INNOVATIVE FISHWAYS – MANIPULATING TURBULENCE IN THE VERTICAL-SLOT DESIGN TO IMPROVE PERFORMANCE AND REDUCE COST

Martin Mallen-Cooper, Brenton Zampatti, Ivor Stuart, and Lee Baumgartner

June 2008

Fishway Consulting Services
Kingfisher Research
South Australian Research and Development Institute
NSW Department of Primary Industries
Arthur Rylah Institute for Environmental Research

Produced for: Murray-Darling Basin Commission
EXECUTIVE SUMMARY

A major goal of the MDBC’s Native Fish Strategy is restoring fish passage and one of the most successful mechanisms of doing this is to construct vertical-slot fishways. The fishways presently being installed on the Murray River Locks are the vertical-slot design and are world-class in functionality, passing a diversity of migratory fish species and a wide size range from 60 mm to 1000 mm in length. These fishways, however, are costly and their broad-scale application across the thousands of barriers throughout the Basin is unlikely to be practical.

A major factor in the capital cost of vertical-slot fishways is the gradient (slope) of the fishway channel, which determines the total length of the fishway. The present study tested two methods of increasing slope and improving fish passage by reducing turbulence within the fishway pools, by i) improving energy dissipation with wall roughness and ii) reducing fishway discharge using middle sills placed in each vertical-slot baffle. The study focused on improving the passage of small-bodied fish (< 60 mm long) as these have poor swimming ability and are often the biologically limiting factor in increasing the gradient of fishways.

Wall roughness and middle sills greatly improved fish passage in a short (two standard pools) experimental 1:20 gradient fishway, with hundreds of small-bodied fish (25-55 mm long) ascending the fishway in 30 minutes. From 6 to 13 times more small fish ascended the fishway with middle sills compared with an unmodified fishway with standard turbulence. Middle sills appeared to be slightly more effective than wall roughness and are a simple solution to significantly improving fish passage. Fishway discharge and attraction, however, are reduced with middle sills, primarily at low flows, and this needs further assessment, both in 1:18 and 1:32 gradient fishways.

The principle of reducing discharge to improve passage of small-bodied fish provides scope to change the shape of the vertical-slot baffle to suit a range of different ecological and hydrological needs, such as passing large-bodied fish with wider slots or operating at low flows in low-discharge streams with narrower slots. A ‘flared-slot’ design is presently being applied to three new fishways on the lower Darling River. These fishways will be built on a 1:20 gradient but the fish passage functionality, in species and size range, is intended to be greater than the present 1:32 fishways on the Murray River, although attraction discharge will be reduced.

The present study assessed passage through two pools of a 1:20 gradient fishway. A pilot test using middle sills in the full length (26 baffles) of the Lock 8 fishway (1:32 gradient) resulted in 649 carp gudgeon, 25 to 45 mm long, ascending the fishway in less than one day, showing the potential for small-bodied fish to ascend long fishways with reduced turbulence. It also shows the potential to improve the functionality of the existing Murray River fishways as the Lock 8 fishway had previously passed only 4 carp gudgeon in 20 days, whilst 9528 were collected at the fishway entrance (Stuart et al. 2008).

The passage of carp gudgeons, which are very poor in ascending fishways, is an indication that a range of small-bodied fishes can ascend modified fishways, including small threatened species such as olive perchlet and Murray hardyhead. Restoring the ecological processes of dispersal and recolonisation, through effective fishways, will be an important part of recovering the populations of these species.
Innovation in fishway design

The fishway entrance had much higher abundance of fish than any of the other treatments, with up to 35,000 fish collected in 30 minutes. Whether the reduced turbulence designs can pass these fish over an extended time or prevent this aggregation by operating continuously is unknown and requires investigation. The high abundance of fish easily collected at the fishway entrance confirms that a fish lock provides the greatest surety of passing these fish quickly and meeting the ecological objectives of fish passage.

The present experiments have shown that turbulence, or energy dissipation, can be manipulated or reduced to greatly improve fish passage of small-bodied species. This is a major advance in our understanding of fishway design and has broad-scale application across the Murray-Darling Basin. The results have already led to new fishways with improved functionality at lower cost in the Basin and have major potential to improve the functionality of existing 1:18 and 1:32 gradient fishways.

Key recommendations

Further work is needed on: i) extrapolating the results to long fishways, ii) passage rates required to prevent aggregations below weirs and iii) assessing the effects of reduced entrance discharge on fish attraction. These three aspects should be investigated for both large and small-bodied fish at a:

- long 1:18 fishway (e.g. at Torrumbarry Weir), with potential application to many existing fishways in the Murray-Darling Basin
- long 1:32 fishway (e.g. at Lock 8), with potential application to the new Murray River fishways.
1 INTRODUCTION

1.1 Background

The Murray-Darling Basin Commission (MDBC) is presently undertaking the restoration of fish passage along the Murray River from Hume Dam to the sea (Barrett and Mallen-Cooper 2006). The major component of this program is the construction of vertical-slot fishways on the main stem of the river. Vertical-slot fishways have been proven to be effective in passing native fish, notably at Torrumbarry Weir (Lock 26) and more recently at Locks 7, 8, 9, and 10. The vertical-slot fishways presently being designed and built for the Locks on the Murray River are world-class in functionality, passing a high diversity of migratory fish species and a wide size range from 60 mm to 1000 mm in length. These fishways, however, are costly and their broad-scale application across the thousands of barriers throughout the Basin is unlikely to be practical.

A major factor in the capital cost of vertical-slot fishways is the gradient of the fishway channel, which determines the total length of the fishway. The present study tests innovations of the vertical-slot fishway design that are aimed at increasing the gradient while retaining, or improving, the present functionality of the new vertical-slot fishways on the Murray River.

1.2 Vertical-slot fishway design

There are two major hydraulic characteristics used in the design of vertical-slot fishways to optimize passage of small-bodied and large-bodied fish: i) the turbulence in the fishway pool and ii) the maximum water velocity in the slot between each pool. These two parameters directly influence the gradient, length and cost of these fishways.

In 2005 the MDBC funded experiments at the Lock 8 fishway on manipulating the shape and roughness of the vertical slot to create zones of low water velocity; the objective being to enhance passage of small-bodied fish. These experiments showed that in the present designs of vertical-slot fishways being used in the Murray-Darling Basin, turbulence is more limiting for fish passage than the maximum velocity in the slot (Fishway Consulting Services 2005). The MDBC also funded CFD (Computational Fluid Dynamics) modeling to test variations of the vertical-slot-fishway design and this showed that adding coarse-scale roughness to the walls of the fishway pools has the potential to significantly reduce turbulence (WorleyParsons 2005).

Turbulence can be manipulated in a fishway pool either by: i) improving dissipation of energy in the pool or ii) reducing the amount of energy entering the pool. The present study tested the first method by adding wall roughness and the second by reducing discharge by partly blocking the vertical-slot.

The gradient of the vertical-slot fishway selected for testing was 1:18, as this passes large-bodied native fish (> 100-120 mm long) well but does not pass small-bodied native fish (< 90 mm long), which includes a range of species that do not grow larger than 90 mm (Mallen-Cooper 1999, Stuart et al. 2008). Hence, the aim was to improve the passage of small-bodied fish in a fishway design known to pass large-bodied fish, and develop knowledge that could be extrapolated to other fishway designs.
2 METHODOLOGY

2.1 Site

The experiments were conducted in February 2008 using the vertical-slot fishway at Lock 8 on the Murray River. The fishway is on a 1:32 gradient and false floors were installed to provide a steeper gradient of 1:18 in the lower three pools.

2.2 Test Treatments

Four treatments were used:

i) **Wall roughness**, to assess fish passage by improving energy dissipation while maintaining fishway discharge.

Pilot experiments tested a variety of designs of wall roughness with 0.3 m diameter PVC black pipe screwed onto plywood and these were assessed visually. The design with the most efficient energy dissipation used 0.3 m long sections of pipe mounted at 45° to the plywood board. Holes of 50 mm diameter were drilled in each pipe and a hole was cut into the board where the base of each pipe was mounted, which allowed flow to pass through (Fig. 1). The whole board was angled at 20° to the wall so that the pipes were angled into the flow (Fig. 2).

One wall unit was used per fishway pool except in the 90° degree corner pool where two were used (Fig. 3). Each unit was positioned opposite the vertical-slot in the baffle with the intent of absorbing the energy from the jet of water entering the pool.

ii) **Middle sills**, to assess fish passage by reducing the amount of energy entering the pool, by reducing discharge while maintaining pool volume.

Sills that were 250 mm high were positioned in the middle of the slot of the vertical-slot baffle (Fig. 4 & 5). The total water depth was 900-910 mm, which enabled water to flow under and over the sill.

iii) **Top control**, to assess which fish could ascend the unmodified fishway at a 1:18 gradient.

iv) **Entrance control**, to assess fish that were moving upstream and entering the fishway from the river.

This sample comprised fish captured one baffle upstream of the fishway entrance with the head loss per baffle and entrance reduced to 20 - 40 mm. The low head loss reduces water velocities to 0.63 – 0.89 m s\(^{-1}\) in the vena contracta, approximately 0.3 m downstream of the slot, and to 0.44 - 0.62 m s\(^{-1}\) in the slot. Turbulence is also reduced to less than 10 W m\(^{-3}\). These low velocities and turbulence were intended to enable all small fish and crustaceans that were attempting to migrate upstream in the river to enter the fishway.

For the first two treatments, **wall roughness** and **middle sills**, fish passage was assessed through three baffles and two pools. The upper pool was at a fishway corner that had a higher pool volume with reduced turbulence and hence did not represent a typical fishway.
pool. The treatments in the corner pool provided the antecedent conditions for flow patterns in the following test pools. Videos showing the turbulence of the standard 1:18 fishway, wall roughness, and middle sills are shown in Figures 6 to 8.

![Wall roughness unit](image1)

**Fig. 1.** Wall roughness unit.

![Flow in fishway](image2)

**Fig. 2.** Wall roughness unit in the fishway.
Fig. 3. Layout of the lower pools of the Lock 8 fishway showing the location of the: false floors providing a 1:18 gradient, wall roughness units, and fish-trap.
Fig. 4. Diagram of *middle sills* shown in the slot of the vertical-slot baffle that were used to reduce fishway discharge and turbulence.

Fig. 5. *Middle sills* placed in the slot of the vertical-slot baffle of the Lock 8 fishway.
Fig. 6. Video of the Lock 8 fishway showing the turbulence of an unmodified 1:18 vertical-slot fishway (double-click picture to start video).

Fig. 7. Video of the Lock 8 fishway showing the turbulence with a roughened wall in a 1:18 vertical-slot fishway (double-click picture to start video).

Fig. 8. Video of the Lock 8 fishway showing the turbulence with middle sills of a 1:18 vertical-slot fishway (double-click picture to start video).
2.3 Experimental procedure

The experimental procedure was:

i) dewater the fishway,
ii) install the experimental treatment,
iii) pass the maximum discharge through the fishway to flush any small fish downstream,
iv) adjust the discharge through the fishway, by using an upstream fishway gate, and measure the head losses (to calculate approximate water velocity) at each experimental baffle - the target head loss range was 150-170 mm (equivalent to a 1:18 fishway),
v) install the fish-trap at the upstream end of the experimental treatments (or at the downstream end for the entrance control) (Fig. 3),
vi) operate the fishway for 30 minutes (pilot experiments determined that sufficient fish for the experiment used the fishway in this period),
vii) measure the head losses at each experimental baffle to ensure they were still within the range of 150-170 mm (an a priori decision was made to not include results that were outside this range and the experiment would be repeated)
viii) record the numbers of each fish species and crustaceans that ascend the fishway and measure length from a random subsample of 100 fish from each species. High numbers of fish were sub-sampled by counting and identifying fish in three 200 ml samples.

The experiment was designed to test a fishway on a 1:18 gradient, but it was difficult to achieve consistent head losses of 165 mm at each baffle so a range of 150 – 170 mm was used, which represents a fishway gradient of 1:20 to 1:18, using 3 m long pools.

The fish-trap was covered in 2 mm square mesh, which was targeted at catching small-bodied fish. Larger fish may exhibit trap shyness with such fine mesh but the passage of larger fish (> 100 mm in length) in 1:18 vertical-slot fishways is well-known. Temperature and dissolved oxygen were recorded each day. All experiments were done during daylight, as earlier research had shown high numbers and a diverse range of species of small-bodied fish migrating upstream during this period.

2.4 Experimental design

Five replicates of each treatment were conducted, thus twenty samples were collected. A randomised block design was used, where the order of the four experimental treatments was randomised within a block of trials and each block was replicated over time. This design is robust to variations in daily and weekly fish migrations.

2.5 Pilot experiment – full length of fishway with middle sills

A one-off pilot experiment was conducted with middle sills in all 26 baffles of the Lock 8 fishway, at the design gradient of 1:32. The sills were 0.60 m high with 0.30 m depth of water above and below the sill. The experiment was run from mid-afternoon to mid-morning the following day, which was outside the time of other trials that were run during daylight. The same trap was used but located at the exit of the fishway. This experiment enabled a pilot trial of the applicability of a full length fishway with middle sills.
2.6 Data analysis

Two-way analysis of variance (ANOVA) was conducted on the four most common species followed by pairwise comparisons of the treatment means using Bonferroni correction for multiple comparisons ($P<0.05$). The data was log-transformed (Ln +1) to achieve homogeneity of variance for each species (Bartlett’s Test, chi-squared = 1.51 – 3.62, $P = 0.30 – 0.68$) as the untransformed data did not have homogeneous variance (Bartlett’s Test, chi-squared = 23.0 – 70.8, $P < 0.001$)

Using mean abundance alone reveals little about the underlying length frequency distributions of fish gaining passage. Certain size classes may gain passage more efficiently or sub-optimally in one or more treatments. Differences in cumulative length frequency distribution were therefore tested using a two-sample, one-tailed Kolmogorov-Smirnov large sample test. This test was only completed for species where more than 25 individuals were collected per treatment.
3 RESULTS

3.1 Species composition and abundance

The fishway floor was set at a gradient of 1:18 but head losses between baffles, which indicate water velocity and energy entering each pool, varied so that the results conservatively apply to a lower gradient and are referred hereafter as 1:20. In the 20 trials there were five native fish species and two species of crustaceans (*Paratya* and *Macrobrachium*) with a total number of 90,655 (Table 1). No non-native fish species were collected. Water temperature varied from 24.7 to 28.0°C and dissolved oxygen varied from 7.0 to 7.3 mg L⁻¹. More fish were collected from the entrance control than for any other treatment although the *middle sills* treatment passed substantially more fish than the wall roughness trial. The lowest number of fish were collected from the top control (Table 1).

<table>
<thead>
<tr>
<th>EXPERIMENTAL TREATMENT</th>
<th>1:20 Top control</th>
<th>Wall roughness</th>
<th>Middle sills</th>
<th>Entrance control</th>
<th>TOTALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carp gudgeons</td>
<td>222</td>
<td>777</td>
<td>2935</td>
<td>61449</td>
<td>65383</td>
</tr>
<tr>
<td>Australian smelt</td>
<td>445</td>
<td>1811</td>
<td>3718</td>
<td>18344</td>
<td>24318</td>
</tr>
<tr>
<td>Unspecked hardyhead</td>
<td>15</td>
<td>22</td>
<td>103</td>
<td>425</td>
<td>565</td>
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<tr>
<td>Bony herring</td>
<td>25</td>
<td>15</td>
<td>145</td>
<td>156</td>
<td>341</td>
</tr>
<tr>
<td>Murray rainbowfish</td>
<td>1</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>11</td>
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<tr>
<td>Freshwater crustaceans</td>
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<td>1</td>
<td>12</td>
<td>24</td>
<td>37</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90655</td>
</tr>
</tbody>
</table>

The mean number of fish ascending the fishway differed significantly among treatments for carp gudgeons (*F* = 20.17, df = 12, *P* < 0.001), Australian smelt (*F* = 29.74, df = 12, *P* < 0.001) and unspecked hardyhead (*F* = 5.42, df = 12, *P* < 0.014), but not bony herring (*F* = 1.18, df = 12, *P* = 0.35) (Fig. 9). A block, or replicate effect, was also significant for Australian smelt (*F* = 5.71, df = 4, *P* < 0.01).

Pairwise tests identified no statistical difference between the *wall roughness* and *middle sills*, although a greater mean number of fish ascended the latter (Fig. 9, Table 2). The mean abundance of carp gudgeons and Australian smelt ascending the fishway was substantially greater for the *middle sills* treatment than the top control. The *wall roughness* only significantly improved the passage of Australian smelt. For the two most abundant species, carp gudgeons and Australian smelt, the *entrance control* had significantly more fish than any treatment.
Fig. 9. Mean (± S.E.) fish numbers per replicate of the four common species in the four treatments of the experiment.
Table 2. Pairwise ANOVA comparisons using the Bonferroni correction for multiple comparisons.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Carp gudgeons</th>
<th>Australian smelt</th>
<th>Unspecked hardyhead</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Significant</td>
<td>t</td>
<td>Significant</td>
</tr>
<tr>
<td>1:20 Top control v Entrance control</td>
<td>Yes</td>
<td>7.590</td>
<td>Yes</td>
</tr>
<tr>
<td>1:20 Top control v Wall roughness</td>
<td>2.692</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>1:20 Top control v Middle sills</td>
<td>Yes</td>
<td>4.345</td>
<td>Yes</td>
</tr>
<tr>
<td>Wall roughness v Middle sills</td>
<td>1.653</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle sills v Entrance control</td>
<td>Yes</td>
<td>3.244</td>
<td>Yes</td>
</tr>
<tr>
<td>Wall roughness v Entrance control</td>
<td>Yes</td>
<td>4.898</td>
<td>Yes</td>
</tr>
</tbody>
</table>

3.2 Comparison of fish length distribution

There were significantly ($P < 0.05$) smaller carp gudgeons, unspecked hardyhead and Australian smelt, notably in the 20-30 mm size class, at the fishway entrance compared to all treatments (Fig. 10; Fig 11; Table 3). There were no other significant differences among treatments for each species except for Australian smelt, where larger individuals were collected from the top control treatment (Table 3).

Australian smelt had significantly different length distributions among all treatments, but the minimum size class at the fishway entrance, of 25-30 mm, was well-represented in all treatments. There were significantly smaller unspecked hardyhead and bony herring at the fishway entrance compared with the wall roughness but there were no other significant differences among the other treatments for these two species. Nevertheless, the 20-25 mm size class of unspecked hardyhead was only present at the fishway entrance.

3.3 Pilot experiment – full length of fishway with middle sills

The pilot experiment, in which middle sills were installed in all 26 baffles of the Lock 8 fishway (1:32 gradient), was run for 19 hours from 15:30 hr to 10:30 hr. A total of 992 fish were collected at the exit of the fishway, ranging in lengths from 27 - 414 mm (Table 4). The lengths were not significantly different (K-S pairwise comparisons, one-tailed test for large samples, Fig. 12, Table 4) from the middle sills treatment in the main experiment for carp gudgeons and unspecked hardhead but were different for Australian smelt, which had less fish in the smallest size class (25-30 mm) in the pilot full-length experiment.
Fig. 10. Length frequency distributions of carp gudgeons and Australian smelt in the four treatments. Statistical comparisons of these distributions are shown in Table 3.
Fig. 11. Length frequency distributions of unspecked hardyhead and bony herring in the four treatments. Statistical comparisons of these distributions are shown in Table 4.
Table 3. Comparison of length frequency distributions with Kolomogorov–Smirnov two sample, one-tailed test for large samples. Length frequencies that are significantly different have a $P$ value < 0.05 and are shaded in light blue, and ‘NS’ is not significantly different.

<table>
<thead>
<tr>
<th>Top control</th>
<th>Entrance control</th>
<th>Wall roughness</th>
<th>Entrance control</th>
<th>Middle sills</th>
<th>Wall roughness</th>
<th>Middle sills</th>
<th>Wall roughness</th>
<th>Middle sills</th>
<th>26 pools of 1:32 fishway with middle sills</th>
<th>cf.</th>
<th>2 pools of 1:18 fishway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top control</td>
<td>Entrance control</td>
<td>Wall roughness</td>
<td>Entrance control</td>
<td>Middle sills</td>
<td>Wall roughness</td>
<td>Middle sills</td>
<td>Wall roughness</td>
<td>Middle sills</td>
<td>26 pools of 1:32 fishway with middle sills</td>
<td>cf.</td>
<td>2 pools of 1:18 fishway</td>
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<td>cf.</td>
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<tr>
<td>Top control</td>
<td>Entrance control</td>
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<td>Entrance control</td>
<td>Middle sills</td>
<td>Wall roughness</td>
<td>Middle sills</td>
<td>Wall roughness</td>
<td>Middle sills</td>
<td>26 pools of 1:32 fishway with middle sills</td>
<td>cf.</td>
<td>2 pools of 1:18 fishway</td>
</tr>
</tbody>
</table>

Carp gudgeons

| sample m | 136 | 136 | 136 | 151 | 142 | 142 | 50 |
| sample n | 151 | 142 | 150 | 150 | 150 | 150 | 150 |
| $D_{m,n}$ | 49.52 | 0.95 | 5.64 | 22.82 | 37.25 | 1.96 | 3.84 |
| $P$       | $< 0.001$ | NS | NS | $< 0.001$ | $< 0.001$ | NS | NS |

Unspecked hardyhead

| sample m | 71 | 71 | 20 | 71 |
| sample n | 71 | 20 | 71 | 19 |
| $D_{m,n}$ | 11.27 | 6.55 | 0.21 | 3.00 |
| $P$       | $< 0.01$ | $< 0.05$ | NS | NS |

Bony herring

| sample m | 6 | 6 | 6 | 50 | 50 | 19 |
| sample n | 50 | 19 | 50 | 50 | 19 | 50 |
| $D_{m,n}$ | 5.36 | 3.65 | 5.36 | 0.04 | 5.24 | 4.58 |
| $P$       | NS | NS | NS | NS | NS | NS |

Australian smelt

| sample m | 189 | 189 | 189 | 150 | 150 | 200 | 50 |
| sample n | 150 | 200 | 150 | 150 | 200 | 150 | 150 |
| $D_{m,n}$ | 9.78 | 6.00 | 7.62 | 21.33 | 18.40 | 0.60 | 6.00 |
| $P$       | $< 0.01$ | $< 0.05$ | $< 0.05$ | $< 0.001$ | $< 0.001$ | NS | $< 0.05$ |
Table 4. Species composition and length range collected at the exit of the Lock 8 fishway with middle sills installed in all baffles.

<table>
<thead>
<tr>
<th>Species</th>
<th>Fishway exit</th>
<th>Length range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carp gudgeons</td>
<td>649</td>
<td>27 – 42 mm</td>
</tr>
<tr>
<td>Australian smelt</td>
<td>280</td>
<td>25 - 54 mm</td>
</tr>
<tr>
<td>Unspecked hardyhead</td>
<td>19</td>
<td>27 – 48 mm</td>
</tr>
<tr>
<td>Bony herring</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Murray rainbowfish</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Freshwater shrimps</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Golden perch</td>
<td>5</td>
<td>392 - 414 mm</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>992</strong></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 12. Length frequency distributions of small-bodied fish collected at the exit of the Lock 8 fishway with *middle sills* installed at all baffles.
4 DISCUSSION

4.1 Passage of small-bodied fish – abundance

Adding wall roughness redistributes turbulence in a fishway pool by creating a zone of high turbulence and energy absorption on the side with wall roughness, and a zone of low turbulence on the opposite side of the pool. This creates a continuous path between fishway pools, of low turbulence and low water velocities that weaker-swimming fish can exploit to ascend the fishway. Adding middle sills to the fishway baffle reduced discharge and turbulence throughout the fishway pool, again creating continuous zones of low turbulence.

The unmodified, high turbulence, vertical-slot fishway on a gradient of 1:20 provided very poor passage of small-bodied fish (25-55 mm long), which is expected as these fishways are designed for fish greater than 100 mm long. Changing turbulence, while keeping the same fishway gradient, greatly improved functionality with hundreds of small-bodied fish passing through two pools of the fishway in 30 minutes. Adding middle sills increased passage of small-bodied fish 6 to 13 times compared with an unmodified fishway and adding wall roughness increased passage up to four times. This is the first time, to the authors knowledge, that small-bodied fish (25-55 mm long) have been recorded using a relatively steep (1:20) vertical-slot fishway, designed with large pools for large-bodied fish, in the Murray–Darling Basin.

Although the two experimental treatments improved fish passage, significantly higher numbers of carp gudgeons, Australian smelt and unspecked hardyhead were collected from the fishway entrance, with up to 35,000 fish collected in 30 minutes, indicating that passage was still restricted. At sites within the Murray-Darling Basin that have lower abundances of small-bodied fish than at Lock 8 the fish passage demonstrated in the present experiment may be sufficient to pass the migratory population. A knowledge gap that remains is whether the improvements achieved by changing turbulence in the vertical-slot design are sufficient to pass large aggregations of fish and meet the ecological objectives of fish passage. These objectives include: maintaining gene flow between populations, dispersal of immature and mature fish to maintain upstream and downstream abundances, facilitating spawning movements and minimizing predation caused by aggregations below weirs.

At Lock 8 there are very high abundances of small-bodied fishes, particularly carp gudgeons and Australian smelt, which is partly due to the habitat and flow downstream and to the poor passage of some small-bodied fish species in the present fishway (Stuart et al. 2008). Over the three weeks of the experiment the numbers of fish at the fishway entrance declined from 35270 to 2301, as we captured and released fish upstream, indicating that the accumulation of small-bodied fish below the weir was deceasing. At sites with high fish abundance, like Lock 8, a fishway operating continuously with the functionality demonstrated in the present study has potential to prevent aggregations below weirs and should be investigated.

To provide the greatest degree of certainty of meeting the ecological objectives for fish passage on the Murray River and the NFS goal of native fish recovery, a small fish lock is recommended. The high numbers of small-bodied fish captured at the experimental fishway entrance (i.e. the second pool of the Lock 8 fishway) confirm that these fish can be attracted into a fish lock chamber and, hence, can then be passed upstream in one lock cycle (e.g. 60 minutes).
4.2 Passage of small-bodied fish – size

There were significant differences in fish lengths between the fishway entrance and the two turbulence treatments but the greater experimental and ecological difference is in the abundances of fish as described above. There was a greater proportion of the smallest size class of Australian smelt and carp gudgeons at the fishway entrance, but most small size classes were well represented in all treatments. Unspecked hardyhead had a significant group of fish 20-30 mm, which may be young-of-year, that was present at the fishway entrance but poorly represented in the other treatments. The ecology and fish passage requirements of these fish need further investigation.

Carp gudgeons are very poor at ascending the Lock 8 fishway (Stuart et al. 2008) and their ability to ascend the modified fishway, as well as the full length of the Lock 8 fishway in the pilot experiment, is promising. These findings may be applicable to other small-bodied fishes, including species that are threatened or have fragmented populations in the lower Murray River (e.g. southern pygmy perch, Murray hardyhead, flathead galaxias, purple-spotted gudgeon, olive perchlet). Recovery of these populations will partly depend on re-establishing the ecological processes of dispersal and recolonisation through effective fish passage.

4.3 Application and transferability

The results show that either wall roughness or middle sills greatly improve fish passage, although the latter appears to be slightly more effective. The advantage of wall roughness is that it does not reduce attraction at the fishway entrance by reducing discharge through the fishway, but the disadvantage is the complexity of the structure and the reduction in pool volume that is available for large-bodied fish.

Middle sills have the advantage of simplicity but reduce fishway discharge and attraction. If middle sills are applied to the lower section of the vertical-slot baffle the impact of reduced discharge would be less at high flows, because there would be a deep unblocked section of the slot above the sill. Hence, the fishway would be a low turbulence design at low flows that could pass small and large-bodied fish and a high turbulence design for larger fish at higher flows. The ecological assumption with this application is that small-bodied fish are mainly moving upstream at low flows.

The fishway design principle of low turbulence at low flows and high turbulence at high flows can also be applied to fishway designs that do not have multiple exit gates, providing that headwater rises as the flow increases. This is the most common scenario at fixed crest weirs in the Murray Darling Basin. For most sites the middle sills are likely to be more applicable than wall roughness, with the caveat that there may need to be an assessment of the effects of reduced discharge on fish attraction at low flows.

The present experiment describes passage of fish through two fishway pools. The recommended next stage of investigation is to assess extrapolating the results to long fishways. The pilot test result of 649 carp gudgeons, 25 to 45 mm long, ascending the full length of the Lock 8 fishway in less than one day showed the potential for small-bodied fish to ascend long fishways with reduced turbulence. It also shows the potential to improve the functionality of existing fishways as the Lock 8 fishway had previously passed only 4 carp gudgeons in 20 days, whilst 9528 were collected at the fishway entrance (Stuart et al. 2008).

Middle sills were used in the present experiment to elucidate the relationship between fish passage and turbulence. Rather than developing a prescriptive design the findings open up
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Scope to change the slot shape of the vertical-slot baffle to suit a range of different ecological and hydrological needs. For example, the vertical-slot could be wider at the base to enable passage of large-bodied fish like adult Murray cod with narrower or blocked sections above to reduce discharge and turbulence.

Alternately the slot can be flared, with a narrower section at the base to minimize water use in low discharge streams and provide passage of small fish at low flows, with a wider section above for greater attraction for large-bodied fish at high flows. The flared-slot design is presently being applied to new fishways along the lower Darling River, at Burtundy (under construction), Pooncarie (detailed design stage), and Weir 32 (concept design stage). These fishways will be built on a 1:20 gradient but the fish passage functionality, in species and size range, is intended to be greater than the present 1:32 fishways on the Murray River. Passage of high biomass and attraction discharge would be less but the lower Darling River sites are much narrower (e.g. 25 m) than the lower Murray River, the drown-out flows are more frequent and the migratory biomass when the fishway is functioning is expected to be less. The flared-slot design at these sites also served the additional function of not draining the storage in the weir pool at low flows which enabled the fishway to operate longer.

4.4 Recommendations

The findings of the present study can start to be applied at appropriate sites, as described above. Further work is needed on: i) extrapolating the results to long fishways, ii) passage rates required to prevent aggregations below weirs and iii) assessing the effects of reduced entrance discharge on fish attraction. These three aspects should be investigated at a:

- long 1:18 fishway (e.g. at Torrumbarry Weir), with potential application to many existing fishways in the Murray-Darling Basin,
- long 1:32 fishway (e.g. at Lock 8), with potential application to the new Murray River fishways.

If the results of these studies were positive, middle sills should be applied to the 1:32 Murray River fishways to improve their functionality.

5 CONCLUSION

Earlier studies at the Lock 8 fishway and computer (CFD) modeling, both funded by the MDBC, demonstrated that turbulence within fishways may limit fish passage more than the maximum velocity in low-gradient fishways. The present experiments have shown that turbulence, or energy dissipation, can be manipulated or reduced to greatly improve fish passage. This has resulted in a major development in our understanding of fishway design.

The results are widely transferable across the Murray-Darling Basin and have already led to fishways with improved functionality at lower cost in the Basin. The Murray Fishways Tri-State Assessment Program has found that more fish species, life stages and aquatic biota are migrating than previously considered. The response of the Program has been to investigate new methods of improving fish passage to respond to the new ecological data. The present development in fishway design will significantly improve fish passage in the Murray-Darling Basin and aid in achieving the objective of the Native Fish Strategy of recovery of native fish populations, whilst decreasing the capital cost of fishways.
ACKNOWLEDGEMENTS

The project was funded by the Murray-Darling Basin Commission (MDBC). We would like to thank Jim Barrett and John Prentice (MDBC) for their ongoing support in this area of research. We thank Richard Staehr (SA Water) for installing the false floors of the fishways; Robbie Bonner (SA Water) for organising the construction of the wall roughness units and John Mc Neill (SA Water, Lock 8) for building them. Nathan Reynoldson and Adam Baumgartner (New South Wales Department of Primary Industries) provided technical assistance in the field and on-site support was provided by David Sly and John Mc Neill (SA Water, Lock 8).

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