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Influence of Inflow and Outflow Boundary Conditions on Flow Situation in Vertical Slot Fishways

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Abstract: *Fishways are of importance for stabilization and regeneration of fish populations. Since most waterways and rivers are anthropogenic modified—e.g., to make them navigable or to produce energy, etc.—the effect on biology and morphology is not negligible. Some fish species are nearly extinct because they cannot reach their natural habitat to spawn or feed or the genetic diversity is lacking due to barriers that cannot be overcome. In the past decades a growing effort was made to decrease the ecological impact. Consequently, several fishways were built to provide migration corridors for various aquatic organisms. Since the 1980s different kinds of fishways have been biologically and hydraulically investigated. Numerous nature-like structures as well as technical structures were studied in physical, numerical, and prototype models. Vertical slot fishways can be categorized as technical fishways with a series of pools and a sloping bottom, where vertical openings in the cross walls provide a migration corridor. Hence, vertical slot fishways represent a technical bypass for dams and other lateral barriers. Even though vertical slot fishways are well studied, further hydraulic effects can be observed. In this context, the present paper investigates the hydraulics of vertical slot fishways and deals with the effect of downstream water levels on the hydraulic flow situation on vertical slot fishways. While most hydraulic models assume a quasi-uniform flow, it can be observed that varying water levels in geometrically equal pools are frequent. Herein, results of an experimental model are presented. Water levels in the pools and their dependence on inlet and outlet boundaries (water levels and discharge) are investigated. It can be shown that downstream water levels—pre-set with an installed tailgate—as well as upstream water levels (as a result of the inflow conditions) have an influence on the pools' water depths, while the influenced area, and consequently the number of affected pools, majorly depends on the specific discharge. A uniform distribution of total height difference at the fishway from one pool to the next could not be confirmed. Water level reduction and backwater effects result in continuously non-uniform flow situations on the structure.*

Keywords: *Fish passage, vertical slot fishway, VSF.*

1. Introduction

1.1. General

Fishways are important facilities in current waterway and river systems. They facilitate fish to migrate beyond artificial (man built) hydraulic barriers, such as dams or hydropower plants, and thereby restore river connectivity. One type of fishway is the technical type known as vertical slot fishway (VSF). VSF are mostly rectangular channels with sloped bottoms. A sequence of pools is formed by vertical cross walls to produce small hydraulic drops between adjacent pools. Vertical openings over the entire height in the cross walls provide the migration corridor for fish (e.g., Clay 1961; Rajaratnam et al. 1986). Furthermore, flow guiding elements generate the desired flow characteristics. Thereby, permissible velocities and preferred flow characteristics for fish species of interest are created. The benefit of VSF can be found in an almost independent flow (velocities, flow pattern) in respect to discharge. Thus, VSF are suitable for rivers with high water level differences and a wide range of upstream and downstream water levels. Also, the needed area is small compared to nature-like fishways.

Great effort was made to gain an understanding of flow in VSF and widen the scope of application in the past decades. While in Rajaratnam et al. (1986) and Rajaratnam et al. (1992) different designs were investigated concerning the overall hydraulics, other publications examined the relation of pool width B to pool length L (e.g., Bermúdez et al. 2010) or even several inserts of flow guiding purpose (e.g., Tarrade et al. 2006). Still new flow features are discovered. For example, the influence of lateral flow guiding elements (FGE) on the flow was investigated only recently (e.g., Bombač et al. 2017; Klein and Oertel 2017). The majority of publications focused on water surface profiles, depth-discharge relations, velocities, turbulent kinetic energy, and energy dissipation rates within regular pools.

1.2. Issue of Boundary Conditions

Dimensioning of VSF is based on physical modelling of certain standard designs. One of two commonly used discharge equations is:

$$Q = C_d\, b_0\, h \sqrt{2g\Delta h} \tag{1}$$

where Q is the fishway's discharge, C_d is the discharge coefficient, b_0 is the slot width, h is a flow depth, g is the gravity acceleration, and Δh is the head drop between two pools. Eq. (1) was first stated by Clay (1961). Via physical models Eq. (1) was verified by Rajaratnam et al. (1986), Rajaratnam et al. (1992), Larinier (1992), Puertas et al. (2004), Wang et al. (2010), and more. Often forgotten is the fact that these models were performed under "quasi-uniform" conditions. Via manipulating the downstream water level in the flume, a quasi-uniform flow, defined by achieving similar flow depth characteristics in each pool, was generated. Chorda et al. (2010) stated that the third pool of five pools in a VSF model was uniform and therefore suitable for taking measurements. In Puertas et al. (2004) two designs, each with four pools, were tested, arranged in one flume successively. In Rajaratnam et al. (1986), besides uniform flow experiments, submerged and drawdown experiments were also conducted with several slopes and discharges. The non-uniform experiments were made with 18 VSF-pools. It was shown that for a given discharge the flow depth in the tailwater region has to be higher than a certain value to affect the flow depth in the adjacent pool; below this value it is invariant. In the figures it can be seen that in the drawdown experiments, a quasi-uniform flow developed only in the middle pools, while the last eight pools were influenced by the drawdown. The submerged state showed submerged pools over almost the entire model. Also, with a VSF model of four pools a uniform state could not be reached. Rajaratnam et al. (1986) also defines: 'When the flow profile is uniform, the head drop per pool will be the same for all pools, whereas for a non-uniform flow, it will be different for each pool.' However, it has to be noted that the measurements were taken with a metal ruler, which may withhold a high error. Fuentes-Pérez et al. (2014) tested two common dimensioning equations on their application on non-uniform flow of VSF in field measurements and concluded that both equations could be applied on VSF but only with considering the water level and its drop at each pool. Consequently, this proceeding results in one discharge coefficient for each pool. Those observations could be verified by further field measurement campaigns and observations: Musall et al. (2015) stated, that in an VSF at Koblenz, both flow pattern and fluctuations between them could be observed. Also, significant influence of downstream water level is described. Marrinier et al. (2014) found in field measurements non-uniform flow characteristics in 12 of 16 pools (downstream) due to high tailwater and resulting influence of the discharge coefficient.

The data presented herein, though, showed that achieving a quasi-uniform flow depends on the downstream water depth as well as on the inflow situation of the model and the number of pools. Unfortunately, there have been few attempts to characterize the hydraulics in VSF concerning inlet or outlet boundary conditions. Thus, several hydraulic models were conducted, and the handling of boundary conditions in a vertical slot fishway model with limited number of pools was not yet disclosed. Observations at FH Luebeck's water research laboratory showed non-uniform flow behavior and flow fluctuations at a model of seven pools. The issue with non-uniform behavior is that the dimensioning with Eq. (1) is based on the above stated manipulated quasi-uniform appearance.

Gebler (2015) defined four states of non-uniform flow in VSF, which were observed in the field:

1. Increased tailwater and constant inlet water level leads to backwater with increasing water level drop in flow direction.
2. Increasing of both boundary water levels with constant water level drop but increased discharge.
3. Increased tailwater and constant or less increased inflow water level leads to reduction of overall water level drop and increasing water level drop between pools dh in flow direction.
4. Increased inlet water level leads to an increased overall water level drop. The discharge is increased and the water level drop between the pools is rising in flow direction.

The aim of this study is to develop a detailed description and an initial analysis of the inlet and outlet boundary conditions of VSF—not directly with the purpose on how to handle dimensioning and calculation discharge coefficients, but to give guidelines and hints/references on the handling of boundary conditions in hydraulic models.

2. Experimental Setup

The hydraulic model was located at the water research laboratory at Luebeck Universtity of Applied Science. A vertical slot fishway consisting of seven pools was installed in a 0.8 m wide flume with a total length of approximately 10 m. The clear length of each vertical slot fishway pool L_L was 1.0 m (parallel to the bottom). Pool dimensions are shown in Figure 1. The bottom slope was set to 5 %. While the overall pool dimensions stay the same in all measurements, two positions of lateral flow guiding element (FGE) are realized. This resulted in different slot angles C (37° and 67°), whereas the slot width itself stayed the same for both designs. Displacing the lateral FGE led to a change of flow pattern (FP) from FP 1 to FP 2. Figure 2 shows the different flow pattern. For more information on the influence of lateral FGE and the overall model geometry, see Klein and Oertel (2017).

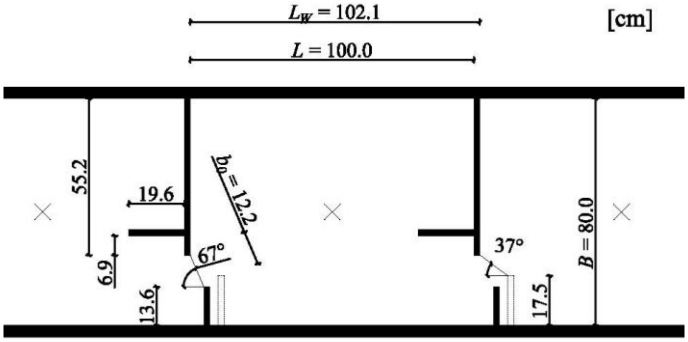
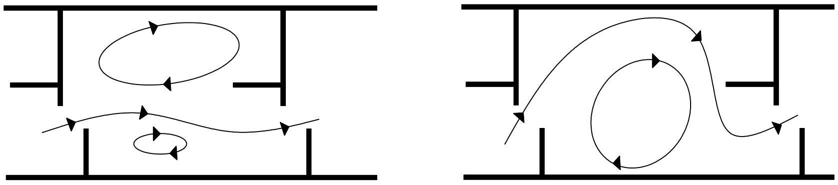


Figure 1. Pool geometry; × = sensor points.



(a) FP 1 (b) FP 2

Figure 2. Flow pattern according to Wang et al. (2010).

The hydraulic model was equipped with ultrasonic sensors (mic+130/IU/TC, microsonic, range: 200 mm to 1300 mm, precision: ±1 %) to measure the flow depth in the center h_c in each pool as well as $0.5 \times L_L$ in front of the first cross wall for 180 s at 75 Hz. The measurement time of 180 s had proved to be sufficiently accurate to approximate a time-averaged water depth. Furthermore, reproduction of measurements with the same boundary condition was ensured. The system's water was supplied by a head tank connected to a DN200 pipe system with frequency-controlled pumps in a closed circuit. Discharge measurements were conducted by means of an electromagnetic flow meter (Krohne Optiflux 2000, precision ±0.1 ls^{-1}). The downstream water level was set with a tailgate at the end of the flume (circa 1 m downstream the last cross wall), which was positioned by a step motor.

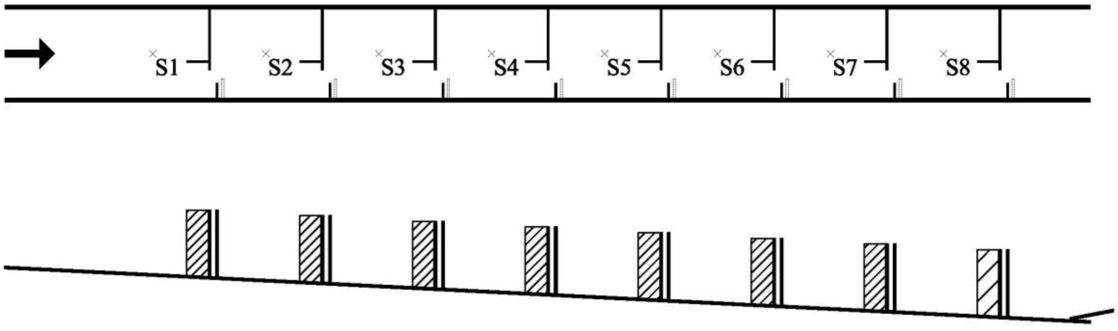


Figure 3. Plan view and longitudinal cross section of hydraulic model, × = Sensor points.

For each design (C = 37° resp. C = 67°) the flow depth was measured for ten resp. five discharges and three to thirteen tailgate positions were recorded. Earlier investigations at FHL have shown that the flow depth at the center of the pool approximates the mean pool flow depth with an error of up to +2 %. With the conducted measurements the mean water level difference between two pools can be calculated by the adding the difference in flow depth to the difference of bottom slope:

$$\Delta h_m = h_{c,i+1} - h_{c,i} + S \cdot L_W \tag{2}$$

where S is the bottom slope and L_W is the pool length (incl. cross wall). For dimensioning a VSF the average water surface difference between two adjacent pools Δh_m is assumed to be as big as the bottom slope difference:

$$\Delta h_m = \Delta h_S = S \cdot L_W \tag{3}$$

But as stated before this depends on the inflow and outflow water level and on the overall water level difference:

$$\Delta H_S = \Delta h_S \cdot n \tag{4}$$

where n is the number of pools in the fishway. With natural inflow and overall water level difference equal to the bottom slope difference, uniform flow with the same flow depth in every pool is expected. This flow depth, in the following named as h_{uni}, is unknown and hydraulic modelling aims to predict it to formulate design guidelines.

3. Results

Table 1 shows the measured flow depth for each model run. For all investigated model runs three resp. five flow states (FS) can be defined. The herein described flow states refer to the flow characteristics of the investigated VSF model consisting of seven pools. Whereas upstream (US) flow behavior and downstream (DS) flow behavior is described in respect to the later investigation pools in the middle of the structure. This description aims to provide a possibility to evaluate the inlet (US) and outlet (DS) boundary conditions and their influence of the pools in the middle of the structure for studies of uniform flow in VSF.

Table 1. Measured quasi uniform water depth in the pool's center.

h_{uni} [mm]	Q = 16 ls^{-1}	Q = 20 ls^{-1}	Q = 24 ls^{-1}	Q = 28 ls^{-1}	Q = 32 ls^{-1}	Q = 36 ls^{-1}	Q = 40 ls^{-1}
C37	166		242		323		324
C67	151	193	237	287	322	363	407

3.1. State 1a: US Draw, DS Minor Backwater

The overall water level difference $\Delta H_{1\text{-}8}$ (the index indicates ΔH was calculated with flow depth values of Sensor 1 and Sensor 8) was equal to the bottom level difference ΔH_s. In this case a uniform flow could be expected (marked in cyan, **Figure 4**a), but the flow depth in the following pool sunk while the adjacent Δh_m were higher than Δh_S (**Figure 5**). In the middle pools a nearly uniform flow, as described by Rajaratnam et al. (1986), was developed. Three adjacent pools had nearly the same flow depth and $\Delta h_m/\Delta h_S \approx 1$. In the three downstream pools a typical backwater curve was observed, characterized by increasing flow depth and decreasing flow depth difference from pool to pool Δh_m. The upstream pools, however, were not influenced by the downstream water level. This shows, that the inflow flow depth (flow depth 0.5 L in front of the first cross wall, S1) was higher than h_{uni} in most model runs because the flow depth increased significantly in the following two to three pools and the water level difference between each pool Δh_m was 10 to 50 % higher than Δh_S (**Figure 5**). Consequently, the uniform flow must develop in a number of prior pools before measuring.

3.2. State 1b: US Draw, DS Minor Draw

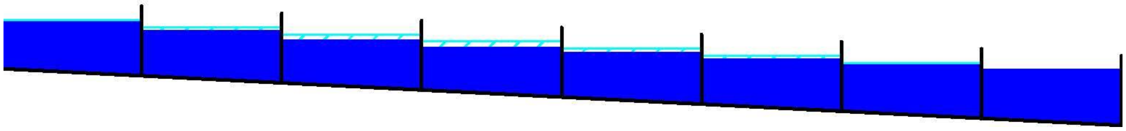
The overall water level difference $\Delta H_{1\text{-}8}$ was bigger than the bottom level difference ΔH_s. The flow depth in the following pool sunk while the adjacent Δh_m were higher than Δh_S (**Figure 4**b and **Figure 6**). In the middle pools a nearly uniform flow was developed characterized by nearly the same flow depth and $\Delta h_m/\Delta h_S \approx 1$. In the last three pools a typical drawdown curve was observed characterized by decreasing flow depth and increasing flow depth difference Δh_m from pool to pool. The upstream pools, however, were not influenced by the downstream water level. Thus, two separate drawdown curves were found. All flow depth, however, were lower than the inflow depth (marked in cyan, **Figure 4**b).

3.3. State 2: Partial Quasi-Uniform Flow

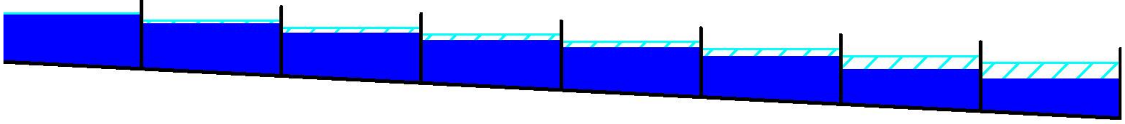
State 1 showed that the inflow depth in the model was higher than the flow depth at uniform flow h_{uni}. So, the flow has to develop throughout at least two pools. State 2 showed the flow situation when the water level difference between the third pool (see Figure 3, S4) and the seventh pool (see Figure 3, S8) was equal to the bottom level difference. It was found that the flow depth in each pool was lower than the inflow depth (**Figure 4**c and **Figure 9**), but between these pools a uniform flow was present: the flow depth was the same in each pool , and the water level difference between adjacent pools Δh_m was equal to Δh_S. On the contrary, the first two pools withheld higher flow depth and water level differences Δh_m. This should be the preferred flow state for hydraulic models.

3.4. State 3a: US Draw, DS Major Backwater

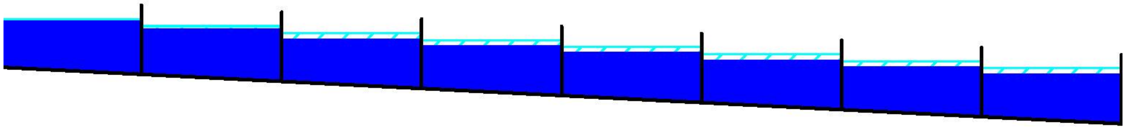
At flow state 3 the downstream water level had a major impact on the VSF flow. Flow state 3a showed a typical backwater curve reaching at least the investigation pools (third and fourth pool). In some cases the backwater continued throughout the whole length of VSF, reaching to the inlet (**Figure 4**d and **Figure 7**). The flow depth in every pool was higher than the inlet flow depth without backwater influence (marked in cyan, **Figure 4**d); wherefore, the water level difference of adjacent pools Δh_m was lower than Δh_S. The influence of the downstream flow depth decreases with increasing distance from the downstream end of VSF, shown by increasing $\Delta h_m/\Delta h_S$ towards the inlet.



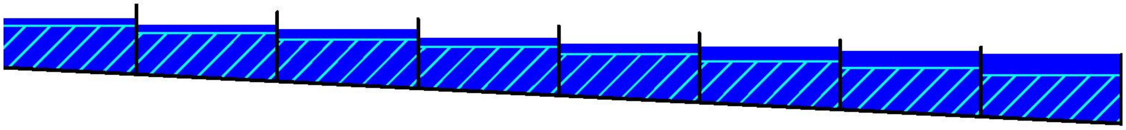
(a) FS 1a



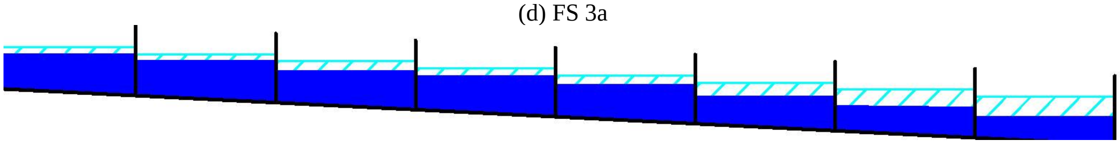
(b) FS 1b



(c) FS 2



(d) FS 3a



(e) FS 3b

Figure 4. Schematic sketch of flow states in VSF.

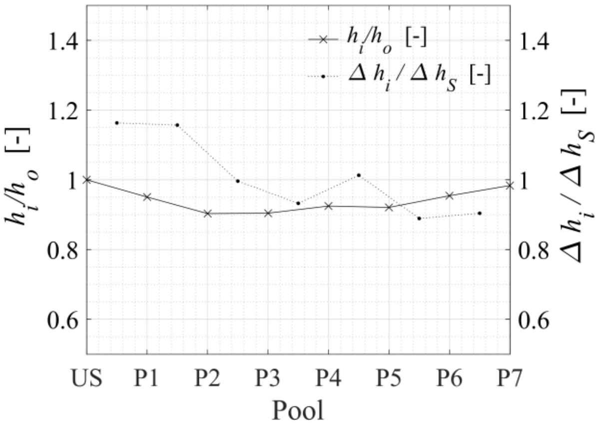


Figure 5. Example of FS 1a (Q = 16 l/s).

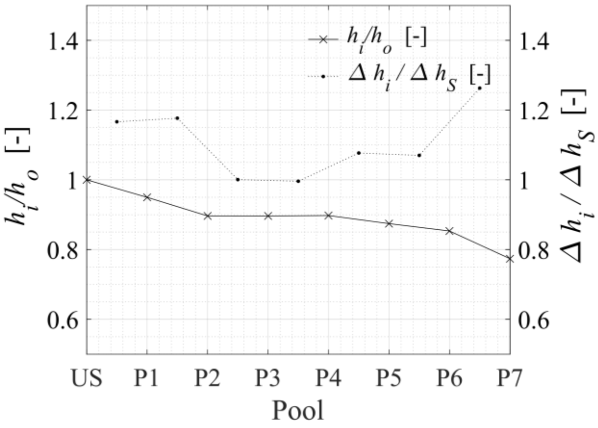


Figure 6. Example of F 1b.

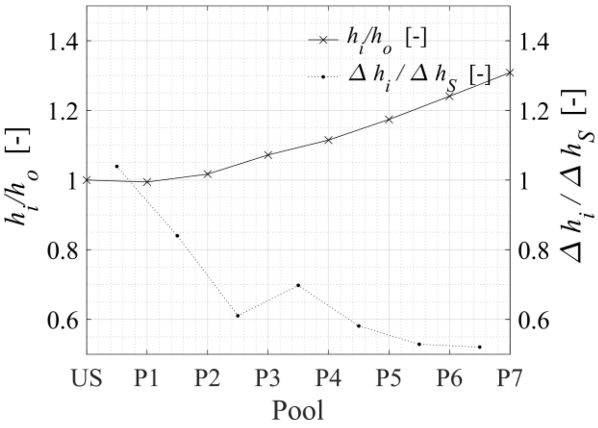


Figure 7. Example of FS 3a.

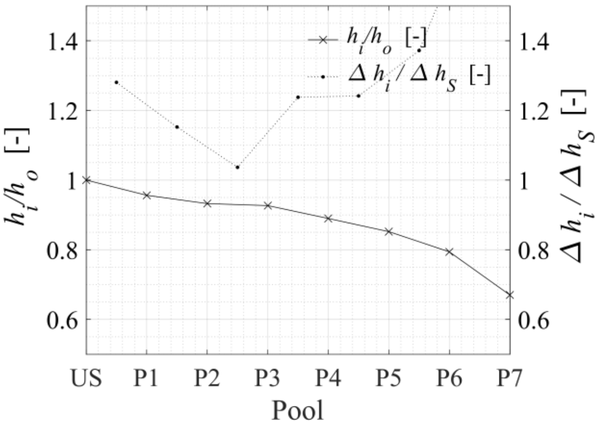


Figure 8. Example of FS 3b.

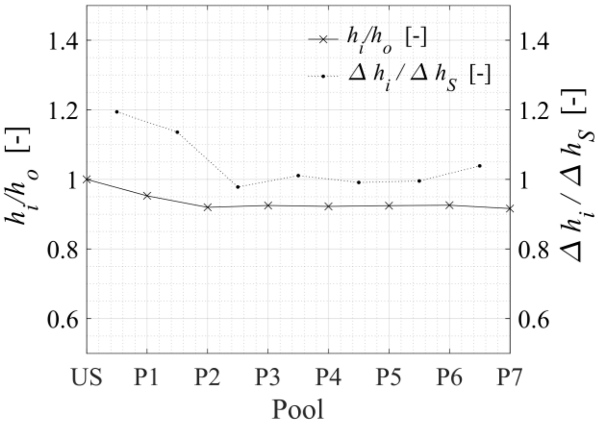


Figure 9. Example of FS 2.

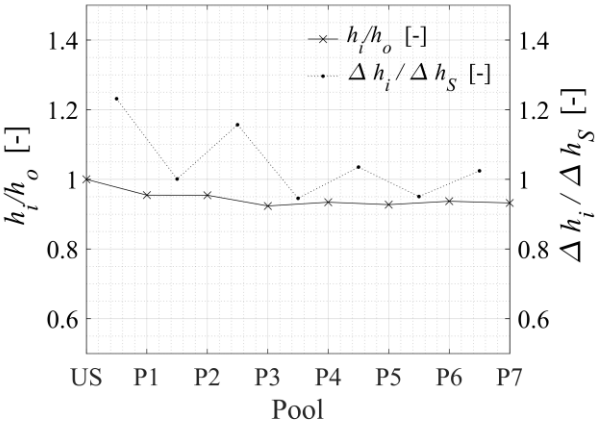


Figure 10. Nearly uniform flow.

3.5. State 3b: US Draw, DS Major Draw

Flow state 3b showed a typical drawdown curve throughout the whole length of VSF. The flow depth in every pool was lower than the inlet flow depth without influence of the downstream flow depth (marked in cyan, Figure 4e);

wherefore, the water level difference of adjacent pools Δh_m was higher than Δh_S decreasing upstream the structure (Figure 8).

Both designs (C = 37° resp. C = 67°) showed similar behavior, whereas the higher slot angle of $C = 67°$ seems to be more sensitive to change of downstream water level. This might be due to FP 1, where the flow travels directly from pool to pool and thereby no decoupling of the pools is given like with FP 2. Nonetheless, general statements for both designs can be made. The higher the overall water level difference $\Delta H_{1\text{-}8}$ is, the further upstream is the drawdown continued. In general, it can be said, that if

$$\Delta H_{1-8}/\Delta H_S > 1 \qquad \rightarrow \text{drawdown is present} \tag{5}$$

$$\Delta H_{1-8}/\Delta H_S < 1 \qquad \rightarrow \text{backwater is present.} \tag{6}$$

Also, it is important to check if the inlet flow depth is higher than the flow depth, which would occur at uniform flow. In models with a small number of pools, like the presented model, it is difficult to estimate the uniform flow depth. Hence, not considering the first two pools resp., consider that the first two pools as “flow development pools” might be better for uniform flow experiments. Thereby, natural flow development is given. Considering the first and second pool in the presented model as pools for flow development, the measured water level differences for evaluation uniform flow will be calculated between the third and last pool (Figure 3, S4 and S8). As a dimensionless value, it is divided by the bottom slope between the measurement locations:

$$\Delta H_{4-8} \ = h_{c,S8} - h_{c,S4} + S \cdot L_W \tag{7}$$

$$\Delta H_{S,4-8} = n \cdot S \cdot L_W \tag{8}$$

$$\rightarrow \ H = \Delta H_{4-8}/\Delta H_{S,4-8} \tag{9}$$

where $n = 4$ as number of pools between S4 and S8 and $h_{c,S4}$ resp. $h_{c,S8}$ as measured flow depth at location S4 resp. S8.

Figure 11 shows the calculated dimensionless water level difference between pool three and seven of both designs (*y*-axis) and all discharges to evaluate limit values for the influence of downstream flow states on quasi-uniform flow in experimental models. The *x*-axis shows a classification of the downstream flow states. If there were more model runs resp. height of tailwater at one discharge for each flow state than needed for setting the limit values—thus if there were more than two model runs classified as the same flow state, the values in-between are also shown.

The above described flow states are represented here. While at FS 1a and 1b at least pool 3 to 5 show uniform flow. FS 2 shows uniform flow in all pools downstream pool 2. The red marked areas display FS 3a and 3b where no uniform flow can be found.

Analyzing the influence of the downstream water level on the upstream pools, the experiments showed that without a raised downstream water level, uniform flow could not be reached within seven pools. Without a raised downstream water level the drawdown even reached the inlet and decreased the water level in front of the first cross wall. Consequently, a particular increase of downstream flow depth had to be provided to reach uniform flow in the investigation pools (third, fourth, or fifth pool). As seen in **Figure 11**, at least H < 1.2 should be reached to evaluate the inlet flow depth. Between 1.4 < H > 1.2 drawdown reaching throughout seven pools up to the inlet cannot be neglected. Backwater effects can be found at H < 0.97, whereby between 0.97 < H > 0.86 the backwater does not spread to the inlet. Both effects move upstream with increasing difference of downstream flow depth to uniform flow depth. But there is a fine line between sufficient backwater to reach quasi-uniform flow and backwater influencing the upper pools especially at high discharges. With high discharges (i.e. 36 to 44 l/s) it is difficult to determine the uniform flow depth h_{uni}, because it might occur that two adjacent pools show uniform behavior even without sufficient downstream water level. This can be identified if by rising the downstream water level further, all pools show increasing flow depths. It has to be noted, that at 44 l/s, the smallest increase of downstream water level results in increasing flow depth in every pool. Hence, with the present model setup it might not be possible to reach a uniform flow at 44 l/s.

Also, just before a total quasi-uniform flow is reached, it was observed that the water level difference of adjacent pools Δh_m shows a zigzag course (**Figure 10**). Due to these observations it is recommended to meet the following limits to achieve uniform flow in a short ($n \leq 8$) VSF model:

1. At least two pools upstream the investigation pools to guarantee flow development
2. $H = 1.0 \pm 3\ \%$
3. $\Delta h_m/\Delta h_S = 1 \pm 5\ \%$

In the case of doubt, e.g., with high or low discharges, individual cases should be investigated and a number of downstream water levels near the expected h_{uni} should be studied.

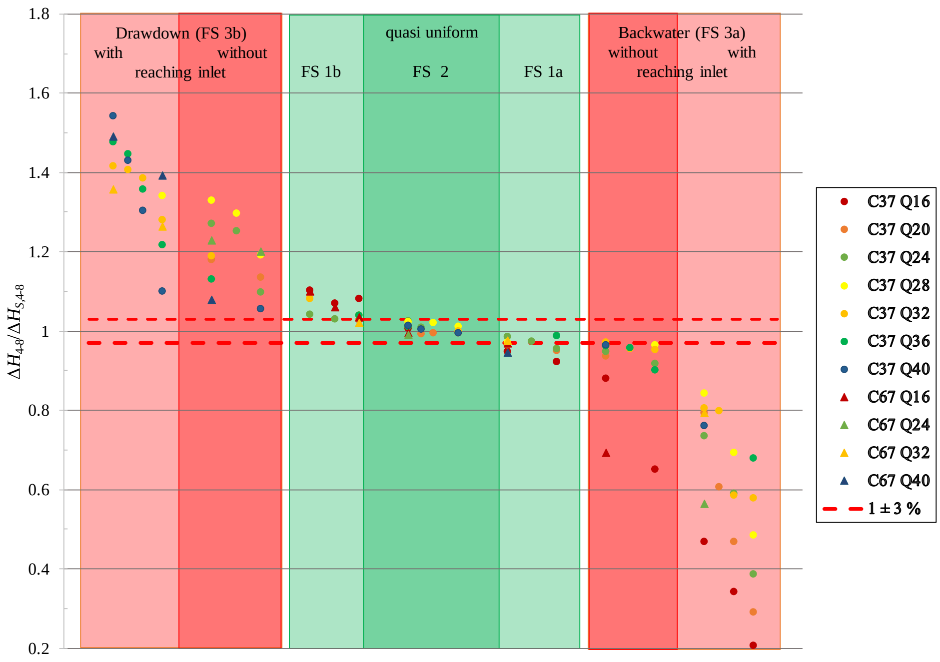


Figure 11. Observed dimensionless water-level/geodetic-height-difference H for all flow states.

4. Conclusion

Several model runs confirmed Rajaratnam et al. (1986); a uniform flow in a VSF is achieved in pools with the same flow depth and when the water level difference between adjacent pools is the same as the difference of bottom slope. Furthermore, an indicator of quasi-uniform flow is when the water level difference between adjacent pools is the same as the difference of bottom slope with a deviation of maximum ± 5 %. This state is announced by alternating high and low water level differences of consecutive pools (zigzag course as explained above). To achieve a quasi-uniform flow in VSF models, it is thereby possible to manipulate the downstream water level in defined limit values. The downstream water depth can be increased up to the water depth in the third or fourth pool of a VSF model, whereby the deviation of total measured water level difference and the bottom slope difference H should not exceed 3 %. The limits between quasi-uniform and backwater or drawdown influence are narrow for short VSF models. Caused by the influence of boundary water levels on the structure, which are transported from pool to pool, with increasing number of pools, it will be easier to achieve a quasi-uniform flow in a VSF model. Also, flow patterns have influence of the propagation of inlet and outlet effects caused by the rate of decoupling.

The model presented herein showed that not only the downstream water level, but the inflow depth, is important for development of uniform flow. At least two pools upstream the investigation pools are suggested to ensure flow development.

In practical field situations the uniform flow is the design state but in everyday operation of the fishway, this state might only occur rarely. Therefore, it is important to consider the above stated flow states in the practical field situations and their influence of fish migration. For example, at drawdown situations the maximum capable flow velocity might be exceeded, and migration cannot be proceeded, which is caused by the resulting higher water level differences. As it was shown here it is important to consider two locations of drawdown: (1) drawdown in consequence of high upstream water levels in the upper pools or (2) drawdown in consequence of low downstream water levels in the lower pools. On the contrary, backwater effects might result in low flow velocities and in not finding the entrance of the fishway.

5. Acknowledgements

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