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Experimental hydraulics on fish-friendly trash-racks: an ecological approach

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ABSTRACT

The obstruction of fish migratory routes by hydroelectric facilities is worldwide one of the major threats to freshwater fishes. During downstream migration, fish may be injured or killed on the trash-racks or in the hydropower turbines. Fish-friendly trash-racks that combine both ecological and technical requirements are a solution to mitigate fish mortality at a low operational cost. This study presents results from an experimental investigation of head-losses and the hydrodynamic performance of six angled trash-rack types with 15 mm bar spacing, varying bar-setup (vertical-streamwise, vertical-angled and horizontal bars) and bar profiles (rectangular and drop shape) under steady flow conditions. The trash-racks were positioned at 30° to the wall of the flume and combined with a bypass at their downstream end. The impact of the different trash-rack types on the upstream flow field was characterized using Image based Volumetric 3-component Velocimetry (V3V) and at the bypass-entrance using an Acoustic Doppler Velocimeter (ADV). The results show that trash-racks with vertical-streamwise and horizontal oriented bars with drop-shape profiles have similar head-losses (13% difference), while trash-racks with vertical-angled bars provide 3–8 times larger head-losses compared to the remaining configurations. The velocity measurements showed that the highest flow velocities occurred for configurations with vertical-angled bars (0.67 $m\,s^{-1}$ and 0.81 $m\,s^{-1}$ on average, respectively). Turbulence related parameters (e.g. Reynolds shear stresses and Turbulent kinetic energy) were also investigated to evaluate the performance of the alternative trash-racks from both, engineering and ecological perspectives.

1. Introduction

River fragmentation by hydroelectric facilities is a well-known phenomenon affecting native migratory fish (Larinier, 2001). For example, the populations of anadromous Atlantic salmon (*Salmo salar*) and the endangered catadromous European eel (*Anguilla Anguilla*) decreased significantly in Europe due to the hydropower dams (Hindar et al., 2003; ICES, 2001). This problem is typically associated with the demanding passage through the artificial barriers in both up- and downstream directions (Calles and Greenberg, 2009; Larinier, 2008; Lundqvist et al., 2008; Martignac et al., 2013). During downstream migration, fish face diverted paths as the streamflow is divided at the intake of a hydropower plant (HPP). The entrance to the intake channel is in most cases equipped with trash-racks to protect the turbines from debris, sediment and floating ice (Mosonyi, 1991). They are typically perpendicularly oriented to the flow with 50–150 mm bar spacing (Mosonyi, 1991) and can therefore, besides their operational purpose, be used to prevent larger fish from entering the intake of a HPP. The trash-racks can affect migrating fish as they delay migration significantly or cause injuries, sometimes lethal, depending on the size and type of the HPP and its intake structures (Bruijs and Durif, 2009). The mortality associated with hydropower intakes and turbines may be high when fish are either small enough to swim/drift through the trash-rack bars and pass through the turbines or large enough to be pinged onto the trash-rack surface in cases when the approach flow exceeds their swimming capability (Adam and Bruijs, 2006). One solution is the adoption of alternative designs of trash-racks, which prevents both rack passage, impingement and guide the fish towards a bypass (Calles et al., 2013).

Several studies have explored different fish friendly trash-racks designs (Amaral et al., 2002; Boubee and Williams, 2006; Larinier, 2008). One approach is to reduce the bar spacing to prevent juvenile fish from passing through the bars (Bruijs and Durif, 2009), another is to incline the trash-racks from the bottom (so called inclined trash-

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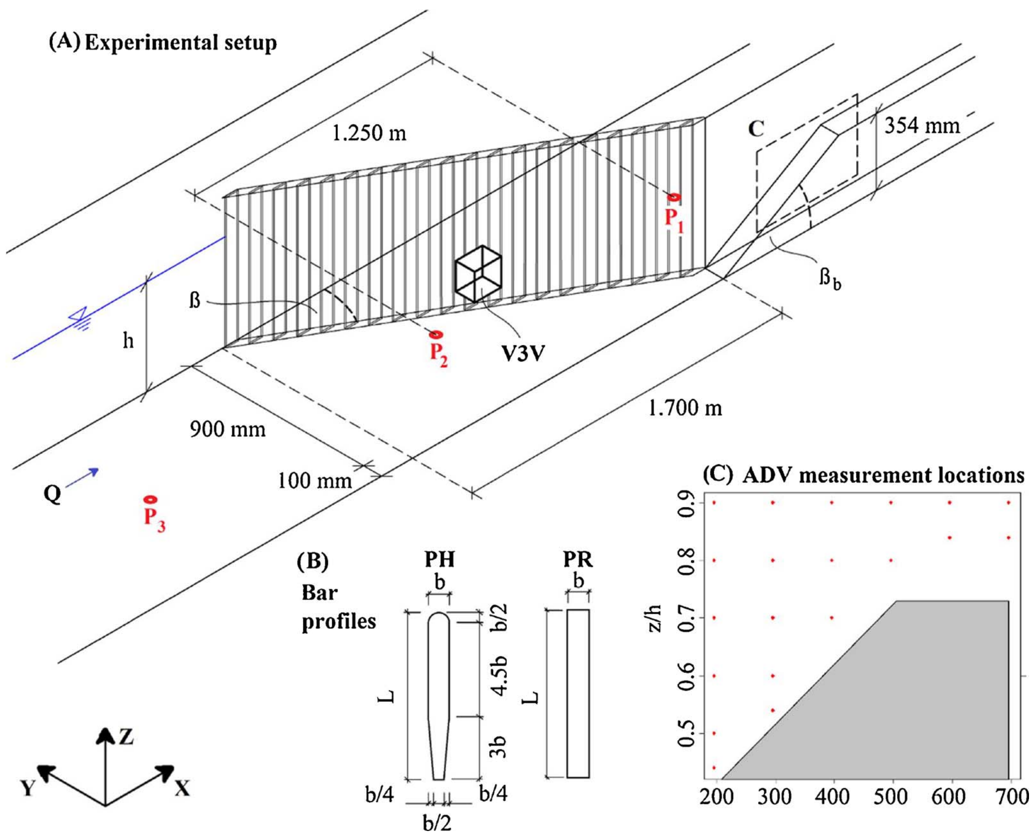

Fig. 1. Experimental setup and sampling locations in a straight open-channel. (A) The position of the trash-rack and the surrounding elements: bypass at the downstream end of the grid, the P_1-P_3 piezometers and the sampled volume of the V3V measurements. (B) The locations of the velocity measurements at the entrance of the bypass section, using ADV. The coordinate system of the bypass is originated at the bottom of the ramp. (C) The adapted bar profiles for the experiments: rectangular (PR) on the right and hydrodynamic shape (PH) on the left.

racks) or angle them to the side (so called angled trash-racks) (DWA, 2005). These designs can be also used to guide the fish either to the surface (at inclined trash-racks), or to the side of the trash-rack (at angled trash-rack types) where the fish may circumvent the obstacle using a bypass channel (Calles et al., 2012). Other studies tested the bars in different positions (Albayrak et al., 2017; Tsikata et al., 2014). The study of Boes et al. (2016) indicated that trash-racks with horizontal bars combined with a bypass can be a preferable solution for fish protection at smaller HPPs, while trash-racks with vertical bars can be an alternative for larger HPPs. The design of an optimal solution taking into account economy and ecology requires the consideration of a number of abiotic parameters such as head-losses and maintenance. In this context, Raynal et al. (2013) investigated the effect of bar-alignment (vertically streamwise oriented bars and vertically angled bars so called ‘classical’ trash-racks) on head-losses and flow characteristics upstream of the trash-racks. They found that trash-racks with vertically angled bars are characterized by significantly larger head-losses and higher velocities at the upstream side of the trash-racks.

The efficiency of a bypass for downstream passage of fish is strongly dictated by the hydraulic conditions at the entrance of the structure, which vary with the design of the associated trash-racks. The effect of hydrodynamics of the flow on the swimming performance and behavior of fish has long been recognized (Kroese et al., 1978; Kroese and Schellart, 1992). Fish can detect water motions in their immediate surroundings by using neuromasts, that can be located superficially all over the fish skin (superficial neuromasts) or under the skin in the head and along the length the fish (canal neuromasts). Superficial neuromasts have been shown to respond to changes in external flow velocity while canal neuromasts respond to variations in external flow acceleration (related with changes in external flow pressure) (Barbier and Humphrey, 2009; Chagnaud et al., 2007; Kroese et al., 1978; Kroese and Schellart, 1992). Thus, it is imperative to improve knowledge on the hydraulic conditions at the vicinity of trash-racks and associated bypasses.

Besides the standard flow characteristics (e.g. time-averaged velocity distributions) typically explored in trash-rack experiments (Albayrak et al., 2017; Tsikata et al., 2009), turbulent flow characteristics may be important for fish movement and the tolerance and preferences of fish to the surrounding flow patterns (Drucker and Lauder, 1999; Silva et al., 2016). Fish are also known to react to flow heterogeneity on smaller distances of centimeters to body length (Enders et al., 2012), which can compromise their orientation, stability and swimming capacity, concomitantly increasing the energetic costs associated to swimming (Silva et al., 2016). For instance, Tritico (2009) found that vortexes play a critical role for fish swimming stability showing that more detailed analysis of flow patterns offer better understanding of the flow conditions from fish perspectives. Moreover, several studies have shown that turbulence parameters such as turbulent kinetic energy and Reynolds stress can be essential to seize the difference between fish preferences and repulsion (Enders et al., 2003; Liao, 2007; Silva et al., 2011). Turbulent flow characteristics can be determined in experiments with trash-racks by using advanced measurement technologies such as Particle Image Velocimetry (PIV) (e.g. Raynal et al., 2013; Sayeed-Bin-Asad et al., 2016; Tsikata et al., 2009).

Here we explored the head-losses and the hydrodynamic performance of six angled trash-rack designs with varying bar-angles, – profiles and – orientation under steady flow conditions using a combination of Acoustic Doppler Velocimeter (ADV) and Volumetric 3-component Velocimetry (V3V) techniques. This facilitated a detailed study of the hydrodynamics of the flow for different trash-racks configurations and associated bypasses. The hydraulic results are discussed in relation to existing knowledge on behavioral responses of salmonid smolts and silver eels, and the operational feasibility of the designs.