Proceedings of the 37th IAHR World Congress
August 13 – 18, 2017, Kuala Lumpur, Malaysia

BAFFLE SYSTEMS TO FACILITATE UPSTREAM FISH PASSAGE IN STANDARD BOX CULVERTS: HOW ABOUT FISH-TURBULENCE INTERPLAY?

HANG WANG(1) & HUBERT CHANSON(2)

(1,2)The University of Queensland, School of Civil Engineering, Brisbane QLD 4072, Australia
hang.wang@uqconnect.edu; h.chanson@uq.edu.au

ABSTRACT

Waterway culverts are very common hydraulic structures along streams and water systems, in rural and urban drainage networks. Current expertise in environmental hydraulics of culverts is limited, sometimes leading to inadequate fish passage with adverse impact on the catchment eco-system. Recent recognition of the ecological impact of culverts on natural streams led to changes in culvert design guidelines. It is believed that fish-turbulence interplay may facilitate upstream migration, albeit an optimum design must be based upon a proper characterisation of both hydrodynamics and fish kinematics. Basic dimensional considerations highlight a number of key parameters relevant to upstream fish passage, including the ratio of fish speed fluctuations to fluid velocity fluctuations, the ratio of fish response time to turbulent time scales, the ratios of fish dimension to turbulent length scale, and the fish species. Combining the equation of conservation of momentum applied to an individual fish, the instantaneous thrust and power expended during fish swimming may be derived from fish kinematic data, including the associated energy consumption. Within basic assumptions, the present findings suggest that the culvert invert slope may affect significantly the energy spent by the fish to provide thrust during upstream culvert passage.

Keywords: Standard box culverts; fish passage; fsh-turbulence interactions; dimensional considerations; energy consumption.

1 INTRODUCTION

Culverts are covered channels designed to pass floodwaters beneath an embankment, typically a roadway or railroad. Figure 1 presents a few examples of standard box culverts in Australia. The three-cell structures seen in Figure 1 (Top) would be typical of a large majority of road culvert structures. Culverts may cost about 15% of total road construction costs (Hee, 1969). Their designs are very diverse, using various shapes and construction materials determined by stream width, peak flows, stream gradient, and minimum cost (Henderson, 1966; Hee, 1969). While the key design parameters of a culvert are its design discharge and the maximum acceptable afflux (Chanson, 2004), the variability in culvert dimensions is closely linked to the various constraints of each site (Figure 1), resulting in a wide diversity in flow patterns (Hee, 1969; USBR, 1987; Australian Standard, 2010).

In recent decades, recognition of the ecological impact of culverts on natural streams and rivers led to changes in culvert design guidelines (Behlke et al., 1991; Chorda et al., 1995). The culvert discharge capacity is basically based upon the hydrological and hydraulic engineering considerations, which may result in large flow velocities creating some fish passage barrier. In this paper, the interactions between the turbulence and fish are reviewed in the context of upstream fish passage in standard box culverts. Basic dimensional analysis is presented, before fish kinematics and energetic considerations are developed and results are discussed.

2 FISH-TURBULENCE INTERPLAY: A REVIEW

One of the primary ecological concerns regarding culvert crossings is the potential velocity barrier to upstream fish passage resulting from the constriction of the channel as illustrated in Figures 1 and 2A. Several jurisdictions developed culvert design guidelines to ensure that the designs will allow for the upstream passage of fish. In Canada, guidelines are based upon a number of criteria including the average flow velocity and minimum embedment depth (Hunt et al., 2012). For culvert rehabilitation applications, baffles may be installed along the invert to provide some fish-friendly alternative (Olsen and Tullis, 2013; Duguay and Lacey, 2014; Chanson and Uys, 2016). At low flows, baffles decrease the flow velocity and increase the water depth to facilitate fish passage. For larger discharges, baffles would induce locally lower velocities and generate recirculation regions. Unfortunately, baffles can reduce drastically the culvert discharge capacity for a given afflux (Larinier, 2002).

(A) (B)

(C)

Figure 1. Standard box culverts in Australia.(A) Culvert outlet beneath Haydon Drive, Canberra ACT on 15 December 2011.(B) Culvert outlet on Marom Creek beneath Bruxner highway B6, Wollongbar NSW on 28 October 2016.(C) Culvert inlet along Gin House Creek, Carrara, Gold Coast QLD on 5 December 2007.

The critical parameters of a culvert in terms of fish passage are the dimensions of the barrel, including its length and cross-sectional characteristics and the invert slope. Generally, the box culverts are considered the most effective for fish passage, although the culvert length may be a key factor for some fish species, with long culverts limiting upstream fish passage (Brigg and Galarowicz, 2013). The behavioural response by fish species to culvert length, light conditions and flow turbulence could play a role in their swimming ability and culvert passage rate. The broad range of culvert designs results in a wide diversity in turbulent flow patterns observed in prototype culverts (Figure 2A). When the fish swimming power is greater than the maximum volumetric power (Bates, 2000), the fish may be able to pass the successive baffles and rest in each pool. There is no simple technical means for measuring the turbulence characteristics in fish passage with baffles, although it is understood that the flow turbulence plays a key role in fish behaviour (Liu et al., 2006; Yasuda, 2011; Breton et al., 2013). Several studies argued that the most important parameters to assist fish passage include the turbulence intensity, Reynolds stress tensor, turbulent kinetic energy, vorticity, and dissipation (Pavlov et al., 2000; Hotchkiss, 2002; Nikora et al., 2003). Recent observations showed that fish may take advantage of the unsteady character of turbulent flows (Liao, 2007; Wang et al., 2010) and it was shown that fish can save energy by swimming as a school (Plew et al., 2015; Chen et al., 2016). Importantly, the interactions between fish and turbulence are very complicated, and naive *"turbulence metrics cannot explain all the swimming path lines or behaviors*" (Goettel et al., 2015).

First mentioned by Leonardo Da Vinci (Keele, 1983), the interactions between swimming fish and vortical structures involve a broad range of relevant length scales (Lupandin, 2005; Webb and Cotel, 2011). The turbulent flow patterns are one key element determining the capacity of the system to pass successfully targeted fish species. A seminal discussion argued for the role of secondary flow motion and "*the importance of performing three-dimensional turbulent flow measurements to precisely identify the effects of secondary flows on fish motion*" (Papanicolaou and Talebbeydokhti, 2002). The discussion was extended by recent contributions, suggesting that "*a proper study of turbulence effects on fish behaviour should involve, in addition to turbulence energetics, consideration of fish dimensions in relation to the spectrum of turbulence scales*" (Nikora et al., 2003), and that large-scale "*turbulent structures associated with wakes can be beneficial if fish are able to exploit them*" (Plew et al., 2007).

While the literature on culvert fish passage focused mostly on fast-swimming fish species, recent studies acknowledged the needs for better guidelines for small-bodied fish including juveniles (Behlke et al., 1991; Fairfull and Witheridge, 2003; Rodgers et al., 2014; Forty et al., 2016; Wang et al., 2016a).

3 DIMENSIONAL ANALYSIS AND SIMILITUDES

3.1 Basic considerations

In experimental fluid dynamics, the model study of a prototype is to provide reliable predictions of the flow properties of the associated prototype (Liggett, 1994; Foss et al., 2007; Novak et al., 2010). This type of study is based upon the basic concept and principles of similitude to ensure a reliable extrapolation of the results from the hydraulic model study to the prototype. That is, physical measurements from the model (*e.g.,* pressure, velocity, drag) are used to predict the extrapolated values for the same quantities to be present in the prototype flow (Henderson, 1966; Novak and Cabelka, 1994). The processing, analysis and interpretation of experimental data constitutes an essential activity in physical modelling (Darrozes and Monavon, 2014). Two basic principles are: (1) the simplest relationships have the fewest number of relevant variables and (2) they are dimensionless (Foss et al., 2007). The presentation of numerical results must have the most extensive validity, and dimensional analysis is the basic procedure to deliver dimensionless parameters.

For any dimensional analysis, the relevant parameters include the fluid properties and physical constants, the channel geometry and initial flow conditions. Considering the simple case of a steady turbulent flow in a rectangular open channel, a dimensional analysis yields a series of relationship between the flow properties at a location (x,y,z) and the upstream flow conditions, channel geometry and fluid properties:

$$d, \vec{V}, v', p, L_t, T_t, ... = F_1\left(x, y, z, B, k_s, \theta, d_1, V_1, v_1', \rho_w, \mu_w, \sigma, g, ...\right) \qquad [1]$$

where d is the flow depth, V is the velocity, v' is a velocity fluctuation, p is the pressure, L_t and T_t are integral turbulent length and time scales, x, y and z are the longitudinal transverse and vertical coordinates, respectively, B is the channel width, k_s is the equivalent sand roughness height of the channel boundary, θ is the angle between the invert and horizontal, d_1, V_1 and v_1' are the inflow depth, velocity and velocity fluctuation, respectively, ρ_w and μ_w are the water density and dynamic viscosity, respectively, σ is the surface tension, and g is the gravity acceleration. In Equation [1], right handside term, the 4th, 5th and 6th variables characterise the boundary conditions, whereas the 7th, 8th and 9th terms are the inflow (initial) conditions, and the following terms are fluid and physical properties.

The Π-Buckingham theorem states that a dimensional equation such as Equation [1] with N dimensional variables may be simplified in an equation with N-3 dimensionless variables, when the Mass, Length and Time units are used among the N dimensional variables (Liggett, 1994). Thus Equation [1] may be rewritten as:

$$\frac{d}{d_c}, \frac{V_x}{V_c}, \frac{v_x'}{V_c}, \frac{p}{\rho_w \times g \times d_c}, \frac{L_t}{d_c}, T_t \times \sqrt{\frac{g}{d_c}} ... = \qquad [2]$$
$$F_2\left(\frac{x}{d_c}, \frac{y}{d_c}, \frac{z}{d_c}, \frac{B}{d_c}, \theta, \frac{k_s}{d_c}, \frac{d_1}{d_c}, \frac{V_1}{\sqrt{g \times d_1}}, \frac{v_1'}{V_1}, \rho_w \times \frac{V \times D_H}{\mu_w}, \frac{g \times \mu_w^4}{\rho_w \times \sigma^3}, ...\right)$$

where d_c is the critical flow depth ($d_c = (Q^2/(g \times B^2))^{1/3}$), V_c is the critical flow velocity, Q is the water discharge and D_H is the equivalent pipe diameter, or hydraulic diameter. In Equation [2], right handside term, the 7th term is the inflow Froude number (Fr_1), the 8th and 9th terms are the Reynolds number (Re) and Morton number (Mo). The Π-Buckingham theorem states that any dimensionless number can be replaced by a combination of itself and other dimensionless numbers. In Equation [2], the Morton number is introduced because it is a constant in most hydraulic model studies when both laboratory experiment and prototype flows use the same fluids, namely air and water.

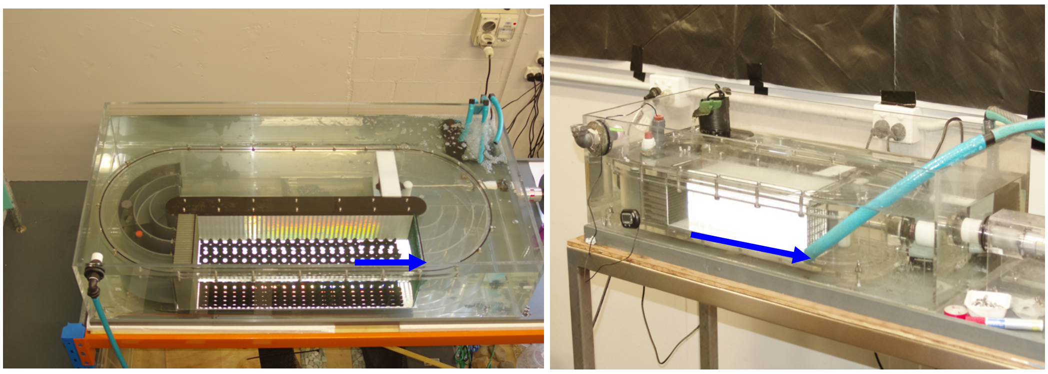
Traditionally hydraulic model studies are performed using geometrically similar models. In the geometrically similar physical model, the flow conditions are said to be similar to those in the prototype if the model displays similarity of form (geometric similarity), similarity of motion (kinematic similarity) and similarity of forces (dynamic similarity) (Liggett, 1994; Chanson, 1999). If any similarity (geometric, kinematic or dynamic similarity) is not fulfilled, scale effects may take place. Scale effects yield discrepancy between the model data extrapolation and the prototype performances. In a physical model, true similarity can be achieved if and only if each dimensionless parameter (or Π-terms) has the same value in both model and prototype:

$$\begin{aligned} Fr_m &= Fr_p \\ Re_m &= Re_p \\ Mo_m &= Mo_p \end{aligned} \qquad [3]$$

where the subscripts m and p refer to the model and prototype conditions, respectively. Scale effects may take place when one or more dimensionless terms have different values between the laboratory and prototype. Let us consider a prototype culvert flow (Figure 2A) and fish passage experimental flumes in Figures 2B and 2C, how can we extrapolate the laboratory results to full-scale real-world culverts with minimum scale effects?

(A)

(B)



(C)

Figure 2. Physical modelling of culvert hydraulics: Comparison between a prototype culvert operation and laboratory studies of upstream fish passage in culverts - Blue arrow shows flow direction. (A) Multi-cell box culvert inlet along Norman Creek, Brisbane QLD during a small flood on 20 May 2009. (B) 12 m long 0.5 m wide tilting flume in the UQ Bio-hydrodynamics laboratory, looking upstream for Q = 0.261 m^3/s and θ = 0. (C) Medium-size and small-size recirculating water tunnels.

Open channel flows including culvert flows are typically studied based upon a Froude similarity because gravity effects are important (Henderson, 1966; Liggett, 1994; Chanson, 1999). The turbulent flow motion is dominated by viscous and dissipative effects. Thus, a true similarity of culvert flow requires achieving identical Froude, Reynolds and Morton numbers in both the prototype culvert and its laboratory model (Equation [3]). This is impossible to achieve using geometrically similar models unless working at the full-scale. Practically, the Froude and Morton dynamic similarities are simultaneously employed with the same fluids, air and water, used in prototype and model. In turn, the Reynolds number is grossly underestimated in laboratory flow conditions. This may lead to viscous-scale effects in small-size hydraulic models seen in Figure 2C.

Similarly, a dimensional analysis may be conducted for the fish motion in a turbulent flow (Alexander, 1982; Blake, 1983). Considering the simplified motion of a fish travelling upstream in a prismatic open channel with a steady turbulent flow, the dimensional considerations yield a series of relationship between the fish motion characteristics at a location (x,y,z), the fish characteristics, the channel boundary conditions, the turbulent flow properties and the fluid properties. It becomes:

$$\vec{U}, u', O_2, \tau_f, ... = F_3 \begin{pmatrix} x, y, z, \\ L_f, l_f, h_f, \rho_f, \text{specie}, \\ B, k_s, \theta, \\ d, V, v', L_t, T_t, \\ \rho_w, \mu_w, \sigma, g, ... \end{pmatrix} \qquad [4]$$

where U is the Eulerian fish speed for a fixed observer, positive upstream since this study is concerned with the upstream fish passage, u' is a fish speed fluctuation, O_2 is the oxygen consumption, τ_f is the fish response time, L_f, l_f and h_f are the fish length, thickness and height, respectively, and ρ_f is the fish density. While Equation [4] is simplistic, for example, ignoring the effects of fish fatigue, the Π-Buckingham theorem implies that Equation [4] may be rewritten in dimensionless form as:

$$\frac{U}{V_c}, \frac{u'}{v'}, O_2, \frac{\tau_f}{T_t}, ... = F_4 \begin{pmatrix} \frac{x}{d_c}, \frac{y}{d_c}, \frac{z}{d_c}, \\ \frac{L_f}{L_t}, \frac{l_f}{L_t}, \frac{h_f}{L_t}, \frac{\rho_f}{\rho_w}, \text{specie}, \\ \frac{B}{d_c}, \frac{k_s}{d_c}, \theta, \\ Fr, Re, Mo, \frac{L_t}{d_c}, T_t \times \sqrt{\frac{g}{d_c}}, ... \end{pmatrix} \qquad [5]$$

3.2 Discussion

The present result (Equation [5]) emphasises a number of key parameters and variables relevant to the upstream fish passage in turbulent open channel flows, including the ratio u'/v' of fish speed fluctuations to fluid velocity fluctuations, the ratio τ_f/T_t of fish response time to turbulent time scales, the ratios of fish dimension to turbulent length scale and the fish species. To date, few studies provided quantitative and detailed characteristics of both fish motion and fluid flow (Nikora et al., 2003; Plew et al., 2007). Even fewer studies reported fish speed fluctuations and fluid velocity fluctuations, as well as fish response time and integral time scales (Wang et al., 2016a). The fish swimming accelerations have also important implications in terms of energy expenditure required to swim against the current over a period of time.

The effect of intrusive probe sensor on laboratory hydrodynamics is rarely considered, despite non-trivial flow disturbances and blockage and Equation [2] did not account for such effects. A recent investigation tested systematically the impact of an acoustic Doppler velocimeter (ADV) in a 0.5 m wide channel (Simon and Chanson, 2013). Even though the sampling volume was 50 mm away from the probe head, the submerged ADV system induced some blockage effect which affected adversely the flow motion including increasing locally the water depth and generating some turbulence in the stem wake. Blockage effects were also documented in a 0.25 m wide channel with a 'vane wheel' propeller meter (Wang et al., 2016b). The propeller casing induced some blockage effect, generating a local fluid acceleration around the propeller, with its readings overestimating the longitudinal velocity by 5% to 30% depending upon the propeller elevation. The usage of intrusive instruments in small flumes and tunnels, as seen in Figure 2C, could lead to biased data.

4 FISH KINEMATICS AND ASSOCIATED ENERGY CONSUMPTION

4.1 Basic considerations

When a fish swims upstream in a culvert barrel, its motion provides critical information on locomotion dynamics that can be used to calculate energy expenditure, with significant implications for the understanding of energetics and biomechanics of aquatic propulsion (Lauder, 2015). Assuming carangiform propulsion, the main forces acting on each fish individual include the thrust force, the gravity force, the buoyancy force, the shear/drag force, the lift force, the virtual mass force (or inertial force). Newton's law of motion applied to a fish yields:

$$m_f \times \frac{d\vec{U}}{dt} = \vec{F}_{thrust} - \vec{F}_{drag} - \vec{F}_{inertial} - m_f \times \vec{g} + \vec{F}_{lift} + \vec{F}_{buoyancy} \qquad [6]$$

where m_f is the fish mass. The virtual mass force might be neglected when the fish density is about the water density. The buoyancy and lift forces act along the normal direction: *i.e.,* perpendicular to the flow streamlines. The drag force acts along the flow direction, and includes a skin friction component and a form drag component. The former is associated with a boundary layer development along the fish surfaces, while the latter is linked to the vortex and wake development downstream of the fish. For a fish swimming upstream along a streamtube and neglecting the virtual mass force, Newton's law of motion applied to the fish in the longitudinal x-direction yields in first approximation:

$$m_f \times \frac{\partial U_x}{\partial t} = F_{thrust} - F_{drag} - m_f \times g \times \sin\theta \qquad [7]$$

where the forces acting on the fish are the thrust (F_{thrust}), drag force (F_{drag}), and the last term is the gravity force component in the flow direction. For a fish in motion, the drag force may be expressed as (Lighthill, 1969):

$$F_{drag} = C_d \times \rho_w \times (\overline{U_x} + V_x)^2 \times A_f \qquad [8]$$

where C_d is the drag coefficient, U_x is the fish speed positive upstream, V_x is the fluid velocity at the fish location, positive downstream, A_f is the projected area of the fish. $\overline{U_x} + V_x$ 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 (Figure 3A) (Alexander, 1982). In Equation [8], the total drag force (F_{drag}) includes a combination of the skin friction on the fish skin surfaces and the form drag and turbulence dissipation in the wake of the fish (Schultz and Webb, 2002).

An estimate of the drag coefficient (C_d) might be derived from trajectory data when the fish drifts (Figure 3B). During drifting in a horizontal channel, the fish deceleration is driven by the drag force. In first approximation, Newton's law of motion becomes:

$$m_f \times \frac{\partial U}{\partial t} \approx -C_d \times \rho_w \times (\overline{U_x} + V_x)^2 \times A_f \qquad [9]$$

Namely the drag force and drag coefficient may be derived from the rate of deceleration, assuming implicitly that the form drag is identical during glide and during thrust, and unaffected by body motion. Figure 3A presents a typical time-variation of fish speed and acceleration during a drift event, for a fish individual swimming next to the corner between a rough sidewall and rough invert (Wang et al., 2016a). For that individual event and fish, Equation [9] gives: $C_d \times A_f = 1.8 \times 10^{-4}$ m^2.
Despite its underlying assumptions, Equation [7] implies that the fish thrust may be derived from the fish acceleration, fish speed and fluid velocity time-series. In turn, the rate of working of the fish and associated energy consumption may be estimated with a fine temporal scale.

The power that the fish expends during swimming is the product of the thrust and the relative fish speed. Neglecting efforts spent during lateral and upward motion, the mean rate of work by the fish is expressed by Equation [10a] (Lighthill, 1960; Behlke et al., 1991). Combining with Equations [7] and [8], it yields Equation [10b]:

$$P = F_{thrust} \times (U_f + V_x) \qquad [10a]$$

$$P = \left(m_f \times \frac{\partial U}{\partial t} + C_d \times \rho_w \times (\overline{U_x} + V_x)^2 \times A_f + m_f \times g \times \sin\theta \right) \times (U_f + V_x) \qquad [10b]$$

with P the instantaneous power spent by the fish to provide thrust and (U_x+V_x) is the local relative fish speed, at the fish location. Equation [10] expresses the rate of working by the fish, to counterbalance the effects of inertia, drag and gravity.

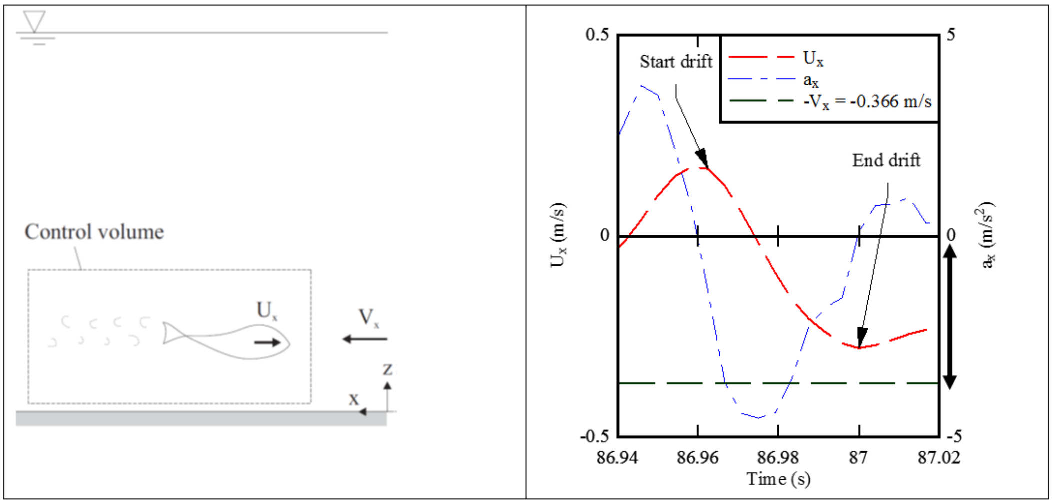


Figure 3. Drag force on a swimming fish (A, Left) Definition sketch of drag force acting on swimming fish. (B, Right) Time-variation of fish speed and acceleration during a drift event - Data from Wang et al. (2016a), Duboulay's rainbowfish No. 22 (m_f = 3.6 g, L_f = 72 mm) swimming along a rough sidewall, fluid flow conditions: V_x = +0.366 m/s, v_x' = 0.315 m/s, θ = 0 - The double-edged arrow shows the relative fish speed $U_x + V_x$.

The energy spent by the moving fish during a time (T) is:

$$E = \int_{t=0}^{T} P \times dt \qquad [11a]$$

$$E = \int_{t=0}^{T} \left(m_f \times \frac{\partial U}{\partial t} + C_d \times \rho_w \times (U_x + V_x)^2 \times A_f + m_f \times g \times \sin\theta \right) \times (U_f + V_x) \times dt \qquad [11b]$$

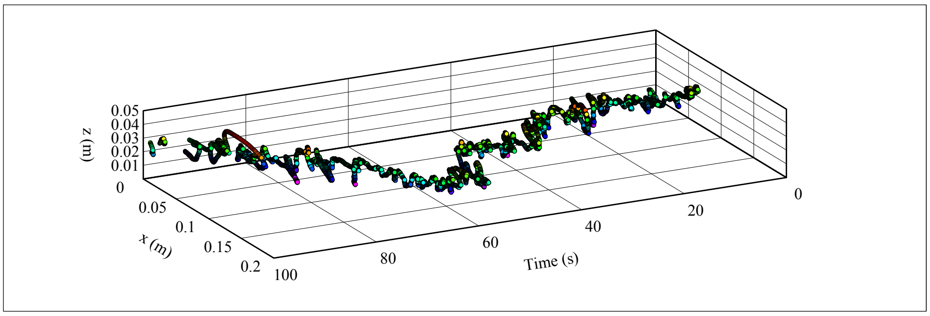
where t is the time. If T is the time of transit in a culvert structure, Equation [11] provides some estimates of the energy spent by the fish to navigate the culvert, albeit it does not take into account the heat transfer nor any fish metabolism.

4.2 Energetic considerations

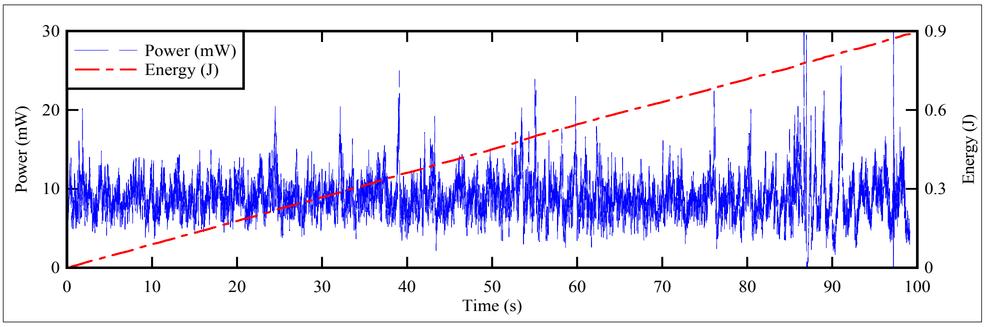
The present results provide a deterministic means to quantify the power and energy expended by the moving fish, to counterbalance the drag, inertia and gravity forces (Equations [10] & [11)). Recently, fish kinematic data were recorded with fine spatial and temporal resolution in a 12 m long and 0.5 m wide open channel (Wang et al., 2016a). Figure 4A shows a typical fish trajectory data, with the fish mass and length, and flow conditions listed in the figure caption. The fish swam against the current (*i.e.,* upstream), next to the corner of the channel, exhibiting some carangiform locomotion. For the entire 100 s time series, the fish progressed upstream by 99 mm. Visual recordings, fish trajectory data and fish speed time series showed that the time-series could be sub-divided into some quasi-stationary motion where fish speed fluctuations were small and short upstream burst facilitated by a few strong tail-beats. The instantaneous power and energy spent by the moving fish were calculated using Equations [10] and [11] (Figure 4B). For the same fish and trajectory data shown in Figure 4A, results are presented in Figure 4B. On average, the mean rate of work by the fish was 9.0 mW, with a standard deviation of 2.9 mW, while the first, second and third quartiles were 7.3 mW, 8.7 mW and 10.3 mW, respectively, and the maximum power spent by the fish reached 161 mW. The power distribution was skewed with a preponderance of small power values relative to the mean. Forthe entire trajectory, the energy spent by the moving fish was 0.89 J.

The results may be extrapolated to a 10 m long box culvert barrel, a structure similar to the standard culvert seen in Figure 1A. During the upstream fish migration, assuming that the fish swimming behaviour was identical to the trajectory data shown in Figure 4A, the energy spent by the moving fish would be 89.9 J for a 10 m long horizontal culvert barrel. Assuming that the fish swimming capability and flow conditions are un-affected by the channel slope, Equations [10] and [11] may be applied to test the effects of bed slope (θ) on the same fish individual. For a same 10 m long culvert, the energy spent by the moving fish would be 202 J and 1210 J for a bed slope of θ = 0.05° and θ = 0.5°, respectively. The former slope would be typical of a mild slope flood plain, while the latter would correspond to a steep flood plain. Within the present assumptions, the findings suggest that the channel slope may affect significantly the instantaneous power and energy spent by the fish to provide thrust during upstream culvert passage.

More generally, the bed slope has a drastic impact on the optimum design of fish-friendly culverts. With very flat bed slopes, the energy spent by the moving fish to migrate along the culvert is drastically smaller, hence facilitating upstream fish migration, but the head loss available is very small. The latter implies that any baffle system may drastically reduce the discharge capacity for a given afflux, this increasing substantially the cost of the culvert structure. On another hand, a steep bed slope may provide a greater head loss available, allowing for a wider range of baffle systems without adverse reduction in discharge capacity, albeit with a greater power spent by the moving fish. The latter might be particularly detrimental to weak-swimming fish species.



(A)



(B)

Figure 4. Time-variations of power expended during fish swimming and energy spent by the moving fish - Data from Wang et al. (2016a), Duboulay's rainbowfish No. 22 (m_f = 3.6 g, L_f = 72 mm) swimming along a rough sidewall in an 0.5 m wide open channel, fluid flow conditions: V_x = +0.366 m/s, v_x' = 0.315 m/s, θ = 0.(A) Fish trajectory next to the left rough sidewall (B) Instantaneous power P and energy E spent by the moving fish during the trajectory shown in Figure 4A.

5 CONCLUSIONS

Standard box culverts may constitute barriers to the upstream passage of weal swimming fish, with adverse impact on the upstream and downstream catchment bio-diversity. It is believed that fish-turbulence interplay may facilitate upstream migration, albeit an optimum design must be based upon a careful characterisation of both hydrodynamics and fish kinematics. Basic dimensional considerations highlight a number of key parameters relevant to the upstream fish passage, including the ratio of fish speed fluctuations to fluid velocity fluctuations, the ratio of fish response time to turbulent time scales, the ratios of fish dimension to turbulent length scale, and the fish species. The latter may be possibly a most important variable, since design guidelines developed for one species might be inadequate for another species.

The application of the equation of conservation of momentum provides a deterministic method to quantify the fish thrust and instantaneous power expended during fish swimming. Using kinematic data recorded with fine spatial and temporal resolution, the associated energy consumption may be estimated and the effects of bed slope be tested. Within basic assumptions, the present findings suggest that the bed slope may have a drastic impact on the optimum design of fish-friendly culverts, since the invert slope affects both the energy spent by the fish to provide thrust during upstream culvert passage and the total head loss available.

The present study paves the way for an improved knowledge of fish-turbulence interplay relevant to upstream fish passage in culverts. This is significant given the recent efforts to design cost-effective standard box culverts with enhanced fish passage capability.

ACKNOWLEDGEMENTS

The authors thank their students Ramith Fernando, Rui Shi, Amelia Tatham, Joseph Dowling, Urvisha Kiri, Caitlyn Johnson and Laura Beckingham (UQ). They further thank Professor Craig Franklin, Dr Matthew Gordos and Dr Pippa Kern for helpful discussions and inputs. The financial support through the Australian Research Council (Grant LP140100225) is acknowledged.

REFERENCES

Alexander, R.M. (1982). *Locomotion of Animals*. Tertiary Level Biology. Chapman and Hall, USA.

Australian Standard (2010). *Precast Reinforced Concrete Box Culverts. Part 1: Small Culverts (Not Exceeding 1200 Mm Span and 1200 Mm Height)*, Standards Australia AS 1597.1-2010, 2nd edition, 245 pages.

Bates, K. (2000). *Fishway Guidelines for Washington State*. Washington Department of Fish and Wildlife, 57.

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

Blake, R.W. (1983). *Fish Locomotion*. Cambridge University Press, UK.

Breton, F., Baki, A.B.M., Link, O. Zhu, D.Z. & Rajaratnam, N. (2013). Flow in Nature-Like Fishway and its Relation To Fish Behaviour. *Canadian Journal of Civil Engineering*, 40(6), 567–573.

Brigg, A.S. & Galarowicz, T.L. (2013). Fish Passage through Culverts in Central Michigan Warmwater Streams. *North American Journal of Fisheries Management*, 33(3), 652-664.

Chanson, H. (1999). *Physical Modelling of Hydraulics. In the Hydraulics of Open Channel Flow: An Introduction*. Butterworth-Heinemann, 1st edition, London, UK, Chapter 14, 261-283.

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

Chanson, H. & Uys, W. (2016). Baffle Designs to Facilitate Fish Passage in Box Culverts: A Preliminary Study. *Proceedings of 6th IAHR International Symposium on Hydraulic Structures*, *Hydraulic Structures and Water System Management*, Portland OR, USA, 295-304, 312-321.

Chen, S.Y., Fei, Y.H.J., Chen, Y.C., Chi, K.J. & Yang, J.T. (2016). The Swimming Patterns and Energy-Saving Mechanism Revealed from Three Fish in a School. *Ocean Engineering*, 122, 22-31.

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

Darrozes, S.S. & Monavon, A. (2014). *Analyse Phénoménologique des Ecoulements. Comment traiter un Problème de Mécanique des Fluides avant de résoudre les Equations*. Presses Polytechniques et Universitaires Romandes, Lausanne, Switzerland, 480 pages (In French).

Duguay, J. & Lacey, R.W.J. (2014). Effect of Fish Baffles on the Hydraulic Roughness of Slip-Lined Culverts. *Journal of Hydraulic Engineering*, ASCE, 141(1), 1-10

Fairfull, S. & Witheridge, G. (2003*). Why do Fish Need to Cross the Road? Fish passage requirements for waterway crossings*, NSW Fisheries, Cronulla NSW, Australia, 1-14.

Forty, M., Spees, J. & Lucas, M.C. (2016). Not Just for Adults! Evaluating the Performance of Multiple Fish Passage Designs at Low-Head Barriers for the Upstream Movement of Juvenile and Adult Trout Salmo Trutta. *Ecological Engineering*, 94, 214-224.

Foss, J.F., Panton, R. & Yarin, A. (2007). *Nondimensional Representation of the Boundary-Value Problem. in Springer Handbook of Experimental Fluid Mechanics*, Springer, Editors C. TROPEA, A.L. YARIN and J.F. Foss, Part A, Chapter 2, 33-82.

Goettel, M.T., Atkinson, J.F. & Bennett, S.J. (2015). Behavior of Western Blacknose Dace in a Turbulence Modified Flow Field. *Ecological Engineering*, 74, 230-240.

Hee, M. (1969). Hydraulics of Culvert Design Including Constant Energy Concept. *Proceeding 20th Conference of Local Authority Engineers*, Dept. of Local Government, Queensland, Australia, 9, 1-27.

Henderson, F.M. (1966). *Open Channel Flow*. MacMillan Company, New York, USA.

Hotchkiss, R. (2002). *Turbulence Investigation and Reproduction for Assisting Downstream Migrating Juvenile Salmonids*, Part I. *BPA* Report DOE/BP-00004633-I, Bonneville Power administration, Portland OR, 138.

Hunt, M., Clark, S. & Tkach, R. (2012). Velocity Distributions near the Inlet of Corrugated Steep Pipe Culverts. *Canadian Journal of Civil Engineering*, 39(12), 1243-1251.

Keele, K.D. (1983). *Leonardo Da Vinci's Elements of the Science of Man*. Academic Press, USA, 1-400.

Larinier, M. (2002). Fish Passage through Culverts, Rock Weirs and Estuarine Obstructions. *Bulletin Français de Pêche et Pisciculture*, 364 (18), 119-134.

Lauder, G.V. (2015). Fish Locomotion: Recent Advances and New Directions. *Annual Review of Marine Science*, 7, 521-545.

Liao, J.C. (2007). A review of Fish Swimming Mechanics and Behaviour in Altered Flows. *Philosophical Transactions of the Royal Society B*, 362(1487), 1973-1993.

Liggett, J.A. (1994). *Fluid Mechanics*. McGraw-Hill, New York, USA.
Lighthill, M.J. (1960). Note on the Swimming of Slender Fish. *Journal of Fluid Mechanics*, 9(2), 305-317.
Lighthill, M.J. (1969). Hydromechanics of Aquatic Animal Propulsion. *Annual Review of Fluid Mechanics*, 1(1), 413-446.
Liu, M.M., Rajaratnam, N. & Zhu, D.Z. (2006). Mean Flow and Turbulence Structure in Vertical Slot Fishways. *Journal of Hydraulic Engineering*, ASCE, 139(4), 424-432.
Lupandin, A.I. (2005). Effect of Flow Turbulence on Swimming Speed of Fish. *Biology Bulletin*, 32(5), 461-466.
Nikora, V.I., Aberle, J., Biggs, B.J.F., Jowett, I.G. & Sykes, J.R.E. (2003). Effects of Fish Size, Time-to-Fatigue and Turbulence on Swimming Performance: a Case Study of Galaxias Maculatus. *Journal of Fish Biology*, 63(6), 1365-1382.
Novak, P. & Cabelka, J. (1981). *Models in Hydraulic Engineering. Physical Principles and Design Applications*. Pitman Publication, London, UK, 459 pages.
Novak, P., Guinot, V., Jeffrey, A. &Reeve, D.E. (2010). *Hydraulic Modelling - an Introduction*. CRC Press, Taylor & Francis, London, UK, 599 pages.
Olsen, A. & Tullis, B. (2013). Laboratory Study of Fish Passage and Discharge Capacity in Slip-Lined, Baffled Culverts. *Journal of Hydraulic Engineering*, ASCE, 139(4), 424-432.
Papanicolaou, A.N. & Talebbeydokhti, N. (2002). Discussion of Turbulent Open-Channel Flow in Circular Corrugated Culverts. *Journal of Hydraulic Engineering*, ASCE, 128(5), 548–549.
Pavlov, D.S., Lupandin, I.A. & Skorobogatov, M.A. (2000). The Effects of Flow Turbulence on the Behavior and Distribution of Fish. *Journal of Ichthyol*, 40, S232-S261.
Plew, D.R., Nikora, V.I., Larne, S.T., Sykes, J.R.E. & Cooper, G.G. (2007). Fish Swimming Speed Variability at Constant Flow: *Galaxias maculatus*. *New Zealand Journal of Marine and Freshwater Research*, 41(2), 185-195
Plew, D.R., Klebert, P., Rosten, T.W., Aspaas, S. & Birkevold, J. (2015). Changes to Flow and Turbulence Caused by Different Concentrations of Fish in a Circular Tank. *Journal of Hydraulic Research*, IAHR, 53 (3), 364-383.
Rodgers, E.M., Cramp, R.L., Gordos, M., Weier, A., Fairfall, S., Riches, M. & Franklin, C.E. (2014). Facilitating Upstream Passage of Small-Bodied Fishes: Linking the Thermal Dependence of Swimming Ability to Culvert Design. *Marine and Freshwater Research*, 65(8), 710-719.
Schultz, W.W. & Webb, P.W. (2002). Power Requirements of Swimming: Do New Methods Resolve Old Questions? *Integrative and Comparative Biology*, 42(5), 1018-1025.
Simon, B. & Chanson, H. (2013). *Turbulence Measurements in Tidal Bore-like Positive Surges over a Rough Bed,* Hydraulic Model Report No. CH90/12, School of Civil Engineering, The University of Queensland, Brisbane, Australia, 176 pp.
USBR (1987). *Design of Small Dams*. Bureau of Reclamation, US Department of the Interior, Denver CO, USA, 3rd edition.
Wang, H., Chanson, H., Kern, P. & Franklin, C. (2016a). Culvert Hydrodynamics to enhance Upstream Fish Passage: Fish Response to Turbulence. *Proceedings of 20th Australasian Fluid Mechanics Conference*, Australasian Fluid Mechanics Society, G. Ivey, T. Zhou, N. Jones, S. Draper Editors, Perth WA, Australia, Paper 682, 4 pages.
Wang, H., Beckingham, L.K., Johnson, C.Z., Kiri, U.R. & Chanson, H. (2016b). *Interactions between Large Boundary Roughness and High Inflow Turbulence in Open channel: a Physical Study into Turbulence Properties to Enhance Upstream Fish Migration*, Hydraulic Model Report No. CH103/16, School of Civil Engineering, The University of Queensland, Brisbane, Australia, 74 pp.
Wang, R.W., David, L. & Larinier, M. (2010). Contribution of Experimental Fluid Mechanics to the Design of Vertical Slot Fish Passes. *Knowledge and Managementof Aquatic Ecosystems*, 396(02), 21.
Webb, P.W. & Cotel, A.J. (2011). *Stability and Turbulence*. in Encyclopedia of Fish Physiology: from Genome to Environment, Academic Press, Dan Diego, USA, 1-3, 581-586.
Yasuda, Y. (2011). *Guideline of Fishway for Engineers*, Corona Publishing, NPO Society for Fishway in Hokkaido, Japan, 154 pages (In Japanese).