fields have been used in the Cann River to capture and store sand delivered to the channel since European settlement (Figure 18). The works have been ongoing in the system for a number of years and are supporting the natural recovery process of the system (East Gippsland CMA, 2021). This is a template for what could be implemented in the Tharwa reach of the UMDR.

Concerns are often raised regarding the potential to increase flood risks if riparian or instream revegetation is present in a waterway. Rutherfurd et al. (2007) provide some rules of thumb for the effect of vegetation on flood levels:

- If vegetation does not block more than 10% of the cross-sectional area, it will probably have little effect on the flood stage. Therefore, vegetation has more effect on small waterways than large ones.
- Vegetation in the bed has more influence on flow than vegetation on the top of the bank.
- If the vegetation lies down during a flood, it probably has little effect on the flood stage.

Hydraulic modelling can be used to assess the impact of increased instream vegetation of flood levels as well as sediment mobilisation in the remaining channel areas.

Pile fields

Pile fields are lines of timber logs installed vertically into the bed of the channel that can have multiple benefits for waterway management including capturing and storing sediment. The use of timber provides a porous material that allows for low velocity through flow assisting with sediment deposition both upstream and downstream of the structure. Pile fields work most effectively when combined with revegetation and care should be taken to avoid common failure mechanisms such as outflanking and undermining (DSE, 2007).

Figure 18. Cann River in the 1970s (above) and in 2000 (below). (Photo: Rex Candy EGCMA).

4.5 Hybrid interventions

Large wood

Installation of large wood in the form of engineered log jams and other similar structures is a well-tested approach which combines the benefits of trapping and storing sediment, initiating local scour and improving habitat complexity (Brooks *et al.*, 2006; Pilotto *et al.*, 2016). There is a large variety of different type of large wood intervention that can be used in the restoration of waterways. The various types of large wood intervention and some of their benefits are outlined in Figure 19. Large wood is the ultimate ecosystem engineer; however, all wood is not equal in the benefit it provides to waterway condition and ecological health. The structural complexity of large wood – highest in natural wood loads – has been shown to generate the greatest effects on flow hydraulics, sediment characteristics and habitat diversity (Glassford *et al.*, 2016; Cashman, *et al.*, 2021). In sand affected streams, large wood plays an important role in creating pool habitats (Webb and Erskine, 2005) with localised scour initiated beneath and around structures but it is also critical in the long-term storage of sediment (Wohl and Scott, 2017).

There are a variety of design elements to be considered when implementing large wood structures to improve habitat and rehabilitate sand affected streams. Glassford et al. (2016) have highlighted the importance of anchoring large wood structures to banks as well as the consideration of the type and complexity of wood used in structures. Logs that were anchored to the banks were able to better withstand high flows, reducing the risk of structures and logs being transported downstream and more complex logs resulted in more diverse habitat features (Glassford *et al.*, 2016).

Log placement and orientation have also been found to alter the patterns of scour and deposition that are observed after installation (Hilderbrand *et al.*, 1998). Wood orientation relative to the direction of flow has been found to impact on both the amount and location of streambed changes and consideration should be given to the most appropriate configuration for site conditions (Figure 20).

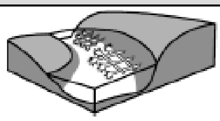
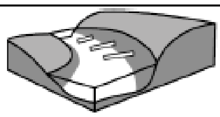
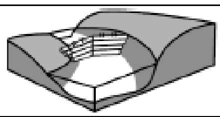
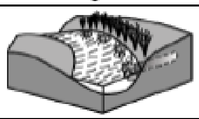
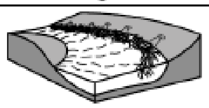
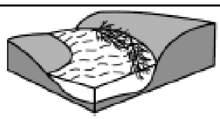
Configuration	Sketch	Description	Strength	References
Engineered logjams		Intermittent structures built by stacking whole trees and logs in crisscross arrangements	Emulates natural formations. Creates diverse physical conditions, traps additional debris	Abbe, Montgomery, and Petroff (1997); Shields, Morin, and Cooper (2004)
Log vanes		Single logs secured to bed protruding from bank and angled upstream. Also called log bendway weir	Low-cost, minimally intrusive	Derrick (1997); D'Aoust and Millar (2000)
Log weirs		Weirs spanning small streams comprised of one or more large logs	Creates pool habitat	Hilderbrand et al. 1998; Flosi et al. (1998)
Rootwads		Logs buried in bank with rootwads protruding into channel	Protects low banks, provides scour pools with woody cover	
Tree revetments or roughness logs		Whole trees placed along bank parallel to current. Trees are overlapped (shingled) and securely anchored	Deflects high flows and shear from outer banks; may induce sediment deposition and halt erosion	Cramer et al. (2002)
Toe logs		One or two rows of logs running parallel to current and secured to bank toe. Gravel fill may be placed immediately behind logs	Temporary toe protection	Cramer et al. (2002)

Figure 19. Classification of large wood instream structures (Cramer, 2012)

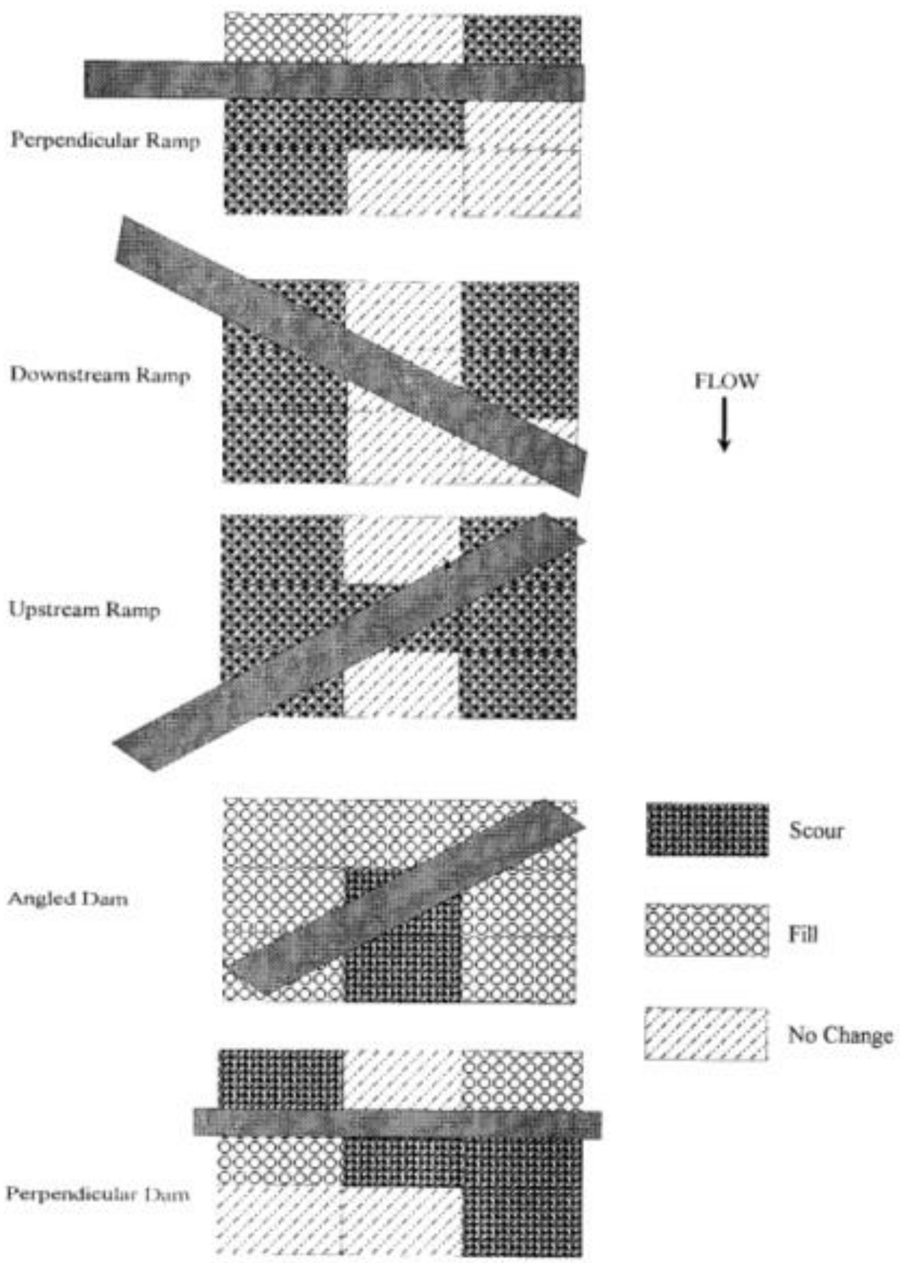


Figure 20. Average changes in channel elevation for different log orientations. Dams were flat on the streambed; ramps had one end propped on the stream bank (Hilderbrand *et al.*, 1998).

Logs with different scour mechanisms have also been tested against a range of flows to investigate the fluctuations in bed level within scour holes. The scour mechanisms investigated included a horseshoe vortex, a plunge pool, and a submerged jet pool beneath a log. The authors found that the plunge pool and the jet pool gradually filled over time and was associated with the average rise in winter flows and were not impacted in spite of freshes and increases in discharge (Borg *et al*., 2007). The plunge pool scour demonstrated the most variation in bed level over time with up to a metre of change, meanwhile the horseshoe vortex scour maintained a constant bed level throughout the monitoring period (Borg *et al.*, 2007). This is relevant to the UMDR reach where the local effect of large wood placed next to engineered structures was overwhelmed by sand waves operating at a larger scale.

There are some constraints on the implementation of large wood to improve instream habitat diversity in rivers, and a useful summary of the potential limitations is provided in Table 5, from NEH (2007).

Table 5. Limitation on the applicability of large wood (LW) structures (Technical Supplement 12J, NEH 2007).

Variable	Consideration for installing LW structures
Sediment load	Generally, not suitable for high-energy streams actively transporting material larger than gravel. LW structures may be rapidly buried in high sediment load reaches, diminishing their aquatic habitat value..
Bed material	Anchoring will be difficult in hard beds such as cobble, boulder, or bedrock.
Bed stability	Not suitable for avulsing, degrading, or incising channels. The best situations include areas of general or local sediment deposition along reaches that are stable or gradually aggrading. Deposition induced by LW structures may be stabilized by planted or volunteer woody vegetation, fully rehabilitating a naturally stable bank by the time the placed woody materials decay (Shields, Morin, and Cooper 2004). Unlike some of the other structures, rootwads often create scour zones, not deposition.
Bank material	LW structures placed in banks with >85% sand are subject to outflanking on the bank side which can destabilise the adjacent bank.
Bank erosion processes	Not recommended where the mechanism of failure is mass failure, subsurface entrainment, or channel avulsion. Best when toe erosion is the primary process.
Flow velocity & structure stability	Well-anchored structures have been applied to situations with estimated velocities of 2.5 m/s (D'Aoust and Millar, 2000). Rootwad installations have withstood velocities of 2.7 to 3.7 m/s (Allen and Leech 1997). Engineered logjam (ELJ)-type structures withstood 1.2 m/s in a sand-bed stream (Shields, Morin, and Cooper 2004). Flow velocity and anchoring arrangements need to be considered to prevent large wood installations being transported downstream.
Site access	Heavy equipment access usually is needed to bring in and place large trees with rootwads.
Conveyance	LW structures can increase flow resistance if they occupy significant parts of the channel prism (Shields and Gippel 1995; Fischenich 1996).

Concerns are often raised regarding the potential to increase flood risks of riparian or instream revegetation is installed in a waterway. However, for large wood or riparian vegetation to have a significant local hydraulic effect on water levels, it must act to restrict the hydraulic control (i.e., cause a significant narrowing or shallowing of the channel) (Department of Environmental Land Water and Planning, 2018).

Large wood in areas where the waterway cross-section is narrow and/or shallow, are more likely to be hydraulically significant than large wood in pools. While large wood can locally elevate water levels, at the catchment scale the roughness of large wood slows the progress of flood waves (Department of Environmental Land Water and Planning, 2018).

As for deflectors discussed previously, introduction of LW aims to provide cover and scour in stream beds to promote pool development and introduce habitat complexity. Response of fish to introductions of LW to rehabilitate sand affected streams are again variable and change over time.

In the case of the installation of two engineered log jams in the Murrumbidgee River at Tharwa, the works have resulted in localised scouring and an increase in Murray Cod. Bond and Lake (2005) found that introducing timber structures into heavily sedimented creeks in the Granite Creeks system in central Victoria did result in an Increase in native fish abundance. However, impacts of a severe drought overran the study shortly after installation which limited further inference of the efficacy of the structures over a longer timeframe.

Brooks et al. (2004) installed 20 ELJs in the Williams River in NSW, to increase habitat complexity, and found an increase in pool and riffle area as well as an increase in pool depth. They also found an increase in fish species richness and abundance than that of a reference reach. Howson et al. (2009) evaluated the effect of introduction of woody debris and sediment removal in the sand slugged lower Glenelg River. They found that there was no significant impact of the introduction of the structures on either structure dependent species, or the fish community in general over the two years of monitoring post Installation. The authors, also acknowledge that severe drought may have hampered fish recovery at this reach during the timeframe of the study.

Riparian revegetation

Riparian revegetation, including emergent aquatic vegetation can be used in conjunction with other sand management measures to improve habitat values within the waterway. The vegetation acts as a filter for sediments and nutrients entering the waterway from overland flows. Shade from riparian vegetation also helps regulate water temperature and reduce the likelihood of algal blooms (Lovett and Price, 2007; DELWP, 2018), while providing habitat areas in and out of the water (Figure 21). Riparian vegetation also plays an important role in providing the ideal conditions for macrophyte growth whose abundance has been correlated with spatial variations in fish distribution. Macrophytes in turn provide general habitat, refuge from high velocity flows and predators and in some cases, also provide a food source for some native fish (Pusey and Arthington, 2003). Furthermore, a diverse and healthy riparian zone plays an important role in aquatic food webs, particularly in upland streams where the majority of trophic inputs are derived from terrestrial environments. The terrestrial inputs to the aquatic system may also stabilise food webs by providing a buffer against short-term changes in the supply of food instream (Pusey and Arthington, 2003).

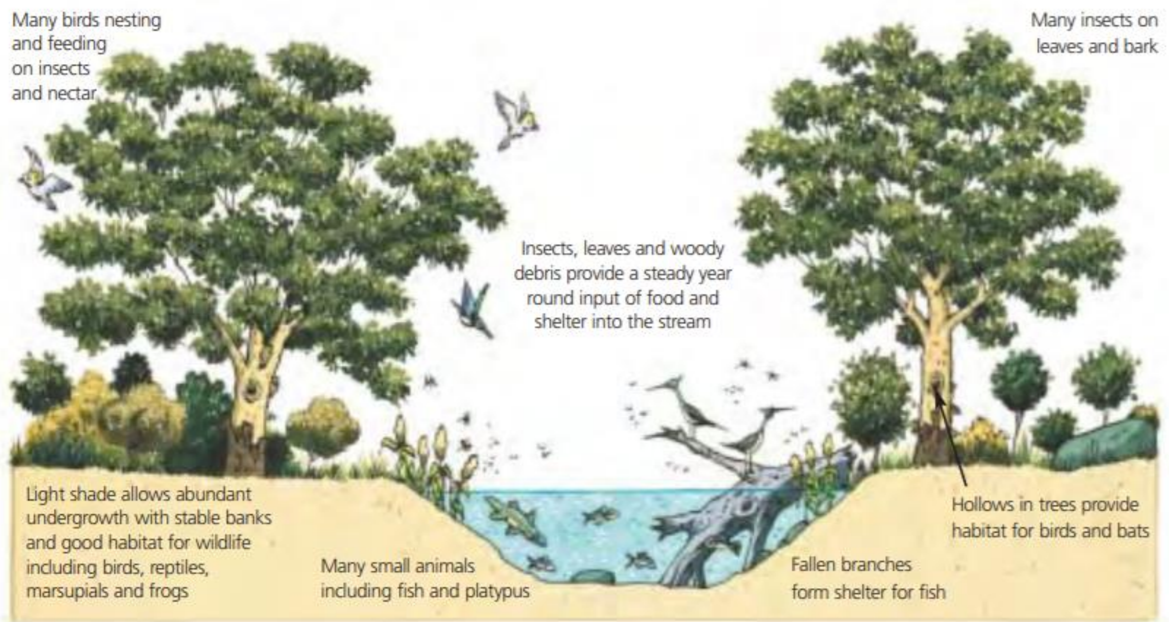


Figure 21. The benefits of native vegetation in riparian areas (from Lovett and Price, 2007).

Removal of riparian vegetation has a major effect on channel form, leading to widening, deepening, and straightening. Erosion of banks can mobilise large volumes of sediment which is then deposited in the waterway (Rutherfurd, Anderson and Ladson, 2007).

A study by Alluvium (2011) on the impact of revegetation on waterway erosion during floods in Victoria found the absence of native riparian vegetation increases the occurrence and scale of flood-related channel change in waterways, and associated flood related recovery costs. To increase the resistance to flood-related change, riparian vegetation needs to be:

- structurally diverse,
- of an appropriate width (Box 1) from the edge of the waterway bank to ensure it is ecologically and physically functional, and
- largely continuous along the waterway

Box 1. Riparian buffer widths

The riparian zone plays multiple functions within the riverine systems. Wide, intact riparian zones provide the greatest benefit to the health of functioning of river systems, however the riparian zones along many waterways have been cleared or are in poor condition. Revegetating riparian zones is a key river restoration activity, however there is some uncertainty about the riparian buffer widths required to achieve river health improvements. The efficacy of riparian zone function is strongly influenced by the hydrological regime, the degree of fragmentation within the riparian zone and the presence of invasive plant species. Given these uncertainties and dependencies, recommendations for minimum riparian buffer width have been developed for Victorian CMAs based on management objective and land use intensity (Hansen *et al.*, 2010). Minimum buffer widths are outlined below.

Management objective	High Land use intensity	Moderate Land use intensity	Low Land use intensity	Wetland/lowland floodplain/off-stream water bodies	Steep catchments/ cleared hillslopes/low order streams
Improve water quality	60 m	45 m	30 m	120 m	40 m
Moderate stream temperatures	95 m	65 m	35 m	40 m	35 m
Provide food and resources	95 m	65 m	35 m	40 m	35 m
Improve in-stream biodiversity	100 m	70 m	40 m	Variable*	40 m
Improve terrestrial biodiversity	200 m	150 m	100 m	Variable*	200 m

*Variability in width is related to the lateral extent of hydrological connectivity and thus, any recommendation will be site specific

Fish hotels and other woody debris

Fish hotels and other woody debris can be installed instream to improve habitat where sand mitigation is not feasible. The use of large woody debris to improve aquatic habitat and enhance the condition of fish populations is a well-established river restoration activity (Tonkin *et al.*, 2020). The installation of large woody debris for the purposes of habitat improvement only (i.e., not with the combined purpose of managing instream sand) generally take the form of fish hotels or mixed timber structures.

Fish hotels are constructed using small timber branches arranged in a square or rectangular shape which are connected by metal rods and are occasionally weighted down with concrete or anchored into place with piles. Other large wood arrangements include using single large whole trees, arrangements that include the key branches trunk and root ball, arrangements that retain just the root ball and 1 m of trunk and arrangements where the crown and root ball are removed but the trunk and key branches remain intact (ARI, 2019).

Figure 22. Types of large wood installation used for habitat improvement. (L) fish hotel, (R) large wood arrangement using two root balls and four large trunks. Source: ARI, 2019

To ensure success, each river restoration project seeking to reintroduce large wood needs to consider the specific timber requirements for the waterway. Timber requirements vary based on a range of factors including site characteristics, project objectives, stream energy, timber availability and size of the waterway. The preferred timber option for large wood installations is green, native hardwood species such as box eucalypts and red gum because of their density and guidance to the Victorian CMAs recommends a branch diameter of no less than 30 cm. The arrangement and design of large wood installations will vary to meet site conditions and also considering its intended function. Designing and pre-planning of large wood installations helps to ensure that timber is removed from its source retaining its most functional elements (ARI, 2019)

Installation of large wood structures has demonstrated improvements in fish populations in waterways where they have been deployed. North Central CMA have undertaken works in recent years to install a variety of large wood structures including fish hotels which provide high productivity feeding sites, resting sites, spawning sites and ambush sites for predator species. Initial macroinvertebrate studies have shown that abundance has increased three-fold compared with sites where no large wood structures were installed. Fish surveys have not yet been undertaken, however the increase in the abundance of macroinvertebrates indicates a change in the availability of food for native fish and angler catches have anecdotally recorded the catch of large Murray Cod and golden Perch at large wood installations (North Central CMA, no date).

One of the largest river restoration projects which involved re-snagging with large wood structures was undertaken along the Murray River as part of the Living Murray Program. The program sought to arrest major declines in river health and native fish populations and re-snagged 194 km of the Murray River between Lake Hume and Lake Mulwala with 4,450 woody habitat structures (each > 1 tonne) (DEPI, 2014). Monitoring of Murray Cod and golden Perch was undertaken over seven years on an annual basis in the intervention reach as well as three control reaches. The monitoring program collected catch, effort, length and tagging data which was also supplemented with telemetry and angler phone-in data. Monitoring of the restoration program found that there was a three-fold increase in the abundance of Murray Cod in the intervention reach compared to a decline or fluctuating abundance in the control reaches. There was also found to be a two-fold increase in the density of golden Perch in the intervention reach, demonstrating that installation of large wood structures is beneficial for improving the habitat conditions of important native fish species. The authors did stress the importance of considering restoration projects across appropriately large spatial and temporal scales, emphasising that the successful restoration of poor quality habitats relies on connectivity with high-quality source habitats (Lyon *et al.*, 2019).

4.6 Physical removal

The physical removal of sediment from the waterway, via either dredging or excavating is another option for managing instream sediment. The removal of sediment via these means interrupts the movement of sediment and creates localised erosion which is distributed throughout the reach via upstream knickpoint migration and downstream clear water effects (Rutherfurd *et al*., 2000). In their investigation of the feasibility of sand management options, GHD (2011a) also considered sand extraction. They summarised that:

“The extraction of sand within sediment impacted reaches along the UMDR would aim to improve fish habitat by reducing the amount of sediment transported to reaches downstream of the extraction site. The desired response to the reduction in sand delivery would be for the thalweg (low flow channel) in downstream reaches to incise and deepen. The other key potential positive of a strategy based on sand extraction is that the costs of the operation can be offset through the sale of sand depending on market demand” (GHD, 2011a).

The physical removal of instream sediment has been considered and implemented in a range of systems in south-eastern Australia (e.g. Bannockburn Creek, Glenelg River (Brizga *et al.*, 2003; New South Wales Department of Primary Industries, 2013)). However, there are several important considerations to be aware of prior to implementing a sand extraction program. These have been summarised by Rutherfurd et al., (2000) and include:

- Potential damage to the natural values of the system.
- Location of extraction which should be limited to reaches where the bed has aggraded with sediment from outside the reach and should not occur below the low flow water level which can have negative consequences for instream ecology.
- Location of nearby infrastructure which could be threatened as a result of extraction.
- Channel conditions including the presence of an armoured layer (the disturbance of which could result in deepening) and if the channel has undergone significant bed and bank erosion which could undermine efforts of rehabilitation.
- Timing – sediment extraction is easiest during low flows however in these conditions, extraction can significantly increase turbidity.

The reaches at Bredbo and the Tharwa Sandwash have previously been identified as the only reaches where there is an accessible quantity of commercially viable sand (GHD, 2011a). However, sediment extraction has previously been ruled out for several reasons including potential environmental impacts, uncertainty about downstream response and the quantity of sand that should be removed, market demand for sand, acceptability to local residents and legislative impediments (AWT and Fluvial Systems, 1999).

Worldwide, sandmining in otherwise undisturbed waterways has been found to have many direct and indirect impacts on fish (Koehnken *et al.*, 2020). Potential risks for fish species of the UMDR would be increases in turbidity (which may affect foraging success of visual predators), suspension of fine sediments (which could smother spawning habitat and eggs e.g., Macquarie Perch) and instream works activity (which could act as a deterrent for fish migration). Bed destabilisation associated with sand mining was also shown to change the way in which foodwebs established, moving from a benthic driven energy pathway to a phtyoplankton and detritus driven energy pathway, which had flow on effects for food web structure (Kanehl and Lyons, 1992). However, in sand affected rivers many of these adverse outcomes have also occurred because of the presence of the excess sand.

The strategic and sustainable removal of excess sediment from a sand affected river system could be considered as part of an overall recovery program of works. DPI (2013) undertook a study to assess the feasibility of removal of sediment from Bannockburn Creek and the Macintyre River as an approach to reinstate refuge habitat for fish and other aquatic species and allow re-establishment of aquatic vegetation until these reaches begin to refill. The report notes that:

"...the physical extraction of sand may provide potential "breathing space" for identified reaches within the sediment slug, but should be implemented in conjunction with other activities such as instream rehabilitation works (installation of woody debris) and works to control sediment input from the surrounding catchment."

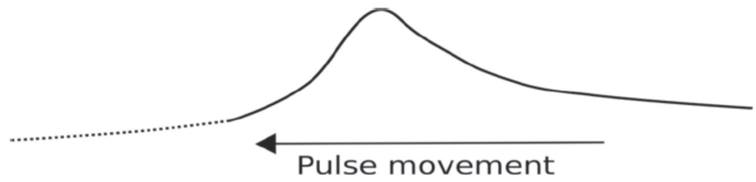
Sims and Rutherfurd (2021) provide a review of local scale interventions for Bryan Creek, a sand affected river in the Glenelg River catchment. In those reaches where sand extraction was used in conjunction with stock exclusion and revegetation the waterway experienced an accelerated pattern of recovery. This accelerated pattern of recovery was largely attributed to the exclusion of stock from the waterway and associated revegetation activities. The overall amount of sediment in the waterway needs to be assessed, especially where there is a large amount of instream sediment upstream of the extraction site. In this case the removal of sediment may require repeat extractions over time as the sediment continues to move along the waterway reach, filling in the extraction areas with new sediment from upstream.

4.7 Suitability for sand conditions and river types

It is likely there will be a need to use a range of options to manage excess sand and enhance habitat for fish in sand affected rivers. The volume of sand and its distribution along the waterway together with the physical form of the river, its hydrology and flow conditions will all influence how successful different interventions or combinations of interventions might be.

Sims and Rutherfurd (2017) outlined a decision framework for management of sand affected waterways, which identified that to be successful the management action needs to consider the management goals as well as the location of the sand slug (termed 'pulse'), Figure 23.

Schematic of the pulse



Pulse stage	Downstream of pulse - not yet affected	Pulse peak	Tail of pulse	Source area
Management goal	Protection	Mitigation	Remediation	Reduce further inputs
	• Avoid damage to infrastructure. Protect restoration assets and high value reaches.	• Reduce flood risk • Reduce risk of avulsion • Maintain navigability • Limit habitat destruction	• Accelerate recovery	
Management actions	• Trap and/or extract at leading edge of pulse • Prepare for high sediment loading, projects to accelerate transport of approaching pulse.	• Accelerate transport, • Store and flush sediment • Trap and extract.	• Stabilise sediment sources • Limit mobility (trap and store)	• Stabilise sediment sources • Cease activity contributing sediment

Figure 23. Generalised management framework for sand affected rivers (Sims and Rutherfurd, 2017).

However, as described by Sims and Rutherfurd (2021), it can be difficult to predict how a river will respond to interventions, when the target reaches are impacted by processes operating at a range of scales and which change over time.

"Because a reach will be at a different pulse stages at the time of any intervention than other reaches, the timing of works is as important as the spatial scale of those interventions. Intervene too soon and the catchment scale processes will undermine the intervention (for example by burying vegetation with sediment), intervene too late and the catchment scale processes will make a reach insensitive to intervention (for example in the clay bed reaches of Bryan Creek)."

Table 6 summarises the different sand management and habitat improvement options that are available and highlights their benefits, constraints, and applicability to different sand pulse stages.

Table 6. Summary of sand management options and their potential application.

Management Option	Requirement for success	Sand Pulse Stage	Benefits (sand management and/or fish habitat)	Constraints
Source Control				
From diffuse sources: (e.g., riparian / hillslope revegetation)	• Vegetation establishment, weed control, and stock exclusion / management. • Works in combination with bank attached structures, pile fields and large wood / woody debris.	Source	• Suitable for all river types. • Reduced bank, gully or slope erosion & volumes of sand and fine sediment supplied to waterways. • Improved riparian habitat. • Reduced smothering of bed sediments by fine material to maintain spawning habitat. • Vegetation can shade the waterway, reducing water temperatures and evaporation, improving condition for macrophyte growth and abundance. • Macrophytes provide general habitat, refuge from high velocity flows and predictors.	• Removal of weed species and an absence of other flora may reduce habitat values and shading on streams. • Initially there may be an increase erosion rates until native plants become established.
From point sources: (e.g., hillslope treatments such as silt fences, hay bales, coir logs)	• Rapid implementation necessary following trigger events (i.e., fires). • Revegetation program for longer term soil stabilisation along with hillslope treatments.	Source	• Limits or slows the rate of sediment delivery to waterways, particularly fine sediments, ash, and charcoal after fires which can smoother the bed material reducing spawning habitat. • Suitable for moderate slopes (<35 degrees) with low to moderate velocity flows[1]. • When used instream, more suitable for smaller tributaries or localised protection (specific habitat sites).	• Access following fires can be dangerous. • There is a need for rapid implementation if used as a post-fire sediment control. • Treatments may need to cover a sizable area. • Typically considered a short-term response, which will need to be combined with hillslope revegetation to provide a longer-term solution. • Correct installation required and on-going monitoring and maintenance to ensure performance.

[1] (Morris, et al., 2008)

Management Option	Requirement for success	Sand Pulse Stage	Benefits (sand management and/or fish habitat)	Constraints
				• Not suitable for areas of concentrated flow or in fine or dispersive soils.
From point sources: (e.g., hillslopes or instream works such as constructed log jams, debris barriers, and check dams)	• Requires implementation prior to sediment being mobilised. • Inclusion of large wood / woody debris for habitat features.	Source	• Limits or slows the rate of sediment delivery to waterways. • Suitable for mild slopes (<10%). • In-stream structures can be combined with large woody / fish hotels to provide habitat features for fish.	• Needs long-term monitoring and maintenance to maintain performance. • Will require regular sediment removal for long term applications.
Flushing sediment through				
Through flow regime change (e.g., enhanced environmental flows)	• Ability to manipulate or supplement the flow regime sufficiently to mobilise sediment or flow cues for native fish.	Downstream Peak and Tail	• Encourages recovery of the system without physical intervention. Depths can be increased as excess sediment is moved through. • Works best for enhancing sediment movement in confined reaches with medium to high energy flow regimes. • Spawning habitat maintenance and increased connectivity.	• Moves sediment downstream, so sediment impacts on downstream reaches must be considered, particularly effects on critical life stages of native fish. • Flow rates, volumes and frequency must be sufficient to mobilise sediment in target reaches. • Timing is critical as flow releases may impact on recruitment of native fish negatively if delivered during nursery season (October - December). • Monitoring of sediment movement and fish responses required to optimise flow regime.
Waterway structures (e.g., bank attached deflectors such as groynes)	• Sufficient length and spacing to enable scour holes to merge, forming a deeper channel section. • For wide sand affecting rivers stabilisation of the opposite bench or bar	Peak, Tail, Downstream (leading edge)	• Encourages scour at the head of the structure and can form deeper main channel if scour holes from multiple groynes merge. • Increased sand movement through the reach.	• Spacing and length of groynes required relative to the size of the river and sand transport rates. • High cost for design and construction. • Needs long-term monitoring and maintenance to maintain performance.

Management Option	Requirement for success	Sand Pulse Stage	Benefits (sand management and/or fish habitat)	Constraints
	through revegetation may assist in maintaining the deeper channel section.		• Can increase the abundance and biomass of fish species by increasing longitudinal connectivity and providing water depths and pool extents suitable for fish habitat requirements.	• Long-term benefit to native fish can be variable.
Waterway structures (e.g., bank attached deflectors such as pile fields)	• Requires vegetation establishment in depositional areas within the pile field. Best achieved through active revegetation programs.	Peak, Tail, Downstream (leading edge)	• Encourages contraction of the channel (through sedimentation) for initiation of scour and enhanced sediment transport through the remaining flow channel. • Provides increasing longitudinal connectivity for fish through greater water depths in the main flow channel.	• Revegetation program required in conjunction with structures. • High cost for design and construction. • Needs long-term monitoring and maintenance to maintain performance.
Waterway structures (e.g., instream deflectors such as vanes)	• Consistent flow regime required (i.e., perennial flow conditions to ensure vanes maintain interaction with flow)	Peak, Tail	• Encourages sediment mobilisation which moves excess sand through a reach. • Scour holes can be formed, which increasing longitudinal connectivity and provide water depths and pool extents suitable for fish habitat requirements.	• Detailed investigation of sediment transport and flow conditions required for design. • High cost for design and construction. • Limited existing application directly for sand management and/or fish habitat creation. • Needs long-term monitoring and maintenance to maintain performance.
Waterway structures (e.g., boulder seeding)	• Medium to high velocity flows needed. • Stable riverbanks.	Tail	• Encourages local scouring of the riverbed which provides habitat opportunities - i.e., medium for algal growth. • Can increase longitudinal connectivity for fish through an increased number and extent of pools.	• Not suitable in sand bed or braided systems.
Storing sediment				
Revegetation	• Appropriate vegetation establishment on in-stream bars and benches.	Tail, Peak and Downstream	• The presence of vegetation on instream bars and benches reduces sand mobility during high flow events and limits the	• Inappropriate plant selection or planting may result in localised increases in flood levels.

Management Option	Requirement for success	Sand Pulse Stage	Benefits (sand management and/or fish habitat)	Constraints
	• Flow conditions suitable for vegetation establishment.	(leading edge)	downstream migration of sand. This can protect downstream reaches from excessive sand transport and deposition in the channel. • As the vegetation establishes it leads to the contraction of the low to moderate flow channel, with incision creating a deeper and faster flowing remaining channel. • This increases water depths and longitudinal connectivity for fish passage. • Vegetation can shade the waterway, reducing water temperatures and evaporation, improving condition for macrophyte growth and abundance. • Macrophytes provide general habitat, refuge from high velocity flows and predictors.	• May require revegetation maintenance works following high flow events.
In-stream structures (e.g., pile fields, silt fencing)	• Design of suitable placement, including length and spacing relative to the flow condition and channel form. • Used in combination with revegetation of zones between pile fields or revegetation of instream bars or benches.	Tail, Peak	• The structures act to stabilise sediment in channel and trap sediment being transported downstream. • Structures such as pile fields concentrate flows to one section of the channel, allowing a deeper pool or low to moderate flow channel to form, and increases longitudinal connectivity for fish passage. • Silt fences can enhance the success of revegetation establishment on instream bars and benches.	• Potential increase in local flood levels due to the contraction of the main flow channel. This is related volume of stabilised sediment as a proportional of the channel area. Not suitable for narrow streams where the structure takes up a >10% of the channel area.
Hybrid Interventions				
Large Wood	• Used in combination with revegetation to stabilise depositional areas.	Tail, Peak	Provides physical diversity cover, velocity shelter, substrate sorting, pool development,	Not suitable for: • Channels subject to debris flows.

Management Option	Requirement for success	Sand Pulse Stage	Benefits (sand management and/or fish habitat)	Constraints
	• Provides habitat for fish. • Can be combined with other woody debris structures such as fish hotels.		undercut banks, and sites for terrestrial plant colonization using natural materials.	• Located within 500m upstream of a bridge or culvert. • In confined channels where valley floor width is less than twice the bank full flow. • Alluvial stream gradients > 2%, other < 4%. • Anchoring of the wood. • Availability of suitable wood and volumes required.
Riparian revegetation & stock exclusion	• Used in combination with any of the other options to enhance instream habitat suitability for fish.	All	• Overhanging vegetation can shade the waterway, reducing water temperatures and evaporation, improving condition for macrophyte growth and abundance. • Macrophytes provide general habitat, refuge from high velocity flows and predators.	• Does not directly address sand management or presence of excess sand in a section of channel.
Fish hotels and other woody debris	• Used in combination with any of the other options to enhance instream habitat suitability for fish	All	• Directly provides habitat for fish, as feeding sites, resting sites, spawning sites and ambush sites for predator fish. • Leads to increased abundance of macroinvertebrate species.	• Anchoring of the wood. • Availability of suitable wood and volumes required. • Needs to consider connectivity with existing high quality habitat.
Physically removing sediment				
Extraction of the sand	• Used in conjunction with other activities such as instream rehabilitation works (installation of woody debris) and works to control sediment input from the surrounding catchment.	Peak	• Reduced sediment volumes in a channel and change bedload composition. • Deep pools can be formed. • Depending on the scale of sand removal, longitudinal connectivity can be enhanced by increased flow depths.	• Requires detailed investigations of where and how to remove the sediment to minimise adverse effects. • Has significant regulatory requirements and require further studies such as an Environmental Impact Statement. • May require on-going removal rather than one-off extraction.

Management Option	Requirement for success	Sand Pulse Stage	Benefits (sand management and/or fish habitat)	Constraints
	• Sediment usually needs to be commercially viable to extract.			• Many potential negative impacts on aquatic biota - increased turbidity, fine sediment disposition, barrier to passage. • Cost for extraction and disposal can be high but can also be offset if the sand can be sold as a resource. • Sediment contamination must be considered depending on the source of the sediment (e.g., sand from historic river and floodplain gold mining)

5 Conclusions

The aim of this project was to undertake a review of options to manage sand and improve habitat in the sand affected upper Murrumbidgee and provide appropriate intervention options that could be implemented. As structural interventions such as engineered log jams have previously been deployed, important criteria for assessing appropriate options as a part of this project included options that were lower cost and could be implemented with the involvement of community groups.

Based on these criteria and the options that have been assessed revegetation and stock exclusion are the most cost-effective, community friendly option that will provide good outcomes for habitat and sand management. Revegetation of sandy bar and benches in the most sand affected reaches will help to store sediment by preventing its mobilisation and create a concentration of flow through the centre of the channel resulting in deeper water habitats in the middle of the stream and shallow, slow water habitats along the edges of the channel. Riparian revegetation and stock exclusion will assist in preventing sediment derived from bank erosion sources entering the waterway and will also provide substantial habitat benefits through shading effects which reduce waterway temperatures and evaporation and provide ideal conditions for macrophyte growth. Overhanging vegetation, rootballs and inputs of woody debris will also enhance the diversity of habitats available instream and provide important carbon inputs over the long-term. The importance of local scale interventions such as these in contributing to reach scale improvements have been demonstrated with Sims and Rutherfurd (2021) finding revegetation and stock exclusion in Bryan Creek had the most significant impact on improving geomorphic complexity of the interventions that were implemented. This intervention option will also likely improve the effectiveness and result that can be achieved with the engineered structures that have already been implemented in the upper Murrumbidgee.

Revegetation and stock exclusion can also be implemented in conjunction with the addition of large wood structures specifically targeting habitat improvements such as fish hotels. Unlike engineered log jams that have already been deployed within the upper Murrumbidgee, fish hotels and other woody debris have a specific focus on improving habitat. These structures provide a diversity of cover, velocity shelter, substrate sorting, pool development and dedicated spawning and resting sites. As these interventions do not have sand management as their primary focus, they would be best implemented at the tail of the sediment pulse.

Options to manage catchment sources of sediment have been reviewed as part of this project and their effectiveness will depend on their implementation. A review of information available about catchment sources of sediment revealed that a large proportion of sediment inputs were the result of gully development and enlargement which has now largely ceased. The key risks in terms of sediment inputs from the catchment are as a result of earlier clearing or in the form of debris flows and erosion following bushfires. Options for managing sediment following bushfires include the use of check dams, silt fences, coir logs and hillslope mulching with hay or wood shred. Managing post bushfire sediment inputs pose a range of challenges, particularly as they cannot be effectively deployed in advance of a bushfire and there can be a short window of opportunity to appropriately implement control options between fire and potential erosion event. Options to control sedimentation following bushfire have had mixed results and a combination of control options is usually required.

The physical extraction of sediment from the river was also reviewed as an option for this project. Sediment extraction does not meet the aims of the program given it is a high-cost intervention and has little to no community involvement. The physical extraction of sediment can be effective, but it also needs to be undertaken in conjunction with other restoration activities such as revegetation and the addition of woody debris. Physical removal of sediment has a range of constraints associated with it which include the need to commercially viable, significant regulatory approvals, consideration and understanding of downstream impacts, high-cost and the potential for sediment to be contaminated depending on its source. For these reasons the physical removal of sediment is considered the least favourable option.

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