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Numerical Simulation of Fish Passage Over a Weir

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Numerical Simulation of Fish Passage Over a Weir

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Abstract: *Downstream migration over weir structures has been a mostly neglected element of ecological continuity in the last decades. The guidelines currently applied in Germany to prevent damage to fish do not sufficiently consider the conditions present at weirs. To improve knowledge of the risks of fish passage over a weir due to physical strike, pressure changes and shear stress, a numerical method using the three-dimensional computational fluid dynamics package OpenFOAM® was developed to simulate fish passage over a weir by tracking passively transported particles. In this study, the method is tested on an overshot and an undershot weir and the results are compared to known critical parameters to assess the hazard potential of these weirs. As expected, pressure changes are much more relevant in the undershot scenario, physical strike and shear stress are dominant in the overshot scenario. Altogether both situations result in only collisions with low impact velocities and relatively low shear stress and pressure changes, assuming little threat to fish due to the relatively low drop height and absence of baffle blocks or an end sill. To improve the methods reliability, additional enhancements are necessary.*

Keywords: *numerical modelling, OpenFOAM, weir, fish, migration*

1. INTRODUCTION

By implementing the European Water Framework Directive in 2000 the member states of the European Union have set the good ecological status of surface water bodies as an objective. To achieve this goal, one important measure is to establish ecological continuity by providing adequate fishways at barrages for upstream and downstream migration. Whereas upstream migration as well as downstream migration through turbines or over spillways has been a focus of research in the last decades, downstream migration over weirs with low and medium heads (approx. 5 m) has been mostly neglected.

To prevent significant effect on fish, a German guideline (DWA 2005) recommends, that the plunge pool depth should be equal to a quarter of the drop height but at least 0,9 m and the impact velocity should not exceed 13 m/s. These currently applied design criteria refer to uncited design guidelines mentioned in Odeh and Orvis (1998), lack advanced scientific proof and can only be understood as documented recommendations by experts. Thorenz et al. (2018) showed that the currently applied guidelines aren't sufficient to judge on the safety of fish passage in many cases. Using the three-dimensional simulation package OpenFOAM® they modelled a weir passage adhering and not adhering to the DWA guidelines. As it can be seen in Figure 1, in some situations the far-field tailwater level has a negligible effect due to its displacement by the nappe. According to the DWA guideline, the situation on the right is acceptable, the far-field tailwater level is sufficient, the situation on the left is not acceptable. In this case, adhering to the DWAs tailwater guideline has only a marginal effect, whereas the thickness of the nappe seems to be of much more importance (Thorenz et al. 2018).

With several weir structures in federal waterways that need to be replaced in the near future, a thorough assessment of downstream fish passage over weir structures is needed (Thorenz et al. 2018). To evaluate the risk for migratory fish, a method has been developed to model the downstream passage for different weir structures by tracking passively transported particles in 3D-CFD simulations. By tracking the particles path, collisions, surrounding pressure and shear forces the risk of injury for different weir structures is estimated.

In this paper sources of risk for fish during downstream passage over a weir and threshold values for fish injuries from literature are discussed and compared with first results of the described 3D-CFD method for an exemplary weir.

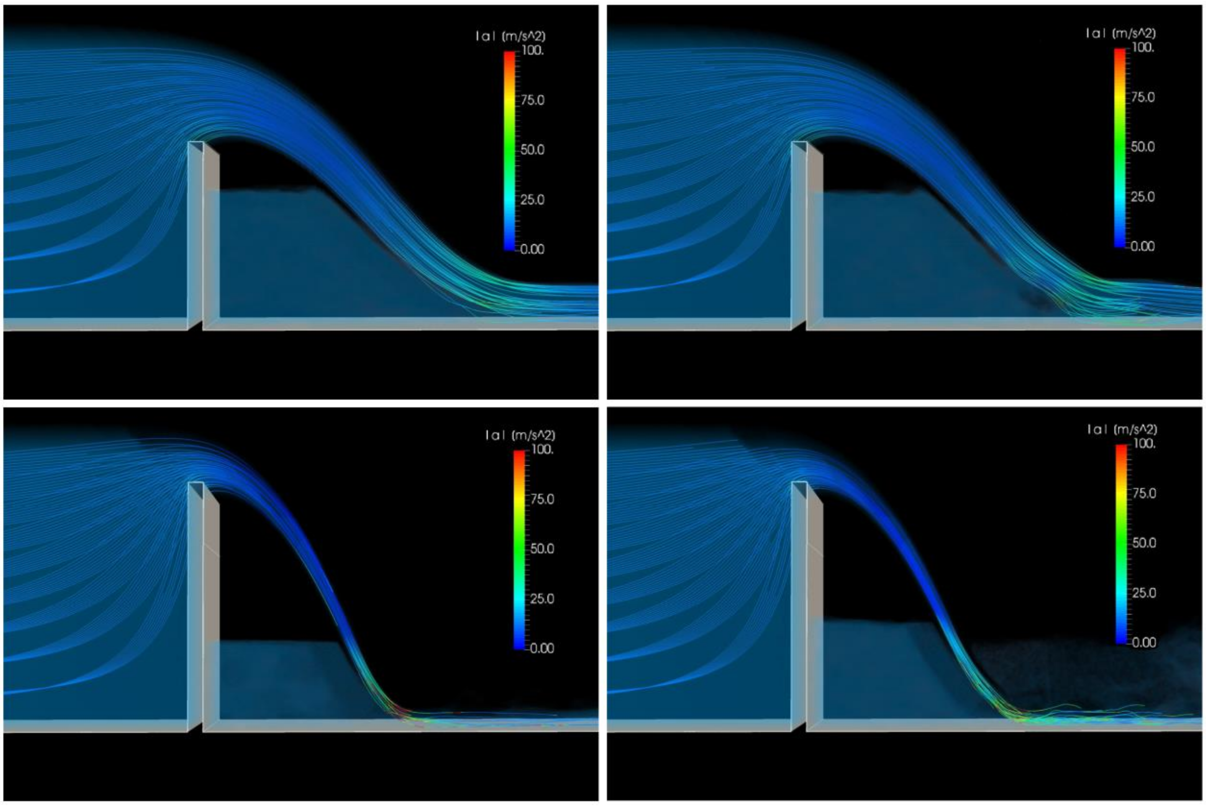

Figure 1 – Comparison of different weir heights and tailwater levels. Convective acceleration plotted in streamtubes for weir heights of 3 m (top figures) and 4 m (bottom figures) and different far-field tailwater levels of 0 m (left figures) and 2 m (right figures) over the weir sill (Thorenz et al. 2018).

2. HYDRAULIC STRESSORS DURING DOWNSTREAM PASSAGE

Fish moving downstream over or under a weir structure can be exposed to a variety of stressors. Studies on downstream migration of fish have found three major sources of injury and mortality that are most relevant for the majority of low-head weirs. These are rapid pressure changes, physical strike and excessive shear stress. In certain situations, other stressors can also have substantial impact on fish like gas supersaturation or higher vulnerability to predation due to disorientation, often a complex series of interacting stressors can facilitate injuries which makes it hard to isolate the impact of a single hydraulic characteristic. (Baumgartner et al. 2014)

2.1. Physical strike

Especially at low-head weirs, physical strike can be the most severe stressor (Pflugrath et al. 2019). Physical strike occurs when a fish collides with an object such as a baffle block, stilling basin end sill, flow splitter or other hard structure, but also with the water surface when the fish is not embedded in the nappe. The probability of sustaining an injury depends on many factors. Generally, the chance of contact with an object is higher if the fish loses mobility control due to high velocities and turbulence. When a physical strike occurs factors like the impact velocity but also the objects shape, material or the condition of the surface influences the likelihood of injury or mortality. Sharp edges and rough surfaces lead to a higher hazard potential.

Physical strike is generally associated with both overshot and undershot weirs. The weir design, but also how it is operated, plays a role regarding its danger for fish. Situations that lead to injuries are for example discharge into low tailwater environments or high velocity and turbulence in the stilling basin (Baumgartner et al. 2013).

For the downstream passage through hydropower turbines, blade strike injuries have been studied extensively. The strike chance depends on several factors like blade rotation speed, fish length and blade spacing, which makes it possible to use mathematical modelling to predict the probability of strike (Deng et al. 2007). In contrast to fish passage through hydropower turbines, few data on injuries or mortality due to physical strike during the passage over or under low-head weirs is available. In the formerly mentioned DWA guideline (2005), an impact velocity of 13 m/s on a water surface is associated with small fish damage. Other threshold values are listed in the following Table 1.

Regarding impact velocities it is import to mention free fall acceleration. Depending on their size varying heights are necessary to reach critical velocities falling through air, small fish of around 10 cm - 15 cm have a terminal velocity of less than 15 m/s free falling through air, even smaller fish might not reach critical speed at all (Schwevers and Adam 2020).

Altogether, knowledge regarding injury or mortality of physical strike during downstream passage is inadequate especially if considered that the effect on fish depends on not only the impact velocity but also many additional factors as previously stated.

Table 1 – Effect on fish for collision with water or solid objects for different velocities from literature.

Collision with	Velocity [m/s]	Effect on fish	Reference
Water surface	13	Small damage	(DWA 2005)
Water surface	15	3 % mortality	(Odeh and Orvis 1998)
Water surface	20	0 % mortality	(USACE 1991)
Water surface	28	35 % mortality	(USACE 1991)
Water surface	45	100 % mortality	(USACE 1991)
Water surface	15-16	Critical value	(Schwevers and Adam 2020)
Solid object	5	0 % mortality	(USACE 1991)
Solid object	18	60 % mortality	(USACE 1991)
Solid object	26	90 % mortality	(USACE 1991)
Solid object embedded in water	11	Critical value	(Schwevers and Adam 2020)

2.2. Shear stress

Shear stress occurs when two water masses of different velocities intersect or are adjacent to each other. Due to the viscosity of water, an object caught between two intersecting masses experiences a force, depending on the objects size and the water velocity and mass. Throughout the world, shear stress naturally occurs in rivers and streams. Fish are adapted to it even partially rely on it to move and prevent displacement (Cada et al. 1999). Only when shear stress exceeds tolerable levels, it becomes a substantial problem for fish (Guensch et al. 2002).

High shear levels occur at hydroelectric turbines, spillways, fish bypass systems or downstream of undershot weirs but also in natural environments like waterfalls or rapids. Due to the natural occurrence, some fish are well adapted to shear stress, other species who avoid fast flowing water are not. But the threshold fish can withstand does not only differ among species but also within species. Fish size also plays a role and some life stages, especially fish eggs, are particularly sensitive to shear stress. A fish could therefore have different thresholds for shear stress over its life, which makes it difficult to evaluate the impact over a range of species and sizes (Baumgartner et al. 2013). Another factor concerning fish tolerance to shear stress is the fish’s orientation (Neitzel et al. 2000).

Areas with high shear stress are characterized by intersecting water bodies with high velocities. At weirs high shear forces can be expected for instance downstream of undershot weirs, especially close to the gate. Generally, high shear stress often occurs in small locally constrained areas. Susceptibility to injury for downstream migrants would be largely determined by the proximity of passage to these critical areas (Baumgartner et al. 2013). Therefore, it is important to not only know the general occurrence of shear stress near weir structures but also the fish’s path.

As previously stated, tolerance to shear stress highly differs among and within fish species. For some sizes and species experiments with shear stress created by jets have been performed. The results of some of these studies have been summarized in the following table 2. Knowledge of tolerance to shear stress of European freshwater fish is still low.

Table 2 – Observed effect of shear stress on fish, based on a spatial resolution of Δy = 1.8 cm.

Species, life stage	**Strain rate [m/(s*m)]**	**Effect on fish**	**Reference**
Oncorhynchus mykiss, juvenile	517	No signif. injuries	(Neitzel et al. 2000)
Alosa sapidissima, juvenile	688	No signif. injuries	(Neitzel et al. 2000)
Balantiocheilos melanopterus	600	Threshold mortality	(Thorncraft et al. 2013)
Balantiocheilos melanopterus	1200	20 % mortality	(Thorncraft et al. 2013)
Oncorhynchus tshawytscha, juvenile	677	10 % injury	(Deng et al. 2005)
Oncorhynchus tshawytscha, juvenile	933	10 % mortality	(Deng et al. 2005)
Bidyanus bidyanus, egg	148	100 % mortality	(Navarro et al. 2019)
Bidyanus bidyanus, larva	600	No signif. injuries	(Navarro et al. 2019)
Trichopodus trichopterus, adult	688	> 50 % injury	(Colotelo et al. 2018)
Pangasionodon hypophtalmus, juv.	1008	> 50 % injury	(Colotelo et al. 2018)

2.3. Pressure changes

The most important factors concerning pressure change is the structure height and operation mode (overshot or undershot). Because fish usually acclimate to their surrounding pressure and pressure linearly increases with depth, undershot weirs with large heights pose great risks for fish. During downstream passage through an undershot weir, the pressure changes rapidly from high pressure due to deep water to low pressure after the weir passage. Due to high velocity the static pressure can even fall under the atmospheric pressure, in extreme cases even below the vapor pressure, leading to cavitation which can pose another risk for fish. Fish exposed to a rapid pressure change may experience barotrauma which is caused by the rapid and unregulated expansion of gas and fluid filled structures within the fish. In extreme cases of barotrauma fatal injuries like swim bladder rupture or hemorrhaging can occur. (Baumgartner et al. 2013)

Pressure changes are commonly given in the ratio of pressure change (RPC). The RPC is the change of pressure that a fish experiences between the pressure it is acclimated to (neutrally buoyant) before passage, and the lowest pressure it is exposed to during weir passage (Boys et al. 2014). As for the other stressors, knowledge of effects of pressure changes in general and especially on European freshwater fish is still low. To minimize these shortcomings and give recommendations for species that were not studied yet, Boys et. al (2016a) followed a precautionary principle. Table 3 shows their multispecies recommendation of an RPC of 0.7 and other literature values.

Table 3 – Observed effect of rapid pressure change on fish given in the ratio of pressure change RPC. No effect on eggs at any RPC was found.

Species, life stage	**RPC [-]**	**Effect on fish**	**Reference**
Maccullochella peelii, egg	-	No effect on eggs	(Boys et al. 2014)
Maccullochella peelii, larva	0.4	No injury	(Boys et al. 2014)
Maccullochella peelii, juvenile	0.6	No injury	(Boys et al. 2014)
Oncorhynchus tshawytscha, juvenile	0.5	6 % mortality	(Carlson et al. 2010)
Bidyanus bidyanus, egg	-	No effect on eggs	(Boys et al. 2016b)
Bidyanus bidyanus, larva	0.4	No injury	(Boys et al. 2016b)
Multispecies precautionary principle	0.7	No injury	(Boys et al. 2016a)
Most fish species and life stages	0.6	No injury	(Cada and Charles 1997)

Not all fish are in the same way susceptible to pressure change. Bony fish (teleosts) can be largely divided into physostomes and physoclists (Schreer et al. 2009). Physostomes have a pneumatic duct connecting the swim bladder and the intestinal tract. They can actively vent excessive swim bladder gas and therefore quickly adapt to pressure changes. Adult physoclists do not have this pneumatic duct and consequently lack the ability to rapidly adapt to pressure changes (Baumgartner et al. 2013). Therefore, physoclists like the European perch (perca fluviatilis) are much more susceptible to pressure changes than physostomes like the Antlantic salmon (Salmo salar). Fish’s tolerance to pressure changes also differs between life stages. Eggs are not affected by pressure changes and also the larvae of many fish are much more tolerant because they have not actively filled their swim bladder yet (Boys et al. 2014).

3. NUMERICAL SIMULATION

To get a better understanding of the hazard potential for downstream migrating fish and evaluate if and where fish are exposed to the described potentially harmful situations, numerical models were used to simulate the fish's passage over a weir. The simulations were performed with the three-dimensional simulation package OpenFOAM®, using the two-phase solver interFoam (Weller et al. 1998). In the model, fishes were replaced by particles, which represent passively transported fish. These are calculated in a Langrangian approach. To achieve this, the particle phase basicKinematicParticle was added to the interFoam solver. The extended Eulerian/Lagrangian-solver models the fluids as continuous phases while the positions of particles, which represent passively transported fish, are calculated discretely. As the volume fraction of the solid material "fish" of up to 10^{-4} is rather small and as the fish have the same density as the surrounding water, not a two-way coupling, but a one-way coupling mechanism was chosen. This means that the flow of the carrier fluid influences the particle trajectories but the particles have no effect on the carrier fluid (Greifzu et al. 2016). Using a one-way coupling mechanism and also ignoring collisions between particles creates a situation where every particle can be examined autonomously, without being influenced by other particles.

Two different scenarios were simulated, an overshot and an undershot situation at the same radial gate with an additional flap gate. Both numerical models had a width of 4 m and a length of 40 m. The computational grids had approximately 11 million cells and 8 million cells respectively and was iteratively refined around the gate and in the vicinity of the nappe from a base cell edge length of 20 cm down to 2.5 cm. The cell size was determined by previous independence studies and the particle size. The particle diameter had to be substantially smaller than the cells. The downstream boundary conditions were defined as outlet with fixed water level at 1.7 m while the upstream boundary conditions were defined as inlet with constant inflow and free water level. A water level of approximately 5.4 m was achieved by a flow rate of 7.2 m^3/s and 11.6 m^3/s respectively. In the overshot scenario 784 and in the undershot scenario 948 spherical particles with a diameter of 1 cm and a density of 1000 kg/m^3 were added. The initial situation of the simulations is depicted in Figure 2. The particles are added without any velocity in an area with a surrounding water velocity between 1.2 m/s and 3.5 m/s, the typical top speed of European freshwater fish with a length between 10 cm and 30 cm (Ebel 2014). After the addition, the particles quickly adapt to the surrounding velocity, simulating a passively drifting fish. These simulations were used to evaluate the hazard potential of this weir on fish during downstream passage due to physical strike, pressure changes and shear stress.

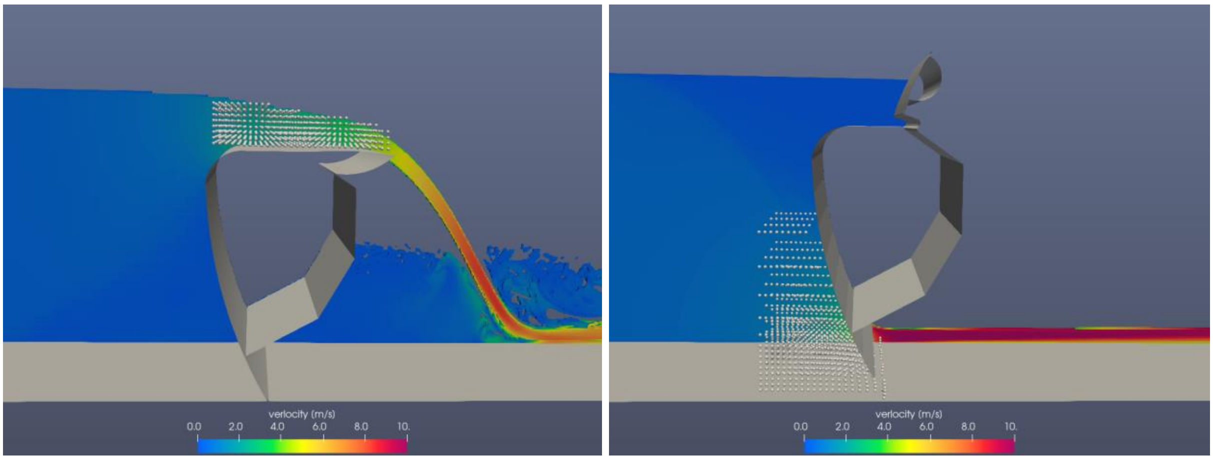

Figure 2 – Initial situation of the overshot scenario (left) with particles over the weir and the undershot scenario with particles in front of the outlet. The fluid velocity is plotted on a vertical slice in the background.

3.1. Physical Strike

The utilized method is able to detect collisions of particles with selected patches. In addition to the impacts time, also the particles velocity and the location of the collision is tracked. However, it currently was not possible to assign collisions to a certain particle due to limitations in the postprocessing procedure. Explicit identification was not possible due to the used parallel computation, which works on decomposed computational grids. This leads to particles with the same identification number in the different decomposed domain areas. Therefore, it was not possible to track which particle was responsible for a collision and consequently multiple collisions by a single particle could not be detected properly. This skews the average number of collisions by particle because an overwhelming amount of collisions go back to a few particles that got dragged along the river bed. But because of the low impact velocity, these collisions are mostly negligible.

In the undershot scenario a total number of 796 collisions were detected, in the overshot scenario 2448. Figure 3 shows the collisions divided according to impact velocity. Whereas all impact velocities at the undershot scenario are below 3 m/s, at the overshot scenario the highest impact velocity is at 7.5 m/s.

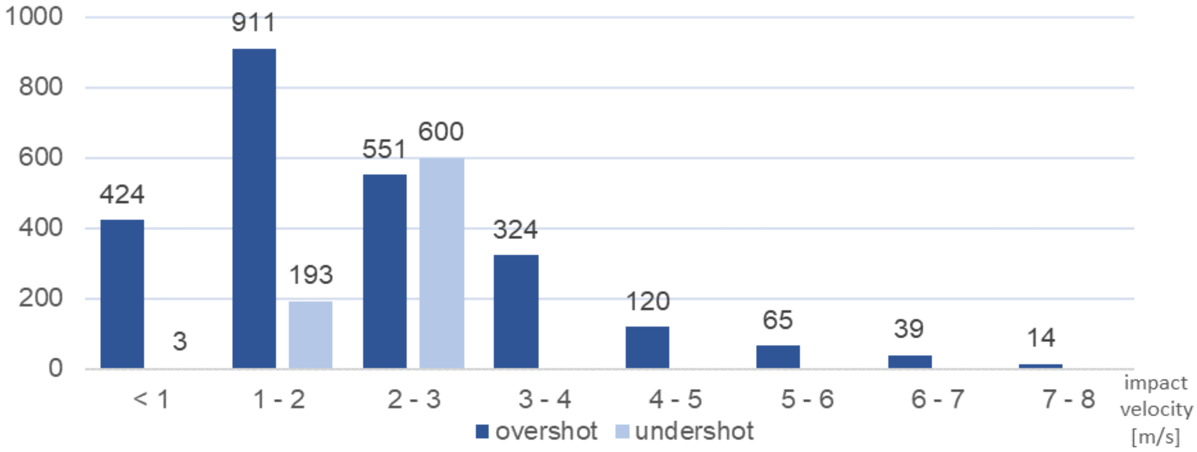

Figure 3 – The numbers of collisions for both the overshot and the undershot scenario divided according to impact velocity.

3.2. Shear stress

To evaluate if shear stress is a hazard potential in the observed situations it was analysed if potential harmful areas exist in the undershot or overshot scenario. To detect shear stress, the velocity in all cells in areas with potentially high velocity gradients was tracked and the velocity difference between adjacent cells calculated. Because of the cell edge length of 2.5 cm, the calculated shear stress is based on a spatial resolution of Δy = 2.5 cm. The highest detected shear stress in the undershot scenario was 154 m/(m*s). To allow comparison with laboratory trials which used a spatial resolution of Δy = 1.8 cm, the same change of velocity over a distance of only 1.8 cm would give a shear rate of 214 m/(m*s). Again, the hazard potential seems to be higher at the overshot scenario with shear stress of up to 232 m/(m*s) or 322 m/(m*s) based on a theoretical spatial resolution of Δy = 1.8 cm. In laboratory trials with fish that seem to be susceptible to shear stress, the lowest values that injured fish have been found to be at 339 m/(m*s) for the blue gourami (Trichopodus trichopterus, Colotelo et al. 2018) and 444 m/(m*s) for the silver shark (Balantiocheilos melanopterus, Thorncraft et al. 2013). Some minor injuries to very susceptible fish species might be possible here, but significant impairment seems unlikely.

3.3. Pressure changes

Tracking the pressure of every single particle was not feasible at this stage. To evaluate the danger of sudden pressure changes on fish, selected particles where tracked. Due to the greater depth, the particles in the undershot scenario are subjected to a higher pressure which decreases rapidly when passing under the gate. The particles in the overshot scenario, on the other hand, are subjected to a

much lower starting pressure.
Relevant to evaluate the danger of pressure changes is the ratio between the starting pressure, which a fish would be acclimated to, and the lowest pressure during the downstream passage, given in the RPC. As expected, the RPCs of the overshot scenario seem unproblematic with the lowest being 0.84 (95% CI: 0.85 – 0.87). During the undershot situation, the pressure change is much higher and therefore the RPCs smaller, with the smallest detected RPC of 0.67 (95% CI: 0.68 – 0.70). Also in this situation, severe injuries seem unlikely with Cada and Charles (1997) seeing a RPC of 0.6 as unproblematic for most fish species and life stages and Boys (2016a), applying a multispecies precautionary principle, considering a RPC of 0.7 as safe for fish.

4. CONCLUSION

Summarized, both the overshot and the undershot scenario seem unlikely to have significant impact on fish due to physical strike, high shear stress or rapid pressure changes. Further information on tolerable levels of these stressors are necessary to improve reliability. As expected, the undershot scenarios most relevant stressor is the change of pressure, unlike the overshot scenario, in which elevated shear levels and collisions with higher impact velocities pose the greatest threat.

The method of tracking particles in a numerical simulation has proven to be promising to evaluate the potential hazards on fish during downstream passage over a weir. Consequences of using small particles to simulate passively transported fish need to be evaluated to further improve this methods reliability, as well as additional enhancements to the method itself. To calculate a particles probability of collision and not only the average number of collisions per particle, it is necessary to detect multiple collisions by a single particle and to track each particles collisions during the weir passage. In this case, evaluating the highest shear values present was sufficient. Even those were not high enough to pose significant threat. In other cases, with higher shear levels, it is necessary to track if and how many particles come in contact with these dangerous shear stress areas. Tracking the pressure changes worked fine, to improve the results conclusiveness, the utilized method has to be performant enough to track each individual particle and not only a few selected ones. Integrating those improvements can make this method a valuable tool to evaluate weir passage hazards.

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