RBRH

Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 24, e20, 2019
Scientific/Technical Article

https://doi.org/10.1590/2318-0331.241920180174

Three-dimensional numerical simulation of flow in vertical slot fishways: validation of the model and characterization of the flow

Simulação numérica 3D do escoamento em escadas para peixes com ranhura vertical: validação do modelo e caracterização do escoamento

Daniela Guzzon Sanagiotto[1], Júlia Brusso Rossi[1], Luísa Lüdtke Lauffer[1] and Juan Martín Bravo[1]

[1]Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brasil
E-mails: dsanagiotto@ufrgs.br (DGS), julia.rossi@ufrgs.br (JBR), luisalauffer@gmail.com (LLL), jumarbra@iph.ufrgs.br (JMB)

Received: October 28, 2018 - Revised: January 29, 2019 - Accepted: March 02, 2019

ABSTRACT

Vertical slot fishways allow energy dissipation as a function of the pool, longitudinal slope, baffle and vertical slot design. The mean and turbulent flow patterns in these structures must be compatible with the fish target. The design of these structures is commonly based on previous successful fishways as well as simplified theoretical equations and empirical relationships. To aid in the design of these structures, a three-dimensional hydrodynamic model was used to simulate the flow, and experimental studies were used to validate the model. The mean velocities, pressures and parameters indicative of turbulence were analyzed. The maximum flow velocities were up to 32% higher than the values obtained using a simplified theoretical equation. The evaluation of the volumetric dissipated power indicated that the mean value for the pool was lower than 150 W/m^3; however, analysis of the spatial distribution showed that in some areas, the values can exceed 1000 W/m^3. The results indicate that the numerical simulation was able to adequately represent the flow considering the computational cost involved. Accordingly, it can be used as a complementary tool for the design of new fishways and for the analysis of modifications in existing ones.

Keywords: Fishpass; Velocity; Turbulence; CFD; Fish.

RESUMO

As escadas para peixes com ranhuras verticais permitem que ocorra a dissipação da energia do escoamento em função da forma da bacia, dos defletores, da declividade longitudinal e da largura da ranhura vertical. Estas estruturas devem apresentar padrões médios e turbulentos do escoamento compatíveis com os peixes que irão transpô-la. Tipicamente a concepção das escadas para peixes é baseada na utilização de geometrias empregadas com sucesso em situações anteriores e a estimativa das características do escoamento através de equações teóricas simplificadas e relações empíricas. Para contribuir na concepção dessas estruturas, foi utilizado um modelo hidrodinâmico tridimensional para simular o escoamento e estudos experimentais para validar o modelo. Velocidades médias, pressões e parâmetros indicativos da turbulência foram analisados. As velocidades máximas do escoamento foram até 32% superiores aos valores obtidos utilizando uma equação teórica simplificada. A avaliação da potência dissipada por unidade de volume indica que o valor médio para o tanque é inferior a 150 W/m^3, no entanto, a análise da distribuição espacial desta grandeza no tanque, mostra que valores pontuais podem ultrapassar 1000 W/m^3. Os resultados indicam que a simulação numérica foi capaz de representar de forma adequada o escoamento, considerando o custo computacional envolvido e pode ser utilizada como uma ferramenta complementar para o projeto de novas escadas para peixes e para a análise de modificações em estruturas existentes.

Palavras-chave: Passagens para peixes; Velocidade; Turbulência; CFD; Peixes.

INTRODUCTION

The river fragmentation caused by the construction of physical barriers causes major changes in the environment. Among these impacts is the impediment of the free transit of aquatic organisms, which need to move for reproduction and feeding, among other reasons. Possibly the most affected species of fish are those that migrate during the reproduction process. To diminish this negative effect, technical fish passes have been implemented for the operational life of many physical barriers. Such mechanisms, can be fishways or fish ladders, locks, elevators, or systems of capture, transport and release (MIRZAEI, 2017; SANAGIOTTO et al., 2012). These structures should ensure the movement of fish to their areas of interest as well as a return path in a manner compatible with the swimming skills and biological characteristics of the particular species.

Fishways in general are characterized by channels, with transverse baffles forming pools. The total height of the obstacle is divided into smaller falls through the pools to provide adequate hydraulic conditions for the capacity of the ichthyofauna and to allow passage through the obstacle (FUENTES-PÉREZ et al., 2017). An effective fishway should quickly attract migratory fish and allow them to enter, pass through the pools and leave safely with minimal costs in terms of time and energy. If the velocity and turbulence kinetic energy in the pools are very high, or if the water depth is too low, the fish will be unable to swim through the structure (BOMBAČ; ČETINA; NOVAK, 2017).

Among the various types of fishways, vertical slot fishways have advantages for the movement of fish. Figure 1 shows a schematic of a vertical slot fishway. In these structures, fish can choose the swimming depth according to their preference because there is no obstruction of the aperture between the baffles along the entire depth of the pool. Between consecutive slots, a main jet forms, where the maximum velocities are found, allowing the fish to clearly identify the upstream direction and thus minimizing the chance that individual fish will become disoriented along the course. Inside each pool there is a large area with lower velocities than those found in the main jet. This area can be considered a resting zone for fish along the course. The presence of regions with lower velocities is a required element, as it favors less robust fish and/or allows transit on longer fishways. Some fish species may need to rest, or holding areas may be necessary to overcome a large number of pools, associated with high vertical physical barriers (WILLIAMS et al., 2012). The wide range of flows for the operation of vertical slot fishways should also be noted as a favorable feature: discharge variations affect the depth of the flow, but flow patterns are maintained inside the pools.

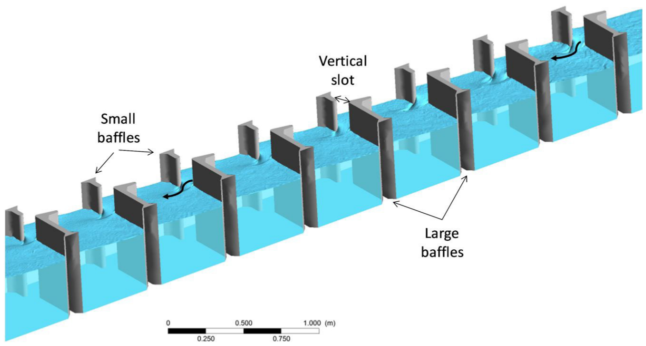


Figure 1. General view of a vertical slot fishway.

The flow in vertical slot fishways has been the subject of prior experimental studies (e.g., BOMBAČ et al., 2014; CALLUAUD et al., 2014; MARRINER et al., 2016; RAJARATNAM; VAN DER VINNE; KATOPODIS, 1986; RAJARATNAM; KATOPODIS; SOLANKI, 1992; SANAGIOTTO et al., 2012, 2011; VIANA; FARIA; MARTINEZ, 2014; WU; RAJARATNAM; KATOPODIS, 1999) and numerical evaluations (e.g., AN et al., 2016; BOMBAČ; ČETINA; NOVAK, 2017; MARRINER et al., 2014).

Analysis of the results obtained by these previous experimental and numerical studies allows us to satisfactorily describe the main characteristics of the flow in many of vertical slot fishways. However, the wide range of combinations of geometric parameters (e.g., pool size, aperture width, longitudinal slope, presence of elements in pools) requires that their selection be linked to a prediction of the mean and turbulent flow characteristics. These characteristics should be within acceptable limits for the fish species present at the site of the obstacle to be transposed.

The maximum velocity, as well as the velocity distribution within the fishway pool, is the first requirement for evaluation. Excessive maximum velocities may represent a barrier to the course of certain fish species. Generally, a simplified evaluation of maximum flow velocities can be performed through analysis of the potential theoretical velocity:

$$V_t = \sqrt{2g\Delta h} \tag{1}$$

where g is the gravitational acceleration and Δh is the difference in depth between consecutive pools. This relationship is obtained from the Bernoulli equation, assuming that velocities within the pools are insignificant and that the difference in water depth between consecutive pools produces the maximum velocity in the region of the slot, which is the potential theoretical velocity (MARRINER et al., 2014). Some studies (e.g., AN et al., 2016; LIU; RAJARATNAM; ZHU, 2006; MARRINER et al., 2016; PUERTAS; PENA; TEIJEIRO, 2004; WU; RAJARATNAM; KATOPODIS, 1999) have indicated good agreement between the potential theoretical velocity and the maximum velocity in the slot. However, depending on the ratio of the aperture width to pool size (width and length), the maximum velocity may be underestimated, as reported by Bombač, Četina and Novak (2017), Calluaud et al. (2014), Klein and Oertel (2015) and Sanagiotto, Rossi and Bravo (2019), among others.

Parameters indicative of flow turbulence include volumetric dissipated power, turbulence kinetic energy, the turbulence intensity and Reynolds shear stress. Generally, these quantities help to explain the behavior of fish inside pools, by the selection of certain preferred ranges or supported limit values.

The volumetric dissipated power is possibly the first criterion proposed to evaluate the adequacy of flow for fish traffic, considering the energy dissipation in pools and, in a simplified way, turbulent flow patterns. Bell (1990) considered the limit value of 191 W/m^3 for maximum energy dissipation in the pool tolerated by salmonids. Later studies associated upper limits of the order of 200 W/m^3 (FAO, 2002; LARINIER, 2002) or 250 W/m^3 (WANG; DAVID; LARINIER., 2010) for salmonids, and about 150 W/m^3 (FAO, 2002; LARINIER, 2002) for cyprinid and other weaker fish. Puertas, Pena and Teijeiro (2004) commented that in small fishways, the volumetric dissipation power can be up to 400 W/m^3. On the other hand, sometimes the maximum values considered are much lower, for example 40 W/m^3, for some species of Australian fish (LAUCHLAN ARROWSMITH; ZHU, 2014). These values refer to average magnitudes of volumetric dissipated power per pool. From measurements and flow simulations, fields can be constructed with the distribution of these quantities within the pool. Likewise, fields of other parameters indicative of the turbulence mentioned, such as turbulence kinetic energy and Reynolds shear stress, can be defined.

The limit values and preferred ranges of parameters indicative of turbulence by fish are still poorly understood for most species. Some information can be obtained by comparing the hydraulic characteristics of the flow in an existing fishway and the species that can successfully pass through the structure. In this way, values of certain parameters indicative of turbulence can be associated with particular individuals.

The flow in fishways is analyzed through computational fluid dynamics for most applications using two-dimensional (2D) hydrodynamic models in the horizontal plane (e.g., BERMÚDEZ et al., 2010; BOMBAČ; ČETINA; NOVAK, 2017). These evaluations are suitable for vertical slot fishways with a low slope and where vertical velocity components are very small in practically the entire pool. For evaluation of structures with higher slopes and detailing of the region near the vertical slot, where there are important vertical components, it is necessary to use three-dimensional (3D) numerical modeling (e.g., ABDELAZIZ, 2013; AN et al., 2016; BALLU et al., 2017; MARRINER et al., 2014).

For a given scheme, experimental data can be used to validate the computational fluid dynamics method. If the model is validated, it can be used to simulate conditions different from those tested experimentally. Therefore, promoting the validation of 3D hydrodynamic models to describe and characterize mean and turbulence patterns of flow is an extremely important area of research for better understanding of the flow in fishways (HOTCHKISS; FREI, 2007).

In this context, this work uses 3D computational fluid dynamics resources to reproduce the flow conditions observed in an experimental study of a vertical slot fishway. Through the validated numerical model, the influences on flow by variations of geometry (i.e., slope, pool dimensions, baffle shape and others) can be evaluated. The main contribution of this work is to provide a 3D numerical simulation process with relatively low computational costs that can reliably represent the main quantities of interest in regard to the flow in vertical slot fishways. The results of this work will be useful for the definition of future project geometries and the determination of adequate flows for the species at specific sites. Further, it is expected that the work will contribute to the analysis of small changes in existing geometries of vertical slot fishways with the aim of making the flow less selective.

MATERIALS AND METHODS

Scope of the research

The focus of this work is the vertical slot fishway installed at Igarapava Hydropower Plant (HPP) in Brazil, described by Viana, Martinez and Marques (2007) and Viana, Faria and Martinez (2014). Prior studies have presented results on the behavior of the flow in this structure, obtained through a partial physical model at a 1:5 scale (SANAGIOTTO et al., 2012, 2011). In this work, we validate a 3D computational fluid dynamic model for analysis of vertical slot fishways. Simulated results are compared with experimental data.

Simulations were conducted with the same dimensions of the scale model for the purpose of direct comparison of the results without additional scale effects. The structure of the present study has nine consecutive pools that are 0.60 m long, 0.60 m wide, and have a vertical slot width (b_0) of 0.08 m and a slope of 6.00%. In addition to the nine equal pools, the model has an inlet region and an outlet region, with a total length of approximately 9.00 m (Figure 2a,b).

The experimental studies used an acoustic doppler velocimeter (ADV), to measure velocities in a 3D mesh of a control pool (central pool) with 50 Hz frequency. Pressure measurements at the bottom of the control pool were made using piezo-resistive pressure transducers. Locations of pressure and velocity measurement points are shown in Figure 2c. Details of the experimental studies, including data treatment and analysis of the mean and turbulent flow behavior, are described in Sanagiotto et al. (2012, 2011).

Governing equations

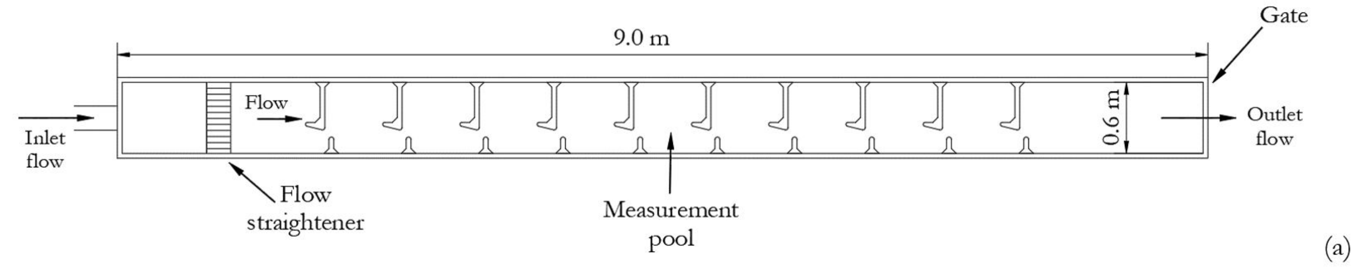
For 3D numerical simulation of the flow, the commercial Ansys-CFX program (ANSYS, 2013) was used. This program was also used by Marriner et al. (2014) for the analysis of vertical slot fishways.

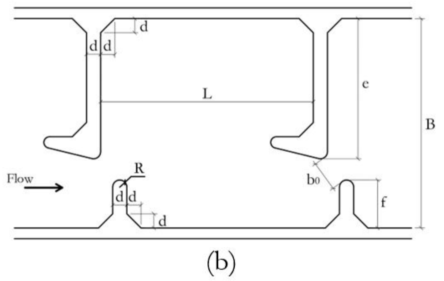
The model uses the finite volume method to solve flow equations. Turbulence was modeled using the Reynolds decomposition—Reynolds Averaged Navier-Stokes (RANS)—in 3D. The k-ε turbulence model was used (JONES; LAUNDER, 1972). This model has been widely tested and successfully applied to determine the turbulent viscosity for a wide range of complex flows. The k-ε model is most commonly used to represent turbulence in modeling of vertical slot fishways (AN et al., 2016; KHAN, 2006; MARRINER et al., 2014, 2016; QUARANTA et al., 2017; UMEDA et al., 2017) and other types of fishways (ABDELAZIZ, 2013; BAKI; ZHU; RAJARATNAM, 2016; BLANK, 2008; MAO et al., 2012; SHAMLOO; AKNOONI, 2012; TRAN et al., 2016).

The equations of continuity and conservation of momentum for steady flows solved by the program are, respectively:

$$\frac{\partial}{\partial x_j}\left(\rho U_j\right)=0 \tag{2}$$

$$\frac{\partial}{\partial x_j}\left(\rho U_i U_j\right)=-\frac{\partial p'}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\left(\mu+\mu_t\right)\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\right]+S_M \tag{3}$$





Dimension	Model	Prototype
L (m)	0.60	3.00
B (m)	0.60	3.00
b_0 (m)	0.08	0.40
R (m)	0.02	0.10
D (m)	0.04	0.20
e (m)	0.40	2.00
f (m)	0.14	0.70

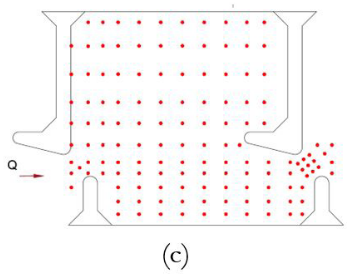


Figure 2. (a) General configuration in top view (dimensions in meters, referring to the model in scale); (b) pool detail with model and prototype dimensions; (c) points of the experimental measurements. Adapted from Sanagiotto et al. (2011).

where ϱ is the fluid density; U represents the velocity time series, which can be divided into an average component and a time-varying component; μ is the dynamic viscosity of fluid; μ_t is the turbulent viscosity of fluid; p' is the modified pressure; and S_M is the sum of the body forces (ANSYS, 2013). The modified pressure is defined as:

$$p' = p + 2/3.\rho.k \quad (4)$$

where p is the pressure and k is the turbulence kinetic energy.

In the k-ε model, the turbulent viscosity (μ_t) is related to the turbulence kinetic energy (k) and turbulence dissipation rate (ε) and described as:

$$\mu_t = C_\mu.\rho.\frac{k^2}{\varepsilon} \quad (5)$$

where C_μ is a dimensionless constant and equal to 0.09. The values of k and ε are taken directly from the differential transport equations.

The free surface between air and water was modeled using the volume of fluid (VOF) method (HIRT; NICHOLS, 1981), where each computational cell is composed of fractions of each of the two phases (water and air). The VOF method solves the set of momentum equations in the domain, while storing the volume of the two phases in each computational cell. In Equations 2 and 3, the physical properties of density and viscosity are obtained from the volume fractions of air and water phases in each cell:

$$\rho = \alpha_{water}.\rho_{water} + \alpha_{air}.\rho_{air} \quad (6)$$

$$\mu = \alpha_{water}.\mu_{water} + \alpha_{air}.\mu_{air} \quad (7)$$

where α is the volume fraction of each of the phases, according to the water or air subscripts.

Boundary conditions and discretization

Unstructured tetrahedral mesh with approximately 4.0×10^5 nodes and 2.2×10^6 elements was used at the beginning of the simulations. A mesh adaptation feature was used at the water-air interface to improve the accuracy of the free surface definition. At the end of the simulations, the mesh presented around 1.6×10^6 nodes and 8.4×10^6 elements. Figure 3 is a partial representation of the mesh used. The dimensions of the elements varied between 4.6×10^{-3} m and 0.09 m. The smaller elements were located in the region of the vertical slot and the larger elements in the pools, between the two larger baffles, and in the entrance and exit of the structure. These characteristics of the mesh were taken from a mesh independence study performed by Sanagiotto, Rossi and Bravo (2019) for the simulation of flow in another vertical slot fishway, but with the same number of pools. These values are also in agreement with those used in previous simulation studies on vertical slot fishways, such as Khan (2006), with elements ranging between 0.025 m and 0.100 m, and Quaranta et al. (2017) with elements ranging between 0.025 m and 0.050 m. Considering that the purpose of this simulation is to determine flow fields that allow verification of the adequacy of flow for the behavior of fish, these dimensions of elements are sufficient to represent typical flows in vertical slot fishways (QUARANTA et al., 2017). An appropriate balance between accuracy of the results and the computational cost involved in the simulations was also ensured.

The non-slip boundary condition was applied to all walls (bottom, lateral walls and baffles). The roughness of the walls was considered null in all situations. The consideration of null roughness is valid, since the experimental data were obtained in a model with walls and bottom of glass and acrylic, which have almost zero roughness. In addition, previous studies have pointed out that surface roughness does not play an important role for this type of flow (BOMBAČ et al., 2014; CEA et al., 2007).

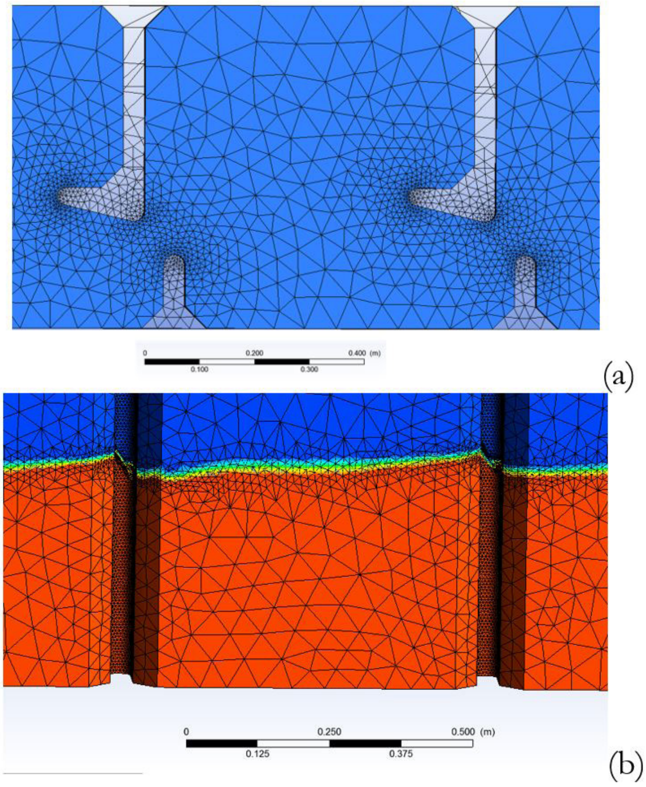


Figure 3. Partial view of the mesh used in the simulations: (a) detail of the top view of one of the pools; (b) detail of the mesh adaptation (red = water, blue = air).

At the inlet, the mass flow of water was specified, and at the exit, the static pressure was applied. For the inlet, a high turbulence intensity of 10% was employed. Considering the inlet is more than 4 m from the central pool, where the data were collected, it can be assumed that the values obtained during the simulation were not influenced by the turbulence intensity assigned at the inlet. This statement is reinforced by previous studies such as those by Baki, Zhu and Rajaratnam (2016) and Ma et al. (2002). Ma et al. (2002), for example, verified that velocity fields are not influenced by turbulence intensities of 5%, 10% and 20% at the inlets and outlets, and that the turbulence kinetic energy is influenced only in regions close to the boundary conditions for which the intensities are assigned.

Numerical flow simulations were performed for three discharge rates: 0.02159 m^3/s, 0.02451 m^3/s and 0.02916 m^3/s, which are the same flow rates evaluated experimentally by Sanagiotto et al. (2011, 2012). These discharges correspond to prototype flow rates of 1.21 m^3/s, 1.37 m^3/s and 1.63 m^3/s, respectively.

Data analysis

Both the experimental measurements (SANAGIOTTO et al., 2012, 2011) and the numerical simulations were performed in a reduced model at a 1:5 scale. Viana, Faria and Martinez (2014) evaluated the same geometry as the present work (vertical slot fishway of the Igarapava HPP), and compared experimental data in the prototype and in a 1:20 scale model. The results of Viana, Faria and Martinez (2014) indicated that the 1:20 scale model was adequate to represent the flow in the structure's pools. Thus, in this work, where the scale is four times larger (1: 5), it can be considered that the scale effects are neglected.

As the flow characteristics that are of interest are those obtained in the real-scale (prototype) structure, it is important to establish the relationship between magnitudes in the scaled model and in the prototype. For the flow in hydraulic structures, where gravitational and inertial forces play a fundamental role in the flow, models with similarity in Froude number are the most appropriate. The criterion of equality of Froude number is most frequently applied in the hydraulics of open channels (HELLER, 2011).

From the equality of Froude number (Equation 8) in model and prototype, the following relations between magnitudes in scale of prototype and of model are valid:

$$F = \frac{V}{\sqrt{gh}} \tag{8}$$

$$\frac{V_m}{V_p} = \lambda^{1/2} \tag{9}$$

$$\frac{Q_m}{Q_p} = \lambda^{5/2} \tag{10}$$

$$\frac{k_m}{k_p} = \lambda \tag{11}$$

$$\frac{P_m}{P_p} = \lambda^{1/2} \tag{12}$$

where V is the mean flow velocity at any point of interest; g is the gravitational acceleration; h is the depth of the flow; λ is the scaling factor, given by $\lambda = L_m / L_p$; L is length; the subscripts m and p refer to values in the model (reduced scale) and the prototype (actual scale), respectively; Q is the water discharge; k is the turbulence kinetic energy; and P is the volumetric dissipated power in the fishway pool (Equation 14). In this study, the scale factor $\lambda = 1/5$; that is, the physical model and the numerical model are five times smaller than the actual structure (prototype).

The Reynolds number (Re) is also a dimensionless quantity of interest for flow in fishways. For flow through the vertical slot, considering the slot width as the characteristic dimension, the Reynolds number is given by:

$$Re = \frac{Q.\rho}{h.\mu} \tag{13}$$

where Q is the water discharge; ρ is the water density; h is the depth of the flow; and μ is the dynamic viscosity of the water.

The values for velocities, pressure and turbulence kinetic energy were obtained during the flow simulation and are output quantities of the process.

The volumetric dissipated power can be calculated from the following equation:

$$P = \frac{\gamma.Q.\Delta h}{B.L.h_m} \tag{14}$$

where γ is the specific weight of water; Q is the water discharge; Δh is the difference in depth between consecutive pools, which depends on the longitudinal slope of the fishway; B and L are the pool size, width and length, respectively; and h_m is the mean depth of the flow in the pool. As the simulated structure represents nine pools of the fishway, plus an inlet and an outlet region, it was possible to obtain uniform flow in the central pools of the model. In this way, the difference between consecutive pools can be considered equal to the difference in the bottom elevation between successive baffles.

The result of Equation 14 can be compared with some limits presented in the literature, which seek in a simplified way, to evaluate the suitability of the turbulence characteristics of the flow inside the pool for certain species of fish.

Using the results obtained in the numerical simulation of the flow, the spatial distribution of the power dissipated inside the pool can be evaluated. The volumetric dissipated power in each position *i* of the tank is calculated by:

$$P_i = \rho.\varepsilon \tag{15}$$

where ρ is the water density and ε is the turbulence dissipation rate for the *i* position inside the pool.

From Equation 15, volumetric dissipated power fields can be constructed, with detail that contributes to a better evaluation of the suitability of a fishway for the swimming capacity of the target species (BOMBAČ et al., 2014).

For comparison of simulated and experimental results, two performance measures were used: root mean square error (RMSE) and mean absolute percentage error (MAPE), according to:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(O_i - S_i\right)^2} \tag{16}$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{O_i - S_i}{O_i}\right| \times 100 \tag{17}$$

where O_i and S_i are observational and simulated results, respectively, and N is the total number of data points.

RESULTS AND DISCUSSION

The results obtained in the simulations for the central pool of the analyzed structure are presented. These results are compared with those obtained for the reduced physical model, whose measurements were also taken in the central pool. The values that are not dimensionless are generally presented in two scales: the scale in which the simulations and/or experimental measurements were performed, which is the scale of the model, and the scale of interest for comparison with information on the ichthyofauna, which is the prototype scale.

Although the simulations and laboratory measurements allow characterization of the 3D behavior of the flow, the results are often represented in planes parallel to the bottom to facilitate their visualization.

Results are presented for mean velocities, general flow pattern, turbulence kinetic energy and volumetric dissipated power in different planes and the mean pressures at the bottom of the pool.

Main hydraulic characteristics

Table 1 presents the main hydraulic characteristics obtained in the simulations and compares them with the experimental values. These include mean depths of the flow (h_m), the magnitude of the maximum velocity (Vmax) and its relation to the potential theoretical value (Equation 1), the Reynolds number (Equation 13) and the Froude number (Equation 8) for flow through the vertical slot, and the volumetric dissipated power (Equation 14).

Analysis of the basic hydraulic characteristics of the flow indicates that the simulations were able to satisfactorily represent the flow features. The differences between the values obtained through the numerical simulations and the experimental data are acceptable.

The maximum values of measured and simulated mean velocities were in the passage through the slot, with magnitudes up to 0.99 m/s and 1.11 m/s, respectively (referring to the 1:5 scale model), in some small regions. The magnitude of the maximum mean velocity obtained experimentally is up to 18% higher than the potential theoretical value, and up to 32% higher in the simulations. Previous studies have pointed out that some configurations of vertical slot fishways present flows with maximum velocities that are underestimated using theoretical equations (e.g., BOMBAČ; ČETINA; NOVAK, 2017; BOMBAČ et al., 2015; CALLUAUD et al., 2014; KLEIN; OERTEL, 2015; SANAGIOTTO; ROSSI; BRAVO, 2019). The maximum values presented in Table 1 represent local values measured in small portions of the pool. Section 3.2, which analyzes the velocity fields, verifies that in most of the pool, the velocities are much lower than the potential theoretical value.

The Froude number values in the slot were always lower than unity, characterizing subcritical flow. There was no relationship between the Froude number and the discharge. The values in the model and prototype are the same, since the Froude similarity model was adopted for the transposition of the results.

Table 1. Main hydraulic characteristics obtained in the simulations compared to the experimental results in the 1: 5 model scale.

Q (m^3/s)	Hydraulic characteristic	Simulated	Experimental
0.02159	h_m (m)	0.380	0.380
	Vmax (m/s)	1.07	0.92
	Vmax/V_t	1.27	1.10
	F	0.37	0.37
	Re	5.68E+04	5.68E+04
	P (W/m^3)	55.74	55.74
0.02451	h_m (m)	0.395	0.398
	Vmax (m/s)	1.11	0.92
	Vmax/V_t	1.32	1.09
	F	0.39	0.39
	Re	6.21E+04	6.16E+04
	P (W/m^3)	60.87	60.41
0.02916	h_m (m)	0.460	0.470
	Vmax (m/s)	1.10	0.99
	Vmax/V_t	1.31	1.18
	F	0.37	0.36
	Re	6.34E+04	6.20E+04
	P (W/m^3)	62.19	60.86

The corresponding Reynolds numbers in the prototype varied between 6.3x10^5 and 7.1x10^5 and were higher for the larger discharges. Although the Reynolds numbers in the 1:5 scale model are lower (between 5.7x10^4 and 6.3x10^4), they are still sufficient to accurately estimate turbulence scales. According to Wang and Chanson (2016), turbulent scales can be estimated with satisfactory accuracy for Re > 4x10^4. This comparison reinforces that the use of the Froude similarity model is satisfactory to represent flow in the 1:5 scale model with small scale effects. The Reynolds number for the swimming of several species of fish varies within the range $10^4<Re<10^8$ (WU, 1977). The geometry analyzed in this study presents Reynolds numbers within this range for the model and the prototype.

The volumetric dissipated power, when analyzed for the prototype scale (Equation 12), varies between 125 W/m^3 and 139 W/m^3. These values are lower than expected for fishways used by cyprinids or other weaker fish (FAO, 2002; LARINIER, 2002), whose limit is 150 W/m^3. Studies on fish using the fishway at the Igarapava HPP show that it allows the transit of a wide variety of species, including adults and juveniles (CASALI et al., 2010).

Mean velocities and flow patterns

Analysis of the mean velocity fields in planes parallel to the bottom showed the general flow characteristics observed in previous studies: a main jet between consecutive slots and the formation of two recirculation regions adjacent to it — a larger one between the larger baffles and a smaller one between the smaller baffles (e.g., SANAGIOTTO et al., 2012; VIANA et al., 2016). In general, analysis of the different velocity fields in planes parallel to the bottom indicates that there are no significant variations in the pattern of flow behavior with depth (Figure 4) and discharge (Figure 5).

The analysis of vertical velocity components shows that these are much less expressive (observe the scale change between Figures 4 and 5 and Figure 6). However, there are vertical velocity components, descending in the region of the entrance of the jet in the pool, as well as ascending components at the end of the pool, upstream of the long baffle (Figure 5). This pattern was previously verified by Wu, Rajaratnam and Katopodis (1999) and Liu, Rajaratnam and Zhu (2006). The vertical velocity components represent up to 30% of the resulting velocity. In most of the pool, the value of the vertical velocity component is close to zero. These results indicate that the 3D numerical simulations are important for evaluating the flow in vertical slot fishways (STAMOU et al., 2018), especially in the region of the slot, which is a mandatory area of passage. Vertical flows have been shown to have an impact on fish behavior (SANTOS et al., 2013; TRITICO; COTEL, 2010) and thus should be considered.

The results obtained in the simulations were compared with the information obtained experimentally in a physical model. In Figure 7, the measured and simulated velocities are compared at points located in the middle of the vertical slot, at different distances from the bottom (0.01 cm, 10%h_m, 20%h_m, 25%h_m, 30%h_m,. 40%h_m,. 50%h_m,. 60%h_m,. 70%h_m and 80%h_m, where h_m is the mean depth of the flow). The values are compared in terms of the resulting velocity and the velocities in components. Velocities obtained from the simulation were found to be adequate to represent the measured values.

Figures 8 and 9 show some additional comparisons between simulated and measured velocities, in the dimensionless form, for the three discharges tested. In these figures, the velocities are divided by the potential theoretical velocity (Equation 1). In the 1:5 scale model, V_t = 0.87 m/s, and in the prototype, V_t = 1.88 m/s. These results confirm adequate agreement between measured and simulated velocities, showing the same pattern of behavior.

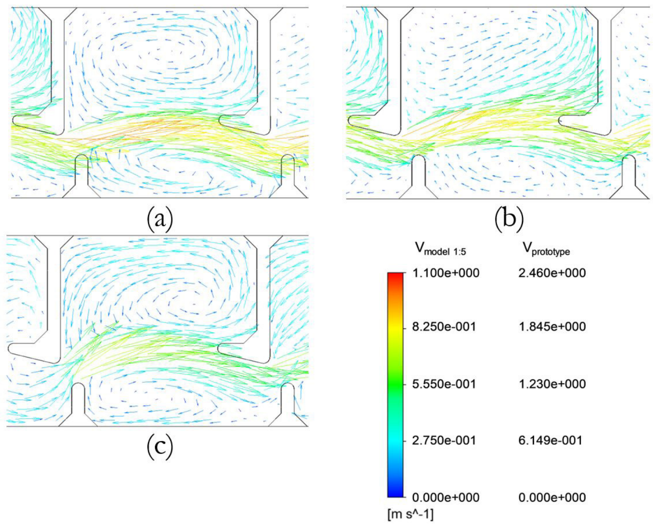


Figure 4. Mean velocity fields obtained by numerical simulation of the flow for Q_m = 0.02451 m^3/s (Q_p = 1.37 m^3/s), in planes parallel to and far from the bottom: (a) 0.10 h_m; (b) 0.25 h_m; and (c) 0.80 h_m, where h_m is the mean depth of the flow in the pool.

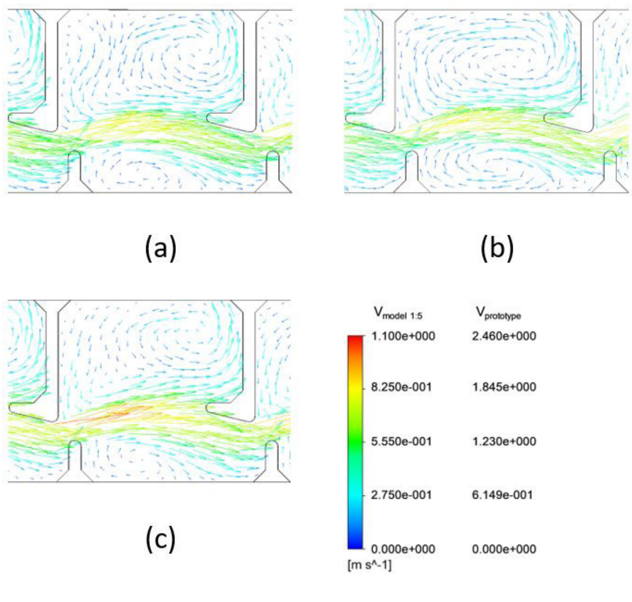


Figure 5. Mean velocity fields obtained by numerical simulation of the flow in a plane parallel to and far from the bottom of 0.50 h_m for different discharges in model: (a) 0.02159 m^3/s; (b) 0.02451 m^3/s; and (c) 0.02916 m^3/s (equivalent discharges in prototype of 1.21 m^3/s, 1.37 m^3/s and 1.63 m^3/s).

In the recirculation regions of the flow, in all planes parallel to the bottom, the velocity does not exceed 40% of the potential theoretical velocity. In the main flow zone, some regions with velocities between 80% and 100% of the potential theoretical velocity can be observed, but in most of the jet, the values are between 60% and 80% of the potential theoretical velocity (Figure 9). These results are in agreement with the experimental evaluations reported by Sanagiotto et al. (2011, 2012).

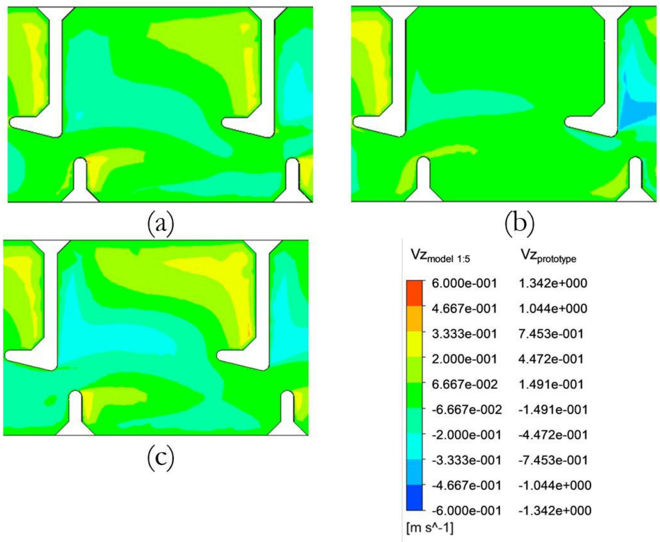


Figure 6. Vertical velocity component contours obtained through numerical simulation of the flow in the plane parallel to the bottom of 0.50 h_m for different discharges: (a) 0.02159 m^3/s; (b) 0.02451 m^3/s; and (c) 0.02916 m^3/s in model (equivalent discharges of 1.21 m^3/s, 1.37 m^3/s and 1.63 m^3/s in prototype).

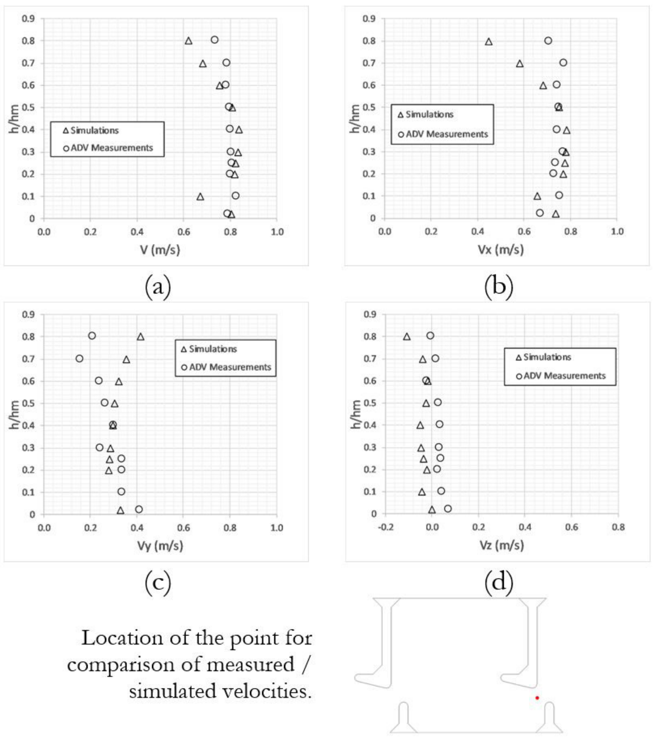


Figure 7. Measured and simulated velocities (a) V; (b) Vx; (c) Vy and (d) Vz; at points located in the vertical slot at different depths, for discharge of 0.02916 m^3/s in the model (h_m = mean flow depth; V = resulting velocity; Vx = longitudinal velocity component; Vy = transverse velocity component; and Vz = vertical velocity component).

The quantitative comparison between experimentally observed and simulated velocity magnitudes indicates RMSE values (Equation 16) of 0.077 m/s, 0.082 m/s and 0.088 m/s, for model discharges of 0.02159 m^3/s, 0.02451 m^3/s and 0.02916 m^3/s, respectively. The respective MAPE values (Equation 17) are 9.97%, 3.05% and 7.11%. Tran et al. (2016) found that errors of up to 10% for velocities are not significant for the analysis of fishways.

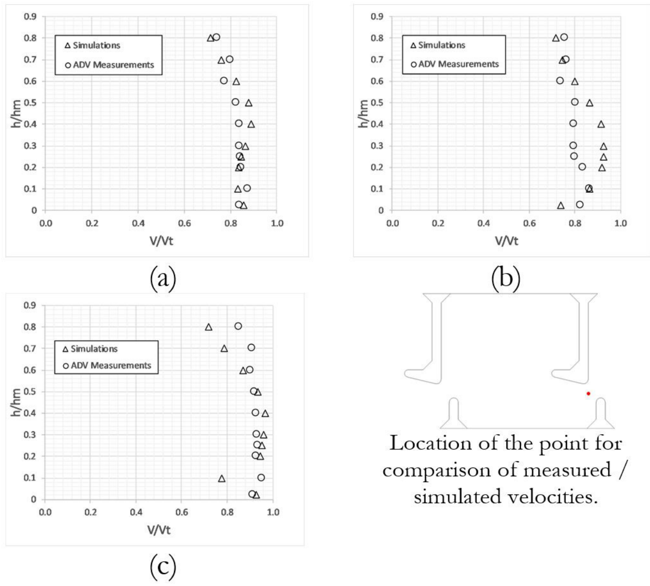


Figure 8. Comparison of measured and simulated velocities in the slot region passing through the main jet for discharges of (a) 0.02159 m^3/s; (b) 0.02451 m^3/s; and (c) 0.02916 m^3/s (h_m = mean flow depth; Table 1; and Vt = potential theoretical velocity, Equation 1).

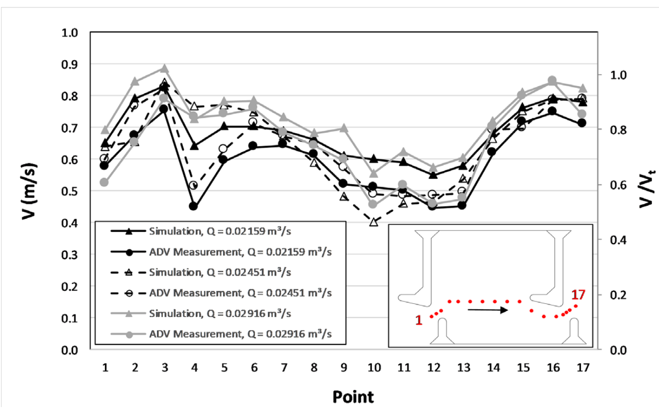


Figure 9. Measured and simulated velocities (V) in points far from the bottom of 0.50h_m, in the main jet, for different discharges (h_m = mean flow depth, Table 1; V_t = potential theoretical velocity, Equation 1).

In general, the simulations overestimated velocities. The values found in this work are adequate to validate the simulation, through criteria adopted in previous studies using the same simulation software for the analysis of the flow in fishways (BAKI; ZHU; RAJARATNAM, 2016).

It should be noted that the major differences between simulated and measured velocities correspond to points located close to the walls (baffles and bottom) or near the free surface, where the accuracy of the experimental and simulated results is lower. The equipment used in Sanagiotto et al. (2012) experimental measurements, a 16 MHz MicroADV, performs measurements in a sampling volume of 0.09 cm^3 (SONTEK, 2001). Manufacturers recommend that the sampling volume boundary be at least 1 cm from solid boundaries. The center of the sampling volume had a distance of 1 cm from the bottom at the "points" of measurement closer to the bottom. In these cases, the boundary of the sampling volume was about 0.5 cm from the bottom. This scenario reduces the accuracy of measurements. Likewise, the equipment does not have an ideal response for aerated flow, which can be observed in some regions close to the free surface during the passage of the jet through the slot. The reduction in accuracy at the regions near the bottom and at the air-water interface can also be attributed to the data obtained in the simulation. In the air-water interface region, mesh adaptation was used to improve accuracy. For most of the pool, where fish should swim more frequently, there was good agreement of the measured and simulated results. The simulation results address the objective of determining flow fields to verify the adequacy of flow to fish. However, future studies should be carried out with greater refinements to the mesh at the bottom and surface regions to investigate significant differences between numerical and experimental data.

Mean pressures

Comparisons of the mean pressures measured and obtained through simulation are presented in Figure 10 for points located in the main jet path (Points 1 to 12 are indicated in detail in Figure 10). Good agreement between the measured and simulated values can be observed. Comparison was made for only two discharges,

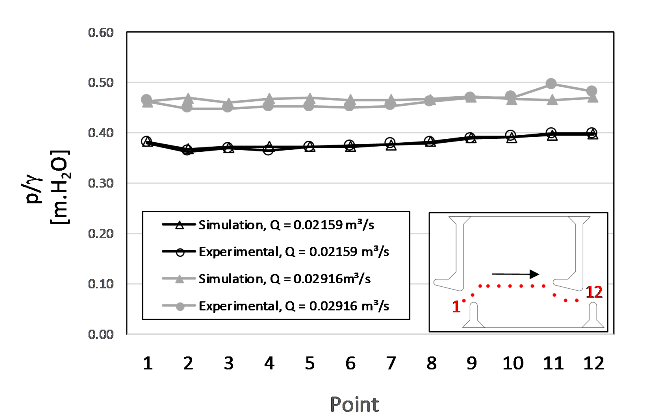


Figure 10. Measured and simulated pressures in the bottom of the pool, at points along a line passing through the main jet, for discharges of 0.02159 m^3/s and 0.02916 m^3/s in the model.

0.02159 m^3/s and 0.02916 m^3/s. For the intermediate discharge, no experimental pressure data are available for comparison.

The RMSE for the pressure head is 0.003 $m.H_2O$ and 0.014 $m.H_2O$ for the discharges of 0.02159 m^3/s and 0.02916 m^3/s in the model, respectively, and the MAPE is 0.47% and 1.02%.

Turbulence kinetic energy

Analysis of the turbulence kinetic energy distribution in the pools indicates that the highest values are associated with high velocity regions. Higher values of turbulence kinetic energy occur in the region near the aperture between pools, usually near the smaller baffle, which favors the approach of fish from the larger recirculation side, as seen in Figure 11. The maximum values obtained in the numerical simulation are close to the measured values presented in Sanagiotto et al. (2011), as well as the distribution pattern of the turbulence kinetic energy of the flow in the pools. Figure 12 shows the comparative analysis between measured and simulated values for some points located in the main jet. In general, there is adequate agreement between the measured and simulated turbulence kinetic energy values for the region corresponding to the most central part of the jet inside the pool and differences for the points near the baffles.

Quantitative analysis shows that the numerical model is less efficient in representing the turbulence kinetic energy compared to velocities and pressure, as earlier studies that used the same software to simulate flow in fishways have pointed out (BAKI; ZHU; RAJARATNAM, 2016; TRAN et al., 2016). The RMSE for the turbulence kinetic energy is 0.024 m^2/s^2, 0.022 m^2/s^2 and 0.023 m^2/s^2, for the discharges 0.02159 m^3/s, 0.02451 m^3/s and 0.02916 m^3/s, respectively. MAPE, for the same discharges is 60.6%, 24.0% and 38.1%. The simulations generally overestimated

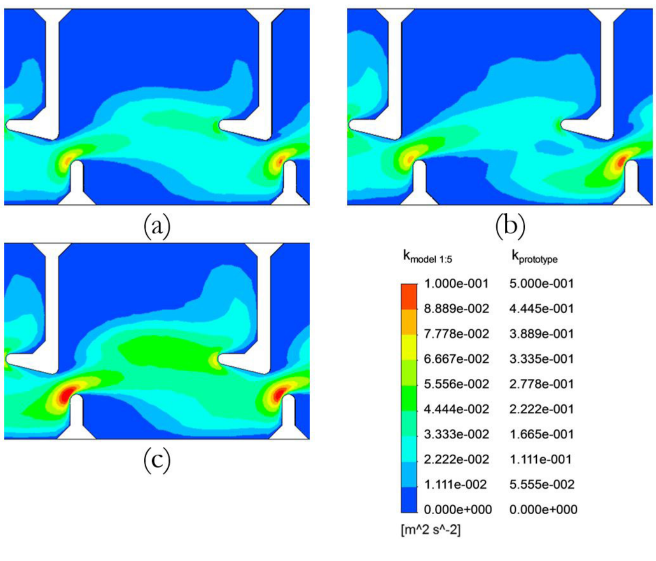


Figure 11. Turbulence kinetic energy contours obtained through numerical simulation of the flow in a plane parallel to the bottom, far from the bottom of 0.50 h_m, for discharges of: (a) 0.02159 m^3/s; (b) 0.02451 m^3/s; and (c) 0.02916 m^3/s in the model (equivalent prototype discharges of 1.21 m^3/s, 1.37 m^3/s and 1.63 m^3/s).

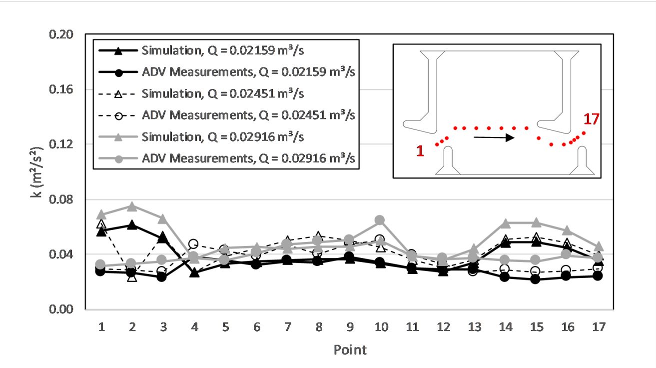


Figure 12. Measured and simulated turbulence kinetic energy in points of a line passing through the main jet, in the same plane as Figure 11.

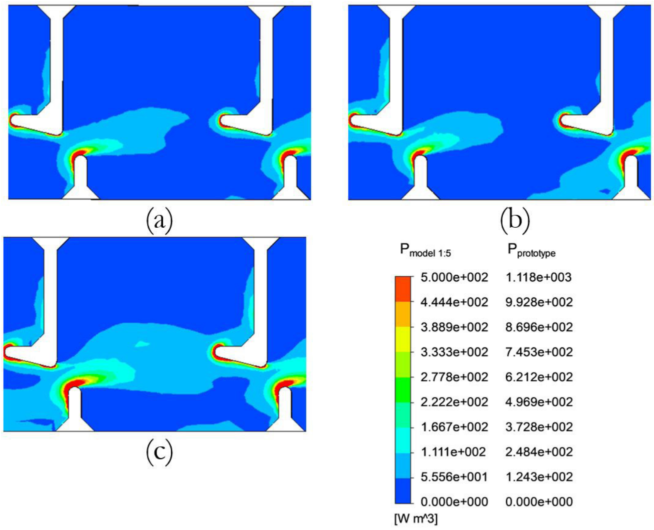


Figure 13. Contours of dissipated power in the pool obtained through numerical simulation of the flow in a plane parallel to the bottom located at half depth (0.50 h_m) for discharges: (a) 0.02159 m^3/s; (b) 0.02451 m^3/s; and (c) 0.02916 m^3/s in the model (equivalent to 1.21 m^3/s, 1.37 m^3/s and 1.63 m^3/s in the prototype).

the turbulence kinetic energy, with the largest discrepancies at points close to the baffles. For all their simulations in fishways, Baki, Zhu and Rajaratnam (2016) reported MAPE values greater than 50% for turbulence kinetic energy.

The discrepancies found may be due to isolated or combined factors, such as experimental uncertainties, turbulence model selection and numerical mesh used, as pointed out by Baki, Zhu and Rajaratnam (2016). Tran et al. (2016) performed 2D flow simulations on a fishway with the k-ε turbulence model using two meshes. These authors verified that for the estimation of velocities, the mesh did not influence the results. However, Tran et al. (2016) found that for the estimation of turbulence kinetic energy, finer mesh was able to reproduce values that were larger but still smaller than those measured experimentally.

The evaluation of turbulence kinetic energy could be better investigated through numerical simulation of the flow. Studies that have used the k-ε turbulence model have produced results that underestimate the turbulence kinetic energy values (BAKI; ZHU; RAJARATNAM, 2016; TRAN et al., 2016). On the other hand, in the present work that uses the same turbulence model, the simulated turbulence kinetic energy values are superior to the experimental ones, which was also verified by Bombač, Četina and Novak (2017) and Sanagiotto, Rossi and Bravo (2019). Some studies, such as Cea et al. (2007) and Stamou et al. (2018), have sought to evaluate other types of turbulence models for RANS simulations in fishways. There are also some large-scale simulation (LES) approaches to estimating the flow in fishways, such as Fuentes-Pérez et al. (2018) and Quaresma et al. (2018). However, RANS simulations have lower computational costs and are more accessible (TAJNESAIE et al., 2018).

Volumetric dissipated power in the pools

For the geometries analyzed in this study, the average volumetric dissipated power values, calculated through Equation 14, ranged from 125 W/m^3 to 139 W/m^3 in the prototype, with the highest value associated with higher flow. Figure 13 shows the distribution of volumetric dissipated power in the pool, obtained by the flow simulation and Equation 15. It can be observed that for most of the pool, the values are below the maximum limits generally considered adequate for the swimming of a great diversity of fish species. In the regions near the baffles, especially the areas close to the smallest baffle, maximum volumetric dissipated power values of about 1120 W/m^3 were observed. This pattern of volumetric dissipated power distribution within the vertical slot fishway pool has been reported in experimental studies (VIANA et al., 2016) and numerical simulations (BOMBAČ et al., 2014). This region of occurrence of maximum values of the volumetric dissipated power of the flow is the same as that associated with higher velocities and maximum turbulence kinetic energy. This justifies the preference of fish to approach on the side of the large recirculation when crossing the slot, as conditions there are more favorable, as reported in Viana (2005).

The previously presented results can be useful for comparison of the flow characteristics with the swimming capacity of fish present in Brazilian rivers. Prior studies have evaluated the swimming capacity of some species present in Brazilian rivers (SANTOS et al., 2012, 2008; SANTOS; POMPEU; MARTINEZ, 2007). However, such data are limited, and information on preferred values for fish in Brazil related to flow turbulence is not yet known.

CONCLUSIONS

For numerical simulation of a vertical slot fishway, the flow was modeled using the Reynolds decomposition, RANS in 3D, with the k-ε turbulence model. The analysis of the results of this work shows that there is adequate agreement between the values measured in a scaled physical model and the results obtained through 3D numerical simulation of the flow, considering the computational costs involved.

Analysis of the components of mean flow velocities allows the identification of the typical flow pattern in this type of structure: a main jet between consecutive slots and two adjacent recirculations between the baffles, with velocities much lower than those observed in the main jet. The vertical velocity components reach 30% of the resulting velocity, justifying the use of 3D simulation and/or 3D measurements.

The maximum velocity values found in the flow were up to 32% higher than the potential theoretical value. This result demonstrates that a highly simplified analysis can be extremely detrimental since the maximum flow velocities can be underestimated and thus the use of the fishway by certain species may be unfeasible.

The higher discharges in the structure are associated with higher mean depths of the flow in the pools and slightly higher values for the volumetric dissipated power. The analysis of velocity fields indicates that there are few variations of velocities with depth and discharge. The turbulence kinetic energy fields and the volumetric dissipated power fields are influenced by the discharge in the region close to the baffles. It should be noted that in this region there is a slight increase of the quantities associated with an increase of the flow rate. Nevertheless, the variations in the discharge are insignificant considering the distribution of the quantities within the pool and the maximum values observed. This feature of vertical slot fishways makes them quite versatile, allowing fish swimming for a wide range of discharges, as the discharge changes result in little variation in the flow, as long as the flow remains uniform along the fishway.

The comparison between measured and simulated pressure values in the bottom of the pool and velocities at various positions inside the pool reinforces that the model adequately represents these characteristics of the flow. The RMSE was less than 10% for velocities and about 1% for pressures.

The comparison of measured and simulated turbulence kinetic energy data show that the model is less accurate for this evaluation, which is usually verified using RANS simulation. However, the model still represents well the distributions of this quantity within the pool although it overestimates the maximum values. Complementary studies using other turbulence models, for example, can be conducted to improve the accuracy of the evaluation of this magnitude.

The results for distribution of the volumetric dissipated power in the fishway, together with the velocity data and other parameters indicative of turbulence, such as turbulence kinetic energy, allow comparison of the flow characteristics with conditions considered adequate for ichthyofauna.

The validation of the numerical scheme used is of great importance for the design of new geometries of fishways or the modification of existing ones. The impacts on flow due to the modification of geometry can be tested and new flows can be found that are appropriate to the fish species of the place of interest.

ACKNOWLEDGEMENTS

This research was made possible through funding from Conselho Nacional de Desenvolvimento Científico e Tecnológico of Brazil (444180/2014-1) and a scholarship grant from Universidade Federal do Rio Grande do Sul, Brazil. The authors are thankful for the editor and anonymous reviewers for their helpful comments.

REFERENCES

ABDELAZIZ, S. M. A. *Numerical simulation of fish behavior and fish movement through passages*. München: Technische Universität München, 2013.

AN, R.; LI, J.; LIANG, R.; TUO, Y. Three-dimensional simulation and experimental study for optimising a vertical slot fishway. *Journal of Hydro-environment Research*, v. 12, p. 119-129, 2016. http://dx.doi.org/10.1016/j.jher.2016.05.005.

ANSYS. *C.F.X. ANSYS, solver theory guide*: release 15, 209. Canonsburg, 2013.

BAKI, A. B. M.; ZHU, D. Z.; RAJARATNAM, N. Flow simulation in a rock-ramp fish pass. *Journal of Hydraulic Engineering*, v. 142, n. 10, p. 04016031, 2016. http://dx.doi.org/10.1061/(ASCE)HY.1943-7900.0001166.

BALLU, A.; PINEAU, G.; CALLUAUD, D.; DAVID, L. Characterization of the flow in a vertical slot fishway with macro-roughnesses using unsteady (URANS and LES) simulations. In: IAHR WORLD CONGRESS, 37., 2017, Kuala Lumpur, Malaysia. *E-Proceedings…* Beijing: IAHR, 2017.

BELL, M. *Fisheries handbook of engineering requirements and biological criteria*. 3rd ed. Portland: Corps of Engineers, North Pacific Division, 1990.

BERMÚDEZ, M.; PUERTAS, J.; CEA, L.; PENA, L.; BALAIRÓN, L. Influence of pool geometry on the biological efficiency of vertical slot fishways. *Ecological Engineering*, v. 36, n. 10, p. 1355-1364, 2010. http://dx.doi.org/10.1016/j.ecoleng.2010.06.013.

BLANK, M. *Advanced studies of fish passage through culverts*: 1-D and 3-d hydraulic modeling of velocity, fish energy expenditure, and a new barrier assessment method. 2008. 214 f. Thesis (PhD in Philosophy) - Montana State University, Montana, 2008.

BOMBAČ, M.; ČETINA, M.; NOVAK, G. Study on flow characteristics in vertical slot fishways regarding slot layout optimization. *Ecological Engineering*, v. 107, p. 126-136, 2017. http://dx.doi.org/10.1016/j.ecoleng.2017.07.008.

BOMBAČ, M.; NOVAK, G.; MLAČNIK, J.; ČETINA, M. Extensive field measurements of flow in vertical slot fishway as data for validation of numerical simulations. *Ecological Engineering*, v. 84, p. 476-484, 2015. http://dx.doi.org/10.1016/j.ecoleng.2015.09.030.

BOMBAČ, M.; NOVAK, G.; RODIČ, P.; ČETINA, M. Numerical and physical model study of a vertical slot fishway. *Journal of Hydrology and Hydromechanics*, v. 62, n. 2, p. 150-159, 2014. http://dx.doi.org/10.2478/johh-2014-0013.

CALLUAUD, D.; PINEAU, G.; TEXIER, A.; DAVID, L. Modification of vertical slot fishway flow with a supplementary cylinder. *Journal of Hydraulic Research*, v. 52, n. 5, p. 614-629, 2014. http://dx.doi.org/10.1080/00221686.2014.906000.

CASALI, R. C. V.; VONO, V.; GODINHO, H. P.; LUZ, R. K.; BAZZOLI, N. Passage and reproductive activity of fishes in the Igarapava fish ladder, Grande River, Southeastern Brazil. *River Research and Applications*, v. 2, p. 157-165, 2010.

CEA, L.; PENA, L.; PUERTAS, J.; VÁZQUEZ-CENDÓN, M. E.; PEÑA, E. Application of deveral depth-averaged turbulence models to simulate flow in vertical slot fishways. *Journal of Hydraulic Engineering*, v. 133, n. 2, p. 160-172, 2007. http://dx.doi.org/10.1061/(ASCE)0733-9429(2007)133:2(160).

FAO – FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS. DVWK – Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. *Fish passes*: design, dimensions and monitoring. Rome, 2002.

FUENTES-PÉREZ, J. F.; GARCÍA-VEGA, A.; SANZ-RONDA, F. J.; MARTÍNEZ DE AZAGRA PAREDES, A. Villemonte's approach: a general method for modeling uniform and non-uniform performance in stepped fishways. *Knowledge and Management of Aquatic Ecosystems*, v. 418, p. 23, 2017. http://dx.doi.org/10.1051/kmae/2017013.

FUENTES-PÉREZ, J. F.; SILVA, A. T.; TUHTAN, J. A.; GARCÍA-VEGA, A.; CARBONELL-BAEZA, R.; MUSALL, M.; KRUUSMAA, M. 3D modelling of non-uniform and turbulent flow in vertical slot fishways. *Environmental Modelling & Software*, v. 99, p. 156-169, 2018. http://dx.doi.org/10.1016/j.envsoft.2017.09.011.

HELLER, V. Scale effects in physical hydraulic engineering models. *Journal of Hydraulic Research*, v. 49, n. 3, p. 293-306, 2011. http://dx.doi.org/10.1080/00221686.2011.578914.

HIRT, C. W.; NICHOLS, B. D. Volume of fluid (VOF) Method for the dynamics of free boundaries. *Journal of Computational Physics*, v. 39, n. 1, p. 201-225, 1981. http://dx.doi.org/10.1016/0021-9991(81)90145-5.

HOTCHKISS, R. H.; FREI, C. M. *Design for fish passage at roadway-stream crossings*: synthesis report. Virginia: Federal Highway Administration, 2007.

JONES, W.; LAUNDER, B. The prediction of laminarization with a two-equation model of turbulence. *International Journal of Heat and Mass Transfer*, v. 15, n. 2, p. 301-314, 1972. http://dx.doi.org/10.1016/0017-9310(72)90076-2.

KHAN, L. A. A three-dimensional computational fluid dynamics (CFD) model analysis of free surface hydrodynamics and fish passage energetics in a vertical-slot fishway. *North American Journal of Fisheries Management*, v. 26, n. 2, p. 255-267, 2006. http://dx.doi.org/10.1577/M05-014.1.

KLEIN, J.; OERTEL, M. Comparison between crossbar block ramp and vertical slot fish pass via numerical 3D CFD simulation. In: IAHR World CONGRESS, 36., 2015, Hague, Netherlands. *Proceedings*… Beijing: IAHR 2015. p. 1-9.

LARINIER, M. Pool fishways, pre-barrages and natural bypass channels. *Bulletin Francais de la Peche et de la Pisciculture*, v. 364, p. 54-82, 2002. http://dx.doi.org/10.1051/kmae/2002108.

LAUCHLAN ARROWSMITH, C. S.; ZHU, Y. Comparison between 2D and 3D hydraulic modelling approaches for simulation of vertical slot fishways. In: IAHR INTERNATIONAL SYMPOSIUM ON HYDRAULIC STRUCTURES, 5., 2014, Brisbane, Australia. *Proceedings*… Brisbane: The University of Queensland, 2014.

LIU, M.; RAJARATNAM, N.; ZHU, D. Mean flow and turbulence structure in vertical slot fishways. *Journal of Hydraulic Engineering*, v. 132, n. 8, p. 765-777, 2006. http://dx.doi.org/10.1061/(ASCE)0733-9429(2006)132:8(765).

MA, L.; ASHWORTH, P. J.; BEST, J. L.; ELLIOTT, L.; INGHAM, D. B.; WHITCOMBE, L. J. Computational fluid dynamics and the physical modelling of an upland urban river. *Geomorphology*, v. 44, n. 3-4, p. 375-391, 2002. http://dx.doi.org/10.1016/S0169-555X(01)00184-2.

MAO, X.; FU, J. J.; TUO, Y. C.; AN, R. D.; LI, J. Influence of structure on hydraulic characteristics of T shape fishway. *Journal of Hydrodynamics*, v. 24, n. 5, p. 684-691, 2012. http://dx.doi.org/10.1016/S1001-6058(11)60292-8.

MARRINER, B. A.; BAKI, A. B. M.; ZHU, D. Z.; COOKE, S. J.; KATOPODIS, C. The hydraulics of a vertical slot fishway: a case study on the multi-species Vianney-Legendre fishway in Quebec, Canada. *Ecological Engineering*, v. 90, p. 190-202, 2016. http://dx.doi.org/10.1016/j.ecoleng.2016.01.032.

MARRINER, B. A.; BAKI, A. B. M.; ZHU, D. Z.; THIEM, J. D.; COOKE, S. J.; KATOPODIS, C. Field and numerical assessment of turning pool hydraulics in a vertical slot fishway. *Ecological Engineering*, v. 63, p. 88-101, 2014. http://dx.doi.org/10.1016/j.ecoleng.2013.12.010.

MIRZAEI, P. A. Development of a fish leaping framework for low-head barriers. *Journal of Hydro-environment Research*, v. 14, p. 34-43, 2017. http://dx.doi.org/10.1016/j.jher.2016.07.001.

PUERTAS, J.; PENA, L.; TEIJEIRO, T. Experimental approach to the hydraulics of vertical slot fishways. *Journal of Hydraulic Engineering*, v. 130, n. 1, p. 10-23, 2004. http://dx.doi.org/10.1061/(ASCE)0733-9429(2004)130:1(10).

QUARANTA, E.; KATOPODIS, C.; REVELLI, R.; COMOGLIO, C. Turbulent flow field comparison and related suitability for fish passage of a standard and a simplified low-gradient vertical slot fishway. *River Research and Applications*, v. 33, n. 8, p. 1295-1305, 2017. http://dx.doi.org/10.1002/rra.3193.

QUARESMA, A. L.; ROMÃO, F.; BRANCO, P.; FERREIRA, M. T.; PINHEIRO, A. N. Multi slot versus single slot pool-type fishways: a modelling approach to compare hydrodynamics. *Ecological Engineering*, v. 122, p. 197-206, 2018. http://dx.doi.org/10.1016/j.ecoleng.2018.08.006.

RAJARATNAM, N.; KATOPODIS, C.; SOLANKI, S. New designs for vertical slot fishways. *Canadian Journal of Civil Engineering*, v. 19, n. 3, p. 402-414, 1992. http://dx.doi.org/10.1139/l92-049.

RAJARATNAM, N.; VAN DER VINNE, G.; KATOPODIS, C. Hydraulics of vertical slot fishways. *Journal of Hydraulic Engineering*, v. 112, n. 10, p. 909-927, 1986. http://dx.doi.org/10.1061/(ASCE)0733-9429(1986)112:10(909).

SANAGIOTTO, D.; PINHEIRO, A.; ENDRES, L.; MARQUES, M. Estudo experimental das características do escoamento em escadas para peixes do tipo ranhura vertical: turbulência do escoamento. *Revista Brasileira de Recursos Hídricos*, v. 16, n. 4, p. 195-205, 2011. http://dx.doi.org/10.21168/rbrh.v16n4.p195-205.

SANAGIOTTO, D.; PINHEIRO, A.; ENDRES, L.; MARQUES, M. Estudo experimental das características do escoamento em escadas para peixes do tipo ranhura vertical: padrões gerais do escoamento. *Revista Brasileira de Recursos Hídricos*, v. 17, n. 1, p. 135-148, 2012. http://dx.doi.org/10.21168/rbrh.v17n1.p135-148.

SANAGIOTTO, D. G.; ROSSI, J. B.; BRAVO, J. M. Applications of computational fluid dynamics in the the design and rehabilitation of nonstandard vertical slot fishways. *Water*, v. 11, n. 2, p. 199, 2019. http://dx.doi.org/10.3390/w11020199.

SANTOS, H. A.; POMPEU, P. S.; MARTINEZ, C. B. Swimming performance of the migratory Neotropical fish Leporinus reinhardti (Characiformes: Anostomidae). *Neotropical Ichthyology*, v. 5, n. 2, p. 139-146, 2007. http://dx.doi.org/10.1590/S1679-62252007000200007.

SANTOS, H. A.; POMPEU, P. S.; VICENTINI, G. S.; MARTINEZ, C. B. Swimming performance of the freshwater neotropical fish: Pimelodus maculatus Lacepède, 1803. *Brazilian Journal of Biology = Revista Brasileira de Biologia*, v. 68, n. 2, p. 433-439, 2008. http://dx.doi.org/10.1590/S1519-69842008000200029. PMid:18660976.

SANTOS, H. A.; VIANA, E. M. F.; POMPEU, P. S.; MARTINEZ, C. B. Optimal swim speeds by respirometer: an analysis of three neotropical species. *Neotropical Ichthyology*, v. 10, n. 4, p. 805-811, 2012. http://dx.doi.org/10.1590/S1679-62252012000400013.

SANTOS, J. M.; BRANCO, P. J.; SILVA, A. T.; KATOPODIS, C.; PINHEIRO, A. N.; VISEU, T.; FERREIRA, M. T. Effect of two flow regimes on the upstream movements of the Iberian barbel (Luciobarbus bocagei) in an experimental pool-type fishway. *Journal of Applied Ichthyology*, v. 29, n. 2, p. 425-430, 2013. http://dx.doi.org/10.1111/jai.12043.

SHAMLOO, H.; AKNOONI, S. 3D-numerical simulation of the flow in pool and weir fishways. In: INTERNATIONAL CONFERENCE ON WATER RESOURCES CMWR 2012, 19., 2012, Urbana, IL, USA. *Proceedings*… Urbana-Champaign: University of Illinois, 2012. p. 1-8.

SONTEK. *SonTek/YSI ADVField/hydra acoustic doppler velocimeter (field) technical documentation*. San Diego, 2001. Tech. Doc. SonTek/YSI.

STAMOU, A. I.; MITSOPOULOS, G.; RUTSCHMANN, P.; BUI, M. D. Verification of a 3D CFD model for vertical slot fish-passes. *Environmental Fluid Mechanics*, v. 18, n. 6, p. 1435-1461, 2018. http://dx.doi.org/10.1007/s10652-018-9602-z.

TAJNESAIE, M.; NODOUSHAN, E. J.; BARATI, R.; MOGHADAM, M. A. Performance comparison of four turbulence models for modeling of secondary flow cells in simple trapezoidal channels. *ISH Journal of Hydraulic Engineering*, p. 1-11, 2018. http://dx.doi.org/10.1080/09715010.2018.1469053.

TRAN, T. D.; CHORDA, J.; LAURENS, P.; CASSAN, L. Modelling nature-like fishway flow around unsubmerged obstacles using a 2D shallow water model. *Environmental Fluid Mechanics*, v. 16, n. 2, p. 413-428, 2016. http://dx.doi.org/10.1007/s10652-015-9430-3.

TRITICO, H. M.; COTEL, A. J. The effects of turbulent eddies on the stability and critical swimming speed of creek chub (Semotilus atromaculatus). *The Journal of Experimental Biology*, v. 213, n. Pt 13, p. 2284-2293, 2010. http://dx.doi.org/10.1242/jeb.041806. PMid:20543127.

UMEDA, C.; LIMA, G.; JANZEN, J.; SALLA, M. One- and three-dimensional modeling of a vertical-slot fishway. *Journal of Urban and Environmental Engineering*, v. 11, p. 99-107, 2017.

VIANA, E. M. F. *Mapeamento do campo de velocidades em mecanismos de transposição de peixes do tipo slot vertical em diferentes escalas*. 2005. 226 f. Tese (Doutorado em Hidráulica e Recursos Hídricos) - Universidade Federal de Minas Gerais, Belo Horizonte, 2005.

VIANA, E. M. F.; FARIA, M. T. C.; MARTINEZ, C. B. Experimental flow analysis of a pool-type fishway using velocity fields from reduced model and prototype. *International Review of Mechanical Engineering*, v. 8, n. 3, p. 655, 2014. http://dx.doi.org/10.15866/ireme.v8i3.1197.

VIANA, E.; MARTINEZ, C.; MARQUES, M. Mapeamento do campo de velocidades no mecanismo de transposição de peixes do tipo ranhura vertical construído na UHE de Igarapava. *Revista Brasileira de Recursos Hídricos* , v. 23, p. 5-15, 2007. http://dx.doi.org/10.21168/rbrh.v12n1.p5-15.

VIANA, E. M. F.; MARTINEZ, C. B.; FARIA, M. T. C.; TOLENTINO, B. S.; TOMÉ, F. L. F. O.; SALIBA, A. P. M. Análise do comportamento hidráulico de um mecanismo de transposição de peixes do tipo escada com ranhura vertical em duas declividades. *Revista Brasileira de Recursos Hídricos*, v. 21, n. 4, p. 2016, 2016. http://dx.doi.org/10.1590/2318-0331.011615129.

WANG, H.; CHANSON, H. Self-similarity and scale effects in physical modelling of hydraulic jump roller dynamics, air entrainment and turbulent scales. *Environmental Fluid Mechanics*, v. 16, n. 6, p. 1087-1110, 2016. http://dx.doi.org/10.1007/s10652-016-9466-z.

WANG, R. W.; DAVID, L.; LARINIER, M. Contribution of experimental fluid mechanics to the design of vertical slot fish passes. *Knowledge and Management of Aquatic Ecosystems*, v. 396, p. 1-21, 2010. http://dx.doi.org/10.1051/kmae/2010002.

WILLIAMS, J. G.; ARMSTRONG, G.; KATOPODIS, C.; LARINIER, M.; TRAVADE, F. Thinking like a fish: a key ingredient for development of effective fish passage facilities at river obstructions. *River Research and Applications*, v. 28, n. 4, p. 407-417, 2012. http://dx.doi.org/10.1002/rra.1551.

WU, S.; RAJARATNAM, N.; KATOPODIS, C. Structure of flow in vertical slot fishway. *Journal of Hydraulic Engineering*, v. 125, n. 4, p. 351-360, 1999. http://dx.doi.org/10.1061/(ASCE)0733-9429(1999)125:4(351).

WU, T. Y. Introduction to the scaling of aquatic animal locomotion. In: PEDLEY, T. J. (Ed.). *Scale effects in animal locomotion*. New York: Academic Press, 1977. p. 203-232.

Authors contributions

Daniela Guzzon Sanagiotto: Conceptualization, methodology, simulations, validation, formal analysis, project administration and writing of the paper.

Júlia Brusso Rossi: Simulations, validation, formal analysis and writing of the paper.

Luísa Lüdtke Lauffer: Simulations, validation, formal analysis and writing of the paper.

Juan Martín Bravo: Conceptualization, formal analysis and review of the text.