Hydraulics of vertical slot fishways: Non-uniform profiles

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Abstract

Vertical slot fishways (VSFs) are hydraulic structures which allow fish to swim around obstacles in rivers. These structures are subject to variations in discharge of either hydrological or operational origin, which result in non-uniform water depth profiles, i.e. differences in the water drops across the slots (ΔH) and mean depths (h_0) across the pools. Although non-uniform conditions are present in most VSFs, they are rarely considered in the design and evaluation of fishways. The aim of this work is to provide an introductory analysis of how non-uniform water depth profiles affect the hydrodynamics within the pools of VSFs. This study shows that flow patterns are controlled by changes in ΔH and h_0 in addition to slope and other geometrical alterations, as previously suggested. Non-uniformity alters the flow structure in pools and the spatial distributions of hydrodynamic variables. Consequently, critical thresholds of hydrodynamic variables for fish may be reached in VSFs designed with recommended slopes when operating under non-uniform conditions.

Keywords: Fishways; Water depth; Hydraulic design; Water flow; Hydraulic structures.

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Introduction

Vertical slot fishways (VSFs) are one of the most widely used structural mitigation measures to facilitate fish passage around obstacles in rivers (Fuentes-Pérez et al. 2017). These structures consist of a sloped channel with cross-walls, each of which has a vertical slot that divides the total height of the obstacle (*H*, difference between head- and tailwater levels) into a series of smaller drops (ΔH) which enable fish passage and create a step-like profile (Fig. 1).

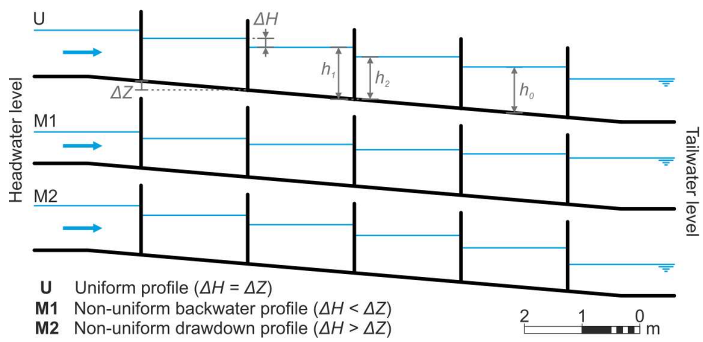

Fig. 1. Representation of the three different water depth profiles studied: (1) uniform profile (U), (2) non-uniform backwater profile (M1) and, non-uniform drawdown profile (M2). h_1 is the mean water depth upstream and h_2 is the mean water depth downstream.

VSFs have been widely studied. The first comparative studies of different VSF typologies were carried out by Rajaratnam et al. in 1986 and 1992, who defined a series of dimensionless equations to describe their performance. Since these initial studies, several authors have made further advances in the characterization of VSFs (Liu et al. 2006; Marriner et al. 2016; Puertas et al. 2004; Wang et al. 2010; Wu et al. 1999). Most studies have focused on uniform water depth profiles (here referred to as U), a specific combination of head- and tailwater levels that produces the same ΔH and mean water depths (h_0) at each of the cross-walls and pools of the fishway (Fig. 1). However, VSFs are subject to hydrological and operational variations in discharge and, thus, they exhibit a range of boundary conditions (i.e. different head- and tailwater levels combinations). Therefore, in addition to uniform profiles, two non-uniform profiles can also be created: a backwater profile (M1) and a drawdown profile (M2) (Fig. 1) (Fuentes-Pérez et al. 2014, 2017).

The classification of these profiles was first proposed by Rajaratnam et al. (1986) comparing the distribution generated by h_0 in pools (e.g. Fig. 2(b)) to the typical gradually varying flow profiles.

Poleni's (1717) equation (Eq.(1)) together with Villemonte's (1947) discharge coefficient (C_s) equation (Eq.(2)) can be used to correctly model these non-uniform water depth profiles (Fuentes-Pérez et al. 2014, 2017).

$$Q = \frac{2}{3} \cdot C_s \cdot b \cdot h_1^{1.5} \cdot \sqrt{2 \cdot g} \quad (1)$$

$$C_s = \beta_0 \left[1 - \left(\frac{h_2}{h_1} \right)^{1.5} \right]^{\beta_1} \quad (2)$$

where g is the gravitational acceleration, h_1 is the water depth upstream the cross-wall, h_2 is the water depth downstream the cross-wall, b is the width of the slot and, β_0 and β_1, are coefficients which depend on the geometry of the slot and pool dimensions

Non-uniform water depth profiles have the potential to alter the local flow structure and the spatiotemporal distributions of the hydrodynamic variables between pools (e.g. velocity, vorticity and pressure) as opposed to uniform profiles. This is due to the change in pool volume (dependent on h_0) and the water velocity at the slot, which is proportional to ΔH (Rajaratnam et al. 1986). Given the direct relation of hydrodynamic properties and the distribution of fish preferences and behavior (Cornu et al. 2012; Damien et al. 2014; Larinier 2002; Silva et al. 2011), non-uniformity may have direct consequences on fishway passage efficiency, i.e. on the percentage of fish that enter and successfully travel through a fishway (Bunt et al. 2012).

In Fuentes-Pérez et al. (2014, 2016, 2017) the discharge calculation and one dimensional water-depth profile prediction under non-uniform performance were studied for VSF, pool-weir fishways and step-pool nature-like fishways, respectively. In addition, in Fuentes-Pérez et al. (2018) 3D modelling of non-uniform performance was examined in a VSF without slope, showing that different M2 profiles could exhibit different flow patterns.

Here, the possible consequences of non-uniformity in fishway local hydrodynamics and of hydrodynamics in fishway passage efficiency are considered. Specifically, in this study the focus is on the differences between hydrodynamic variable contours in VSF pools under uniform and non-uniform water depth profiles (Fig. 1). It is demonstrated that non-uniform profiles produce similar flow pattern alterations to those observed when the VSF's slope is modified. Furthermore, it is shown that not only the mean quantities and hydrodynamic variable distributions are affected, but also their extreme values. As fish passage is known to depend on the distributions and magnitudes of local hydrodynamic variables, it is imperative that future studies consider non-uniform profiles in the research and design of VSFs.

Materials and Methods

Experimental Arrangement and Experiments

The experiments were conducted in an indoor 1:1 scale VSF at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon, Portugal. The VSF is a glass-walled open channel 10.0 m long, 1.0 m wide and 1.2 m high.

The VSF type corresponds to design 11 as defined by Rajaratnam et al. (1992). It consists of six pools divided by five cross-walls with a bottom slope (S) of 8.5 %. The cross-walls were made of wood (0.022 m thick (e)) with 0.105 m width slots (b measured between baffle vertices, if measured parallel to the cross-wall b_o = 0.125 m (according to Rajaratnam et al. (1992)). The facility also includes an upstream chamber (1.5 m long, 1.0 m wide and 1.2 m high) and a downstream tank (4.0 m long, 3.0 m wide, and 4.0 m high). The water level in the downstream tank is regulated by a gate, which allows to boundary conditions to be modified (Table 1) to reach different water depth profiles.

Table 1. Overview of the studied scenarios and their boundary conditions. Q is the discharge through the facility, $h_{2,final}$ is the tailwater depth, $h_{0,2}$ is the mean water depth in the target pool (i = 2) and ΔH_2 is the water drop in the slot upstream the target pool.

Scenario	Q (m^3/s)	$h_{2,final}$ (m)	$h_{0,2}$ (m)	ΔH_2 (m)
U – Uniform profile	0.081	0.65	0.72	0.178
M1 – Backwater profile	0.050	0.79	0.71	0.074
M2 – Drawdown profile	0.081	0.43	0.61	0.212

The water depth was measured with 1 mm precision at each cross wall by means of rulers installed downstream and in the opposite side of the slots. The water level oscillations were recorded for 8 seconds using a camera (Canon EOS 600D) with a sampling rate of 25 Hz.

The flow field of the VSF was measured using a Vectrino 3D ADV (Nortek AS) in the second pool, starting from the downstream end of the VSF. The ADV sampling interval was 180 s at a rate of 25 Hz. This sampling time was chosen to ensure convergence of time-averaged values of velocity (u), turbulent kinetic energy (k) and Reynolds shear stress (τ_{xy}) (Romão et al. 2017). The selected variables were chosen considering their demonstrated relevance for fish (Branco et al. 2013; Romão et al. 2017; Silva et al. 2011, 2012; Wang et al. 2010). For all three study cases, two profiles parallel to the floor were measured at $0.5h_0$ and $0.75h_0$, above the floor. Measurements were post-processed using WinADV (release 2.031) software using the Goring and Nikora (2002) phase-space threshold despiking as modified by Wahl (2003). Additionally, a minimum signal correlation of 70% was applied as the threshold for valid data. Invalid data were eliminated without substitution. The 76.54 % of data in average was used for subsequent analysis.

Table 2 shows the conventional velocity-based variables based on ADV measurements. Reynolds decomposition of the instantaneous velocity ($u = \overline{u} + u'$) was performed on all measurements.

Table 2. Variables calculated after Acoustic Doppler Velocimeter (ADV) data processing. ADV (180s at 25Hz) measurements taken at the studied pool (second pool, starting from the downstream end of the VSF) (velocity ($\overline{u}$), turbulent kinetic energy (k) and, horizontal Reynolds stress tensor (τ_{xy})).

Variables	Equation	
Time-averaged velocity ($\overline{u}$)	$\overline{u}=\frac{\sum_{j=1}^{n}\sqrt{u_{x,j}^2+u_{y,j}^2+u_{z,j}^2}}{N}$	(3)
Turbulence kinetic energy (k)	$k=\frac{1}{2}\left(\overline{u_x'^2}+\overline{u_y'^2}+\overline{u_z'^2}\right)$	(4)
Horizontal Reynolds stress (τ_{xy})	$\tau_{xy}=-\rho\overline{u_x' u_y'}$	(5)

Data treatment and validation

All fits were performed using the least squares method, and the accuracy of each fit was evaluated using the coefficient of determination (R^2), visual comparisons of the error distributions and graphical analysis. The comparison of predicted water depth profiles using the fits with the observed profiles were carried out graphically and by the calculation of mean relative errors (MRE). Contour analysis was performed to investigate differences between the three water depth profiles studied. The triangulated natural neighbor interpolation method was used to plot the contours. All data analyses and fits were conducted using MATLAB (release R2017a).

Experimental Results and Discussion

Discharge equations for varying water depth profiles

Fig. 2(a) shows the discharge coefficient for the studied fishway including the water depth profiles investigated in this study (Fig. 2(b)). It can be seen that Villemonte's equation (Eq.(2)) is capable of adequately representing discharge coefficient. In contrast to dimensionless equations (Rajaratnam et al. 1986, 1992), any water depth profile (uniform and non-uniform) can be represented if the boundary conditions of the scenario are known (Fuentes-Pérez et al. 2018). The profile calculation (Fig. 2(b)) can be achieved solving Eq. 1 and Eq. 2 by a downstream to upstream calculation, considering fishway geometry, the discharge of the fishway and the h_2 at the most downstream slot and assuming a horizontal water surface in each pool (Table 1) (Fuentes-Pérez et al. 2014). The MRE between the observations and simulations were of 2.01 %, 2.27 % and 1.68 % for U, M1 and M2, respectively. The differences between the calculated and observed profiles (Fig. 2(b)) can be explained by the assumption of a geometrically perfect structure in the numerical representation of the simulation (e.g. identical width in all the vertical slots or the same topographic difference between all cross-walls). When comparing the average depth observed in uniform profiles with the estimated one by dimensionless relations for design 11 a deviation of 7.46 % was observed (0.72 m (Table 1) *vs* 0.67 m (Rajaratnam et al. 1992). This indicates a slightly smaller discharge coefficient for the studied VSF and could be explained by differences in wall thicknesses.

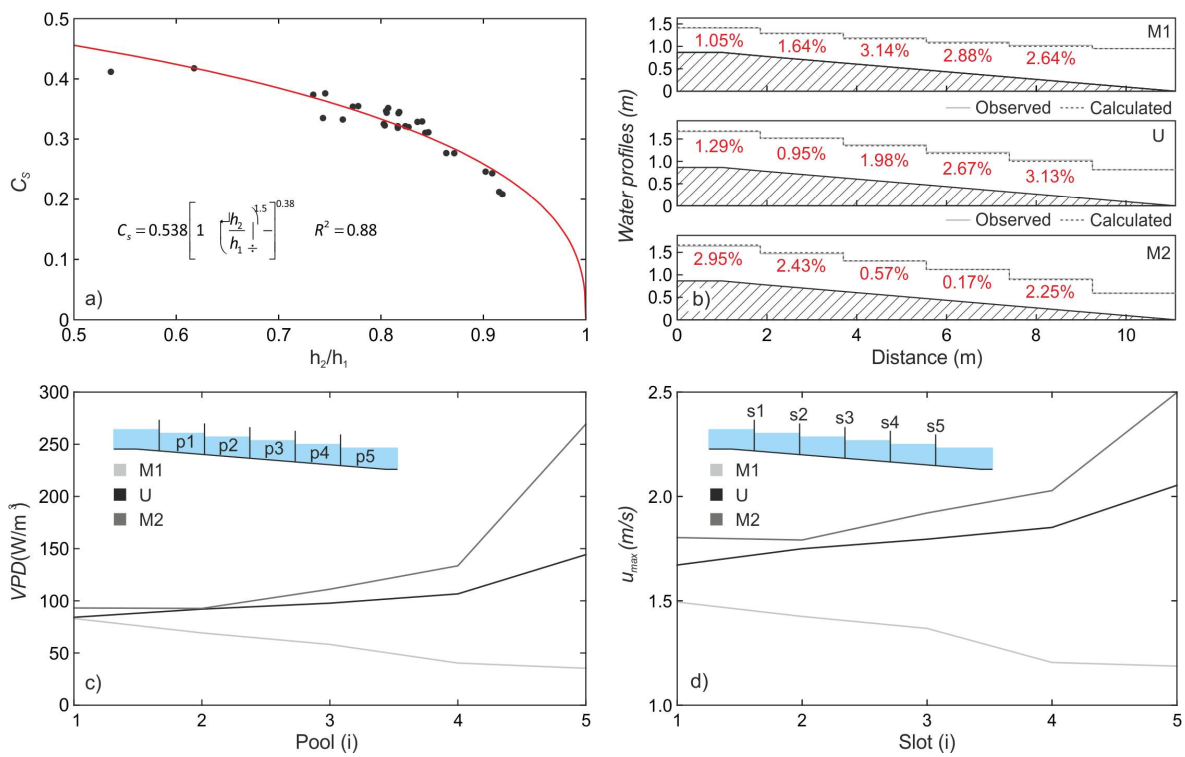

Fig. 2. Summary of the fishway performance. a) Fit of Villemonte's discharge coefficient (C_s, Eq. 2) distribution in relation to submergence ratio of the cross-wall (h_2/h_1). b) Calculated and observed water profiles (relative difference between calculated and observed h_1 in each pool and scenario in red). c) Distribution of volumetric power dissipation ($VDP = Q \cdot \Delta H \cdot g \cdot \rho / (L \cdot B \cdot h_0)$) in pools during studied scenarios. d) Distribution of theorical maximum velocity ($u_{max} = (2 \cdot g \cdot \Delta H)^{0.5}$) in slots during studied scenarios.

Drops and water depths were observed to differ substantially between the uniform and non-uniform profiles (Fig. 1 and Fig. 2(b)), resulting in either a systematic increase or decrease of ΔH and h_0. M2 profiles resulted in a decrease of h_0 and an increase of ΔH, causing the reduction of the pool volume and the increase of the theorical maximum velocity in the slot ($u_{\max} = \sqrt{2g\Delta H}$) (Fig. 2(c)) and the volumetric power dissipation ($VDP = Q \cdot \Delta H \cdot g \cdot \rho / (L \cdot B \cdot h_0)$)) (Fig. 2(d)). In some case these values can reach the theorical recommendations (Larinier 2002). M1 profiles were characterized by the increase of h_0 and the decrease of ΔH, which reduces the expected u_{max} in the slot (Fig. 2(c)) and the *VDP* (Fig. 2(d)). These results show that non-uniform performance may modify the conditions that the fish will need to face when negotiating the fishway (Larinier 2002). Therefore, considering non-uniform performance in the design of fishways is vital to detect problems and design solutions when variable river boundary conditions exist.

Hydrodynamic variable contours

Fig. 3 shows the spatial pattern of the observed flow structure and hydrodynamic variable distributions of the time-averaged flow velocity magnitude ($\overline{u}$), turbulent kinetic energy (k) and the streamwise-transverse component of the Reynolds stress tensor (τ_{xy}) for the different water depth profiles studied at two different depths ($0.5h_0$ and $0.75h_0$, above the floor) in the second pool, starting from the downstream end of the VSF.

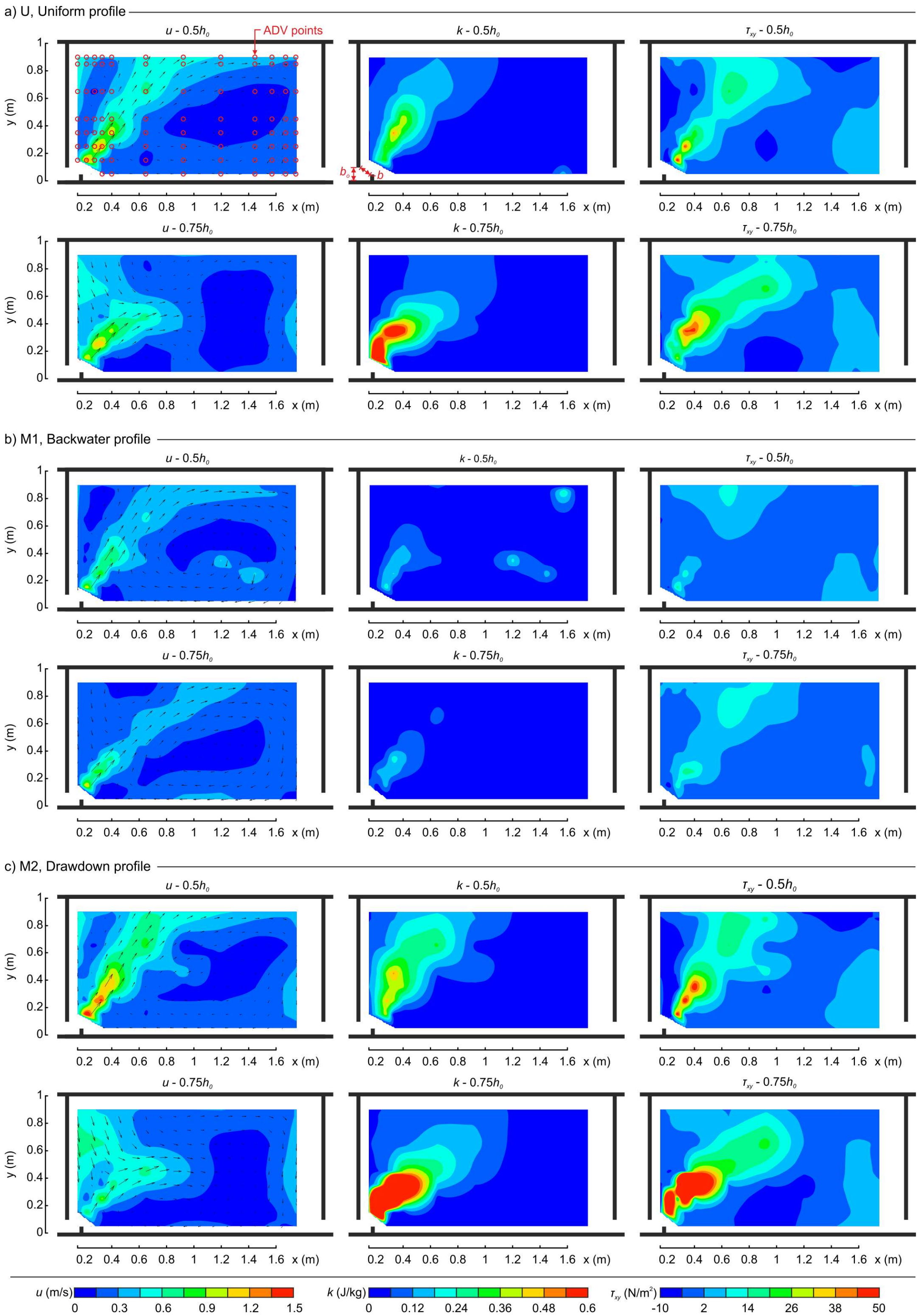

Fig. 3. Spatial distribution of hydrodynamic variables derived from Acoustic Doppler Velocimeter (180s at 25Hz) measurements in the studied pool (second pool, starting from the downstream end of the VSF) (velocity ($\overline{u}$), turbulent kinetic energy (k) and, horizontal Reynolds stress tensor (τ_{xy})). a) Uniform profile. b) Backwater profile (M1). c) Drawdown profile (M2).

The observed flow structure (u, Fig. 3) can be explained by the evolution of ΔH and h_0 in the different water depth profiles. First, considering U (Fig. 3(a)) and M2 profiles (Fig. 3(c)) ($\Delta H \geq \Delta Z$) similar spatial patterns were observed. In both cases, it seems that the overall hydrodynamic parameter distribution is fully three-dimensional. The jet from the slot exhibited a high vertical component, penetrating deeply into the pool and reaching the side-wall opposite to the slot. The jet had higher hydrodynamic variable magnitudes near the slot and was oriented towards the surface (u – $0.5h_0$, Fig. 3(a, c)). At lower depth contours (u – $0.75h_0$, Fig. 3(a and c)), the jet decayed rapidly as it travelled through the pool. This was driven by its vertical orientation, which resulted in the bulk flow at deeper regions being pushed towards the surface nearest to the side-wall area, leading to its rapid deceleration. In the case of M1 ($\Delta H < \Delta Z$), the flow structures observed at the two investigated depths were similar due to the lower vertical component of the jet.

The flow pattern observed was similar to the evolution observed for design type 18 VSF (Rajaratnam et al. 1992) when subject to slope changes (Liu et al. 2006; Wu et al. 1999), despite the geometrical differences between fishways types. During U and M2 ($\Delta H \geq \Delta Z$) the pool presented a pattern similar to the one observed during higher slopes (S = 10 %, pattern 2, Wu et al. (1999)) while during M1 ($\Delta H < \Delta Z$) the pattern was similar to the one observed during lower slopes (S = 5 %, pattern 1, Wu et al. (1999)).

This suggests that ΔH and, in extension non-uniformity, is also a driver for the different flow patterns in the pools in addition to the geometrical characteristics of the fishway (Bermúdez et al. 2010; Liu et al. 2006; Wu et al. 1999). Therefore, it is possible to have different flow structures with different combinations of ΔH and h_0, independently of the VSF bottom slope or other geometrical changes. For example, it has been shown that the angle between baffles or baffle, slot and pool dimensions can modify flow structures (Bombač et al. 2017; Puertas et al. 2012).

Similar conclusions can be drawn from the spatial hydrodynamic variable distributions of k and

τ_{xy} (Fig. 3). The hydrodynamic variables tended to have a higher dependency on the depth in U and M2 than in M1. In addition, both profile types had higher variable magnitudes, which can be attributed to the higher velocity in the slot, as a result of a larger ΔH, and the lower volume in the pool.

Flow patterns are also directly related with u_{max} and the *VPD*, as they all depend in ΔH or/and h_0. These variables have demonstrated to influence the local hydrodynamic variables which impact fish passage in VSF (Cornu et al. 2012; Damien et al. 2014). Therefore, it is strongly recommended to include non-uniform profiles in the study, design and analysis of VSF hydraulic performance and fish passage efficiency.

Summary and conclusions

This technical note illustrates that non-uniform water depth profiles produce different water depths and drops than those observed during uniform water depth profiles. This results in a systematic transformation of the local spatial distributions of hydrodynamic variables as well as their magnitudes.

Differences in pool flow patterns caused by non-uniform water depth profiles were found to be related with previous observations that consider uniform conditions and VSFs of different slopes. Therefore, this study suggests that ΔH (indicator of energy slope) can produce different flow patterns within the pool for the same bed slope. Although in uniform conditions ΔH changes for different slopes ($\Delta H = \Delta Z$), when fixing the slope and operating with non-uniform profiles, VSFs may have a wide range of ΔH conditions ($\Delta H > \Delta Z$ or $\Delta H < \Delta Z$). Consequently, further analyses considering both different slopes and non-uniform water depth profiles should be carried out to establish the relative influence of each variable.

Finally, it was shown that the spatial distributions of hydrodynamic variables were altered significantly when considering non-uniform water depth profiles in VSFs. Due to the influence of local hydrodynamic variables in fish passage, the overall fishway efficiency may be altered when subjected to non-uniform water depth profiles. It is therefore recommended that future fishway studies explicitly include non-uniform water depth profiles. This will ensure that the actual variability encountered in rivers, which may be driven by both hydrological and operational changes, is considered in the design and evaluation of fishways.

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Notation

The following symbols are used in this technical note:

b = slot width measured between baffle vertices (m)

b_o = slot width measured parallel to the baffle, considering Rajaratnam et al. (1992) (m)

C_S = discharge coefficient for Eq. (2)

e = thickness of the cross-wall (m)

g = acceleration due to gravity (m/s^2)

h_0 = mean water depth in the center of the pool (m)

$h_{0,i}$ = mean water depth in the center of the pool i (m)

h_1 = mean water depth upstream of the slot (m)

$h_{1,i}$ = mean water depth upstream of the slot i (m)

h_2 = mean water depth downstream of the slot (m)

$h_{2,i}$ = mean water depth downstream of the slot i (m)

i = slot or pool number

k = turbulence kinetic energy (m^2/s^2 = J/kg)

n = total number of slots

Q = discharge or flow rate (m^3/s)

R^2 = determination coefficient

S = slope of the fishway (m/m)

u = velocity (m/s)

u' = velocity fluctuations (m/s)

u_{max} = maximum velocity in the slot (m/s)

u_x u_y u_z = velocity components (m/s)

VDP = volumetric power dissipation (W/m^3)

β_0, β_1 = dimensionless coefficients for Eq. (2)

ΔH = difference in water level between pools or head drop ($h_1 - h_2$) (m)

ΔZ = topographic difference between slots (m)

τ = Reynolds stress (N/m^2)

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