7th International Symposium on Hydraulic Structures Aachen, Germany, 15-18 May 2018
ISBN 978-0-692-13277-7 DOI: 10.15142/T3C061

Smart Baffles to Assist Upstream Culvert Passage of Small-Bodied Fish

J. Cabonce[1], H. Wang[1] & H. Chanson[1]
[1]*The University of Queensland, School of Civil Engineering, Brisbane QLD 4072, Australia*
E-mail: h.chanson@uq.edu.au

Abstract: *Current culvert designs have little evolved since ancient designs. Some recognition of the ecological impact of culverts on natural streams and rivers led to changes in culvert design guidelines, too often associated with un-economical design recommendations. A simple small triangular corner baffle system may assist upstream passage of small body-mass fish in box culvert structures on very flat bed slope, while inducing little reduction in discharge capacity at design flow conditions and creating sizeable slow flow regions at less-than-design flow conditions. The system was tested systematically in a near-full-scale physical model, 0.5 m wide and 12 m long. The present investigation delivered a detailed characterisation of the flow field in smooth and triangular baffled channels, at a scale comparable to a small standard box culvert barrel. Tests showed that small-bodied fish preferred to swim in slow-velocity regions, typically in the baffle corner. To be most effective, the corner baffle size has to be comparable with the fish dimensions, and strong flow reversal must be avoided, since it might confuse fish attempting upstream passage. Finally, design guidelines of fish-friendly culverts must be re-thought, with a focus on fish passage for less-than-design flows and maximising the discharge capacity at design flow. Current design practices must evolve from a semi-empirical approach based heavily on simplistic observations and educated guesses to advanced physics-based theoretical considerations and sound engineering guidelines.*

Keywords: *Box culverts, upstream fish passage, small-bodied fish, triangular corner baffles, physical modelling, fish testing, fish-friendly culvert design guidelines.*

1. Introduction

Longitudinal stream connectivity is a basic requirement for a healthy ecosystem and waterway, and aquatic diversity. During the last four decades, concerns regarding the ecological impact of road crossings have led to an evolution in their design (Chorda et al. 1995, Warren and Pardew 1998, Hotchkiss and Frei 2007). The environmental impact on fish passage may affect the upstream and downstream catchments with adverse effect on the stream ecology (Briggs and Galarowicz 2013). Common culvert fish passage barriers include excessive vertical drop at the culvert outlet (perched outlet), high velocity in the barrel, excessive turbulence, and debris accumulation at the culvert inlet (Behlke et al. 1991, Olsen and Tullis 2013). The increased velocities in the barrel can also produce reduced flow depths, which may potentially yield inadequate flow depths for fish passage, relative to the culvert size. Higher culvert exit velocities may increase perched outlet fall heights, i.e. fish barrier, with increased scour hole development downstream. Hydraulic jumps and standing waves in the inlet or outlet could generate further hindrance to fish passage (Wang et al. 2017).

A better understanding of the ecological impact of culverts on natural river systems led to changes in culvert design guidelines, too often leading to un-economical designs (Behlke et al. 1991, Chorda et al. 1995, Fairfull and Witheridge 2003). Figure 1 shows a typical multi-cell box culvert in Brisbane (Australia), at the end of a rainstorm event, for a discharge less than its design capacity. Baffles may be installed along the barrel invert to provide fish-friendly alternatives (Olsen and Tullis 2013, Duguay and Lacey 2014). For low discharges, the baffles decrease the flow velocity and increase the water depth to facilitate fish passage, while offering rest areas (Cahoon et al. 2007). But baffles do reduce substantially the culvert discharge capacity (Larinier 2002, Olsen and Tullis 2013), thus increasing substantially the total cost of the structure to achieve the same design discharge and afflux. The additional costs may encompass those for additional precast cell units, construction of a second structure in an anabranch or selection of a bridge structure instead of a culvert.

A simple small triangular corner baffle system was herein tested systematically in a near-full-scale physical facility of a box culvert barrel. The system was developed to assist upstream passage of small-bodied fish for less-than-design flows, while having little impact on the afflux at design discharge. It is the aim of this study to deliver a detailed characterisation of the flow field in smooth and triangular baffle rectangular channels, at a scale comparable to a small standard box culvert barrel. The investigation provides relevant data to derive a predictive physically-based model of the flow characteristics of triangular baffle culverts, for a range of less-than-design flows. Both hydrodynamic measurements and fish endurance tests were repeated with several configurations to assess the benefits in terms of small-bodied fish.

Figure 1. Standard box culvert along Whitton Creek, below Kale St, Chapel Hill QLD (Australia) on 30 March 2017 at the end of a major rainstorm

2. Physical Investigation, Instrumentation and Methods

2.1. Experimental Apparatus and Instrumentation

Laboratory experiments were conducted in two 12 m long 0.5 m wide rectangular horizontal flumes, representing a box culvert barrel. Both flumes were supplied by a constant head system and equipped with an intake structure equipped with calming devices, flow straighteners, and a three-dimensional convergent to deliver a quasi-uniform velocity field at the upstream end of the flumes. The channel boundaries were made of smooth PVC invert and glass sidewalls (Fig. 2). One flume was supplied with fish-friendly waters and equipped with upstream and downstream stainless steel screens to ensure fish safety. The second flume did not have screens; experiments in that flume are reported in Table 1 with an asterisk (*). The size of the flumes was comparable to a small single-cell culvert structure typical of eastern Australia, and would correspond to a 1:4 scale model of a single cell of the large culvert seen in Figure 1.

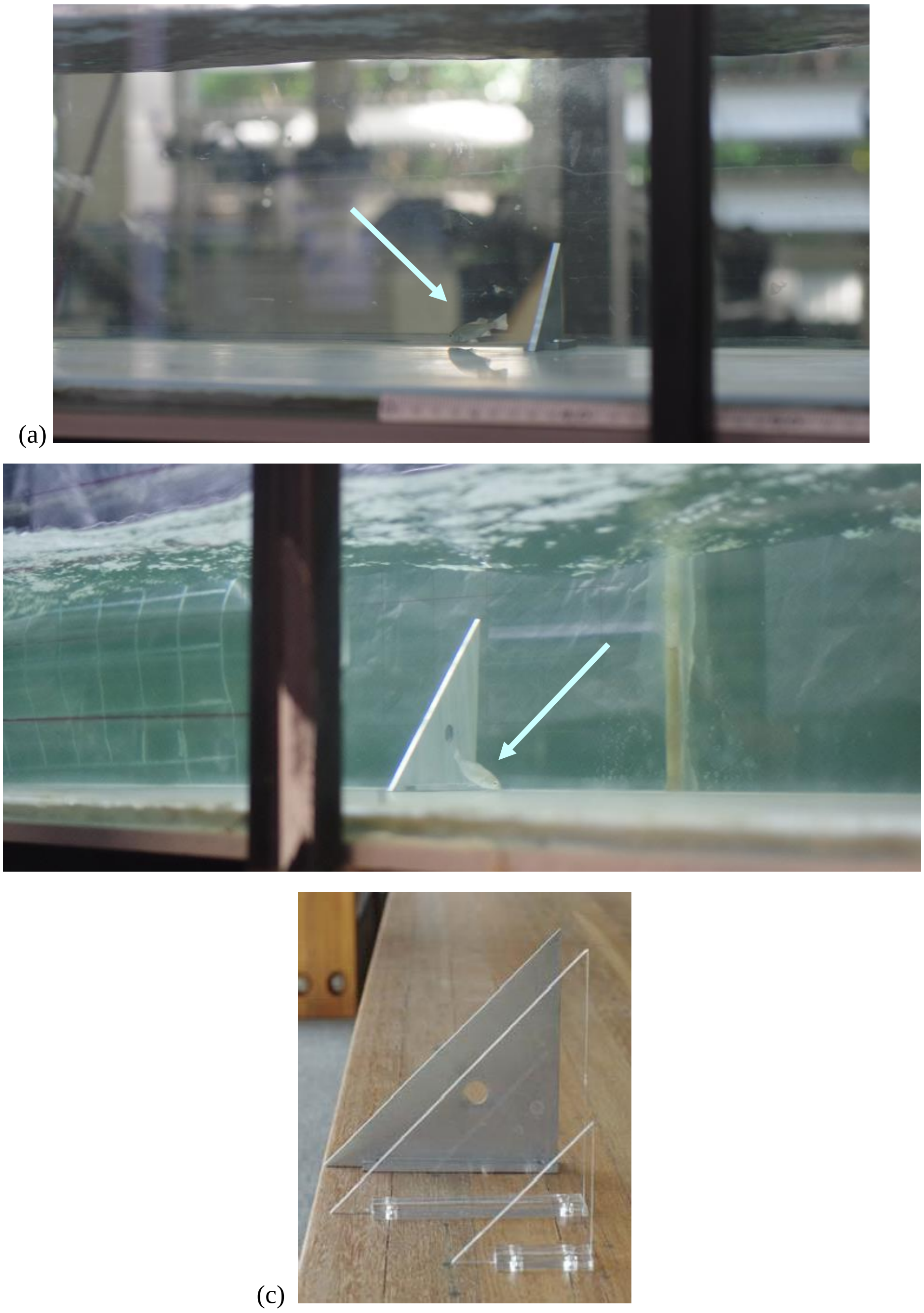
The water discharge was measured using an orifice meter or Venturi meter, designed based upon the British Standards. The water depths were recorded with rail mounted point gages. Velocity measurements were performed with a Prandtl-Pitot tube and an acoustic Doppler velocimeter (ADV). The Prandtl-Pitot unit was a Dwyer® 166 Series tube with a 3.18 mm diameter tube, and enabled pressure and velocity measurements. The ADV unit was a Nortek™ Vectrino+ equipped with a side-looking head and sampled at 200 Hz. The translation of the velocity probe in the vertical direction was controlled by a fine adjustment traverse connected to a digimatic scale unit. The experiments were documented using digital SLR cameras and digital video-cameras, including a Casio™ Exilim EX-10 with high-speed video capabilities.

Table 1. Experimental flow conditions for detailed velocity measurements in smooth and baffled culvert barrel (present study)

Configuration	Q (m^3/s)	d (m)	h_b (m)	L_b (m)	Comment
Smooth channel	0.0261 0.0556 0.0556 (*)	0.096 0.162 0.133 (*)	N/A	N/A	Prandtl-Pitot tube & ADV system.
Medium baffles	0.0556	0.1625	0.067	0.67	Prandtl-Pitot tube.
Large baffles	0.0556	0.173	0.133	0.67	Prandtl-Pitot tube.
	0.0556	0.172	0.133	1.33	
	0.0261	0.1035	0.133	1.33	
Baffles with holes	0.0556 (*)	0.160 (*)	0.133	0.67	Baffles with Ø 13 mm hole. Prandtl-Pitot tube & ADV system.

Notes: d: flow depth measured at x ~ 8 m; h_b: baffle height; L_b: baffle spacing; Q: flow rate; (*): experiment conducted without downstream screen.

A total of five boundary configurations were tested. The reference experiments were conducted with the smooth boundaries (Table 1, Smooth channel). Further experiments were performed with several types of isosceles triangular corner baffles (Fig. 2). The triangular baffles were fixed in the bottom left corner of the flume. Each baffle was an isosceles triangle with a 45º angle. Two baffle heights were tested: h_b = 0.067 m and 0.133 m. For one experiment, a Ø 13 mm hole was cut in each large baffle to reduce the flow reversal intensity (see below) (Fig. 2b & 2c). The Ø 13 mm hole centre was located 45 mm above the bed and 45 mm from the left sidewall. Two different longitudinal baffle spacings were used: L_b = 0.67 m and 1.33 m. Experiments were conducted for water discharges Q = 0.0261 m^3/s and 0.0556 m^3/s (Table 1), corresponding to less-than-design flow for which a subcritical flow motion would be observed in the culvert barrel.



(a) (b) (c)

Figure 2. Experimental flume - (a) Juvenile silver perch (*Bidyanus bidyanus*) resting in the stagnation zone upstream of a medium baffle (h_b = 0.067 m, L_b = 0.67 m), with flow direction from left to right (Q = 0.0556 m^3/s); (b) Juvenile silver perch (*Bidyanus bidyanus*) resting in the recirculation zone immediately downstream of a large baffle (h_b = 0.133 m, L_b = 0.67 m) equipped with a hole, with flow direction from left to right (Q = 0.0556 m^3/s); (c) Comparison between medium baffle, large baffle (plain) and large baffle with Ø 13 mm hole from foreground to background

2.2. Fish Testing

Fish swimming observations were performed with juvenile silver perch (*Bidyanus bidyanus*). Fish were fasted for 24 h before being tested at 24.5 ±0.5 C. Fish were placed for 5 min in a pervious containment installed in the operating channel. The short conditioning phase allowed the fish to adjust to the flow and channel. After 5 min, the containment box would be removed, and the fish were released. Recording would begin after a 2 min acclimation period. Fish observations were conducted for 15 min. If fish showed signs of fatigue, the test would be stopped and fish removed from the flume. After each test, the fish were weighted, measured and photographed. Fish were herein selected randomly for each experiment and each fish was tested once only. All experimentation was conducted with the approval of The University of Queensland Animal Ethics Committee (Certificate no. SBS/312/15/ARC). The tests were conducted for a less-than-design culvert discharge Q = 0.0556 m^3/s (Table 2), for which the bulk velocity was close to the critical swimming speed (Ucrit) of the fish. Note that this flow rate was nearly twice the flow rate used by Wang et al. (2016), who conducted fish tests with smooth and very-rough boundaries. Four boundary conditions were selected herein: (a) smooth channel, (b) medium baffle (h_b = 0.067 m, L_b = 0.67 m), (c) large baffles (h_b = 0.133 m, L_b = 0.67 m), and (d) large baffles with holes (h_b = 0.133 m, L_b = 0.67 m, ∅ = 13 mm).

The fish positions were recorded manually using a 3-D grid scale based upon bed and sidewall square patterns. The recordings showed that the fish spent most time in a reasonably thin vertical layer close to the sidewalls, in particular the left sidewall corner for the triangular baffle configurations. In addition, high-resolution photographs were taken with a Pentax™ K-3 dSLR camera equipped with prime lenses with negligible lens distortion.

Table 2. Experimental flow conditions for fish observations in smooth and baffled culvert barrel channel (Present study)

Configuration	Q (m^3/s)	d (m)	h_b (m)	L_b (m)	Nb of fish	Fish mass (g) ([1])	Fish length (mm) ([1])
Smooth channel	0.0556	0.162	N/A	N/A	20	1.50 ±1.16	53.0 ±11.8
Medium baffles	0.0556	0.1625	0.067	0.67	26	1.30 ±0.85	47.0 ±9.6
Large baffles	0.0556	0.173	0.133	0.67	26	3.70 ±2.81	70.5 ±16.7
Baffles with holes	0.0556	*0.173*	0.133	0.67	15	3.20 ±1.40	66.0 ±8.7

Notes: d: flow depth measured at x ~ 8 m; h_b: baffle height; L_b: baffle spacing; Q: flow rate; ([1]): median value ±standard deviation; All tests conducted in flume equipped with upstream and downstream screens, and water temperature at 24.5 ±0.5 C.

2.3. Discussion

In this study, both the fish and the baffles were selected to be at full-scale in a channel which was nearly the full-scale representation of a single-cell box culvert barrel beneath a two-lane road embankment. The targeted fish species was juvenile silver perch (*Bidyanus bidyanus*), and the baffle size was selected to be comparable to the fish dimensions, because the literature shows that fish benefit from large-scale turbulence when the eddy size is comparable to the fish size (Webb and. Cotel 2011).

3. Basic Hydrodynamics

In the smooth channel in absence of baffles, the velocity field was quasi-uniform at the start of the channel (x = 0). The water surface elevation decreased with increasing downstream distance, indicating a H2 backwater profile. A bottom boundary layer developed, and the boundary layer's outer edge interacted with the free-surface for x > 4 to 6 m. Further downstream, the flow was fully-developed. The sidewall boundary layers remained thin. With the smooth boundaries, about 10% of the flow area experienced time-averaged longitudinal velocities less than $0.5\times V_{mean}$, where V_{mean} is the bulk velocity: $V_{mean} = Q/(W\times d)$, Q is the discharge, W is the channel width, and d is the flow depth. For all flow conditions, the water surface was relatively smooth along the entire channel length.

In presence of triangular baffles in the left corner, the flow was skewed towards the smooth right wall. The velocity field was asymmetrical, because of the presence of a sizeable wake behind each baffle. Negative velocities were recorded behind the baffles (Fig. 3). Figure 3 presents typical contour plots of longitudinal velocity data, with x the longitudinal co-ordinate positive downstream, y is the transverse distance from the right sidewall, z the vertical elevation above the invert, $x-x_b$ the longitudinal separation from the upstream baffle and x_b the longitudinal position of the upstream baffle. With plain triangular baffles, a well-defined flow reversal region was observed in the wake of each baffle, with strong flow reversal. This is seen in Figure 3b, with negative velocity as large -0.8 m/s in the near wake of the plain baffle. The recirculation "bubble" had a height of about the baffle size h_b and was about three baffle heights in length ($3\times h_b$). Further and immediately upstream of each baffle, a marked stagnation region was observed, characterised by a change in fluid direction, as the corner flow decelerated and the streamlines spread around the baffle. The longitudinal velocity was relatively small in this stagnation region, and this region was found to be a preferred resting zone for fish travelling upstream (Fig. 2a).

Figure 3c shows the velocity contour plot immediately downstream of the large baffle with ∅ 13 mm hole. The data may be compared with Figure 3b obtained at the same location downstream of a plain baffle. The ∅ 13 mm hole provided some cavity ventilation and lesser negative flow reversal was observed. For example, the largest negative velocity was -0.35 m/s in the near wake of the baffle in Figure 3c.

The hydraulic roughness of the various channel boundary configurations was tested. The spatially-averaged boundary shear stress was deduced from the measured free-surface profiles and estimated friction slopes in the fully-developed flow region ($x > 5$ m). Results are presented in Figure 4, showing that the Darcy-Weisbach friction factor increased with increasing relative baffle height h_b/D_H, where D_H is the hydraulic diameter. In the smooth channel, the data followed closely the Karman-Nikuradse formula developed for smooth turbulent flows (Schlichting 1979, Chanson 2004). In presence of corner baffles in the left corner, the friction factor was best correlated by:

$$f = f' + 0.25\times(h_b/D_H)^{1.64} \qquad (1)$$

where f' is the smooth turbulent flow fiction factor. Equation (1) is compared to the data in Figure 4.

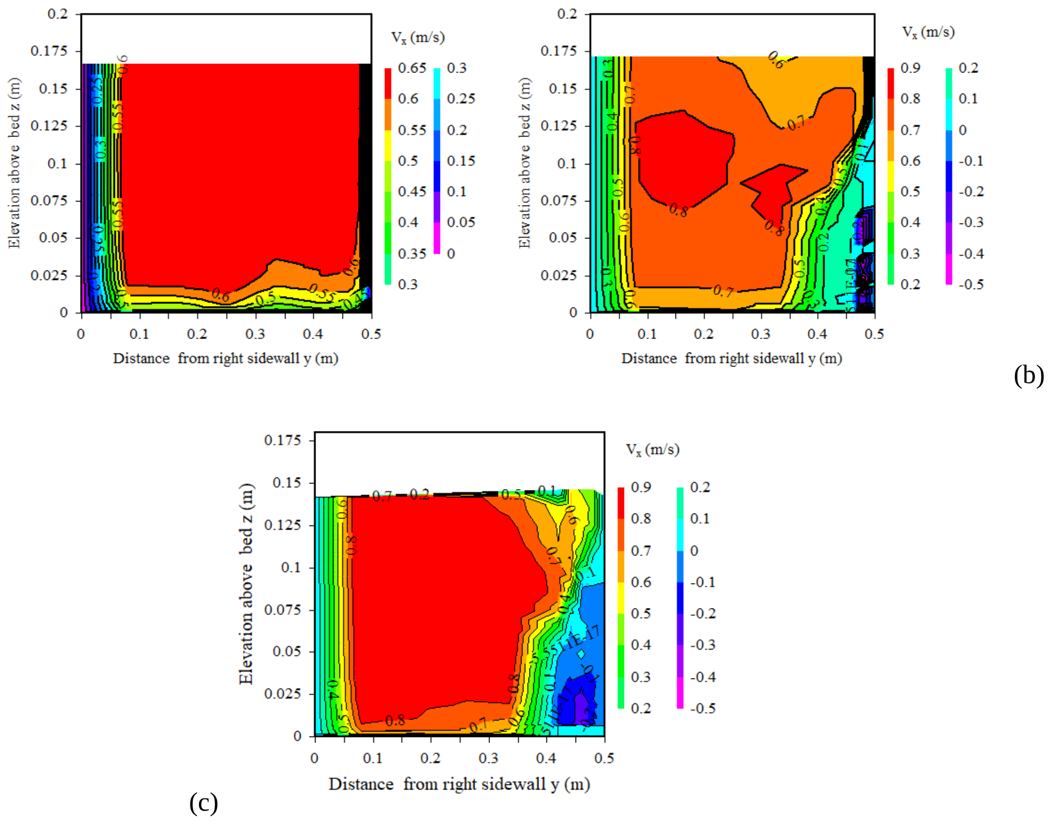


Figure 3. Contour plots of time-averaged longitudinal velocity V_X (in m/s) in smooth and baffled channels - (a) Smooth channel, $Q = 0.0556$ m^3/s, $x = 8.15$ m, $d = 0.171$ m; (b) $Q = 0.0556$ m^3/s, $d = 0.172$ m, $h_b = 0.133$ m, $L_b = 1.33$ m, $x_b = 8.12$ m, $x-x_b = 0.03$ m; (c) $Q = 0.0556$ m^3/s, $d = 0.172$ m, $h_b = 0.133$ m, $L_b = 0.67$ m, ∅ 13 mm hole, $x_b = 8.12$ m, $x-x_b = 0.03$ m

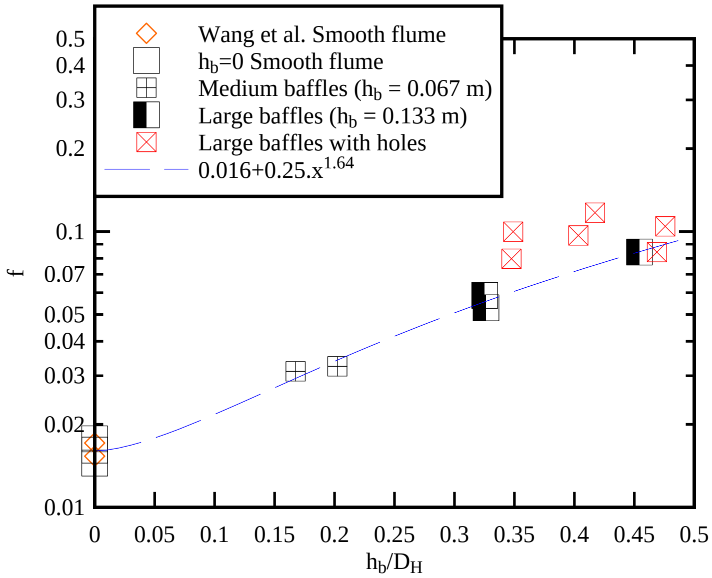


Figure 4. Darcy-Weisbach friction factor f as a function of the relative baffle height h_b/D_H for smooth and baffled channels

4. Fish Behaviour and Kinematics

4.1. Presentation

Initial observations were briefly conducted with transparent baffles. Several fish individuals seemed unable to see the baffle and would hit the corner baffles while swimming upstream. Thereafter, the baffles were painted and all experiments with fish were conducted with grey-painted baffles (Fig. 2).

Juvenile silver perch fish were tested with four boundary configurations (Table 2). During the tests, a number of fish fatigued before the end of testing: 12 out of 20 with smooth boundaries, 9 out of 26 with medium baffles, 10 out of 26 with large baffles, and none out of 15 with large baffles with ∅ 13 mm hole. The last configuration was introduced because a number of fish appeared to be disoriented by the strong velocity reversal behind the plain baffles (see below).

4.2. Fish Behaviour and Endurance

In the smooth channel, the fish tended to swim next to the sidewalls and corners, as previously reported by Wang et al. (2016). There was no obvious preference between the left and right sidewalls.

In presence of triangular baffles, the visual observations indicated that the fish swam against the current, i.e., upstream, and preferentially in the left corner of the flume, where the triangular baffles were located. Fish were able to pass upstream by taking advantage of the slow-velocity regions, and by resting in the stagnation zone immediately upstream of a baffle or in the wake behind each baffle. Observations and fish trajectory data showed several behaviours. These included fish 'resting' immediately upstream of baffle in the stagnation region (Fig. 2a & 5a), fish resting in the near-wake region immediately downstream of baffle (Fig. 2b & 5b), fish progressing upstream along the corner between two adjacent baffles, and fish negotiating the upstream passage of baffle (Fig. 5c). Figures 2 and 5 present typical illustrations of these behaviours. It was noted that some fish seemed trapped in the flow reversal region immediately downstream of large plain baffle. They would typically face downstream there (Fig. 5b), and a few individuals appeared confused by the flow direction and unable to negotiate the upstream passage of the baffle. For that reason, some cavity ventilation was introduced by installing a hole in the baffle. The water jet through the hole reduced the strength of the recirculation process, and the data showed a drastic improvement in fish endurance as seen in Figure 6.

The observations showed overall that the presence of small triangular corner baffles allowed fish to rest and facilitated substantially their upstream passage, as illustrated by comparative endurance swim results (Fig. 6). The results were even further improved with the 'ventilated' baffles equipped with holes. Figure 6 shows the cumulative percentage of fish swimming after durations ranging from 1 to 15 minutes.

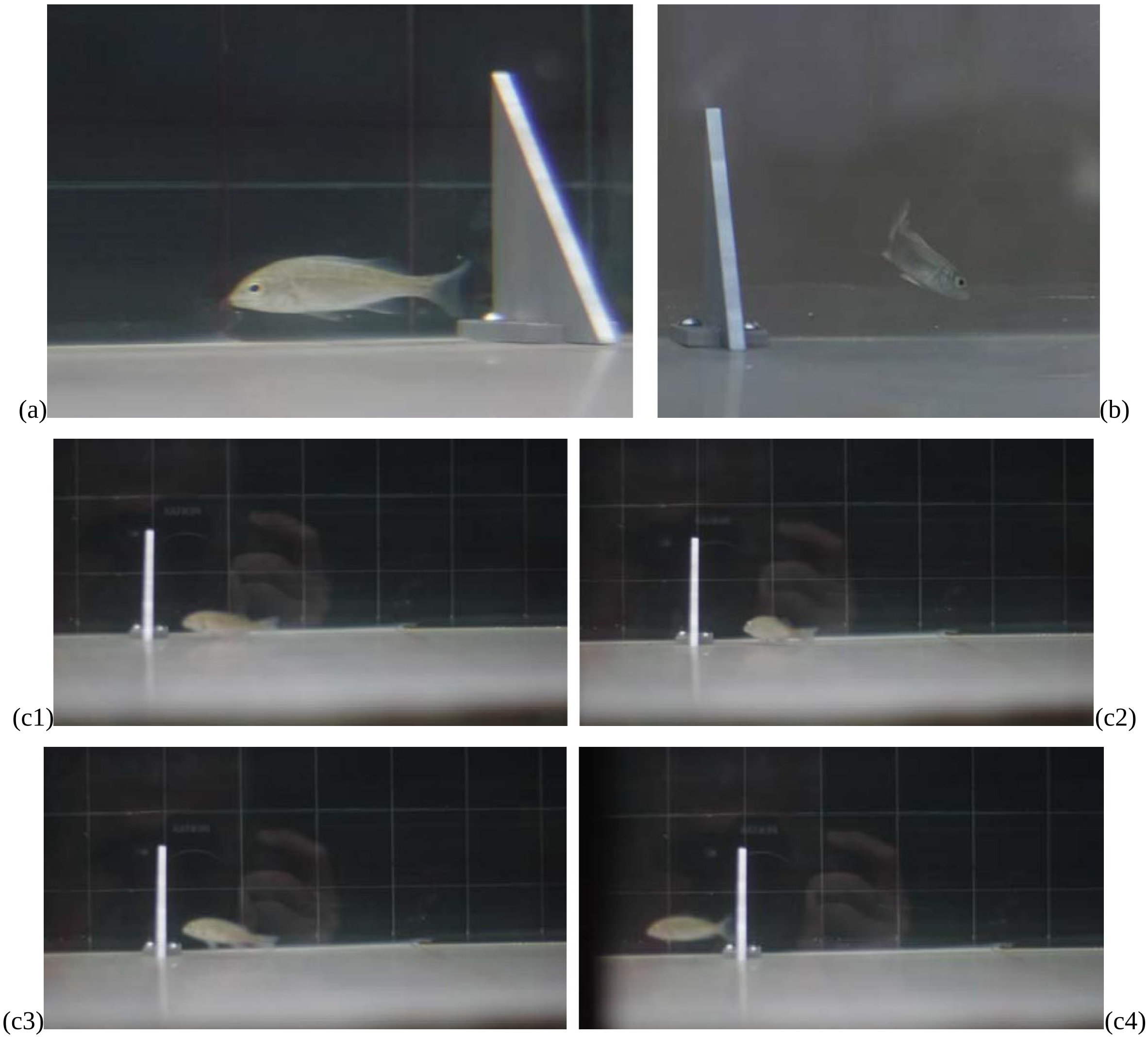


Figure 5. Photographic observations of juvenile silver perch (*Bidyanus bidyanus*) negotiating upstream passage in the 12 m long 0.5 m wide flume, with flow direction from left to right, Q = 0.0556 m^3/s, $S_o = 0$, $h_b = 0.067$ m, $L_b = 0.67$ m - (a) Fish resting in the stagnation region, immediately upstream of baffle; (b) Fish in the wake region immediately downstream of baffle, with the fish facing downstream; (c) Fish negotiating the upstream passage of a baffle: from left to right, top to bottom, with 0.12 s between two successive photographs

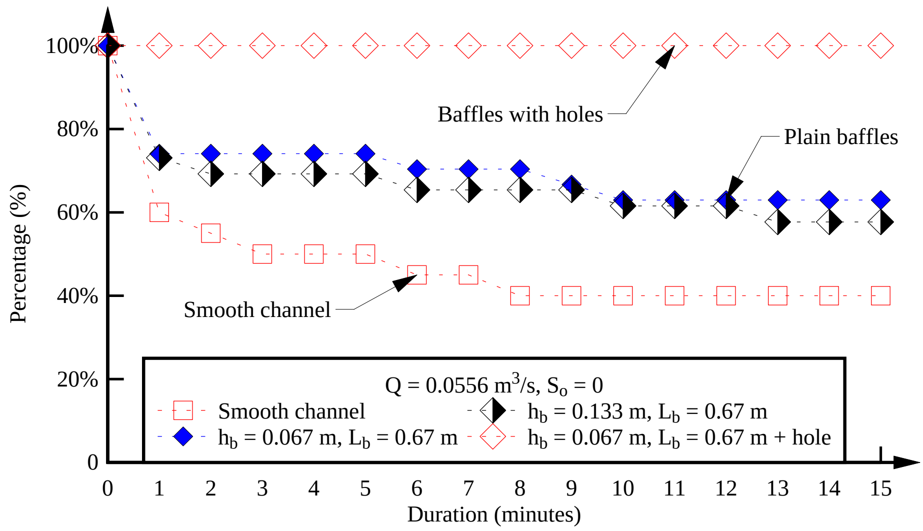


Figure 6. Cumulative endurance test duration data for juvenile silver perch (*Bidyanus bidyanus*) negotiating upstream passage in the 12 m long 0.5 m wide flume: Q = 0.0556 m^3/s, $S_o = 0$ - Comparison between all four boundary configurations

5. Discussion

5.1. On Fish-friendly Culvert Design Guidelines

Current standard culvert designs are very similar to ancient designs, like the Roman culverts (O'Connor 1993, Chanson 2002). Namely, standard culverts are characterised by a significant afflux at the design discharge (Henderson 1966). The afflux is the rise in the upstream water level caused by the presence of the culvert structure. In terms of hydraulic engineering design, the optimum size of a culvert is the smallest barrel size allowing for inlet control operation (Herr and Bossy 1965, Chanson 2000, 2004). The current engineering approach is focused on design flow conditions and does not consider upstream fish passage requirements and less-than-design flow conditions.

When culvert fish passage is most important during rainfall events (e.g. flood), it is recomended that fish passage in culvert should be optimised for a range of flow conditions corresponding to less-than-design flow conditions, in particular below a certain discharge threshold: e.g., below 40% of the design flow rate. Above that threshold, the structure would be optimised in terms of discharge capacity for a given design afflux. A different reasoning could suggest that fish passage in culvert would be optimised for some duration of the design rainfall-and-runoff event, outside of the peak flow period, e.g. ±20% of event duration around the peak flow. In both approaches, the culvert design would be optimised in terms of fish passage for flow conditions corresponding to non-design less-than-design flow conditions (Fig. 7), for which current engineering guidelines are very limited and typically not provided.

When the culvert discharges all the time, and fish passage requirements are not directly linked to some major hydrological event, another approach for determination of fish passage discharge range would be its proper operation for certain proportion of the year, e.g. 300 days.

The proposed small triangular corner baffle design provides a proven means to increase upstream fish passage for small-bodied fish during less-than-design flow conditions, while having little effect in terms of discharge capacity at larger design discharges. The former was evidenced with juvenile silver perch (Fig. 6), and the latter is seen in terms of flow resistance, with a decreasing resistance with decreasing relative baffle height h_b/D_H, hence increasing discharge (Fig. 4). Importantly the present corner baffle design must have dimensions (h_b) comparable to the fish dimensions and significantly smaller than the barrel flow depth at design flow: i.e. $h_b << (q_{des}^2/g)^{1/3}$ where q_{des} is the design discharge per unit width in the barrel and g the gravity acceleration. Further cavity ventilation is strongly recommended, based upon present results.

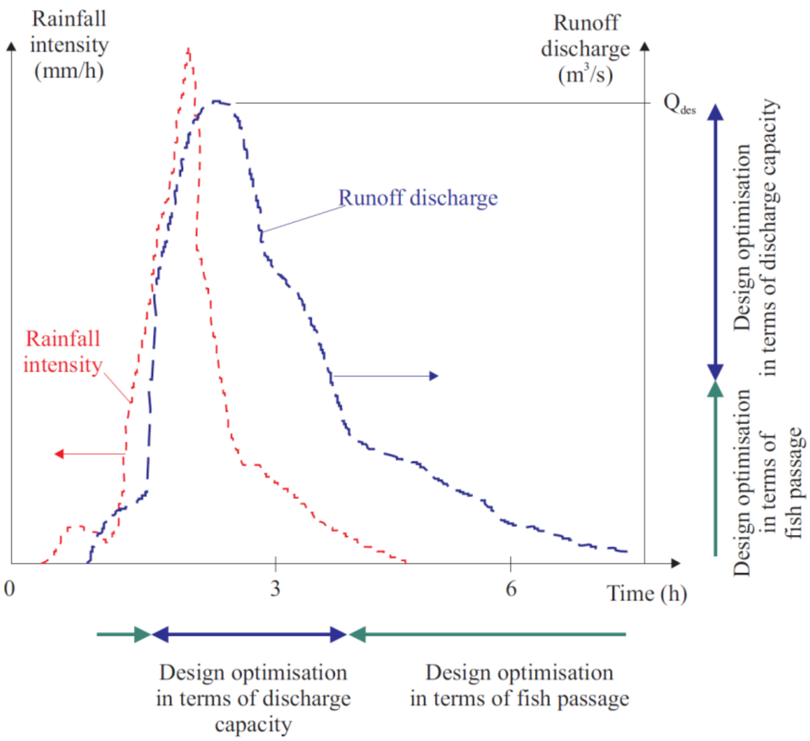


Figure 7. Schematic of typical rainfall intensity and discharge hydrograph in a small catchment in eastern Australia with fish-friendly culvert design guideline recommendations in terms of discharge (far right) or event duration (bottom)

5.2. On Matching Biology and Hydrodynamic Data Sets

The upstream fish passage may be analysed like an optimisation process, in a manner comparable to that used in competitive swimming (Wang and Wang 2006). It is indeed conceivable that fishes might adapt their swimming stroke to minimise drag and maximise their efficiency, as observed with swimmers during international competitions (Kolmogorov and Duplishcheva 1992, Wei et al. 2014). The latter brings up more questions on the limitations and significance of current fish swim tunnel tests (Katopodis and Gervais 2016, Wang and Chanson 2017). One may query their relevance for upstream fish passage in culverts, when field observations (Behlke et al. 1991, Blank 2008, Goettel et al. 2015) and near-full-scale experiments (Wang et al. 2016, Present study) reported fish seeking low velocity zones, associated with high turbulence intensity levels, to pass through hydraulic structures. Such hydrodynamic conditions differ substantially from tube testing conditions.

A related challenge is matching swimming performance data to hydrodynamic measurements. Swim tests lack standardised test methods (i.e., two different studies rarely use the same protocol), and the output is either a single-point measurement or a bulk velocity (Katopodis and Gervais 2016). In contrast, physical and numerical modelling of fluid flow deliver a detailed flow map, including contours of time-averaged velocity, e.g. Figures 3a, 3b, and 3c are each based upon 300 measurement points, and turbulence properties, i.e, typically based upon a minimum of 12,000 samples per measurement point, with a fine spatial resolution (total: minimum of 3,600,000 samples). Regulatory agencies face a difficult task to match hydrodynamic observations and swimming performance information, when the data were collected with markedly different spatial and temporal resolution, standardisation level and metrology expertise.

Fish-friendly culvert design guidelines must be based upon the most realistic data sets, alike the present study conducted in near-full-scale barrel channels (12 m long 0.5 m).

6. Conclusion

Detailed experiments were conducted in a box culvert barrel model to investigate the effects of small triangular corner baffles on upstream fish passage. The investigations were performed in 12 m long 0.5 m wide horizontal flumes operating at sub-critical flow conditions, typical of less-than-design discharges. Simple triangular corner baffle configurations were tested systematically and compared to a smooth channel configuration. Both hydrodynamic measurements and fish endurance tests were repeated to assess the benefits in terms of small-bodied fish.

The presence of triangular corner baffles allowed fish to rest and substantially facilitated their upstream passage. Fish transited upstream by taking advantage of the slow-velocity regions in the left corner, and by resting in the stagnation zone immediately upstream of a baffle or in the wake behind each baffle. The results were further improved with 'ventilated' baffles equipped with holes, since strong flow reversal behind plain baffles was found to be detrimental. The ∅ 13 mm holes generated water jets feeding the recirculation cavity and reducing the strength of flow reversal. The present corner baffle design is believed to work best with baffle dimensions (h_b) comparable to the fish dimensions, and must be smaller than the barrel design flow depth: i.e., $h_b << (q_{des}^2/g)^{1/3}$.

Finally, the design of fish-friendly culverts must be re-considered, as an optimisation in terms of fish passage for low flow conditions, and a maximisation of the discharge capacity and minimisation of afflux for large discharges including design flow conditions. Current fish-friendly culvert design practices must evolve from semi-empirical approaches based heavily upon simplistic observations and educated guesses, to advanced physics-based theoretical considerations and sound engineering standards. The approach is novel and challenges current design guidelines.

7. Acknowledgements

The authors acknowledge the helpful assistance of Angela Arum, Michael Cheung, Thi My Tram (Stephanie) Ngo and Eric Wu (The University of Queensland, Australia) in collecting physical data. The authors acknowledge the technical assistance of Jason Van Der Gevel and Stewart Matthews (The University of Queensland), and the assistance of Dr Jabin Watson and Prof. Craig Franklin (The University of Queensland) with fish testing. The financial support through the Australian Research Council (Grant LP140100225) is acknowledged.

8. References

Behlke, C.E., Kane, D.L., McLeen, R.F., and Travis, M.T. (1991). "Fundamentals of Culvert Design for Passage of Weak-Swimming Fish." *Report FHW A-AK-RD-90-10*, Department of Transportation and Public Facilities, State of Alaska, Fairbanks, USA, 178 pages.

Blank, M.D. (2008). "Advanced Studies of Fish Passage through Culverts: 1-D and 3-D Hydraulic Modelling of Velocity, Fish Energy Expenditure, and a New Barrier Assessment Method." *Ph.D. thesis*, Montana State University, Department of Civil Engineering, 231 pages.

Briggs, A.S., and Galarowicz, T.L. (2013). "Fish Passage through Culverts in Central Michigan Warmwater Streams." *North American Journal of Fisheries Management*, Vol. 33, pp. 652-664.

Cahoon, J.E., McMahon, T., Solcz, A., Blank, M., and Stein, O. (2007). "Fish Passage in Montana Culverts: Phase II - Passage Goals." *Report FHWA/MT-07-010/8181*, Montana Department of Transportation and US Department of Transportation, Federal Highway Administration, 61 pages.

Chanson, H. (2000). "Introducing Originality and Innovation in Engineering Teaching: the Hydraulic Design of Culverts." *European Journal of Engineering Education*, Vol. 25, No. 4, pp. 377-391 (DOI: 10.1080/03043790050200421).

Chanson, H. (2002). "Hydraulics of a Large Culvert beneath the Roman Aqueduct of Nîmes." *Journal of Irrigation and Drainage Engineering*, ASCE, Vol. 128, No. 5, pp. 326-330 (DOI: 10.1061/(ASCE)0733- 9437(2002)128).

Chanson, H. (2004). "The Hydraulics of Open Channel Flow: An Introduction." *Butterworth-Heinemann*, 2nd edition, Oxford, UK, 630 pages.

Chorda, J., Larinier, M., and Font, S. (1995). "Le Franchissement par les Poissons Migrateurs des Buses et Autres Ouvrages de Rétablissement des Ecoulements Naturels lors des Aménagements Routiers et Autoroutes. Etude Expérimentale." *Rapport HYDRE n°159 - GHAAPPE n°95-03*, Groupe d'Hydraulique Appliquée aux Aménagements Piscicoles et à la Protection de l'Environnement, Service d'Etudes Techniques des Routes et Autoroutes, Toulouse, France, 116 pages (in French).

Duguay, J., and Lacey, R.W.J. (2014). "Effect of Fish Baffles on the Hydraulic Roughness of Slip-Lined Culverts." *Journal of Hydraulic Engineering*, ASCE, Vol. 141, No. 1, Paper 04014065, 10 pages (DOI: 10.1061/(ASCE)HY.1943-7900.0000942).

Fairfull, S., and Witheridge, G. (2003). "Why do fish need to cross the road? Fish passage requirements for waterway crossings." *NSW Fisheries*, Cronulla NSW, Australia, 14 pages.

Goettel, M.T., Atkinson, J.F., and Bennett, S.J. (2015). "Behavior of western blacknose dace in a turbulence modified flow field." *Ecological Engineering*, Vol. 74, pp. 230-240.

Herr, L.A., and Bossy, H.G. (1965). "Capacity Charts for the Hydraulic Design of Highway Culverts." *Hydraulic Eng. Circular*, US Dept. of Transportation, Federal Highway Admin., HEC No. 10, March.

Hotchkiss, R.H., and Frei, C.M. (2007). "Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report." *Publication No. FHWA-HIF-07-033*, Federal Highway Administration, US Department of Transportation, 280 pages.

Katopodis, C., and Gervais, R. (2016). "Fish Swimming Performance Database and Analyses." *DFO CSAS Research Document No. 2016/002*, Canadian Science Advisory Secretariat, Fisheries and Oceans Canada, Ottawa, Canada, 550 pages.

Kolmogorov, S.V., and Duplishcheva, O.A. (1992). "Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity." *Journal of Biomechanics*, Vol. 25, No. 3, pp. 311-318.

Larinier, M. (2002). "Fish Passage through Culverts, Rock Weirs and Estuarine Obstructions." *Bulletin Français de Pêche et Pisciculture*, Vol. 364, No. 18, pp. 119-134.

O'Connor, C. (1993). "Roman Bridges." *Cambridge University Press*, Cambridge, UK, 235 pages.

Olsen, A. and Tullis, B. (2013). "Laboratory Study of Fish Passage and Discharge Capacity in Slip-Lined, Baffled Culverts." *Journal of Hydraulic Engineering*, ASCE, Vol. 139, No. 4, pp. 424-432.

Schlichting, H. (1979). "Boundary Layer Theory." *McGraw-Hill*, New York, USA, 7th edition.

Wang, H., and Chanson, H. (2017). "How a better understanding of Fish-Hydrodynamics Interactions might enhance upstream fish passage in culverts." *Research Report No. CE162*, School of Civil Engineering, The University of Queensland, Brisbane, Australia, 38 pages.

Wang, H., Chanson, H., Kern, P., and Franklin, C. (2016). "Culvert Hydrodynamics to enhance Upstream Fish Passage: Fish Response to Turbulence." *Proceedings of 20th Australasian Fluid Mechanics Conference*, Australasian Fluid Mechanics Society, G. Ivey, T. Zhou, N. Jones, S. Draper Editors, Perth WA, Australia, 5-8 December, Paper 682, 4 pages.

Wang, H., Uys, W., and Chanson, H. (2017). "Alternative Mitigation Measures for Fish Passage in Standard Box Culverts: Physical Modelling." *Journal of Hydro-environment Research*, IAHR, Vol. 16 (DOI: 10.1016/j.jher.2017.03.001) (In Press).

Wang, X.F., and Wang, L.Z. (2006). "Preliminary Probe into Optimization on Propulsion in Short Distance Competitive Swimming." *Applied Mathematics and Mechanics*, Vol. 27, pp. 117-124 (DOI: 10.1007/s 10483-006-0115-z).

Warren, M.L., Jr., and Pardew, M.G. (1998). "Road crossings as barriers to small-stream fish movement." *Transactions of the American Fisheries Society*, Vol. 127, pp. 637-644.

Webb, P.W., and Cotel, A.J. (2011). "Stability and Turbulence." in "Encyclopedia of Fish Physiology: from Genome to Environment", *Academic Press*, Dan Diego, USA, Vol. 1-3, pp. 581-586 (DOI: 10.1016/B978-0-12-374553-8.00221-5).

Wei, T., Mark, R., and Hutchison, S. (2014). "The Fluid Dynamics of Competitive Swimming." *Annual Review of Fluid Mechanics*, Vol. 46, pp. 547-565 (DOI:10.1146/annurev-fluid-011212-140658).