



Streamwise C-sections in smooth pipe culverts to assist small-bodied fish passage

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Received: 15 June 2026 / Accepted: 30 September 2026
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Abstract

Modern attention has focused on a variety of barriers that hinder fish passage. The most prevalent fish barriers are culverts which negatively impact waterway connectivity and fish habitats. For small-bodied mass fish, high culvert barrel velocities and turbulence adversely impact their upstream passage performance because of their weak swimming capabilities. In the present study, physical testing was conducted under controlled flow conditions to assess the extent and magnitude of turbulence characteristics, secondary flow, and the formation of low velocity-zones in a 0.5 m diameter circular pipe culvert barrel. Two cases were investigated: a reference case consisting of a smooth semi-circular channel, and a low-cost design solution consisting of a single 57 mm × 32 mm extruded aluminium C-section fitted to the invert of a smooth semi-circular channel. The C-section was fitted at 30° to the centreline to induce an asymmetric flow, reduce overall energy losses and create low velocity zones in the vicinity of the C-section corners. The C-section induced a strong turbulent flow motion, along with a distinct channel flow asymmetry. The low velocity zone was significantly expanded by the well-defined C-section corners. The C-section also influenced the distributions of normal turbulent stresses ($v_z'^2 - v_y'^2$), which in turn influenced the location of secondary flow cells. These secondary flow cells redirected low momentum fluid into the low velocity zones, setting hydraulic conditions potentially favourable to the upstream passage of small-bodied fish. This study provides *prima facie* evidence to support further laboratory and field investigations into the use of C-sections for improving successful fish passage in pipe culverts.

Article Highlights

- Structural C-sections may offer a simple, cost-effective means to enhance temporary or permanent fish passage within pipe culverts.
- The C-section can be readily sourced from structural steel suppliers and, with minimal fabrication, can be quickly installed within new or existing culvert barrels.
- The C-section creates small low velocity zones which may be suitable to assist fish passage for small-bodied or juvenile fish.
- The C-section has a moderate impact on discharge capacity of small pipe culverts with diameters < 0.5 m, however, discharge impacts are expected to diminish as diameters increase.

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- A novel approach to calculating friction factors to account for culvert appurtenances in flow cross-section is presented.

Keywords Smooth pipe culverts · Fish passage · Physical modelling · Friction factors · Secondary flow · Low velocity zones · Structural channel section · Longitudinal rib · C-section

1 Introduction

Culverts are an important component of transportation infrastructure, providing an effective means to convey storm flows in small to medium sized catchments in lieu of more expensive bridge options [1, 2]. However, it is widely recognised that culverts also represent a significant barrier to the movement of terrestrial and aquatic species. These impacts are particularly felt for small-bodied fish species which are vulnerable to higher barrel velocities and excessive turbulence caused by culverts [3, 4]. Whilst the literature on cross-drainage culverts indicated that box culverts are relatively more effective in assisting the passage of fish [5, 6], pipe culverts remained a popular option for transport agencies in addressing specific engineering design scenarios [7].

In most design cases, culverts are designed to cater for open channel flows within the culvert barrel [7]. For box culverts, one-dimensional hydraulic design is relatively simple as culvert barrels can rely on simple rectangular cross-sectional relationships. The design of partially-filled circular culverts is more complex due to the non-linear change in hydraulic flow properties with respect to hydraulic depth [9, 10]. Despite these challenges, smooth circular pipe culverts are hydraulically efficient drainage structures exhibiting miniscule low velocity zones (LVZs) for a range of design flows including low discharge or low-submergence flows [11]. A variety of design modifications have been devised to improve the likelihood of fish passage in smooth circular pipe culverts. Conceptually, these can be categorised into three types of culvert modifications. Firstly, regular surface modifications in selected locations of culverts, which include substrate or macro surface roughening, uniformly distributed to achieve local LVZs. This roughening can occur naturally or be induced or installed in culverts. Examples include deposits of stone/gravels etc., or localised texturing of culvert wall surfaces [12]. Secondly, transverse modifications, which rely on the discontinuity of culvert appurtenances along the longitudinal axis of the culvert to achieve the LVZ. These installations included invert-mounted offset baffles [13] and similar devices such as slotted weirs, weir baffles and spoiler baffles [14–16] and corner baffles [12]. In these devices, localised LVZs and resting zones exist between baffles. Recently, side-wall baffles (also commonly known as ‘Quad’ baffles, See Fig. 1 Left) and similar variants have also been employed [17]. Longer baffle spacings have resulted in larger relative local velocities and reduced reverse flow regions [15, 18]. Furthermore, these large baffles were observed to adversely impact the overall discharge capacity of some culvert barrels and trap large debris, in turn reducing further the flow capacity [6, 19]. The commonly accepted baffle solutions in Queensland Australia, such as the full height sidewall baffle systems [20], are also expensive and time consuming to install. These devices may disorientate fish in certain locations behind the baffle during high velocity conditions [21] and potentially result in



Fig. 1 Smooth circular pipe culverts located on fish-mapped waterways [8]. (LEFT) “Quad” baffles fitted to a 1050 mm diameter reinforced concrete pipe culvert at Walloon, Queensland, Australia (RIGHT) Outlet flow from a 3/1500 mm diameter slip-lined pipe culvert at Brookfield, Queensland, Australia after a storm event on 28th February 2022

seiching fluid motion in certain flow conditions that could potentially disorientate fish [22]. Thirdly, streamwise modifications include various longitudinal ribs and rails, including the proposed C-section. These typically comprise of continuous longitudinal installations of culvert appurtenances and rely on localised corners and extended surfaces to achieve LVZs. These configurations may result in reduced installation cost and in certain circumstances reduced discharge impacts. Notable examples include rectangular section longitudinal ribs [11, 23] which provides a small LVZ to assist small-bodied fish passage in partially filled circular pipe culverts.

A culvert comprises of three physical flow zones: these being the inlet zone, barrel zone and outlet zone. In this paper, the physical modelling was focused on the culvert barrel zone and the exploration of streamwise section variants in partially filled smooth circular culverts by investigating the hydrodynamics of a novel device to induce LVZs capable of enhancing small-bodied fish passage. The device comprises of a longitudinal section, commonly known as a C-section, asymmetrically mounted within the lower semi-circle of a smooth pipe culvert barrel. Herein, this device was then physically modelled under controlled laboratory conditions at near-full scale. The outcomes of this investigation will be later used to guide future laboratory and field trials involving native small-bodied fish.

2 Physical facilities and experimental testing

Experimental testing was conducted in the AEB Hydraulics Laboratory at the University of Queensland using a 15 m long 0.5 m diameter horizontal semi-circular PVC flume, ending with a free-edge overfall. The flume was previously used by Li, Harley and Chanson [23]. The water discharge was measured by an in-line Venturi meter installed and calibrated in accordance with British Standards [24]. Rail-mounted pointer gauges were used to measure flow depths. The velocities were measured with a Prandtl-Pitot tube, a roving Preston tube (RPT) [25], an acoustic Doppler velocimeter (ADV) Vectrino+ equipped with a side-looking probe, and an acoustic Doppler velocimeter Vectrino II (Profiler) fitted with a down-looking probe. The vertical location of all instruments was recorded with a HAFCO® digital scale unit with an accuracy of 0.05 mm. The ADV Vectrino + was sampled at 200 Hz at each mea-

surement point for a total of 100,000 samples for the smooth semi-circular channel, whilst 60,000 samples were taken for the smooth semi-circular channel fitted with the C-section. The ADV Profiler signal was sampled at 100 Hz for 54,000 samples. The ADV data was processed by removing erroneous data with an average signal-to-noise ratio (SNR) of less than 5 dB and an average correlation value (across all beams) of less than 60%. Statistical outliers were then removed using the phase-space thresholding (PST) technique and followed by data replaced using linear interpolation [26, 27]. The ADV was unable to measure velocities at the free surface, and these were estimated by adopting the last vertical reading in the profile. Dye injections were employed to visualise flow motion, complemented by digital photography and video recordings (Table 1).

The 0.5 m diameter smooth semi-circular PVC flume was fitted with a single extruded aluminium C-section, installed along the entire semi-circular culvert barrel flume (Fig. 2). The C-section was fitted on the right-hand side of the PVC flume (facing downstream) at an angle of 30° to the flume centreline (Fig. 2). This C-section was similar in shape to galvanised steel channel sections commonly used in engineered structures. The difference between the C-section and other sections such as the longitudinal rail [11, 23] is the additional surfaces and corners provided by the C-section. The C-section dimensions along with longitudinal sections used in other related studies are listed in Table 2.

The longitudinal extent of the C-section was between $x = 1.22$ m (located within the flume inlet zone) to $x = 14.25$ (terminating 220 mm from the channel outlet brink).

The physical experiments used water discharges between $0.015 \text{ m}^3/\text{s}$ and $0.075 \text{ m}^3/\text{s}$ for free-surface measurements conducted between $x = 1.22$ m and $x = 14.47$ m. Detailed velocity cross-section measurements at $x = 7.15$ m were only conducted at $Q = 0.075 \text{ m}^3/\text{s}$. This location was chosen as it exhibited fully-developed flow characteristics. The measurements were conducted with both the smooth semi-circular channel and the semi-circular channel equipped with the C-section (Table 3). Along the wetted perimeter, boundary velocities were measured at approximately 20 mm spacing using the Prandtl Pitot tube. Vertical profiles were measured using both Prandtl Pitot tube and ADV Vectrino+, depending on the location of the vertical profile. For locations adjacent to the C-section, where instrument access was very difficult, the velocity measurements were supplemented using the roving

Table 1 Velocity measurement instruments

Element	ADV (side-looking)	ADV (down-looking)	Prandtl pitot tube	Roving preston tube
Variant	Nortek™ Vectrino+	Nortek™ Vec- trino II (Profiler)	Dwyer™ 166 Series	RPT C1.4R
Instrument configura- tion	4 probe	4 probe	Ø = 2.98 mm with semi- hemi- spherical nose	Ø = 1.43 mm with sharp nose
Expected time- averaged velocity error	+/- 1% #	+/- 1% #	+/- 1%	+/- 2%

#As reported by Voulgaris and Trowbridge [28]. However, Finelli, Hart and Fonseca [29] and Dombroski and Crimaldi [30] noted that in high velocity gradient regions, error may increase to 5% due to sampling volume size. Thomas, Schindfessel, McLelland, Creelle and De Mulder [31] also highlighted that ADV calibration matrices may slightly vary with velocity

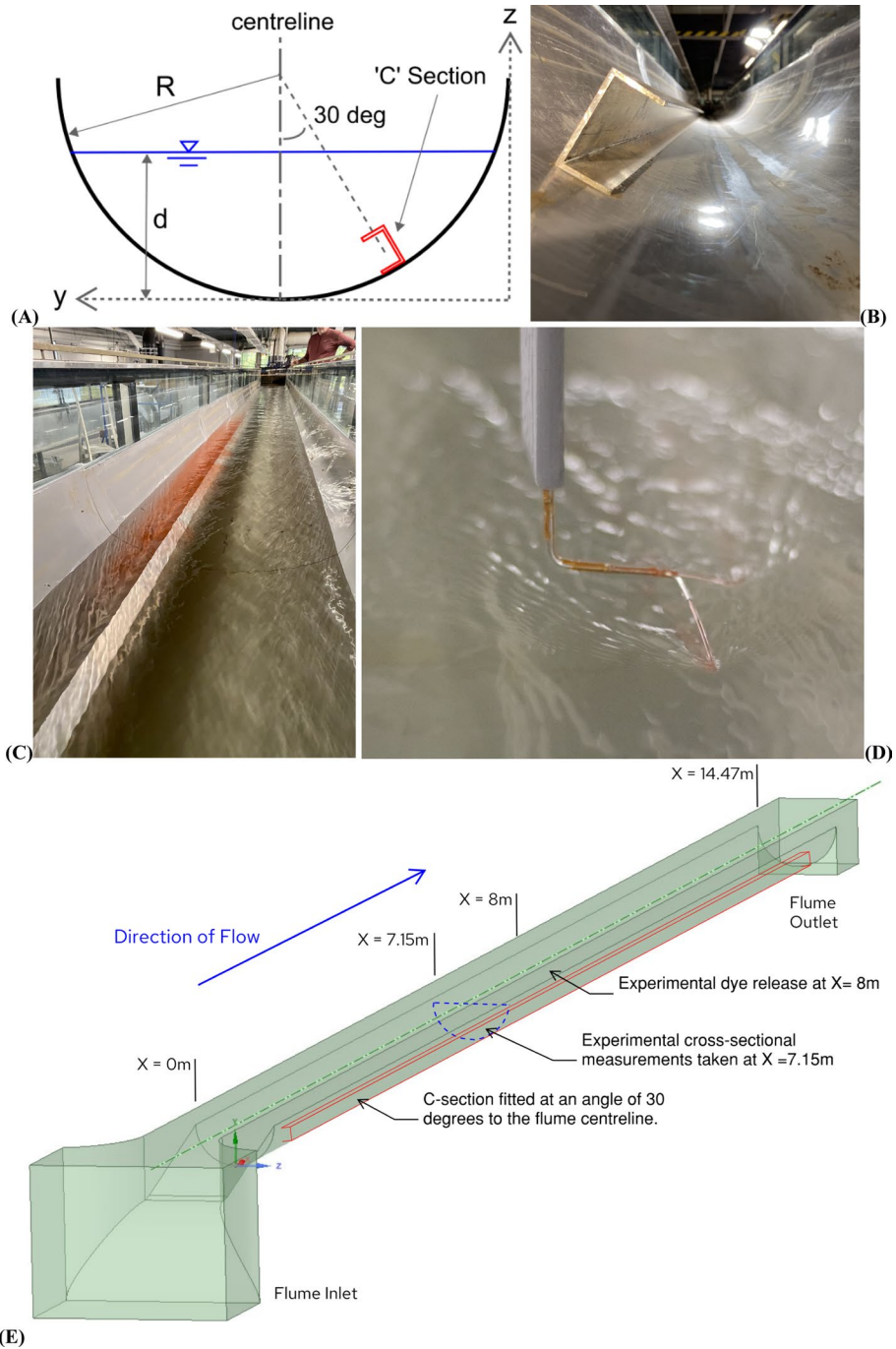


Fig. 2 C-section installation. **A** definition sketch (looking downstream in the x direction). **B** C-section installation in a smooth semi-circular PVC flume (Photograph taken at $x = 14.5 \text{ m}$ looking upstream). **C** Looking upstream for $Q = 0.015 \text{ m}^3/\text{s}$, with a puff of coloured dye injected above the C-section, advected from background to foreground. **D** Details of the roving Preston tube, looking downstream while the tube was purged. **E** Experimental flume setup showing location of measurement stations

Table 2 Channel section and installation dimensions

Section type	Section thickness (mm)	Section depth (mm)	Section width (mm)	Fitted angle to vertical centreline	Source
Smooth	N/A	N/A	N/A	N/A	Present study
C-section	3	57	32	30 deg	Present study
Longitudinal rail	N/A	60	20	30 deg	[19]
Longitudinal rail	N/A	30	20	30 deg	[10]

Table 3 Comparison of Prandtl-Pitot tube results between smooth semi-circular channel and smooth semi-circular channel fitted with longitudinal appurtenances at $x = 7.15$ m for $D = 0.5$ m, $S_0 = 0\%$

References	Configuration	Q (m ³ /s)	V_{mean} (m/s)	Bulk reynolds number	Froude number	Depth (m)	Darcy Weisbach friction factor
Present study	Smooth semi-circular channel	0.075	0.87	4.6×10^5	0.67	0.227	0.021
Present study	Smooth semi-circular channel fitted with a C-section	0.075	0.85	4.2×10^5	0.64	0.231	0.023
[23]	Smooth semi-circular channel fitted with a 60 mm $\times$ 20 mm longitudinal rail	0.065	0.82	3.7×10^5	0.65	0.223	0.019
[11]	Smooth semi-circular channel fitted with a 30 mm $\times$ 20 mm	0.055	0.81	3.0×10^5	0.66	0.194	0.016

Preston tube C1.6R variant inside the C-section (Fig. 2D). The roving Preston tube C1.6R variant was calibrated to the Prandtl Pitot tube results obtained at $y = 0.250$ m [32]. The ADV Vectrino Profiler was also used to measure velocities of locations in the vicinity of the C-section that could not be accessed by the ADV Vectrino+.

3 Culvert pipe barrel hydrodynamics

3.1 Visual observations

Table 3 highlighted a comparison of basic flow results between the smooth semi-circular channel and the smooth semi-circular channel fitted with longitudinal ribs variants for similar water discharge.

For the present study, a subcritical flow was observed, gradually varying for the full length of the channel, except within 0.5 m of the free brink at the downstream end ($x = 14.47$ m). The outlet conditions induced a H2 free-surface profile within the flume [10, 33]. Some small free-surface undulations were observed within the developing zone ($0 < x < 4$ m). The free-surface undulations diminished in the streamwise direction and were negligible at the measurement station ($x = 7.15$ m). Along the full length of the channel, the flow was observed to be very turbulent. For the smooth semi-circular channel, dye injections ($x = 8.0$

m) showed the presence of large-elongated flow structures, comprising of two distinct secondary flow cells. An upwelling zone was also observed between $y = 0.2$ m and $y = 0.3$ m. The elongated flow structures did not laterally meander to any significant extent although, within the upwelling zone, the dye tended to moderately disperse. Some longitudinal streaking was observed, and this was similar to the structures observed by Imamoto and Ishigaki [34] during their visualisation experiment on smooth rectangular channels with an aspect ratio of five.

For the semi-circular channel fitted with a C-section, some slight free-surface undulations and strong turbulence was observed along the length of the channel. The overall flow depth was slightly larger than for the smooth channel, coinciding with an increase in flow resistance. Some dye injection showed further the presence of two distinct secondary flow cells either side of the C-section. No lateral meandering of secondary flow cells was observed. Dye injection immediately above the top of the C-section showed vigorous upwelling, dispersing dye until it reached the free surface. Dye injections into the internal left-hand corner of the C-section and the outer right-hand corner remained coherent for some distance downstream (Fig. 3). These flow patterns generally matched the secondary flow vectors shown in Fig. 7.

Detailed velocity measurements were conducted at $x = 7.15$ m, located within the fully developed flow zone. The time-averaged longitudinal local velocities were presented in the form of streamwise velocity ($\bar{V}_x$) contour maps (Fig. 4). The velocity was integrated to check for conservation of mass.

$$\hat{Q} = \int_A \bar{V}_x dA \quad (1)$$

The integration results closely matched the discharge measurements obtained from the Venturi meter to within 0.8% for the smooth semi-circular channel and 1.8% for the smooth semi-circular channel fitted with a C-section.

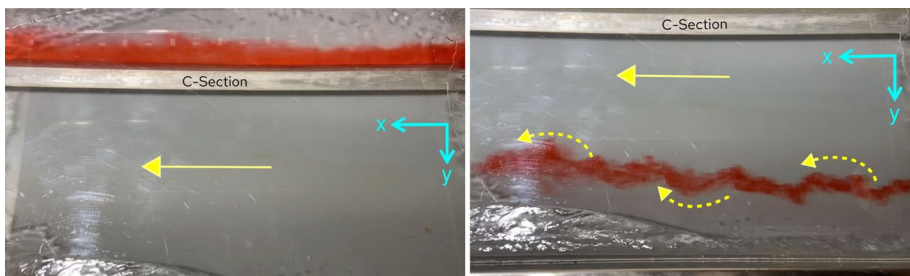


Fig. 3 Photographs of dye injection tests in the smooth semi-circular channel fitted with a C-section, $Q = 0.075 \text{ m}^3/\text{s}$, $x = 8.0$ m. Arrow showed the direction of flow. (LEFT) Top view of dye injection at $y = 0.1$ m showed a coherent streamline within the LVZ (between the C-section and the right-hand side of the channel, photograph taken in the z direction (down). (RIGHT) Top view of dye injection at $y = 0.3$ m, $z = 0.1$ m showed the left-hand secondary flow vortical cell, photograph taken in the z direction (down)

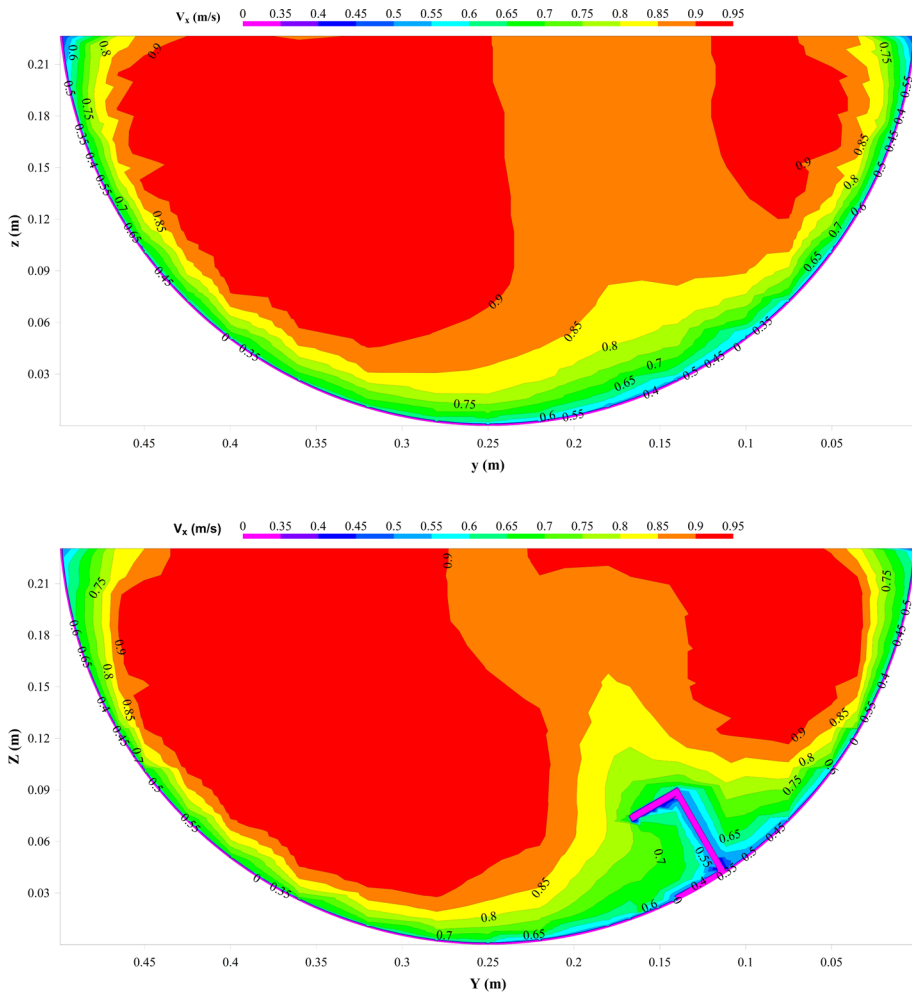


Fig. 4 Contour maps of time-averaged longitudinal local velocity (facing downstream), $\bar{V}_x$, $Q=0.075 \text{ m}^3/\text{s}$, $x=7.15 \text{ m}$. $y=0.25 \text{ m}$ was the centreline and $y=0 \text{ m}$ was the right-hand sidewall, velocity scale in m/s, based on Prandtl-Pitot tube and roving Preston tube data. (TOP) Smooth semi-circular channel, $d=0.227 \text{ m}$. (BOTTOM) smooth semi-circular channel fitted with a C-section, $d=0.231 \text{ m}$

3.2 Velocity field and low velocity zones

In the context of fish passage, a low velocity zone (LVZ) refers to an area within a culvert, where the fluid movement is significantly slower than other areas of the flow cross-section. These zones provide fish with a less challenging environment to navigate, allowing them to rest and expend less energy when moving upstream. For the smooth semi-circular channel case, the streamwise velocity maps generally showed two near-symmetric high velocity cells. These features generally aligned with dye test observations, although some flow asymmetry was observed (Fig. 4 TOP).

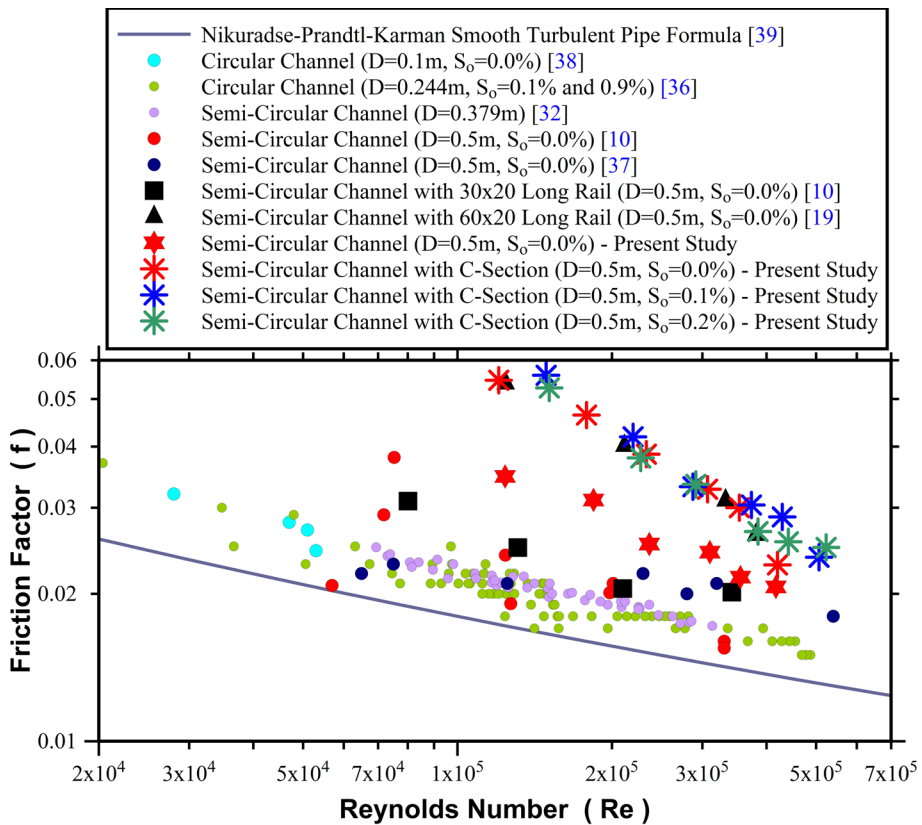


Fig. 5 Darcy-Weisbach friction factors for smooth semi-circular channel fitted with C-section at $x = 7.15$ m ($Q = 0.015, 0.025, 0.035, 0.050, 0.060$ and 0.075 m³/s and $S_0 = 0\%, 0.1\%$ and 0.2%). Comparison between experimentally derived friction factors, the Nikuradse-Prandtl-Karman smooth turbulent pipe flow formula [39] and relevant experimental pipe data. Data sourced from [11, 23, 36, 40–42]

A lower velocity gradient, $\frac{dV_x}{dz}$, was observed between $y = 0.15$ m and $y = 0.20$ m and this indicated a zone of upwelling low momentum fluid. Lower velocities were present in the top corner zones, where the free surface intersected with the channel, which also matched the dye injection observations. These patterns were consistent with earlier physical modelling studies [11, 23, 35, 36].

For the semi-circular channel fitted with a C-section, a lower velocity gradient, $\frac{dV_x}{dz}$, was observed at the upwelling zone, although this was now clearly located at $y = 0.15$ m and extending above the top of the C-section. Moderately sized LVZs were present in both the internal left-bottom corner and outer right-bottom corner of the C-section. These enhanced LVZs may provide improved prospects for the upstream passage of small-bodied fish within smooth circular pipe culverts.

3.3 Flow resistance and friction factors

The flow resistance of the pipe culvert channel was estimated based upon longitudinal free-surface measurements and the application of the backwater equation. The standard step method [10] (Eq. 2) was used to calculate the water surface profile from measured depths between $x = 1.22$ m to 14.47 m for $Q = 0.015, 0.025, 0.035, 0.050, 0.060$ and 0.075 m³/s. The Darcy-Weisbach friction factor calculations relied on the bulk hydraulic diameter, D_H and no adjustments to the cross-sectional area and the wetted perimeter were incorporated into the calculations. This decision was based on noting the sensitivity of Eqs. 2 and 3 to changes in hydraulic diameter, in particular, the impact of significant increases in wetted perimeter by accounting for the dimensions of the C-section. Inclusion of the C-section resulted in significant reductions in the value of the hydraulic diameter of between 17 and 23%, and the subsequent calculation of unrealistic friction factor values well below values calculated for the smooth bore case. According to Gioia and Bombardelli [37], the hydraulic diameter is inherently the characteristic length scale of the eddies associated with the bulk flow velocity. Therefore, it is posited that significantly adjusting the hydraulic diameter by accounting for the C-section, overly distorts the calculation of the change in mean specific energy in the standard step method calculations.

Haaland's explicit friction factor formula was employed [38] (Eq. 3) and the calculated water surface profiles generally matched measured profiles to within ± 0.003 m.

$$\frac{\partial d}{\partial x} (1 - Fr^2) = S_0 - S_f \text{ where } S_f = \frac{f V_{\text{mean}}^2}{2g D_H} \quad (2)$$

$$f = \left\{ -1.8 \log \left[\left(\frac{k_s}{3.7 D_H} \right)^{1.11} + \frac{6.9}{Re} \right] \right\}^{-2} \quad (3)$$

where k_s is the equivalent sand roughness height and Re is the Reynolds number and the hydraulic diameter $D_h = 4 \times A / P$, where A is the bulk flow cross-sectional area, and P is the bulk wetted perimeter.

The friction factors for the C-section configuration were higher than those obtained from the smooth semi-circular channel, yet similar to those obtained from the 60 mm x 20 mm longitudinal rib [23]. It should be noted that friction factors for the 30 mm x 20 mm longitudinal rib were calculated by accounting for the rib cross-sectional area and the increase in wetted perimeter due to the rib surface, which explained their lower friction factor values [11]. The impact of the C-section on channel flow resistance was represented by the following relationship (Eq. 4).

$$f = f_{\text{NKP}} + 0.016 \left(\frac{344105}{Re} \right)^{0.9} \quad (4)$$

where f_{NKP} is the smooth turbulent pipe friction factor based on the Nikuradse-Karman-Prandtl smooth turbulent pipe formula [39]. The experimental data sets and Eq. 4 implied that a C-section fitted to a semi-circular channel would have a lesser impact on the culvert

flow resistance for increased discharges, increased channel diameters and overall larger Reynolds numbers. The increase in friction factors due to the C-section was especially noted during low discharge events ($Q = 0.015\text{--}0.035\text{ m}^3/\text{s}$), where the vee-shaped flow cross-section, located between the C-section and the channel wall, was observed to contain low velocities. However, friction factors tended to converge to the smooth bore case for higher flow depths and higher discharges. Figure 6 showed that friction factors decreased in value as the dimensionless hydraulic diameter decreased, such that the impact of the C-section appeared negligible for scenarios where the dimensionless hydraulic diameter approached 1.8.

Care should be exercised when applying this relationship to design scenarios, especially for scenarios where $d/D > 0.5$, because the present experiments were restricted to semi-circular channels.

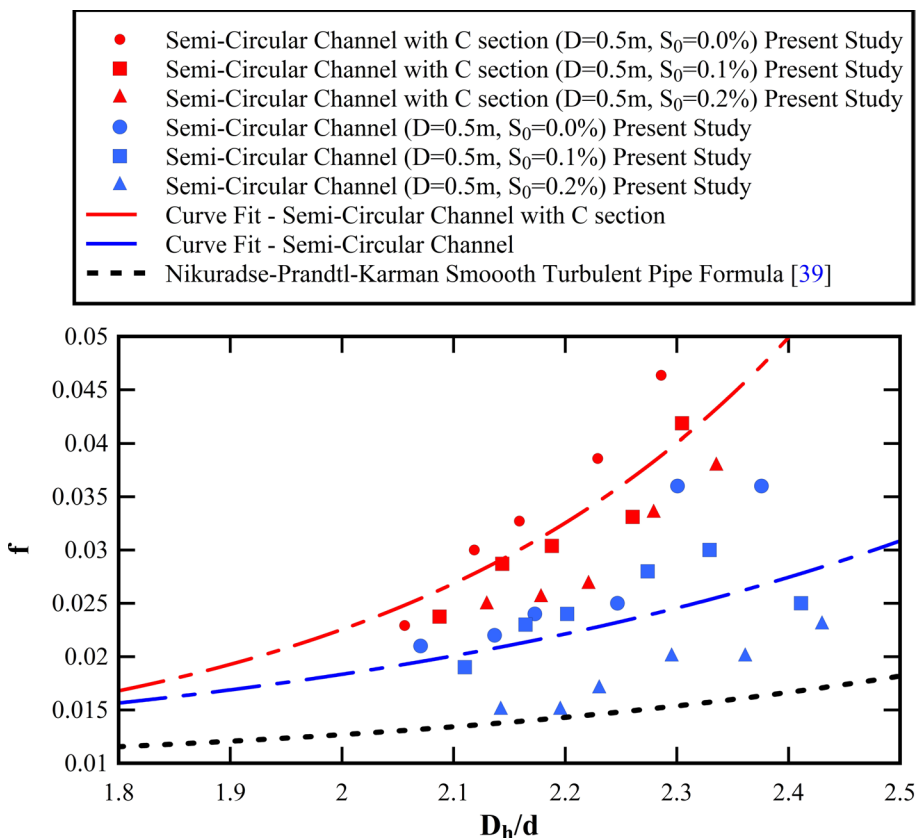


Fig. 6 Darcy-Weisbach friction factors for smooth semi-circular channel and smooth semi-circular channel fitted with C-section at $x = 7.150\text{ m}$ ($Q = 0.015, 0.025, 0.035, 0.050, 0.060$ and $0.075\text{ m}^3/\text{s}$ and $S_0 = 0\%$, 0.1% and 0.2%) plotted against the dimensionless hydraulic diameter D_h/d , where d is the depth of flow. Comparison between experimentally derived friction factors, the Nikuradse-Prandtl-Karman smooth turbulent pipe flow formula [39]

3.4 Secondary flow motion

In a channel, the secondary flows characterise the motion in the plane perpendicular to the main flow motion, i.e. the y - z plane herein. Secondary flow structures in the smooth semi-circular channel comprised of two dominant counter-rotating cells spanning the channel centreline (Fig. 7 TOP). Smaller circulation cells were observed using dye injections in the upper corners (where the invert meets the free surface), although the proximity to the free surface prevented the ADV unit from measuring velocities. About the channel centreline ($y = 0.2$ m), the confluence of counter-rotating circulation cells coincided with the upwelling of fluid from the invert to the free-surface, where fluid was eventually redirected to the side walls. These secondary flow patterns were likely caused by the unique experimental flume inflow configuration, where the open channel inflow contracted both horizontally and vertically. The flow contractions were likely responsible for the observed upwelling

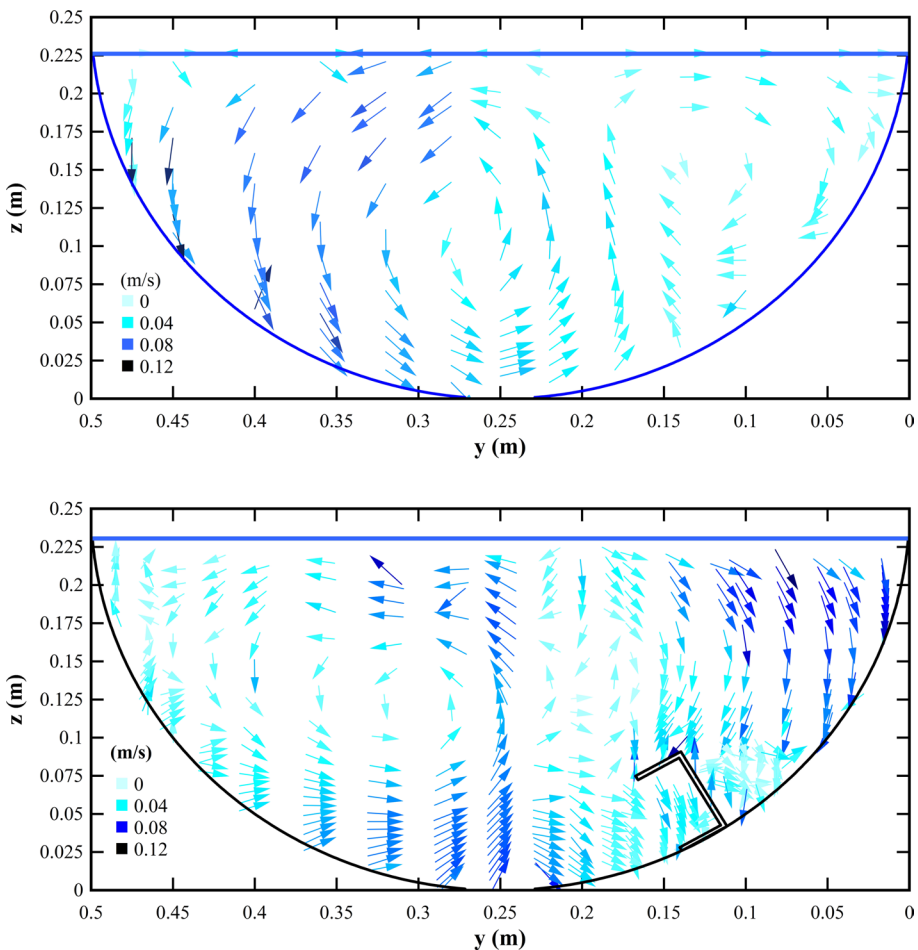


Fig. 7 Secondary flow maps (facing downstream), $Q=0.075 \text{ m}^3/\text{s}$, $x=7.15 \text{ m}$. $y=0.25 \text{ m}$ was the centreline, velocity vector plot scaled in m/s , based on ADV data. (TOP) Smooth semi-circular channel, $d=0.227 \text{ m}$. (BOTTOM) smooth semi-circular channel fitted with a C-section, $d=0.231 \text{ m}$

counter-rotating cell patterns, which were transported downstream due to conservation of angular momentum and exacerbated by the low channel aspect ratio. To support this inference, dye injections confirmed the presence of a vigorous upwelling of fluid at the centreline and strong similar counter-rotating cells at the flume inlet ($x = 0$ m). The upwelling of fluid about the channel centreline did not match the flow patterns measured by Clark and Kehler [43] on a 0.8 m diameter corrugated metal pipe (CMP) culvert barrel, who observed a downwelling counter-rotating cell pattern. Similarly, PIV experiments conducted by Ng, Cregan, Dodds, Poole and Dennis [42] on 100 mm diameter smooth cylindrical borosilicate glass tubes, also showed a downwelling of fluid at the centreline. Whilst the inlet conditions for the Clark and Kehler [43] experiments were unknown, the inlet conditions of Ng, Cregan, Dodds, Poole and Dennis [42] were based on pressure pipe entry. The differences in secondary flow patterns were not restricted to physical modelling. Large-eddy simulations conducted by Liu, Stoesser and Fang [44], also showed a downwelling counter-rotating cell pattern. Understanding these differences emphasised the importance of identifying upstream flow conditions and their influence on the formation and transportation of secondary flow structures along circular pipe culvert barrels. These differences also need to be considered when assessing the variety of inlet flow conditions that potentially exist for operational field conditions.

In the smooth semi-circular channel, the magnitude of mean secondary flow velocities was $0.04\text{--}0.09 V_{\max}$, which was higher than the $0.02 V_{\max}$ results reported by Nezu and Nagakawa [45] and $0.02\text{--}0.03 V_{\max}$ results reported by Ng, Cregan, Dodds, Poole and Dennis [42]. The presence of large secondary flow velocities may also partly account for the increase in flow resistance within circular open channels for the present study as shown in Fig. 6.

The presence of the C-section appeared to modify the secondary flow patterns and increase the secondary velocity magnitude in the centreline upwelling zone, in comparison to the smooth semi-circular channel (Fig. 7). However, the magnitude of mean secondary flow velocities remained between 0.04 and $0.09 V_{\max}$, for the main counter-rotating secondary flow cells. Whilst the left-hand secondary rotational cell was preserved, the C-section appeared to shift the centre of this rotational cell to $y = 0.3$ m, along with a minor increase in upwelling zone secondary velocity from 0.04 m/s to 0.06 m/s. Complex flow structures were noted in the region above the top of the C-section, supported by strong secondary flow velocities in the top right-hand corner of the channel. Low secondary velocity magnitudes were observed in the bottom left-hand and right-hand corners of the C-section, similar to observations made in similar open channel experiments [23, 46–48].

Turbulent shear stress gradients were likely created by a combination of turbulence generated from the invert, well-defined corners of the C-section, the channel corner zones where the free surface intersects the invert, as well as turbulence anisotropy transported from upstream sources. The differences in turbulent normal stresses ($vz'^2 - vy'^2$) appeared to be associated with secondary flow [45, 49]. The difference ($vz'^2 - vy'^2$) characterised the generation of streamwise vorticity [50, 51], and typical results were presented in Fig. 8. This contour map of ($vz'^2 - vy'^2$) showed that the differences in turbulent normal stresses for the C-section were intensified (Fig. 8). Most of the flow cross-section showed strong positive turbulent normal stresses located either, close to the channel invert, inside the C-section or directly above the top of the C-section. To the right of the C-section, low negative turbulent normal stresses coincided with the presence of the right bottom corner LVZ. Whilst it was

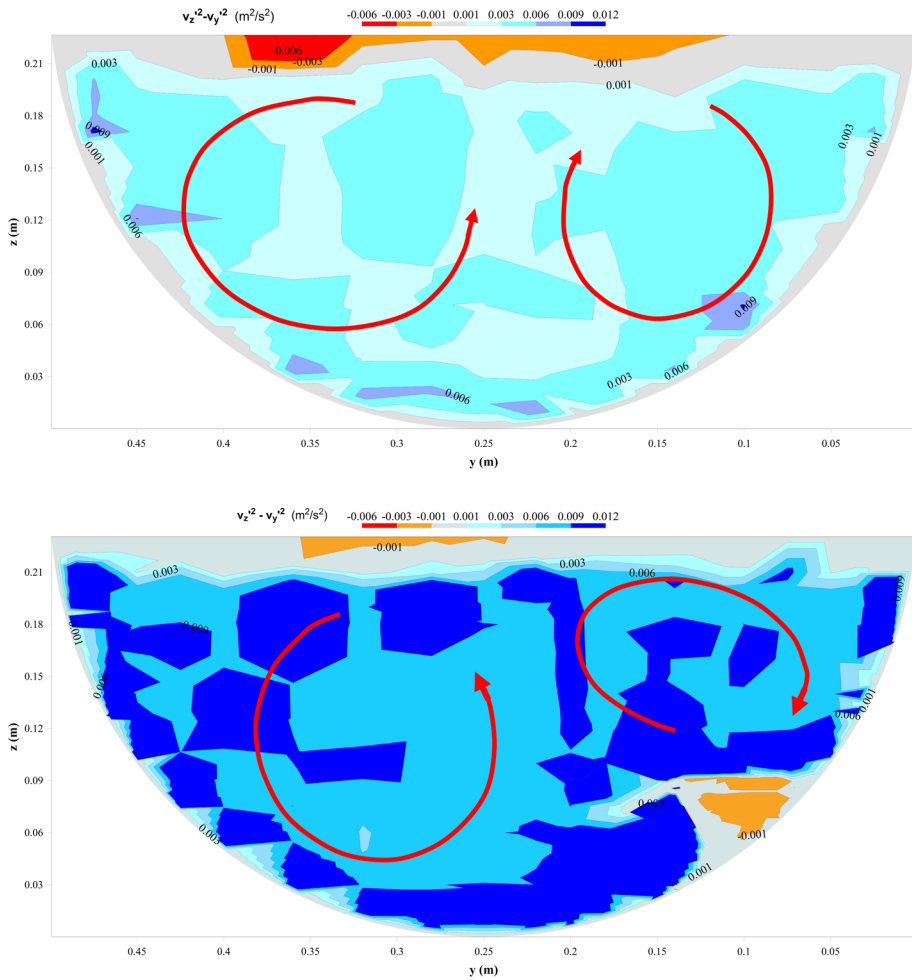


Fig. 8 Contour maps of the difference ($v_z'^2 - v_y'^2$) (facing downstream), $Q=0.075 \text{ m}^3/\text{s}$, $x=7.15 \text{ m}$, $y=0.25 \text{ m}$ at the centreline, velocity vector plot scaled in m^2/s^2 , ADV data. (TOP) smooth semi-circular channel, $d=0.231 \text{ m}$. (BOTTOM) smooth semi-circular channel fitted with a C-section, $d=0.237 \text{ m}$. Solid red arrows indicated main secondary flow structures

proposed that some proportion of secondary flow originated from upstream sources, the presence of the C-section appeared to have intensified the difference in turbulent normal stresses within the channel.

4 Discussion

Swimming performance of fish can significantly vary within natural populations depending on age, species, and the type of barriers [2]. Small-bodied or juvenile fish are particularly vulnerable to high culvert barrel velocities conditions [52], with many small-bodied and juvenile fish having U_{crit} values ranging from 0.1 to 0.6 m/s [53, 54], and U_{sprint} values

ranging from 0.4 to 0.9 m/s [55]. Whilst Fig. 4 showed that streamwise velocities were reduced to approximately 0.5–0.7 m/s on either side of the C-section, smaller sized LVZs of less than 0.5 m/s were also present which could accommodate some fish species with standard lengths less than 70 mm. These LVZs may be small enough to allow target groups of small-bodied and juvenile fish to traverse short distances within structures such as roadside culverts. Regardless of fish size, the rate of work exerted by a fish to negotiate flow is proportional to the cube of the local streamwise velocity [56], which further implied that devices that reduced local streamwise velocities, even marginal reductions, will further improve the endurance of other higher performing fish species in their upstream journey.

Smooth pipe culverts are hydraulically efficient, and most associated LVZs are thin and located close to the pipe culvert wall. These zones may be far too small to be utilised by small-bodied fish because of the high gradients of streamwise velocity that occur in this thin layer. Furthermore, this layer hosts the primary mechanism for smooth pipe energy dissipation, i.e. boundary skin friction, which is characterised by high normal and shear stresses. In contrast, the C-section provides a bottom corner zone which replicates the hydrodynamics of box culvert bottom corner zones [6]. These corner LVZs are the result of complex three-dimensional velocity fields, where the dominant secondary flow typology are Prandtl's secondary currents of a second kind [39]. In the current configuration, the well-defined edges of the C-section created hydrodynamic singularities, which in turn generated stresses that created and sustained the secondary flow required to form LVZs in corners [46, 57]. Consequently, the efficacy of any small longitudinal rib/beam variant within a smooth pipe culvert ultimately depends on its capacity to project those well-defined edges into high velocity zones to generate the necessary differences in turbulent stresses. Developing and maintaining well-defined edges, therefore, has manufacturing, construction, and maintenance implications. Finally, the C-section may result in maintenance challenges, with the possibility of increased risk of sedimentation and trapping of debris. Due to the long smooth continuous sections mounted within circular culvert section, the risk of trapping woody debris would appear less likely than regularly spaced baffles. Although, it is feasible that sand and gravels may deposit in the upper corner, and in small quantities, this could provide some benefit to fish passage. However, a fully blocked upper corner may induce further reductions in culvert discharge capacity and reduce the extent of the LVZ. Ultimately, the performance of the C-section will require an assessment of inflow sediment loads, and this investigation will feature in future field trials.

Care should be taken in ascribing the causation of secondary flow to instream devices such as longitudinal ribs. In the present study, vigorous counter-rotating secondary flow cells were observed, however, it was ascertained that the main source of these structures were based on upstream flow conditions. Whilst Prandtl [39] and more recently Chanson [57] have highlighted the role of turbulent anisotropy due to well-defined edges and asymmetrically positioned longitudinal cross-section devices, the relative contribution of these features may overplay the importance of the transport of angular momentum from upstream sources. Longitudinal ribs may preserve or enhance secondary flow rather than being the sole cause. This also suggests that the difference in turbulent normal stresses plays a role in the conservation of angular momentum of secondary flow in open channel flow.

5 Conclusion

Physical modelling was conducted for a range of flow rates corresponding to less-than-design flows in a smooth circular pipe culvert barrel operating as a subcritical free-surface flow. The reference configuration, a smooth semi-circular channel was thoroughly tested. The study then investigated a smooth semi-circular channel, fitted with a C-section placed at 30° to the centreline. The C-section enhanced the flow asymmetry, creating a small LVZ in the bottom left-hand and right-hand corners of the C-section, which created hydraulic conditions potentially conducive to upstream fish passage. Strong secondary flow structures were maintained. The distributions of normal turbulent stresses ($vz'^2-vy'^2$) showed distinct differences between each boundary treatment, with the position of the C-section firmly delineating the extent of secondary flow motion. The secondary flow structures observed for the C-section in a semi-circular channel were similar to those observed in similar experiments employing longitudinal ribs in a semi-circular channel [11, 23]. In engineering practice, expedient devices to assist fish passage are often retrofitted to existing culverts; either as temporary devices for fish passage diversions, or permanently in low/medium risk waterways due to limited infrastructure budgets. The C-section represents a simple 'off-the-shelf' item that can be easily fitted to existing or new culverts. It can be supplied as a standard galvanised channel section and directly fixed to a pipe wall, fixed with clamps that are mechanically wedged within the pipe culvert joints or mounted from a culvert endwall. Its low impact on culvert discharge provides an attractive option compared to solutions involving bulky baffles, that significantly reduce culvert discharge. Whilst the local target fish species are a key design criterion for fish passage devices, in many situations, fish management agencies have great difficulties implementing measures to assist all local species. Hence, expedient fish passage devices that provide a pragmatic trade-off between limited budgets and environmental efficacy will remain an ongoing reality for the near future. Finally, the impact of boundary treatments on small-bodied fish performance were not tested in the laboratory and in the field. Furthermore, these experiments focused on measurements conducted in the fully-developed zone of a culvert under gradually-varied flow conditions. Therefore, the performance of C-sections in the inlet and outlet zones of culvert is not well known. Also, the size of the C-section in relation to the target culvert diameter requires careful consideration. Any change in C-section dimensions, and also the ratio of the C-section profile height with respect to the bulk hydraulic diameter may result in different LVZs and culvert discharge impacts. Comprehensive fish testing trials will be required in future investigative stages before C-sections are deemed to be suitable for operational implementation.

6 Notation

The following symbols are used in this paper:

A channel flow cross-section area (m^2)

B free-surface width (m)

D pipe diameter (m)

D_H hydraulic diameter (m), where $D_H = 4 \times \frac{A}{P_w}$

d water depth (m) measured above the bottom invert of the semi-circular channel

Fr Froude number for an irregular channel section, where $Fr = \frac{V}{\sqrt{g \times \frac{A}{B}}}$

f Darcy-Weisbach friction factor, where $f = \frac{2gD_H S_f}{V_{mean}^2}$

g gravity acceleration (m/s^2), where $g=9.792 m/s^2$ in Brisbane, Australia

H total head (m)

k_s Colebrook-White equivalent sand roughness height (m)

L channel length (m)

N Power law coefficient

P_w wetted perimeter (m)

Q discharge (m^3/s) $\hat{Q}$ water discharge calculated by integrating the longitudinal velocity distribution across the flow cross-section area where $\hat{Q} = \int_A \bar{V}_x \times dA$

R pipe radius (m)

Re Bulk Reynolds number defined in terms of hydraulic diameter, where $Re = \frac{V_{mean} \times D_H}{\nu}$

S_f friction slope

S_o bed slope where $S_o = \sin\theta_b$

U_{fish} characteristic fish swimming speed (m/s) set by the relevant fish agency based upon fish swimming performance

V velocity (m/s)

V_{max} maximum velocity (m/s)

V_{mean} cross-sectional mean (bulk) velocity (m/s), where $V_{mean} = \frac{Q}{A}$

$\bar{V}_i$ time averaged velocity (m/s) where i represents the x, y, z component

v_i velocity fluctuation (m/s) where $v_i = V_i - \bar{V}_i$ and where i represents x, y, z component

v'_i standard deviation of velocity (m/s), where $v'_i = \sqrt{\frac{1}{n} \sum v_i^2}$ and where i represents the x, y, z component

x longitudinal distance (m) positive downstream

y transverse distance (m) measured from the right sidewall positive towards the left sidewall

z vertical distance (m) positive upwards with $z=0$ at the bottom invert

z_{bed} local bed elevation (m)

μ dynamic viscosity (Pa.s)

θ_b angle of flume bed slope to the horizontal

ρ density (kg/m^3)

ν kinematic viscosity (m^2/s) of water

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10652-026-10111-2>.

Acknowledgements The authors acknowledge Ensilon Consulting, Australia for photographs of culverts and fish passage devices. The authors also acknowledge the technical assistance of Jason Van Der Gevel and Stewart Matthews (The University of Queensland).

Author contributions J.H.: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Software, Validation, Visualization, Writing – Original Draft, Writing – Review and Editing, H.C.: Resources, Data Curation, Writing – Review and Editing, Supervision, Project administration, Funding acquisition.

Funding The authors declare that funding was received from Apiary Financial, Grantor RE333704.

Data availability Data Availability Statement Some or all data, or models that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interest The authors declare no competing interest.

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