Ventilated Corner Baffles to Assist Upstream Passage of Small-Bodied Fish in Box Culverts

Joseph Cabonce[1]; Hang Wang[2]; and Hubert Chanson[3]

Abstract: Standard box-culvert designs are similar to ancient designs. The acknowledgment of the ecological impact of culverts and road crossings on rivers has led to changes in culvert design guidelines. A small triangular corner baffle system was tested to assist upstream passage of small body-mass fish in box-culvert structures on a flat bed slope. The study was conducted in a near full–scale physical facility, which had a width of 0.5 m and a length of 12 m. The investigation presented a detailed characterization of the flow field. Tests showed that small-bodied fish preferred to swim in slow-velocity regions (i.e., in the baffles' corner). The most effective baffles had heights comparable to fish length. A key outcome of the study is the adverse impact of strong flow reversal on small-bodied fish, because strong flow reversal may confuse small-bodied fish attempting upstream culvert passage. A remedial measure is the ventilation of baffles, tested successfully herein.
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Introduction

Longitudinal stream connectivity is a basic requirement for a healthy ecosystem, waterway, and aquatic diversity (Anderson et al. 2012; Januchowski-Hartley et al. 2014). For the last few decades, the ecological impact of road crossings has been recognized, leading to an evolution in road crossing design (Chorda et al. 1995; Warren and Pardew 1998; Hotchkiss and Frei 2007). The impact on fish passage may have an adverse effect on the stream ecology of both upstream and downstream catchments (Williams et al. 2012; Briggs and Galarowicz 2013). Common culvert barriers to fish passage encompass excessive vertical drop at the culvert outlet, such as a perched outlet, high velocity in the culvert barrel, debris accumulation at the culvert inlet, excessive turbulence, and standing waves in the inlet (Behlke et al. 1991; Olsen and Tullis 2013).

A better understanding of the ecological impact of culverts on natural river systems led to changes in culvert design guidelines, often leading to costly designs (Behlke et al. 1991; Chorda et al. 1995; Fairfull and Witheridge 2003). Baffles may be installed along the barrel invert to provide viable alternatives of fish-friendly designs (Quadrio 2007; Duguay and Lacey 2015). 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; Khodier and Tullis 2014). On the other hand, baffles substantially reduce the culvert discharge capacity (Larinier 2002; Olsen and Tullis 2013), affecting the structure's performances at design flow conditions.

A small corner baffle system was tested in a near full–scale physical facility. It is the aim of this study to deliver a detailed characterization of the flow field in smooth and corner baffle rectangular channels, at a scale comparable with a small standard box-culvert barrel cell, including the benefits of baffle cavity ventilation for small fish. The investigation provides relevant data to derive a predictive physically based model of the flow characteristics of small triangular baffle culverts, for a range of less-than-design flows. Both hydrodynamic measurements and small fish endurance tests were repeated with several configurations to assess the benefits in terms of small-bodied fish.

Experimental Facility, Instrumentation, and Methods

Laboratory experiments were conducted in two rectangular horizontal flumes that were 12 m in length and 0.5 m in width (Fig. 1). Both flumes were supplied by a constant head system and equipped with an intake tank equipped with calming devices, flow straighteners, and a three-dimensional (3D) convergent section 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. 1). 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 (denoted by footnote [a]). The length and internal width of the flumes were similar to a small single-cell culvert structure typical of eastern Australia (Cabonce et al. 2017).

The water discharge was recorded using an orifice meter (i.e., Venturi meter), based on the British Standards. The water depths were recorded with rail-mounted point gages. Velocity measurements were conducted using a Prandtl-Pitot tube and an acoustic Doppler velocimeter (ADV). The Prandtl-Pitot tube [166 Series tube (ϕ3.18 mm), Dwyer, Michigan City, Indiana] was used to measure pressure and velocity. The ADV unit (Nortek Vectrino+, Rud, Norway) was 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 accuracy on the vertical position of the

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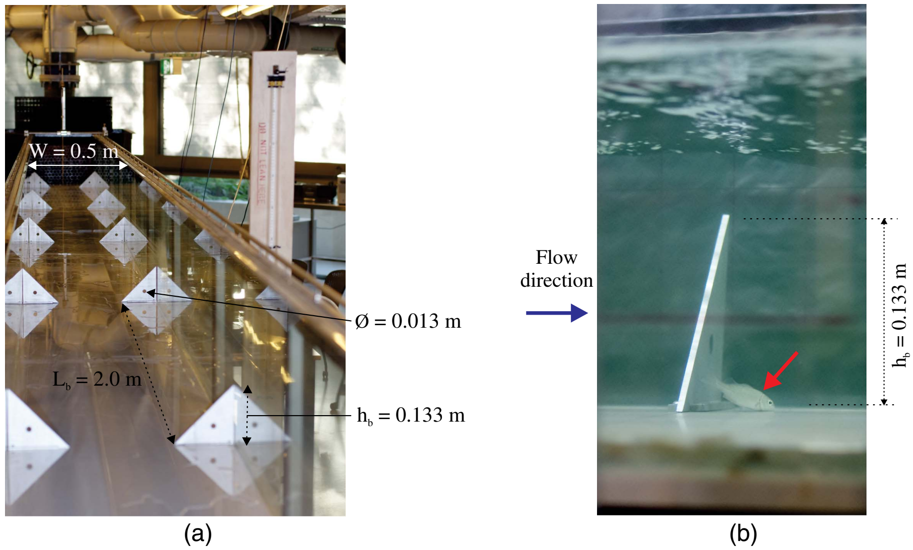

Fig. 1. Experimental channel: (a) flume equipped with two rows of baffles (double-sided baffles, $h_b = 0.133$ m; $L_b = 2.0$ m; and ϕ13-mm hole) looking upstream; and (b) juvenile silver perch (*Bidyanus bidyanus*) resting downstream of a baffle (single-sided baffles, $h_b = 0.133$ m; $L_b = 0.67$ m; and ϕ13-mm hole), with flow direction from left to right ($Q = 0.0556$ m^3/s). Arrow points to the fish.

Table 1. Experimental flow conditions for detailed velocity measurements in smooth and baffled culvert barrels

Configuration	Q (m^3/s)	d (m)	Baffle location	h_b (m)	L_b (m)	Comment
Smooth channel	0.0261	0.096	N/A	N/A	N/A	Prandtl-Pitot tube and ADV system
	0.0556	0.162				
	0.0556[a]	0.133[a]				
Plain baffles	0.0556	0.173	Left corner	0.133	0.67	Prandtl-Pitot tube
	0.0556	0.172	Left corner	0.133	1.33	
	0.0261	0.1035	Left corner	0.133	1.33	
Baffles with holes (ϕ13 mm)	0.0556	0.160[a]	Left corner	0.133	0.67	Prandtl-Pitot tube and ADV system

Note: d = flow depth measured at $x \sim 8$ m; h_b = baffle height; L_b = baffle spacing; and Q = flow rate.
[a]Experiment conducted without downstream screen.

probe was $\Delta z < 0.025$ mm. The precision on the longitudinal position was estimated as $\Delta x < \pm 2$ mm. The accuracy on the transverse position of the probe was less than 1 mm. All ADV signals were post-processed (Wang et al. 2016a).

Experimental Flow Conditions

Seventeen boundary configurations were tested. The reference experiments were conducted with a smooth boundary condition (no baffles). Further experiments were performed with two types of isosceles triangular corner baffles: plain and with a hole (Fig. 1). The triangular baffles were fixed either along both bottom corners [Fig. 1(a)] or in the bottom left corner [Fig. 1(b)] of the flume. Four longitudinal baffle spacings were tested: $L_b = 0.67$, 1.33, 1.67, and 2.0 m, yielding a dimensionless spacing $5 < L_b/h_b < 15$ for which wake interference occurred, providing continuous low-velocity zones along the corner regions. Each baffle was an isosceles triangle with a 45° angle and height $h_b = 0.133$ m. The baffle height was selected to be similar to the targeted fish length. For eight boundary configurations (two corner configurations by four longitudinal spacings), the baffles were plain. For the other eight configurations, a ϕ13-mm hole was cut in each plain baffle to ventilate the baffle wake and to reduce the flow reversal intensity (discussed later in this report). The ϕ13-mm hole center was located 45 mm above the bed and 45 mm from the sidewall (Fig. 1).

Flow patterns and free-surface observations were performed for three discharges: $Q = 0.0261$, 0.035, and 0.0556 m^3/s with all seventeen boundary conditions. These flow rates corresponded to less-than-design flows for which a subcritical open-channel flow motion would be observed in the culvert barrel. Detailed velocity measurements were conducted with five boundary configurations and two water discharges: $Q = 0.0261$ and 0.0556 m^3/s (Table 1).

Fish Passage Testing

Fish swimming observations were conducted with juvenile silver perch (*Bidyanus bidyanus*), based on a protocol developed with biologists. Fish were fasted for 24 h before tests were conducted at a water temperature of 24.5 ± 0.5 °C. Fish were placed for 5 min in a pervious containment in the flowing channel. The short conditioning phase allowed the fish to adjust to the flow and channel. Once the fish were released from the containment box, recording would begin after a 2-min acclimation period. All fish observations were conducted for 15 min. If fish showed signs of fatigue, the test was stopped, and fish were removed from the flume. For each experiment, fish were selected randomly, 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 fish passage tests were conducted for $Q = 0.0556$ m^3/s and three boundary conditions:

Table 2. Experimental flow conditions for fish observations in smooth and baffled culvert barrel channels

Configuration	Q (m^3/s)	d (m)	Baffle location	h_b (m)	L_b (m)	Number of fish	Fish mass (g)[a]	Fish length (mm)[a]
Smooth channel	0.0556	0.162	N/A	N/A	N/A	20	1.50 ± 1.16	53.0 ± 11.8
Large baffles	0.0556	0.173	Left corner	0.133	0.67	26	3.70 ± 2.81	70.5 ± 16.7
Baffles with holes	0.0556	0.173	Left corner	0.133	0.67	15	3.20 ± 1.40	66.0 ± 8.7

Note: d = flow depth measured at $x \sim 8$ m; h_b = baffle height; L_b = baffle spacing; and Q = flow rate. Water temperature: 24.5 ± 0.5°C.
[a]Median value $\pm$ standard deviation.

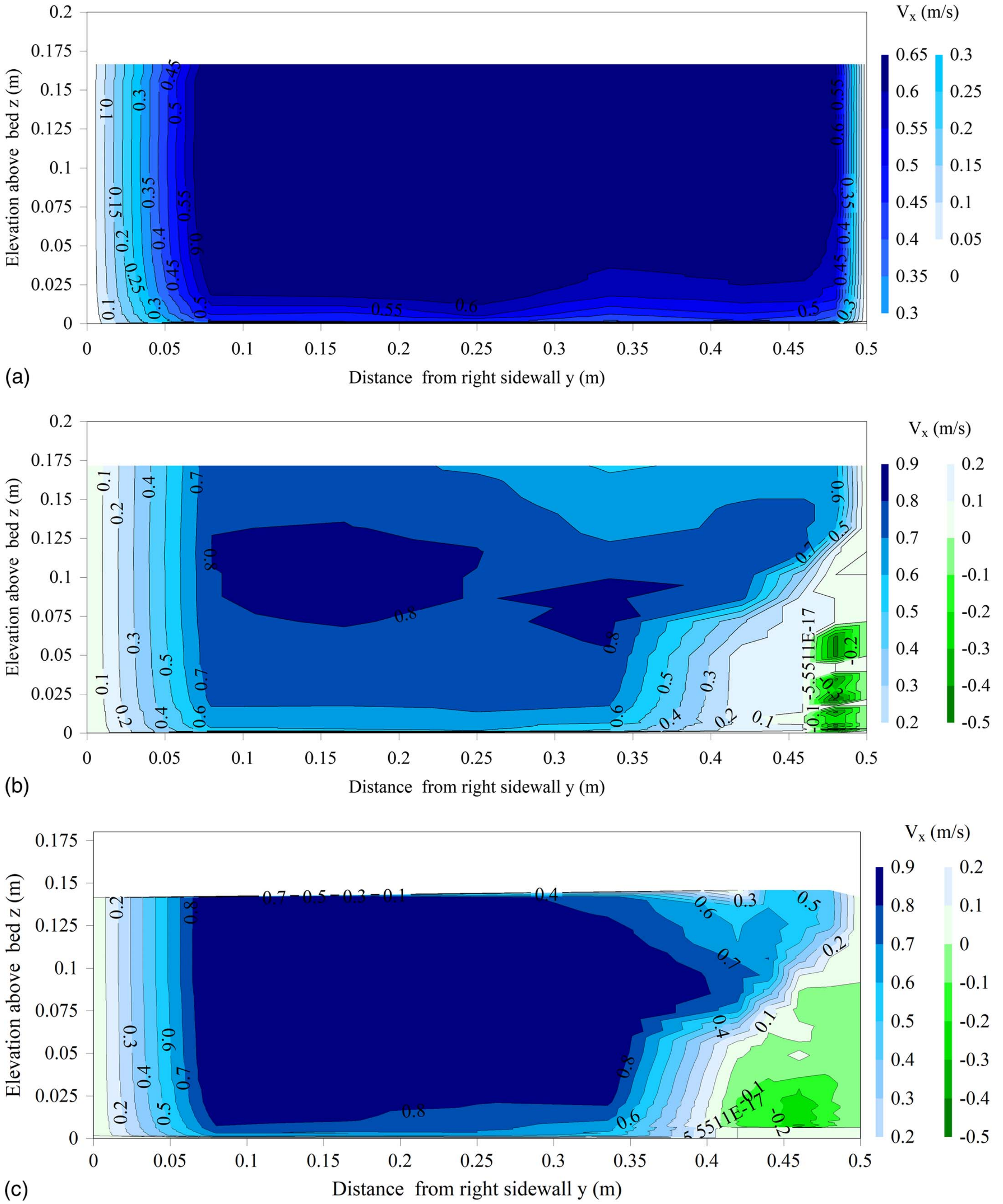

Fig. 2. Contour plots of local time-averaged velocity V_x (m/s) in smooth and corner baffled channels for $Q = 0.0556$ m^3/s: (a) smooth flume channel, $x = 8.15$; and $d = 0.171$ m; (b) plain baffles in left corner, $d = 0.172$ m; $h_b = 0.133$ m; $L_b = 1.33$; $x_b = 8.12$ m; and x-$x_b = 0.03$ m; and (c) baffles with hole in left corner, $d = 0.172$ m; $h_b = 0.133$ m; $L_b = 0.67$ m; ϕ-13 mm hole; $x_b = 8.12$ m; and x-$x_b = 0.03$ m.

smooth channel, plain baffles ($h_b = 0.133$ m and $L_b = 0.67$ m), and baffles with holes ($h_b = 0.133$ m, $L_b = 0.67$ m, and $\phi = 13$ mm) (Table 2).

The fish positions were recorded manually, using a 3D grid scale based on bed and sidewall square patterns. Observations showed that the fish spent most of their time in a reasonably thin vertical layer close to the sidewalls, especially the left sidewall corner for the corner baffle configurations. In addition, high-resolution photographs were collected using a Pentax K-3 dSLR camera (Pentax, Tokyo, Japan) equipped with prime lenses. Furthermore, high-speed movies were recorded with a digital camera Casio Exilim EX-10 (Casio, Tokyo, Japan), with movie mode set at 240 fps (512×384 pixels). Fish were tracked by their eye, because such a point on the body had the least lateral motion. Their positions were digitized off high-speed video images, using semiautomatic tracking with the software TEMA 2D Motion version 3.9. The trajectory data were smoothed using a Gaussian filter (7 points, unit standard deviation) following Wang et al. (2016b). Eulerian fish speed and acceleration were derived respectively from the first and second differentiation, calculated using central location differences at each time step. This filtering method was found to be robust for fish trajectories, including both stationary and nonstationary time subseries.

Flow Patterns and Hydrodynamics

In the smooth boundary configuration (i.e., in the absence of baffles), the velocity field was quasi-uniform at the start of the flume. The flow was subcritical for all investigated flow conditions. The water depth decreased with increasing downstream distance, consistent with an H2 backwater profile. A bottom boundary layer developed, and the outer edge of the turbulent boundary layer interacted with the water surface for $x > 4$–6 m. Downstream, the flow was fully developed, and the sidewall boundary layers remained thin. With smooth boundaries, about 10% of the flow area experienced local time-averaged velocities less than $0.5 \times V_{\text{mean}}$, where V_{mean} is the bulk velocity: $V_{\text{mean}} = Q/(W \times d)$, in which Q is the discharge, W is the channel width, and d is the flow depth.

In the presence of small corner baffles in the left corner, the flow was skewed toward the smooth right wall. The velocity field was asymmetrical, because of the presence of a sizable wake behind each baffle. Negative velocities were recorded behind the baffles (Fig. 2). Fig. 2 presents typical contour plots of longitudinal velocity data, with x-x_b being the longitudinal separation from the upstream baffle and x_b being 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. The flow reversal was clearly seen with dye injection and is presented in Fig. 2(b) (bottom left corner), with negative velocity as large as -0.8 m/s in the near wake of the plain baffle. Further downstream and immediately upstream of each baffle, a stagnation region developed, which was associated with a change in fluid direction, as the corner flow decelerated, and the streamlines spanned around the baffle. The longitudinal velocity was relatively small in this stagnation region, which was found to be a resting zone for fish travelling upstream (discussed later in this report).

With a hole in the baffle, the recirculation region was naturally ventilated by the jet flow through the hole. Fig. 2(c) shows the velocity contour plot immediately downstream of the baffle, with a ϕ13-mm hole. The data may be compared with Fig. 2(b) obtained at the same location downstream of a plain baffle. The baffle hole provided some cavity ventilation and created lesser negative flow reversal. For example, the largest negative velocity was -0.35 m/s in the near wake of the baffle in Fig. 2(c), corresponding to a reduction of more than 50% of the flow reversal intensity, compared to plain baffles.

The flow resistance of the various channel boundary configurations was tested systematically. 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). The data are shown in Fig. 3, with the Darcy-Weisbach friction factor that presented a function of the relative baffle height h_b/D_H, with D_H the hydraulic diameter. Fig. 3 includes results with baffles located in the left corner only and along both corners, for four longitudinal spacings ($5 < L_b/h_b < 15$) and three discharges: $0.0261\ \text{m}^3/\text{s} < Q < 0.0556\ \text{m}^3/\text{s}$. In the smooth flume, the data followed closely the Karman-Nikuradse formula developed for smooth turbulent flows (Schlichting 1979; Chanson 2004). In the presence of corner baffles, the flow resistance increased with increasing relative baffle height. With corner baffles, the friction factor was best correlated by:

$$f = f' + 0.25 \times (h_b/D_H)^{1.64} \text{ Baffles in left corner only} \quad (1a)$$

$$f = f' + 2.71 \times (h_b/D_H)^{2.5} \text{ Baffles along both corners} \quad (1b)$$

where f' = smooth turbulent flow fiction factor, i.e., $f \approx 0.016$ herein. Eqs. (1a) and (1b) are compared with the data in Fig. 3.

Fish Passage Results

Juvenile silver perch fish were tested with three boundary configurations for the same discharge (Table 2). With plain baffles, several fish appeared to be disoriented by the strong velocity reversal behind the plain baffles (discussed later in this report). Baffle cavity ventilation was introduced to reduce the adverse impact of the flow reversal in small-bodied fish. During all the tests, several fish fatigued before the end of testing: 12 out of 20 fish with the smooth boundary configuration, 10 out of 26 fish with plain baffles but

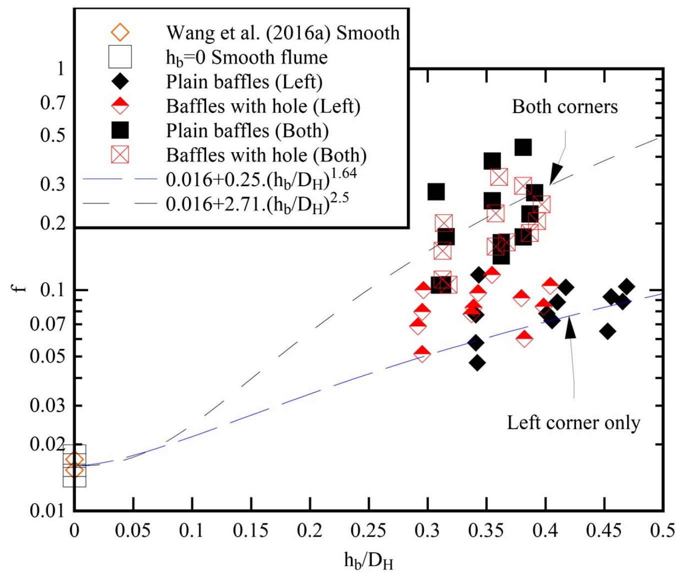

Fig. 3. Flow resistance in small corner baffle channel flows: Darcy-Weisbach friction factor as a function of the relative baffle height h_b/D_H, with baffles located in the left corner only and along both corners. Comparison with the smooth flume data of Wang et al. (2016a).

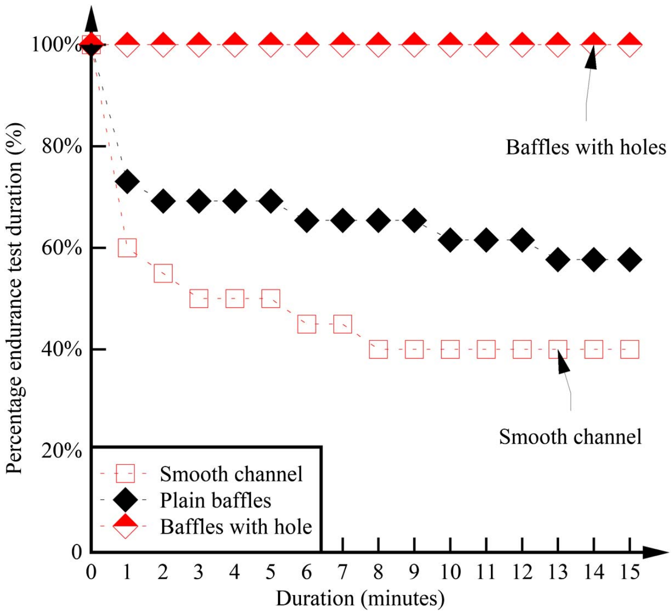

Fig. 4. Cumulative endurance test duration data for juvenile silver perch (*Bidyanus bidyanus*) negotiating upstream passage in the 12 m in length and 0.5 m in width culvert barrel flume: $Q = 0.0556\ \mathrm{m}^3/\mathrm{s}$; $S_o = 0$; test duration: 15 min. Comparison between all three boundary configurations (Table 2). Baffle characteristics: $h_b = 0.133$ m; and $L_b = 0.67$ m.

none out of the 15 fish with the baffles that had the ϕ13-mm hole. Fig. 4 presents the cumulative percentage of the test duration for the tested fish. Fish were mostly seen swimming upstream, against the direction of the flow. For the same flow rate, the presence of small corner baffles increased the capability of the fish to traverse the flume and can be attributed to the regions of low velocity where fish can minimize their energy expenditure (Blank 2008; Abdelaziz et al. 2011; Wang and Chanson 2018). The presence of baffles also improved the endurance of fish within the flow. The baffle configuration with the ϕ13-mm hole had all fish enduring the 15-min testing period (Fig. 4). This drastic enhancement in endurance was attributed to the reduction in flow reversal and turbulence behind the baffles, induced by the cavity ventilation, although the finding was observed with one discharge and one specie only.

The individual fish behavior was recorded for all three boundary configurations (Table 2). Typical individual fish trajectories are presented in Fig. 5 and Fig. 6 shows the percentage of time spent by each fish within the various areas of the flume cross section, averaged with respect to test duration and fish samples. In the smooth configuration, fish swam next to the sidewalls and corners. No obvious preference was shown between the left and right sidewalls [e.g., Fig. 5(a)]. In the presence of small corner baffles, fish showed a preference for swimming on the left side (looking downstream) where the baffles were installed, taking advantage of the slow velocity regions [Figs. 5(b) and 6(b and c)].

With baffles, several basic swimming patterns were observed. Often, fish were observed swimming in a quasi-stationary position immediately upstream of baffles, utilizing the stagnation region. Upstream fish motion would typically start in the stagnation region, with fish moving forward in the low-velocity zone along the left corner. Baffle negotiation was observed, when fish would swim through the turbulent region behind the baffle and pass the baffle into the region immediately upstream of the baffle. With plain baffles, the flow reversal region immediately downstream of the baffles was shown to affect some fish, causing them to face downstream [e.g., Fig. 1(b)]. These fish were often unable to negotiate baffles, at times exiting the recirculation region swimming downstream and being swept away by the prevailing flow. With ventilated baffles (i.e., baffles with a hole), the fish spent more time in the left corner, likely as a result of the reduction in flow reversal in the recirculation region.

Fish Kinematics

The fish movements in the x- and z-directions were tracked frame-by-frame from high-speed video movies, where x is the

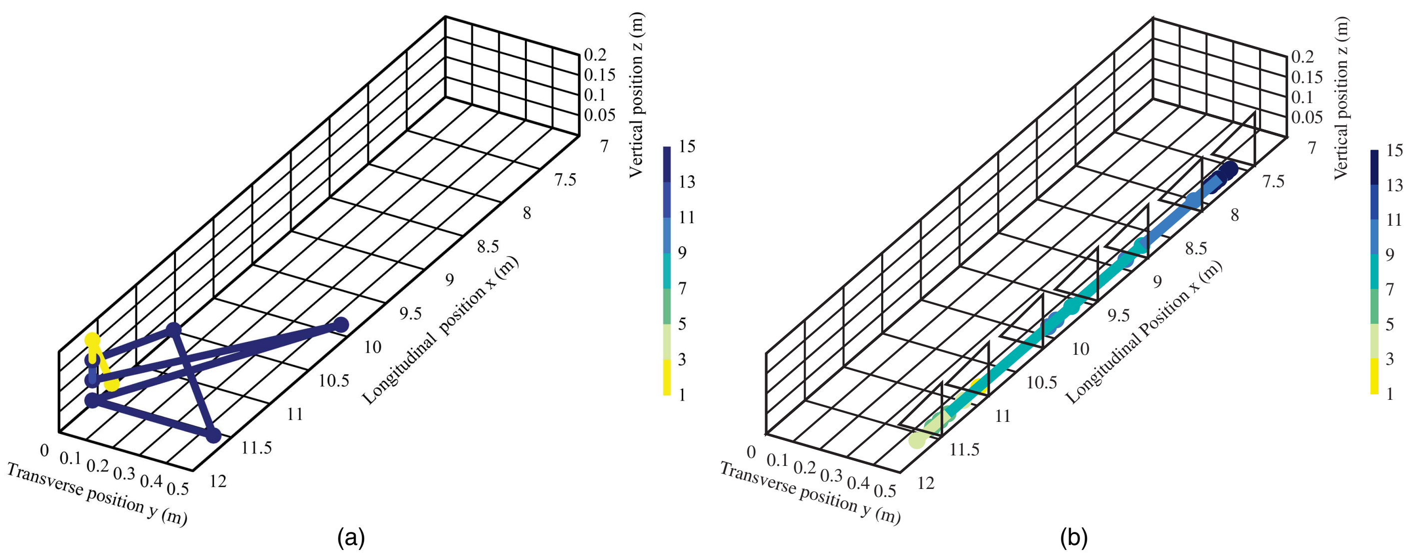

Fig. 5. Typical fish trajectories during fish testing: $Q = 0.0556\ \mathrm{m}^3/\mathrm{s}$; $S_o = 0$; $W = 0.5$ m; flow direction of top right to bottom left. Fish species: juvenile silver perch (*Bidyanus bidyanus*). The scale in minutes corresponds to test duration: (a) smooth flume; and (b) plain baffles: $h_b = 0.133$ m; and $L_b = 0.67$ m. Baffles located along the left corner ($y = 0.5$ m).

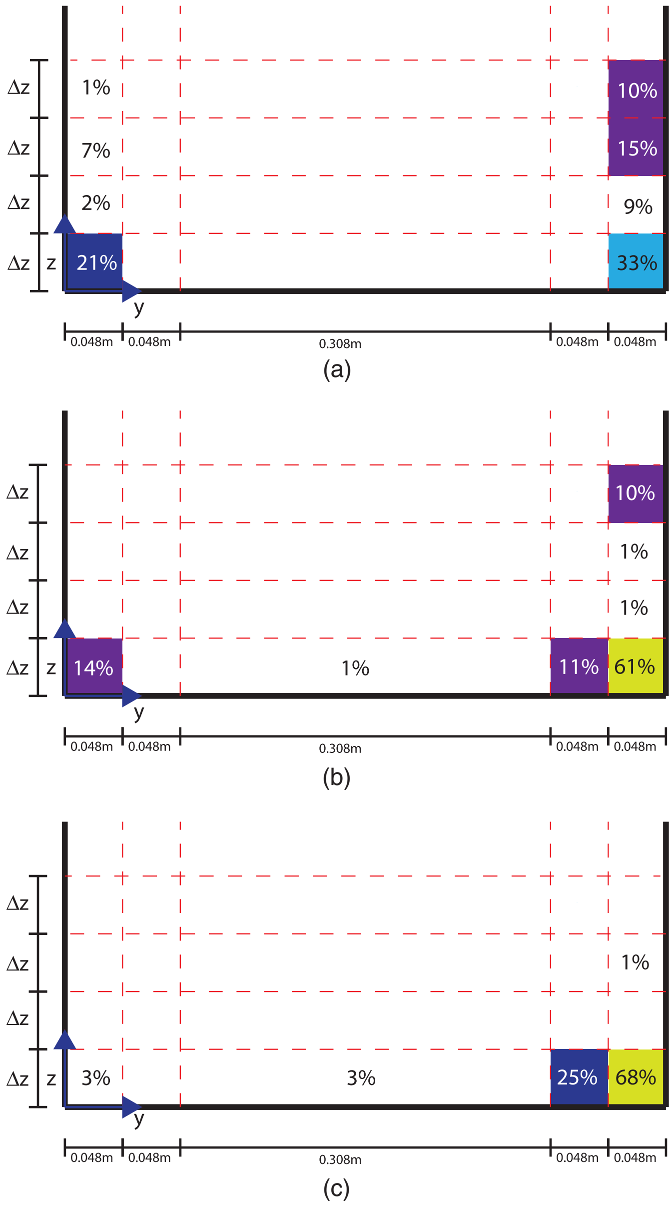

Fig. 6. Percentage of time spent by fish [juvenile silver perch (*Bidyanus bidyanus*)] within the channel cross-section, weighted with respect to time with the scale of percentages (right). Flow conditions: $Q = 0.0556\ \mathrm{m^3/s}$; $S_o = 0$; and $W = 0.5$ m. The scale corresponds to test duration, $\Delta z = 0.05$ m: (a) smooth flume; (b) plain baffles: $h_b = 0.133$ m; $L_b = 0.67$ m; and (c) baffles with holes: $h_b = 0.133$ m: and $L_b = 0.67$ m; and $\phi = 13$ mm.

longitudinal position and z is the vertical position. Herein, fish speed and acceleration are perceived as positive in the upstream direction.

Statistical information was extracted from fish testing conducted with a flow rate $Q = 0.0556\ \mathrm{m^3/s}$ in various boundary conditions (Table 2). In the smooth flume, fish swimming motions were observed to widely vary because of the absence of sizable low-velocity zones. The ratio of fish velocity to fluid velocity were within $-0.5 < U_x/V_x < 1.49$, with standard deviations within $0.14 < u'_x/v'_x < 1.42$. Of note, the present finding in the smooth flume was similar to observations in a rough sidewall and invert flume, with two small-bodied fish species (Wang et al. 2016b).

Within plain baffles, the ratio of fish speed to fluid velocity were typically $-0.03 < U_x/V_x < 0.01$, with standard deviations within $0.05 < u'_x/v'_x < 0.06$. With ventilated baffles, the ratio of fish velocity to fluid velocity was typically negligible, close to zero, with standard deviation ratios within $0.02 < u'_x/v'_x < 0.11$. In general, fish exhibited lesser fluctuations in swimming speed in the baffled flume than in the smooth flume configuration. The variance in fish swimming speed had implications in terms of energy expenditure for the fish when overcoming forces involved with swimming, as well as during acceleration phases (Wang and Chanson 2018). In baffled configurations, it may be inferred that the baffles were creating fish rest areas, reducing the energy expenditure, and, therefore, increasing endurance. Qualitatively, this is exhibited in the cumulative fish endurance data (Fig. 4).

Discussion

Current standard culvert designs are characterized by a significant afflux at the design discharge (Henderson 1966). 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.

Current culvert design guidelines for fish passage are based on design flow considerations and are costly for small fish. It is proposed that fish passage in culverts should be optimized for a range of flow conditions that correspond to less-than-design flows, in particular below a characteristic discharge (e.g., below 20–40% of the design flow rate). Above that threshold, the culvert structure would be optimized in terms of discharge capacity for a given design afflux. This could suggest a culvert design optimization in terms of fish passage for periods of the design rainfall-and-runoff event, outside of the peak flow time, e.g., defined as ±20% of event duration around the peak flow. In both approaches, the culvert design would be optimized for less-than-design flow conditions in terms of fish passage, for which current engineering guidelines are very limited and typically not provided.

The proposed ventilated baffle design provides a proven means to increase upstream passage for small-bodied fish during less-than-design flow conditions, having little effect in terms of discharge capacity at larger design discharges. The former was evidenced with juvenile silver perch (Fig. 4), 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. 3). Thus, the corner baffle design must have dimension (h_b) similar to the fish dimensions and be significantly smaller than the barrel flow depth at design flow [i.e., $h_b \ll (q_{\mathrm{des}}^2/g)^{1/3}$] to have minimum impact in terms of afflux at design flow, where q_{des} is the design discharge per unit width in the barrel and g is the gravity acceleration. The ventilation of the baffle is strongly recommended, based on present data.

The development of culvert design guidelines for upstream fish passage brings up questions on the limitations of current fish swim tunnel tests (Katopodis and Gervais 2016; Wang and Chanson 2017). One may query their relevance, when field observations (Behlke et al. 1991; Blank 2008; Goettel et al. 2015) and near full–scale experiments such as this study and that of Wang et al. 2016b, which 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. Fish-friendly culvert design guidelines must be based on the most realistic data sets, like the present study conducted in near full–scale box-culvert barrel flumes (12 m in length and 0.5 m in width). It is acknowledged that the present data represented some measure of endurance and capability to traverse the rectangular flume. Limitations of the testing procedure indeed include: (1) the finite test duration [i.e., $15(+2)$ minutes during which a number of fish individuals did not reach the channel's upstream end], and (2) the upstream flow conditions, affected by the turbulence generated by the upstream screen.

Conclusion

Hydrodynamic measurements and fish endurance tests were performed to assess the benefits of small corner baffles in terms of upstream culvert passage of small body-mass fish. The investigation was conducted for subcritical flow conditions, typical of less-than-design discharges. The presence of small triangular corner baffles allowed fish to rest and facilitated their upstream passage for the same flow rate. Fish swam upstream by taking advantage of the slow-velocity regions in the culvert barrel corner, where the baffles were installed, and by resting in the stagnation zone immediately upstream of a baffle or in the wake behind each baffle. The results were improved with ventilated baffles, because strong flow reversal behind plain baffles was found to be detrimental to upstream fish passage. The baffle ventilation fed the recirculation cavity and reduced the strength of the flow reversal. The present corner baffle design is believed to work best with baffle dimensions similar to the fish dimensions and must be smaller than the barrel design-flow depth. A key finding is the lesser fluctuations in fish swimming speed in the baffled flume, compared with the smooth flume configuration. Although the small corner baffles generated low-velocity zones and fish rest areas, they also reduced the energy expenditure and increased the endurance of small-bodied fish.

Design guidelines for fish-friendly culverts must be reconsidered as an optimization in terms of fish passage for less-then-design flow conditions and a maximization of the discharge capacity and minimization of design afflux at large discharges, including for the design flow condition. Current design practices must evolve from semiempirical approaches derived from simplistic observations and educated guesses, to advanced theoretical considerations and sound engineering standards.

Overall, a key outcome of the study is the adverse impact of strong flow recirculation and flow reversal on small-bodied fish and upstream culvert passage. It is believed that this has not been documented before. A remedial measure is the ventilation of baffles. In the present study, a simple cavity ventilation method (ϕ13-mm hole) was tested successfully, although it is acknowledged that other cavity ventilation systems might work better with other fish species and discharges.

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Notation

The following symbols are used in this paper:

D_H = hydraulic diameter (m);
d = water depth (m);
g = gravity acceleration $(\mathrm{m/s^2})$: $g = 9.794\ \mathrm{m/s^2}$;
h_b = triangular baffle height (m);
L_b = longitudinal spacing (m) between baffles;
Q = water discharge $(\mathrm{m^3/s})$;
q = water discharge per unit width $(\mathrm{m^2/s})$: $q = Q/W$;
S_o = bed slope: $S_o = \sin\theta$;
U_x = longitudinal fish speed (m/s) positive upstream;
u' = fish speed fluctuation (m/s);
V_{mean} = cross-sectional mean velocity (m/s): $V_{\mathrm{mean}} = Q/A$;
V_x = longitudinal velocity component (m/s) positive downstream;
v' = velocity fluctuation (m/s);
W = channel width (m);
x = longitudinal distance (m) measured from upstream end of flume and positive downstream;
x_b = longitudinal baffle position (m) measured from upstream end of flume;
y = transverse distance (m) measured from the right sidewall positive toward the left sidewall;
z = vertical distance (m) positive upwards with $z = 0$ at the invert;
θ = angle between bed slope and horizontal; and
ϕ = diameter (m).

Subscript

x = longitudinal direction positive downstream.

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