On upstream fish passage in standard box culverts: interactions between fish and turbulence

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ABSTRACT

The challenge to understanding the fluid mechanics of fish swimming is knowing exactly what the water is doing where the fish swims. Recent field and laboratory observations in box culvert barrel showed that fish tend to swim preferentially close to the channel sidewalls, in regions of slow velocity and often high turbulence intensity. An analogy with human swimming is developed herein. Fish minimise their energy expenditure by swimming in inter-connected low-velocity zones (LVZs) and minimising acceleration-deceleration amplitudes. In a box culvert barrel, the mechanical energy expenditure is drastically reduced in sidewall and corner flow regions, characterised by low velocities and secondary current motion. These regions were "sweet spots" used by small bodied fish to minimise their rate of work. Both bed and sidewall roughness must be scaled to the fish dimensions. More generally, the methodology brings rigorous scientific insights into why certain culvert designs, possibly equipped with baffles and apertures, are more efficient in promoting fish passage. One may foresee an evolution of the scientific approach towards using advanced physics-based theory supported by high-quality data sets. The results also raise questions on limitations of current fish swim tunnel tests, and matching swimming performance data to hydrodynamic measurements.

Introduction

Fishes display a wide range of biological adaptations linked to a broad variety of swimming techniques and performances in response to different habitats (Videler 1993). In turn, it is important to understand the essential dynamics, without being distracted by the shear complexity of the problem. The challenge to understanding the fluid mechanics of fish swimming is knowing exactly what the water is doing where the fish swims and what the resulting forces on the fish are. Considering a fish swimming downstream of a culvert (Figure 1), potential obstacles for its upstream migration include the downstream approach, the culvert barrel with large fluid velocities and low light conditions, and the upstream inlet area, all of which could be potential barriers when the fish has used a large amount of its available energy and is near exhaustion while trying to migrate upstream (Behlke et al. 1991). Culverts are common road crossing structures designed to pass rainfall runoff under embankments. They are covered channels of relatively short length installed to drain water through an embankment (e.g. highway, railroad, and dam). The design of a culvert is based on hydrological, hydraulic, structural and geotechnical considerations. Culvert structures may contribute to a sizeable component of total road construction costs (Hee 1969). In terms of hydraulic engineering, the optimum size is the smallest barrel

A primary ecological concern regarding culvert structures is the potential barrier to impede stream connectivity including upstream fish passage, resulting from the constriction of the waterway (Figure 1). Several jurisdictions, councils and authorities have developed design guidelines to ensure that new culverts allow for upstream fish passage, with most being based on a number of criteria, including bulk velocity and minimum water depth (Chorda et al. 1995; Fairfull and Whiteridge 2003; Hotchkiss and Frei 2007). For a number of applications, baffles and boundary roughening may be installed along the barrel invert to slow down the water flow and provide some fish-friendly alternative design option (Olsen and Tullis 2013; Wang et al. 2017). A baffle is a device designed to slow down the flow of the water. During flow, baffles and rough boundaries decrease the flow velocity, generate recirculation regions and increase the water depth to facilitate fish passage. Unfortunately, however, such apertures can drastically reduce the culvert discharge capacity for a given afflux (the rise of water level above normal level, i.e. natural flood level, on the upstream

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cross-sectional size allowing for inlet control operation at design flow conditions (Bossy 1961; Chanson 2000, 2004). In a culvert, the barrel is the central section where the cross-section is minimum; another term is the "throat". Namely, the hydraulic design is currently optimized for design flow only.

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Figure 1. Standard culvert structures. (A) Box culvert outlet on Marom Creek beneath Bruxner highway B60, NSW (Australia). (B) Box culvert outlet operation along Norman Creek in Greenslope QLD (Australia) on 30 March 2017. Discharge estimated to 60–80 m³/s (Re $\approx 2 \times 10^7$). Flood flow direction from right to left.

side of a culvert or of a hydraulic structure) (Larinier 2002; Olsen and Tullis 2013). This creates a need for additional precast cell units, construction of a second structure in an anabranch, or selection of a bridge structure instead of a culvert, all at a greater cost.

In this study, fish swimming upstream through a box culvert is analysed using an analogy with classical sport physics and studies of competitive swimming. The complexity and non-linearity of fluid dynamics require the mechanics of fish swimming to be analysed at a whole-body level. Combining basic theory, together with fish kinematic and hydrodynamic data, the current study shows that fish can minimize their energy by swimming upstream in low-velocity zones (LVZs) and decreasing their acceleration–deceleration pattern.

Methods

The literature on human swimming provide fascinating details on interactions between swimmers and turbulence, and basic sport physics, applied to swimmers, has been successfully applied to competitive swimming (Clanet 2013, Wei and Hutchison 2014). The outcomes are relevant particularly to fish swimming in a simple channel geometry like a box culvert barrel, although humans swim typically in a pool and fishes swim against a current, e.g. in a culvert barrel. In both cases,

human and fish swimmers try to minimize their energy expenditure, to go faster (e.g. Olympic swimmers), to successfully pass a hydraulic structure (e.g. fish) or to minimize their fatigue. In a pool, a human swimmer may change his/her stroke, possibly use the wake of another swimmer, to minimize the drag and will manage his/her thrust and energy expenditure. Similarly a fish swimming upstream in a box culvert barrel will seek LVZs, use transient turbulent eddies and recirculation zones, to minimize its fatigue and achieve a successful upstream migration. By analogy with competitive swimming and sport physics (Counsilman 1968; Clanet 2013), the physics of a fish swimming upstream in a culvert barrel is analysed (Figure 2). The most elementary concepts of the fish dynamics are the notions that the rate of mechanical work exerted by the fish equals the thrust times the relative fish speed. Assuming carangiform propulsion, the fish is subjected to a number of forces, including thrust, gravity, buoyancy, virtual mass, drag and lift (Lighthill 1960, 1969). By definition, the lift force, and buoyancy force in open channel flow, are applied along the direction perpendicular to the flow streamlines: in the longitudinal x-direction, their contribution is nil. Gravity applies along the vertical direction, while the drag force acts along the longitudinal x-direction. Considering a fish swimming upstream, and ignoring the virtual mass force, the main force contributions acting in the x-direction are thrust, drag force, and the gravity force component (Wang and Chanson 2017). In turn, assuming carangiform propulsion, Newton's law of motion applied to the fish gives a relationship between the three main force contributions and the product of fish mass times its instantaneous acceleration (Figure 2). During active propulsion, both fish body and tail contribute to the thrust production, shedding one vortex per half tailbeat when the tail reaches its most lateral position, resulting in an inverted Karman vortex street sketched in Figure 2 (bottom right).

The drag force includes a combination of skin friction and form drag, including the turbulent dissipation in the fish wake. The drag force is proportional to the square of the relative fish speed times the fish's frontal (projected) area times a drag coefficient (Figure 3) (Lighthill 1969). The drag coefficient times the projected area of the fish might be derived from fish trajectory data when a fish stops to propel itself and glides. In a horizontal channel, the drag force becomes related to the rate of deceleration and relative fish speed (Wang and Chanson 2017). When a fish swimming upstream starts drifting in a horizontal channel, the fish deceleration is driven by the drag force and Newton's law of motion becomes: $m_f \times \partial U_x / \partial t \approx -C_d \times \rho_w \times (\overline{U_x + V_x})^2 \times A_f,$ with m_f the fish mass, U_x the fish speed positive upstream, C_d the drag coefficient, ρ_w the water density, V_x the fluid velocity at the fish location, positive downstream



Figure 2. Application of Newton's law of motion to a fish swimming upstream in a box culvert. The box corresponds to the barrel and the fish swims upstream from bottom left to top right.

and A_f the fish's projected area (Figures 2 and 3). Figure 4 shows experimental observations of changes in fish speed and acceleration during drift motion. The figure captions include the local flow properties, including the time-averaged velocity $\overline{V_x}$ and velocity standard deviation v_x' . Note that the drag coefficient C_d is a total drag coefficient that includes a form factor for the fish and considerations for skin friction.

The ability to measure energy expenditure may be derived from high temporal and spatial resolution video recordings. By tracking a point (e.g. the eye) on the fish's body from frame to frame, it is possible to generate a trace of the fish's position through time (Plew et al. 2007; Wang et al. 2016). First and second derivatives of that position versus the time trace of course provide velocity and acceleration, albeit the data must be filtered to remove noise (Wang et al. 2016). The fish mass can be easily measured, and the instantaneous net thrust produced by the fish can be determined from the video record trajectory.

The product of velocity and thrust is the power or rate of work done by the fish during swimming (Lighthill 1960; Behlke et al. 1991). Neglecting efforts spent during lateral and upward motion, the mean rate of work by the fish is:

$$P = \left(m_f \times \frac{\partial U}{\partial t} + C_d \times A_f \times \rho \times (\overline{U_x + V_x})^2 + m_f \times g \times \sin\theta \right) \\ \times (U_f + V_x)$$
(1)



$Drag = C_d \times Water density \times (Re lative fish speed)^2 \times A_f$

Figure 3. Drag force acting on a fish swimming upstream. The drag force equals the product of the drag coefficient C_d , water density, and fish projected area A_f times the square of the relative fish speed.



Figure 4. Time variation of relative fish speed and acceleration during drift events. Data-set: high-speed video movies taken during experiments by Wang et al. (2016); the arrow points to drift motion. (A, left) Juvenile silver perch (*Bidyanus bidyanus*) individual no. 20, mass: 29.1 g, length: 130 mm, fish swimming along a rough sidewall with rough invert, local flow conditions: $\overline{V_x} = +0.366$ m/s, $v_x' = 0.315$ m/s, $\theta = 0 - C_d \times A_f \approx 1 \times 10^{-2}$ m². (B, right) Duboulay's rainbowfish (*Melanotaenia duboulayi*) no. 19, mass: 1.6 g, length: 53 mm, fish swimming along a smooth sidewall with smooth invert, local flow conditions: $\overline{V_x} = +0.517$ m/s, $v_x' = 0.072$ m/s, $\theta = 0 - C_d \times A_f \approx 7.5 \times 10^{-3}$ m². (C) Duboulay's rainbowfish (*M. duboulayi*) No. 26, mass: 1.8 g, length: 60 mm, swimming along a rough sidewall with rough invert, local flow conditions: $\overline{V_x} = +0.366$ m/s, $v_x' = 0.315$ m/s, $\theta = 0 - C_d \times A_f \approx 1.50$ m/s, $v_x' = -0.366$ m/s, $v_x' = 0.315$ m/s, $\theta = 0 - C_d \times A_f \approx 1.50$ m/s, $\theta = 0 - C_d \times A_f \approx 1.50$ m/s, $\theta = 0.50$ m/s, $\theta = 0 - C_d \times A_f \approx 1.50$ m/s, $\theta = 0.50$ m/s, $\theta = 0 - C_d \times A_f \approx 1.50$ m/s, $\theta = 0.50$ m/s, θ

where $\overline{U_x + V_x}$ is the mean relative fish speed over a control volume selected such that the lateral surfaces are parallel to the streamlines and that it extends up to the wake region's downstream end, and θ is the angle between the invert and horizontal (Wang and Chanson 2017). The work *W* spent by the moving fish during a time *T* is:

$$W = \int_{t=0}^{T} P \times dt$$
 (2)

The above method is applied to re-analysed datasets obtained in a 12 m long 0.5 m wide horizontal rectangular flume, corresponding to a nearly full-scale box culvert barrel (Wang et al. 2016). Fish swimming tests were performed with adult Duboulay's rainbowfish (*Melanotaenia duboulayi*) and juvenile silver perch (*Bidyanus bidyanus*). We compared the fish swimming data of the two species in the same 12 m long flume

for the same flow rate of 0.0261 m³/s, selected after discussion with fish biologists, such that the bulk velocity was slightly less than the critical speed of the targeted small-bodied fish species. The fish behaviour and kinematic data were comparable qualitatively, despite the obvious difference in fish length and mass (Table 1). The fish energetic analysis yielded further similar findings for both species (data not shown in paper for conciseness). In the following discussion, we present mostly adult Duboulay rainbowfish data, because that species was the weaker swimmer (e.g. in terms of critical swimming speed U_{crit}) and the data are most relevant to the upstream culvert passage of weakswimming small-bodied fish. The sample size, range of tested fish, and experimental flow conditions are summarized in Table 1. Experimental observations were undertaken with a smooth configuration and later in a configuration with very-rough sidewall and bottom. ("Very-rough" means boundary surface irregularities ± 10 mm and equivalent sand roughness height about

Table 1. Laboratory studies on fish swimming in a 12 m long 0.5 m culvert barrel model: fish data (mass m_f and total length L_f).

Q (m ³ /s) (2)	<i>d</i> (m) (3)	V _{mean} (m/s) (4)	Fish specie (5)	Nb of fish (6)	Fish mass <i>m_f</i> (g) (7)	Fish length L _f (mm) (8)
0.0261	0.123	0.424	Duboulay's rainbowfish (Melanotaenia duboulayi)	22	2.75 ± 0.65	68.5 ± 6.3
0.0261	0.133	0.392	Duboulay's rainbowfish (M. duboulayi)	23	3.6 ± 1.08	74.0 ± 5.5
0.0261	0.129	0.424	Juvenile silver perch (Bidyanus bidyanus)	23	39.7 ± 33.7	145 ± 31.5
			Duboulay's rainbowfish (M. duboulayi)	23	$\textbf{3.2} \pm \textbf{1.07}$	$\textbf{70.5} \pm \textbf{8.0}$
	Q (m ³ /s) (2) 0.0261 0.0261 0.0261	Q d (m ³ /s) (m) (2) (3) 0.0261 0.123 0.0261 0.133 0.0261 0.129	$\begin{array}{cccc} Q & d & V_{mean} \\ (m^3/s) & (m) & (m/s) \\ (2) & (3) & (4) \end{array}$	QdV (m)V (m/s)(2)(3)(4)Fish specie0.02610.1230.424Duboulay's rainbowfish (Melanotaenia duboulayi)0.02610.1330.392Duboulay's rainbowfish (M. duboulayi)0.02610.1290.424Juvenile silver perch (Bidyanus bidyanus) Duboulay's rainbowfish (M. duboulayi)	Q (m3/s)d (m)V (m/s) (4)Fish specieNb of fish (6)0.02610.1230.424Duboulay's rainbowfish (Melanotaenia duboulayi)22 230.02610.1330.392Duboulay's rainbowfish (M. duboulayi)23 23 Duboulay's rainbowfish (M. duboulayi)23 23 230.02610.1290.424Juvenile silver perch (Bidyanus bidyanus)23 23 23	

Notes: Q: water discharge; d: water depth; V_{mean}: bulk velocity; fish data: median value ± standard deviation; experiments conducted at 24.5 ± 0.5 C.

30-40 mm.) Time traces of fish speed, acceleration and power were derived from high-speed video movies. The camera frame rate was 240 Hz with a spatial resolution of 512 × 384 pixels over a field of view of approximately 0.2 × 0.1 m².

Typical examples of image analysis are shown in Figures 5 and 6: time traces of relative fish speed,

acceleration, and power were generated for two fish individuals. Among the Duboulay's rainbowfish population, individuals with similar mass and length, and comparable swimming behaviour (i.e. in corner) and kinematics, were selected, both being representative of more than 50% of their respective samples in terms of swimming behaviour. The fluid velocity has been



Figure 5. Time variations of relative fish speed, absolute acceleration and rate of work done by a fish swimming upstream in a 12 m long 0.5 m wide open channel. Duboulay's rainbowfish (*M. duboulayi*) swimming along a smooth sidewall (smooth boundary flume), fish no. 19, mass: 1.6 g, length: 53 mm, local water flow conditions: $\overline{V_x} = +0.517$ m/s, $v_x' = 0.072$ m/s, $\theta = 0 - C_d \times A_f \approx 7.54 \times 10^{-3}$ m². (A) Entire data-set lasting 90 s during which fish progressed 4.2 mm upstream. (B) Details of high-speed video data.



Figure 6. Time variations of relative fish speed, absolute acceleration and rate of work done by a fish swimming upstream in a 12 m long 0.5 m wide open channel. Duboulay's rainbowfish (*M. duboulayi*) swimming along a rough sidewall (rough sidewall and bed flume), fish no. 26, mass: 1.8 g, length: 60 mm, local water flow conditions: $\overline{V_x} = +0.366$ m/s, $v_x' = 0.315$ m/s, $\theta = 0 - C_d \times A_f \approx 9.5 \times 10^{-3}$ m². (A) Entire data-set lasting 12.63 s during which fish progressed 38 mm upstream. (B) Details of high-speed video data.

added to the measured fish swim speed plotted in Figures 5 and 6.

Results

Considering the upstream swimming of small-bodied fish in the 12 m long 0.5 m wide box culvert barrel channel, the observations showed common features as well as differences between all data-sets (Table 1).

In both smooth and rough-boundary channels, the fish were swimming against a steady current, set to a speed slightly lower than their endurance speed. In each case, the fish swam in a reasonably thin vertical layer close to a sidewall. The vertical plan projection of the fish trajectories served as an approximation of the 3D trajectories. Figure 5 presents typical observations in the smooth flume seen in Figure 7(B). The local fluid speed $\overline{V_x}$ at the fish location was about 0.52 m/s, with a relative velocity fluctuation $v_x'/\overline{V_x} = 0.14$. Figure 6

shows typical data obtained in the flume equipped with a very-rough bed and very-rough left sidewall (Figure 8(B)). The fish was swimming close to the very-rough sidewall, where the local fluid speed was 0.37 m/s, with a relative fluctuation $v_x'/\overline{V_x} = 0.86$.

In comparing the entire data-sets, it is apparent that, in the smooth channel, the fish swam faster and harder, despite a lower mean absolute speed. For example, in Figure 5, Fish No. 19 spent more energy, with a mean rate of work more than twice the power spent by Fish No. 26 in the rough-boundary channel (Figure 6). In examining the body position in relation to the velocity field, basic observations may be drawn. In the rough-boundary flume, the fish benefited from some sheltering generated by the sidewall roughness and left corner geometry. Perhaps the learning opportunities made available by this type of analysis are best seen when considering the differences in power spent by the fish in both scenarios. For example, Figures 5



Figure 7. Upstream fish passage in a 12 m long box culvert model with smooth boundaries - B = 0.5 m, $S_o = 0$, $Q = 0.0261 \text{ m}^3/\text{s}$, d = 0.123 m, and Re = 2×10^5 . (A) Definition sketch and velocity contour data; with smooth boundaries, the bulk velocity in the channel was 0.42 m/s. (B) Duboulay's rainbowfish (*M. duboulayi*) swimming along the right smooth sidewall, with the flow direction from bottom left to far right.

and 6 include time traces of rate of work of Fish 19 and 26, respectively: a key difference here is that Fish 19 worked harder because of a larger relative fish speed in the smooth channel. A close-up at all-time traces shows clearly that the power spent by the fish to provide thrust is directly proportional to the relative fish speed and acceleration (e.g. Figures 5(B) and 6(B)). Visual observations and speed time series enabled accurate quantitative estimates of the instantaneous rate of work spent by the moving fish. For example, in Figure 5 (smooth channel), the median rate of work by Fish No. 19 was 1.04 W, with the first and third quartiles being 0.993 W and 1.090 W respectively, the maximum instantaneous power reaching 1.57 W; in Figure 6 (rough-boundary channel), the median rate of work by Fish No. 26 was 0.477 W, with the first and third quartiles being 0.419 and 0.544 W, respectively. For all observations, the distributions of rate of work were skewed with a preponderance of small values relative to the mean.

Discussion

Critical culvert parameters in terms of fish passage include the barrel characteristics, cross-sectional shape and invert slope, as well as the water discharge and hydrodynamic flow conditions. Box culverts are believed to be more effective for fish passage than circular culverts, albeit the barrel length is a key factor for some fish species, with increasing fish passage limitations as culvert length increases (Brigg and Galarowicz 2013). The behavioural response by fish species to culvert dimensions and flow turbulence may play a role in their swimming ability, and hence on their ability to successfully pass the culvert. The broad range of culvert designs result in a wide diversity in turbulent flow patterns. There are on-going discussions to ascertain the turbulence characteristics most relevant to fish passage in channels, with or without baffles, but it is understood that the flow turbulence plays a key role in fish behaviour (Liu et al. 2006; Yasuda 2011).



Figure 8. Upstream fish passage in a 12 m long box culvert model with a very-rough bed and very-rough left sidewall - B = 0.4785 m, $S_o = 0$, Q = 0.0261 m³/s, d = 0.129 m, and Re = 2×10^5 . (A) Definition sketch and velocity contour data – the cross-sectional velocity profile shows the "sweet spots" or low velocity regions used by juvenile silver perch (*B. bidyanus*) and Duboulay's rainbowfish (*M. duboulayi*); in terms of swimming performance, these low velocity regions experienced local time-averaged longitudinal velocities of 0.25 m/s or less; for comparison, the bulk velocity in the channel was 0.42 m/s. (B) Juvenile silver perch (*B. bidyanus*) swimming along the very-rough left sidewall, with the flow direction from left to right.

Turbulence corresponds to a flow motion characterized by unpredictable behaviour, strong mixing and a broad spectrum of time and length scales (Bradshaw 1971; Chanson 2014). Its proper characterization requires a full spectrum of properties (Tropea et al. 2007). Figure 9 shows a basic definition sketch of turbulent flow motion and lists a number of key turbulence characteristics. The latter includes the turbulence intensity characterizing the relative fluctuations in longitudinal velocity, the turbulent kinetic energy averaging the velocity fluctuations in all three directions, the Reynolds stress tensor representing the shear stresses within the fluid, and the vorticity vector that describes the local rotations.

Several studies have debated on the most important turbulence parameters to assist the upstream passage of fish (Pavlov et al. 2000; Hotchkiss 2002; Crower and

Diplas 2002; Nikora et al. 2003; Goettel et al. 2015). Laboratory observations showed that fish may take advantage of turbulent flow unsteadiness (Liao 2007). Fish can also save energy by swimming as a school (Plew et al. 2015; Chen et al. 2016). The fish-turbulence interplay involves a broad range of relevant length and time scales (Lupandin 2005; Webb and Cotel 2011). The turbulent flow patterns constitute a determining factor characterizing the capacity of the hydraulic structure to successfully pass targeted fish species. A seminal discussion emphasized the role of secondary flow motion (Papanicolaou and Talebbeydokhti 2002). Next to a sidewall, the channel flow is retarded and complicated flow patterns develop, e.g. next to the corners. In turn, some flow motion is generated at right angle to the longitudinal current, i.e. some secondary current. Fish performances may be functions of the



Figure 9. Definition of flow turbulence and its characterization.

ratio of vortex size to fish length (Webb and Cotel 2011), with some fish performing best when roughness elements and coherent structures are "*scaled with the size of the fish*" (Monk et al. 2012).

Energetics linking biomechanics, fluid dynamics and fish physiology is a major challenge, and could learn from recent progresses in competitive swimming and sport physics (Wang and Wang 2006; Wei et al. 2014). An analogy with human swimming may be applied to fish swimming upstream in a culvert. Although it might not be intuitively obvious, fish minimize their energy expenditure by swimming in continuous, inter-connecting low-velocity regions and by minimizing their acceleration-deceleration amplitude (i.e. swimming at near-constant speed). The present approach provides a science-based reasoning for assessing what the best swimming trajectory should look like. The ability to conduct temporally resolved analysis of speed, thrust, and power then represents a powerful tool in the study of culvert fish passage. By analogy with competitive swimming physics, it is now possible to evaluate culvert fish passage in terms of any of these three parameters at any point in the culvert. In so doing, the engineer can now provide the biologists with rigorous physics-based insights into why certain culvert designs, including possibly baffles, boundary roughening, and apertures, are better than others.

Recent field observations and near-full-scale laboratory experiments recorded fish swimming in a box culvert barrel (Blank 2008; Wang et al. 2016; Cabonce et al. 2017). Data showed that fish tended to swim preferentially close to channel sidewalls, in regions of low velocity and high turbulence intensity. This finding is on par with other studies (Goettel et al. 2015). Figures 7 and 8 illustrate such swimming behaviour observed in a 12 m long flume: Figure 7 for the smooth bed and

wall configuration, and Figure 8 for the same flume equipped with a very-rough bed and very-rough left sidewall. The longitudinal velocity contour plots are shown in Figures 7(A) and 8(A), in the form of un-distorted velocity contour maps (i.e. the y- and z-axes having the same scale) providing a physically realistic description of the velocity field. A striking difference between the two configurations is the size of LVZs. In the presence of rough boundaries, 28% of the flow cross-section area experienced velocities less than 0.4 m/s, in comparison to a cross-sectional maximum velocity of 0.75 m/s. For comparison, with smooth walls and bed, only 14% of the flow had velocities less than 0.4 m/s, when the cross-sectional maximum velocity was 0.64 m/s. With rough boundaries, one sees the "sweet spots" and slow velocity regions that the fish exploit, highlighted in Figure 8(A).

The rate of work and energy expenditure are both proportional to the cube of the fluid velocity: $P \propto V_x^3$ (Equation (1), Figures 2 and 3). Since fishes typically minimize their efforts (Blank 2008; Abeldaziz et al. 2011), a fish swimming upstream in a culvert barrel will minimize its energy consumption by selecting a trajectory in slow-velocity zones. The present findings apply to any bed slope and imply that any fish-friendly culvert design must provide sizeable low-velocity regions for a range of relevant flows to assist with upstream migration of targeted fish species. Considering a culvert equipped with smooth boundaries (Figure 7), fish swim preferentially next to the lower part of the barrel walls (Blank 2008; Wang et al. 2016). The finding is consistent with detailed velocity measurements in the culvert barrel, showing low velocity regions next to the side wall particularly in the lower half, albeit for a thin region (Figure 7(A)). For a culvert barrel equipped with a rough wall and rough invert, large-scale experiments indicated that small fish preferred to swim next to the corner between the rough sidewall and invert (Figure 8(A)) (Wang et al. 2016). Such a region is characterized by both low velocities, high turbulence levels and secondary current motion, in which the fish mechanical energy expenditure is drastically reduced. The key feature is the role of the corner region and the development of a relatively large low-velocity region with secondary current (Figure 8 (A)). Present expertise suggests further that the bed and sidewall must be very rough, with a characteristic roughness size linked to the fish dimensions, i.e. about $(A_f)^{1/2}$ with A_f the fish's frontal area (Figure 3) (Wang and Chanson 2017). A comparable finding was reported by Monk et al. (2012) with rock substrate. The large roughness induces large-scale vortical structures, which best interact with fish when the ratio of eddy size to fish length is about unity. Wang et al. (2016) reported data in terms of ratio of fish speed to fluid velocity auto-correlation time scales being within $0.3 < t_{xx}/T_{xx} < 3$ with a median value about 1.5, where

 t_{xx} is the fish speed auto-correlation time scale and T_{xx} is the fluid velocity auto-correlation time scale. Since the fish speed auto-correlation time scale characterized a typical reaction time of the fish, the finding suggested that the fish tended to react predominantly to the larger vortical structures, and did not modulate their speed in response to small and short-lived vortical structures.

An important issue for fish is to maintain as constant a relative speed as possible. In fluid dynamics terms, the fish must "*waltz dance*" with the flow turbulence to minimize acceleration/deceleration and minimize the associated energy consumption. In other words, the fish must not fight the turbulence, rather use it. An analogy with long-distance running could be developed: distance runners often seek the most effective stride rate to improve running economy, by minimizing bursts and sprints. Similarly, a fish must use large coherent structures and not fight them.

Conclusion and future outcomes

One can foresee the evolution from a biological science approach based heavily on pseudo-quantitative observations (i.e. scientists observing fish; clocking fish passage times or spot positions; and then applying educated guesses, experience, and varying degrees of scientific understanding) to the introduction of advanced physics-based theory supported by highquality experimental data-sets. Although further refinement is necessary, a capability now exists to directly compute critical mechanistic information with high spatial and temporal resolution. The study of the fluid dynamics of upstream fish passage in hydraulic structures is growing from empirical observation and interpretation to direct measurements, computational and experimental, backed by fundamental principles of physics.

The upstream passage of fish may be further analysed like an optimization process, in a manner comparable to that used in competitive swimming (Wang and Wang 2006). It is indeed conceivable that fishes might adapt their swimming stroke to minimize drag and maximize their efficiency, as observed with swimmers during international competitions (Kolmogorov and Duplishcheva 1992; Wei et al. 2014). The latter brings up more questions on the limitations and significance of current fish swim tunnel tests (Katopodis and Gervais 2016). One may query their relevance or not to upstream fish passage in culverts, when field observations reported fish seeking LVZs, associated with high turbulence intensity levels, to pass through hydraulic structures (Behlke et al. 1991; Blank 2008; Goettel et al. 2015; Cabonce et al. 2017). Such hydrodynamic conditions differ substantially from tube testing conditions.

A related challenge is matching swimming performance data to hydrodynamic measurements. Swim tests lack standardized test methods (i.e. two different studies rarely use the same protocol) and the output is either a single-point measurement or a bulk velocity, assuming implicitly some uniform velocity distribution. In contrast, physical and numerical modelling of fluid flow deliver a detailed flow map (Figure 9), including contours of time-averaged velocity, e.g. Figures 7 and 8 are each based on 300 measurement points and a wide range of turbulence properties, i.e. typically based on a minimum of 12,000 samples per single measurement point, with a fine spatial resolution. Such maps provide flow properties at very-fine spatial and temporal details. Regulatory agencies face a difficult task to match hydrodynamic observations and swimming performance information, when the data were collected with markedly different spatial and temporal resolution, data quality, standardization level, and metrology expertise.

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