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Optimizing attraction flow for upstream fish passage at a hydropower dam employing 3D Detached-Eddy Simulation

David C. Gisen[a,*], Roman B. Weichert[a], John M. Nestler[b]

[a] Federal Waterways Engineering and Research Institute (BAW), Kußmaulstr. 17, 76187 Karlsruhe, Germany
[b] Fisheries & Environmental Services, 9320 Mt. Moriah Road, Edwards, MS 39066, USA

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ABSTRACT

Restoration of upstream fish passage requires construction of efficient fishways. Selection of attraction flow rates and entrance velocities is one of the fundamental research tasks on medium-sized German rivers as general recommendations are ambiguous.

We used a transient 3D Computational Fluid Dynamics model of a hydropower dam tailrace calibrated with Acoustic Doppler Current Profiler velocity data and Detached-Eddy Simulation turbulence modeling to produce seven flow fields. Hydraulic results were linked to fish performance by means of fish-size-speed relations (ethohydraulic scale).

Resulting attraction flow relationships agree well with literature recommendations if the competing flow is defined as the adjacent turbine flow. Further, we found that entrance velocity clearly determines the downstream influence of the attraction flow plume over the attraction flow rate if no rapid mixing is present.

1. Introduction

Compliance with the European Water Framework Directive requires restoration of river continuity by 2027 through construction of efficient fishways (Scholten et al., 2014). The fishways must enable all major migratory fish species to bypass dams that block their movements. In Germany, the medium-sized rivers Neckar (mean annual flow at mouth 145 m^3/s), Main (225 m^3/s), Moselle (328 m^3/s), and Weser (383 m^3/s) are extensively regulated. Fishways at most of their dams are either non-existent or non-operational, preventing migratory fish from accessing important upstream spawning and rearing habitats. Motivated by timely compliance with the requirements of the European Water Framework Directive, the Federal Waterways Engineering and Research Institute (BAW) and Federal Institute of Hydrology (BfG) embarked on an intensive program to develop guidelines that address critical questions associated with effective fishway designs and operations. The selection of attraction flow rate is one of the fundamental tasks.

The two major biological goals of fishway attraction design for upstream migrating fish are maximizing fish entry rates and minimizing search durations. Two design questions are crucial for meeting these goals: "Where should the fishway entrance be positioned?" and "How should the near-entrance flow field be specified?". Basic guidelines for entrance positions are well established (Clay, 1995; Larinier, 2002). In contrast, general attraction flow rate and entrance velocity recommendations are not scientifically founded and are, therefore, ambiguous (Katopodis, 2005). From a strictly biological view, the ideal attraction flow rate would equal the river discharge; however, water demands for other project purposes compete for water that could be used for fishway attraction (Williams et al., 2012) and overbuilt fishways are unnecessarily expensive to construct and operate. Therefore, fishway design requires that fishway size, location, and attraction flow properties be treated as an optimization problem.

We focused on the well-established hydraulic parameters of attraction flow rate Q_{attr} and velocity at the fishway entrance v_{entr} (mean and maximum values, cf. Fig. 7, Appendix A), but acknowledge that other variables can influence fish attraction including turbulence (Coutant, 1998), spatial and temporal derivatives of velocity (Goodwin et al., 2014), the release location of the attraction flow (Burnett et al., 2016), and noise, smell, temperature and oxygenation (Williams et al., 2012). For Q_{attr}, existing international guidelines differ widely in proposed percent ranges and associated reference values (Weichert et al., 2013). For example, US-American guidelines (NMFS, 2011) recommend between 5% and 10% of the design high flow (defined as "mean daily average streamflow that is exceeded 5% of the time" during migration periods) for salmonids on rivers with mean annual flow greater than about 28 m^3/s. Ger-

* Corresponding author.
E-mail addresses: david.gisen@baw.de (D.C. Gisen), roman.weichert@baw.de (R.B. Weichert), john.m.nestler@gmail.com (J.M. Nestler).

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man (DWA, 2014) and British (EA, 2010) guidelines refer to Larinier (1992, 2002), who generally recommends "approximately 1–5% of the competing flow" during the migration period for "well-positioned entrances". Larinier (2008) specifies the percent range to 2–5% of the competing flow defined as "either the turbine discharge, the ecological flow or the spilling discharge at the dam". However, it is still left to the judgment of the designer to determine fixed values or operating limits within these ranges.

Only a few published investigations document detailed tests of alternative Q_{attr} at hydropower dams. Weichert et al. (2013) conducted hydraulic physical model investigations for the Lauffen dam (Neckar River). The authors proposed a Q_{attr} of 5% of the adjacent turbine flow during the design high flow with Q_{attr} decreasing in proportion to lowering tailrace water level as flows decrease. Mader et al. (2014) evaluated different percentage values for three sites using 2D numerical modeling and fish tagging, but found no correlation between attraction and flow rate. Other 3D numerical studies focused on positioning the fishway entrance based on overlaying fish tracks with hydraulic conditions (Andersson et al., 2012; Lindberg et al., 2013) or based solely on hydraulic conditions (Musall et al., 2008).

Our study aimed to use 3D transient CFD models to: (1) evaluate the benefits of a numerical modeling approach to design an optimal Q_{attr} and v_{entr} versus a literature recommended approach; (2) assess alternative Q_{attr} for their ability to create a continuous *migration corridor* as required by DWA (2014); (3) evaluate findings of Weichert et al. (2013) linking Q_{attr} to turbine flow and tailwater elevation; (4) explore the synergy between Q_{attr} and v_{entr} proposed by Larinier (2002) and Clay (1995). Meeting these objectives would be a step towards developing widely applicable guidelines for fishway entrance hydraulic conditions including refined estimates of Q_{attr} that balance environmental goals and economic realities.

2. Materials and methods

2.1. Study site

We conducted our studies at the Kochendorf Dam located in Bad Friedrichshall-Kochendorf, Germany, in the mid-reach (River-km 103.8) of the Neckar River. Kochendorf Dam is the 11th of 27 Neckar River barrages moving upstream from the confluence with the Rhine River. From the right to the left bank, the facility consists of double navigation locks, a 105 m-long navigation guide wall and a powerhouse (Fig. 1). Design hydraulic head of 8.0 m is used to power three vertical Kaplan turbines with a combined maximum discharge of $Q = 100\,m^3/s$ (mean annual flow = $88\,m^3/s$). The elbow-type draft tubes do not exhibit internal splitter walls common in larger draft tubes.

2.2. Boundary conditions

The proposed vertical-slot fishway has an operating flow of $Q_{Op} = 0.67\,m^3/s$ and head drops of 0.12 m at each internal weir. Fishway entrances are planned for both sides of the powerhouse and will be located immediately adjacent to the most outside draft tube outlets, per accepted guidance (Clay, 1995; Larinier, 2002; Williams et al., 2012; DWA, 2014). The dual locations minimize the *dead end effect* where fish following the bulk flow upstream are unable to locate the fishway entrance. Future plans will extend the existing draft tubes to the same longitudinal distance as the proposed fishway entrances (Fig. 2). Both entrance pools connecting the fishway bottom and the river bed have a bottom slope of 1:2 and point downstream (0° to the bulk flow) in compliance with DWA (2014). The right-most fishway pool will be connected to the left-bank fishway via a concrete channel (not shown) embedded in the draft tube

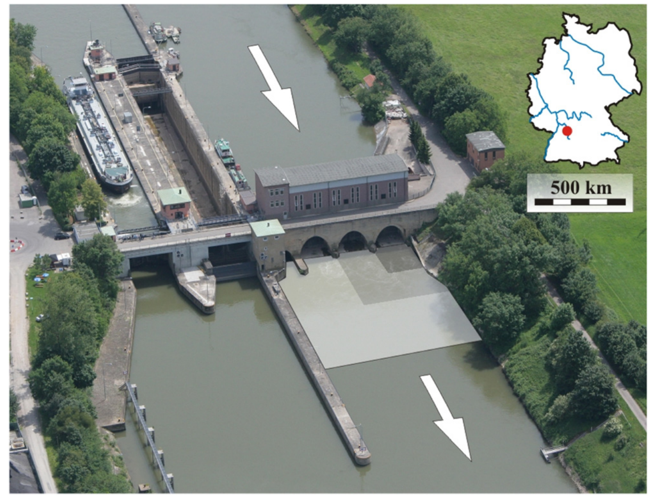

Fig. 1. Aerial view of Kochendorf double navigation lock (left), powerhouse (right), and tailrace model area (highlighted, darker areas show increasing mesh density). Insert shows site location (dot) at the Neckar River with respect to the German federal waterways (Courtesy Amt für Neckarausbau Heidelberg). Decimal degree coordinates: N 49.217348 E 9.207492.

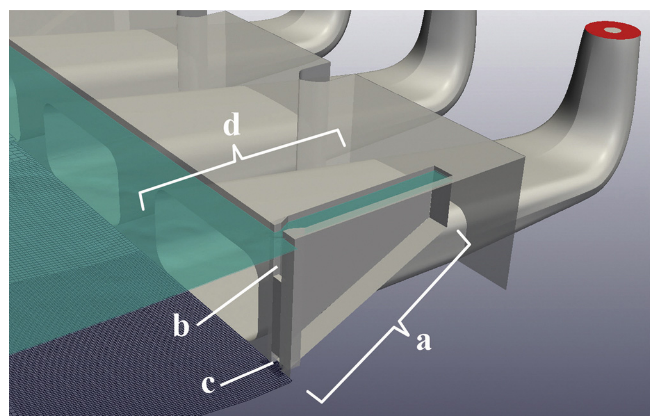

Fig. 2. (a) Left bank entrance pool of the projected fishway with (b) surface notch (0.5 m wide × 1.1 m high during low tailrace water level W_{30}) and (c) submerged orifice (0.5 m wide × 0.5 m high) adjacent to (d) the draft tube extensions. Flow from right (inlets) to left.

extensions. Auxiliary flow will be added through grates in the side walls of the fishway entrance pools.

German guidelines (DWA, 2014) specify the design and operation range for fishways from low (Q_{30}) to high flow conditions (Q_{330}) calculated from ranked, long term mean daily discharges and their corresponding tailrace water levels (W_{30} and W_{330}). Eliminating extreme dry or wet conditions from design considerations substantially simplifies fishway design and, therefore, reduces construction and operational costs. The high and low flow conditions for Kochendorf Dam (Table 3) serve as hydrological boundary conditions for two simulation scenarios.

Typically, fishway designers must consider three coupled entrance parameters: attraction flow rate Q_{attr}, mean entrance velocity $v_{design,entr}$, and water-level dependent cross-sectional area A. We varied Q_{attr} and $v_{design,entr}$ in four simulations for Q_{330} with full load of the powerhouse and three simulations for Q_{30}, where only the near-bank turbine was operational (Figs. 5 and 6 and Table 3). For the first run at Q_{330}, we selected $Q_{attr} = 5.1\%$ ($1.70\,m^3/s$) and $v_{design,entr}$ equal to the design velocity in the fishway (1.5 m/s) closely matching recommendations from Weichert et al. (2013). Thus, we determined A and fixed it for all subsequent analyses after making sure width and height of the openings (Fig. 2) matched