Environmental Modelling & Software 99 (2018) 156–169

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

3D modelling of non-uniform and turbulent flow in vertical slot fishways

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ARTICLE INFO

Article history:
Received 22 October 2016
Received in revised form
21 August 2017
Accepted 29 September 2017

Keywords:
Fishways
CFD
RANS
LES
OpenFOAM
Hydraulic design
Non-uniform performance

ABSTRACT

Global stocks of freshwater fish have been on the decline for decades, driven in part by the obstruction of their migration routes by anthropogenic barriers. To mitigate such impacts, fishways have been developed to facilitate bidirectional fish migration. These structures are affected by the hydrological variability of rivers, which can cause changes in the up and downstream boundary conditions of fishways, leading to non-uniform hydraulic performance. Current methodologies in fishway design and analysis often assume uniform performance, most commonly relying on 1D approximations of the water level distribution. In this study we highlight the necessity of considering non-uniform performance. We provide an in-depth analysis methodology for non-uniform conditions, demonstrating the necessity of 3D models to correctly characterize non-uniformity and leveraging the synergy between 1D and 3D models. For this VOF method together with two turbulence modelling technics, RANS Standard k-ε and LES Smagorinsky models, are analyzed using OpenFOAM CFD platform.

1. Introduction

River fragmentation caused by man-made structures is a major driver of ecological disruption in aquatic systems, as it limits the free movement of freshwater organisms (Branco et al., 2012; Nilsson et al., 2005). The current focus of restoration science is to reestablish connectivity of regulated river systems. Considerable efforts have been devoted to the development and improvement of fish passage structures, in order to define design criteria adequate to the migration requirements of multiple species and life-stages. Pool type fishways are the most popular alternative to allow free bidirectional movement of fish (Clay, 1995; FAO/DVWK, 2002; Fuentes-Pérez et al., 2016; Larinier, 2002a). This type of hydraulic structures consists of consecutive pools separated by cross-walls arranged in a stepped pattern, equipped with slots, weirs or orifices, which are used by the fish to move from pool to pool. These structures aim to facilitate fish passage by reducing the total height of the obstacle (H) into a series of smaller drops (ΔH) providing compatible hydraulic conditions (e.g. velocity, turbulence level, power dissipation or flow distribution) with the fish biomechanics skills.

In the past years, studies have been focusing in understanding the impact of hydraulics on fish behaviour and swimming capability within fishways. This analysis is commonly simplified by assuming uniform flow profiles within the fishway, where ΔH is equal to the topographic difference between pools (ΔZ) (i.e. same water depth in all pools) (Bermúdez et al., 2010; Cea et al., 2007; Puertas et al., 2012, 2004; Rajaratnam et al., 1992, 1986; Tarrade et al., 2011; Wu et al., 1999). However, all constructed fishways are subject to the hydrological variability of the rivers they are connected to, and thus uniformity is seldom observed under natural conditions (Fuentes-Pérez et al., 2016; Marriner et al., 2016). Non-uniform profiles cause a range of different drops between all pools ($\Delta H \neq \Delta Z$) and the varied hydraulic conditions may lead to significant differences in the passage efficiency (defined as the

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https://doi.org/10.1016/j.envsoft.2017.09.011
1364-8152/

percentage of fish which entered and successfully moved through a fishway) observed under uniform conditions (Fig. 1).

Non-uniform performance will produce different mean water levels (h_0) between the pools of a fishway, in idealized conditions manifested as a progressive decrement or increment of h_0 distribution [Fig. 1(a)]. These profiles were named by Rajaratnam et al. (1986) comparing the distribution generated by h_0 in pools to the water profiles provided by the Bakhmeteff-Chow method [Fig. 1(b)], resulting in two mean non-uniform water level distributions: backwater (M1) and drawdown (M2) profiles (Fig. 1). M1 profiles are generated by the decrease of headwater or the increase of tailwater levels, producing higher h_0 and lower drops ($\Delta H < \Delta Z$) in the downstream pools. Conversely, M2 profiles are produced when the headwater level increases or the tailwater level decreases, generating lower h_0 and higher drops ($\Delta H > \Delta Z$) in the downstream pools (Fuentes-Pérez et al., 2016). Furthermore, depending on the complexity of the design (e.g. mixed cross-wall connections, different slopes or direction changes) both profiles can appear mixed.

The modification of h_0 and ΔH profiles (Fig. 1) may have direct consequences on fishways efficiency, as these variables have the potential to alter the spatial distribution and magnitude of velocity and turbulence fields (Tarrade et al., 2008; Wu et al., 1999). Turbulence has a direct impact on fish behaviour, due to its influence on fish locomotion (Lupandin, 2005), fish stability (Silva et al., 2012), as well as on path selection (Goettel et al., 2015). Elevated turbulence has also been found to increase energy expenditure of swimming fish (Enders et al., 2005, 2003; Guiny et al., 2005). Likewise, high turbulence levels can alter the detection of walls and avoidance of other hazards, causing bodily damage of fish and in drastic situations leading to fish mortality (e.g. impingement and entrance in intakes of hydropower stations) (Odeh et al., 2002). Furthermore excessive ΔH will produce high velocities and turbulent levels which may limit the entrance or passage of fish (Larinier, 2002a).

Thus, it is possible to account for possible misinterpretation of fish behaviour by under or over-estimate of fishway efficiency when assuming that fishways run only under uniform profiles. Therefore, it is imperative to study non-uniform conditions in fishways to improve the knowledge of the local hydrodynamics under field conditions. Few studies have analyzed the non-uniform profiles within a fishway at one dimensional (1D) level (water level) (Fuentes-Pérez et al., 2017, 2014; Krüger et al., 2010; Marriner et al., 2016). Nonetheless, the hydrodynamics of non-uniform conditions within a fishway is a complex phenomenon that produces alterations of the flow at a three-dimensional (3D) level, and should be taken into consideration.

In order to analyze and to understand the consequences of non-uniformity within fishways for bidirectional passage of fish, as well as to demonstrate the feasibility of modelling this hydraulic situation, in this work 3D modelling of vertical slot fishways (VSF) was studied under uniform and non-uniform conditions. This was accomplished using OpenFOAM, an open source computational fluid dynamics (CFD) software (Greenshields, 2015). The unsteady flow was simulated using the volume of fluid (VOF) method (interFoam solver) with two different turbulence modelling techniques: (1) Reynolds-averaged Navier-Stokes (RANS) method using standard k-ε model, which is a benchmark in fishway studies (Barton et al., 2009; Cea et al., 2007; Khan, 2006; Marriner et al., 2016, 2014; Xu and Sun, 2009), and (2) large eddy simulation (LES) method using the Smagorinsky turbulence model, which has demonstrated, in some cases, better simulation performance of turbulence parameters than RANS (Van Balen et al., 2010; Vuorinen et al., 2015). The numerical model results were compared to measured data from an acoustic Doppler velocimeter (ADV) in a laboratory fishways model.

The main goals of our work were to: (1) show the effect of non-uniformity in VSFs in the 3D domain; (2) validate 3D modelling results for non-uniform conditions comparing them with measured data; (3) illustrate the use of 1D models to define boundary conditions for 3D models; and (4) highlight the necessity of considering non-uniform performance to adapt fishways hydrodynamics to the requirements of target species.

2. Numerical models

2.1. 1D model

1D numerical methods are the benchmark for simulating non-uniformity in stepped fishways. However, these methods tend to oversimplify the underlying physics of flow field, as they provide an average estimation of the mean water levels of each of the pool of the fishways, neglecting the vertical and horizontal spatial distribution of the flow.

Water levels are calculated via an iterative bottom-up calculus considering the boundary conditions of the system, which are the discharge through the fishway (Q) or the headwater level upstream ($h_{1,1}$) and tailwater level ($h_{2,n}$, where n corresponds to the total number of cross-walls in the fishway) (Fig. 1), the discharge equations involved in cross-walls (Fuentes-Pérez et al., 2014) and the basic geometrical parameters of the fishway [in case of VSF: ΔZ and slot width (b)] (Fig. 2).

The main component in the workflow are the discharge equations, as they must be able to calculate discharge correctly during different boundary conditions. In this regard, it is possible to predict accurately uniform and non-uniform profiles using Poleni's discharge equation [Eq. (1)] (Poleni, 1717) together with Villemonte's submergence coefficient (C_V) [Eq. (2)] (Villemonte, 1947).

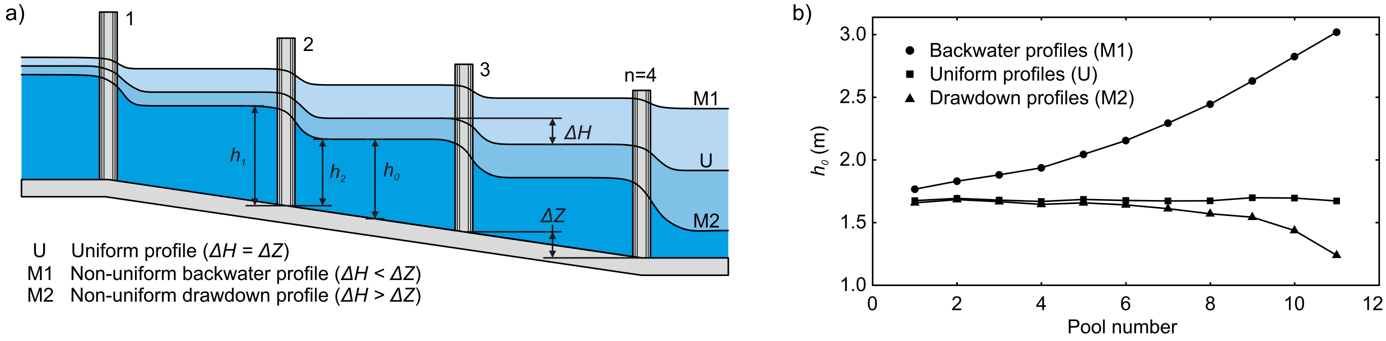

Fig. 1. Example of uniform and non-uniform profiles in a stepped fishway. h_0 is the mean water level in the pool, h_1 is the mean water depth upstream and h_2 is the mean water depth downstream. a) Diagram showing the possible profiles. b) Experimental results of Rajaratnam et al. (1986).