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Vision paper

Challenging hydraulic structures of the twenty-first century – from bubbles, transient turbulence to fish passage

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ABSTRACT
Hydraulic structures are man-made waterworks interacting with the rainfall run-off to store and convey water, or mitigate the impact of run-off. Current approaches in hydraulic structure design tend to be conservative, not much differing from ancient designs. Modern structures are often designed based upon simplistic concepts to optimize their performances. However, today's hydraulic engineers must embrace a number of new challenges, emerging in response to the quickly growing world population, changing climate, evolving agriculture, and growing industrial needs. Herein, new challenges are reviewed using diverse examples of air entrainment at hydraulic structures, transient turbulence during surge events in conveyance structures, and upstream fish passage at road crossings. It is argued that many technical solutions are not satisfactory, e.g. in terms of sustaining aquatic flora and fauna, fluid–structure interactions and operational constraints. Indeed, the current and emerging technical challenges in hydraulic structure design are massive for the twenty-first century hydraulic engineers. The solutions rely upon engineering innovation, excellence in hydraulic research and quality education in universities, complemented by indispensable interactions between engineers, scientists and water stakeholders.

Keywords: Air bubble entrainment; hydraulic design; hydraulic structures; road crossings; unsteady transient surges; upstream fish passage

1 Introduction

A hydraulic structure is a man-made waterwork built across, along or beside a water body, in fluvial, estuarine and coastal environments, that interacts with the rainfall run-off, to store and distribute water. Examples include a dam and its spillway (Fig. 1a), a spur dyke impacted by an incoming tidal bore (Fig. 1b) and a culvert beneath a road (Fig. 1c). The three main purposes of hydraulic structures are water storage, water conveyance and mitigation of water impacts, e.g. a breakwater or a stilling basin (Novak et al., 2001; Sawaragi, 1995; USBR, 1987). The construction of hydraulic structures is one of the oldest civil engineering activities, reflecting the fact that life is totally dependent upon drinking water supply (Schnitter, 1994; Smith, 1971). Although the oldest hydraulic structures remain unknown, a number of world-famous engineering heritage systems include the Assyrian water supply of Nineveh, the Roman aqueducts, the Intervalley canal system in coastal Peru, and the large sewer systems beneath European and North-American cities which brought modern water sanitation. Two key requirements for the development of civilizations have been the storage and transportation of water, especially for irrigation water supply arising from the development of intensive agriculture, drinking water demands, public health and sanitary requirements of large urban systems.

Basic hydraulic engineering calculations rely upon fundamental hydrodynamics and theoretical studies with a range of trusted and proven solutions. Although hydraulic engineers were at the forefront of science for centuries, current hydraulic structures are too often designed and optimized for

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Figure 1 Challenging hydraulic structure designs. (a) Self-aeration at the Hinze Dam spillway (Australia) on 31 March 2017 ($d_c/h = 3.55$, $\mathsf{R}_e = 1.1 \times 10^8$); (b) transient positive surge (Qiantang River bore) impacting a spur dyke between Yanguan and Laoyanchang (China) on 11 October 2014; (c) standard box culvert outlet operation along Witton Creek (Australia) on 18 March 2019

simplistic situations, in light of the knowledge available at the time, leading to conservative designs which might not be conservative according to current findings, while they do not differ much from ancient designs (Chanson, 2007, 2008). Modern hydraulic structures are typically designed based upon steady single-phase Newtonian fluid flow concepts for a fixed (design) discharge, e.g. to optimize the cross-sectional shape of a canal, the discharge capacity of a spillway crest, the energy dissipation performance of a stilling basin, the size of a culvert barrel, among others. A number of underlying assumptions might become invalid, e.g. in catchments affected by flash flooding, in sediment-laden river floods with suspended sediment concentrations in excess of 100 kg m^{-3}. The design optimization of hydraulic structures for a single discharge might need

Table 1 Selection of vision papers related to hydraulic structures published by the *Journal of Hydraulic Research* and their impact

Title (listed in alphabetical order)	Number of citations		Reference
	Web of Science	Google Scholar	
Hydraulics of aerated flows: qui pro quo?	56	96	Chanson (2013)
Hydraulic structures: a positive outlook into the future	15	22	Hager and Boes (2014)
Reservoir sedimentation	95	177	Schleiss et al. (2016)

Note: citation data collected on 12 November 2020.

to be reviewed in the light of a number of recent failures during operation at situations different from design flow conditions, as happened e.g. in the Paradise dam stilling basin and Oroville dam (primary and emergency) spillways (McDonald, 2013; Wahl et al., 2019).

In 2021, hydraulic engineers must embrace new challenges, as water plays a key role in human perception and it is indispensable to all forms of life. In dam engineering, the continuous re-evaluation of spillway discharge capacity leads to much-needed novel spillway (re-)designs, in particular in geographical regions of extreme hydrology and limited rainfall and run-off data. For example, the Yaté dam spillway in New Caledonia was built to pass $4500\,m^3\,s^{-1}$ in 1959 and modified to pass $12{,}000\,m^3\,s^{-1}$ following a catastrophic flood in 1992; the Wivenhoe dam spillway in Australia was built with a spillway capacity of $12{,}400\,m^3\,s^{-1}$ in 1984, later extended to $27{,}000\,m^3\,s^{-1}$ in 2005, with a surcharge capacity of $1.96 \times 10^9\,m^3$ (Gill et al., 2005; Lemperière et al., 2012). Major advances in two-phase flows in mechanical, chemical and nuclear engineering have brought up new forms of multiphase gas–liquid and liquid–solid models, that could be embedded in hydraulic structure designs (Bung & Valero, 2016; Chanson, 2013; Jhia & Bombardelli, 2009). The interaction between hydraulic structures and aquatic flora and fauna is another complicated challenge, rarely appreciated and/or addressed properly (Kemp, 2012; Maddock et al., 2013; Nepft, 2012). Physical modelling free from scale effects is nearly impossible in considering biota–structure interrelations, unless at full-scale, while some aquatic life forms might adapt their swimming patterns in man-made hydraulic structures to maximize their efficiency (Wang & Chanson, 2018a). Reservoir siltation has been a recurrent issue worldwide for more than 2000 years, exacerbated by the reduction of freshwater resources and suitable dam sites in recent decades (e.g. Chanson, 2008).

Since the introduction of the Vision Papers in the Journal of Hydraulic Research, few articles discussed key research directions that would foster most significant advancement of science and knowledge relevant to hydraulic structures (Table 1). In this invited Vision Paper, the writers outline a number of the representative challenges for current and future hydraulic structures, and show how a combination of innovative engineering, research excellence and broad-based expertise is often required for a successful outcome. These challenges are illustrated using self-aeration in hydraulic structures, transient turbulence in conveyance structures, and the adverse impact on upstream fish passage caused by culverts, as examples.

2 Self-aeration at hydraulic structures

During discharge operations at a hydraulic structure, the interactions between the high-velocity turbulent water flow and the atmosphere may lead to significant self-aeration associated with strong interactions between entrained air bubbles and coherent flow structures (Rao & Kobus, 1974; Wood, 1991) (Fig. 1a). Traditionally, air entrainment in free-surface flows has been classified into singular (i.e. spatially localized) aeration, e.g. at plunging jets and hydraulic jumps, and interfacial (i.e. spatially extended) aeration, e.g. in chute flows and water jets discharging into air (Chanson, 1997, 2009; Kobus, 1984; Wood, 1991). Recent experimental observations suggested that the simplifications in current approaches mask a number of significant physical processes. In stationary hydraulic jumps, recent fine air–water flow measurements showed that the air entrapment at the roller toe accounts for only one third of the total air entrainment in the roller, with extensive interfacial aeration along the upper surface of the breaking roller (Wang & Chanson, 2015) (Fig. 2a). Complicated three-dimensional interactions between bubbles and turbulence occur as illustrated in Fig. 2a. In free-surface flows down spillways, the air–water exchanges in the upper flow region consist of a combination of interfacial aeration, air advection in surface waves, and ejected droplet impinging into the air–water mixture, with local singular bubble entrainment at the drop impacts (Chanson & Carosi, 2007; Ervine & Falvey, 1987; Toombes & Chanson, 2008) (Fig. 2b). The flow down a spillway and in a water jet is further complicated by the interactions with the atmospheric boundary conditions and particle clustering in large-scale turbulent structures. "White waters" encompass air bubbles, water drops, foams and packets, with very dynamic transient interfacial processes such as breakup, coalescence, rebounds and collapses. The air–water column presents an evolution in its structure from a disperse bubbly region next to the bottom to a complicated intermediate region, and an upper spray region above (Fig. 2b) (Chanson & Toombes, 2003; Felder & Chanson, 2016).

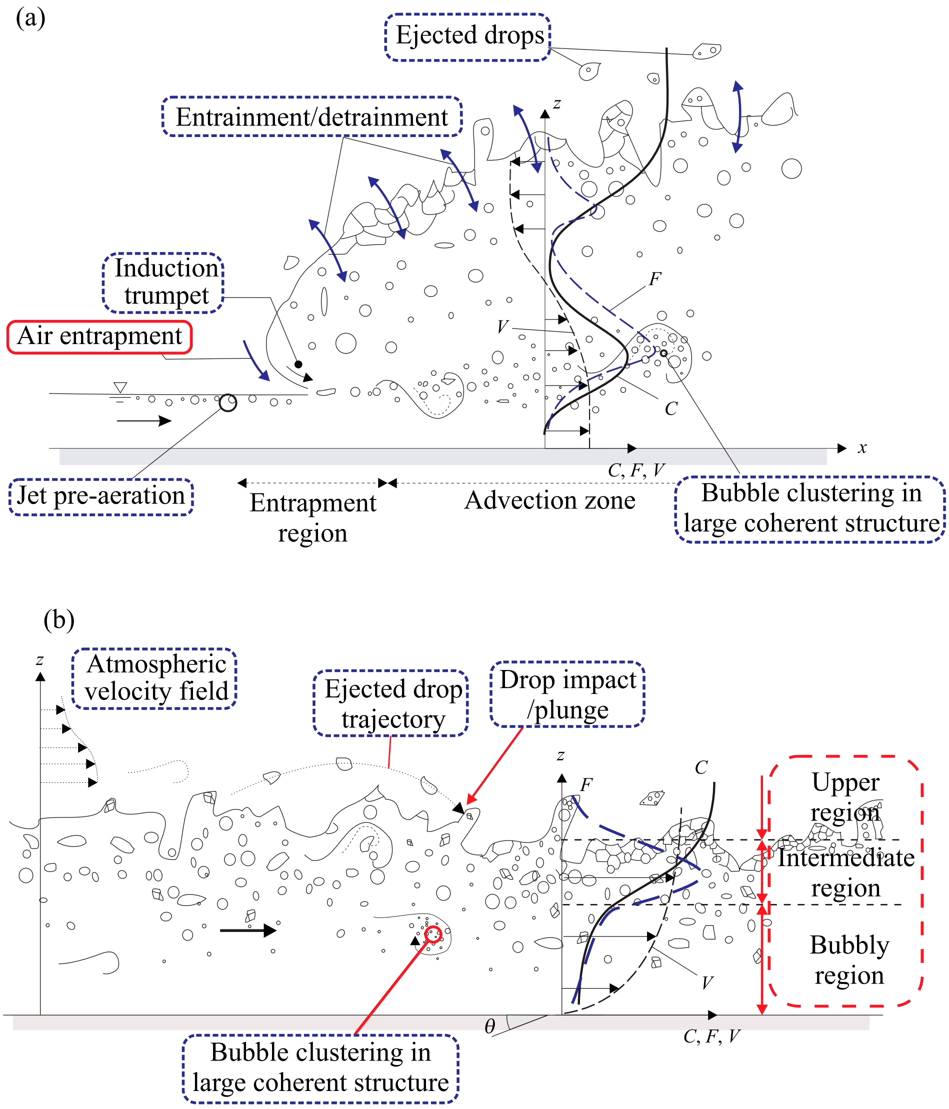

Figure 2 Self-aeration at hydraulic structures including seminal air–water flow features. (a) Air entrainment processes at a hydraulic jump. (b) Free-surface-aeration down a supercritical spillway flow. C = void fraction, F = bubble count rate, V = velocity, θ = slope (or angle) from the horizontal

For design engineers, the conditions for air entrainment inception constitute a key design parameter. The seminal works of Hino (1961) and Ervine et al. (1980) related self-aeration to the inflow turbulence, as illustrated in Fig. 3a. Recently, the onset of self-aeration has been linked to a threshold level in tangential Reynolds stresses in the water acting next to the free surface (Chanson, 2009, 2013). Physically air entrainment occurs when the turbulent shear stress next to the air–water interface is large enough to overcome the surface tension (Chanson, 2009; Ervine & Falvey, 1987):

$$\frac{|v\,v|}{|V|^2} > \frac{\pi\,\sigma\,(r_1 + r_2)}{\rho_w\,A_{fs}\,V^2} \quad (1)$$

where ρ_w is the water density, σ is the surface tension, V is the instantaneous longitudinal water velocity, v is the instantaneous turbulent velocity fluctuation, the vertical bars | | mean the absolute value of the time average, r_1 and r_2 are the two principal radii of curvature of the free surface deformation, assuming an elongate spheroid, and A_{fs} is the surface deformation area. For a spherical bubble of radius $r = r_1 = r_2$, and assuming isotropic turbulence, Eq. (1) may be simplified as:

$$\frac{\mu_w\,|V|}{\sigma} > \sqrt{\frac{{\mu_w}^2}{2\,\rho_w\,\sigma\,\pi\,r\,\frac{|v\,v|}{|V|^2}}} \quad (2)$$

for the onset of air bubble entrainment, where μ_w is the water dynamic viscosity. Eq. (2) is compared to experimental observations in Fig. 3b, predicting entrained bubble sizes within 0.2–100 mm at inception, for the normalized jet impact normal stress $|v_x v_x|/{V_1}^2$ between 10^{-4} and 2.25×10^{-2}, with V_1 the longitudinal jet impact velocity. Despite the simplified development (spherical bubble, isotropic turbulence), Eq. (2) predicts entrained bubble sizes comparable to physical observations at

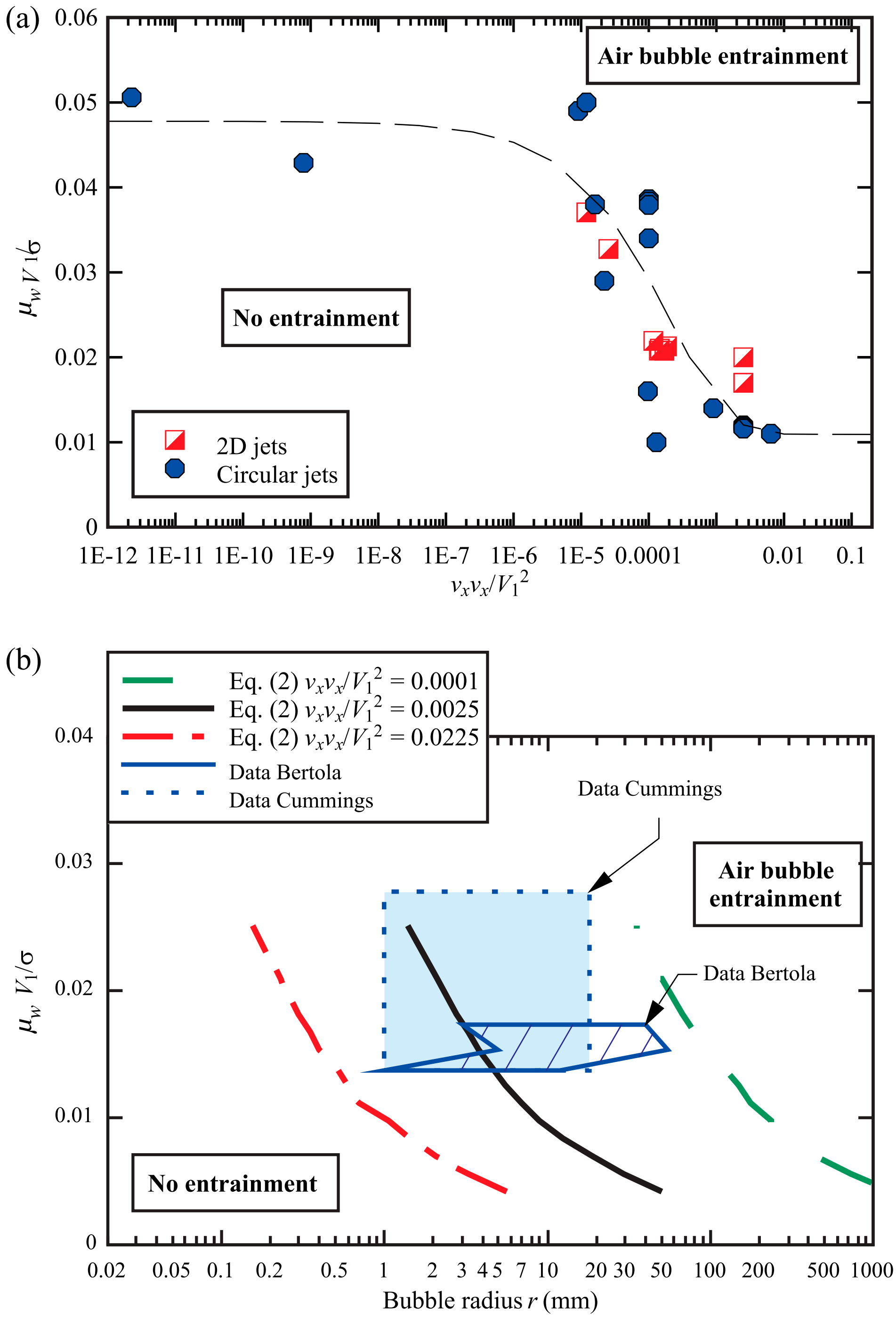

Figure 3 Inception conditions of air bubble entrainment. (a) Vertical two-dimensional and circular plunging jets: dimensionless impact velocity V_1 as a function of the dimensionless normal stress $v_x v_x$ of the impinging jet (datasets: Bertola et al., 2018; Chanson & Manasseh, 2003; Chirichella et al., 2002; Cummings & Chanson, 1999; El-Hammoumi, 1994; Ervine et al., 1980; McKeogh, 1978). (b) Dimensionless impact velocity V_1 as a function of the entrained bubble radius and jet impact dimensionless normal stress $v_x v_x$ (Eq. 2); comparison with the experimental observations of Cummings and Chanson (1999) and Bertola et al. (2018)

the onset of bubble entrainment in vertical plunging jets, as seen in Fig. 3b. For these data (Bertola et al., 2018; Cummings & Chanson, 1999), the normalized inflow normal stress $|v_x v_x|/V_1^2$ ranged from 4×10^{-4} to 2.5×10^{-3} in the physical experiments.

Once entrapped, the entrained air is convected within the water column by the combined effects of streamwise advection, turbulent diffusion and buoyancy. Various diffusion models were developed and applied successfully to a range of air–water flow typology and flow conditions (Chanson, 1997; Chanson & Toombes, 2002; Wood, 1984). Recent analyses showed a marked decrease in the ratio D_t/ν_T of air bubble diffusivity to the momentum exchange coefficient ν_T with increasing Reynolds number (Chanson, 1997). This finding suggests the intrinsic

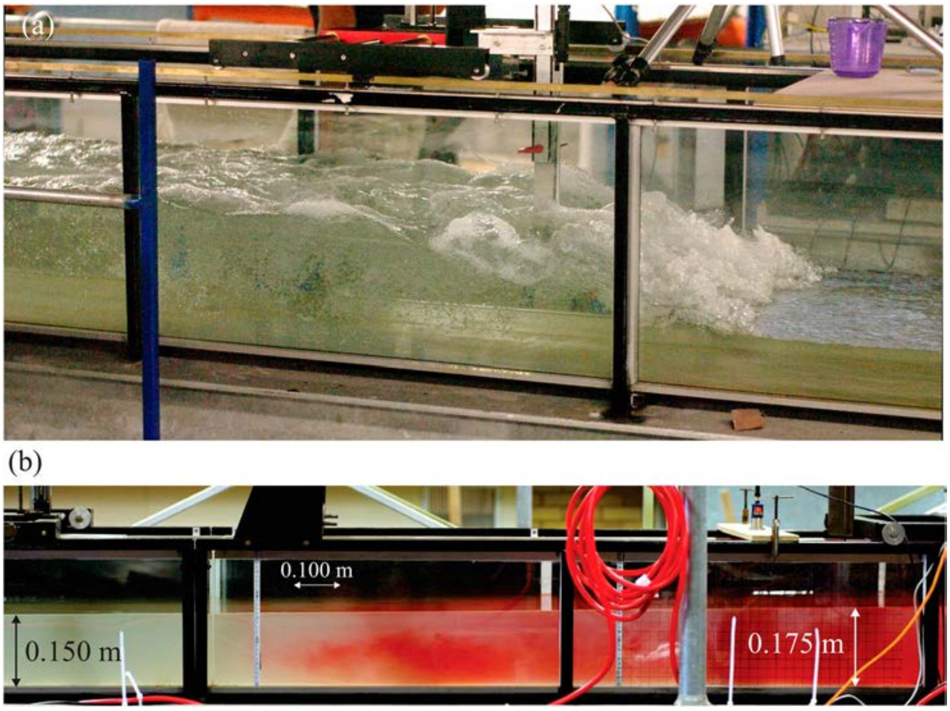

Figure 4 Positive and negative surge in conveyance canals propagating upstream from left to right, with initial main flow direction from right to left. (a) Positive surge generated by a rapid gate closure ($Q = 0.10\,\mathrm{m^3\,s^{-1}}$, $S_o = 0.0077$, $W = 0.7\,\mathrm{m}$). (b) Negative surge induced by a rapid opening of a downstream gate in an initial steady flow ($Q = 0.020\,\mathrm{m^3\,s^{-1}}$, $S_o = 0$, $W = 0.5\,\mathrm{m}$); rapid red dye dispersion beneath the negative surge

limitations of laboratory investigations of the air bubble diffusion process in self-aerated air–water flows and of their extrapolation to full-scale prototype applications (Zhang & Chanson, 2017). Simply, an undistorted Froude similitude might be insufficient to describe accurately the air bubble diffusion process in self-aerated flows, when the ratio D_t/ν_T in laboratory models is larger than in prototype set-up. Physical modelling of air–water flows in laboratory might overestimate the importance of the air bubble diffusion process in comparison to momentum exchanges and turbulent processes in large prototype hydraulic structures.

Despite significant progresses within the last five decades, the above complexities of aerated flows, typical for hydraulic structures, require urgent development of new knowledge (Chanson, 2013). Detailed field studies remain a missing link. Air–water flow measurements in large hydraulic structures are very difficult and dangerous, and yet are so needed for physical and numerical computational fluid dynamics (CFD) model validation. Real-world free-surface aerated flows are typically sediment-laden. The resulting three-phase air–sediment–water turbulent flow motion is governed by three sets of equations of fluid motion, combined with some interface tracking and complicated coupling of equations at the various gas–solid–liquid interfaces, while the correct implementation of the boundary conditions is not trivial. Scale effects have been a well-known challenge in physical modelling of air–water flows (Chanson, 1997, 2009; Wood, 1991). The application of distorted scale models to air–water flows would be another worthwhile research topic. While the relevance of scale distortion and the interpretation of distorted physical model results have been well-documented in river hydraulics (Novak & Cabelka, 1981), it is surprising that the approach has not been systematically tested in self-aerated flow.

3 Transient turbulence in canals and conveyance structures

In canals, a brusque operation of control gates or sudden unexpected blockage of the channel may induce large unsteady flow motion called surges, which might overtop the channel banks, damaging and eroding the canal structure, or impact on bridges and tunnels (e.g. Favre, 1935; Treske, 1994). In an open channel, a sudden increase in water depth is called a positive surge (Fig. 4a), while a rapid lowering of the water surface elevation is termed a negative surge (Fig. 4b). From a visual perspective, a positive surge appears very turbulent, either in the form of an undular surge or a breaking jump (Fig. 4a), with a sharp discontinuity of the free-surface elevation in both cases. Conversely, a negative surge appears to be a deceivingly gentle drawdown of the water surface, sometimes barely perceptible by observers standing on the side (Fig. 4b).

In a canal, any gate operation induces simultaneously both positive and negative surges (Fig. 5). This is clearly seen in Fig. 5, presenting a partial gate opening, generating both positive and negative surges propagating downstream and upstream respectively following the gate operation. Free-surface measurements in large-size laboratory channels highlighted the rapid

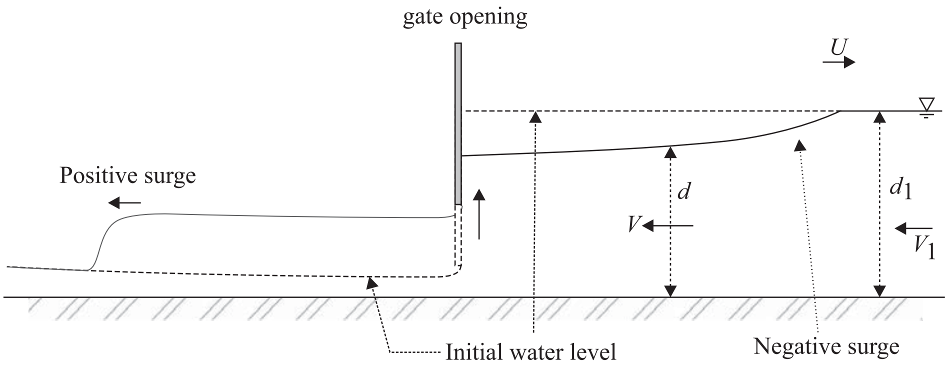

Figure 5 Sketch of a partial gate opening generating both positive and negative surges propagating downstream (left) and upstream (right) respectively following the gate operation. Main flow direction from right to left

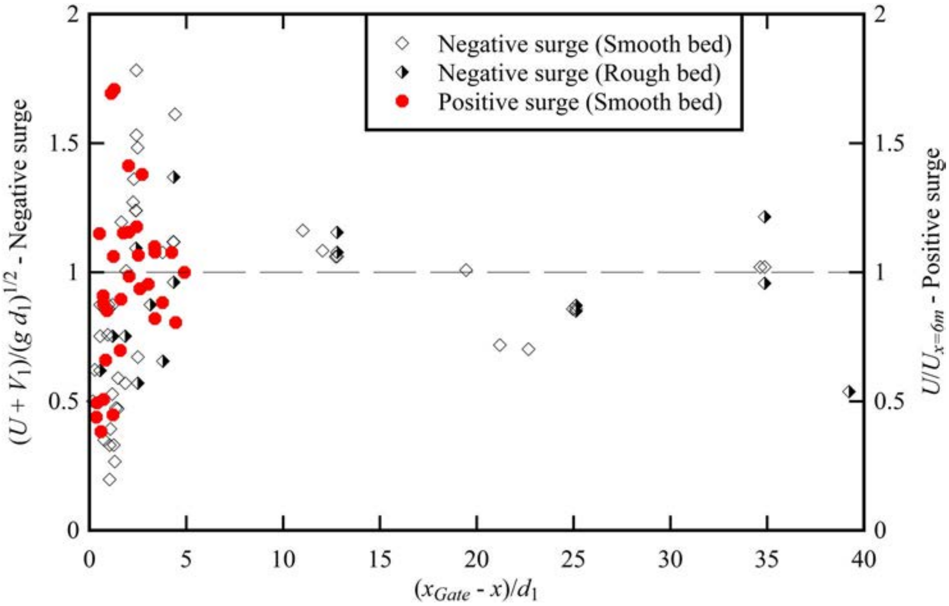

Figure 6 Instantaneous dimensionless celerity of positive and negative surges in rectangular canals during surge generation by a very rapid gate closure and opening respectively as a function of the dimensionless distance from the gate. The gate location corresponds to the left axis ($x_{Gate} - x$) = 0. Negative surge data (black symbols): Reichstetter and Chanson (2013), Leng and Chanson (2015a). Positive surge data (red symbols): Reichstetter (2011)

deformation of the free-surface in the immediate vicinity of the gate during the positive/negative surge generation process (Lubin et al., 2010; Sun et al., 2016). Instantaneous velocity measurements further indicated significant variations in longitudinal velocity during the positive/negative surge generation, as well as large fluctuations in all velocity components during the surge passage further upstream. The large instantaneous velocity fluctuations were associated with large Reynolds stress magnitudes. With both positive and negative surges, maximum instantaneous turbulent stresses were recorded, well in excess of the critical shear stress for sediment inception, nearly independently of the bed roughness (Chanson, 2010; Leng & Chanson, 2015a). The surge generation is further associated with a rapid acceleration of the positive/negative surge's leading edge immediately after gate operation, until the surge propagation becomes more gradual. This is seen in Fig. 6, presenting the celerity of the leading edge of the positive and negative surge as a function of the distance from the gate. In practice, an active regulation operational mode may cause unacceptable transient structural loads, yielding restrictions on free-board of canals, hydro-turbine operation, shipping and operation of locks, gates and seals (Cunge, 1966; Riquois & Ract-Madoux, 1965). The successive rapid closure and opening of gates may also provide optimum conditions to scour silted channels made of fine cohesive and non-cohesive materials, with the scour materials being rapidly advected downstream after the gate operation. A similar procedure is already implemented to cleanse sewers (Riochet, 2008).

During recent tsunami disasters, a number of observations showed massive inundation caused by tsunami waters following river courses, as well as major damage caused during the backrush along the estuarine channels. While the former was well documented (Adityawan et al., 2012; Tanaka et al., 2014), the latter is less well known. With the 2010 Chilean tsunami, retreating tsunami currents approached 6–7 m s^{-1} at the Ventura Harbor channel (California), causing significant scour at the mouth of the harbour. During the 2011 Tohoku earthquake and tsunami, significant erosion and scour of the subsurface soil deposits was caused by repetition of inflow and backrush of the tsunami in the river systems.

Positive and negative surges are most common in hydropower canals, water supply channel systems and navigation canals. The canal operation in an active regulation mode may generate complicated interactions between successive surge events, surge reflections and transient forces on man-made structures. These phenomena have many practical consequences, including in terms of the design of the freeboard of the canals, potential hydro-turbine operational restrictions and shipping conditions, while frequent pressure fluctuations cause high structural loads on regulation gates, navigation locks and gate seals. A major research finding has been that the visual appearance of the surge does not provide a reliable proxy of the turbulent stresses generated by the surge propagation nor the potential for bed scour. This important, yet counterintuitive result implies that traditional one-dimensional modelling, and generally any depth-averaged model, cannot deliver reliable predictions of the hydrodynamic impact of surges. Fluid–structure and fluid–sediment interactions need to be resolved at the smallest scales through detailed three-dimensional modelling, physical and/or numerical computational fluid dynamics (CFD).

With breaking bores, the roller presents a complicated two-phase turbulent flow motion (Fig. 4a). The breaking roller propagates in a highly turbulent three-dimensional fashion. Although the mean bore celerity U is quasi-constant in a horizontal channel, the instantaneous celerity u fluctuates very rapidly with both time and transverse location. The instantaneous roller toe perimeter forms a pseudo-continuous curve, at which the abrupt change in water depth generates a flow singularity, that is a line source of vorticity and entrained air, albeit interfacial aeration/de-aeration takes further place along the roller's upper surface (Leng & Chanson, 2015b; Wang et al., 2017). Experimental observations of the roller toe perimeter, based upon high-speed video movies, showed a wide range of instantaneous transient perimeter shapes and three-dimensional roller features, with very rapid variations with time and space. The longitudinal motion of the roller suggested a three-dimensional fluctuating behaviour, including some backshifts from time to time, with a ratio of standard deviation to temporal mean celerity $u'/U \sim 1$ (Leng & Chanson, 2015b). Such large fluctuations are linked to the generation and advection of large coherent structures in the roller, associated with air entrapment in the breaker and fascinating transient macro-structures (Leng & Chanson, 2019a, 2019b). The transverse profile of the roller toe perimeter presented some pseudo-periodicity with a characteristic transverse wavelength L_w such that $1 < L_w/d_1 < 10$ mostly (Chanson, 2016; Wang et al., 2017). Such unsteady, three-dimensional roller motions may highlight the need for consideration of transverse mixing of dissolved gas, sediments, nutrient and pollutant, and fine aquatic life particles, across the waterway during surge events.

Current and future research challenges must encompass high-quality field data, unsteady flow metrology and advanced three-phase unsteady flow modelling. Detailed field measurements are a necessity "because Nature is the final jury" (Roache, 1998, p. 697). Yet the safety of individuals and protection of instrumentation have been ongoing challenges that cannot be under-stated. The selection of suitable instruments and their usage, combined with the relevant signal processing and analyses, is very challenging in unsteady rapidly-varied flows, whether in the field or in laboratory. In natural channels, the propagation of surges is always associated with highly enhanced sediment dynamics and air entrainment in breaking bore rollers (Figs 1b and 4a). Future numerical CFD modelling must be developed in terms of multiphase flow equations, inclusive of the coupling between the different phases, and this must be validated with newer multiphase unsteady flow datasets of high quality for validation.

4 Upstream fish passage at road culverts

4.1 *Fish passage in culverts*

The culverts are among the most common hydraulic structures along rivers and streams, in both rural and urban water systems (Fig. 1c). A culvert is a covered structure allowing the passage of flood waters beneath an embankment, operating typically as free-surface flows. The designs are very diverse, using various shapes and construction materials determined by stream width, peak flows, stream gradient, road direction and minimum cost, with a broad range of shapes and sizes (e.g. Chanson, 2004a; Herr & Bossy, 1965). During water run-off, the turbulent flow motion in the structure is complicated because of the boundary conditions and flow turbulence. The culverts cause physical and hydrodynamic barriers that may reduce access to and prevent essential spawning, breeding and feeding habitats. The negative impacts on fauna, flora and fish species have been well documented in the literature (e.g. Warren & Pardew, 1998). The manner in which culverts block fish movement encompass perched outlets, high velocity and insufficient water depth in the culvert barrel, debris accumulation at the inlet, and standing waves in the outlet or inlet, all of which are closely linked to the targeted fish species (Katopodis, 1999; Olsen & Tullis, 2013). Although the initial focus was on commercial species, e.g. trout, salmon and eels, recent interests have extended to small native fish species, including small body-mass fish and juvenile of larger fish, which are typically less than 100–150 mm long and poor swimmers.

While a number of swimming performance and fish passage studies have been conducted in laboratories, the extrapolation of the results to prototype hydraulic structures is not trivial, because many studies do not fulfil the fundamental similarity

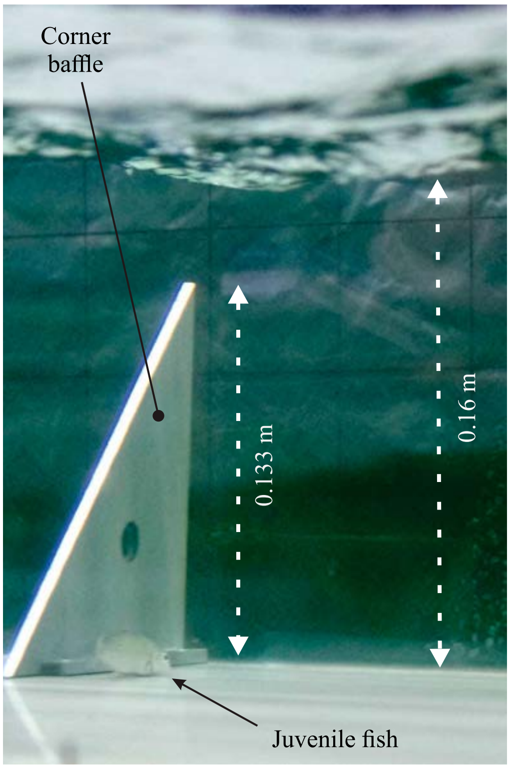

Figure 7 Juvenile silver perch (*Bidyanus bidyanus*) ($L_f = 63$ mm, $m_f = 2.8$ g) sheltering in the bottom left corner of a 12 m long 0.5 m wide culvert barrel channel equipped with small triangular baffles on one side (longitudinal spacing $L_b = 0.67$ m, height $h_b = 0.133$ m, ventilation hole: $Ø = 0.012$ m) against a steady flow ($Q = 0.0556\ \text{m}^3\ \text{s}^{-1}$, $V_{mean} = 0.695$ m/s, $d = 0.16$ m, $S_o = 0$) – flow direction from left to right, with fish resting immediately behind a corner baffle about mid-barrel

requirements in terms of a number of key relevant dimensionless parameters, including the intrinsic limitations of current fish swim tunnel tests and lack of standardization (Katopodis & Gervais, 2016; Wang & Chanson, 2018a, 2018b). Too few studies measured detailed quantitative characteristics of both turbulent fluid flow and fish motion (Nikora et al., 2003; Plew et al., 2007). Fewer investigations documented fish speed fluctuations and fluid velocity fluctuations, and fish response time and integral time scales (Cabonce et al., 2018; Wang et al., 2016). All the findings demonstrated that a number of key relevant parameters, including the ratios of fish speed to water velocity fluctuations, fish response time to turbulence time scale and fish length to turbulent integral length scale, are scale dependant when the same fish are used in laboratory and in the full-scale structure (Wang & Chanson, 2018a). In simple words, a complete similarity between laboratory data and full-scale observations is unachievable, and one must seek full-sale modelling. For example, Fig. 7 shows a photograph of an endurance test of small-bodied fish in a full-scale box culvert barrel cell (12 m long, 0.5 m wide) and Fig. 8 presents some results for another test in a smooth full-scale culvert barrel channel. Full-scale and near-full-scale modelling is likely to become the norm for any study of fish–turbulence interrelations.

4.2 *Modelling upstream fish passage in box culverts*

Observations of fish swimming and behaviour were recently recorded in box culvert barrels, based on field and full-sale laboratory studies (Blank, 2008; Cabonce et al., 2019; Wang et al., 2016). In smooth box culvert barrels, the fish swim preferentially next to the bottom corners, in regions of high turbulence, intense secondary motion and low velocity (Fig. 8). Figure 8 presents the trajectory of a juvenile fish in a 12 m long and 0.5 m wide culvert barrel channel. These recent findings are fundamental, highlighting the “sweet spots” where the fish shelter from high velocities and exploit to traverse the structure. The barrel corners represent regions of low water velocities where the fish interact with strong coherent vortices and the secondary currents. The fish use the turbulent eddies to minimize their energy spending. An upstream passage often cannot be successful when the fish need to fight strong turbulence! In a full-scale box culvert barrel channel, similar to that shown in Fig. 7, endurance swimming tests and fish kinematics data hinted at two preferential fish responses to open channel turbulence and vortical structures. In the first response mode, the fish react passively to eddies, their slow response enabling them to be advected by the flow turbulence, e.g. in recirculation and secondary currents. In the second mode, the fish tend to be pro-active, responding very rapidly to any change in turbulent flow conditions and using the changes in instantaneous flow conditions to migrate upstream (Cabonce et al., 2018; Wang et al., 2016).

Fish response to turbulence is not trivial but directly relevant to fish passage and fish-friendly culvert design. An accurate modelling, physically or numerically (CFD), of box culvert hydrodynamics is essential to deliver sizeable low velocity zone to assist upstream fish passage. A comprehensive understanding of fish behaviour is further a pre-requisite for advanced studies, e.g. how fish sense fluid flow turbulence to select optimum upstream path in turbulent flows. The most beneficial studies should provide a simultaneous characterization of both fluid and fish kinematics (Cabonce et al., 2018; Nikora et al., 2003; Plew et al., 2007; Wang et al., 2016). Fish kinematics, based upon high-speed video movies, may provide critical insights into the fluid–fish interactions, including fish trajectories, fish speed and acceleration, tailbeat frequencies and fish swimming energetics in turbulent channel flows (Chanson & Leng, 2021). Further investigations should consider the characteristic fish acceleration frequencies as well as the autocorrelation time scales of the fish acceleration, and a quantitative description of the fish energy consumption during their upstream migration in canonical turbulent flow motions. This knowledge would significantly help in designing flow control structures in newly designed and already constructed fish passages.

Future research topics should include the flow structure in pipe culverts, simultaneous turbulence and fish kinematics data, and some qualification and quantification of scale effects affecting fish swimming experiments. Circular culverts are the most common type of standard culverts. While the hydraulics of open

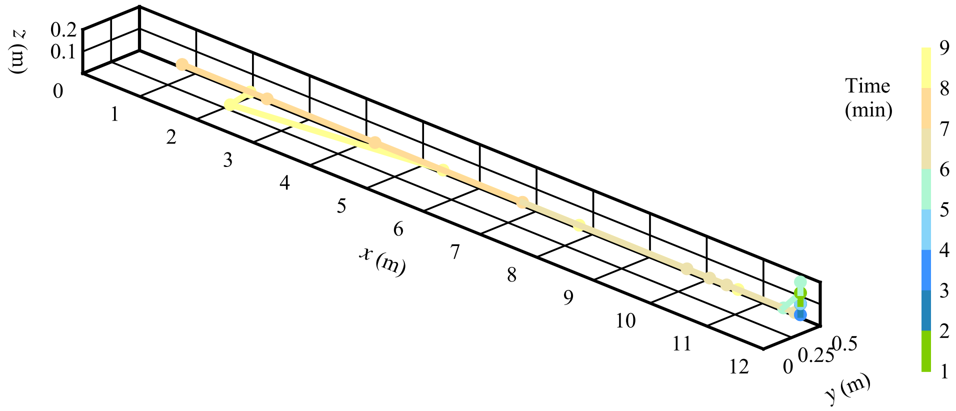

Figure 8 Trajectory of a juvenile silver perch (*Bidyanus bidyanus*) ($L_f = 37$ mm, $m_f = 0.6$ g) swimming upstream in a 12 m long 0.5 m wide smooth culvert barrel channel until complete culvert barrel traverse (8 minutes). Flow direction from top right to bottom left. The scale is in minutes

channel pipe flows is complicated because the rapid variation in cross-sectional shape with changes in water depth, the literature in relation to fish passage remains thin. Detailed simultaneous measurements of fluid turbulence and fish kinematic are critical to deliver a basic understanding of the fish–fluid interactions. Recent experiences hinted that a proper investigation necessitates a team of researchers with hydraulic engineering, bio-mechanics and fish biology expertise. In practice, many flume studies use real fish in laboratory channels, without consideration of similitude, similarities and potential scale effects (Wang & Chanson, 2018a). A qualification and quantification of the scale effects, and the impact on full-scale hydraulic structure design, remains to be undertaken.

5 Discussion and concluding remarks

Hydraulics structures have been built for more than 12,000 years and floods have been recorded for more than 8000 years, e.g. on the Nile River. Based on this massive experience, open channel hydraulics should be considered a fairly mature science and many would argue that current open channel textbooks are largely derived from the seminal lecture notes of Professors Bélanger and Bresse, at the Ecole des Ponts et Chaussées (France) (Bélanger, 1841; Bresse, 1868). But the development of cost-effective hydraulic structures, friendly to fauna and flora and adapted to multiphase flow, is a truly new challenge for the twenty-first century. Hydraulic designers are facing massive tests linked to the many technical challenges, including a re-evaluation of discharge capacity, sedimentation and siltation, environmental impacts, interactions between flow, fauna and flora, and multiphase coupling. This Vision Paper re-visits the self-aeration processes at hydraulic structures, the transient turbulence generated in conveyance structures during surge events, and the upstream fish passage in box culverts. While all these topics have previously been investigated with simplified models, a number of technical solutions are not satisfactory in terms of aquatic fauna and flora, fluid–structure interactions and operational restrictions. Our knowledge of self-aerated air–water flows in hydraulic structures lacks insights into the physical interfacial phenomena at the millimetric and sub-millimetric scales, including the turbulence modulation, although the implications in terms of design have been well-known for decades, e.g. flow bulking, drag reduction and re-oxygenation. Similarly, the characteristics of transient turbulence during surge propagation in conveyance structures remain mostly ignored and the practical applications largely untapped, despite the millions of kilometres of water channels worldwide. The adverse impact of road crossings on aquatic life is an emerging concern. Biological science studies have been largely based upon pseudo-quantitative observations, although very recent engineering and bioengineering research has been undertaken, hinged on advanced physics-based theory supported by high-quality experimental data.

Hydraulic structures have been traditionally designed based upon simplistic optimization developed for one-dimensional steady single-phase Newtonian fluid flow performances at a fixed design discharge. While the approach might be valid for simple hydraulic structures with a proven operational record, the twenty-first century has seen a shift towards modern designs based upon advanced methods, encompassing hybrid modelling combining analytical, physical, CFD and field methods, accounting for coupling between turbulence and particles (e.g. air, sediments, aquatic life and plants), and optimized for a broad range of operational flow conditions.

There is no doubt that the second half of the twentieth century marked a change in the perception of the structures by our society, but these man-made waterworks shall continue to play a major role in human life and activities because water is an indispensable element. The technical challenges in hydraulic structure design are formidable. For twenty-first century engineers, the future lies in strong links between engineering innovation, excellence in hydraulic research and quality education in universities. Innovative designs rely upon technically sound methods, some good common sense, as well as thinking "outside of the box". Professional engineering must be assisted by excellent research and development, often relying upon theoretical, physical and numerical modelling. Hydraulic engineers can benefit from recent advancement in fluid dynamics, including CFD, albeit validation remains a challenging issue (Bombardelli, 2012; Lubin & Glockner, 2015). The needs for multi-disciplinary expertise of high-level require research teams interacting across a broad range of disciplines, which is anything but trivial. The implications in terms of higher education are far reaching. On one hand, the universities have experienced a massive reduction in funding per full-time student, particularly in western countries. Fewer university academics have prior professional experiences, often dismissed by university selection panels. On the other hand, hydraulic engineering continues to experience a progressive evolution in skill requirements, e.g. CFD modelling, eco-hydraulics and interactions with aquatic life, multiphase flow coupling, sediment processes, water quality and quantity monitoring. Such a shift is not unlike the one discussed by Hunter Rouse in the 1930s (Rouse, 1938). University graduates need to be exposed to practical experiences in hydraulic engineering, and there are strong arguments for more laboratory experiences, field trips and field works in the undergraduate curricula (Chanson, 2004b). All these interactions must be complemented by indispensable exchanges between professionals, researchers and educators in engineering and other fields, e.g. ecology, biology, geomorphology, water chemistry and geopolitics.

Finally, what would be the most relevant PhD topics, which could qualify as top priority, especially for emerging researchers wanting to develop successful directions in their careers? Field measurements are likely the single most important drive of future research in hydraulic structures. This is true for all three topics discussed in this Vision Paper, albeit with some difference and specificity. Many spillway structures experience three-dimensional high-velocity flows, which would require measurements of three-dimensional two-phase gas–liquid flows in high turbulence conditions. Current gas–liquid instrumentation is not adapted to three-dimensional measurements and new developments are necessary. A similar need exists to investigate breaking bores at large-scale, e.g. tsunami bores and dam break waves, although a further complexity is the flow unsteadiness. The onset of self-aeration in turbulent free-surface flows is a massive topic with many research questions: e.g. what are the effects of bio-chemicals and surfactants on the inception conditions? In culverts, the flood discharge is typically sediment- and debris-laden. What are the interactions between aquatic life and sediments, e.g. in the barrel? How do wooden debris, e.g. in the inlet, impact onto upstream and downstream migration of small fish and juveniles? A recent study (Leng & Chanson, 2020) showed the potential for hybrid modelling combining physical modelling, theoretical calculations and CFD modelling. Could the approach be extended to devise smart efficient appurtenance suitable of the upstream passage of a broad range of fish guilds? Altogether the authors hope that the research topics highlighted above will attract a deserved attention from emerging hydraulic and hydro-environment researchers who will bring their enthusiasm, new ideas and innovative approaches.

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Supplemental data

Supplemental materials including tabular data are presented in Chanson et al. (2019) and can be accessed online at {https://espace.library.uq.edu.au/list/author_id/193/}.

Notation

A = channel cross-section area (m^2)
A_{fs} = surface deformation area (m^2)
B = free-surface width (m)
C = void fraction (–)
D_H = hydraulic diameter (m): $D_H = 4\,A/P_w$
D_t = air bubble diffusivity ($m^2\ s^{-1}$)
d = water depth (m)
d_c = critical flow depth (m)
d_1 = inflow depth (m)
F = bubble count rate (Hz)
g = gravity acceleration ($m\ s^{-2}$): $g = 9.794\ m\,s^{-2}$ in Brisbane, Australia
h = vertical step height (m)
h_b = baffle height (m)
L_b = longitudinal baffle spacing (m)
L_f = total fish length (m)
L_w = roller toe perimeter wave length (m)
m_f = mass of fish (kg)
P_w = wetted perimeter (m)
Q = water discharge ($m^3\ s^{-1}$)

$\mathrm{R_e}$ = Reynolds number defined in terms of the hydraulic diameter (–)
r = radius (m) of curvature
r_1, r_2 = principal radii (m) of curvature of an elongate spheroid
S = bed slope: $S_o = \sin\theta$ (–)
U = mean surge celerity (m s^{-1})
u = instantaneous surge celerity (m s^{-1})
u' = root mean square of instantaneous surge celerity (m s^{-1})
V = velocity (m s^{-1})
V_{mean} = cross-sectional mean velocity (m s^{-1}): $V_{mean} = Q/A$
V_x = longitudinal velocity component (m s^{-1})
V_1 = inflow velocity (m s^{-1})
v = velocity fluctuation (m s^{-1})
W = channel width (m)
x = longitudinal distance (m) positive downstream
x_{Gate} = longitudinal location (m) of gate
y = transverse distance (m)
z = vertical distance (m) positive upwards with $z = 0$ at the invert
μ_w = dynamic viscosity (Pa s) of water
ν_T = momentum exchange coefficient (m^2 s^{-1})
θ = angle between bed slope and horizontal
ρ_w = water density (kg m^{-3})
σ = surface tension (N m^{-1}) between air and water
$\varnothing$ = diameter (m)

Subscript

b = baffle characteristics
c = critical flow conditions
f = fish characteristics
x = longitudinal component
y = transverse component
z = vertical component
1 = upstream flow conditions

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