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Numerical Study on the Hydraulic Conditions for Species Migrating Downstream Over a Weir

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Abstract: *The German Waterways and Shipping Administration (WSV) has to replace several weirs in the near future. In addition to maintenance and operation, the WSV is also responsible for the establishment of the ecological continuity, i.e., free migration of species like fish along the river and thus over weirs. The downstream migration over weirs with low to medium heads was a mostly neglected issue and was commonly considered to be an insignificant hazard for fishes. Recently, this assumption was tackled by fish biologists by applying design rules for plunge pools at fish bypasses to weirs. As a consequence, an additional plunge pool may be required in order to fulfill this criterion at a weir. In a numerical study with the three-dimensional computational fluid dynamics package OpenFOAM®, the hydraulic characteristics of a sharp crested weir were analyzed in detail, in particular the nappe deflection at the weir sill. The hydraulic conditions were evaluated in terms of accelerations and were compared to acceptable accelerations for different species in order to assess the possible endangerment of fishes. Additionally, the conditions for fish plunging into pools of acceptable depths were evaluated numerically with a numerical model based on the software Star-CCM+®. The results of both studies support the thesis that the "plunge pool criterion" is an insufficient tool to assess the safety of fish migration over weirs with significant overflow and that substantial further research is required in order to derive a suitable criterion that can ensure the safe passage of fishes over medium height weirs with low tailwater levels.*

Keywords: *Gate, weir, fish, migration, OpenFOAM, STAR-CCM+, numerical modeling.*

1. Introduction

With the implementation of the European Water Framework Directive (WFD), the good ecological status of surface water bodies has been set as an objective for all member states of the European Union. One important measure to achieve this goal is to establish ecological continuity at European surface waters. According to the amendment of the German Water Act in 2010, the Federal Waterways and Shipping Administration (WSV) has to restore the ecological continuity at about 250 barrages at the German waterways it owns or operates. Re-establishing ecological connectivity at barrages is mainly achieved by providing measures that allow for safe fish passage for both long distance migratory fish and resident fish species. It is important to note that different structures are required for upstream and downstream fish passage as fish behavior differs considereably. According to the German Federal Ministry of Transport and Digital Infrastructure (BMVI), the principle of causal responsibility is applied to measures of downstream fish passage. Following this, hydropower companies are responsible for the protection and bypassing of fish at turbines, whereas WSV has to ensure safe downstream fish passage at weirs. In the recent past, downstream passage of migratory and resident fish over weirs with low to medium heads (approx. 5 m) was a mostly neglected issue, as it was assumed that downstream migration especially of surface-oriented fishes is unaffected under natural flow regimes. However, recent studies, as well as expert assessments of fish biologists, suggest that weir structures may have a negative effect on fish passage, and threats to fish are possible. As numerous weir structures in federal waterways are in a bad condition, there is need for action to replace those structures. In this context, a serious consideration of downstream fish passage processes is evident. In this article, first results of a hydraulic study on downstream fish passage over a weir are presented and are discussed in the context of the existing recommendations.

2. Downstream Migration of Fish

Barriers in rivers can have major impacts on fish populations by preventing or restricting movement to habitats required for essential stages of fish life history (Gauld et al., 2013). This concerns both upstream and downstream fish passage. Regarding downstream fish passage, two basic topics can be distinguished. First, there are open questions on how fish behave approaching a barrage. The simple assumption that fish passage is proportional to water flow through the routes (weir, ship lock, power plant) does not correspond with observed fish passage patterns (Goodwin et al., 2014). In addition to discharge proportions, there are several other influencing factors, e.g., bed morphology, bank structure, or local hydraulic patterns. It is fundamental to notice that fish behavior differs for different species, making general solutions difficult. Furthermore, the most relevant processes are time dependent, e.g., discharge, water levels, weir management, and morphologic structures. However, barrage operation and, thus, discharge proportions significantly influence the distribution of fish in a forebay. Following this, the importance of fish passage at the components 'hydropower plant' and 'weir' is evident. The second general topic is related to the passage process itself. In this case, fish behavior is rather less relevant as it is assumed that fish are flushed passively within the water body. Following this, prospective studies should focus on processes that may damage fish and how damaging mechanisms can be diminished. It is obvious that the individual design of the weir, as well as upstream and downstream water levels, affect the species-dependent processes. Comparing the routes of fish migration, it must be noted that hydraulic turbines at many sites are the major problem for fish migration. Passing through hydraulic turbines can cause high mortality ratios of up to 90% for Francis turbines. On average the observed mortality ratio is lower in Kaplan turbines, with a high variety depending on study design, site design, and considered species. As an example, Marmulla (2001) mentioned mortality ratios of 5% to 20% for Kaplan turbines. Nowadays, so-called fish friendly turbines have become more popular. These reduce the mortality by using large spacings between the blades, smaller gaps, and a reduced rotational speed.

In Germany and Switzerland, several research projects are currently focused on fish behavior at trash racks and bypasses at hydropower plants (e.g., Boes et al., 2016; Lehmann et al., 2015). Contrarily, fish behavior at weir structures is a rarely considered task. Transfer of knowledge from the studies at hydro power plants to weirs is generally questionable, as fish behavior at low-head weir structures may differ significantly to fish behavior at trash racks.

3. Criteria for the Downstream Transit of Fish over Weirs

3.1. Literature Review

As mentioned above, the impacts of low-head weir structures on downstream fish passage are poorly known. Gauld et al. (2013) considered downstream salmonid smolt migration in a river with a number of small weirs and showed that weir structures without bypasses in combination with low-flow periods have a significant effect on fish migration. In this context, effects can vary from short delays to complete blockage. If fish decide to pass a weir structure, they are potentially exposed to a hazard due to the possible collision with structural elements of the weir, to exceeding shear forces or local negative pressures. Here we are focusing only on the damages due to dropping over a low head weir. Thus, other mechanisms for injuries of fishes, like shear at the weir or negative pressures, are not regarded here.

In Germany, assessment of potential fish damage is usually based on recommendations for downstream passage at hydro powerplants (DWA, 2005; LUBW, 2016). These guidelines, in turn, refer to criteria from uncited design guidelines mentioned in Odeh and Orvis (1998), and mix the citation with individual expert opinions. Odeh and Orvis (1998) stated that the required plunge pool depth should be equal to a quarter of the total drop height, with a minimum of 0.9 m at total drop heights less than 3.6 m. The minimum plunge pool volume is given with 10 m³ for every 1 m³/s of flow, which seems strange, as the kinetic energy of the jet should be a relevant parameter.

Generally, fish that are disoriented after passing a weir structure are prey to predators, so hydraulic conditions should not be too challenging. In addition to the tailwater conditions, threshold values are given for the total drop height and the impact velocity, respectively. In DWA (2005) an impact velocity threshold of 13 m/s (equivalent to a free fall from 9 m) is associated with small fish damage, if favorable tailwater conditions exist. For comparison: human high divers jump from a height of 25 m in competitions (Napolitano et al., 2013). A smolt mortality ratio of 3% at a barrage in the Connecticut River is mentioned by Odeh and Orvis (1998) for an 11 m drop and a discharge of 8.5 m³/s. Without giving more details of the underlying study, USACE (1991) presents a relation between impact velocity and lethality (i.e., the mortality ratio) for fish colliding with the water surface and solid objects, respectively. According to this, no kills occur for fish impacting a water surface with velocities of 20 m/s (v_{impact}). For fish striking solid objects, the value is significantly smaller (5 m/s). Figure 1 shows that mortality ratios of 50% are reached at velocities of 30 m/s for fish entering water and 16 m/s for fish striking a solid object. After applying a regression formula on the dataset for impact on solid objects ($R^2 > 0.99$), the lethality L in percent for this case can be expressed as:

$$L = 4.303 \cdot (v_{impact} - 4.6) \quad (1)$$

This can be converted to the lethality for the impact on solid objects after a free fall of the fish from a certain height h_{fall}, assuming free acceleration due to gravity only, zero initial vertical velocity, and no air resistance:

$$L = 4.303 \cdot \left(\sqrt{2 \cdot g \cdot h_{fall}} - 4.6\right) \qquad (2)$$

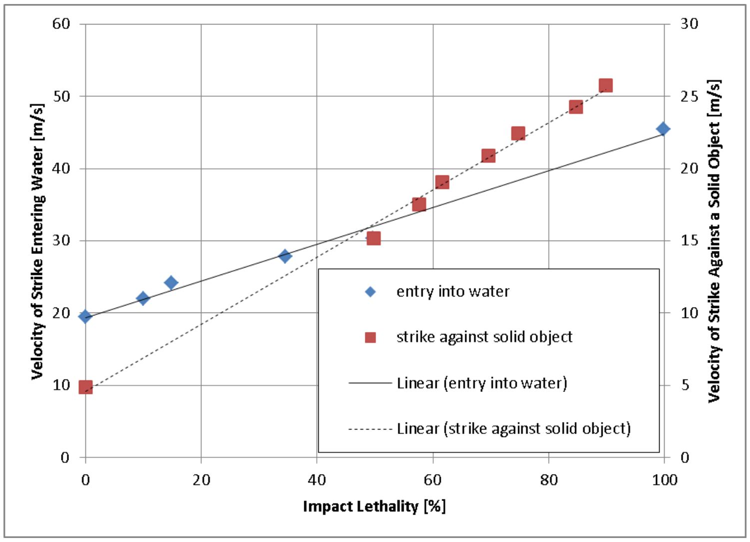

Figure 1. Fish mortality ratio (impact lethality) for collision with solid objects or fish impacting on a water surface, adapted from USACE (1991)

It should be mentioned that a delayed mortality of fish facing small injuries is often described in literature, so that harmless hydraulic conditions presumably exhibit smaller velocity values.

Generally, the actual basis for a sound assessment of downstream fish passage at weir structures is unsatisfactory. Strongly deficient information in existing publications given together with individual expert opinions demonstrate the need for research.

3.2. Numerical Study on Fish Impact on the Water Surface

As stated above, only very limited knowledge is available on the criteria for acceptable conditions for fish in a nappe behind a low-head weir. In Germany, a value of 13 m/s for the impact velocity of a fish on the water surface is generally accepted (DWA, 2005), though it must be stated that the scientific foundation of this value is rather weak. But, due to the general acceptance, it was decided to derive further information for the conditions that occur for a fish in this situation and to use them as acceptable values for the conditions that occur behind a weir.

For the numerical tests, a virtual fish was used. The fish was largely simplified by omitting the fins and by building the body from several distorted ellipsoids. The resulting fish body (Figure 2) has a length of 20 cm, a height of 5 cm, and a width of 2 cm. The fish has the same density as the surrounding water, resulting in a mass of 117 g.

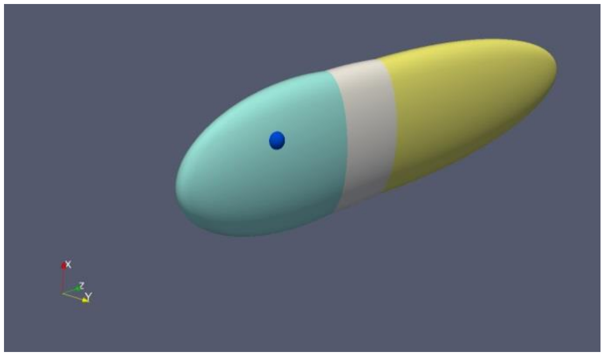

Figure 2. Rendering of the virtual fish used in the simulations

The simulations of the impact on the water surface were performed with the commercial software STAR-CCM+®. The simulations were fully three-dimensional and treated the position of the water surface with a volume-of-fluid approach (Hirt and Nichols, 1981). The movement of the fish was realized with a so-called overset or chimera grid approach. For this approach, the moving fish body is embedded in its own computational grid, which moves "through" the computational grid of the larger outer domain. The simulation domain has a size 2 m x 2 m x 1.4 m and the moving inner domain is of cylindrical shape with a diameter of 40 cm. The computational grid has ~ 2 million cells with edge length ranging from 2.5 cm to 1.25 mm near the fish. In order to check for grid convergence, refined meshes with ~ 14 million cells and a minimum grid size of 0.6 mm were used additionally. For the simulations, a very short time step length of 10^{-5} s was used in order to accurately capture the highly transient effects at the moment of the impact. The total simulation time was limited to 0.1 s.

In the simulations, two scenarios were regarded as the most relevant ones. The first one is the "head first" scenario. In this one, the fish hits the water surface vertically and perfectly aligned. The second scenario is a worse case: the fish hits the water surface lying on the side and, thus, exposes the largest possible area to the fluid. As the DWA (2005) guideline states that no damage occurs for the fish at all for the regarded impact velocity, both positions are suitable for the extraction of further data. The simulations were started with the fish positioned a few centimeters above the water level and with a downward velocity of 13 m/s. Figure 3 shows the development of the water surface directly after the impact of the fish in the "side first" position.

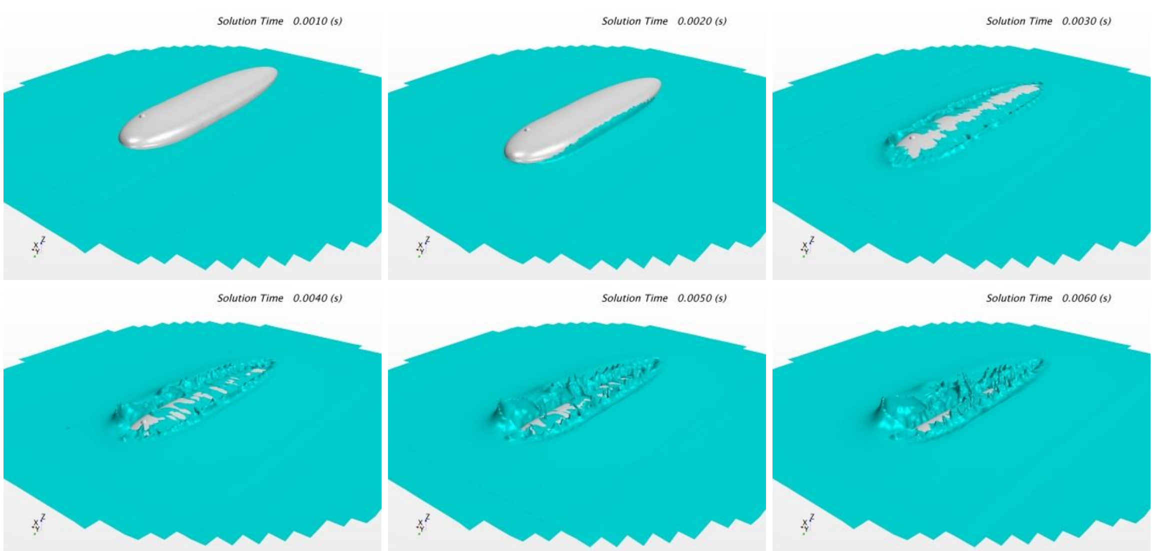

Figure 3. Fish impacting the water surface in the "side first" position, computed on the coarse grid

For the evaluation of the hydraulic properties during the plunging into the water body local pressures, the acceleration of the fish and the force acting on the fish were chosen. An evaluation of the data showed extreme peaks in the recorded quantities at the moment of the first impact on the water surface. At this moment, the fluid has to be accelerated enormously to the sides, resulting in peaks in the pressure at the fish body (Figure 4) and subsequently in the force acting on the fish and the acceleration of the fish (Figure 5). However, it must be taken into account that the virtual body is a rigid body, while a real fish is at least partially flexible. Thus, in reality the side of the fish will deform and the occurring pressures at the first impact will be lower. As a consequence, the peak acceleration will be lower, too, and the subsequent acceleration will be higher, as a higher velocity remains. Due to the missing deformation, the peak values for the "side first" case are probably not fully representative, and, thus, it can be doubted if they should be used in the further considerations.

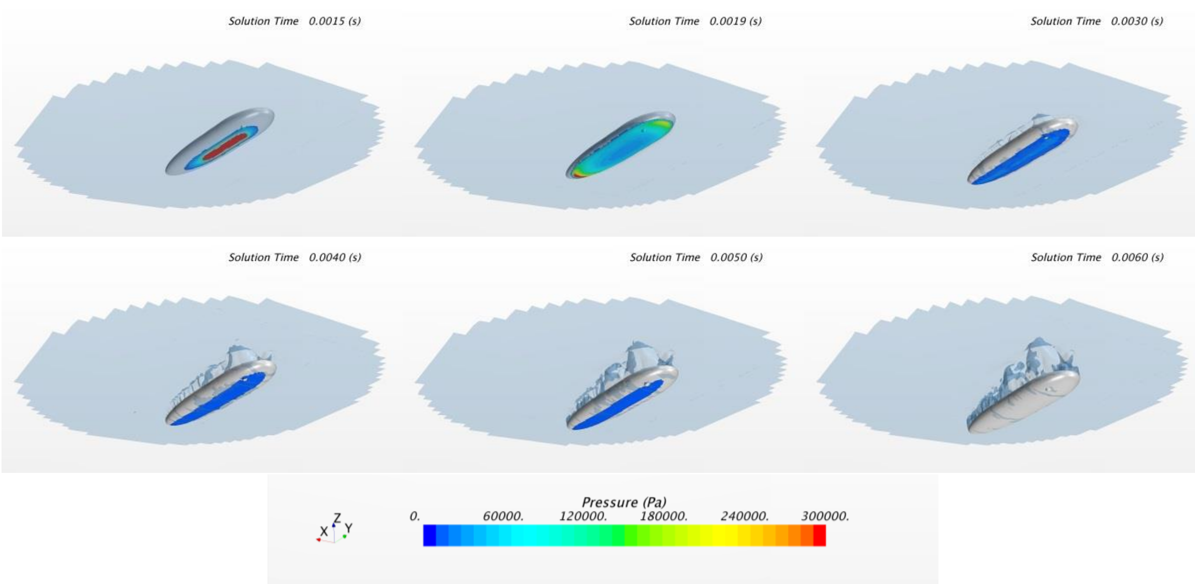

Figure 4. Pressure on the fish surface when impacting the water surface in "side first" position, observed from below the surface, computed on the coarse grid

Figure 5 shows a comparison of the recorded accelerations of the fish for the "side first" with the "head first" case for the computations performed on the coarse and on the fine mesh. The differences between the results of the two meshes are rather small, so the grid dependent uncertainties can be regarded as small in comparison to the global uncertainties of the setup. In this plot negative values (i.e., the free fall) were omitted, and the positive accelerations were plotted on a logarithmic axis.

For the "side first" case, we see that the deceleration starts even before the fish touches the water surface. This is because of the air, which has to be squeezed out between the fish and water surface. Afterwards a very strong initial acceleration peak is visible, reaching over 10000 m/s^2 for a very short period of time. In reality, this peak will be smaller due to the deformation of the fish, but the actual value cannot be determined with this kind of model. After approximately 0.002 s, a plateau with an acceleration of ~ 300 m/s^2 - 400 m/s^2 is reached, which lasts 0.01 s. Afterwards, the acceleration drops continuously to a value of 100 m/s^2 at 0.02 s.

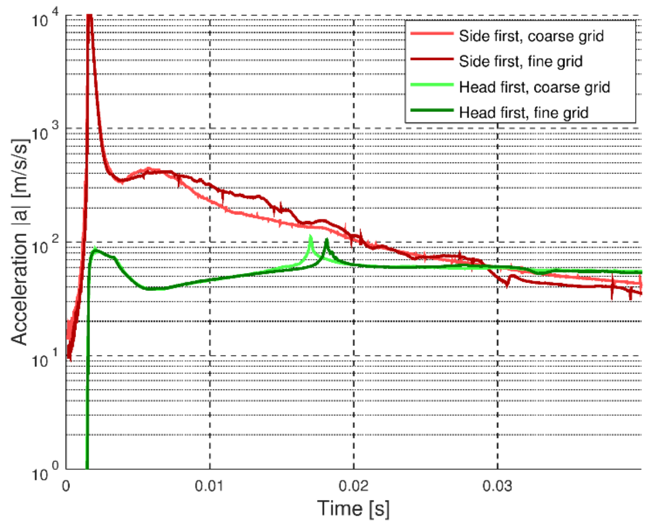

Figure 5. Acceleration of the virtual fish falling into a pool in "side first" or "head first" configuration, computed on coarse and refined grid

For the "head first" case, a very different behaviour is observed. Because of the very streamlined body, the deceleration due to air below the fish is negligible. In general, the accelerations are much smaller. The initial peak is probably useable here, because the head of the fish is more rigid than the sides of its body; thus, the deformation will have a smaller effect. An initial acceleration of 80 m/s^2 is recorded, which drops after the head has completely entered the water body and later rises again to 100 m/s^2 at ~ 0.017 s. The second peak is due to the slightly blunt shape towards the tail, which enforces suction behind the fish. After 0.02 s we see a constant acceleration of about 60 m/s^2. This is more or less due to the friction of water on the submerged fish. But it must be pointed out that the numerical model was not tuned for the computation of friction on smooth surfaces, and, thus, these values should be used with care.

From these recordings it can be concluded that for the described test configuration an acceleration of 100 m/s^2 to 400 m/s^2 can be expected for fishes to occur on impact of the water surface. This range will be used as a threshold to determine acceptable conditions in the nappe impact region behind a weir in terms of accelerations. It can be assumed that actually much higher accelerations can be tolerated by fishes, but only very little data is available on the topic. For humans, when not protected by a body of water around them, it was found that the level of injuries not only depends on the magnitude of the acceleration but also on the direction of the acceleration, the length of the exposure, and on the rate of onset. For short time spans (< 0.1 s) accelerations of 200 m/s^2 to 300 m/s^2 would be acceptable, even for humans, with little to no harm (Ruff, 1950; Shanahan, 2004). For the human test subjects, a cause of harm was the belt systems, which were used for fixation of the body to the test sled. As fishes are not belted, but are embedded in water like human jet pilots in a g-suit, it might be possible that fishes can endure significantly higher accelerations.

4. Hydraulic Conditions in Nappe and Tailwater

4.1. General Description

Situations which are potentially hazardous behind a weir are more probable if the nappe thickness is small and the water depth at the weir sill is small compared to the size of the fish. For thicker nappes, it may be assumed that the fish is embedded into the water body and, thus, will be deflected at the sill together with the main flow, which acts as a water cushion to the fish. In Germany, currently the guidelines from DWA (2005) are commonly used to determine the acceptability of the conditions behind a weir. Unfortunately, these guidelines are based only on a publication which describes a plunge pool for a very narrow nappe behind a fish bypass (Odeh and Orvis, 1998). It can be doubted if this can be generalized for weirs. At a weir the nappe is typically very wide compared to its thickness. This changes the hydraulic conditions fundamentally, because the impacting nappe cannot spread into all directions, but only into the direction of the tailwater. This will result in the aggregation of a water cushion between weir and nappe, because, otherwise, the necessary force for the deflection of the jet into the direction of the weir sill would not be available. An example for this process is shown in Figure 6, where the water cushion is clearly visible behind the nappe (red dotted line). This changes the situation for descending fishes, because, depending on the situation, they do not necessarily fall directly onto the sill. Instead, the contact to the water cushion will start to deflect and decelerate the nappe and the fish before the sill is reached. The thickness of the cushion can be estimated by different formula, as given in Moore (1943) or refined in Rajaratnam and Chamani (1995).

Figure 6. Aggregation of a significant water cushion (red dotted line) at the weir Auxonne (France)

In this situation a lot of air is entrained into the water. This can be advantageous from an ecological point of view if the river has a lack of oxygen. Basics of air entrainment in jets are explained in Chanson (2004). In Germany, the water quality has enhanced significantly in the last decades. Thus, aeration at a weir is no longer a relevant advantage and the potential damage to fish is regarded as a more relevant factor.

4.2. Hydraulic Conditions behind the Weir

4.2.1. Numerical Evaluation of Local Conditions for Fishes

For the examination of the flow field behind the weir the simulation package OpenFOAM® was used. The BAW OpenFOAM® has been widely used for the investigation of flow features near hydraulic structures for several years (i.e., Thorenz and Strybny, 2012). In order to gain a better understanding of the governing processes, a simplified test case was set up. The flow over a simple rectangular gate, erected on a flat surface, was tested in a numerical model. The numerical model resembled a flume of 2 m width. The computational grid had approximately 3 million cells and was iteratively refined in the vicinity of the nappe to a cell length of 1.6 cm.

For the tests, an upstream water level of 5 m was fixed and different downstream water levels and gate heights were tested. The primary goal of the investigation was to evaluate the criteria given in DWA (2005) and LUBW (2016) to describe the flow situation behind the weir. A secondary goal was to test further hydraulic criteria for their suitability to assess fish migration. Other criteria, like negative pressure or shear in separation zones were not regarded.

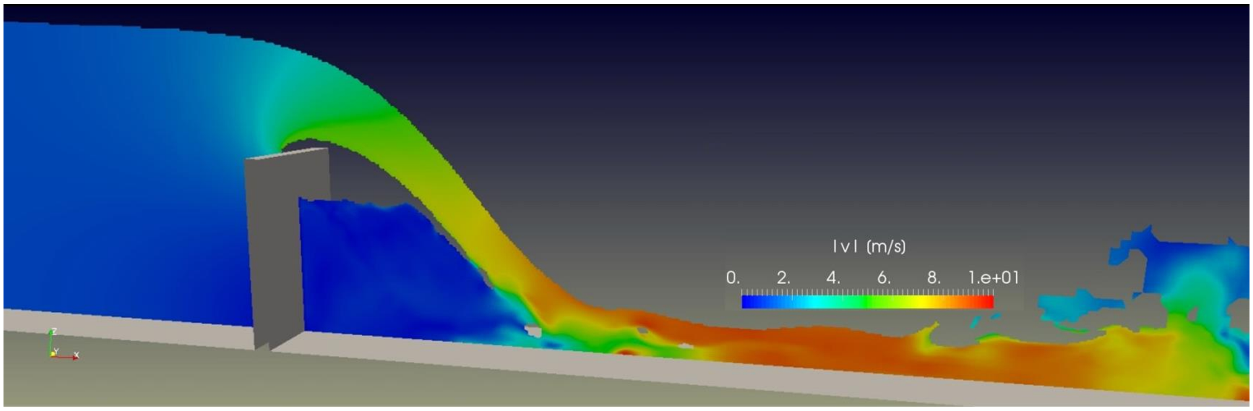

Figure 7. Velocity plotted on a vertical slice through the model domain. The weir height is 3 m, the upstream water level 5 m, and the downstream water level 2 m.

In these tests it became obvious that the relation between the downstream water level and the drop height (DWA, 2005) is not a sufficient criterion to determine whether fishes can safely transit over a weir of certain height. Figure 7 presents a typical example for the issue. In the shown situation, the prescribed tailwater level has no impact on the flow situation at the weir. In the picture presented the tailwater level fulfills the criterion after DWA (2005), but also a lower tailwater level would not result in a different flow situation at the weir, because the momentum of the overflow is so large that the tailwater cannot counteract against it. In the presented situation, the thickness of the nappe and the smooth deflection because of the water cushion behind the weir are the relevant parameters for the safety of fish transit.

Further test criteria for the transit of fish over weirs were sought after. The absolute value of the flow velocity is not a suitable criterion to determine the situation for fishes, because the velocity itself does not harm the fish. Derived quantities like the shear rate or accelerations within the fluid body can be useful as a criterion for the evaluation of the flow situation. Also, the velocities perpendicular to a surface can be a hint for potential problems.

In this study, the convective acceleration of the fluid was evaluated as a potential test criterion. If a fish is embedded into the fluid, it can be assumed that the acceleration of the fish is the same as the acceleration of the surrounding fluid, because both have the same density. Here, the acceleration a is computed from the gradient of the pressure field p and the density ρ (Equation 3):

$$a = \frac{-grad(p)}{\rho} \tag{3}$$

This results in a value of zero for a fluid particle which is freely falling, i.e., a is equivalent to the convective acceleration minus the acceleration of gravity and will have a value of 1 g for a body that is not in motion.

Figure 8 presents the acceleration in stream tubes within the nappe up to the point where the nappe is deflected at the weir sill. It can be seen that the far-field tailwater level has only a minor impact on the flow situation (left images vs. right images), whereas the thickness of the nappe is more important (upper images vs. lower images) for the level of the accelerations. The observed values for the accelerations of 50 m/s^2 to 100 m/s^2 (5 g to 10 g) are far below the values which were computed for the fish freely falling into a pool and, thus, probably can be regarded as uncritical. But according to the DWA (2005) guideline, only the situations on the right hand side of Figure 8 are acceptable, while the situations on the left are not acceptable. This example shows that this criterion is insufficient to divide good from bad, as the flow field characteristics like the convective accelerations differ strongly for different overflow heights and only slightly for the regarded different tailwater depth. Thus, a better criterion must not only include the water depth and the drop height, but also the overflow height or the jet thickness.

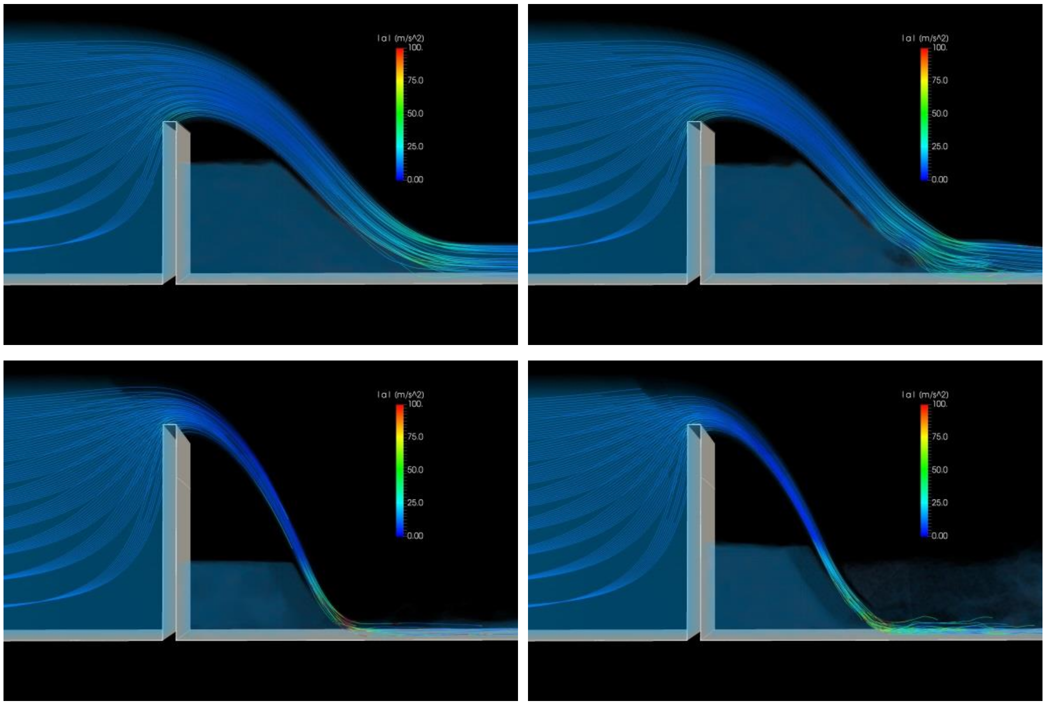

Figure 8. Convective acceleration plotted in streamtubes for weir heights of 3 m (top figures) and 4 m (bottom figures) and different far-field tailwater levels of 0 m (left figures) and 2 m (right figures) over the weir sill

The relation between impact velocity and lethality (compare Chapter 3.1) can be used to roughly evaluate how lethal a certain weir height can be for fish impact on the weir sill, but it does not take into account the effects of a water cushion below the fish or the deflection of the nappe above the sill. If used at a weir, only the part of the velocity vector that is perpendicular to the surface can be used as impact velocity.

As an example, the situation at an inflatable dam is presented here. In contrast to the rectangular weir presented before, the inflatable dam is equipped with large breakers on the surface. For small overflow heights (cross-section shown in the lower picture of Figure 9), the nappe is divided by the breakers into several jets, and, thus, the backwater cushion is less pronounced compared to the rectangular weir without breakers. Air mixes into the water, and this makes the determination of convective accelerations for the fish difficult, as it can no longer be assumed that the fish moves like the surrounding water. For this situation, it can be helpful to evaluate the velocity of the flow field perpendicular to the weir sill instead.

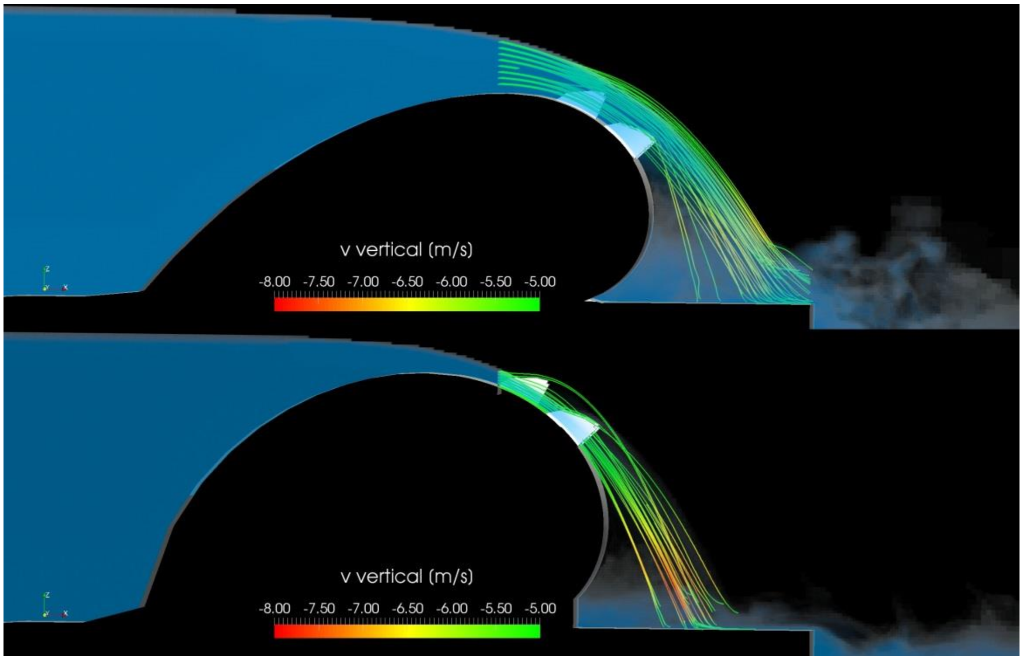

Figure 9. Evaluation of velocity components perpendicular to the weir sill for an inflatable dam with a height of 3.78 m (bottom figure) and 3.16 m (top figure) at an upstream water level of 4.28 m over the sill.

For the smaller overflow height the observed perpendicular velocities reach up to ~7.7 m/s in a height of approximately 10 cm above the weir sill before the deceleration starts. If it is assumed that a fish actually impacts on the surface with this velocity, this could be translated to a mortality ratio of roughly 14 %. For the larger overflow height (Figure 9, top), the vertical velocity components seem to be only slightly smaller (~7 m/s). But in this situation it can be observed that the deceleration takes place already 20 cm above the surface, so that the “impact” criterion is probably no longer useful for small fishes. Furthermore, the probability is high that fishes are embedded in the rather thick nappe and, thus, will not have contact with the sill. However, it should be mentioned that lethality is not the only relevant parameter. The question for what conditions a fish passes a weir without any significant impact has yet to be answered.

5. Conclusions

In Germany, the Federal Waterways and Shipping Administration is obliged to enhance the possibilities for species to migrate over dams and weirs. While the upstream migration through fish ladders, etc., is a topic that has been worked on intensively, the downstream migration was largely out of focus for scientific research.

Recent investigations showed that the transfer of criteria made for other situations to weirs (DWA, 2005) lead to erroneous expectations concerning fishes migrating downstream over low-head weirs. For current projects, this lead to demands of stakeholders to construct bypasses, etc., though the scientific foundation of the criteria is rather weak.

This paper shows that the currently used criteria are insufficient to evaluate the hydraulic conditions behind a weir and, thus, should not be used for the evaluation of fish migration over weirs. The results show that the overflow height is a relevant parameter which must not be omitted in the considerations.

Simple alternative criteria like the convective acceleration and the impact velocity were presented together with first estimates for acceptable values and the application to typical situation. But it must be pointed out that these are based on considerations about the acceptable impact velocities which themselves have certain uncertainties.

From these investigations a need for more thorough considerations can be derived. Apart from the already mentioned criteria, these should take into account the movement of fishes in air-water mixtures and the probabilities for impacts on hard surfaces. Subsequently, new criteria for fish damages, and, thus, the passage over low-head weirs should be developed.

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