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Developing Cost-Effective Design Guidelines for Fish-Friendly Box Culverts, with a Focus on Small Fish

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Abstract

Low-level river crossings can have negative impacts on freshwater ecosystems, including blocking upstream fish passage. In order to restore upstream fish passage in culverts, we developed physically-based design methods to yield cost-effective culvert structures in order to maintain or restore waterway connectivity for a range of small-bodied fish species. New guidelines are proposed for fish-friendly multi-cell box culvert designs based upon two basic concepts: (1) the culvert design is optimised for fish passage for small to medium water discharges, and for flood capacity for larger discharges, and (2) low-velocity zones in the culvert barrel are defined in terms of a percentage of the wetted flow area where the local longitudinal velocity component is less than a characteristic fish speed linked to swimming performances of targeted fish species. This approach is novel and relies upon an accurate physically-based knowledge of the entire velocity field in the barrel, specifically the longitudinal velocity map, because fish tend to target low-velocity zone (LVZ) boundaries. The influence of the relative discharge threshold Q_1/Q_{des}, characteristic fish swimming speed U_{fish}, and percentage of flow area on the size of box culvert structures was assessed. The results showed that the increase in culvert size and cost might become significant for a smooth culvert barrel with $U_{fish} < 0.3$ m/s and $Q_1/Q_{des} > 0.3$, when providing 15% flow area with $0 < V_x < U_{fish}$. Similar trends were seen for culvert barrel with recessed cell(s).

Keywords Box culverts · Upstream fish passage · Design guidelines · Low velocity zones

Introduction

Low-level river crossings, i.e. culverts and causeways, are important for delivering a range of valuable socio-economic services, including transportation and flood control. However, such structures are also known to have negative impacts on freshwater river system morphology and ecology, including the blockage of upstream fish passage (Warren and Pardew 1998; Anderson et al. 2012). The manner in which waterway crossings block migrating fish include perched outlets and excessive vertical drops at the culvert exit, high velocity and insufficient water depth in the culvert barrel, debris accumulation at the culvert inlet, and standing waves in the outlet or inlet (Behlke et al. 1991; Olsen and Tullis 2013). In particular for smaller, weaker-swimming fish, the upstream traversability of the culvert barrel can be a major obstacle, particularly at high water velocities. In order to restore upstream fish passage in culverts over the widest extent possible, the aim of this work is to use physically-based design methods to yield cost-effective culvert structures in order to maintain and restore waterway connectivity for a range of small-bodied fish species.

Freshwater fish species constitute about one quarter of all living vertebrates, and are considered an at-risk group due to deleterious habitat impacts. In Australia, for example, there are about 250 freshwater fish species, with ~30% listed as threatened under State and Commonwealth legislation (Allen et al. 2002; Lintermans 2013). The negative effects of river crossings on freshwater fish species are well documented in the literature (Warren and Pardew 1998; Briggs and Galarowicz 2013). Culvert structures often

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create physical or hydrodynamic barriers that prevent or reduce access to essential breeding or feeding habitats. The direct consequences of losing access too and fragmentation of river habitats on fish encompass reduced recruitment, restricted range size, and changes in fish population composition, all of which being potentially exacerbated by long-term climate changes (Dynesius and Nilsson 1994; O'Hanley 2011; Wilkes et al. 2018). Apart from impeding fish passage, road crossing barriers can act in other disruptive ways. Examples include: suspended and bed load sediment transport, river substrate composition and morphology changes, and nutrients and large woody debris supply (Hotchkiss and Frei 2007). The resulting environmental changes can extend across river reaches in both the downstream and upstream directions, creating conditions potentially favourable to the establishment and development of non-native invasive species (Olson and Roy 2002; Milt et al. 2018). The end result can often be a reorganisation of the riverine biophysical structure, most often associated with a reduction in the numbers and diversity of native fish species (O'Hanley 2011).

Given the enormous environmental problems created by road crossings, it is not surprising that various culvert design guidelines (e.g. Fairfull and Witheridge 2003; Hunt et al. 2012) have been developed to facilitate upstream fish passage in culverts (refer to Table 1), albeit not always successfully. Recent field and laboratory work has yielded markedly different recommendations (Table 2). Relatively little work has been published regarding the development of systematic design methods for cost-efficient fish-friendly culverts, to deliver un-impeded fish connectivity over wide geographic areas. In most cases, design methods have focused predominantly on baffle installation and boundary roughening along the culvert barrel invert to slow down the water velocity, although the additional flow resistance can reduce drastically the culvert discharge capacity for a given afflux. The afflux is the increase in upstream water level caused by the presence of the culvert, typically derived from design charts or hydraulic modelling (Herr and Bossy 1965; Chanson (1999, 2004)). Such a reduction in culvert capacity markedly increases the total cost of the culvert for a design discharge and afflux, as demonstrated by Larinier (2002) and Olsen and Tullis (2013). In only a few cases have more robust engineering-based methods been examined. This includes works by Papanicolaou and Talebbeydokhti (2002); Hotchkiss and Frei (2007), and Olsen and Tullis (2013).

In this article, a hydraulic engineering approach is used to rationally devise fish-friendly standard box culverts, which are the preferred culvert design for effective fish passage relative to pipe culverts (Briggs and Galarowicz 2013). Structurally, this new design method is most closely related to aero- and hydrodynamic studies, in that it does

Table 1 Design guidelines for freshwater fish passage in standard culverts

Reference	Country and region	Targeted fish species	Design criteria	Flow conditions
Fairfull and Witheridge (2003)	Australia		Depth > 0.2–0.3 m V_{mean} < 0.3 m/s for d < 0. 5 m	Smooth culvert
Bates et al. (2003)	USA, Washington	Trout, pink salmon, chum salmon, chinook, coho, sockeye, steelhead	Depth > 0.24 to 0.30 m V_{mean} < 0.61 to 1.83 m/s	Smooth culvert
Cahoon et al. (2007)	USA, Montana	Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*), rainbow trout (*Oncorhynchus mykiss*)	V_{mean} < 1.9–2.7 m/s	Box culvert geometry
Kilgore et al. (2010); Schall et al. (2012)	USA		Minimum water depth for $Q > Q_{min}$ Maximum bulk velocity for $Q < Q_{high}$	$Q_{min} < Q_{high} < Q_{des}$
Courret (2014)	France	Trout, European bullhead (*Cottus gobio*), brook lamprey (*Lampetra planeri*), spined loach (*Cobitis taenia*), common minnow (*Phoxinus phoxinus*), eel, crayfish	Baffles, macro-roughness	From drought to 2–3 times the mean annual discharge
DWA (2014)	Germany	European species incl. barbel, brown trout, eel, grayling, salmon,…	$V_{mean} < U_{fish}$ Depth > 2.5 × Fish height Baffles/crossbars, macro-roughness	$Q_{330} < Q < Q_{30}$ each year

Q water discharge, Q_{30} flow rate occurring no more than 30 days per year, Q_{330} flow rate occurring no more than 330 days per year, *q* unit discharge, S_o bed slope, V_{mean} bulk velocity, *z* vertical elevation above the invert

Table 2 Observations and derived recommendations for freshwater fish passage in standard culverts

Reference	Country and region	Targeted fish species	Design criteria	Flow conditions	Type of study
Chorda et al. (1995)	France		Baffles	$S_o = 0.01$ to 0.05	Laboratory work.
Gardner (2006)	USA, North Carolina	Bluehead chub (*Nocomis leptocephalus*), redbreast Sunfish (*Lepomis auritus*), Johnny Darter (*Etheostoma nigrum*), bluegill (*Lepomis macrochirus*), margined madtom (*Noturus insignis*), swallowtail shiner (*Notropisprocne*)	$V_{mean} < 0.55$ m/s	Smooth culvert	Laboratory work. Box culvert geometry.
Blank (2008)	USA, Montana	Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*)	$V_x(z = 0.06\ m) < 1$ to 2 m/s $q < 0.4$ to 0.57 m^2/s	Base flow: 0.28 m^3/s $S_o = 0.02$ to 0.05	Field observations. Box culvert geometry.
Monk and Hotchkiss (2012)	USA, Utah	Leatherside chub (*Lepidomeda aliciae*), speckled dace (*Rhinichthys osculus*)	$V_x(z = 0.02\ m) < U_{fish}$	L_{barrel} ~ 20 m $0.5 < Q < 1.6\ m^3/s$ $0.073 < q < 0.24\ m^2/s$	Field observations. Box culvert geometry.

d water depth, L_{barrel} barrel length, *Q* water discharge, S_o bed slope, V_{mean} bulk velocity, V_x local longitudinal velocity, *z* vertical elevation above the invert

not assume a simplistic one-dimensional flow motion. Rather, culvert barrel flows are considered as a complex three-dimensional flow, in which turbulence is generated by both bed and sidewall boundary friction. The main focus is on improving upstream fish passage in the box culvert barrel to restore connectivity within the riverine system as a whole. The proposed method is more general in comparison to previous approaches. The benefits of this are two-fold. First, the design method is especially well suited to meet the life-cycle requirements of small-bodied native fish species, which regularly change habitats and migrate for recruitment and habitat viability requirements in different parts of a river system. Second, in an effort to keep the design process as simple as possible, and keep cost to a minimal, the design method presented in this article can be applied in a straight-forward manner to any watershed. The methods and results below are largely based on Chanson and Leng (2018).

Current Practices in Hydraulic Engineering Design of Culverts

The primary constraints in the design of a culvert (Fig. 1) are minimising: (a) costs, and (b) afflux. The design procedure is traditionally divided into two parts. First the design rainfall and runoff event is selected based upon the culvert purposes, design data, and site constraints; thereby yielding an estimate of the design discharge Q_{des}. A maximum acceptable afflux h_{max}, at design flow conditions, is then set by the asset owner based upon an impact assessment of the culvert structure on the upstream catchment and embankment. Second the culvert barrel size is selected by an iterative procedure and the optimum size is the smallest barrel size allowing for inlet control operation (Herr and Bossy 1965; Hee 1969; Chanson 2000, 2004). The resulting optimum design is to operate as an open channel system at the design discharge, with critical flow conditions typically occurring in the barrel in order to maximise the discharge per unit width and to reduce the barrel cross-section area. Altogether, the hydraulic design is basically an optimum compromise between discharge capacity, afflux, and construction costs.

Current hydraulic engineering design guidelines of box culverts do not encompass less-than-design flow conditions ($Q < Q_{des}$). Yet fish passage can occur as soon as the water discharge is non-zero: $Q > 0$. As such, new design guidelines for fish-friendly box culverts are critically needed. A further challenge for the design of fish-friendly culverts is matching swimming performance data to hydrodynamic measurements. Many swim tests lack standardised 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 (Katopodis and Gervais 2016).

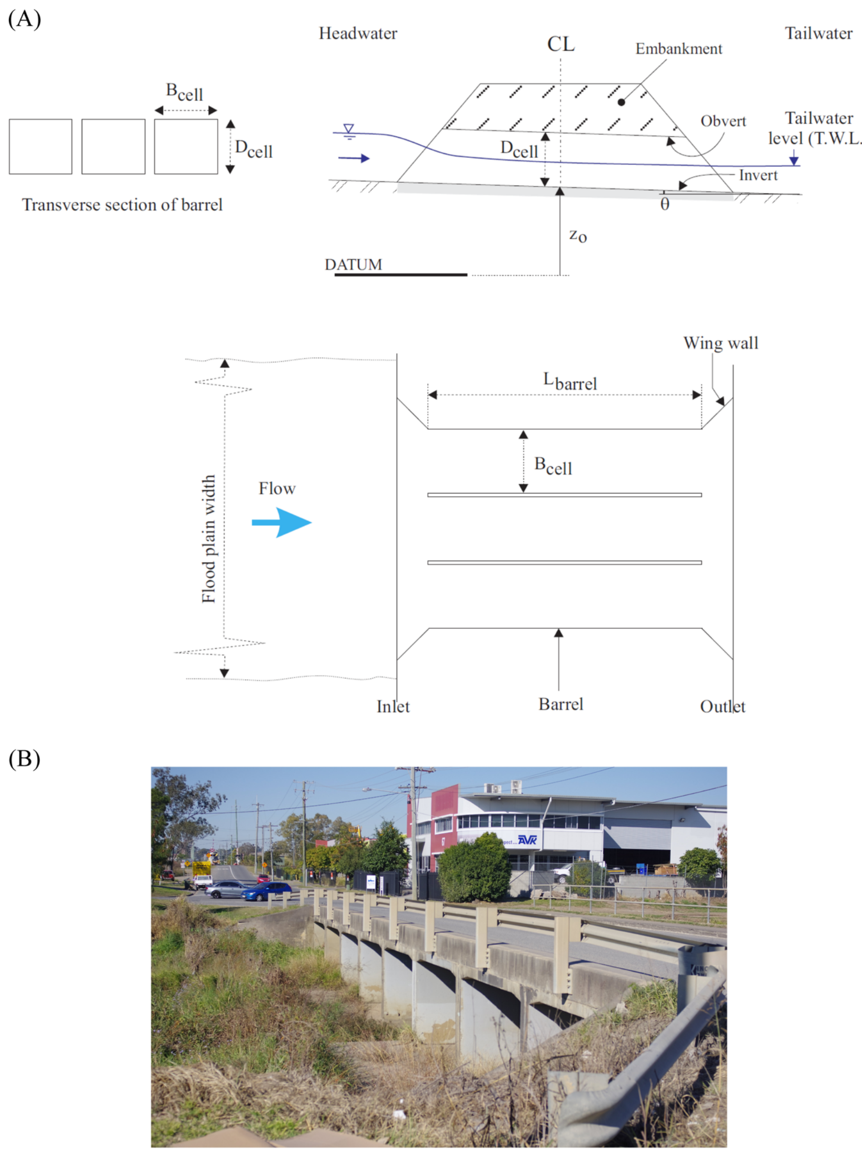

Fig. 1 Standard box culvert structure. **a** Definition sketch of a multi-cell box culvert with invert placed on natural ground level. **b** Multi-cell box culvert structure on Stable Swamp Creek, Salisbury QLD (Australia)

Materials and Methods

Novel engineering design guidelines are considered, based upon two basic concepts:

(a) The culvert design is optimised for fish passage for water discharges $Q < Q_1$; and it is optimised in terms of flood capacity for $Q_1 < Q < Q_{des}$, with Q_1 an upper threshold discharge for less-than-design flow with $Q_1 < Q_{des}$.

(b) Since small-bodied fish predominantly swim next to the channel corners and sidewalls (Gardner 2006; Blank 2008; Jensen 2014), in particular small-bodied Australian native fish species (Wang et al. 2016a; Cabonce et al. 2017, 2019, 2018; Goodrich et al. 2018), the swimming performance data are related to a fraction (i.e. percentage) of the wetted flow area where:

$$0 < V_s < U_{fish} \tag{1}$$

with V_x the local time-averaged longitudinal velocity component and U_{fish} a characteristic swimming speed of targeted fish species, set by a regulatory agency or based upon biological observations and endurance swimming test data.

A novel approach is the provision of a minimum relative flow area where the longitudinal water velocity is less than a characteristic fish swimming speed Eq. (1). The proposed design method aims to be sound, simple, economically acceptable, and meet engineering standards. Three practical questions are tested herein with respect to influencing the

Table 3 Characteristics of multi-cell box culvert structures

	Culvert 1	Culvert 1b	Culvert 2
Hydrology	Gara river NSW	Gara river NSW	
Tailwater conditions	Gauge data	Gauge data	Uniform equilibrium flow
S_o	0	0	0.0012
Design event	1-in-1 year event (2008–2018)	1-in-1 year event (2008–2018)	
Q_{des} (m^3/s)	20.0	–	4.8
Q_{des} (ML/day)	1728	–	415
q_{des} (m^2/s)	2.20	1.92	0.78
$(d_{tw})_{des}$ (m)	0.976	0.976	0.457
L_{barrel} (m)	8	8	14
D_{cell} (m)	1.0	1.3	0.5
B_{cell} (m)	1.3	1.0	1.0
Boundary roughness	Smooth concrete	Smooth concrete	Smooth concrete
Barrel invert	Natural ground level	0.3 m below natural ground level	Natural ground level
Maximum acceptable afflux h_{max} (m)	0.55	0.55	0.20
Number of cells $(N_{cell})_{des}$	7[a]	1	7[a]
$(V_{mean})_{des}$ (m/s)	1.74	1.9	2.0

B_{cell} internal barrel cell width (Fig. 1a), D_{cell} internal barrel cell height, $(d_{tw})_{des}$ tailwater depth at design flow, L_{barrel} culvert barrel length, S_o bed slope, V_{mean} bulk velocity in the barrel

[a]Minimum cross-section area for inlet control operation at design flow conditions

size and cost of standard box culverts: (1) what is the effect of the relative threshold Q_1/Q_{des}, (2) what is the influence of the percentage of low-velocity area, and (3) what is the impact of the characteristic fish swimming speed U_{fish}?

A sensitivity analysis was conducted for two multi-cell box culvert structures, typical of two-lane roadway projects in eastern Australia (Table 3). Natural tailwater conditions were used: i.e. gauge data (Culvert 1, Fig. 2) and uniform equilibrium flow conditions (Culvert 2). The culvert barrel size was calculated to achieve the smallest barrel size with inlet control for the design flow rate Q_{des} and maximum acceptable afflux h_{max}, with the culvert barrel invert at natural ground level, in line with current hydraulic engineering design guidelines (Herr and Bossy 1965; Hee 1969; Chanson 2004). The basic design calculation output was the number of cells $(N_{cell})_{des}$, listed in Table 3.

For less-than-design flow conditions, hydraulic engineering calculations were based upon complete calculations and numerical modelling validated with detailed physical data. In addition and for Culvert 1, detailed three-dimensional computational fluid dynamics (3D CFD) calculations were undertaken. The focus of the latter calculations was to test a lower invert, allowing to retain a 0.3 m deep pool of water in the culvert barrel during dry to very low-flow conditions.

The hydraulic engineering calculations were undertaken for a range of less-than-design discharges: $0.1 < Q/Q_{des} < 0.5$. The tailwater conditions were subcritical and the culvert flow remained subcritical with outlet control. The targeted fish species were originally small-body Australian native species, including Empire Gudgeon, Firetail Gudgeon, Western Carp Gudgeon Striped Gudeon, Mountain Galaxias, Southern Pygmy Perch, Unspecked Hardyhead, Common Jollytail, Olive Perchlet, Fly-specked Hardyhead, Australian Smelt, Duboulay's Rainbowfish, as well as juvenile Australian Bass, Macquarie Perch, Murray Cod, River Blackfish, Golden Perch, Eel-tailed Catfish, Silver Perch and Spangled Perch. The fish swimming speed of the small-body Australian native fish is typically between 0.3 and 0.6 m/s (Hurst et al. 2007; Kapitzke 2010; Koehn and Crook 2013). Within the current study, we expanded the range of characteristic swimming speeds from 0.2 to 1 m/s to broaden the scope of the study. Fractions of flow area corresponding to low-velocity zones, i.e. fulfilling Eq. (1), were tested between 10 and 20%, in line with recent hydrodynamic data (Wang and Chanson 2018; Cabonce et al. 2019; Zhang and Chanson 2018).

The design optimisation is considered in relation to a discharge threshold Q_1, rather than flood event duration. The selection is consistent with current engineering practices since the discharge is a design parameter. Note that the selection of a very-low design discharge could result in a smaller, cheaper culvert structure, with potentially poor ecological outcomes in terms of biological considerations.

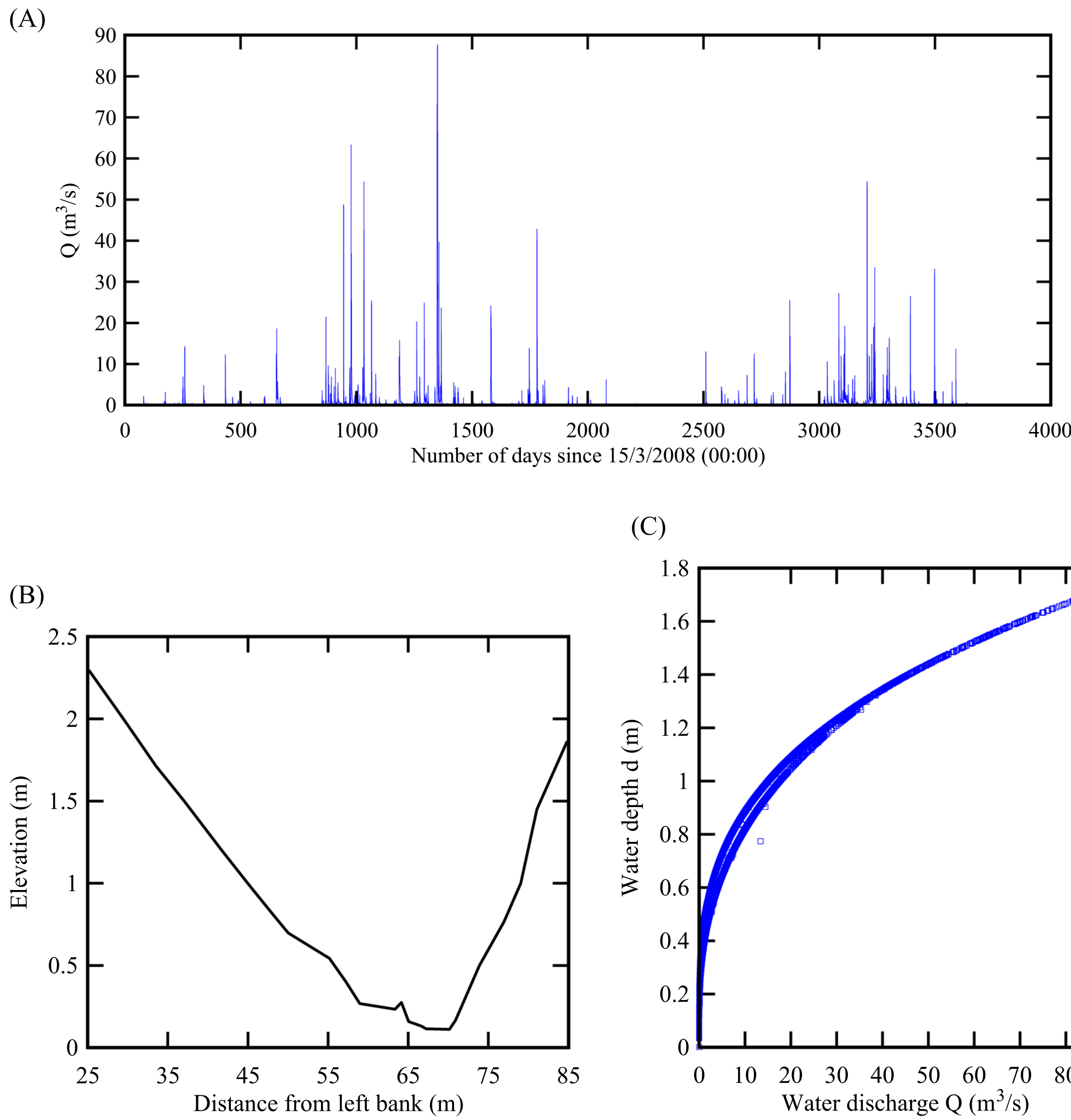

Fig. 2 Characteristics of the Gara River at Willow Glen north-eastern New South Wales (Data courtesy of NSW DPI Office of Water)—Catchment area: 121 km^2, site 20635. **a** Hydrograph of the Gara River from 15 March 2008 to 15 March 2018. **b** Channel cross-section on 4 Feb. 1997. **c** Relationship between water depth and discharge

The timing of fish passage must be considered as part of the determination of appropriate hydrology and hydraulic engineering design specifications for culvert structures (Hotchkiss and Frei 2007; Schall et al. 2012). Fish presence may vary between catchments, and fish migration timing might show great disparity with respect to stream flows and species. Fish movement in a catchment may be triggered by time of year, runoff events and a number or combination of environmental factors. In Australia, for example, flows are one of the main triggers for fish to initiate migrations, with increasing/high flows being a significant trigger response (Mallen-Cooper 1996; Allen et al. 2002).

Results

Basic Results

The hydrodynamic calculations resulted in the number of identical culvert barrel cells N_{cell} required to achieve a given low-velocity zone target, i.e. a percentage of flow area, where $0 < V_x < U_{fish}$ for a given less-than-design discharge Q, with $Q/Q_{des} < 1$. Typical results are reported in Figs 3 and 4, based the entire design process calculations. Figure 3 shows the increase in number of culvert barrel cells to achieve the low-velocity zone target, i.e. 15% of flow area

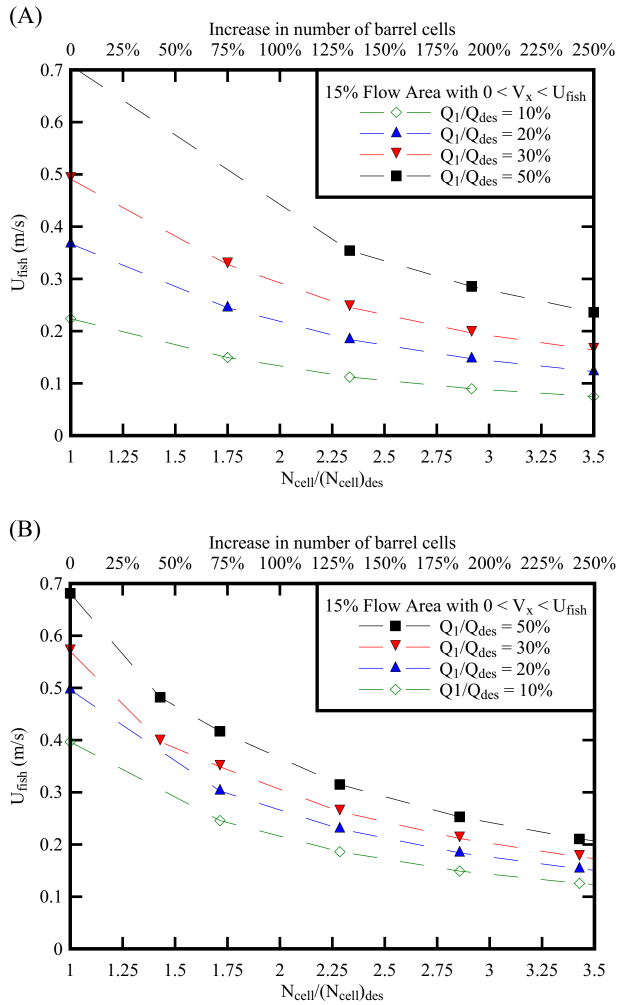

Fig. 3 Relative increase in number of cells $N_{cell}/(N_{cell})_{des}$ for fish-friendly multi-cell box culverts as a function of the threshold discharge Q_1/Q_{des} and characteristic fish swimming speed U_{fish}, with 15% of flow area where $0 < V_x < U_{fish}$, **a** Culvert 1, **b** Culvert 2

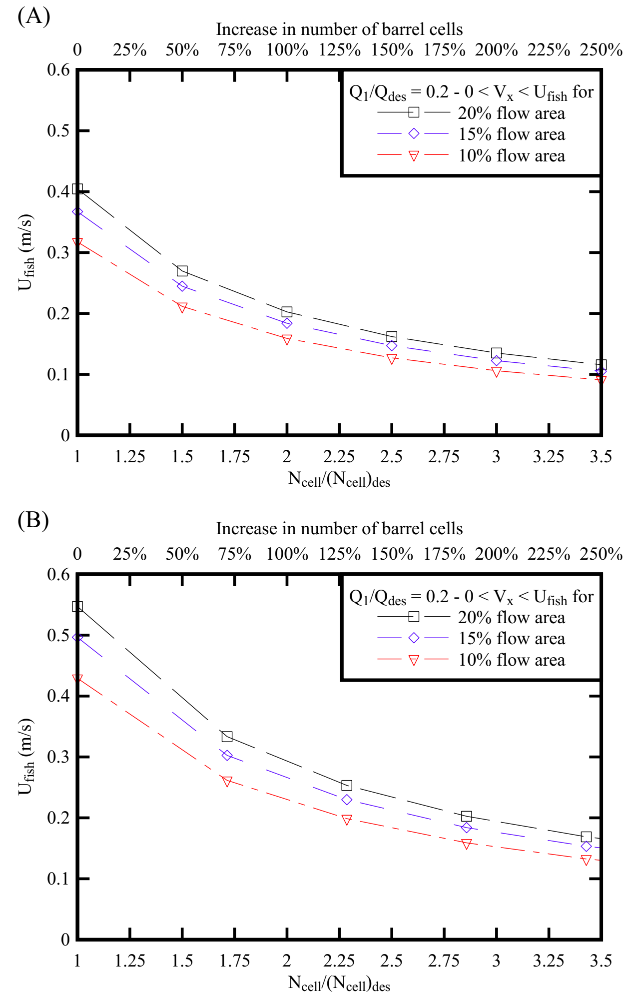

Fig. 4 Relative increase in number of cells $N_{cell}/(N_{cell})_{des}$ for fish-friendly multi-cell box culverts as a function of the percentage of LVZ flow areaa where $0 < V_x < U_{fish}$ and characteristic fish swimming speed U_{fish}, for a threshold discharge $Q_1/Q_{des} = 0.20$. **a** Culvert 1. **b** Culvert 2

where $0 < V_x < U_{fish}$, and Fig. 4 presents the increase in number of culvert barrel cells to achieve different low-velocity zone targets. For each graph, the vertical axis is the characteristic swimming speed U_{fish} of the targeted fish species and the lower horizontal axis is the dimensionless number of cells $N_{cell}/(N_{cell})_{des}$, where N_{cell} is the number of barrel cells for the fish-friendly culvert design and $(N_{cell})_{des}$ is the number of barrel cells for optimum flood capacity design (Table 3). The upper horizontal axis is the relative increase in number of barrel cells compared to the optimum flood capacity design. As a first approximation, the result would correspond to the increase in culvert construction costs to achieve fish passage, in the form of additional precast cell units, although, depending upon the site, the final design might require construction of a second structure or selection of a bridge structure instead of a culvert, all at a much greater cost. That is, the results deliver a lower-bound estimate of the increase in culvert construction costs, and would be, in many cases, an under-estimation.

Overall the results demonstrated conclusively that the cost of a fish-friendly box culvert increases with decreasing characteristic fish swimming speed U_{fish}, for a given discharge threshold Q_1/Q_{des} and relative size of low-velocity zone (%flow area). Similarly, the culvert cost increases with increasing discharge threshold, for a given characteristic fish swimming speed and relative size of low-velocity zone; and the cost increases with increasing relative size of low-velocity zone (%flow area) for a given characteristic fish swimming speed U_{fish}, and discharge threshold Q_1/Q_{des}. The result may be summarised as:

$$\text{Culvert Cost}\uparrow \equiv \begin{cases} U_{fish}\downarrow \\ Q_1/Q_{des}\uparrow \\ \%\text{flow area}\uparrow \end{cases} \tag{2}$$

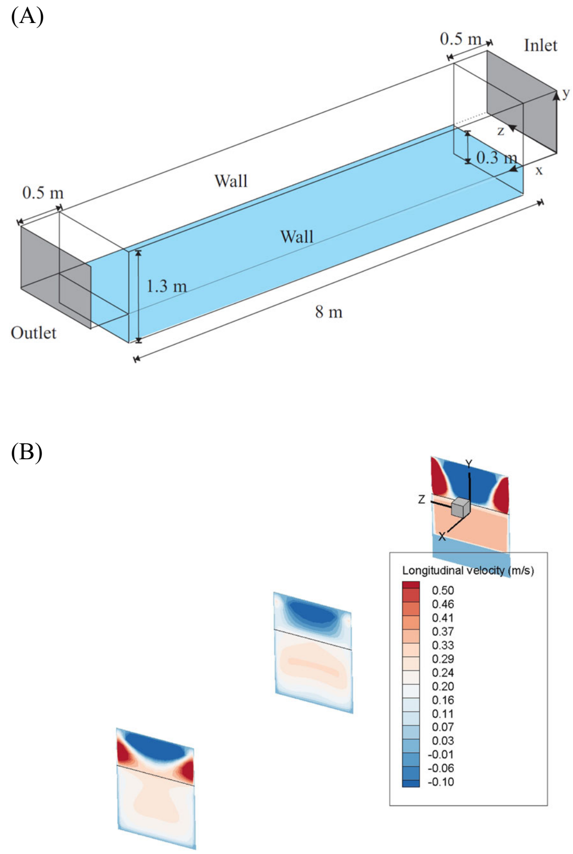

Fig. 5 Hydrodynamics of a culvert barrel with recessed invert - Barrel invert elevation 0.3 m below natural ground level. **a** Definition sketch of pooled (recessed) culvert barrel (Culvert 1b). **b** Longitudinal velocity contours in the culvert barrel (Culvert 1b) for $q/q_{des} = 10\%$—Black line indicate the free-surface—Flow direction from top right to bottom left, Barrel water depth: 0.83 m, $V_{mean} = 0.22$ m/s

The calculations showed a critical impact of the characteristic swimming speed U_{fish} of targeted fish species. Culvert cost-sensitivity increases markedly in order to pass small-bodied fish (<100 mm), and juveniles of large-bodied fish, at swimming speeds less than 0.3 m/s, within the range of investigated flow and boundary conditions. Conversely, a targeted fish speed $U_{fish} > 0.7$ m/s would be achievable for $Q < 0.5 \times Q_{des}$, but biological implications are that most small-bodied fish would be blocked at these high water velocities. We determined that a key design parameter is the discharge threshold Q_1/Q_{des}. The provision of fish passage capability for $Q > 0.5 \times Q_{des}$ would be cost prohibitive for small-bodied fish. The selection of $10\% < Q_1/Q_{des} < 30\%$ is achievable with more moderate increases in culvert number (Fig. 3), while the selection of $Q_1/Q_{des} < 10\%$ does not increase much the culvert number above that required for Q_{des} flows for $U_{fish} > 0.2$ m/s.

The relative size of the low-velocity zone also impacts on the structure costs. Based upon detailed physical modelling for flow boundary conditions with which fish endurance was tested (Wang et al. 2016b; Cabonce et al. 2019), 15% of flow area with $0 < V_x < U_{fish}$ may be an appropriate target (Fig. 4). An important criteria in selecting the low-velocity zone is determining its width/depth to ensure that the zone can easily encompass the size of the target fish species.

Recessed Culvert Barrel Results

Detailed CFD calculations were conducted for a culvert barrel invert installed 0.3 m below the natural ground level (Fig. 5a). The recessed culvert barrel invert configuration was selected based upon current NSW guideline recommendations that require a minimum of 0.3 m to pool through the culverts at initiate-to-flow to ensure adequate depth for fish to swim through the culverts (DPI-Fisheries 2013). First, the results showed a significantly more complicated flow field, compared to a culvert barrel invert at natural ground level (Fig. 5b). For such flow conditions, 22% of the pooled culvert flow area experienced a longitudinal velocity V_x such that $0 < V_x < 0.3$ m/s. Second, the calculations demonstrated the same trends as for a culvert barrel invert at natural ground level, i.e. Eq. (2). Namely, the cost of fish-friendly box culvert increases with decreasing characteristic fish swimming speed U_{fish}, increasing discharge threshold Q_1/Q_{des}, and increasing percentage of low-flow area.

In summary, the design of a culvert with a recessed "wet" cell, also called a low-flow channel, may provide an alternative for low-velocity zones with minimum water depth. However, this option requires more advanced fluid dynamic calculations and likely is more expensive to build compared with standard box culverts with barrel inverts set at natural ground level.

Discussion

Application

The present design approach builds up as a development of current hydraulic engineering design methods (Concrete Pipe Association of Australasia 1991, 2012; Chanson 1999; QUDM 2013). First the minimum number of cells $(N_{cell})_{des}$ is calculated to achieve inlet control at design flow conditions, based upon current standards for optimum flood capacity design at the culvert site. Considerations for upstream fish passage are next embedded into the design methodology, using biological considerations. For the selected discharge threshold Q_1, characteristic swimming speed of targeted fish species U_{fish}, and percentage of low-velocity area, the total number of culvert barrel cells N_{cell} required to fulfil Eq. (1) for $Q < Q_1$ is calculated. When $N_{cell} < (N_{cell})_{des}$, the initial design would be capable to provide upstream fish passage at less-than-design flows ($Q < Q_1$). In the negative, i.e. $N_{cell} > (N_{cell})_{des}$, the revised design must include a larger number of barrel cells. In this case, the afflux for the design discharge would be smaller than the maximum acceptable afflux, and the reduction in upstream flooding might contribute to a lesser total cost of the structure: e.g. with a lower embankment and reduced impact on upstream catchment. The savings might contribute to offset partially the increased cost caused by the larger number of culvert barrel cells.

A detailed design application is presented in the digital appendix (i.e. supplementary material). For both culverts 1 and 2, the step-by-step iterative design procedure is developed for a fish-friendly standard box culvert. Depending upon the characteristic swimming speed of the targeted fish species and guild, the current hydraulic engineering design guidelines of box culverts may or not provide an adequate number of barrel cells to achieve upstream fish passage at 10% of the design discharge.

More generally, the calculated results showed two "unexpected" trends (i.e. findings usually not discussed in traditional culvert design guidelines) in terms of the maximum acceptable afflux and tailwater rating curve. An increase in maximum acceptable afflux h_{max} yields an increase in upstream specific energy, hence an increased bulk velocity in the barrel, at design discharge Q_{des} and a narrower barrel. In turn the requirements for upstream fish passage, i.e. Eq. (1), are less likely to be met at less-than-design flow: i.e. in particular at $Q = Q_1 < Q_{des}$, and a large number of cells may be required: $N_{cell} > (N_{cell})_{des}$. The tailwater rating curve is the relationship between tailwater depth and discharge, or variations of natural downstream water level with water discharges. With outlet control operation at less than design discharges, a larger tailwater depth implies a slower fluid flow in the entire culvert barrel, and Eq. (1) is more likely to be fulfilled. While these trends may be physically derived from basic hydrodynamic considerations, they are rarely discussed in current engineering design manuals of culverts, because less-than-design water discharges are not specifically considered.

Linking Fluid Dynamics and Biology

Intrinsically, open channel fluid dynamics is characterised by the complicated interactions between the water and a number of mechanisms including the boundary friction, gravity, and turbulence. Traditionally, these open channel flows have been modelled based upon one-dimensional depth-averaged equations, which predict the mean flow properties, i.e. the bulk velocity V_{mean} and water depth d, and often encompass a fair level of empiricism: "*this simple 1D approach is clearly problematic*" (Morvan et al. 2008, p. 192). By far a most pertinent flow property is the velocity distribution, especially in the vicinity of solid boundaries, because small fish predominantly swim upstream next to the corners and walls (Gardner 2006; Blank 2008; Jensen 2014; Katopodis and Gervais 2016; Wang et al. 2016a; Cabonce et al. 2019). A complete characterisation of the velocity field requires a detailed investigation, which may be undertaken physically in laboratory and numerically using computational fluid dynamics (CFD), possibly theoretically for a few rare simplistic situations. Laboratory measurements must be based upon a large number of data points to characterise the main stream, boundary regions (i.e. next to bed and walls), and secondary flows. For example, Wang and Chanson (2018) and Cabonce et al. (2018, 2019) recorded 250–300 sampling points per cross-section for a given flow rate. In aeronautics and industrial flows, the implementation of complex three-dimensional (3D) CFD models has become more commonly used (Roache 1998; Rizzi and Vos 1998). This transition is more recent in open channel flows, with inherent difficulties in applying 3D CFD to free-surface flows, e.g. the air-water interface, complicated geometry, and roughness definition (Rodi et al. 2013; Khodier and Tullis 2017; Zhang and Chanson 2018).

A sound linkage between biology and hydrodynamics is a fundamental requirement to advance our understanding of fish-friendly culvert design based upon physically-sound fish performance and hydrodynamic principles. Despite the recent advances in hydrodynamics of culverts, there remains a gap between our knowledge of the characterisation of turbulence and our understanding of its role on biotic communities. Leading scholars stressed the challenge, specifically the need for "*a better understanding of the*

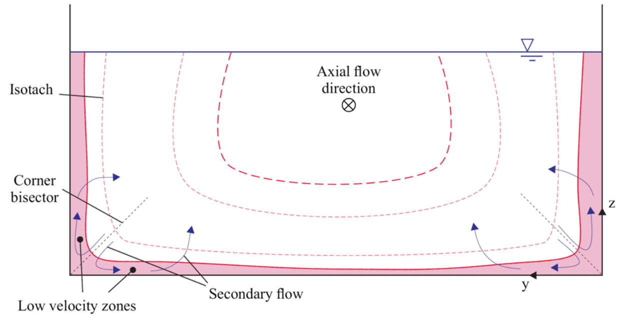

Fig. 6 Sketch of low-velocity zones as defined by Eq. (1) in a box culvert barrel, looking downstream

relationship between the turbulent properties and [their] influence on individual organisms and ecological communities" […] "*to effectively integrate hydraulically realistic information with ecological data*" (Maddock et al. 2013). Several researchers have pointed to the absence of standardised fish swimming tests and data interpretation relevant to engineering design (Kemp 2012; Katopodis and Gervais 2016), because of "*inconsistent metrics in the published literature*" (Kemp 2012, p. 404). Yet there is a physically-based relationship between the local longitudinal velocity and the (mechanical) power and energy required by fish to swim upstream against the discharge (Wang and Chanson 2018). Thus biology and hydrodynamics are linked and Eq. (1) provides the means to deliver a sizeable turbulent low-velocity zone (LVZ), as sketched in Fig. 6, in line with detailed physical and numerical experiments.

It is, however, an open question as to what extent the details not considered by the current work will affect fish passage predictions. It is believed that the interactions between fish and hydrodynamics must be appraised within the context and time scales of a small fish traversing a culvert barrel in the upstream direction against the current. A key question is: what does the characteristic swimming speed U_{fish} relate to? In a 12 m long 0.5 m wide smooth culvert barrel flume, corresponding to a full-scale barrel cell of a 2-lane road embankment, two fish species, juvenile silver perch (*Bidyanus bidyanus*) and adult Duboulay's rainbowfish (*Melanotaenia duboulayi*), were tested in terms of their upstream swimming (Wang et al. 2016a; Cabonce et al. 2017, 2019, 2018). For both fish species, visual observations and high-speed video movies showed that the fish trajectories consisted of a succession of swimming sequences with (a) quasi-stationary motion where fish speed fluctuations were small, (b) short upstream motion facilitated by a few strong tail-beats, and (c) rare burst swimming. The most common observation of upstream fish swimming was the first one: i.e. quasi-stationary motion facing the current. Altogether, the fish took from about 1 min to more than 20 min, to swim the entire culvert barrel flume, spending about 90% of their time in the bottom corners and along the sidewalls. Based upon such detailed fish kinematic observations, the characteristic swimming speed U_{fish} should combine the fish swimming endurance performances and their ability to negotiate low-velocity zones.

Summary and Conclusion

New guidelines for fish-friendly multi-cell box culvert designs are being developed in NSW (Australia), based upon simple practical and physically-based concepts: (a) the culvert design is optimised for fish passage for $Q < Q_1$, and for flood capacity for $Q_1 < Q < Q_{des}$, and (b) low-velocity zones in the culvert barrel are defined in terms of a percentage of the wetted flow area where $0 < V_x < U_{fish}$, with V_x the local longitudinal velocity component and U_{fish} a characteristic fish speed linked to swimming performances of targeted fish species. This study delivers simple guidelines for multi-cell box culvert structures with identical (or nearly-identical) smooth barrel cells, in line with current engineering practices. Low-velocity zones (LVZs) are provided along the wetted perimeter and next to the culvert barrel corners, where small-bodied fish swim and can minimise their energy expenditure. This approach is novel and relies upon an accurate physically-based knowledge of the entire velocity field in the barrel, specifically the longitudinal velocity map, because fish tend to target LVZ boundaries. It is well-suited to weak-swimming fish, like small-bodied Australian native fish species, although the method may be applied to a wider range of fish species.

The influence of the relative threshold Q_1/Q_{des}, characteristic fish swimming speed U_{fish}, and percentage of flow area on the size of box culvert structures was assessed. For smooth culvert barrel invert at natural ground level, the increase in culvert size and cost might become very significant for $U_{fish} < 0.3$ m/s and $Q_1/Q_{des} > 0.3$, when providing 15% flow area with $0 < V_x < U_{fish}$, with smooth culvert barrel. The increase in culvert size would correspond to a lower bound of the increase in culvert construction costs to achieve fish passage compared to a traditional engineering design approach. When the characteristic swimming speed of the targeted fish species is less than 0.3 m/s ($U_{fish} < 0.3$ m/s), a different design approach might be required. One option could target a lower relative threshold Q_1/Q_{des}. Another option could involve a design incorporating a barrel cell with larger low-velocity zones. This could be achieved with boundary roughening and addition of appurtenance, e.g. baffles, although negative velocities and strong recirculation must be avoided for small-bodied fish, and juveniles of large-bodied fish, since a recent study demonstrated their adverse effects (Cabonce et al. (2018). Further detailed CFD calculations for recessed cell(s) with a lower invert indicate similar trends as those for a culvert barrel invert at natural ground level in terms of cost increase. The results, however, showed a significantly more complicated hydrodynamic field in the barrel, in addition to the increased construction costs.

The present study delivers a physically-based rationale for fish-friendly standard box culvert design, embedding state-of-the-art hydrodynamic calculations into current hydraulic engineering design methods to yield cost-effective outcomes. By bridging the gap between engineering and hydrodynamics, such a novel approach may contribute to the restoration of catchment connectivity. The method is more general than previous attempts, yet simple and cost effective enough to be widely endorsed by the various stakeholders. Finally it is acknowledged that the design approach is focused in culvert barrel design. Complete design guidelines must further include inlet and outlet design recommendations.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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References

Allen GR, Midgley SH, Allen M (2002) Field guide to the freshwater fishes of Australia. Western Australia Museum, Australia, p 394

Anderson GB, Freeman MC, Freeman BJ, Straight CA, Hagler MM, Peterson JT (2012) Dealing with uncertainty when assessing fish passage through culvert road crossings. Environ Manage 50:462–477

Bates K, Barnard B, Heiner B, Klavas JP, Powers PD (2003) Design of road culverts for fish passage. Washington Department of Fish and Wildlife, Washington, p 111

Behlke CE, Kane DL, Mcleen RF, Travis MT (1991) Fundamentals of Culvert Design for Passage of Weak-Swimming Fish. Report FHW A-AK-RD-90-10. Department of Transportation and Public Facilities, USA, p 178

Blank MD (2008). Advanced Studies of Fish Passage through Culverts: 1-D and 3-D Hydraulic Modelling of Velocity, Fish Energy Expenditure, and a New Barrier Assessment Method. Ph.D. thesis, Montana State University, Department of Civil Engineering, Bozeman, Montana, USA, p 231

Briggs AS, Galarowicz TL (2013) Fish passage through culverts in central michigan warmwater streams. N Am J Fish Manage 33:652–664

Cabonce J, Fernando R, Wang H, Chanson H (2017) Using Triangular Baffles to Facilitate Upstream Fish Passage in Box Culverts: Physical Modelling. Hydraulic Model Report No. CH107/17. School of Civil Engineering, The University of Queensland, Brisbane, Australia, p 130

Cabonce J, Fernando R, Wang H, Chanson H (2019) Using small triangular baffles to facilitate upstream fish passage in standard box culverts Environ Fluid Mech 19(1):157–179. https://doi.org/10.1007/s10652-018-9604-x

Cabonce J, Wang H, Chanson H (2018) Ventilated corner baffles to assist upstream passage of small-bodied fish in box culverts. J Irri Drain Engg 144(8):Paper 0418020. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001329)

Cahoon JE, Mcmahon T, Solcz A, Blank M, Stein O (2007) Fish Passage in Montana Culverts: Phase II - Passage Goals. *Report FHWA/MT-07-010/8181*, Montana Department of Transportation and US Department of Transportation, Federal Highway Administration, Bozeman, Montana, USA

Chanson H (1999) Culvert Design. In: Chanson H (ed.) The Hydraulics of Open Channel Flow: An Introduction, 1st edn. Butterworth-Heinemann, UK, p 365–401

Chanson H (2000) Introducing originality and innovation in engineering teaching: the hydraulic design of culverts. Euro J Engg Edu 25(4):377–391

Chanson H (2004) The Hydraulics of Open Channel Flow: An Introduction, 2nd edn. Butterworth-Heinemann, Oxford, p 630

Chanson H, Leng X (2018) On the Development of Hydraulic Engineering Guidelines for Fish-Friendly Standard Box Culverts, with a Focus on Small-Body Fish. Civil Engineering Research Bulletin No. 25. School of Civil Engineering, The University of Queensland, Brisbane, p 79

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, p 116

Concrete Pipe Association of Australasia (1991) Hydraulics of Precast Concrete Conduits, 3rd edn. Jenkin Buxton Printers, Australia, p 72

Concrete Pipe Association of Australasia (2012) Hydraulics of Precast Concrete Conduits. CPAA Design Manual, Australia, p 64

Courret D (2014) Petits Ouvrages Hydrauliques et continuite pisicole. Equipement des OH existants: principes de choix et de dimensionnement des dispositifes." *Presentation*, Nancy

DWA (2014) Fischaufstiegsanlagen und fischpassierbare Bauwerke – Gestaltung, Bemessung, Qualitätssicherung. Merkblatt DWA-M 509, Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V., Hennef, Germany, p 334

DPI-Fisheries (2013). Policy and Guidelines for Fish Habitat Conservation and Management. NSW Department of Primary Industries, Wollongbar, NSW, Australia, p 80

Dynesius M, Nilsson C (1994) Fragmentation and flow regulation of river systems in the northern third of the world. Science 266:753–762

Fairfull S, Witheridge G (2003) Why do fish need to cross the road? Fish passage requirements for waterway crossings. NSW Fisheries, Cronulla NSW, p 14

Gardner A (2006) Fish Passage through Road Culverts. North Carolina State University, USA, p 103. Master of Science thesis

Goodrich HR, Watson JR, Cramp RL, Gordos M, Franklin CE (2018) Making culverts great again. Efficacy of a common culvert remediation strategy across sympatric fish species. Ecological Eng. 116:143–153

Hee M (1969) Hydraulics of Culvert Design Including Constant Energy Concept. Proc. 20th Conf. of Local Authority Engineers, Dept. of Local Govt, Queensland, paper 9, pp 1–27

Henderson FM (1966) Open Channel Flow. MacMillan Company, New York

Herr LA, Bossy HG (1965) Capacity Charts for the Hydraulic Design of Highway Culverts. *Hydraulic Eng Circular*, US Dept. of Transportation, Federal Highway Admin, HEC No. 10, March

Hotchkiss RH, Frei CM (2007) Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report." *Publication No. FHWA-HIF-07-033*, Federal Highway Administration, US Department of Transportation, p 280

Hunt M, Clark S, Tkach R (2012) Velocity distributions near the inlet of corrugated steep pipe culverts. Canad J Civil Engg 39:1243–1251

Hurst TP, Kay BH, Ryan PA, Brown MD (2007) Sublethal effects of mosquito larvicides on swimming performances of larvivorous fish *Melanotaenia duboulayi* (Atheriniformes: Melanotaeniidae). J Econ Entomol 100(1):61–65

Jensen KM (2014) Velocity Reduction Factors in Near Boundary Flow and the Effect on Fish Passage Through Culverts. Brigham Young University, USA, p 44

Kapitzke IR (2010) Culvert Fishway Planning and Design Guidelines. Report. James Cook University, Townsville, version 2.0

Katopodis C, Gervais R (2016) Fish Swimming Performance Database and Analyses. DFO CSAS Research Document No. 2016/002. Canadian Science Advisory Secretariat, Fisheries and Oceans Canada, Ottawa, p 550

Kemp P (2012) Bridging the gap between fish behaviour, performance and hydrodynamics: an ecohydraulics approach to fish passage research. River Res Appl 28:403–406. https://doi.org/10.1002/rra.1599

Koehn JD, Crook DA (2013) Movements and migration. In: Humphries P, Walker K (eds) Ecology of Australian Freshwater Fishes. CSIRO Publishing, Australia, pp 105–130

Khodier MA, Tullis BP (2017) Experimental and computational comparison of baffled-culvert hydrodynamics for fish passage. J Appl Water Engg Res 6(3):191–199. https://doi.org/10.1080/23249676.2017.1287018

Kilgore RT, Bergendahl BS, Hotchkiss RH (2010) Culvert Design for Aquatic Passage. Hydraulic Engineering Circular Number No. 26, Federal Highway Administration Publication No. FHWA-HIF-11-008, p 234

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

Lintermans M (2013) Recovering threatened freshwater fish in Australia. Marine Freshwater Res 64:iii–vi. https://doi.org/10.1071/MFv64n9_IN

Maddock I, Harby A, Kemp P, Wood P (2013) Research Needs, Challenges and the Future of Ecohydraulics Research. In: I Maddock, A Harby, P Kemp and P Wood (eds) Ecohydraulics: An Integrated Approach, John Wiley, pp 431–436

Mallen-Cooper M (1996) Fishways and Freshwater Fish Migration in South-Eastern Australia. Ph.D. thesis. University of Technology Sydney, Australia, p 442

Milt AW, Diebel MW, Doran PJ, Ferris MC, Herbert M, Khoury ML, Moody AT, Neeson TM, Ross J, Treska T, O'hanley JR, Walter L, Wangen AR, Yacobson E, Mcintyre PB (2018) Minimizing opportunity costs to aquatic connectivity restoration while controlling an invasive species. Conserv Biol 32(4):894–904. https://doi.org/10.1111/cobi.13105

Monk SK, Hotchkiss RH (2012) Culvert Roughness Elements for Native Utah Fish Passage: Phase II. Report No. UT-12.09. Utah Department of Transportation—Research Division, USA, p 47

Morvan H, Knight D, Wright N, Tang X, Crossley A (2008) The concept of roughness in fluvial hydraulics and its formulation in 1D, 2D and 3D numerical simulation models. J Hydraul Res 46(2):191–208

Oberkampf WL, Trucano TG, Hirsch C (2004) Verification, validation, and predictive capability in computational engineering and physics. Appl Mech Rev 57(5):345–384

O'Hanley JR (2011) Open rivers: barrier removal planning and the restoration of free-flowing rivers. J Environ Manage 92:3112–3120

Olsen A, Tullis B (2013) Laboratory study of fish passage and discharge capacity in slip-lined, baffled culverts. J Hydraul Engg 139(4):424–432

Olson LJ, Roy S (2002) The economics of controlling a stochastic biological invasion. Am J Agric Econ 84:1311–1316

Papanicolaou AN, Talebbeydokhti N (2002) Discussion of "Turbulent open-channel flow in circular corrugated culverts. J Hydraul Engg 128(5):548–549

QUDM (2013) Queensland Urban Drainage Manual, 3rd edn. Queensland Department of Energy and Water Supply, Brisbane, p 459

Rizzi A, Vos J (1998) Toward establishing credibility in computational fluid dynamics simulations. AIAA J 36(5):668–675

Roache RL (1998) Verification and Validation in Computational Science and Engineering. Hermosa Publishers, Albuquerque NM, p 446

Rodi W (2017) Turbulence modeling and simulation in hydraulics: a historical review. J Hydraul Engg 143(5):Paper03117001. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001288

Rodi W, Constantinescu G, Stoesser T (2013) Large-Eddy Simulation in Hydraulics. IAHR Monograph, CRC Press, Taylor & Francis Group, Leiden, p 252

Schall JD, Thompson PL, Zerges SM, Kilgore RT, and Morris JL (2012) Hydraulic Design of Highway Culverts. Hydraulic Design Series No. 5, Federal Highway Administration, Publication No. FHWA-HIF-12-026, 3rd edn, Washington, DC, USA, p 326

Wang H, Chanson H (2018) Modelling upstream fish passage in standard box culverts: interplay between turbulence, fish kinematics, and energetics. River Res Appl 34(3):244–252. https://doi.org/10.1002/rra.3245

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, 5–8 December, p 682

Wang H, Beckingham LK, Johnson CZ, Kiri UR, 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, p 74

Warren Jr. ML, Pardew MG (1998) Road crossings as barriers to small-stream fish movement. Trans Am Fish Soc 127:637–644

Wilkes MA, Webb JA, Pompeu PS, Silva LGM, Vowles AS, Baker CF, Franklin P, Link O, Habit E, Kemp PS (2018) Not just a migration problem: Metapopulations, habitat shifts, and gene flow are also important for fishway science and management. River Res Appl https://doi.org/10.1002/rra.3320

Zhang G, Chanson H (2018) Three-dimensional numerical simulations of smooth, asymmetrically roughened, and baffled culverts for upstream passage of small-bodied fish. River Res Appl 34(8):957–964. https://doi.org/10.1002/rra.3346

LENG, X., CHANSON, H., GORDOS, M., and RICHES, M. (2019). "Developing Cost-Effective Design Guidelines for Fish-Friendly Box Culverts, with a Focus on Small Fish." *Environmental Management*, Vol. 63, No. 6, pp. 747-758 & Supplementary material (7 pages) (DOI: 10.1007/s00267-019-01167-6) (ISSN 0364-152X).

Developing Cost-Effective Design Guidelines for Fish-Friendly Box Culverts, with a Focus on Small Fish - Supplementary Material

by Xinqian LENG, Hubert CHANSON, Matthews GORDOS and Marcus RICHES

Sample Calculation for Design Application

A.1 Presentation

This appendix aims to demonstrate design application examples of the proposed fish-friendly culvert design guidelines. Detailed procedure for designing a fish-friendly culvert is shown herein using two sample cases, being Culvert 1 and 2 (Table 3). The procedure can be summarised into 2 stages: (1) finding the optimum design to pass design flow discharge Q_{des} for a standard box culvert and (2) finding the number of additional culvert cells required to pass fish at less-than-design flow discharge i.e. 10% of the design flow ($0.1\times Q_{des}$). Note that the proposed design guidelines focused primarily on the design of the culvert barrel, using standard box culverts, assuming construction on a mild slope. Designs of culverts outside this scope will not be detailed in the current application.

Both stages of calculations are iterative processes. To find the optimum design for Q_{des} with a maximum acceptable afflux h_{max}, the minimum number of boxes required to achieve inlet control is calculated. Two alternative methods may be used, being an engineering design nomograph (Concrete Pipe Association of Australasia 2012) or a set of theoretical equations based on critical conditions and conservation of energy (HENDERSON 1966, CHANSON 2004, CHANSON and LENG 2018). The theoretical equations give the design discharge per unit width:

$$\frac{Q_{des}}{B} = C_D \times \frac{2}{3} \times \sqrt{\frac{2}{3} \times g} \times \left(H_1 - z_{inlet}\right)^{1.5} \qquad (H_1\text{-}z_{inlet}) \le 1.2\times D_{cell} \quad (A.1)$$

$$\frac{Q_{des}}{B} = C \times D_{cell} \times \sqrt{2 \times g \times \left(H_1 - z_{inlet} - C \times D_{cell}\right)} \qquad (H_1\text{-}z_{inlet}) > 1.2\times D_{cell} \quad (A.2)$$

where B is the internal barrel width and D_{cell} is the internal barrel height, (H_1-z_{inlet}) is equivalent of the head water level (H_1-z_{inlet} = d_{tw} + afflux). When the headwater is less than 1.2 times the cell height, a free-surface inlet is observed and Equation A.1 should be used. Otherwise a submerged entrance and free-surface barrel flow occur, and Equation A.2 is to be used. The constants C_D and C correspond to the shape of the inlet. For the most common square-edged inlet, $C_D = 0.9$ and C = 0.6.

Next, the design must be checked against outlet control situation, using the outlet control nomograph (Concrete Pipe Association of Australasia 2012). The nomograph will give the afflux for the calculated number of cells at outlet control. Ultimately, whichever afflux is bigger controls the flow, e.g. if afflux for inlet control > afflux for outlet control, inlet control is achieved; otherwise, the number of cells must be increased and outlet control calculations are repeated until the afflux is less than h_{max}.

Once the number of cells $(N_{cell})_{des}$ are obtained at design flow conditions, numerical CFD modelling is performed for a single cell to examine the complete velocity field throughout the culvert cell. Using contour plots of longitudinal velocity at different cross-sections of the culvert barrel, the flow area under certain velocity magnitudes can be derived. In section 2, we consider that at least 15% of the flow area is under characteristic fish swimming speed U_{fish}, with the range of U_{fish} being 0.2 - 0.5 m/s. Another criterion might include a minimum area of low velocity zone at the barrel bottom corners to pass the fish bodies. If the results of numerical models do not satisfy the required criteria of fish-friendly design, the number of cells must be revised by adding a further cell, and the modelling is to be repeated with an updated cell number configuration.

Figure A-1 summarises the iterative design procedure for a fish-friendly standard box culvert.

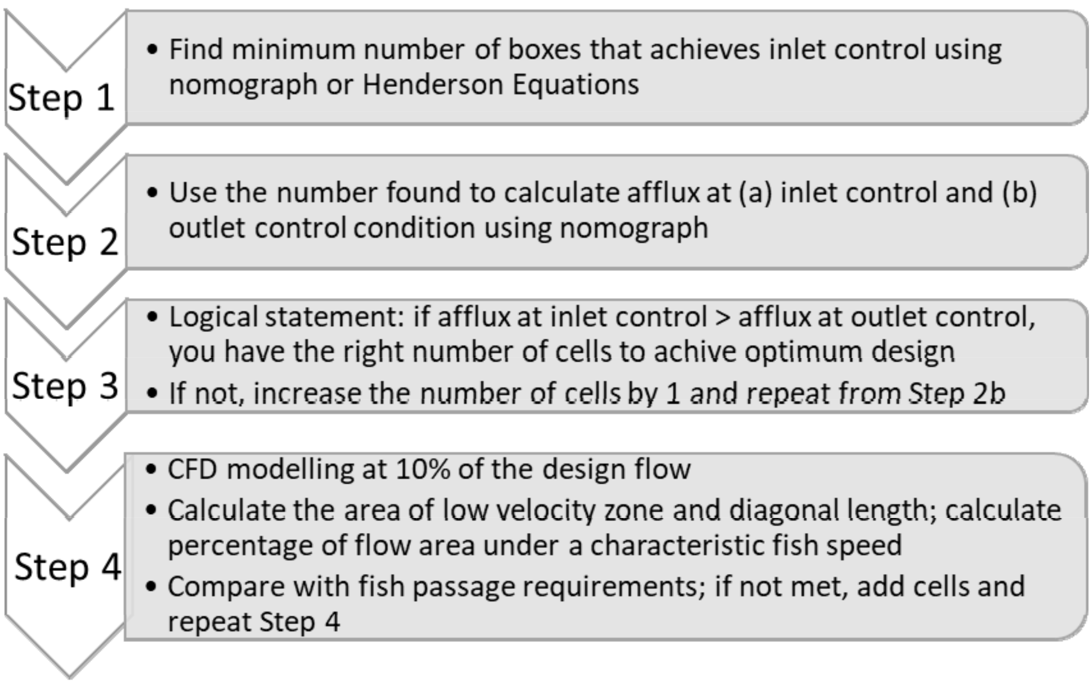

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Fig. A-1 - Flow chart for steps to achieve optimum design at design flow conditions

A.2 Sample case 1: Culvert 1

The design flow conditions for sample case 1 (Culvert 1) is detailed in Table 3. The design flow is a 1 in 1 year event with design discharge Q_{des} = 20 m^3/s (1728 ML/day). The length of the road embankment, i.e. length of the culvert barrel, is L_{barrel} = 8 m. The cells are rectangular smooth-concrete boxes of the same size: width B_{cell} = 1.3 m and height D_{cell} = 1 m. The culvert barrel sat on a horizontal flat flood plain (zero slope). Maximum acceptable afflux of the site is h_{max} = 0.55 m. The tailwater rating curve is extracted from existing gauge data, for which the tailwater depth d_{tw} is fitted as:

$$d_{tw} = 0.416536 \times Q^{0.28415} \tag{A.3}$$

At design flow conditions, the tailwater depth is d_{tw} = 0.976 m.

Using both engineering nomographs and theoretical equations (HENDERSON 1966, CHANSON 2004), the calculation yields a required number of cells $(N_{cell})_{des}$ = 7. The afflux for a seven-cell structure was approximately 0.362 m at design flow rate.

Numerical CFD modelling was conducted for less-than-design flow condition at 10% of the design discharge ($0.1 \times Q_{des}$ = 2 m^3/s). The flow was modelled by ANSYS™ Fluent v. 18.0. The model used a standard k-ε method to resolve the turbulence, and used a Volume of Fluid (VOF) method to resolve the two-phase air-water interface. The k-ε turbulence model is a simple model well-suited to smooth boundaries, including in open channels (OBERKAMPF et al. 2004, RODI 2017). It was selected in the current study for reduced computational times. More complicated turbulence models should indeed be considered for more complicated boundary treatments (e.g. ZHANG and CHANSON 2018). In the current study, transient flow simulation was used for all numerical test cases, where an initial simulation was performed using a coarse mesh, and the results were further interpolated on a refined mesh for transient simulation until convergence (LENG and CHANSON 2018). The transient formulation was solved implicitly with a second order upwind scheme for momentum, first order upwind scheme for turbulent kinetic energy and turbulent dissipation rate. The convergence was ensured by reducing residuals of all parameters to 10^{-4} or less. All simulations were run for a physical time span of over 90 s to ensure a steady equilibrium flow and the conservation of mass was achieved between inlet and outlet. Figure A-2 shows the modelled results of the longitudinal velocity contour near the downstream end of the culvert barrel (0.5 m upstream from the barrel exit). The percentage of flow area under certain velocity magnitudes is shown in Figure A-3.

When the characteristic fish swimming speed U_{fish} is set to 0.5 m/s, the results showed that the current design (seven-cell structure) would satisfy the fish passage requirements. The diagonal length of the low velocity zone (U_{fish} < 0.5 m/s) also fulfil a minimum requirement for 25 mm × 25 mm corner area. If the characteristic fish swimming speed is set to U_{fish} = 0.4 m/s or below, the current design would fail to satisfy the minimum 15% of flow area and a larger number of cells would be required.

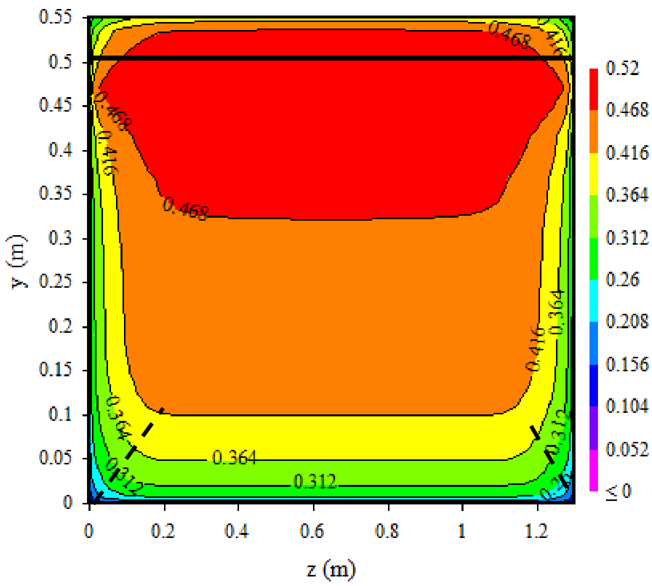

Fig. A-2 - Longitudinal velocity contour of a single cell in a seven-cell structure of case 1 (Culvert 1) at 10% of design flow ($0.1 \times Q_{des}$ = 2 m^3/s); results near the downstream end of the culvert barrel (0.5 m upstream from the barrel exit); free-surface denoted by solid black line; diagonal length of low velocity zone denoted by black dashed line

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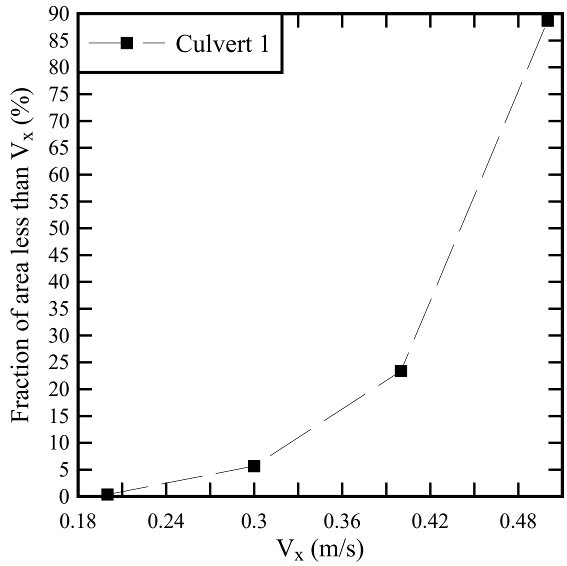

Fig. A-3 - Percentage of flow area under certain velocity values for a single cell in a seven-cell structure of case 1 (Culvert 1) at 10% of design flow ($0.1 \times Q_{des} = 2$ m^3/s); results near the downstream end of the culvert barrel (0.5 m upstream from the barrel exit)

A.3 Sample case 2: Culvert 2

The design flow conditions for sample case 2 (Culvert 2) are presented in Table 3. The design flow is Q_{des} = 4.8 m^3/s (415 ML/day). The length of the culvert barrel is L_{barrel} = 14 m, and the cells are identical rectangular smooth-concrete boxes: width B_{cell} = 1 m and height D_{cell} = 0.5 m. The slope of the flood plain is 0.0012 and the maximum acceptable afflux at design flow is h_{max} = 0.2 m. The tailwater depth d_{tw} is assumed to be at uniform equilibrium, and the tailwater rating curve is best fitted as:

$$d_{tw} = 0.178688 \times Q^{0.598698} \quad \text{(A.4)}$$

with the tailwater depth at design flow condition: d_{tw} = 0.457 m.

Using both engineering nomographs and theoretical equations (HENDERSON 1966, CHANSON 2004), the calculation yields a required number of cells: $(N_{cell})_{des}$ = 7. The afflux for a seven-cell culvert structure is approximately 0.168 m.

Numerical CFD modelling was conducted for less-than-design flow condition at 10% of the design discharge ($0.1 \times Q_{des}$ = 0.48 m^3/s). Figure A-4 shows the modelled results of the longitudinal velocity contour near the downstream end of the culvert barrel, i.e. 2 m upstream of the barrel exit. The percentage of flow area under specific velocity magnitudes is shown in Figure A-5. If the characteristic fish swimming speed U_{fish} is set to 0.5 m/s, the current design (seven-cell structure) would satisfy the fish passage requirements for minimum area (15% of the flow area).

Discussion

While the present structure may fulfil the requirement for upstream passage (Eq. (1)), the low velocity zones are shallow and thin. In the barrel corner, the diagonal length of the low velocity zone (LVZ) is shown in Figure A-4. For $Q = 0.1 \times Q_{des}$ and $U_{fish} < 0.5$ m/s, the corner LVZ would be less than 20 m thick, which might not suitable for a number of fish species. In such a case, a different and more elaborate design might be required. This could include a recessed barrel invert, a downstream pool wall to induce some backwater effect, or the installation of baffles, all of which would increase the water depth the barrel and hence the size of the LVZ.

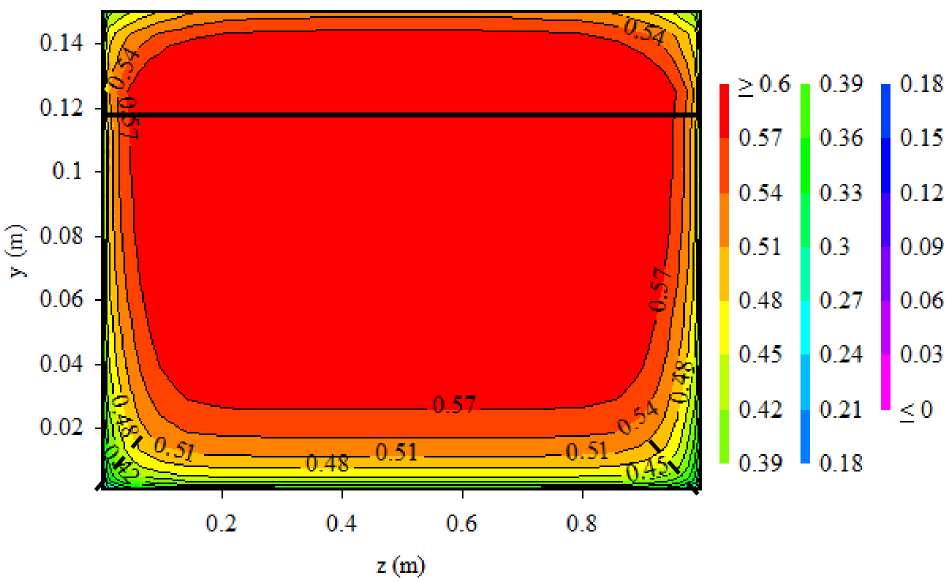

Fig. A-4 - Longitudinal velocity contour of a single cell in a six-cell structure of case 2 (Culvert 2) at 10% of design flow ($0.1 \times Q_{des} = 0.48$ m^3/s); results near the downstream end of the culvert barrel (2 m upstream from the barrel exit); free-surface denoted by solid black line; diagonal length of low velocity zone denoted by black dashed line

LENG, X., CHANSON, H., GORDOS, M., and RICHES, M. (2019). "Developing Cost-Effective Design Guidelines for Fish-Friendly Box Culverts, with a Focus on Small Fish." *Environmental Management*, Vol. 63, No. 6, pp. 747-758 & Supplementary material (7 pages) (DOI: 10.1007/s00267-019-01167-6) (ISSN 0364-152X).

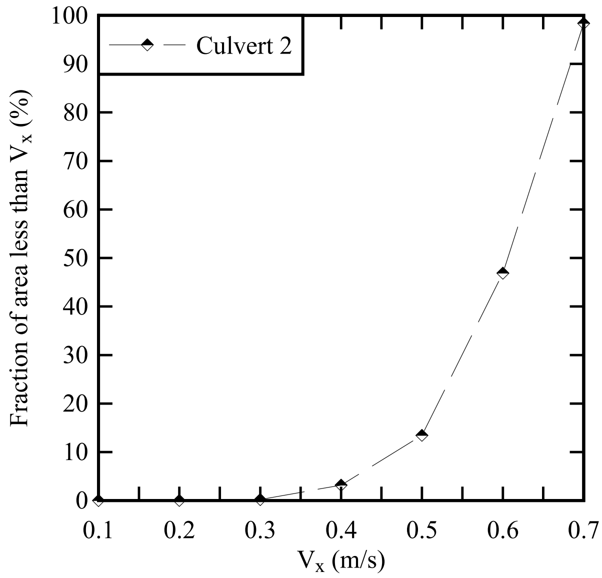

Fig. A-5 - Percentage of flow area under certain velocity values for a single cell in a six-cell structure of case 2 (Culvert 2) at 10% of design flow ($0.1 \times Q_{des} = 0.48$ m^3/s); results near the downstream end of the culvert barrel (2 m upstream from the barrel exit)