



# Turbulence characterisation of low velocity zone in box culvert: application to upstream fish passage

Hui Ling Wong<sup>1</sup> · Hubert Chanson<sup>1</sup>

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## Abstract

The large velocities in a culvert hinder the movements of migratory and non-migratory fish, particularly small-bodied fishes and juveniles of larger fish. To date, limited hydrodynamic characteristics, such as the turbulence structures in the culvert barrel, were considered in the current fish passage design guidelines for box culverts. This presents a gap in knowledge on the fundamental understanding of culvert hydrodynamics and its effect on fish kinematics. New research was conducted, focusing on box culverts, with the aim of designing a fish passage without additional hydraulic appurtenances such as baffles. The research focuses on the use of low velocity zone (LVZ) in the culvert barrel, that corresponds to the observed fish swimming zone for upstream fish passage. Herein, new physical modelling involved detailed free surface and velocity measurements, and the results are detailed in this paper which include the joint mapping of Reynolds Stresses, integral timescale, advection length scale and turbulent burst analysis in a near-full-scale rectangular channel. Three-dimensional velocity measurements showed some strong secondary currents of Prandtl's second kind. The channel boundaries and bottom corners contributed to the occurrence of low-velocity zones (LVZs) and the hydrodynamic characteristics of these LVZs were carefully detailed. For a range of less-than-design flow conditions ( $1.7 \times 10^5 < Re < 4.3 \times 10^5$ ), the low-velocity zone constitutes high Reynolds stress regions with turbulent burst events of large amplitude and long burst duration. Herein, the median secondary current magnitudes corresponded to 4.7% to 6.0% of  $V_{max}$ . The integral timescale in the corner regions is shorter compared to the central flow region, that is  $T_{Ex} = 50\text{--}95$  ms,  $T_{Ey} = 10\text{--}100$  ms,  $T_{Ez} = 5\text{--}15$  ms in the corner regions, whereas the timescale component in the central region can be equalled or more than 260 ms. This also corresponds to the advection length scale of  $L_{xx} = 30\text{--}80$  mm,  $L_{xy} = 10\text{--}100$  mm and  $L_{xz} = 2\text{--}15$  mm in the corners, comparable to the actual size of the small-bodied fishes. From the turbulent burst analysis, the burst durations are in the range of 14–40 ms in the corners, with some turbulent burst amplitude larger than 20. The outcome of the physical modelling provided a fascinating insight into the hydrodynamics of the observed fish swimming zone (i.e. LVZ) and the data set constitutes a stepping stone for future development of fish passage design guidelines using LVZ with turbulence considerations.

## Highlights

- Hydrodynamic characterisation of low velocity zones in box culverts.
- Turbulence in observed fish swimming zones.
- Turbulence characterisation in low velocity zones of box culverts.

**Keywords** Standard box culvert · Secondary current · Reynolds stresses · Turbulent burst · Low velocity zones · Upstream fish passage · Physical modelling

## 1 Introduction

A culvert is a structure designed to channel streams and stormwater through an embankment [1, 2] (Fig. 1), and its barrel is the closed conduit section which has the narrowest cross-section. Since the design of modern drainage systems, e.g. culverts, typically focuses on conveying a large amount of stormwater in a short amount of time, the velocities in a culvert barrel are often high. In Queensland, Australia, the design guidelines recommended a desired maximum flow velocity in a partially full box culvert to be 4.7 m/s [3]. In contrast, the critical swim speeds,  $U_{crit}$ , of small-bodied native fishes are typically around 0.1 m/s to 0.4 m/s, which were referred by most design guidelines as the limiting mean flow or threshold velocity for fish passage design [4, 5], regardless of the testing procedure, selection and determination of such swim speed indicator. As a result of such large velocities, the upstream passage of fishes with weak swimming abilities is adversely impacted, particularly for small-bodied fishes and juveniles of the larger fishes, with body length commonly ranging from 25 mm to 120 mm. Such barrier in turn leads to waterway and habitat fragmentation, and the isolation and decline in the fish populations [6, 7].

The design of fish-friendly culverts requires both an understanding of the hydrodynamic behaviour and the identification of observed fish swimming zone in the culverts through detailed experiments and fish testing. The literature broadly acknowledged that fishes were observed to swim upstream next to the culvert barrel sidewall [8–11]. These regions were found to have lower velocities compared to the mean flow velocity. If the longitudinal velocity in the LVZ is equal or lower than the characteristic fish swim speed, and if the LVZ has sufficient space for fish to manoeuvre, fishes can utilise these low velocity zones (LVZ) to navigate [10–13]. In recent times, the presence of LVZ in the culvert barrel has attracted researchers to develop fish-friendly culverts without the use of additional hydraulic appurtenances such as baffles, with attempts to characterise, manipulate and size the geometric dimensions of these LVZs in standard box culverts [10]. The current initiatives to facilitate upstream fish passage include roughness manipulation and baffle installation [14–16]. Although the increased roughness reduces the water velocity in the culvert barrel, the discharge capacity of the culvert is reduced [14]. This results in a higher cost of culvert design and construction, eventually discourage the relevant stakeholders to prioritise the need for fish passage.

The hydrodynamics in a box culvert barrel leads to a complicated three-dimensional fluid flow. The strongest turbulence is generated in the corner regions with their effects seen in most parts of the channel [17, 18]. Secondary currents develop due to the hydrodynamic singularities generated by the corners and are associated with large turbulent Reynolds stresses next to the singularities. In turbulent flow, the presence of eddies of different timescale and length scale will also interfere with the fish locomotion. The moment produced by the

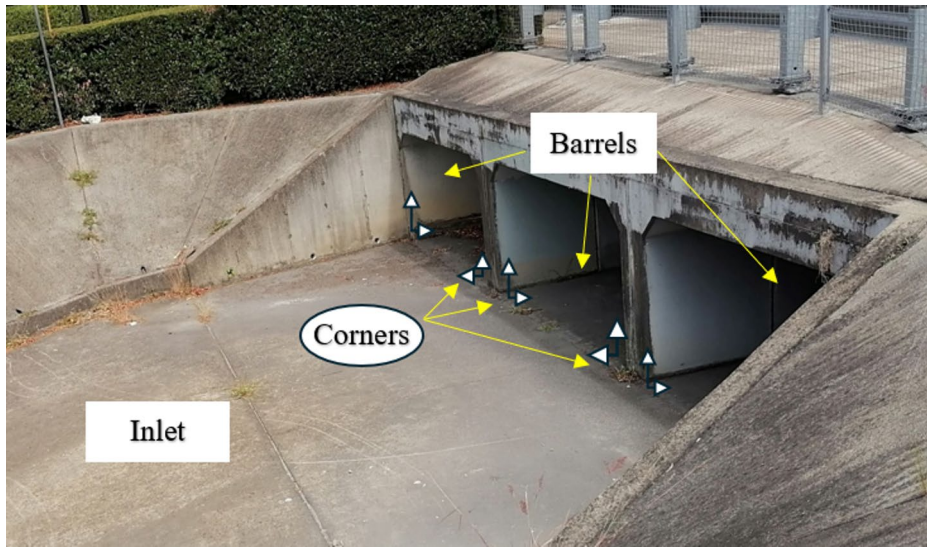


**Fig. 1** Three-cell box culvert near the intersection of Gaskell St and Logan Rd, Eight Mile Plains, Brisbane, Australia – Photo taken on the 23rd of September 2023

vortex favours fish to overturn and lose stability, especially if the size of the vortex and the fish body length are similar [19]. Fish attempt to restore the balance at the expense of their energy, resulting in a decrease in the swimming speed [19]. For instance, it was demonstrated that eddies in the turbulent flow, with sizes approximately three-fourth of the fish length, caused the creek chub to have difficulties maintaining posture in the flow and the critical swimming speed was reduced by 20% [20, 21]. All in all, the manifestation of these complicated hydrodynamic motions interacts with the kinematics and mechanics of fishes, presenting a non-trivial aspect to scrutinise.

To date, the literature and design guidelines provide limited knowledge and attention to the turbulence characteristics in LVZs. With a detailed study of the hydrodynamic characteristics in the low velocity zones (LVZs), a robust design guideline can be developed to facilitate fish passage in culverts without the use of baffles. In the present study, the physical modelling was completed with a detailed study on secondary currents and turbulence characteristics of the box culvert barrel, which include the quantitative mapping of Reynolds stresses, integral timescale, advection length scale with interpretation through a fish-size lens, as well as turbulent burst characteristics in a near-full-scale rectangular channel.

## 2 Methodology, facility and instrumentation

The laboratory experiments were conducted in a 15 m long, 0.5 m wide horizontal rectangular channel, acting as a near-full-scale single-box culvert barrel (Fig. 2). The invert of the flume was a smooth PVC bed, and the sidewalls were in tempered glass. With such a relatively-large-size flume, the extrapolation of the results to larger culvert structures would be based upon a joint Froude and Morton similarity. In open channel flows, Froude similitude is applied because of the significance of gravity effects. When the same fluids, air and

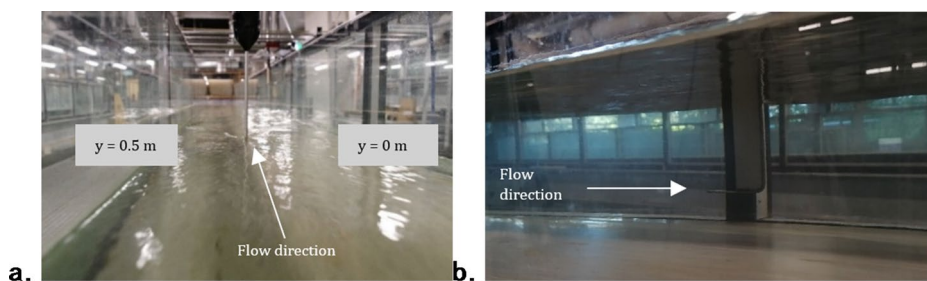


**Fig. 2** Experimental facility and instrumentation at the University of Queensland. Instruments in operation at  $x=8 \text{ m}$ . **a** Acoustic Doppler velocimeter (ADV), with  $y=0.5 \text{ m}$  corresponding to the left side of the channel looking downstream and  $y=0 \text{ m}$  corresponding to the right side of the channel. **b** Prandtl Pitot tube

water, are used in both the model and prototype, this constraint implies a Morton similitude and leads to a basic simplification of the dimensional analysis. Herein, the geometric scaling ratio would range from 1:1 to 1:6 for typical precast concrete box culverts with internal width between 0.5 m and 3 m. In the laboratory, the water was supplied by a constant head reticulation system feeding a 2.0 m long, 1.25 m wide intake basin, equipped with baffles, flow straighteners and three-dimensional convergent section leading to the 0.5 m wide flume. The horizontal flume ended with a free overfall at the downstream end.

The flow rate was recorded using a Venturi meter placed on the pipeline from the constant head tank. The meter was designed based upon the British Standard [22] and built at the University of Queensland with an error of discharge less than 2%. The time-averaged centreline water depth was recorded with a pointer gauge, with a typical variability of  $\pm 0.5 \text{ mm}$ . The water velocities were measured with a Dwyer® 166 Series Prandtl-Pitot tube, and a Nortek™ Vectrino<sup>+</sup> acoustic Doppler velocimeter (ADV) equipped with a side-looking head. The Prandtl-Pitot tube serves as an independent instrument for the measurement of longitudinal time-averaged velocities, and to validate the ADV longitudinal time-averaged velocity data. The Prandtl-Pitot tube is consisted of a  $\varnothing 3.3 \text{ mm}$  stainless steel tube, with a hemispherical total head tapping ( $\varnothing = 1.19 \text{ mm}$ ) and four equally spaced static head tapings ( $\varnothing = 0.51 \text{ mm}$ ) located 25.4 mm behind the tip. The ADV signal was sampled at 200 Hz for 180 s at each measurement location. All ADV signal data were post-processed to remove erroneous data and spikes. Data with an average correlation of less than 60% and an average signal-to-noise ratio (SNR) less than 5 dB were removed. The signal was “despiked” using a phase-space thresholding technique [23, 24]. The post-filtering percentage of good samples of the ADV data was in the range of 70–95%. The mean and variance of velocities at the particular sampling point were similar across multiple runs for each discharge under the same configuration, and the longitudinal time-averaged velocities were systematically compared to the Prandtl-Pitot tube data.

For ADV measurements, the seeding process was done with 4–16  $\mu\text{m}$  Spherical® 110P8 hollow glass spheres to increase the particle counts in the water. Careful observations and selections of the transverse locations were made to ensure the quality and validity of the data. The three-dimensional velocity components measured by the ADV were further analysed to obtain its Reynolds stresses, integral timescale, advection length scale, burst events and the secondary current vector field.

During this study, visual and free-surface observations were carried out for flow rates  $0.029 \text{ m}^3/\text{s} < Q < 0.100 \text{ m}^3/\text{s}$ , simulating less-than design discharge scenarios with free-

surface flow in the barrel. Detailed velocity measurements were performed for  $Q = 0.0556 \text{ m}^3/\text{s}$  and  $Q = 0.100 \text{ m}^3/\text{s}$  at a longitudinal distance  $x = 8 \text{ m}$  from the start of the channel. The flow conditions are summarised in Table 1. The measurements at  $x = 8 \text{ m}$  simulated the hydrodynamic conditions at the middle or near the downstream end of a box culvert barrel. It was located in the fully-developed flow region with the boundary thickness reaches the free surface level, away from the downstream overfall. For a given flow rate,  $Q$ , a total of 15 vertical profiles leading to a total of 555 data points were recorded and analysed for ADV measurements, and 11 vertical profiles with a total of 275 data points for Prandtl-Pitot tube measurements. Herein,  $y$  is the transverse location in the channel, with  $y = 0$  corresponding to the right side of the channel, looking downstream, and  $y = 0.5 \text{ m}$  corresponded to the left side of the channel. For the Prandtl-Pitot tube measurement, the vertical profiles were located at  $y = 0.0016 \text{ m}$ ,  $0.01 \text{ m}$ ,  $0.03 \text{ m}$ ,  $0.065 \text{ m}$ ,  $0.165 \text{ m}$ ,  $0.25 \text{ m}$ ,  $0.335 \text{ m}$ ,  $0.435 \text{ m}$ ,  $0.47 \text{ m}$ ,  $0.49 \text{ m}$  and  $0.4984 \text{ m}$ , with the closest distance from the wall being limited by the thickness or diameter of the Prandtl-Pitot tube. The vertical profiles for ADV measurement were located at similar locations as the Prandtl-Pitot tube measurement, with some additional profiles at  $y = 0.115 \text{ m}$ ,  $0.2 \text{ m}$ ,  $0.3 \text{ m}$  and  $0.385 \text{ m}$ . The sidewall measurements were carried out at  $y = 0.005 \text{ m}$  and  $0.495 \text{ m}$ . The closest distance from the sidewall was  $5 \text{ mm}$  for ADV measurement due to the adverse impact of solid boundary proximity on the ADV probe outputs, as previously reported in the studies [25, 26]. When excessive noise and high standard deviation were detected at a particular transverse location,  $y$ , the ADV was moved from its original transverse position until the noise subsides or when a distinct sampling peak appeared in the ADV probe check.

### 3 Results and analysis

#### 3.1 Free surface profile

For all flow conditions (Table 1), the open channel flow was steady and subcritical in the channel. The depth was larger than the critical depth,  $d_c$ , and the Froude number was less than unity, where  $d_c = \sqrt[3]{\frac{Q^2}{B^2g}}$ . All flows were turbulent with  $Re > 10,000$  and the corresponding flow conditions were between the smooth and fully-rough turbulent flow regimes. The water level across the channel breadth was uniform. The longitudinal free surface profiles for all the discharges were categorised as a H2 profile [1, 2]. The free surface profile measurements were compared to the integration of the backwater equation, assuming a constant equivalent sand roughness height,  $k_s$ , in the fully developed flow region for each discharge. The Darcy-Weisbach friction factor  $f$  and roughness height  $k_s$  were estimated based on the best data fit between the backwater equation and the measured free surface

**Table 1** Flow and boundary conditions (Bed slope, Reynolds number and aspect ratio) for all experiments involved in the detailed flow investigations at a longitudinal distance of  $8 \text{ m}$  from the start of the channel ( $x = 8 \text{ m}$ )

| Bed slope, $\theta_b$ (°) | Width, $B$ (m) | Discharge, $Q$ ( $\text{m}^3/\text{s}$ ) | Depth, $d$ (m) | Bulk Velocity, $V_{\text{mean}}$ (m/s) | Re                | Fr   | B/d  |
|---------------------------|----------------|------------------------------------------|----------------|----------------------------------------|-------------------|------|------|
| 0                         | 0.50           | 0.0290                                   | 0.099          | 0.586                                  | $1.7 \times 10^5$ | 0.59 | 5.05 |
|                           |                | 0.0556                                   | 0.144          | 0.772                                  | $2.8 \times 10^5$ | 0.65 | 3.47 |
|                           |                | 0.1000                                   | 0.207          | 0.966                                  | $4.3 \times 10^5$ | 0.68 | 2.42 |

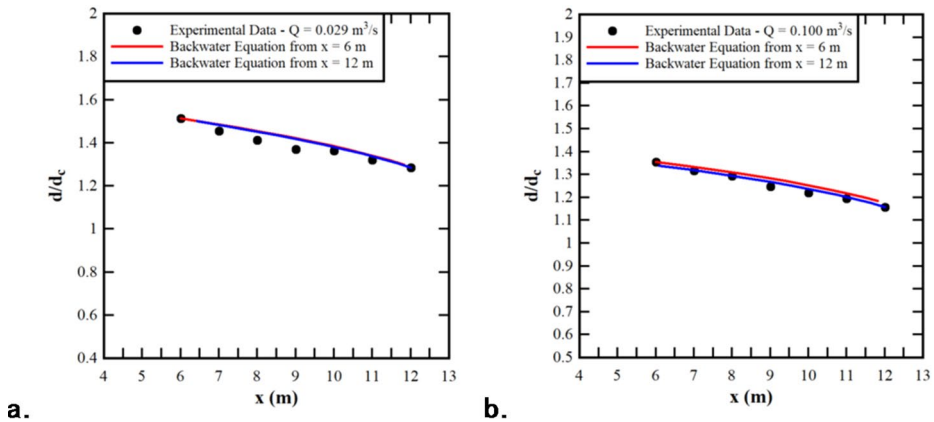


**Fig. 3** Dimensionless free surface profile with the best fitted backwater equation between  $x=6$  m and  $x=12$  m, starting from  $x=6$  m and from  $x=12$  m. **a**  $Q=0.029$  m<sup>3</sup>/s. **b**  $Q=0.100$  m<sup>3</sup>/s

profile. For the present flow conditions, i.e.,  $0.029$  m<sup>3</sup>/s  $< Q < 0.100$  m<sup>3</sup>/s,  $f$  and  $k_s$  decreased from  $0.0264$  to  $0.0216$ , and  $0.0008$  m to  $0.0006$  m respectively as the water discharge and Reynolds number increased. The slight reduction in  $k_s$  is attributed to the increased distribution of the wetted perimeter along the glass sidewall, thereby decreasing the contribution of the roughness from the PVC floor and from the joints of the flume structure. Figure 3 shows the free surface profiles for the discharge of  $Q = 0.029$  m<sup>3</sup>/s and  $0.100$  m<sup>3</sup>/s with the best fitted backwater profile.

### 3.2 Velocity fields

Contour plots of time-averaged longitudinal velocity are illustrated in Fig. 4 for  $Q=0.100$  m<sup>3</sup>/s, and both Prandtl-Pitot tube and ADV measurements are shown. The results were close for both instruments, with the spatial RMS difference of  $\frac{\bar{V}_x}{V_c}$  ranging from  $0.023$  to  $0.094$ . The velocity was set to zero at the boundary because of the no-slip condition. The bulk of the flow corresponded to large time-averaged longitudinal velocities, with maximum velocity  $V_{\max}/V_{\text{mean}}$  of  $1.18$  for  $Q=0.029$  m<sup>3</sup>/s and  $1.11$  for both  $Q=0.0556$  m<sup>3</sup>/s and  $0.100$  m<sup>3</sup>/s, where the bulk velocity is defined as  $V_{\text{mean}} = Q/A$ ,  $Q$  is the volume flow rate and  $A$  is the flow cross-section area. The formation of two large velocity cells and a slight flow asymmetry was seen in the time-averaged longitudinal velocity contour plots despite repeated

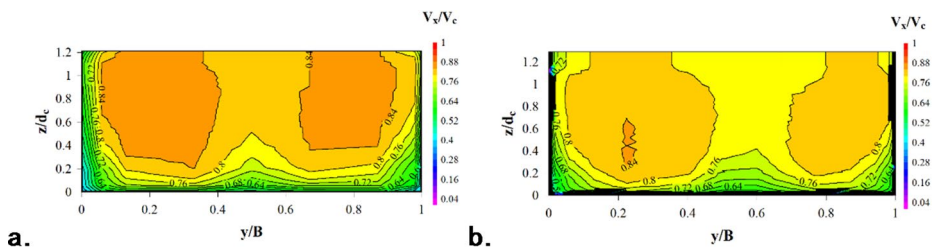


**Fig. 4** Dimensionless contour plots of time-averaged longitudinal velocity,  $\bar{V}_x$ , for  $Q=0.100$  m<sup>3</sup>/s, with  $d_c = 0.16$  m and  $V_c = 1.25$  m/s. **a** Prandtl-Pitot tube measurements. **b** ADV measurements

runs. For instance, in  $0.100 \text{ m}^3/\text{s}$ , for a time-averaged velocity,  $\overline{V}_x$  threshold of  $0.4 \text{ m/s}$ , the area of velocity zones lesser than  $0.4 \text{ m/s}$  in a  $3 \text{ cm} \times 3 \text{ cm}$  corner region is  $190.32 \text{ cm}^2$  on the right side of the channel looking downstream, and  $173.16 \text{ cm}^2$  in the left corner, with an area difference of  $17.16 \text{ cm}^2$ . Such a slight asymmetry could be caused by some inlet flow condition, reflecting a real fluid flow that could be observed in a real full-scale culvert, which could typically be affected by workmanship of the culvert, uneven sediment bed or channel invert, bended inlet configuration etc.

As the friction along the boundaries induced a momentum transfer from the high-velocity regions, the longitudinal velocity was reduced in the vicinity of the invert and sidewalls. Several regions of low velocities (i.e. LVZs) were seen in the bottom corners and next to the sidewalls of the channel (Fig. 4), which would serve as the upstream swimming passage for small-bodied fishes.

The transverse velocity data showed an anti-symmetrical distribution about the centreline of the channel for both discharges (Fig. 5). Negative  $\overline{V}_y$  were distributed in the top right and bottom left region, looking downstream, and vice versa for the positive  $\overline{V}_y$ , resulting in a net zero at the centre of the channel. The time-averaged vertical velocity data were symmetrical about the centreline for  $Q=0.100 \text{ m}^3/\text{s}$  with the strongest downward vertical velocity,  $\overline{V}_z$  observed near the sidewalls (Fig. 6) and the lower  $\overline{V}_z$  located at the central region of the channel. Similarly, the strongest downward vertical velocity was located near the sidewall for  $Q=0.0556 \text{ m}^3/\text{s}$ , accompanied by strong upward vertical velocity at the central region of the channel.

The time-averaged velocity data were checked for continuity, i.e. conservation of volume. The time-averaged longitudinal velocities measured by the Prandtl-Pitot tube and ADV were both integrated over the flow cross-section area and the results were compared with the discharge,  $Q$ , independently measured by the Venturi meter:

$$\int_{y=0}^{y=B} \int_{z=0}^{z=d} \overline{V}_x \, dz dy \quad (1)$$

The integration of the time-averaged longitudinal velocity,  $\overline{V}_x$ , of each data point obtained from over 35 elevation points ( $z$ ) across the 15 transverse locations ( $y$ ) was performed. The integrated volume discharge was compared against the measured discharge set and were within 1% of difference (0.18%- 0.6% for Prandtl-Pitot tube and 0.7% – 1% for ADV). Similarly, the velocity components in the transverse direction,  $\overline{V}_y$  and in the vertical direction,  $\overline{V}_z$  were integrated with respect to depth and width using Eqs. 2 and 3 respectively. The net flow in  $y$  and  $z$  direction was near zero.

$$\int_{y=0}^{y=B} \int_{z=0}^{z=d} \overline{V}_y \, dz dy = 0 \quad (2)$$

$$\int_{y=0}^{y=B} \int_{z=0}^{z=d} \overline{V}_z \, dz dy = 0 \quad (3)$$

In a box culvert barrel channel, the bottom corners play a key role for the secondary currents because transverse flow was directed towards the corner as a direct result of turbulent shear stress gradients normal to the edge bisector [17, 27]. For  $Q = 0.100 \text{ m}^3/\text{s}$ , the measured sec-

**Fig. 5** Dimensionless contour plot of the time-averaged transverse velocity,  $\overline{V}_y$  for  $0.100 \text{ m}^3/\text{s}$ , from ADV measurement

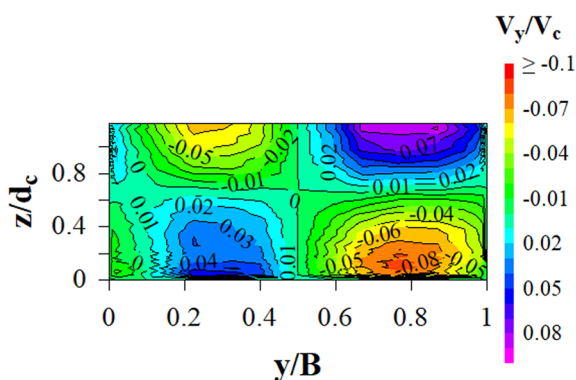
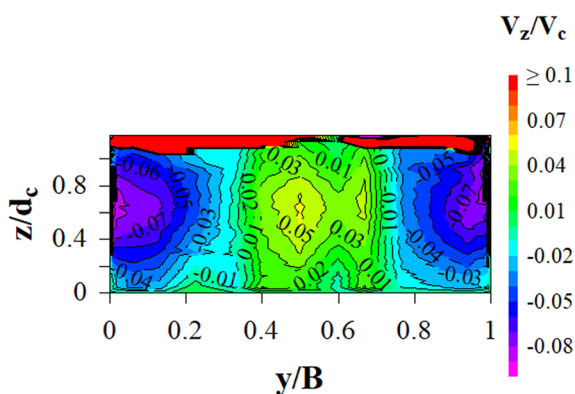


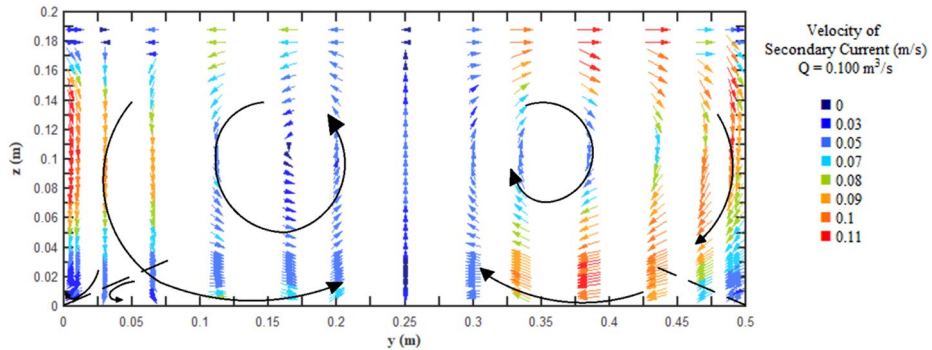
**Fig. 6** Dimensionless contour plot of the time-averaged vertical velocity,  $\overline{V}_z$  for  $0.100 \text{ m}^3/\text{s}$ , from ADV measurement



ondary current vector map is shown in Fig. 7. The magnitudes of secondary currents on the channel centreline were near zero. On each side of the channel centreline, the surface currents circulate towards the wall from the centreline, and the secondary current data showed the formation of two vortical cells typical of Prandtl's second kind. The separation of the clockwise and counterclockwise secondary streamline in the bottom right corner was not symmetrical relative to the corner bisector of  $45^\circ$ . The separation line was observed to be the hypotenuse line of the flow area cross-section (Fig. 7). For  $Q = 0.0556 \text{ m}^3/\text{s}$ , the separation line was  $16.28^\circ$  from the bottom invert, whereas  $\tan^{-1}(d/B)_{55.6 \text{ L/s}}$  is  $16.07^\circ$ . For  $Q = 0.100 \text{ m}^3/\text{s}$ , the separation line was  $21.8^\circ$  from the bottom invert and  $\tan^{-1}(d/B)_{100 \text{ L/s}}$  is  $22.5^\circ$ . At the left bottom corner, looking downstream ( $y = 0.5 \text{ m}$ ), there was no obvious recirculating cell observed for both discharges, despite repeated runs. The secondary current vector plot for  $Q = 0.100 \text{ m}^3/\text{s}$  presented a strong similarity to earlier experiment [28]. A statistical analysis was performed (Table 2) for the secondary current for each discharge. For over 500 sampling points, the present data indicated some secondary current magnitudes, i.e.  $(\overline{V}_y^2 + \overline{V}_z^2)^{1/2}$ , with a median value of  $0.041 \text{ m/s}$  and a 90% percentile of  $0.063 \text{ m/s}$ , corresponding respectively to 4.7% and 7.3% of the maximum velocity  $V_{\max}$  for  $Q = 0.0556 \text{ m}^3/\text{s}$ . For  $Q = 0.100 \text{ m}^3/\text{s}$ , the median value and 90% percentile were  $0.063 \text{ m/s}$  and  $0.1 \text{ m/s}$  respectively, which represented 6.0% and 9.5% of  $V_{\max}$  respectively.

**Table 2** Statistical data of the secondary current magnitudes

| Q<br>(m <sup>3</sup> /s) | Median of<br>( $\overline{V_y^2 + V_z^2}$ ) <sup>1/2</sup><br>(m/s) | IQR of<br>( $\overline{V_y^2 + V_z^2}$ ) <sup>1/2</sup><br>(m/s) | 90% Percentile, P90 of<br>( $\overline{V_y^2 + V_z^2}$ ) <sup>1/2</sup><br>(m/s) | Corresponding<br>Percentage of<br>V <sub>max</sub> (Median;<br>IQR; P90) (%) |
|--------------------------|---------------------------------------------------------------------|------------------------------------------------------------------|----------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| 0.0556                   | 0.041                                                               | 0.025                                                            | 0.063                                                                            | 4.7%; 2.9%;<br>7.3%                                                          |
| 0.1000                   | 0.063                                                               | 0.042                                                            | 0.100                                                                            | 6.0%; 4.0%;<br>9.5%                                                          |

**Fig. 7** Velocity vector field of secondary currents, with the colour codes representing the magnitude of the secondary current and the separation lines dividing the opposing vortical cell in the corners for  $Q=0.100$  m<sup>3</sup>/s

A strong horizontal transverse flow, i.e.,  $|\overline{V_y}| > 0$ , occurred near the free surface, as previously shown [29]. A downward flow motion, i.e.  $\overline{V_z} < 0$ , was observed next to both channel sidewalls. The presence of this downward velocity motion near the sidewall could be one of the relevant parameters for upstream fish passage as such downward velocity with a considerable magnitude could help to maintain and anchor the fish towards the low velocity zones in the bottom corners of the culvert barrel when swimming upstream.

### 3.3 Turbulence characteristics

#### 3.3.1 Reynolds stresses

Turbulence is a time-dependant and three-dimensional process in which the mechanisms of vortex stretching give rise to the spreading of velocity fluctuations to all wavelength [30]. Herein, the instantaneous velocities, measured by the ADV system, were denoted  $V_i(t)$ , with  $i = x, y$  or  $z$ . The fluctuating velocity component,  $v_x(t)$ ,  $v_y(t)$  and  $v_z(t)$  were defined as  $v_i(t) = V_i(t) - \overline{V_i}$ , with  $i = x, y$  or  $z$  and  $\overline{V_i}$  is the time-averaged velocity. In the time-averaged velocity field of the turbulent flow, there is a component that derives from the extra apparent stress  $\rho \overline{v_x^2}$  normal to the face  $dydz$  of a small control volume [30]. Similarly, there are normal stresses  $\rho \overline{v_y^2}$  and  $\rho \overline{v_z^2}$  in the  $y$  and  $z$  directions. Tangential stresses that contributed to an extra mean shear stress on the face  $dx dy$ ,  $dx dz$  and  $dy dz$  were denoted  $\rho \overline{v_x v_y}$ ,  $\rho \overline{v_x v_z}$  and  $\rho \overline{v_y v_z}$  respectively. These extra turbulent stresses produced by the fluctuating motions are referred as the turbulent Reynolds stresses [30, 31].

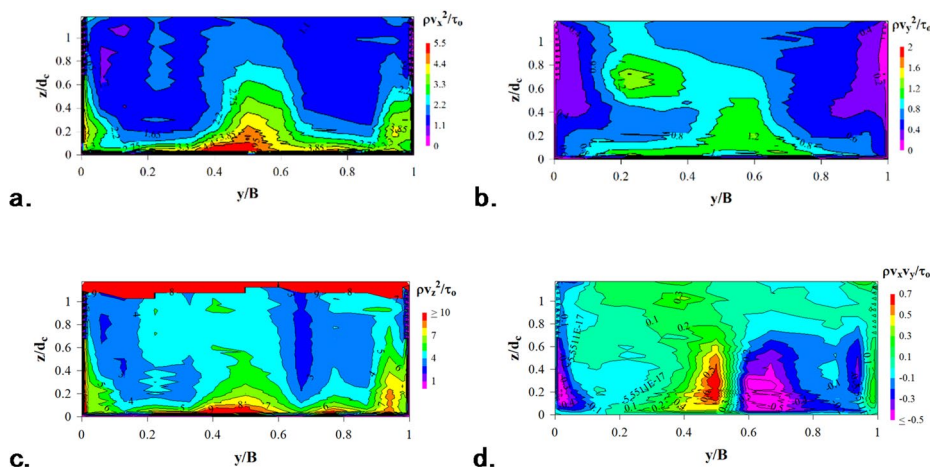


**Fig. 8** Dimensionless contour plots of the time-averaged Reynolds stresses for  $Q=0.100 \text{ m}^3/\text{s}$ , with  $\tau_o=2.5 \text{ Pa}$  estimated from the spatially-averaged Darcy friction factor method. **a**  $\frac{\rho v_x^2}{\tau_o}$ , **b**  $\frac{\rho v_y^2}{\tau_o}$ , **c**  $\frac{\rho v_z^2}{\tau_o}$ , **d**  $\frac{\rho v_x v_y}{\tau_o}$

In the present study, the velocity signal outputs were analysed to estimate the time-averaged normal and tangential Reynolds stresses. The contour plots of the Reynolds stresses are presented in Fig. 8. The results showed that higher Reynolds stresses are located near the sidewalls, bottom corners and next to the channel centreline invert, and these regions corresponded to the lower time-averaged longitudinal velocities. The analyses of the Reynolds stress standard deviations further showed a higher variability of instantaneous Reynolds stresses next to the sidewalls and bottom corners [32].

### 3.3.2 Integral time and length scale

The integral timescale is defined as the integral of the ensemble-average curve when the autocorrelation function is zero, which also indicates the lifespan of the turbulent eddies. The normalised, or Eulerian autocorrelation function,  $R_{ii}(\tau)$ , with  $i = x, y$  or  $z$  is defined for a one-point measurement [33, 34] as:

$$R_{ii}(\tau) = R(V_i(t), V_i(t - \tau)) = \frac{\overline{V_i(t) * V_i(t + \tau)}}{\overline{V_i^2(t)}} \quad (4)$$

where  $V_i(t)$  is the instantaneous velocity component,  $\tau$  is the time lag,  $\overline{V_i}$  is the time-averaged component and  $R$  is the co-variance function. The autocorrelation function is 1 for a zero-time lag ( $\tau = 0$ ). A sensitivity test has been conducted for the selection of the non-overlapping intervals, starting from 30 s, 20 s to 10 s. 20 s was chosen as an outcome of the sensitivity test to capture the larger turbulent structures, while providing at least 9 samples to calculate the statistical average of the autocorrelation curve. While 10 s have higher number of samples, the risk of missing the larger turbulent structure is higher as the yielded timescale was systematically lower than using 20- and 30-seconds intervals. Herein,

for a typical data sample of 180 s, the signal was split into the selected 20s non-overlapping intervals and ensemble-averaged to calculate the integral timescale,  $T_{Ei}$  with  $i = x, y$  or  $z$ .  $T_{Ei}$  was obtained from the area under the curve of the average autocorrelation function, up to the first crossing, where  $R_{ii}(\tau) = 0$ .  $T_{Ei}$  can be considered the longest connection in the turbulent behaviour of the velocity component,  $V_i(t)$  [35].

Typical contour maps of integral timescale,  $T_{Ei}$  are shown in Fig. 9. Next to the sidewalls and corners, i.e. in the low velocity zones, the timescales were smaller than in the central part of the flow region. For  $Q=0.0556 \text{ m}^3/\text{s}$ , the data yielded  $T_{Ex} = 50\text{--}80 \text{ ms}$ ,  $T_{Ey} = 10\text{--}60 \text{ ms}$  and  $T_{Ez} = 5\text{--}14 \text{ ms}$  in the corners (within 4 cm from the wall), whereas for  $Q=0.100 \text{ m}^3/\text{s}$ ,  $T_{Ex} = 60\text{--}95 \text{ ms}$ ,  $T_{Ey} = 10\text{--}100 \text{ ms}$  and  $T_{Ez} = 5\text{--}15 \text{ ms}$ . Although the Reynolds stresses next to the boundaries and bottom corners were higher, the connection or the “lifespan” of the velocity fluctuations was shorter compared to the central region of the channel (i.e. 10–260 ms).

The advection length scales,  $L_{xi}$ , with  $i=x, y$  or  $z$ , which indicate the size of the eddies, were obtained by the product of each integral timescale component,  $T_{Ei}$  with the respective time-averaged longitudinal velocity at the corresponding velocity sampling point. In the present study, the flow of  $Q=0.0556 \text{ m}^3/\text{s}$  yielded  $L_{xx} = 30\text{--}50 \text{ mm}$ ,  $L_{xy} = 10\text{--}70 \text{ mm}$  and  $L_{xz} = 2\text{--}10 \text{ mm}$  in the corners, whereas  $Q=0.100 \text{ m}^3/\text{s}$  yielded  $L_{xx} = 30\text{--}80 \text{ mm}$ ,  $L_{xy} = 10\text{--}100 \text{ mm}$  and  $L_{xz} = 5\text{--}15 \text{ mm}$ . Figure 10 presents the contour plots of the advection length scale normalised by a fish length of 25 mm, that is the typical size of the Australian Smelt at the smaller end of its size range, for  $Q=0.0556$  and  $0.100 \text{ m}^3/\text{s}$ . Most  $L_{xi}$  in the corners were in the range of 0.5–2.5 times the length of the 25 mm fish,  $L_{f,25\text{mm}}$ , with shorter eddy lifespans, whereas  $L_{xi}$  in the central region of the flow were 3–9 times of  $L_{f,25\text{mm}}$ . This indicates that the low velocity zone could be more conducive of upstream fish passage because of the shorter lifespan of eddies and advection length scales in the corners compared to the central regions of the flow.

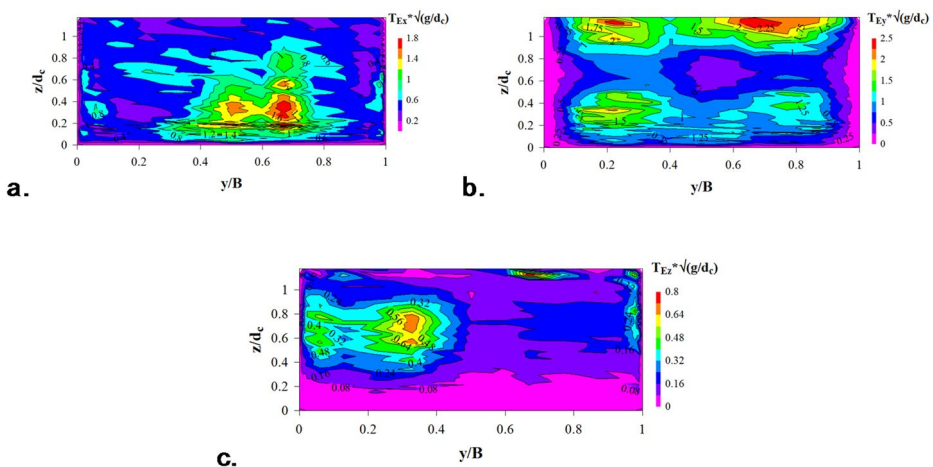


**Fig. 9** Dimensionless contour plots of the integral timescale for  $Q=0.100 \text{ m}^3/\text{s}$ . **a**  $TE_x \sqrt{\frac{g}{d_c}}$ , **b**  $TE_y \sqrt{\frac{g}{d_c}}$ , **c**  $TE_z \sqrt{\frac{g}{d_c}}$

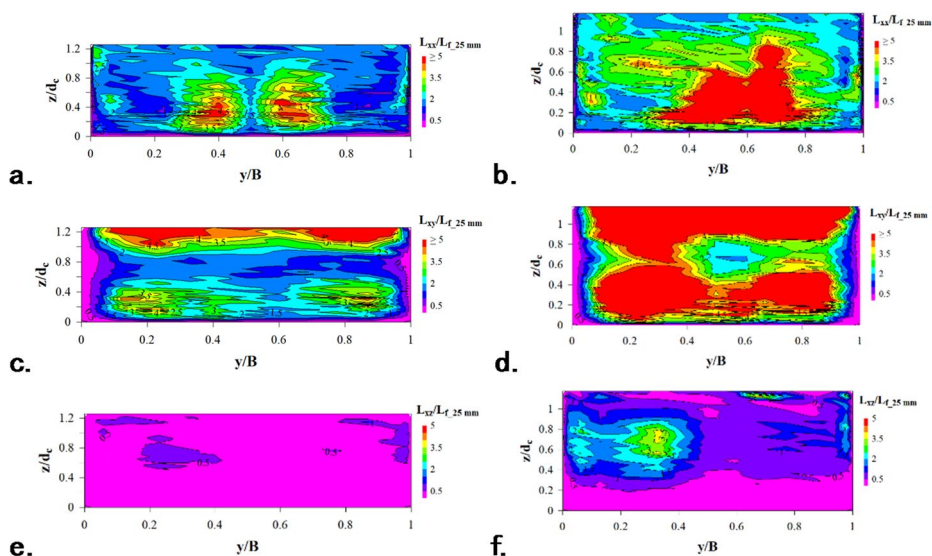


**Fig. 10** Dimensionless contour plots of the advection length scale normalised by a fish length,  $L_f$  of 25 mm for  $Q=0.0556$  ( $d_c = 0.108$  m) and  $0.100$   $\text{m}^3/\text{s}$  ( $d_c = 0.16$  m). **a**  $\frac{L_{xx}}{L_f}$  of  $Q=0.0556$   $\text{m}^3/\text{s}$ , **b**  $\frac{L_{yy}}{L_f}$  of  $Q=0.100$   $\text{m}^3/\text{s}$ , **c**  $\frac{L_{xy}}{L_f}$  of  $Q=0.0556$   $\text{m}^3/\text{s}$ , **d**  $\frac{L_{xy}}{L_f}$  of  $Q=0.100$   $\text{m}^3/\text{s}$ , **e**  $\frac{L_{xx}}{L_f}$  of  $Q=0.0556$   $\text{m}^3/\text{s}$ , **f**  $\frac{L_{yy}}{L_f}$  of  $Q=0.100$   $\text{m}^3/\text{s}$

### 3.3.3 Turbulent burst analysis

Burst events are random events in the time series which its intensity can increase by orders of magnitude locally [36]. The consideration of burst events could be relevant for fish passage as the amplitude of the burst, accompanied by long burst duration could pose physical difficulties for fishes to navigate. While the study of fish interactions with turbulent burst structures are limited, the study herein aimed to quantify the turbulent burst characteristics in the low velocity zone or observed fish swimming zone for a more comprehensive turbulence characterisation in a culvert barrel. A simple mathematical model to quantitatively describe turbulent bursting events based upon hole-size and bursting period was applied [37, 38]. Herein, the detection of burst event was performed based upon the technique of [38] using the standard deviation of the flux as the equivalent hole size. A sensitivity analysis was carried out previously by [38–40], concluding that a threshold equal to the standard deviation of the turbulent flux can capture the presence of most burst event occurrences. Herein, a burst event occurs when the instantaneous turbulent fluxes,  $q$  exceed the threshold value of  $1 \times$  standard deviation of the turbulent flux. If there is only a single point of turbulent flux exceeding the threshold value in the entire burst duration, the event is disregarded as a “spike” caused by the instrumentation in this study.

For the burst analysis, in the context of fish passage, the amplitude, magnitude and burst duration of the turbulent flux were examined in the form of contour plots. The definition of the dimensionless amplitude,  $A_b$  of the burst event is:

$$A_b = \frac{1}{\bar{q}_b} \int_{\tau} (q_b - \bar{q}_b) \frac{dt}{\tau_b} \quad (5)$$

where  $q_b$  is the instantaneous turbulent flux, i.e.,  $v_x \times v_z$ ,  $v_x \times v_y$ ,  $v_y \times v_z$ ,  $v_x \times v_x$ ,  $v_y \times v_y$  and  $v_z \times v_z$ ,  $\bar{q}_b$  is the mean value of the turbulent flux,  $q_b$ ,  $\tau_b$  is the burst duration between the two consecutive mean intersection of the turbulent flux of a burst event, and  $dt$  is the time duration between two instantaneous turbulent fluxes, which is the inverse of the sampling frequency of the ADV,  $F$  (200 Hz). This dimensionless amplitude, introduced by [39], expressed the ratio between the averaged flux amplitude during the event to the long-term mean flux of the entire data section. The relative contribution of an event to the total momentum flux is the relative magnitude,  $m_b$ , defined as:

$$m_b = \frac{A_b \tau_b}{T} \quad (6)$$

where  $T$  is the total duration of the time-series data ( $T=180$  s herein).

The basic definitions of a burst event, burst duration and the enveloping area for burst amplitude calculation are sketched in Fig. 11, and the concept of a subgroup in a burst event is illustrated in Fig. 12. When the instantaneous turbulent flux exceeded the targeted threshold,  $1 \times$  standard deviation of the flux herein, a turbulent burst event begins at the first crossing of  $\bar{q}_b$  before the threshold exceedance and ends at the next crossing of  $\bar{q}_b$  after the threshold exceedance. The burst duration was calculated using the two mean intersec-

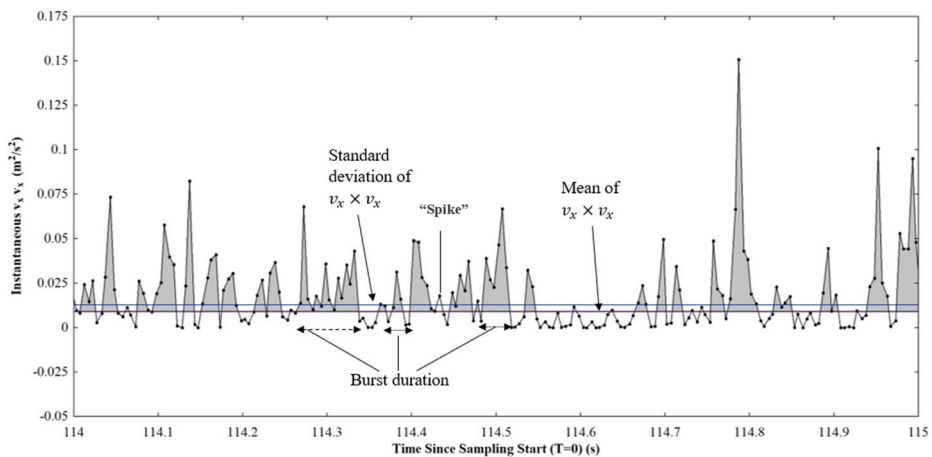


**Fig. 11** Definition sketch of burst event (highlighted in grey), burst duration and “spike”, with data of  $Q=0.0556 \text{ m}^3/\text{s}$ ,  $y=0.2 \text{ m}$ ,  $z=0.0138 \text{ m}$ , data section from  $T=114$  s to  $115$  s

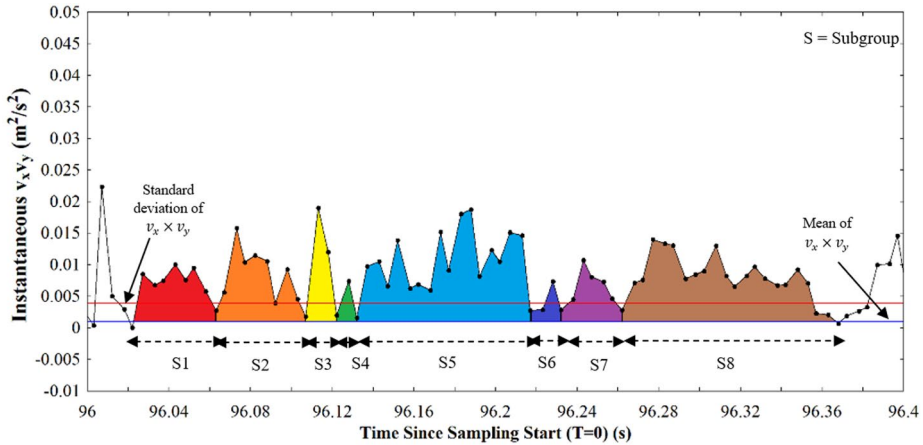


**Fig. 12** Typical dataset with three or more sub-events, with data of  $Q=0.0556 \text{ m}^3/\text{s}$ ,  $y=0.2 \text{ m}$ ,  $z=0.0158 \text{ m}$ . Data section with 8 sub-events from  $T=96 \text{ s}$  to  $96.4 \text{ s}$ . Red indicates the first sub-event in the turbulent burst event (S1), followed by orange (S2), yellow (S3), green (S4), turquoise (S5), indigo (S6), purple (S7) and brown (S8) as the subsequent sub-events in the same burst event

tions encapsulating the burst event. The area for the amplitude calculation was formed by the instantaneous turbulent flux within the burst duration above the mean flux. Some events contained at least two or more sub-events. Sub-events were separated by the instantaneous fluxes within the burst duration that dropped below the threshold value, but remained above the mean flux, as shown in Fig. 12. Overall, the average and median number of sub-events are 2 per burst event, with a few events consisting of 3, 4, 5 or more sub-events.

The median burst duration, amplitude and magnitude of the burst events, for  $Q=0.100 \text{ m}^3/\text{s}$ , are presented in the form of contour plots, with typical plots shown in Fig. 13. Depending on the component of the turbulent fluxes, the distribution of burst event characteristics was not always symmetrical about the channel centreline. The amplitude of the normal turbulent fluxes, i.e.,  $v_x \times v_x$ ,  $v_y \times v_y$  and  $v_z \times v_z$  are relatively small, accompanied by a shorter burst duration compared to the tangential turbulent fluxes. By comparing both corners, the median burst duration and amplitude for  $v_x \times v_x$ ,  $v_y \times v_y$  and  $v_z \times v_z$  are rather consistent and in the same order of magnitude. For  $Q=0.0556 \text{ m}^3/\text{s}$ ,  $\tau_{b_{xx}} = 15\text{--}18 \text{ ms}$ ,  $\tau_{b_{xy}} = 20\text{--}40 \text{ ms}$ ,  $\tau_{b_{xz}} = 25\text{--}33 \text{ ms}$ ,  $\tau_{b_{yy}} = 15\text{--}20 \text{ ms}$ ,  $\tau_{b_{zz}} = 14\text{--}18 \text{ ms}$ , and  $\tau_{b_{yz}} = 20\text{--}37 \text{ ms}$  in the corners, whereas for  $Q=0.100 \text{ m}^3/\text{s}$ ,  $\tau_{b_{xx}} = 16\text{--}17 \text{ ms}$ ,  $\tau_{b_{xy}} = 25\text{--}38 \text{ ms}$ ,  $\tau_{b_{xz}} = 25\text{--}36 \text{ ms}$ ,  $\tau_{b_{yy}} = 15\text{--}19 \text{ ms}$ ,  $\tau_{b_{zz}} = 14\text{--}17 \text{ ms}$ , and  $\tau_{b_{yz}} = 20\text{--}35 \text{ ms}$ . By comparing both normal and tangential turbulent fluxes, the normal turbulent fluxes yield a higher total number of turbulent burst events, with a lower percentage of turbulent burst events with sub-events (Tables 3 and 4). In the bottom corners, the tangential turbulent fluxes,  $v_x \times v_y$  and  $v_x \times v_z$  were observed to have a larger median burst amplitude, i.e.,  $|A_b| > 20$ , accompanied by a longer burst duration. That is, the mean flux amplitude in some events of the tangential turbulence fluxes can be a few times more (i.e. 20–50 times) than the long-term mean flux of the entire sampling duration. In comparison with the integral timescale, the turbulent burst duration,  $\tau_b$  is mostly shorter than the lifespan of the eddies,  $T_{Ei}$  in the corners.

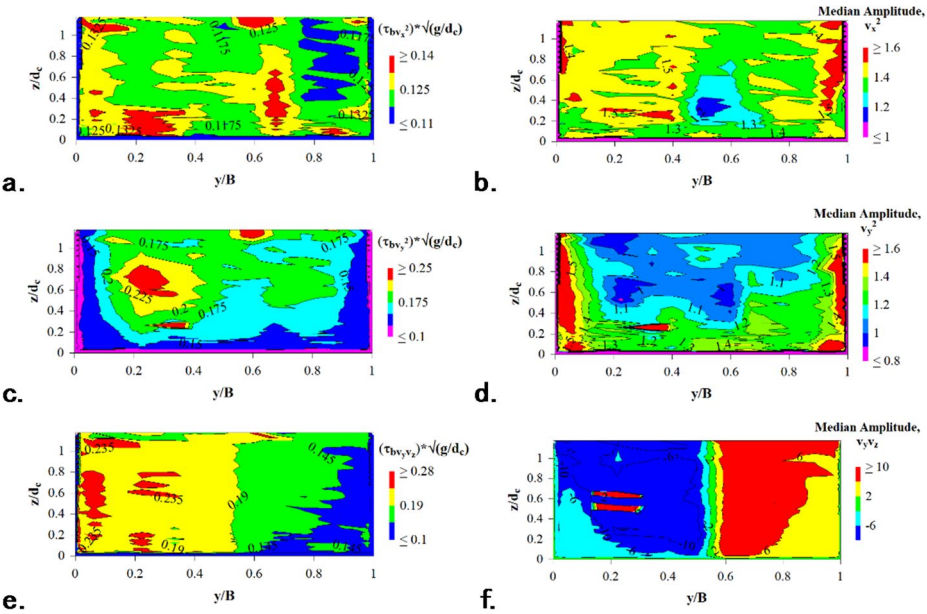


**Fig. 13** Contour plots of turbulent burst characteristics of  $Q=0.100\text{ m}^3/\text{s}$ . **a** Dimensionless turbulent burst duration of  $v_x \times v_x$ , **b** Turbulent burst amplitude of  $v_x \times v_x$ , **c** Dimensionless turbulent burst duration of  $v_y \times v_y$ , **d** Turbulent burst amplitude of  $v_y \times v_y$ , **e** Dimensionless turbulent burst duration of  $v_y \times v_z$ , **f** Turbulent burst amplitude of  $v_y \times v_z$

**Table 3** Comparison of the turbulence burst characteristics in the corner and near-invert of the centreline for  $Q=0.0556\text{ m}^3/\text{s}$

| Turbulent Flux ( $\text{m}^2/\text{s}^2$ ) | y (m)                | z (m)  | IQR of $\tau_b$ | IQR of $A_b$ | Total No. of Events in 180s | No. of Burst Event with Sub-Event | Percentage of Burst Events with Sub-Events (%) |
|--------------------------------------------|----------------------|--------|-----------------|--------------|-----------------------------|-----------------------------------|------------------------------------------------|
| $v_x \times v_x$                           | 0.005 (right corner) | 0.0158 | 0.0080          | 1.155        | 1518                        | 200                               | 13.2                                           |
| $v_y \times v_y$                           |                      |        | 0.0074          | 1.227        | 1775                        | 213                               | 12.0                                           |
| $v_z \times v_z$                           |                      |        | 0.0052          | 1.241        | 1310                        | 144                               | 11.0                                           |
| $v_x \times v_y$                           | 0.25 (centre-line)   | 0.0158 | 0.0196          | 7.859        | 463                         | 222                               | 47.9                                           |
| $v_x \times v_z$                           |                      |        | 0.0215          | 4.132        | 355                         | 161                               | 45.4                                           |
| $v_y \times v_z$                           |                      |        | 0.0184          | 1.156        | 80                          | 26                                | 32.5                                           |
| $v_x \times v_x$                           |                      |        | 0.0070          | 1.221        | 1691                        | 198                               | 11.7                                           |
| $v_y \times v_y$                           |                      |        | 0.0157          | 1.105        | 1662                        | 270                               | 16.2                                           |
| $v_z \times v_z$                           |                      |        | 0.0059          | 1.346        | 1537                        | 177                               | 11.5                                           |
| $v_x \times v_y$                           | 0.495 (left corner)  | 0.0178 | 0.0187          | 8.661        | 749                         | 265                               | 35.4                                           |
| $v_x \times v_z$                           |                      |        | 0.0233          | 2.173        | 325                         | 169                               | 52.0                                           |
| $v_y \times v_z$                           |                      |        | 0.0218          | 2.086        | 446                         | 160                               | 35.9                                           |
| $v_x \times v_x$                           |                      |        | 0.0114          | 1.172        | 1649                        | 169                               | 10.2                                           |
| $v_y \times v_y$                           |                      |        | 0.0134          | 1.152        | 1725                        | 207                               | 12.0                                           |
| $v_z \times v_z$                           |                      |        | 0.0098          | 1.444        | 1427                        | 147                               | 10.3                                           |
| $v_x \times v_y$                           |                      |        | 0.0173          | 2.391        | 1216                        | 291                               | 23.9                                           |
| $v_x \times v_z$                           |                      |        | 0.0162          | 7.513        | 769                         | 215                               | 28.0                                           |
| $v_y \times v_z$                           |                      |        | 0.0137          | 2.312        | 1144                        | 213                               | 18.6                                           |

**Table 4** Comparison of the turbulence burst characteristics in the corner and near-invert of the centreline for  $Q=0.100 \text{ m}^3/\text{s}$ 

| Turbulent Flux ( $\text{m}^2/\text{s}^2$ ) | y (m)                   | z (m)  | IQR of $\tau_b$ | IQR of $A_b$ | Total No. of Event in 180s | No. of Burst Event with Sub-Event | Percentage of Burst Events with Sub-Events (%) |
|--------------------------------------------|-------------------------|--------|-----------------|--------------|----------------------------|-----------------------------------|------------------------------------------------|
| $v_x \times v_x$                           | 0.005<br>(right corner) | 0.0158 | 0.0093          | 1.087        | 1733                       | 214                               | 12.3                                           |
| $v_y \times v_y$                           |                         |        | 0.0072          | 1.162        | 1993                       | 145                               | 7.3                                            |
| $v_z \times v_z$                           |                         |        | 0.0058          | 1.384        | 1318                       | 139                               | 10.5                                           |
| $v_x \times v_y$                           |                         |        | 0.0266          | 1.936        | 351                        | 169                               | 48.1                                           |
| $v_x \times v_z$                           |                         |        | 0.0185          | 6.238        | 462                        | 159                               | 34.4                                           |
| $v_y \times v_z$                           | 0.25<br>(centre-line)   | 0.0158 | 0.0262          | 1.481        | 207                        | 82                                | 39.6                                           |
| $v_x \times v_x$                           |                         |        | 0.0090          | 1.100        | 1688                       | 246                               | 14.6                                           |
| $v_y \times v_y$                           |                         |        | 0.0120          | 1.122        | 1800                       | 226                               | 12.6                                           |
| $v_z \times v_z$                           |                         |        | 0.0059          | 1.396        | 1447                       | 155                               | 10.7                                           |
| $v_x \times v_y$                           |                         |        | 0.0162          | 2.303        | 1221                       | 347                               | 28.4                                           |
| $v_x \times v_z$                           | 0.495<br>(left corner)  | 0.0158 | 0.0225          | 2.509        | 318                        | 157                               | 49.4                                           |
| $v_y \times v_z$                           |                         |        | 0.0195          | 3.997        | 575                        | 205                               | 35.7                                           |
| $v_x \times v_x$                           |                         |        | 0.0090          | 1.167        | 1651                       | 249                               | 15.1                                           |
| $v_y \times v_y$                           |                         |        | 0.0077          | 1.291        | 2087                       | 169                               | 8.1                                            |
| $v_z \times v_z$                           |                         |        | 0.0059          | 1.443        | 1504                       | 151                               | 10.0                                           |
| $v_x \times v_y$                           |                         |        | 0.0120          | 3.944        | 1073                       | 234                               | 21.8                                           |
| $v_x \times v_z$                           |                         |        | 0.0114          | 7.342        | 757                        | 221                               | 29.2                                           |
| $v_y \times v_z$                           |                         |        | 0.0093          | 3.338        | 985                        | 176                               | 17.9                                           |

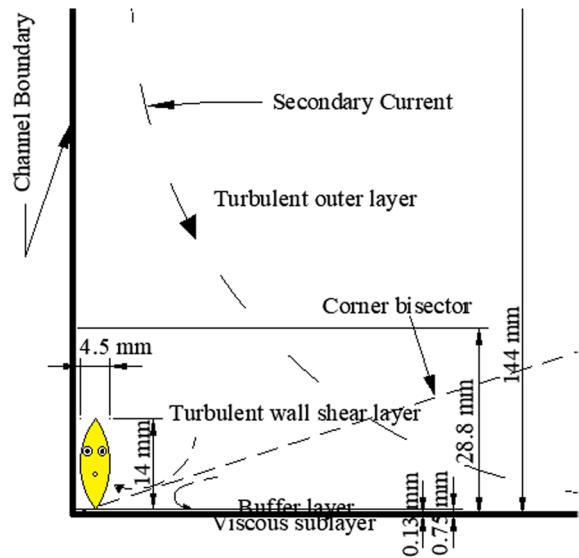
## 4 Discussion

The literature broadly acknowledged that, in rectangular channels, most fishes found to be swimming upstream next to the barrel sidewall, including bottom corners [8–11]. In contrast, a few studies mentioned that fish was observed swimming in regions with lesser turbulence [41–43], although low velocity and low turbulence conditions might not be the preferred swimming location for some species, e.g. for juvenile Atlantic salmon [44]. The present study highlighted that regions of higher turbulence were observed next to the side-walls and bottom corners, in the low velocity zones and observed swimming zones.

The flow field in open channel is traditionally divided into several layers, i.e., the viscous sublayer ( $zV^*/\nu \leq 5$ ), buffer layer ( $5 < zV^*/\nu < 30$ ), turbulent wall shear layer ( $zV^*/\nu \geq 30$ ,  $z/d < 0.2$ ), and turbulent outer layer ( $0.2 \leq z/d \leq 1$ ) [45]. A typical flow field division is sketched in Fig. 14 with  $Q = 0.0556 \text{ m}^3/\text{s}$ ,  $d = 0.144 \text{ m}$  and the dimension of a typical small-bodied native fish (Australian Smelt). The viscous sublayer and buffer layer are very thin compared to the dimension of the fish. The fish typically swim in the LVZ, which is also the turbulent wall shear layer, where the Reynolds shear stress is predominant and viscous shear stress is negligible. The wall shear layer is also the layer dominated by turbulent bursting, where the turbulent kinetic energy (TKE) production rate exceeds the TKE dissipation rate [45, 46]. In the present study, the burst duration and amplitude of some turbulent fluxes were found to be higher near the sidewalls and in the corners, with the tangential turbulent fluxes having a larger amplitude and longer turbulent burst duration, compared to the normal turbulent fluxes.

A few studies showed that some fish species can sustain very high turbulent stresses, e.g. Iberian barbel with minimum total length of 150 mm, and could occupy areas with

**Fig. 14** Turbulent flow field with secondary current in a box culvert corner, with a typical body size of Australian Smelt and flow characteristics of  $Q=0.0556 \text{ m}^3/\text{s}$ ,  $d=0.144 \text{ m}$



Reynolds stresses up to 60 Pa [47], while Hybrid Bass, Rainbow Trout and Atlantic salmon can be exposed to Reynolds shear stresses higher than 50 Pa without significant mortality, even when exposed for more than 48 h [48] under similar definition of Reynolds stress and velocity measurement method. As the Reynolds stresses and turbulent burst events are significant in the low velocity zones, it is relevant to consider the Reynolds stress levels each fish species can withstand comfortably, including extreme turbulent fluxes and their respective burst duration when developing the design guidelines for fish passage in a box culvert.

The present results in terms of the Eulerian time scale and advection length scale provided a fascinating perspective in that context. The turbulent timescale reflects the lifespan of the coherent eddies, and the advection length scales showed the sizes of the dominant vortices. In fish passage application, fishes experience difficulties passing if the length scale of the eddies is similar or exceeds its body length [19].

Based upon the present data for  $Q=0.0556$  and  $0.100 \text{ m}^3/\text{s}$  in the  $0.5 \text{ m}$  wide smooth channel, the upstream accessibility of small-bodied fishes such as Australian Smelt and Common Galaxias was checked based on the size of LVZ and the physical dimensions of the fish (Table 5). For the present data set, only the Australian Smelt with a body dimension of  $14.0 \text{ mm} \times 4.5 \text{ mm}$  ( $H_f \times W_f$ ) would successfully swim upstream through the flow of  $Q=0.0556 \text{ m}^3/\text{s}$  with a water depth of  $0.144 \text{ m}$  at  $x=8 \text{ m}$ , with a limited room for sideway and vertical navigation ( $1\text{--}1.5 \text{ mm}$ ) based on the assumption that fishes cannot partly or fully swim in flow region with time-averaged longitudinal velocity,  $\bar{V}_x$ , above its mean critical fish swim speed,  $U_{\text{crit}}$ . The thickness of the turbulent wall shear layer is about twice the height of the fish in the flow of  $Q=0.0556 \text{ m}^3/\text{s}$ . Biological tests with robust fish-testing procedure should complement the current study, including the determination of the duration and percentage of flow velocity above  $U_{\text{crit}}$  each fish can withstand. The associated turbulence characteristics of the flow and the behavioural interaction of the fish with the turbulence structures during the fish testings would be highly valuable.

The considerations of both time-averaged velocities and the turbulence characteristics are inseparable as fish could be compelled to swim in higher turbulence region if the higher velocity regions are more physically challenging to navigate. Some studies suggested that fish could exploit and interact with vortices, with reduced muscle activities and thus, reduc-

**Table 5** Fish accessibility in the culvert with flow of  $Q = 0.0556 \text{ m}^3/\text{s}$  and  $0.100 \text{ m}^3/\text{s}$ , based on the critical swimming speed of fish species and longitudinal velocity field in the channel

| Dis-charges<br>( $\text{m}^3/\text{s}$ ) | Fish Species                                         | Fish Length,<br>$L_f$ (mm)                     | Mean fish<br>height and<br>width, $H_f \times$<br>$W_f$ (mm $\times$ mm) | Mean critical<br>swim speed,<br>$U_{crit}$ (m/s) | Diagonal<br>Length,<br>DL (mm) | Height of LVZ,<br>$H_{lvz}$ (mm)                                | Width of LVZ, $Bl_{lvz}$<br>(mm) | Thickness<br>of Turbulent<br>Wall Shear<br>Layer (mm) | Height of<br>Viscous<br>and Buffer<br>Layer (mm) |
|------------------------------------------|------------------------------------------------------|------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------|--------------------------------|-----------------------------------------------------------------|----------------------------------|-------------------------------------------------------|--------------------------------------------------|
| 0.0556                                   | Australian Smelt ( <i>Retro-pinna semoni</i> )       | 25–57 <sup>(1)</sup>                           | $14.0 \times 4.5$ <sup>(3)</sup>                                         | 0.466 <sup>(1)</sup>                             | 10.60                          | using 5 mm width - $H_{lvz} = 22$ mm<br>- $Bl_{lvz} = 6$ mm     | using 15 mm height               | 28.05                                                 | 0.75                                             |
| 0.1000                                   | Australian Smelt ( <i>Retro-pinna semoni</i> )       | 25–57 <sup>(1)</sup>                           | $14.0 \times 4.5$ <sup>(3)</sup>                                         | 0.466 <sup>(1)</sup>                             | 2.62                           | using 5 mm width - $H_{lvz} = 1.6$ mm<br>- $Bl_{lvz} = 1.5$ mm  | using 15 mm height               | 40.80                                                 | 0.60                                             |
| 0.0556                                   | Common Galaxias Inanga ( <i>Galaxias maculatus</i> ) | 48 $\pm$ 2.5 to 91.8 $\pm$ 10.3 <sup>(2)</sup> | $10.0 \times 8.0$ <sup>(2)</sup>                                         | 0.19–0.36 <sup>(2)</sup>                         | 2.00                           | using 9 mm width - $H_{lvz} = 1$ mm<br>- $Bl_{lvz} = 1.2$ mm    | using 11 mm height               | 28.05                                                 | 0.75                                             |
| 0.1000                                   | Common Galaxias Inanga ( <i>Galaxias maculatus</i> ) | 48 $\pm$ 2.5 to 91.8 $\pm$ 10.3 <sup>(2)</sup> | $10.0 \times 8.0$ <sup>(2)</sup>                                         | 0.19–0.36 <sup>(2)</sup>                         | 1.39                           | using 9 mm width - $H_{lvz} = 0.9$ mm<br>- $Bl_{lvz} = 0.87$ mm | using 11 mm height               | 40.80                                                 | 0.60                                             |

<sup>(1)</sup> Standard Length (SL) of fish and the tested mean critical swimming speed [50]; <sup>(2)</sup> Fork Length (LF), height of fish and the tested mean critical swimming speed [4]; <sup>(3)</sup> Height of fish [51] with similar body shape as [50];

ing the overall cost of locomotion [49]. Henceforth, the sizing of LVZ can be further manipulated in box-culverts for fish passage, combining the results of turbulence characteristics in the LVZ detailed in this work, applicable for culvert barrels with similar configuration and flow conditions with possible result extrapolation. The suitable size of LVZ should also consider the physical dimension, kinematics and mechanics of the fishes, cost of fish locomotion and their interactions with the hydrodynamics and turbulence in the culvert barrel. The consideration of turbulence in the sizing of LVZ should include but not limit to Reynolds stress, turbulent timescale, advection length scale and turbulent burst characteristics in the fish passage guidelines for box culverts. This study also provides a comprehensive dataset of the velocity field, turbulence and other flow characteristics for a range of less-than-design discharge, which could be referred for any future work of CFD modelling, theoretical model or field investigation related to culvert barrels or open channel flows in rectangular channels with similar configurations.

## 5 Conclusion

New research was carried out with a focus on the development of fish-friendly box culverts, without the use of additional hydraulic appurtenances such as baffles. The present study detailed the results obtained from the physical modelling, carried out in a near-full-scale box culvert barrel (0.5 m wide and 15 m long). Detailed free-surface, velocity and turbulence measurements were performed for a range of flow conditions, corresponding to less-than-design flood events ( $1.7 \times 10^5 < Re < 4.3 \times 10^5$ ), with free-surface flow in the barrel, during which fishes may attempt to traverse upstream the structure.

For this channel configuration and flow conditions, the turbulence properties were characterised in the low velocity zones, which are the observed swimming zones of small-bodied fishes. Three-dimensional velocity measurements showed some strong secondary motion of Prandtl's second kind, with median secondary current magnitudes corresponded to 4.7% to 6.0% of  $V_{\max}$ . A downward secondary current flow motion  $\overline{V_z} < 0$  was observed next to both sidewalls, which could be a relevant key parameter in facilitating upstream fish passage. For the range of less-than-design flow conditions, the low velocity zone lies within the turbulent wall shear layer, which consisted of high Reynolds stress regions and significant turbulent burst events with large amplitude ( $A_b > 20$ ) and long burst duration (14–40 ms). Interestingly, the sidewall and corner regions with the higher Reynolds stress and burst events presented lower Eulerian timescales (5–100 ms) and advection length scales (2–100 mm), which could provide a conducive zone for fish passage. The outcome of the physical modelling provided a fascinating and quantifiable insight into the hydrodynamics of the observed fish swimming zone in a near-full-scale culvert barrel, with novel turbulent characterisation in a fully-developed flow.

The present findings supported the needs to develop a more vigorous set of fish passage guidelines, inclusive of turbulence considerations, which are currently lacking in the literature and industry design guidelines. While this study provides a comprehensive dataset of the hydrodynamic characteristics in a fully-developed flow of a box culvert barrel, careful considerations such as channel configurations, inlet configurations, scaling, presence of sediment, roughness, and all other variables are needed, when referring and extrapolating results from the current study. While experimental studies and CFD modelling are pivotal,

field investigations at an actual culvert site would be invaluable to confirm and complement the current and the previous studies performed to date.

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**Data availability** Data associated with this research is available upon reasonable request from the authors.

## Declarations

**Competing interests** The authors declare no competing interests.

**Conflict of interest** The author declares that there is no conflict of interest.

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## Authors and Affiliations

Hui Ling Wong<sup>1</sup>  · Hubert Chanson<sup>1</sup> 

✉ Hui Ling Wong  
huiling.wong@uqconnect.edu.au

Hubert Chanson  
h.chanson@uq.edu.au

<sup>1</sup> School of Civil Engineering, The University of Queensland, Brisbane, QLD 4072, Australia