Sand slugs and fish movement in the Murrumbidgee River: can you restore and maintain deepwater habitats in sediment-impacted large rivers?

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Abstract

A 1.5 km reach of the upper Murrumbidgee River, Australian Capital Territory, that is affected by sediment provides a barrier to fish movement between high quality fish habitats. The river reach is shallow with a featureless sandy bed and only introduced fish species such as carp, goldfish and gambusia are resident in the affected section. The upstream and downstream dispersal of populations of native fish is impeded by the shallow water depths and lack of cover. A rehabilitation strategy was designed which used a series of regularly spaced flow deflectors to create scour holes to improve fish dispersal. A habitat pool was also created with large woody debris (snags) added for structural complexity, with snags also incorporated into seven of the deflectors. Construction was completed in May 2001, with monitoring in 2002 and 2003 demonstrating the success of the deflectors in creating scour pools. The habitat pool was unsuccessful and has filled with sand. Most of the snags in the deflectors have been swamped by sand.

Background

A section of the Murrumbidgee River in the Australian Capital Territory (ACT) below Tharwa has been severely impacted by habitat degradation, mainly the accumulation of sediments (sand). There is little habitat diversity remaining as the river has changed from a narrow, self-scouring channel to a wide depositional system (**Figure 1**).

Sand has filled the majority of holes, with a consequent loss of the former pool/riffle sequence. Sediment addition is a major threatening process for fish, particularly species which lay demersal eggs on the substrate. Poor land management practices in the mid to late 1800s and three large floods between 1850 and 1870 in the upper Murrumbidgee catchment (**Figure 2**) resulted in extensive erosion and sediment addition to the river (Starr 1995; Starr *et al.* 1997). This sediment originated predominantly in the Bredbo and Numeralla catchments with the majority coming from gully and channel erosion (Olley 1997).

Figure 1. The sand impacted area as viewed downstream from Tharwa Bridge

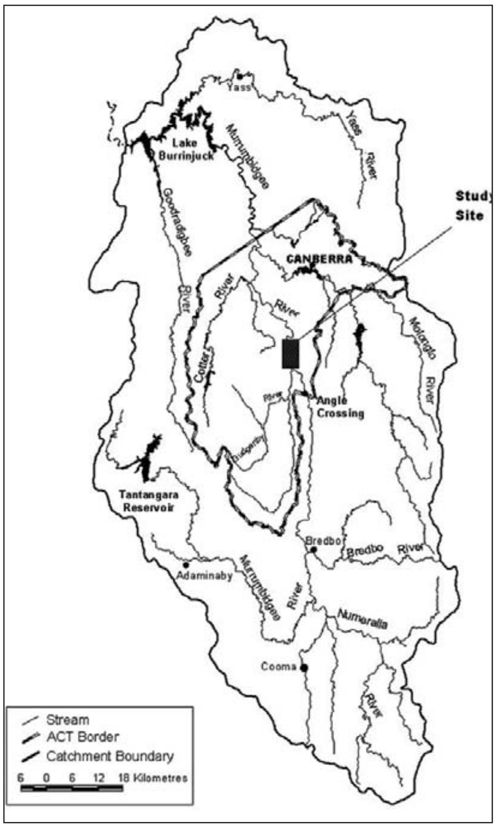

Figure 2. The upper Murrumbidgee catchment showing the study site, major dams and tributaries

Large volumes of sediment are stored in the channel and are being repeatedly reworked and will be for the foreseeable future (Erskine 1997).

The sediment has filled the deep pools in the river which are important as refuges for the larger native fish species such as Murray cod (*Maccullochella peelii*), trout cod (*Maccullochella macquariensis*) Macquarie perch (*Macquaria australasica*) and golden perch (*Macquaria ambigua*). The sediment-affected reach is dominated by introduced fish species such as carp (*Cyprinus carpio*) and eastern gambusia (*Gambusia holbrooki*). The reduction in depth and occurrence of pools has also removed potential refuges for native fish from high summer water temperatures. Increased sediment loads have probably also affected benthic invertebrate communities, the primary food source of the species.

Clearing, cropping and grazing of the riparian zone has eliminated almost all of the large eucalypt species which were previously common in the area. Consequently there is no source of large woody debris (snags) for the river which previously would have provided structural complexity and habitat diversity for both fish and invertebrate populations. Although snag density was probably never particularly high in the upper Murrumbidgee River, the present almost total absence of large woody debris severely compromises the quality of fish habitats. Reconstruction of fish habitats through the creation of pools and addition of snags was required to provide a link between suitable habitats on either side of the impacted section.

The river reach still contains populations of two threatened aquatic species (Macquarie perch and Murray crayfish *Euastacus armatus*), with trout cod present until the mid 1970s (Lintermans *et al*. 1988; Lintermans & Rutzou 1991; Lintermans 2000). The river upstream has recently been restocked with trout cod as part of a national recovery program (ACT Government 1999), with a total of 65,000 fish stocked between 1995 and 2004. The small populations of threatened fish are located upstream of the sand impacted area, whilst non-threatened native species such as Murray cod and golden perch are present downstream.

In 1999 a project to rehabilitate the impacted stretch of river was funded by the Natural Heritage Trust.

Initial investigations

The first stage of the project was to review river hydraulics, fluvial geomorphology, river hydrology, river ecology, catchment processes and risks (AWT & Fluvial Systems 1999). This involved review of the available literature on the study area, analysis of flow duration curves and the effects of the construction of a major impoundment upstream, analysis of aerial photographs since 1944, sediment probing and the construction of sediment budget, and a review of the structural integrity of a historic bridge at the upstream end of the study site

The river downstream of the Tharwa Bridge is fairly straight, approximately 60 m wide at the bed, with a flat sandy channel crossed by a sinuous shallow thalweg. The depth of sand varied from 1.4 to 4 m, with an average of 3 m in the area targeted for rehabilitation.

Anecdotal reports suggest that 160 years ago the river was narrower and deeper, and that catchment land use changes and a series of large floods were responsible for the channel widening and sand deposition (Starr 1995; Starr *et al*. 1997). This particular reach of the river has a low gradient, caused by a prominent rock bar downstream of Lanyon which, hydraulically, acts like a weir crest. This creates a low channel slope above, with the whole section acting as a sediment storage zone. The section of river below Lanyon has a relatively high gradient as far downstream as Burrinjuck Dam. Any sediment removed from the Tharwa reach should be fairly rapidly transported through the ACT to river reach immediately upstream of Burrinjuck (AWT & Fluvial Systems 1999).

The construction of Tantangara Dam in 1960, some 200 km upstream of the study site, has resulted in a significant reduction of the pre-impoundment flow. Immediately below Tantangara less than 1 per cent of average natural flow remains, with the diverted water flowing to Lake Eucumbene as part of the Snowy Mountains Scheme (Pendlebury 1997). This has led to significant sediment storage in the river due to decreased flushing due to flood suppression (Erskine 1997). Inflow from unregulated tributaries downstream of Tantangara means that at the study site the river carries approximately 57 per cent of the pre-Tantangara average natural flow (Pendlebury 1997).

Prior to 1850, the river at Lanyon consisted of 'large deep holes, between which the stream flowed gently over gravel beds during normal summer flow' (Moore 1982). Inspection of aerial photographs from 1944 onwards, and historical photographs from *circa* 1890 indicate that the river had attained its current form of a wide sandy channel by ~1890. The impacted reach was subject to sand extraction from the late 1950s to early 1970s with somewhere between 500,000 and 2,000,000 m^3 removed (Hogg & Kirschbaum 1990; Commonwealth Dept of Works 1972; AWT & Fluvial Systems 1999). This represents an annual extraction rate of between 30,000 and 60,000 m^3 . The average annual bedload movement is estimated to be around 50,000 m^3 (AWT & Fluvial Systems 1999).

The design of the rehabilitation strategy was constrained by a number of historical and cultural factors. The upstream end of the sediment impacted area is marked by the historic Tharwa bridge. Constructed in 1895, it is the oldest Allen Truss bridge in Australia, and is on the Register of the National Estate. The historic significance of the bridge and its maximum load limit meant that heavy machinery was prohibited from crossing the bridge. The in-stream works also had to be designed so that there was no impact on the footings or structural stability of the bridge. The proximity of the small rural village of Tharwa to the study site also imposed constraints on the rehabilitation strategy, as the only access for heavy vehicles and equipment to and from the site is via the village (due to the load constraints of the historic bridge). The socially unacceptable impacts of movement of heavy and noisy vehicles through the village effectively eliminated large-scale mechanical extraction of the sand as a rehabilitation option.

There are also two historic rural properties adjoining the study area. Lanyon Homestead, on the eastern bank of the river was constructed in 1859, and today is managed as a museum and showpiece of a colonial rural enterprise. Lambrigg Homestead, on the western bank of the river, was constructed in the early 1890s and is the property where William Farrer conducted his research into wheat varieties. Both properties are listed on the Register of the National Estate.

Rehabilitation strategy

The objectives of the rehabilitation works were to:

- improve connectivity of fish populations by improving fish passage through the sediment impacted reach,
- increase fish habitat diversity by re-creating small pools, and
- increase structural diversity through the addition of woody debris.

The rehabilitation strategy for the sand impacted area had two components:

- the construction of a series of 'deflectors' (rock groynes keyed into the riverbank), and
- the creation of a habitat pool incorporating woody debris.

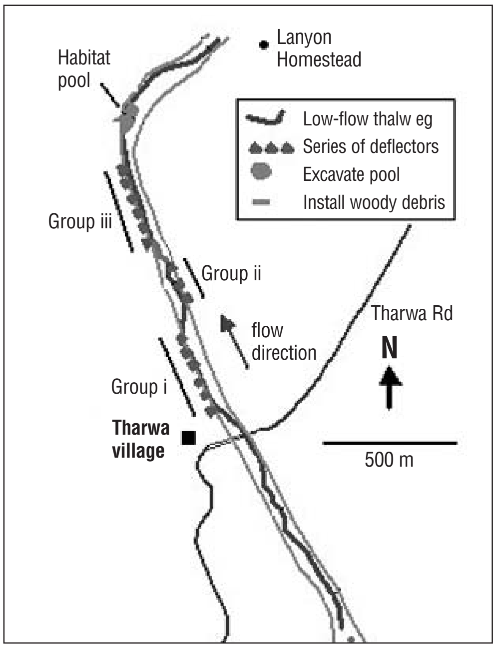

Figure 3. Diagram showing location of the low-flow thalweg, deflectors and habitat pool in in the Murrumbidgee River, ACT

The deflectors were constructed in three groups (**Figure 3**):

i. On the left bank starting 150 m below the bridge, extending for 300 m. Six deflectors were required in this section.

ii. On the right bank starting 550 m below the bridge, extending for 150 m. Three deflectors were required in this section.

iii. On the left bank starting 740 m below the bridge, extending for 320 m. Six deflectors were required in this section.

The grouping of the deflectors was dictated by the position of the low-flow thalweg which crossed from the left bank to the right bank for a distance of 150 m before crossing back to the left bank again (**Figure 3**).

The construction program commenced in March 2000 when streamflow was at a minimum, and there would be no disruption to spawning native fish. A levee bank was constructed mid-stream to divert the flow to the opposite bank, away from the bank on which the deflectors were to be constructed. A series of 15 deflectors, spaced approximately 60 m apart, was constructed along the river between the Tharwa bridge and the first bend downstream. These deflectors will constrict the flow of the river to scour away the accumulated sand, providing deeper holes in the river to facilitate passage between higher quality fish habitats upstream and downstream of the sediment impacted area. Various authors have recommended deflector spacing of between 5 and 7 times the width of the low-flow channel (Brookes *et al*. 1996). As the low-flow channel at the study site varied from 10 to 20 m wide, this meant a recommended spacing of 50–140 m. The closer spacing was decided upon in order to enhance the continuity of the scour holes to maximise fish passage.

Each deflector contains approximately 220 m^3 of rock. At each deflector site, the sand was excavated until a stable base was reached, before placing the rock to form the deflector. The first six deflectors were constructed from the bank, as high water levels precluded access from the river channel (**Figure 4**).

Figure 4. Construction of a deflector from the bank. Note the bank disturbance which has to be stabilised and revegetated.

The remaining nine deflectors were constructed with access from the river channel, which minimised bank disturbance and did not require the creation of access tracks to each deflector.

The banks immediately adjacent to the six deflectors that were not constructed from the river channel were rock armoured to prevent potential scouring and back-cutting (**Figure 5**). Bank armouring was not considered necessary for the nine deflectors where construction access was from the river channel, as there was minimal bank disturbance.

Figure 5. Completed deflector showing logs projecting downstream. The commencement of rock armouring of the bank can be seen to the left of the deflector

Figure 6. Completed deflectors in the Murrumbidgee River. Note the remnant Eucalyptus viminalis *on the near bank which were previously widespread throughout the riparian zone*

The deflectors were between 10 and 14 m long (projecting into water), plus 2 m keyed into the bank. The deflector length was 60% of the low-flow channel width, and they were 1–2 m wide at the water surface. The nose of the deflector was at a height of 0.3–0.6 m above the low-flow water surface, with the angle of the crest downwards to the river at an angle of approximately 5°.

The deflectors were designed to withstand the 1:10 year flood, but the size of rocks used was considerably larger than specified, so the structures are expected to withstand floods larger than the 1:10 year event.

One or two hardwood logs have been incorporated into alternate deflectors to increase structural complexity. These logs are embedded into the deflectors and project approximately 6–8 metres from the downstream side (**Figure 5**). Ideally, complete trees would have been used in the deflector design. However, the lack of native riparian species in the study area meant that logs had to be transported by truck a considerable distance to the rehabilitation site, necessitating some 'simplification' of the logs, i.e. removal of heads and complex root wads.

The construction of the 15 deflectors was completed in early May 2001 (**Figure 6**) and their efficacy in creating small-scale pools will not be able to be assessed until after the high winter flows have ceased.

The objective of the habitat pool was to create a major fish habitat pool in an area where deep pools no longer exist. The pool was 50 long x 15 m wide and was excavated down to stable substrate, giving a depth of 3–5 m.

Eight hardwood logs were incorporated into the pool to provide a snag pile, with the largest logs keyed into the sand on the inside of the bend to provide additional stability (**Figure 7**). It was originally proposed to key the logs into the bank on the outside of the bend, but the steep bank slope precluded the operation of heavy excavation machinery, and so the habitat pool was excavated from within the river channel.

The habitat pool has been excavated on an outside bend of the river, immediately downstream of the deflectors. This location was chosen as the hydraulic forces concentrated on the outside bend might be sufficient to keep the pool from filling with sand. However, as the sediment transport rate is variable, periodic excavation may be required.

Figure 7. Excavation of the habitat pool and placement of logs. Note the shallow water the excavator is standing in, indicative of the general depth of the river prior to rehabilitation

The addition of logs to the habitat pool has provided considerable structural complexity to an area that was previously devoid of complex habitat.

The cost of the in-stream works program was $193,000, with a further $50,000 cost for the preliminary investigations and design of the rehabilitation works. The construction of the 15 deflectors accounted for most of the cost of the in-stream works, with the habitat pool costing approximately $5000 to excavate. The cost of the in-stream works program was minimised by allowing the contractor to retain any sand excavated in the construction of the deflectors and habitat pool. The rehabilitation works were completed in mid May 2001.

Monitoring strategy

It is possible that the native fish community may show little initial response to the rehabilitation works as the fish community is dominated by introduced species. However, if the deflectors fulfil their objective and aid dispersal of native fish through the sand-impacted reach, it is hypothesised that native fish will become more widely distributed in the study area. Whilst the composition and distribution of the fish community will be the ultimate indicator of the success of the project in the long-term, the change in channel dimensions provides a useful short-term surrogate measure of change in fish habitat availability.

Monitoring of channel form and dimensions has involved the measurement of three components:

- Thalweg position and elevation
- Channel cross-sections
- Dimensions of scour pools.

Only the results of the thalweg and scour pool monitoring are presented in this paper.

The low-flow thalweg was surveyed twice prior to the commencement of the in-stream works (1999 and 2000) and once since completion of the works (2002). It is proposed that the thalweg will be resurveyed at intervals of three and five years after the completion of the rehabilitation structures. Monitoring of the scour holes formed at the end of the deflectors has occurred in March 2002 and March 2003.

Results of monitoring of channel form and dimensions

Thalweg monitoring

Prior to the commencement of in-stream works the mean elevation (metres above sea level)(ASL) of the thalweg (the thread of deepest water) in the stream section upstream of the deflectors (between 647 m upstream of bridge and 100 m downstream of bridge) was 563.22 m. The same parameter was 563.01 m ASL in 2002 after the deflectors were installed and operational for 12 months, a difference of 0.21 m between sampling occasions. By contrast, the mean elevation of the thalweg in the stream length affected by the deflectors (from 150 m to 1060 m downstream of bridge) went from 562.86 m ASL in 2000 prior to in-stream works, to 562.23 m ASL after the deflectors were installed and operational for 12 months, a difference of 0.63 m.

Whilst these differences in bed-lowering above and below the in-stream works appear slight, graphs of the change in the bed elevation clearly demonstrate the effects of the deflectors in lowering the bed of the river (**Figure 8**). Figure 8 shows the non-random nature of the change in bed elevation, with a significantly different relationship between bed elevation and distance since the construction of the deflectors.

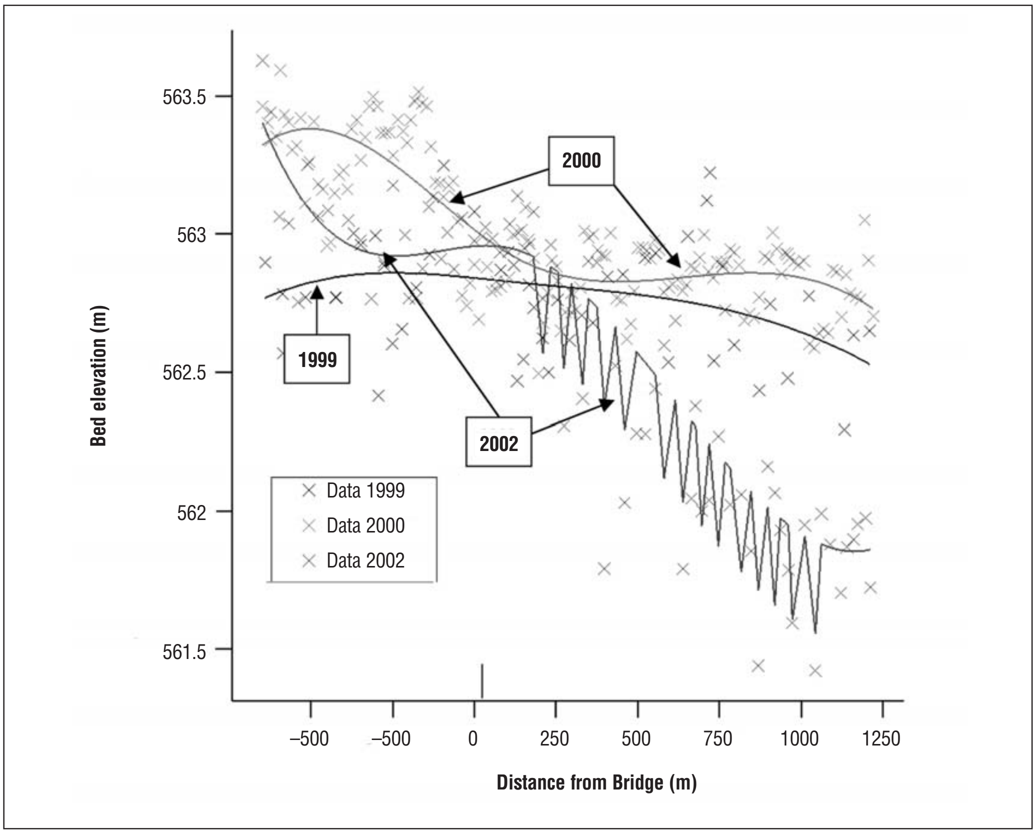

Figure 8. Graphs showing change in bed elevation with distance in the Murrumbidgee River in 1999 & 2000 (pre in-stream works) and 2002 (post in-stream works). The lines represent smoothed functions fitted to the raw data, and allowing it to change from year to year. The statistical analysis takes account of the very strong correlation of one measurement to another. An average effect of the deflectors has been incorporated into the 2002 fitted function. The bridge is at distance 0, with negative distances indicating upstream of the bridge and positive distances downstream of the bridge

Monitoring of scour pools

Preliminary visual monitoring during construction indicated that water velocity around the toe of the deflectors had increased almost immediately and active sand scouring could be observed.
A series of measurements of the scour pools were taken in March 2002, approximately 10 months after the completion of the in-stream works program, and again in March 2003, with the following measurements recorded (**Figure 9**):

- Maximum depth of the scour pool,
- [A] width of scour pool on upstream side of deflector,
- [B] distance from edge of scour pool to tip of deflector,
- [C] upstream extent of scour pool from the midpoint of the tip of deflector, and
- [D] total length of scour pool.

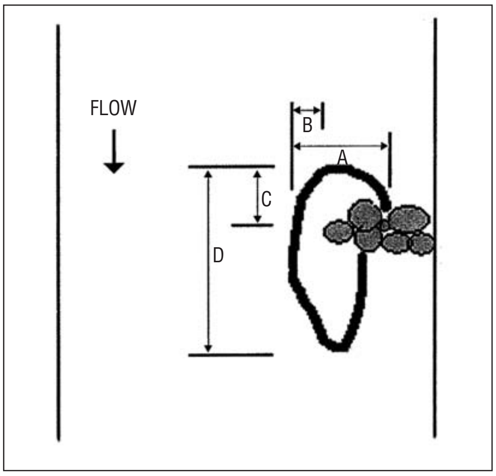

Figure 9. Measurements taken of scour pools formed by deflectors

Monitoring of the effects of the deflectors indicate that they have been successful in creating and maintaining small-scale scour pools. These pools are up to 1.5 m deep and 13.6 m in length (**Table 1, Figure 10**). As well as enhancing water depth, the deflectors are also providing considerable variability in hydraulic conditions, with a range of flow types present, varying from slack water in the lee of the deflector to deep, fast flow (~1 m/second) at the tip of the deflector. These deep and fast-flowing habitats were totally absent from the study area prior to the rehabilitation program.

Table 1. Dimensions of scour pools formed at the end of deflectors. Measurements taken in March 2002 and March 2003. Refer to Figure 3 for details of deflector grouping

Deflector group	Deflector no.	Max. depth (m)		(A) Width (m)		(B) Tip to edge (m)		(C) upstream extent (m)		(D) Length (m)	
		2002	2003	2002	2003	2002	2003	2002	2003	2002	2003
I	1	0.8	0.3	3.2	4.2	1.0	2.2	3.0	3.0	6.5	6.0
I	2	1.15	0.85	4.4	7.2	1.8	4.0	2.7	4.0	4.6	14.0
I	3	1.5	0.82	7.0	7.3	5.7	2.3	3.3	2.5	7.8	13.5
I	4	1.35	0.71	6.8	7.0	3.6	2.2	3.5	3.0	10.3	9.1
I	5	1.55	1.10	6.5	8.2	3.2	4.0	4.8	4.4	13.2	17.4
I	6	1.5	0.76	8.5	7.7	3.3	3.5	3.7	2.9	9.8	11.5
II	7	0.95	0.51	7.7	7.6	3.2	2.1	3.0	4.0	8.3	7.3
II	8	1.2	1.05	8.6	10.0	3.3	4.0	4.0	5.7	9.0	20.0
II	9	0.95	0.73	6.0	7.3	2.5	3.3	2.5	3.1	9.0	17.7
III	10	0.35	0.08	2.8	2.3	1.2	0.8	1.5	0.9	2.9	2.1
III	11	1.05	0.91	4.4	8.5	2.4	3.9	2.5	4.5	7.0	11.5
III	12	1.35	1.31	6.5	11.1	3.6	5.6	3.3	4.3	12.0	14.0
III	13	0.65	0.45	2.2	7.5	1.2	2.3	1.5	3.0	3.8	8.0
III	14	1.3	1.09	7.8	9.9	3.8	5.1	4.5	3.7	11.8	19.0
III	15	1.35	1.01	9.0	7.9	4.0	3.3	4.0	3.5	13.6	19.0
Mean		1.13	0.78	6.09	7.58	2.92	3.24	3.19	3.50	8.64	12.67

Figure 10. The scour pool at the end of deflector No. 3. Note the sand depositing downstream of the scour pool

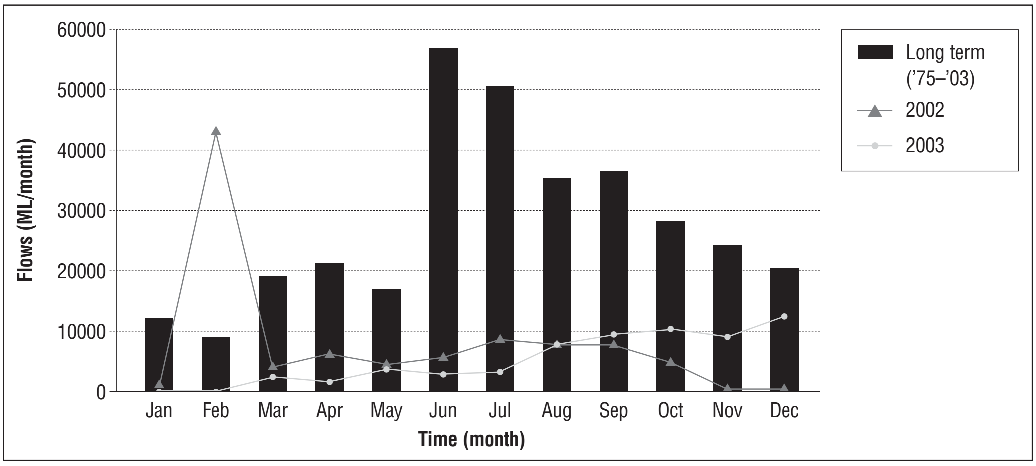

Figure 11. Long-term average monthly flow (histogram) and monthly flows (lines) at Lobbs Hole on the Murrumbidgee River (upstream of Tharwa) in 2002 and 2003 following completion of in-stream works

It must be remembered that streamflows in the Murrumbidgee River following the completion of the in-stream works were extremely low, as a result of the worst drought in 100 years (**Figure 11**). It must also be realised that following the severe Canberra bushfires of January 2003, and subsequent extensive erosion from burnt areas following the fires, coupled with the low drought flows, the ability of the deflectors to create and maintain scour pools under such extreme conditions is remarkable, and that in normal or average years, the depth and extent of the scour pools may have been considerably greater.

Four of the deflectors (Nos. 1, 7, 10 & 13) have not functioned very well, with only small, shallow scour pools produced. Deflectors 1, 7 and 10 are all at the upstream extremities of deflector groups, and so are sensitive to minor shifts in the thalweg position. Deflector 10 has been totally swamped by sand and is now isolated from the main river channel (**Figure 12**), whilst deflector 13 has a structural defect in the middle, which is allowing water to flow through the deflector rather than around it. The deflectors at the upstream end of a group seem to be the least effective, as a minor change in the position of the thalweg can effectively move the flow away from the deflector and leave it prone to being swamped by sand.

It can be seen from **Table 2** that in the majority of cases, the dimensions of the scour pools enlarged between 2002 and 2003, with the only exception being depth. Comparing depth between years is not particularly informative, as depth is a relative measurement dependent on the flow conditions at the date of measurement. Immediately prior to the 2003 measurements, the river was largely dry and had ceased flowing as a result of severe drought in the Canberra region and southeastern Australia generally. Light rain in late February 2003 caused the river to flow and water levels to rise slightly, but the decrease in mean depth is thought to be largely due to lower water levels rather than a decrease in the absolute depth of the scour holes. A series of ad-hoc measurements in March 2003 of water depths in the reach containing the deflectors, but away from the deflectors themselves, revealed the average water depth to be 0.18 m (minimum 0.08, maximum 0.3). The other dimensions of the scour pools are largely independent of water height. A more valid comparison of depth is to compare depths in the scour pools and in areas away from the scour pools at the same time.

Figure 12. Deflector No. 10 which has been swamped by sand

Table 2. Mean dimensions (metres) of scour pools in March 2002 and 2003. Data for 'all' includes all 15 deflectors. Data for 'effective' deflectors is for deflectors considered effective and excludes deflectors 10 and 13 in March 2002 and deflectors 1, 7, 10 and 13 in March 2003 (see discussion above)

Dimension	March 2002	March 2003
Mean maximum depth (all)	1.13	0.78
Mean width (all)	6.09	7.58
Mean tip to edge (all)	2.92	3.24
Mean upstream extent (all)	3.19	3.50
Mean total length (all)	8.64	12.67
Mean maximum depth (effective)	1.23	0.94
Mean Width (effective)	6.65	8.37
Mean tip to edge (effective)	3.18	3.75
Mean upstream extent (effective)	3.45	3.78
Mean total length (effective)	9.45	15.15

The sand that is being scoured to form the scour pools is being deposited between the deflectors, which may over time lead to some narrowing of the low-flow channel. Whether this accumulation of sand remains during the high-flow periods is unknown at this time. The majority of the woody debris that was incorporated in alternate deflectors has been totally swamped by sand, and has not been successful in providing significant amounts of woody debris. When the deflectors were constructed, the woody debris was installed 3–5 m back from the tip of the deflector. This distance was obviously too great as the scouring effect of the deflector does not extend far enough back on the downstream side to keep the woody debris within the scour pool (**Figure 13**). Any future projects that incorporate snags into deflectors should ensure that the snags are located as close as possible to the deflector tip.

The intention behind the deflector spacing was that the scour holes of adjacent deflectors would link up, but examination of the total length of the scour pools in **Tables 1 and 2** indicates that this has not happened. There is a slightly deeper channel that extends from the downstream end of the scour pools, but it does not reach the next downstream scour pool.

The habitat pool completely filled with sand, with the woody debris totally buried. Although only a relatively minor component of the

Figure 13. The scour pool of deflector No. 12. Note the snag near the tip of the deflector is still within the pool, whilst the snag in the middle of the deflector has been buried by sand. (see Figure 6 for how the deflector looked immediately after construction)

rehabilitation strategy, the failure of the river to maintain this pool is disappointing. It indicates that the quantity of sand moving down the river is too large for the river to cope with, and an alternative strategy for the creation of large pools needs to be developed.

Fish sampling conducted in November/December 2000 and 2001 recorded the endangered trout cod present immediately adjacent to the trial deflectors, indicating that the deflectors are fulfilling their anticipated role of providing enhanced fish habitat. Trout cod were not recorded anywhere else in the impacted section. However, the presence of threatened trout cod at a trial deflector indicates that the structures have a good probability of enhancing fish habitat. The success of the rehabilitation measures can only be assessed through the implementation of a long-term monitoring program that will extend far beyond the funded life of the project.

Lessons learnt

This project has significantly advanced our knowledge of mechanisms for dealing with sediment in large streams in Australia. The spacing of deflectors, as suggested by the international literature, was clearly not appropriate for the study site at Tharwa. Even by adopting the most conservative of spacing estimates (three times the low-flow channel width), scour holes failed to link up to provide a continuous thread of deeper water. The results of this project suggest that a deflector spacing of between 1 and 1.5 times the low-flow channel width would have been required to create linked scour pools.

The project has demonstrated that scour pools can be created and maintained by deflectors, even through periods of lower than average flow (drought) and higher than average sediment input (from bushfires).

The study has highlighted the importance of investigating whether the location of the thalweg within a stream channel is constant, as even a relatively minor change in thalweg position can seriously compromise the effectiveness of individual deflectors. The deflectors at greatest risk of isolation or swamping by sand are those at the end of a group, where minor changes in thalweg position can isolate individual deflectors.

In streams with high sediment loads such as the Murrumbidgee at Tharwa, the benefits of incorporating woody debris into deflectors appear minimal, as sediment displaced by scour pools tends to swamp the snags.

If one lesson is to be learnt from this project, it is that it is far more cheap, easy and effective to conserve and protect existing good-quality fish habitats than it is to attempt to restore or recreate them after damage.

Acknowledgements

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