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Abstract: *Worldwide fish passage has increasingly been restored during the last three decades by retrofitting barriers with fish passes. The accessibility and functionality of the entrance are key factors in the efficiency of fish passes. However, the knowledge of the behaviour of the different fish species as well as the entrance design is still insufficient with regards to migration barriers in large rivers with high flows and complex hydraulic conditions. Barriers in large rivers with confined space conditions, difficult topographies, and/or hydraulic structures typically require fish passes with surplus attraction flow at the entrance. Within the framework of the design of large fish passes on European waterways, an innovative fish pass entrance concept and system elements have been developed.*

Keywords: *Fish passage restoration, fish pass design, fishway design, fish pass entrance, fish pass attraction*

1. Introduction

Rivers all over the world have seen severe anthropogenic modifications due to various uses of water, and urban and rural development. Numerous dams, weirs, navigation locks, hydropower plants, water intake structures, and waterway crossings interrupt or impede the continuity of rivers and their tributaries and therewith may delay, hinder, or block migrations of fish. Amongst other things this has resulted in a decline in freshwater fish populations in many countries.

Fish passes have been installed worldwide at migration obstacles and natural barriers for over 300 years and in German rivers for more than 130 years to ensure the upstream passage of fish and aquatic invertebrates. Worldwide fish passage has increasingly been restored during the last three decades by retrofitting barriers with fish passes.

A fishway represents a water passage around or through an obstruction that is found by all fish over a prolonged time of a year without excessive delay and energy loss, and is designed to provide hydraulic conditions suitable for fish to pass the obstruction into the headwater without undue stress or injury (DWA, 2014).

In principle three factors determine the effectiveness and efficiency of fish passes:

- Attraction: general location of the fish pass, entrance position, and attraction flow
- Passage: hydraulic and geometric fish pass design including discharge, flow velocities, and flow patterns; and (with respects to maneuverability of fish) water depths, pool dimensions, and slot sizing
- Operation time: almost all-year-long attraction and functional efficiency

Whereas passage depends on the details of the construction and conditions within the fish pass, the (ease of) location depends on the layout, design, and hydraulic conditions at the fish pass entrance. The accessibility and functionality of the entrance forms the key factor in the total efficiency of fish passes. This was already documented by Gerhardt (1904): "The position and quality of the entrance is of utmost importance in fish pass design. When planning a fishway two tasks need to be solved: first to attract the fish into the fishway, and secondly to move the fish upstream in the fishway. The first task is more important because the success of the second depends on it. It is also more complicated because any solution requires to consider carefully the habits of the fishes" (translated from Gerhardt).

In Germany, the guideline DWA-M 509 (DWA 2014) represents the state of the art in knowledge and technology for the correct design, construction, and operation of fish passes and fish-passable structures. The following factors that are essential for fish pass attraction are described:

- Large-scale location of the fish pass in the water body, taking the site-specific water use(s) into account;
- Perceptibility of the flow velocity, discharge, and angle of the attraction flow;
- Fish pass entrance position and, thus, integration into the downstream environment of a barrier; and
- Design of the entrance, e. g., adaptation to fluctuating tailwater levels and connection to the river bed.

The recommendations in guideline DWA-M 509 represent best practice for faultless technical behavior of fish passes. However, a guideline can never cover all cases and environments. There remain gaps in knowledge on certain aspects.

2. Need for Research

The knowledge of the behavior of different fish species as well as the fish pass entrance design is still insufficient with regards to migration barriers in large rivers with high flows and complex structures and hydraulic conditions, e. g., in the tailwaters of hydropower plants, spillways, and stilling basins.

In principle fish pass attraction is better the higher its outflow/attraction flow in relation to the total (or competing) flow in a river. However, internationally only a few attraction flow recommendations exist (Redeker, 2012). European guidelines and guideline DWA-M 509 generally recommend the guidance values of Larinier et al. (1994). The German Federal Waterway Authority (Wasser- und Schifffahrtsverwaltung, WSV) that manages the large navigable rivers in Germany and its hydraulic structures recommends the guidance values described in Weichert et al. (2013). Accordingly, the cross-section of fish pass entrances must be designed in such a way that in the upper design case Q_{330}[1], the total outflow at the fish pass entrance should amount to 5% of the outflow of the turbine draft tube next to the fish pass entrance.

Within the framework of the design of large fish passes on European waterways, an innovative fish pass entrance concept and system elements have been developed (Heimerl et al., 2015). The following aspects are considered:

- Conditions at hydroelectric power plants downstream of the draft tubes and the adjacent powerhouse typically resulting in intricate flow patterns and confined space situations;
- Placement of multiple fish pass entrances at different locations;
- Hydraulic design and conditions of surplus flow inlet(s) in the entrance area to ensure adequate and uniform attraction flow with different/fluctuating tailwater conditions;
- Connection of the invert of the fish pass to the riverbed for bottom-dwelling fish and benthic organisms; and
- Flood-proof construction of all fish pass elements.

3. Innovative Fish Pass Entrance Concept

3.1. Development of the Fish Pass Entrance Concept

3.1.1. Usual Site-Specific Constraints

At weirs with hydroelectric power plants, the tailwaters adjacent to the draft tubes can typically be described as areas

- with confined space conditions,
- difficult topographies, and/or
- hydraulic structures, e.g., steep reinforced embankments, abutments, anchored sheet-pile walls, etc.

This usually makes it difficult to retrofit a fish pass entrance, which has to be located in this area due to the turbine outflow. Regularly 90° or 180° turns of the fish pass entrance are required to align the fish pass attraction flow in parallel to the hydropower outflow. Adding a surplus attraction flow at or near the fish pass entrance represents an additional challenge, especially if the surplus attraction flow is considerably higher than the fish pass base flow. In addition, a regulating device (e.g., gate) must be installed at the entrance in the case of fluctuating tailwater levels to maintain constant attraction flow velocities. There exist no hydraulic or engineering recommendations with regards to the design of such fish pass entrances. These complex conditions required the development of an innovative solution.

[1] Q_{330} = flow that is not exceeded on 330 days per annum

3.1.2. General Layout of the Fish Pass Entrance Concept

Fishes behave rheotactically, i.e., they align and react to the flow. Fishes' orientation depends on the small-scale flow surrounding them, particularly the flow velocity, flow pattern, and turbulence. In pursuing the overall goal of an improved fish pass attraction, a locally placed lateral inflow of a surplus discharge much larger than the fish pass base flow into a confined section could distract fishes in their upstream movement in the fish pass and therewith affect passage efficiency. Hence, the surplus inflow must be arranged so that fish are not misrouted (i.e., adhere to their migration corridor into the fish pass) but can pass through the entrance without delay. Within the context of the design of a pilot fish pass facility for the WSV (see example Wallstadt, section 3.2), a fish pass entrance concept characterized by the following elements was developed (Figure 1). The German Federal Waterways Engineering and Research Institute (BAW) and the German Federal Institute of Hydrology (BfG) have scientifically investigated the concept (see section 3.2).

- In principle, the entrance consists of a round, hydraulically favorable 180° deflection in order to position the entrance as close as possible to the migration obstacle and to minimize the potential dead-end effect for fishes. A 90° alternative can be realized analogously.
- A regulating device. The device's opening cross-section can be adjusted depending on the attraction flow and tailwater level to generate a uniform flow at the entrance.
- An additional closing device (e.g., stop-log or sluice gate) should be placed immediately at the entrance to enable closures for fish pass maintenance.
- The surplus attraction flow is fed into the fish pass entrance channel upstream of the deflection, laterally via a channel with a flow dissipater and distributor, and a horizontal bar screen placed at a flat angle. The cross-section of the channel gradually widens towards its exit.
- The fish pass or a channel leading towards the fish pass is placed at the upstream end of the screen beside the surplus water inflow structure.

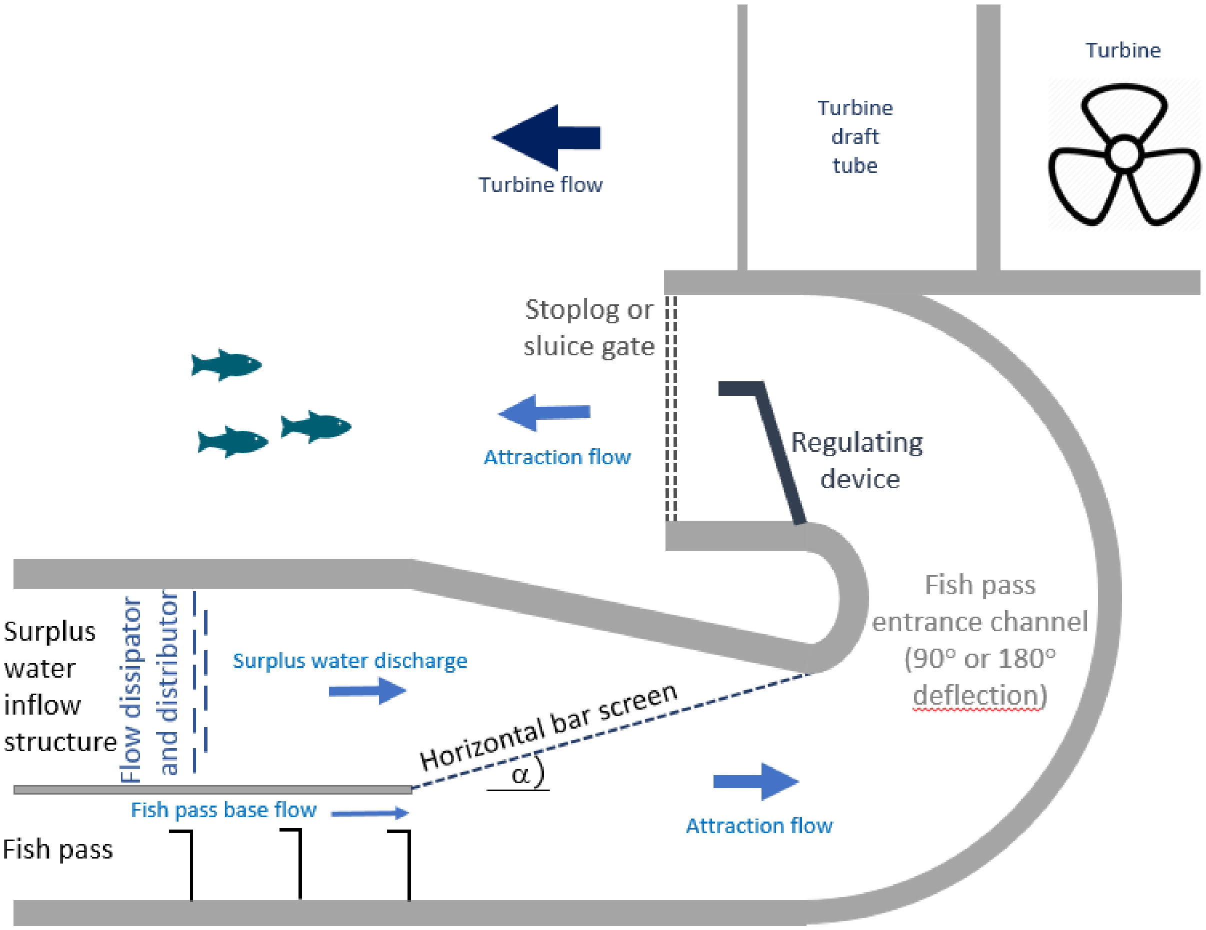

Figure 1. Basic setup of the fish pass entrance concept with surplus attraction flow

3.1.3. Design Hypothesis

The individual system elements were developed and arranged based on the following design assumptions:
Surplus water inflow structure:

- The surplus flow volume may need to be measured and regulated, either at its intake point in the headwater or before it enters the inflow structure, depending on the desired attraction flow (discharge and/or flow velocity).
- In most locations the flow will be conveyed to the surplus water inflow structure by means of a pressure pipe; rarely an open channel. Depending on the available head and flow, the surplus water can be used for power generation in a mini hydropower plant.
- The installation of flow dissipaters and distributors in the surplus water inflow channel assists to generate a homogeneous flow towards the screen.
- Ideally the flows from the surplus water inflow structure and the fish pass converge in parallel in the entrance channel (Figure 1).

Screen:

- A fine bar screen with a clear spacing of 10-15 mm will act as physical screen and prevent most fish species and live stages of swimming into the surplus water inflow structure (DWA, 2005). Therefore, the surplus water must be clear of debris and fish, i.e., screening itself at its intake to prevent clogging or pose an impediment to downstream moving fish.
- A horizontal bar screen aids to form fish-friendly, laminar flow conditions in the confluence of the screen and fish pass flows.
- A flat screen angle (α) of around 10° - 30° is needed to guide fish towards the fish pass. An even flow distribution along the screen surface and over the water column into the entrance channel presents the main challenge from a hydraulic point of view.
- Guideline DWA-M 509 recommends an outflow velocity at the screen of max. 0.4 m/s. In view of fishes swimming capacity, to limit hydraulic screen loss and to prevent backwatering in the entrance channel, an outflow velocity at the horizontal bar screen (orthogonally to the screen) of 0.2 - 0.3 m/s was suggested for the design of the gross screen surface.
- The design of the horizontal bar screen, in particular the screen height, must take into account the tailwater design levels and corresponding variable surplus water volumes.

Fish pass entrance channel:

- The (mean) minimum flow velocity in the entrance channel must be greater than or equal to the rheotactic flow velocities of the design (target) fish species to ensure passage in all tailwater conditions.
- The threshold velocity of channel-type fish passes according to Table 18 in guideline DWA-M 509 represents the (mean) maximum flow velocity in the entrance channel. The threshold velocity depends on the channel length.
- The anatomy and locomotion of the longest design fish determines the minimum radius of the 90°/180° deflection.
- The bottom of the entrance channel needs to be connected to the river bottom to facilitate orientation of bottom-dwelling fish, e.g., by means of a rock ramp.

Regulating device:

- A gate is suggested as a regulating device. To minimize hydraulic losses, the regulating gate should open with the flow. The gates' opening cross-section can be adjusted depending on the attraction flow (discharge and/or flow velocity) and tailwater level. Complete opening and closure was anticipated. Several designs and positions are currently being considered; amongst others a single-leaf gate positioned in front of the 180° turn into the tailwater (Figure 2).

3.2. Fish Pass Entrance Concept applied to Wallstadt Pilot Fish Pass Facility

The new fish pass entrance concept was first applied to the design of the pilot fish pass facility near Wallstadt (River Main in Central Germany) where four different entrance locations (Figure 2: E1, E2 …) will be monitored for several years after commissioning.

Wallstadt Hydropower Plant has a design flow of 135 m³/s. Following the guidance values mentioned above, an attraction flow of 6.8 m³/s (5% Q_{HPP}) is required at the (main) fish pass entrance. The fish pass leading to the headwater has a base flow of around 0.8 m³/s. Hence, a surplus flow volume of up to 6.0 m³/s, i.e., about eight times the fish pass base flow needs to be fed into the fish pass entrance structure. The tailwater design level fluctuation amounts to 0.93 m (between W_{30} and W_{330}).

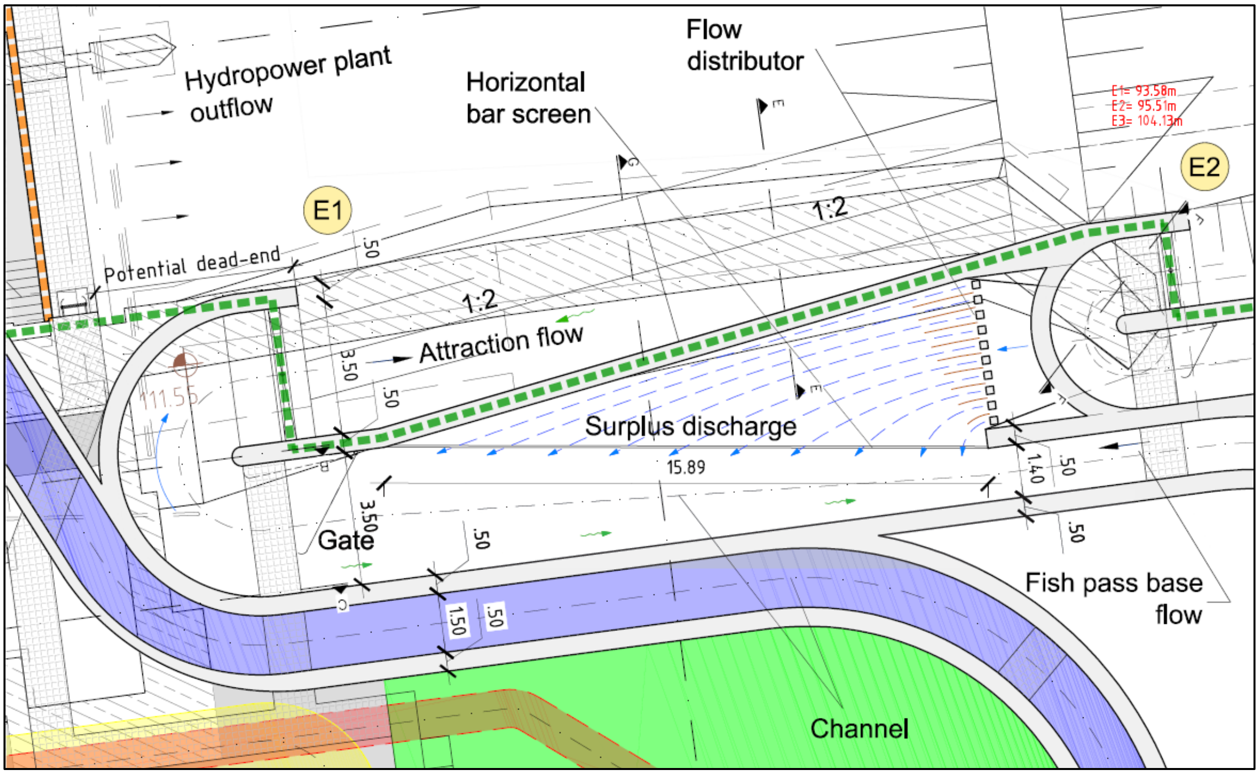

Figure 2. Wallstadt pilot fish pass facility - layout of the fish pass entrance concept. Entrance E1 is the main entrance. (Heimerl 2016)

The predesign layout (Figure 2) was studied by means of hydraulic investigations involving physical and numerical modelling (BAW; Fiedler, 2018) as well as ethohydraulic investigations at the BAW Hydraulic Laboratory (BfG; Czerny; and Schütz, 2017).

Initially, a physical model of the fish pass entrance concept with external dimensions of 4.5 x 11.0 m was created in the BAW Hydraulic Laboratory at a scale of 1:5 (Heimerl et al., 2015; Fiedler, 2016). The objectives of the physical experiments were to assess the inflow into the surplus water inflow structure, the flow pattern at the bar screen, and the flow into the fish pass entrance channel (Fiedler, 2016).

Table 1. Scales of the physical units in the Wallstadt facility Froude Model 1:5 based on Kobus (1984)

	Scale $1{:}M_L$	Scale 1:5
Linear Measure	M_L	5.0
Time	$1{:}M_L^{1/2}$	2.23
Velocity	$1{:}M_L^{1/2}$	2.23
Discharge	$1{:}M_L^{5/2}$	55.90

With his physical models Fiedler (2016) confirmed that an even outflow can be achieved at a screen installed at an acute angle if the surplus water inflow into the structure (channel) is calmed and homogeneous upstream of the screen. Moreover, Fiedler verified that the desired orthogonal flow velocity component of 0.2 m/s of the screen outflow was maintained in this setup. As the design of the surplus water inflow was found to be very important for homogeneous inflow provision, Fieder investigated five different inflow (riser) designs for conveyance (pressure) pipes (Fiedler, 2016 and 2018). He recommends specific layouts that allow mixing processes (turbulence) inside the riser outflow with the purpose to create homogeneous flows towards the screen (Fiedler, 2018). As these designs are likely to require substantial development lengths, precise design recommendations are highly anticipated.

Whereas there exists a fair number of investigations with regards to total fish passage efficiency (e.g., DWA, 2006; Bunt et al., 2012; and Noonan et al., 2012), the knowledge as to the performance of specific fish pass elements as well as the interaction between the hydraulic conditions and fish behavior is extremely limited (Redeker, 2014). Thus, the findings of the ethohydraulic investigations will enable further development of modular solutions for comparable locations in large rivers.

3.3. Application and Development of the Fish Pass Entrance Concept for Fish Pass Doesburg

The fish pass entrance concept was also applied to a recent fish pass design in the Netherlands. The fish pass at Doesburg barrage, consisting of 54 pools, will be the highest fish pass in the Netherlands with a head of 5 m. According to project plans, the fish pass will be put into operation early 2019.

Doesburg barrage is unusual in that the tailwater level fluctuates distinctly. The tailwater design level fluctuation of 3.84 m requires two surplus water inflow structures, one at the fishway entrance (inflow #1) and another in the lower fish pass (inflow #2), to maintain/exceed a) rheotactic flow velocities in the slots, b) a continuous migration corridor in the fish pass including entrance/exit channels and a turning pool, and c) an adequate attraction flow at the entrance.

A total flow of 1 m^3/s is available for fish pass operation. The fish pass has a base flow of 0.30 m^3/s. Surplus water (up to 2.33x fish pass base flow) will either be introduced solely at inflow #1 (during low tailwater levels) or into inflows #1 and #2 (during high tailwater levels). The surplus water supply will be regulated and distributed merely depending on the tailwater level. A 4.80 m high single-leaf gate at the entrance will regulate the outflow to provide mean attraction flow velocities above the rheotactic flow velocity up to 0.78 m/s. It is noted that the gate is not designed to close completely but will maintain a minimum slot width of 28 cm when the tailwater design level is high.

CFD modelling was conducted to design and finetune the surplus water inflow structures (CDM Smith, 2018). Different scenarios (tailwater level conditions and surplus flow constellations) were assessed (Figures 3 & 4):

- We identified that the outflow of the pipe elbow has a distinct influence on the flow pattern in the surplus water inflow structure and at the screen.
- We studied different flow dissipater/distributor arrangements, which had diverse effects on the screen flow pattern. Therefore, we recommend variable dissipater arrangements that can be optimized during operation.
- The entrance velocity clearly determines the length (downstream distance) of the attraction flow plume (Figure 4). A plume that extends further downstream will have a greater encounter volume (impulse) for fishes than a plume that does not extend as far downstream, and most likely a greater attraction to fishes.
- Flow patterns and conditions in tailwaters vary depending on flows, tailwater levels, hydropower/weir operation, and bathymetry. These can have a significant effect on attraction flow plume pattern and distance (Figure 3).
- The gate arrangement (left or right side of channel) also has a noteworthy effect on the attraction flow plume pattern (Figure 4).

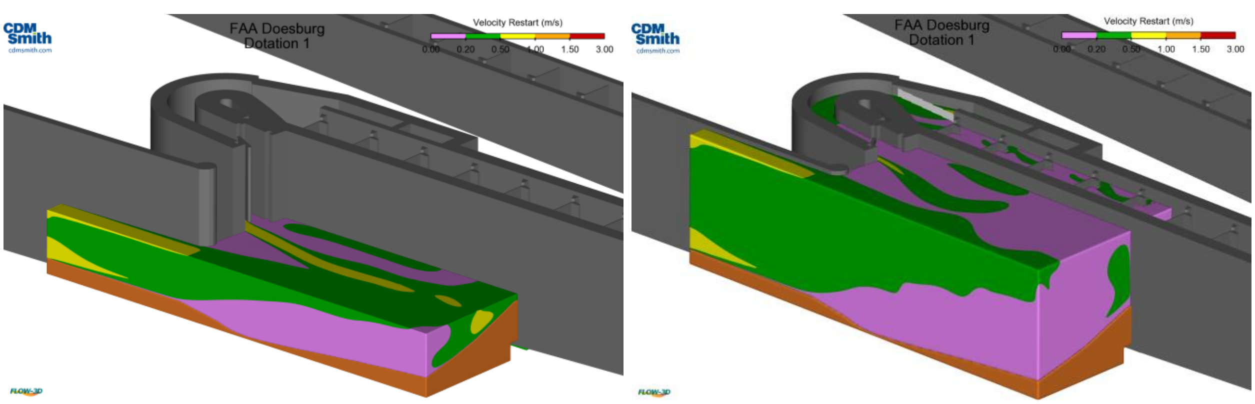

Figure 3. CFD model results of Doesburg fish pass entrance for different tailwater conditions (CDM Smith 2018)

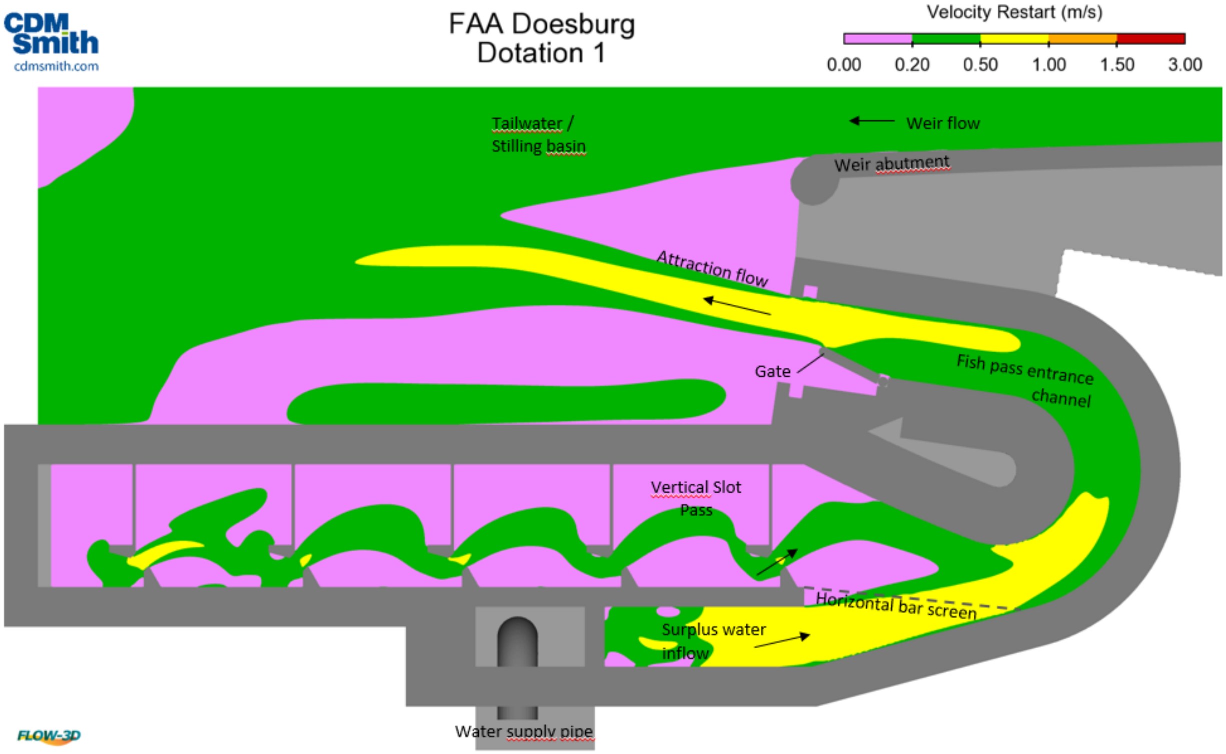

Figure 4. CFD model result of Doesburg fish pass entrance and inflow #1 (top view, ethohydraulic colour scale) (CDM Smith 2018)

4. Advancement of the Fish Pass Entrance Concept

The investigations described above were conducted to confirm the suitability of the fish pass entrance concept for practical use in advance. The aim is to provide all those involved in design processes with concrete solutions for upcoming projects, but also to develop modular solutions that may be transferred to other locations.

Advancements of the fish pass entrance concept by the authors are under way, e.g., the placement and detailed arrangement of functional elements that remain to be assessed hydraulically and/or ethohydraulically such as:

- single-leaf control gate installed downstream of the 180° turn (Figure 4)
- double-leaf control gate installed downstream of the 180° turn (Figure 5)
- multiple-leaf control gate installed downstream of the 180° turn (Figures 6 and 7)

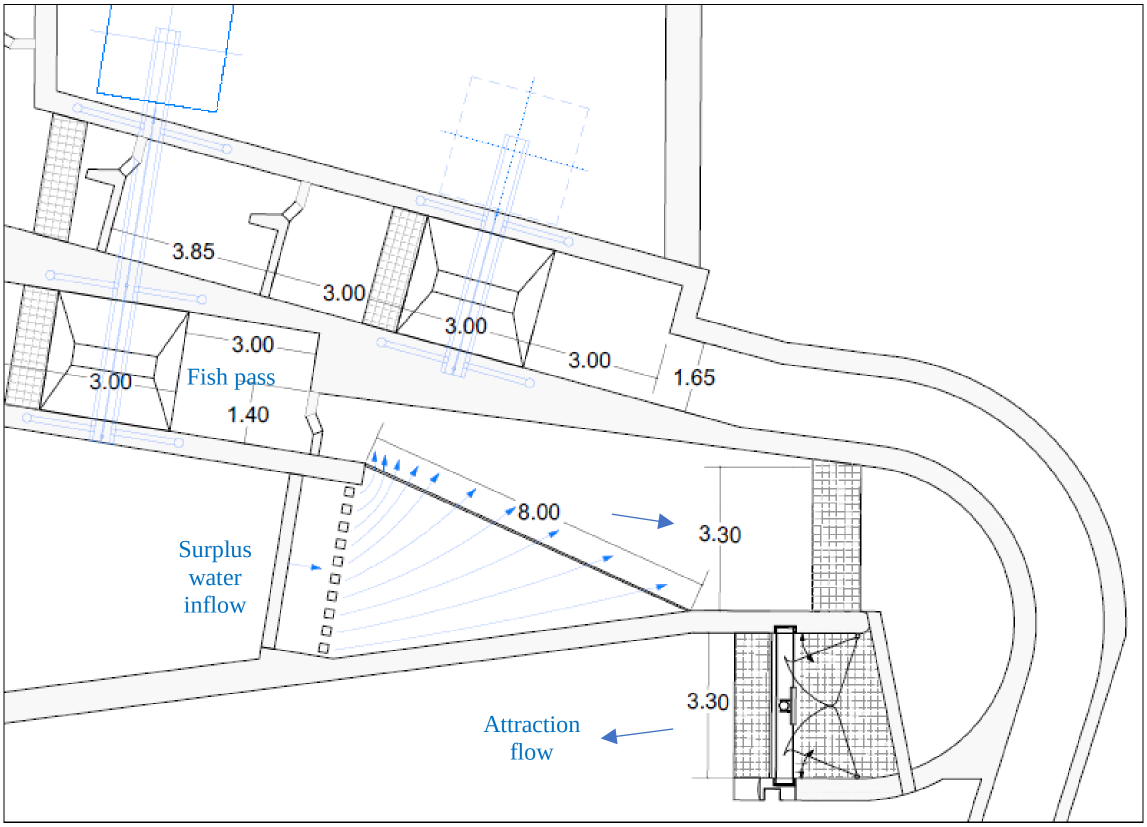

Figure 5. Layout of the fish pass entrance concept with an adjustable double-leaf gate installed downstream of the 180° turn (Heimerl 2016)

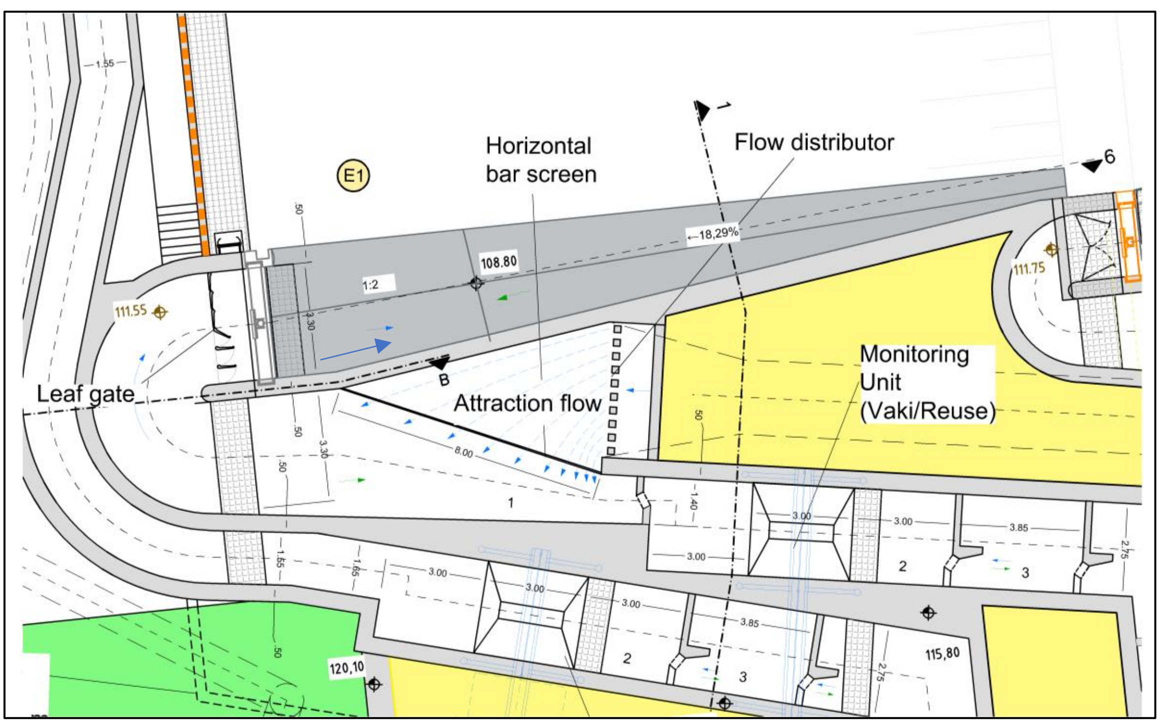

Figure 6. Layout of the fish pass entrance concept with a multiple-leaf gate installed downstream of the 180° turn (Heimerl 2018)

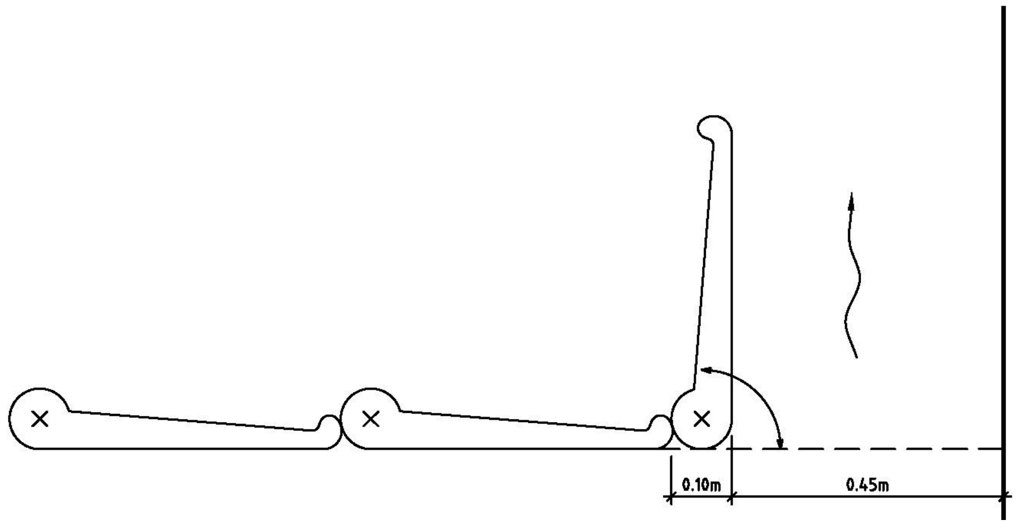

Figure 7. Detail of the multiple-leaf control gate (Heimerl 2018)

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