# Influence of a Hydro Power Plant on Upstream Fish Migration

Master Thesis in Environmental Engineering



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# Abstract

Hydro power plays a major role in the production of electricity worldwide. Especially for migrating fish such power plants are a big threat. Fish ways are supposed to reduce this impact. However, whether the fish find the entrance to it is not always guaranteed. In this thesis the influence of the installation of an additional turbine at an already existing power plant on the efficacy of the fish way is investigated and improvements suggested. Examined is the flow after the outlets of two turbines («G3» and «Streamdiver»), a fish way and the appendant attraction water pipe. A model of the current situation is built numerically by the use of ANSYS CFX 16.0 with the help of drawings provided by the company «Skellefteå Kraft» and observations and measurements carried out on site. With adaptations of the placement and the angle of the fish way the optimum is to be determined.

In this thesis it is assumed that the fish orient themselves towards the highest flow velocity in the channel. If the attraction water flows at a higher speed than the surrounding fluid in the tail race channel, the fish will be enticed by it and find the entrance of the fish way. Literature studies revealed that it is best to position the fish way at the very top of the channel and that the entrance area should be in relatively tranquil zones rather than in turbulent ones. This is not the case in the current situation. The water coming from the fish way and the attraction water flows into the tail race of the turbine «G3» and is in case of high mass flows carried away immediately. However, during low mass flow, the attraction water is blocked by a wall which is positioned between the outlets of the two turbines. The current construction of the fish way is therefore neither suitable for high nor for low mass flows. The installation of the second turbine «Streamdiver» on the opposite side of the channel hardly influences the efficacy of the fish way. By aligning the fish way slightly to the flow in the channel and moving it further downstream, the influence of the attraction water pipe on the main flow increases. It has to be taken into consideration that a displacement further downstream increases the probability that fish migrating upstream find the entrance of the fish way only if they are enticed by the attraction water and follow it at the first attempt. If the fish have passed the fish way without entering it, it is less likely that the fish will move downstream in order to find the entrance. In such a case, a fish way closer to the turbines has a higher chance of being found.

From the simulation results can be concluded that the more the fish way is aligned to the main flow the more the velocity of the attraction water is maintained. However, the flow is better distributed over the channel if the fish way protrudes perpendicularly into it. Therefore an angle of 20° (to the current placement) is recommended. With an angle of 45° the fish way should protrude more into the channel which contradicts recommendations found in the literature study which state that the fish way should be as close to the bench as possible. If the fish way is placed perpendicularly to the flow the speed gained in the attraction water pipe is reduced too much after entering the channel. Increased mass flow of the attraction water leads to an increase in the impact on the main flow in the channel. Therefore the installation of a second attraction water pipe can be recommended.

# Contents

# 1. Symbols and Abbreviations

## 1.1. Symbols

| Sign | Meaning | Unit |
|---|---|---|
| $D$ | diameter | $m$ |
| $L$ | length | $m$ |
| $g$ | gravitational acceleration, $g = 9.81\frac{m}{s^2}$ | $\frac{m}{s^2}$ |
| $h$ | height | $m$ |
| $p$ | pressure | $Pa$ |
| $u^+$ | near wall velocity | $\frac{m}{s}$ |
| $v$ | velocity | $\frac{m}{s}$ |
| $y^+$ | dimensionless distance from the wall | $-$ |
| $\kappa$ | Karman constant | $-$ |
| $\lambda$ | friction factor | $-$ |
| $\rho$ | density | $\frac{kg}{m^3}$ |

## 1.2. Abbreviations

**BSL** Baseline

**MASL** Meters Above Sea Level

**RANS** Reynolds Averaged Navier-Stokes Equations

**RHCM** Rod Held Current Meter

**RMS** Root Mean Square

# 2. Introduction

Hydro power plays a major role in the world wide production of electricity. Power plants in rivers influence the flow behaviour and are a threat to migrating fish. Examined in this thesis is the influence on the migration of Atlantic salmon and brown trout. In order to reduce the impact of power plants, fish ways are built next to them. Their efficacy is, however, often not sufficient and in many cases fish don't find the entrance or are misled by the tail race of turbines. In a river with several power plants it is therefore very difficult for fish to reach the spawning grounds. Fish is attracted to high water flow velocities. Hence, when the water downstream of a hydro plant flows faster then the so-called «attraction water» of the fish way, the fishes are misled and swim into the outlet of the turbine.

In this thesis the situation of the water flow after two turbines run by Skellefteå Kraft in Robertsfors, Sweden, in regard to upstream fish migration is examined. This includes the water flow coming from the two turbines, the fish way as well as the one from the attraction water pipe.


Figure 2.1.: Sketch of Power Plant. Subject of the examination are two turbines in the building on the right and the fish way next to it. In the left part of the building, the «Streamdiver» is located, in the right part «G3».

With adaptations of the model of the current situation, it will be determined what kind of changes have a positive impact on the efficacy of the fish way concerning upstream fish migration. This includes changes in the attraction water flow as well as changes in the angle and the placement of the fish way. In this thesis the term «efficacy of the fish way» will be used to describe the ability of the fish way (and the attraction water pipe) to attract the fish to the entrance. It is assumed that the ability is higher if the velocity of the attraction water flow is higher than the surrounding, or if it seems to have influence on the whole channel and not only in one part.

# 3. Fish Behaviour

In the present thesis, the efficacy of a fish way is to be examined, as well as the influence of changes. This is dependent on the fish concerned and their reaction to the surrounding environment. P. Rivinoja [10] has examined the fish behaviour in the two northern Swedish rivers Umeälven and Piteälven. As this region is close to the one investigated in this thesis, the same fish will be looked at. Rivinoja examines in his work the migration of adult Atlantic salmon, smolts of salmon as well as brown trout. As smolts pass a power plant only downstream, their behaviour can be neglected for the current case. According to Rivinoja, Atlantic salmon (*salmo salar*) usually approaches a water plant in a water depth of 1 to 4 meters. While migrating upstream, adult salmon are looking for the highest flows [10]. According to the Animal Diversity Web [11] brown trout (*salmo trutta*) are usually in a depth in the range of 0.03 m to 1.22 m. Therefore the range of depth from 0 m to 4 m are of interest in this study. As this water depth is in the current case maximally exceeded by 30 cm, the whole water channel has to be taken into consideration. Literature research shows that «a fishway sited on or near the riverbank is usually preferable to a location in the middle of the obstruction, as fish [...] tend to migrate along the banks rather than in the centre of the river» [6]. The velocity at the fish way entrance is ideally in the range $1.2\,\mathrm{m\,s^{-1}}$ to $2.4\,\mathrm{m\,s^{-1}}$ [7]. In the current case this velocity is only exceeded in the attraction water pipe. In respect to the entrance location of the fish way, high velocity and turbulent zones should be avoided in favour of tranquil zones [8]. According to Elianne M. Lindmark, adult fish migrate in the period from April to November (see [7]). This is important to know as the mass flow rate of the river varies between the seasons.

As this thesis is not able to cover all aspects of fish behaviour, it is simplified to the assumption, that the fish orient themselves after the highest flow velocity. The ideal case would be if the velocity field after the turbine entices the fish from the main water stream in the tail race channel to the fish way instead of the turbines.

# 4. Approach

Three different scenarios have to be considered when building up the model for this thesis, as the water flow through the turbines isn't constant all year through. Those three situations are:

Table 4.1.: The three most common scenarios

| Water Level [m] | Flow Steamdiver [$\mathrm{kg\,s^{-1}}$] | Flow G3 [$\mathrm{kg\,s^{-1}}$] | Total Flow [$\mathrm{kg\,s^{-1}}$] |
|---|---|---|---|
| 35.50 m | $6 \times 10^3\,\mathrm{kg\,s^{-1}}$ | $13 \times 10^3\,\mathrm{kg\,s^{-1}}$ (maximum) | $19 \times 10^3\,\mathrm{kg\,s^{-1}}$ |
| 35.13 m | $6 \times 10^3\,\mathrm{kg\,s^{-1}}$ | $4 \times 10^3\,\mathrm{kg\,s^{-1}}$ (minimum) | $10 \times 10^3\,\mathrm{kg\,s^{-1}}$ |
| 35.13 m | $6 \times 10^3\,\mathrm{kg\,s^{-1}}$ | $0\,\mathrm{kg\,s^{-1}}$ | $6 \times 10^3\,\mathrm{kg\,s^{-1}}$ |

These values were gained by analysing data provided by Skellefteå Kraft, illustrated in the following picture. The mean values of the pointed out areas have been calculated. As the fish travel from April to November, only this time period is taken into account.

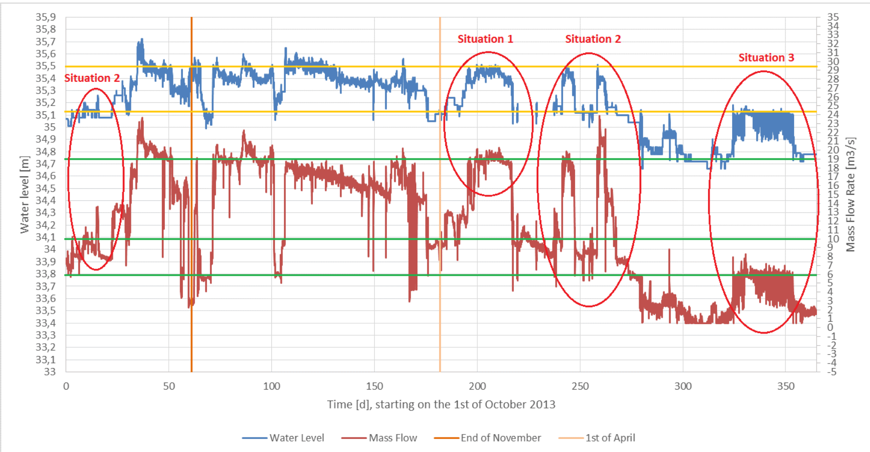



Figure 4.1.: Measured mass flow and water level over the time period of one year. Data from Skellefteå Kraft.

The model includes the flows coming from the two turbines, the fish way and the attraction water. It is a two-phase model (water and air) and performs a free-surface simulation. As there are two water levels most common during the year (with different water flows), both have to be considered. To get the mass flow in the fish way, as well as some more detailed geometric data, measurements on site are carried out. Additionally, the flow behaviour is recorded in order to be able to verify visually the results received by the simulations. The approach during the measurements and the results are discussed in the next chapter.

All simulations are carried out with ANSYS CFX, Version 16.0. The geometry is established by using NX 11.0, based both on drawings provided by Skellefteå Kraft and carried out measurements on site.

# 5. Flow Behaviour

At the beginning of the project the flow behaviour after the turbines is analysed, as well as the boundary conditions defined. These include the two outlets of the turbines (inlets of the model), the flow coming from the fish way as well as the one from the attraction water pipe.

## 5.1. Flows from Water Turbines

Measurements by Skellefteå Kraft recorded over the time period of one year show three typical mass flows, which are described in the previous chapter (see table 4.1). Therefore these values are used as boundary conditions for the inlets of the model which are assumed to have a constant and evenly distributed mass flow. In order to get a better velocity inlet profile for the G3 water flow, a model of the preceding outlet channel was created. However, the results from the model with the improved inlet profiles were so close to the ones with an regular mass flow inlet that it was decided to set the extra model aside and simulate the models without a special inlet profile condition. Hence, the inlet boundary condition of the G3 water flow is defined as a mass flow of minimally $4 \times 10^3\,\mathrm{kg\,s^{-1}}$ and maximally $13 \times 10^3\,\mathrm{kg\,s^{-1}}$. From the Streamdiver $6 \times 10^3\,\mathrm{kg\,s^{-1}}$ flow into the main channel.

## 5.2. Fish way

In order to measure the flow velocity in the fish way and the attraction water, a turbine flow meter (Rod Held Current Meter RHCM, SWEDAQ HB, CO15/0474) by Hydro-Bios is used. It measures the flow velocity. Resulting data is stored on the device and evaluated by using the software OceanLab 3 also provided by Hydro-Bios.

At a narrow passage of the fish way the flow velocity is measured. There the flowing water has a depth of 75 cm and the passage has a width of 50 cm. In order to take differences in velocity into account, it is measured at three different depths: 20 cm, 35 cm and 45 cm.

Table 5.1.: Results of measurements and calculations of the fish way water flow

| Depth | Averaged Velocity | Area | Mass Flow |
|---|---|---|---|
| 0 cm to 30 cm | $0.613\,\mathrm{m\,s^{-1}}$ | $0.150\,\mathrm{m^2}$ | $92\,\mathrm{kg\,s^{-1}}$ |
| 30 cm to 40 cm | $0.401\,\mathrm{m\,s^{-1}}$ | $0.050\,\mathrm{m^2}$ | $20\,\mathrm{kg\,s^{-1}}$ |
| 40 cm to 75 cm | $0.395\,\mathrm{m\,s^{-1}}$ | $0.175\,\mathrm{m^2}$ | $69\,\mathrm{kg\,s^{-1}}$ |
| TOTAL | | | $181\,\mathrm{kg\,s^{-1}}$ |

This total amount of $181\,\mathrm{kg\,s^{-1}}$ flowing through the fish way is used as mass flow inlet condition in the model.

## 5.3. Attraction Water Pipe

Only the perimeter (1 m) and the length (30 m) of the attraction water pipe could be determined, as the water flow within the attraction water pipe couldn't be measured. It is calculated by using Bernoullis equation:

$$\frac{v^2}{2} + gh + \frac{p}{\rho} = const. \tag{5.1}$$

In order to take friction loss into account, the Darcy-Weisbach equation is used:

$$p_{loss} = \lambda \frac{L}{D} \frac{\rho v^2}{2} \tag{5.2}$$

A corrugated plastic pipe has an absolute roughness coefficient $\mathrm{k} \approx 3.5 \times 10^3\,\mathrm{m}$ which gives a relative roughness of $\mathrm{r} = \mathrm{k/D} = 0.011$ (the diameter of the pipe is 0.318 m). Taking a look at the Moody Diagram leads to a friction factor of $\lambda \approx 0.04$. The flow velocity at the upper end of the pipe is assumed to be $0\,\mathrm{m\,s^{-1}}$.

Adapting and combining equation 5.1 with 5.2:

$$2g\Delta h - \lambda \frac{L}{D} v^2 = 0 \tag{5.3}$$

With the values filled in and a height difference $\Delta \mathrm{h}$ of 4.5 m between the inlet and the outlet, the average flow velocity in the pipe is $\mathrm{v} = 4.30\,\mathrm{m\,s^{-1}}$, which corresponds to a mass flow rate of $344\,\mathrm{kg\,s^{-1}}$. In order to fit observations made on site, this value is reduced to $300\,\mathrm{kg\,s^{-1}}$. It is used as mass flow inlet boundary condition for all models. Reversely calculating the above equation leads to a friction factor of $\lambda \approx 0.066$ and therefore to a relative roughness of $\mathrm{r} = 0.044$ and an absolute roughness coefficient $\mathrm{k} \approx 14 \times 10^{-3}\,\mathrm{m}$. The roughness is therefore four times higher than initially assumed. However, it is reasonable as the bending of the pipe has not been taken into account previously.

## 5.4. General Flow Behaviour

In order to determine the flow behaviour of the water, its movement is filmed. This way, only the flow on the surface of the water is observed. This data is used to visually verify the model.

(a) High Mass Flow ($19 \times 10^3\,\mathrm{kg\,s^{-1}}$ total mass flow).

(b) Lower Mass Flow of G3.

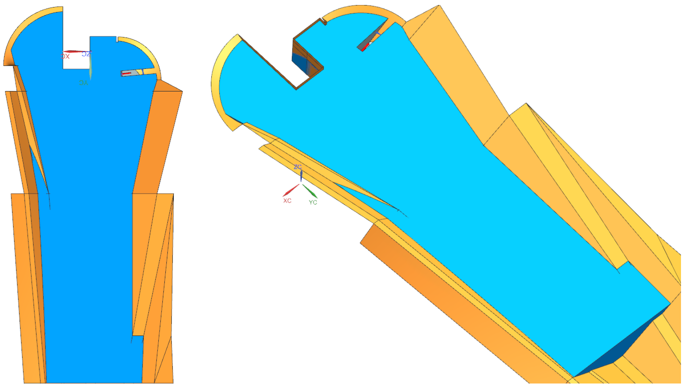
Figure 5.1.: Water Flow between Fish Way and Turbines.

The pictures clearly show a huge difference between the situation with a high total mass flow and the one with the reduced flow of turbine G3. When G3 is running at the maximum, the flow coming from the fish way and the attraction water pipe is completely carried away. Therefore, it doesn't reach the flow coming from the new turbine. However, when the flow through G3 is reduced, the flow from the fish way and the attraction water reach the tail race of the Streamdiver.

With help of the recordings made of the flow behaviour after the turbines the velocity of the attraction water flow after the inlet can be estimated. In the case of the lower mass flow it takes the attraction water on average around 3 s for a distance of 4 m. Therefore an average velocity of $1.3\,\mathrm{m\,s^{-1}}$ should be reached in the models as well.

# 6. Model: Geometry

The construction of the models geometry is based both on provided drawings by the company and on measurements carried out on site. Basically it consists of the outlets of two turbines, the outlets of a fish way and of the attraction water pipe belonging to it, and of a tailrace channel.



(a) Top view. (b) View at turbine outflows, fish way and attraction water pipe.

Figure 6.1.: View on the model. The fluid is marked blue, it consists of water (lower part) and air (uppermost layer). On the right: Fish way with attraction water pipe (red).

While the channel as well as the turbine outlets are mainly constructed with the help of provided drawings, the structure and placement of the fish way is measured. These are obtained on site by using the meter PLR 50 based on laser technology by Bosch and a common meter called FIBAR by Hultafors.

## 6.1. Tail Race Channel

Drawings provided by Skellefteå Kraft are used to model the tail race channel. It basically consists of a ground at 32 meters above sea level flanked by two river banks on each side.

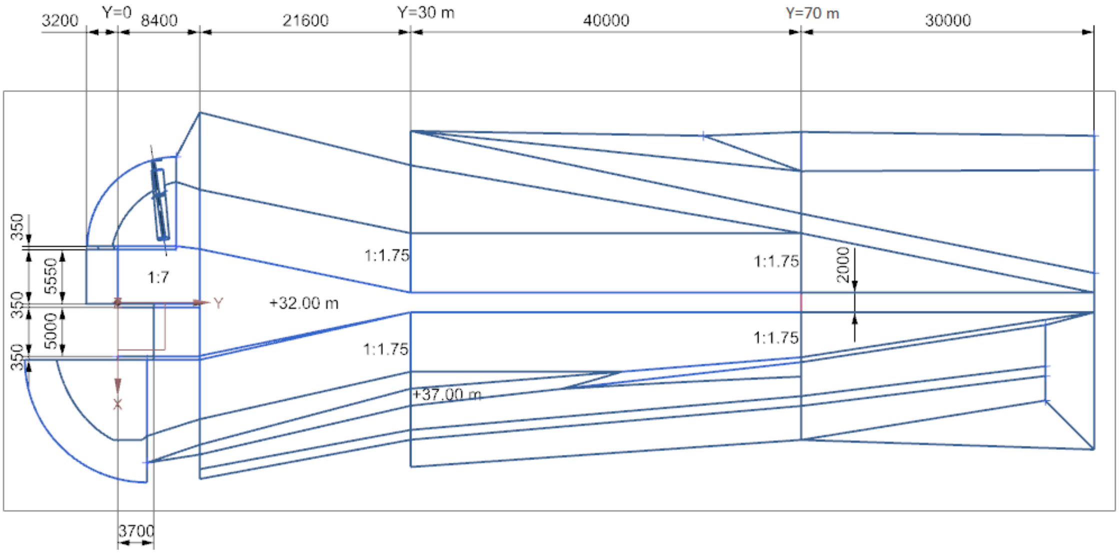



Figure 6.2.: Top view on the whole model. Unit: mm, if not specified differently.

On the left are the building structures of the hydro power plant with the fish way nearby. The model used for the simulations reaches only until Y = 70 m, as the flow far downstream is not of interest for this thesis.

## 6.2. Outlet of the two turbines

Again the model is based on drawings provided by Skellefteå Kraft.

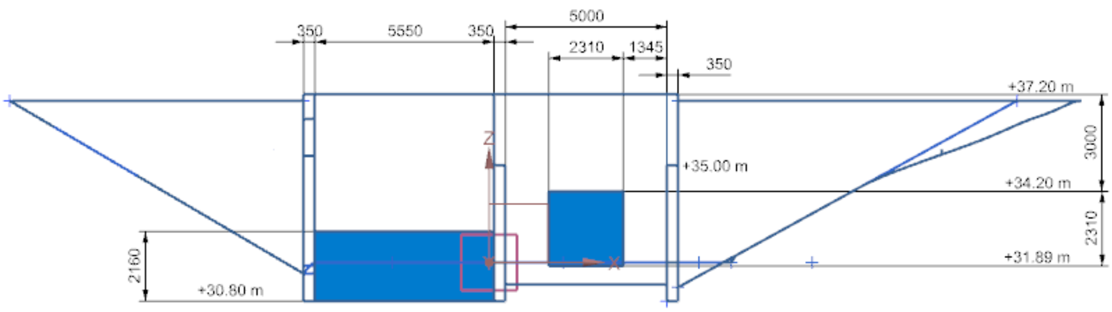



Figure 6.3.: View on the two turbine outlets. Blue area on the left: Outlet of G3. Blue square on the right: Outlet of steamdiver. Unit: mm, if not specified differently.

The ground level of the tailrace is at 32 meters above sea level (MASL) (see figure 6.1). However, the outlets of the turbines (and therefore inlets of the model) are at a lower level. The ground descends at a rate of 1:7 resulting with the old turbine at 30.8 MASL and the new turbine at 31.89 MASL.

## 6.3. Fish Way

Position and length of the fish way are measured on site. With help of the drawings the definitive position can be determined.

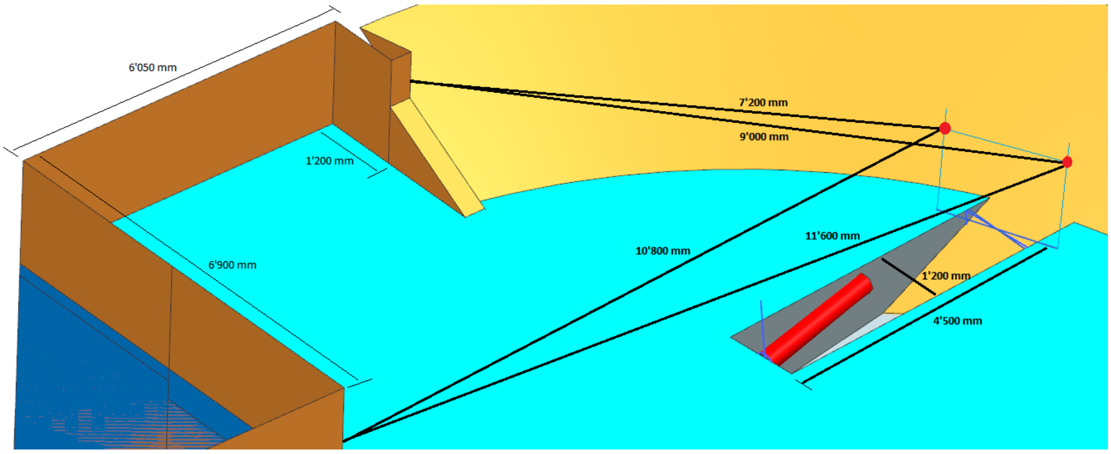



Figure 6.4.: Measurements taken in order to determine the fish way (thicker lines). The fish way is cut out of the (fluid) body. The attraction water pipe (red) is partially underneath the water surface when a high water level is the case.

The angle between the fish way and the (horizontal) water surface is approximately 6.3°. The outlet of the fish way (inlet in the model) is flanked by two walls.

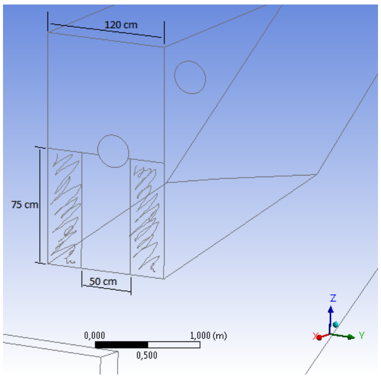



Figure 6.5.: Outlet of the fish way (in the middle). Walls to the left and right of the outlet.

## 6.4. Attraction Water Pipe

The attraction water pipe ends at the same place as the fish way does. However, its angle to the horizontal water surface is slightly higher (around 11°) compared to the fish way (difference of 4.6°). It has a circumference of one meter, which is equivalent to a radius of 0.16 m. The centreline of the pipe ends at 35.4 m above sea level. The total length of 30 m of the pipe is reduced to 2 m in the model, as the friction losses are already included in the boundary conditions of the pipe. The attraction water pipe is not parallel to the fish way but slightly directed downstream.

# 7. Model: Numerical Setup

In total, the model has four inlets and one outlet. Water flow is entering the model from the two turbines, the fish way and the attraction water pipe. The mass flow from the older turbine (G3) is varying (see table 4.1), the one from the Streamdiver is constantly $6 \times 10^3\,\mathrm{kg\,s^{-1}}$. Through the fish way flows a mass flow of $181\,\mathrm{kg\,s^{-1}}$ (see chapter 5.2). In the attraction flow, the constant mass flow is $300\,\mathrm{kg\,s^{-1}}$ (see chapter 5.3). At the outlet a static pressure, with a relative pressure depending on the water depth, is assumed. This allows an outflow with two phases, which is necessary because of an air layer of approximately 1 m at the top of the model. Allowing air to pass through it, the models upper boundary is defined as an opening with entrainment. The river bed is modelled as a rough surface wall, with a sand grain roughness of 0.05 m. The fish way has an assumed roughness of 0.01 m. In the water the Reynolds number is $6.5 \times 10^6$. This high number is influenced by the relatively narrow jets of the inlets [3]. The simulations are run steady state. They are regarded as converged if the RMS values of turbulence, momentum and mass reach a value below $1.0 \times 10^{-5}$ and the values of the monitor points have become steady.

## 7.1. Mesh

Simulations were carried out with meshes differing in their amount of nodes, ranging from $0.6 \times 10^6$ to $4.0 \times 10^6$ Differences were diminishing between $2.1 \times 10^6$ and $4.0 \times 10^6$ nodes. The body is divided into two parts (see figure 7.1), both are meshed with the body sizing method.

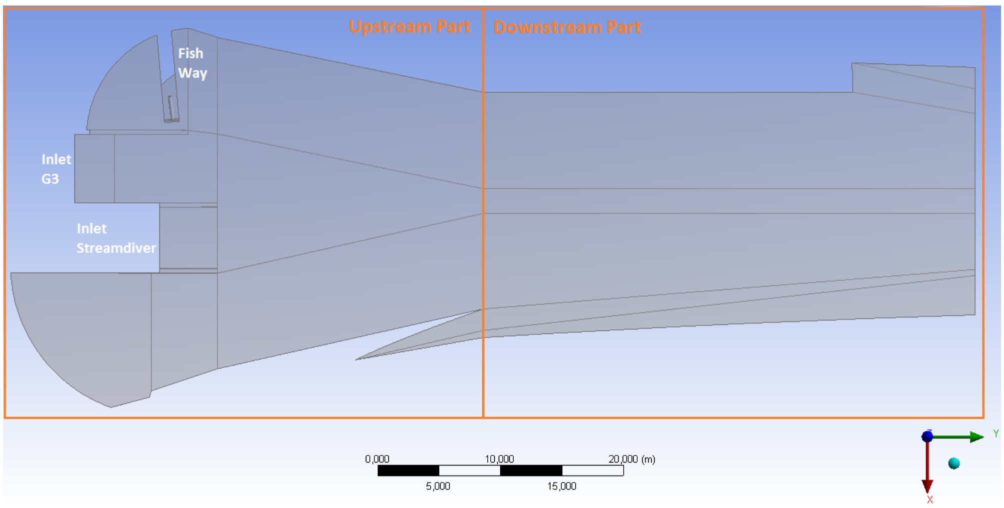
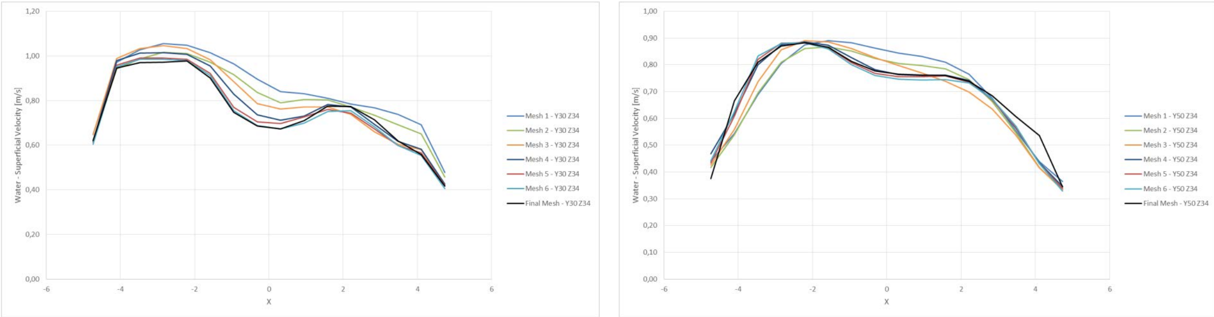



Figure 7.1.: Top view on the model

Letting the model run with different amount of nodes leads to results as follows:




(a) Velocity profile at Y=30m Z=34m

(b) Velocity profile at Y=50m Z=34m

Figure 7.2.: Mesh Study: Water Superficial Velocity vs. X-axis

The difference of the black line (final mesh settings) on the right in figure 7.2(b) can be explained with differences in the inflation-layers settings, which have been adjusted in order to receive a sensible y+ value.

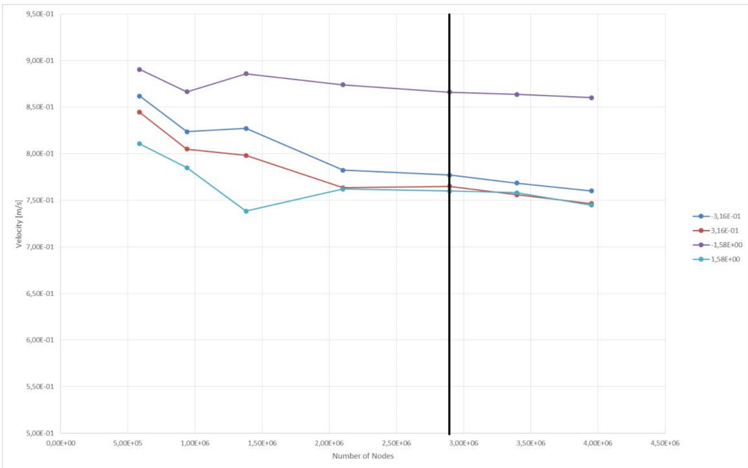


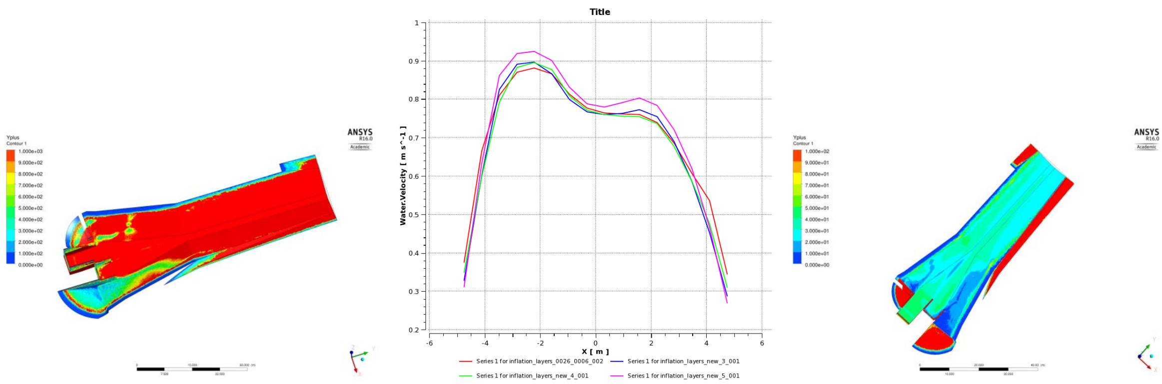

Figure 7.3.: Mesh Study: Superficial Velocity at different points. The black line points out the chosen final settings.

In the mesh with fewer nodes the results are varying. From $2.1 \times 10^6$ nodes on, the values are getting more constant. The mesh with $2.9 \times 10^6$ nodes is chosen for modelling, it is pointed out with a black line in figure 7.1.

The results of a model with mesh element size of 0.11 m in the upstream part and 0.22 m in the downstream part are very close to the ones with a finer mesh, therefore these values are used for future models. In order to get a good resolution close to the wall, inflation layers are used. The thickness of the first inflation layer depends on the roughness of the wall. In the case of rough walls, the wall is virtually moved to half-roughness (to avoid singularities near the wall). The first inflation layer therefore must be thicker than the value of half-roughness. As the sand grain roughness of the river bed is assumed to be 0.05 m, the thickness of first layer there is set to 0.026 m. The fish way has a sand grain roughness of 0.01 m, which leads to a thickness of the inflation layer of 0.006 m. In total, the final mesh has around $2.9 \times 10^6$ nodes.

## 7.2. Y-Plus

A closer look at the results close to the walls show that a y+ value of around 2500 is reached in most parts. This is due to the roughness as a comparison to a model with smooth walls shows, which reaches y+ values around 30. However, a y+ sensitivity study reveals that different heights of the first layers, which lead in the current case with rough walls to similar y+ values, don't have any influence on the results within the flow field. First layer thicknesses between $1 \times 10^{-5}$ m and $2.6 \times 10^{-3}$ m have been examined. All of the show similar results (see figure 7.4(b)). Therefore, and because of the fact, that we are mainly interested in the centre part of the model rather than the walls, this high y+ value is accepted.




(a) Rough Walls (Sand Grain Roughness: 0.05 m)   (b) Sensitivity Study   (c) Smooth Wall

Figure 7.4.: Y-Plus sensitivity study

## 7.3. Roughness

Surface roughness typically leads to an increase in turbulence production near the wall. For the accurate prediction of near wall flows, the proper modelling of surface roughness effects is essential for a good agreement with experimental data [1]. Wall roughness increases the wall shear stress and breaks up the viscous sub-layer in turbulent flows.

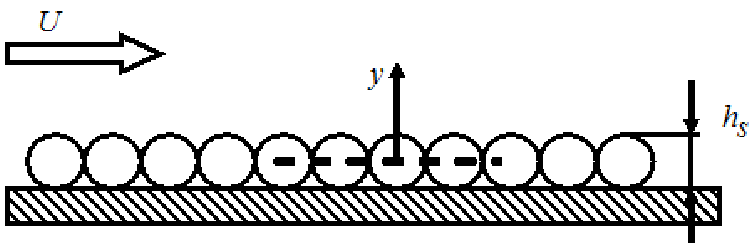
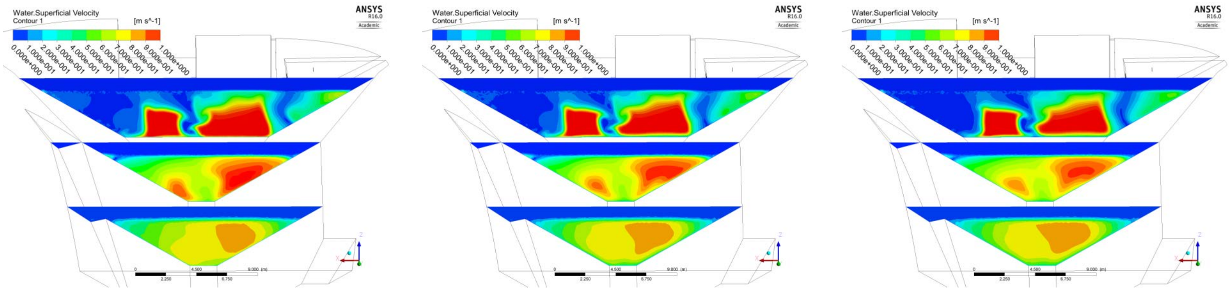



Figure 7.5.: Equivalent sand grain roughness [1]

In the case of rough walls, the wall is virtually moved to half-roughness in order to avoid singularities at the wall.

A roughness study was carried out with three different wall roughnesses: a smooth wall, a wall with a sand grain roughness of 5 cm, and a wall with a sand grain roughness of 10 cm.




(a) Smooth wall.

(b) Rough wall with a sand grain roughness of 5 cm.

(c) Rough wall with a sand grain roughness of 10 cm.

Figure 7.6.: Superficial Velocity (Water) at y = 10 m, y = 30 m and y = 50 m.

A smooth wall leads to a flow with high velocity close to the walls. Through adding a wall roughness, the flow close to the walls is slowed down and the high velocity field moved closer to the surface, which can be observed best in figures 7.6(a) to 7.6(c) at the planes at y = 50 m (at the bottom). The roughness leads also to a slightly higher pressure (100 Pa) mainly in the upstream part.

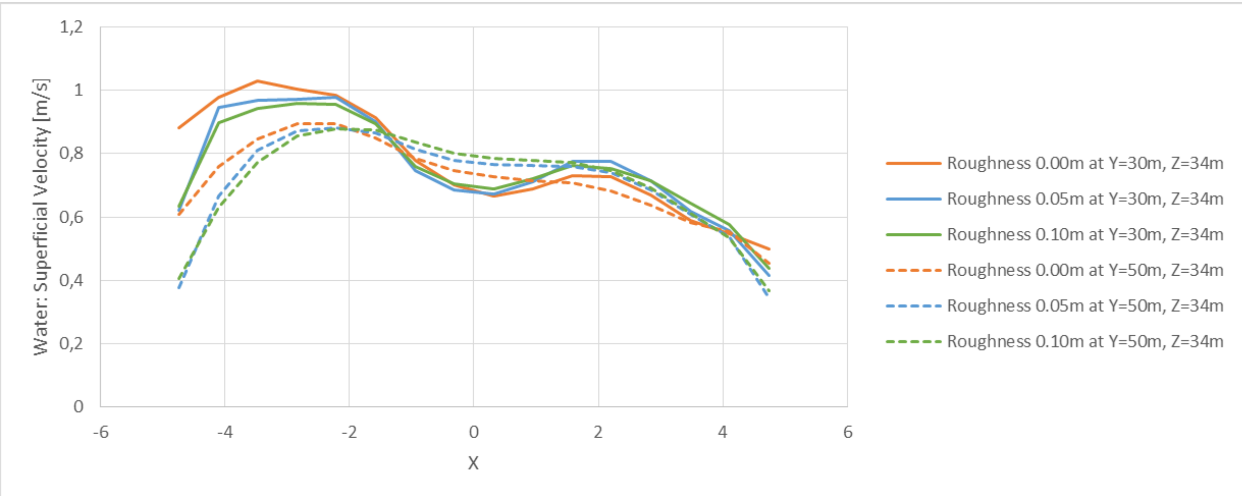



Figure 7.7.: Comparison of the superficial velocity (water) depending on the sand grain roughness at Y = 30 m and Y = 50 m.

As can be seen in the above pictures, the transformation of a smooth wall to a rough wall has a great influence on the results. However, increasing the sand grain roughness from 5 cm to 10 cm hardly influences the flow. The orange line in figure 7.3 shows a different behaviour compared to the other two lines which are quite close. Therefore, a sand grain roughness of 5 cm is chosen for future modelling.

## 7.4. Turbulence

For modelling turbulence, the «BSL (Baseline) Reynolds stress model» is used. It is a Reynolds-Averaged Navier-Stokes (RANS) model, which solves the Navier-Stokes equations time-averaged. The contents of this chapter are mainly based on the ANSYS CFX Theory Guide [1] as well as on Popes «Turbulent Flows» [9].

Reynolds stress models are based on transport equations for all components of the Reynolds stress tensor and the dissipation rate. The Reynolds stresses are additional unknowns introduced by the averaging procedure, hence they must be modelled in order to close the system of governing equations [2]. This is the so-called «closure problem», to which the Reynolds stress models offer an approach. These models do not use the eddy viscosity hypothesis, but solve an equation for the transport of Reynolds stresses in the fluid. The Reynolds stress model transport equations are solved for the individual stress components. The Reynolds averaged momentum equations for the mean velocity are:

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_i U_j) - \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] = -\frac{\partial p''}{\partial x_i} - \frac{\partial}{\partial x_j}(\rho \overline{u_i u_j}) + S_{M_i} \tag{7.1}$$

where $p''$ is a modified pressure, $S_{M_i}$ is the sum of body forces and the fluctuating Reynolds stress contribution is $\rho\overline{u_i u_j}$. Unlike eddy viscosity models, the modified pressure has no turbulence contribution and is related to the static (thermodynamic) pressure by:

$$p'' = p + \frac{2}{3}\mu\frac{\partial U_k}{\partial x_k} \tag{7.2}$$

In the differential stress model, $\rho\overline{u_i u_j}$ is made to satisfy a transport equation. A separate transport equation must be solved for each of the six Reynolds stress components of $\rho\overline{u_i u_j}$. The differential equation Reynolds stress transport is:

$$\frac{\partial \rho\overline{u_i u_j}}{\partial t} + \frac{\partial}{\partial x_k}(U_k \rho\overline{u_i u_j}) - \frac{\partial}{\partial x_k}((\delta_{kl}\mu + \rho C_S\frac{k}{\varepsilon}\overline{u_k u_l})\frac{\partial \overline{u_i u_j}}{\partial x_l} = P_{ij} - \frac{2}{3}\delta_{ij}\rho\varepsilon + \Phi_{ij} + P_{ij,b} \tag{7.3}$$

where $P_{ij}$ and $P_{ij,b}$ are shear and buoyancy turbulence production terms of the Reynolds stresses respectively, $\Phi_{ij}$ is the pressure-strain tensor, and $C$ is a constant. Buoyancy turbulence terms $P_{ij,b}$ also take the buoyancy contribution in the pressure strain term into account and are controlled in the same way as for the $k-\varepsilon$ and $k-\omega$ model.

In Reynolds stress models, model transport equations are solved for the individual Reynolds stresses and for the dissipation, or another quantity that provides length or time scale of the turbulence [9]. In the BSL Reynolds stress model this quantity is the turbulent frequency $\omega$. According to the ANSYS CFX theory guide [1] CFX provides two Reynolds Stress-$\omega$ models: the Omega Reynolds Stress and Baseline (BSL) Reynolds stress models. The two models relate to each other in the same way as the two equation k-$\omega$ and BSL models. In the BSL k-$\omega$ model the Wilcox k-$\omega$ model is multiplied by a blending function $F_1$ and the transformed k-$\varepsilon$ model by a function $1 - F_1$. $F_1$ is equal to 1 near the surface and decreases to a value of zero outside the boundary layer [1].

For further details to the Baseline Reynolds Stress turbulence model take a look at the ANSYS CFX Theory Guide [1].

## 7.5. Multiphase Flow

Information used in this chapter is mainly received by ANSYS CFX Theory Guide [1]. Fields like temperature and turbulence, but also the flow field, are shared by all fluids in a homogeneous multiphase flow. It assumes that the transported quantities (except or the volume fraction) are the same for all phases. The model is therefore sufficient to solve for the shared fields using bulk transport equations rather than solving individual phasic transport equations.

Free surface flow theory is the most common application of homogeneous multiphase flow. A free surface is a boundary between two homogeneous fluids. The most common example is the boundary between liquid water and the atmospheric air. «The reason for the «free» designation arises from the large difference in the densities of the gas and liquid (e.g., the ratio of density for water to air is 1000). A low gas density means that its inertia can generally be ignored compared to that of the liquid. In this sense the liquid moves independently, or freely, with respect to the gas. The only influence of the gas is the pressure it exerts on the liquid surface. In other words, the gas-liquid surface is not constrained, but free.» [5] It is a surface that is subject to zero parallel shear stress. «A free boundary poses the difficulty that on the one hand the solution region changes when its surface moves, and on the other hand, the motion of the surface is in turn determined by the solution. Changes in the solution region include not only changes in size and shape, but in some cases, may also include the coalescence and break up of regions (i.e., the loss and gain of free surfaces).» [4] Free surfaces can be gained for example by vapour production, i.e. droplet formation.

The surface tension used in CFX is based on the Continuum Surface Force model. This models the surface tension force as a volume force concentrated at the interface, rather than a surface force. A primary fluid $\alpha$ (the liquid phase) and a secondary fluid $\beta$ (gas phase) are defined. The surface tension force given by the continuum surface force model is:

$$F_{\alpha\beta} = f_{\alpha\beta}\delta_{\alpha\beta} \tag{7.4}$$

where:

$$f_{\alpha\beta} = -\sigma_{\alpha\beta}\kappa_{\alpha\beta}n_{\alpha\beta} + \nabla_s\sigma \tag{7.5}$$

The two terms summed up on the right hand side reflect the normal and tangential components of the surface tension force. The normal component arises from the interface curvature and the tangential component from variations in the surface tension coefficient.

# 8. Previous Situation

After the turbine «Streamdiver» has been added to the site, it is to be examined whether its installation has lessened or changed the efficacy of the fish way and the attraction water pipe. Therefore two models are run with the following settings:

- Inlet Streamdiver: $0\,\mathrm{kg\,s^{-1}}$
- Inlet G3: $13 \times 10^3\,\mathrm{kg\,s^{-1}}$ (maximum) and $4 \times 10^3\,\mathrm{kg\,s^{-1}}$ (minimum)
- Inlet fish way: $181\,\mathrm{kg\,s^{-1}}$
- Inlet attraction water: $300\,\mathrm{kg\,s^{-1}}$

It is assumed that there was no flow at the place where the Streamdiver is nowadays. There is another turbine at the other bench of the river (see figure 2.1), called «G2». Therefore the additional mass flow is supposed to have run either through that turbine or in the middle between the G2 and G3 building as spill water in the old river bed. For the figures it is chosen to show the superficial velocity of water instead of just the velocity. The superficial velocity is a hypothetical flow velocity calculated as if the given phase or fluid where the only one flowing or present in a given cross sectional area. As we are only interested in the movement of water and not of the air, this simplifies the analysis.

The subsequent chapters are arranged in a chronological order in terms of real time. First, the previous situation is presented, then the current one and afterwards possible future arrangements. The modelling itself, however, was started with the current situations, as these are the ones that can be compared to observations on site. A part of the geometry which will appear often in the analysis is the wall between the outlet of the Streamdiver and the outlet of G3, pointed out in figure 8.1. As this wall blocks the attraction water flow in certain circumstances, it has a great influence on the outcome of the simulations and is therefore described here extra. It is underneath the water surface: 50 cm during high mass flows, and 13 cm when low mass flow occurs.

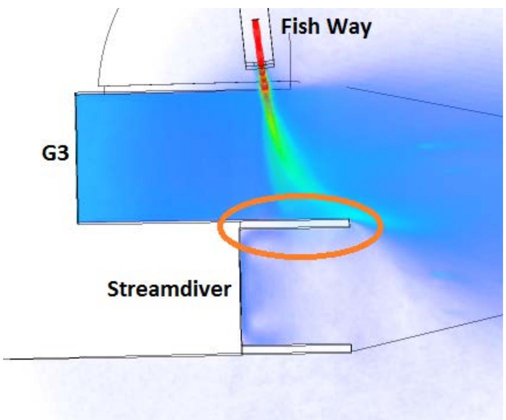
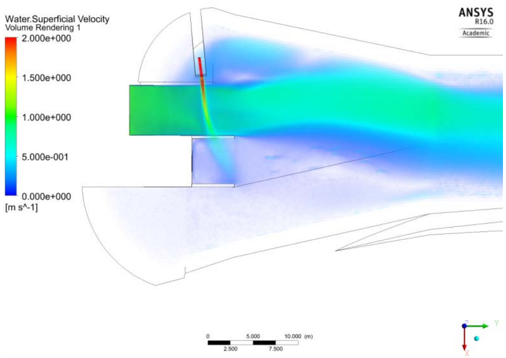


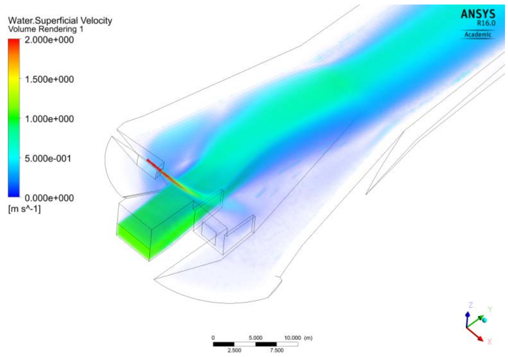

Figure 8.1.: A major drawback on the efficacy of the fish way: the wall between the outlets, marked with an orange circle

## 8.1. High Mass Flow: $13 \times 10^3\,\mathrm{kg\,s^{-1}}$

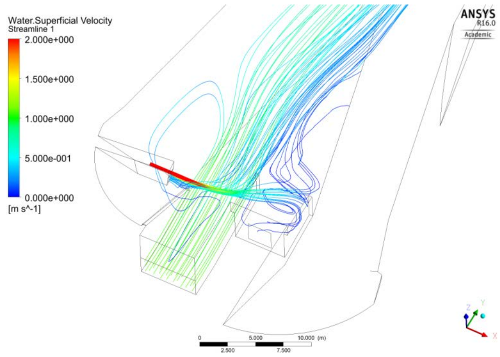
In the first simulation the model is run with the maximum flow coming from G3 ($13 \times 10^3\,\mathrm{kg\,s^{-1}}$). At this flow rate the water level is at 35.5 m.



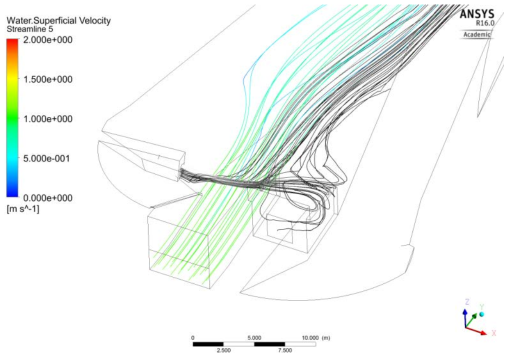
(a) Volume rendering of superficial flow velocity of water.



(b) Volume rendering of superficial flow velocity of water.



(c) Streamlines of the superficial flow velocity of water.



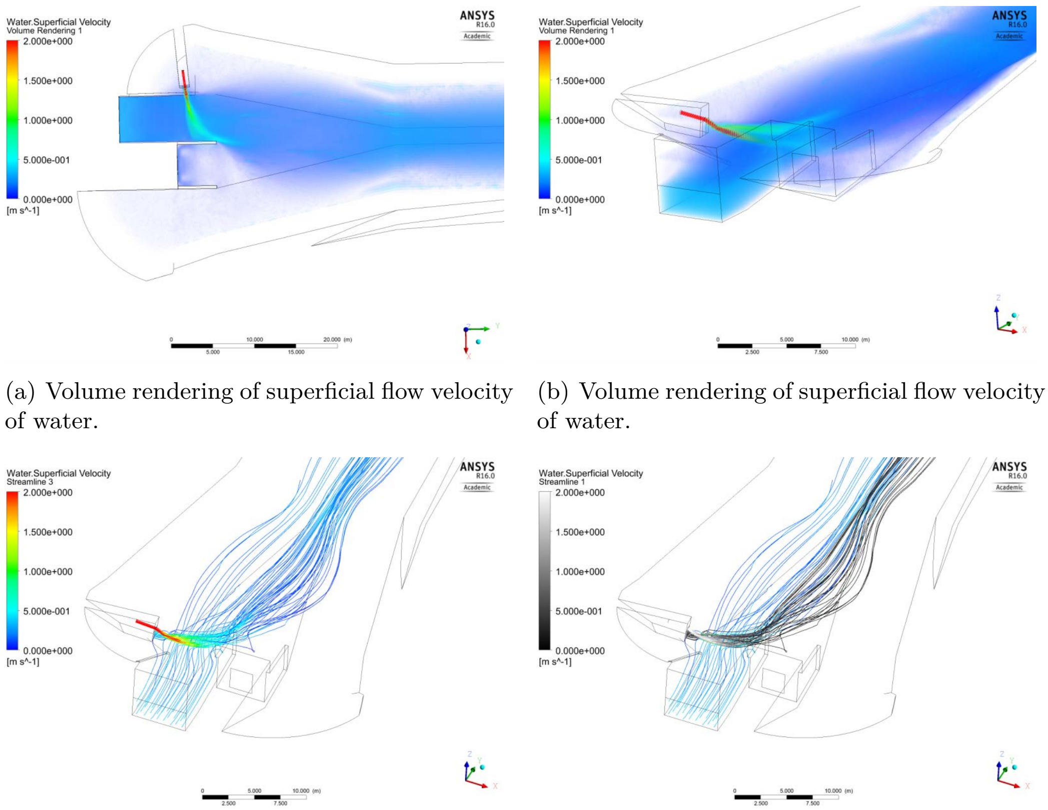
(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow coloured in grey scale.

Figure 8.2.: Superficial flow velocity of water from $0\,\mathrm{m\,s^{-1}}$ to $2\,\mathrm{m\,s^{-1}}$.

Because of the high water level the attraction water flows over the wall which stands perpendicularly to it underneath the water surface (see figure 8.1). However, as can be seen in the current situation (see chapter 5.4), in reality the high water flow coming from G3 carries away the attraction water. Thus, it can be assumed that the result received by the simulation is not realistic enough and that the attraction water flow is carried away in this case as well. As therefore the attraction water will not reach the opposite side of the channel, the fish way is not able to attract fish from there. Due to the high water level the attraction water can, more or less, continue its course after leaving the pipe and remains therefore close to the surface of the channel. From figure 8.2(c) can be stated, that the velocity of the attraction water flow is immensely reduced by the time it accompanies the main flow. The two flows of the turbines dominate therefore the riverbed in respect to mass flow and velocity.

## 8.2. Low Mass Flow: $4 \times 10^3\,\mathrm{kg\,s^{-1}}$

Running the model at a low mass flow $4 \times 10^3\,\mathrm{kg\,s^{-1}}$ through G3, with a water level of 35.13 m in the tail race channel, leads to the following results:




(a) Volume rendering of superficial flow velocity of water.

(b) Volume rendering of superficial flow velocity of water.

(c) Streamlines of the superficial flow velocity of water.

(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow coloured in grey scale.

Figure 8.3.: Superficial flow velocity of water from $0\,\mathrm{m\,s^{-1}}$ to $2\,\mathrm{m\,s^{-1}}$.

With a low mass flow through G3, the attraction water dominates the region on the surface close to the turbine outlets. This behaviour is confirmed with observations on site (see chapter 5.4). It can be assumed, that it attracts fish to the entrance of the fish way if they swim in the upper half of the channel. Like in the case with a higher mass flow, the velocity of the attraction water is slower than the main flow by the time these two flows converge. The turbine outlet will therefore entice fish to swim into the turbine channel. For the reason that the fish way is relatively close to the turbine outlets, fish who seek an alternative to the latter, should be able to find its entrance. Especially as G3 attracts them to the same channel side on which the fish way is. After moving further downstream, the attraction water sticks to the right side of the channel (in downstream direction), probably because this side is now «unoccupied». In figure 8.3(b) it is visible that the attraction water flow divides after hitting the water surface into two parts. One of those two remains at the surface, the other one dives down. For a fish way this is a good behaviour as this way it manages to attract fish swimming in the surface layer as well as the ones swimming deeper down. However, those which swim close to the bottom will not be reached by the attraction water.

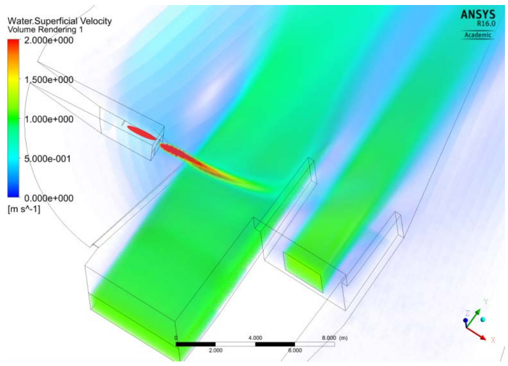
# 9. Current Situation

In order to be able to compare changes and define improvements for the fish way and the attraction water pipe, a model of the current situation has to be established. It is the only one that can be verified. With recordings of the water flow downstream of the hydro power plant this is done visually. It is assumed that the mass flow in the fish way ($181\,\mathrm{kg\,s^{-1}}$) as well as in the attraction water pipe ($300\,\mathrm{kg\,s^{-1}}$) is constant.

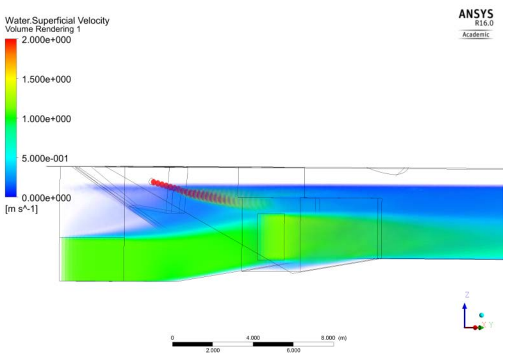
## 9.1. High Mass Flow: $19 \times 10^3\,\mathrm{kg\,s^{-1}}$

At first the scenario with the highest mass flow is analysed. For this purpose the given flows from the turbines ($13 \times 10^3\,\mathrm{kg\,s^{-1}}$ and $6 \times 10^3\,\mathrm{kg\,s^{-1}}$) are combined with $300\,\mathrm{kg\,s^{-1}}$ coming from the attraction water pipe and $181\,\mathrm{kg\,s^{-1}}$ from the fish way. The water level is at $35.5\,\mathrm{m}$.

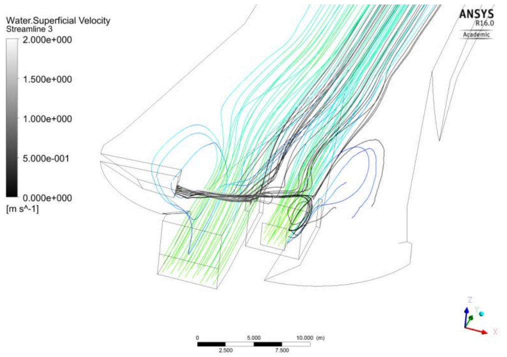
(a) Recorded Flow Behaviour.




(b) Volume rendering of superficial flow velocity of water.




(c) Volume rendering of superficial flow velocity of water.




(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow coloured in grey scale.

Figure 9.1.: Superficial flow velocity of water from $0\,\mathrm{m\,s^{-1}}$ to $2\,\mathrm{m\,s^{-1}}$.

### 9.1.1. Comments to the simulation results

By comparing the recorded flow behaviour (see figure 9.1(a)) to the results from the model, a different kind of flow behaviour can be observed. While in the first one the flow coming from the attraction water pipe is immediately carried away after flowing into the tail race of the turbines, it seems to go straight on in the simulated situation. This is due to the inlet conditions at the turbines outlet which assumes an evenly distributed flow perpendicular to the inlet area. This and the chosen turbulence model «BSL Reynolds Stress» lead to a jet-like behaviour of the flows coming from the turbines. Therefore they stay close to the bottom of the tail race channel and do not mix with the water coming from the attraction water pipe. This behaviour is the main flaw of the model. For all simulation results obtained after running a model with a high mass flow, it is therefore assumed that the flow is more turbulent close to the turbines and that it will carry away the attraction water. Another consequence is that the attraction flow will remain on the side of the channel from which it flows in, and not, like in the simulation results, cross the tail race channel. As figure 9.1(b) shows, the velocity of the attraction water is slower than the turbine flows after it accompanies them. Observation on site confirm this behaviour, which is in that case evoked by the turbulence close to the outlets.

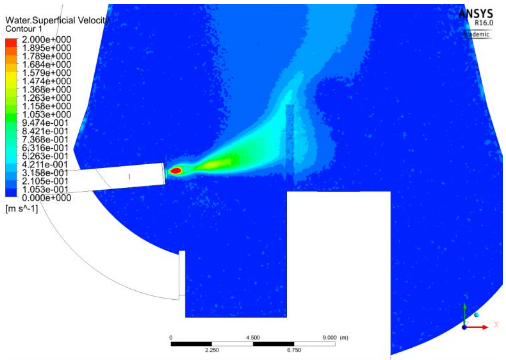
### 9.1.2. Comparison to the previous situation

Whether the Streamdiver is running or not does not seem to have any influence on the results which look very similar close to the G3 outlet for the previous and the current case. On site it could be observed that the flow from G3, when at its maximum, carries away the attraction water flow as soon as it enters the tail race channel. Thus, adding flow from the Streamdiver has no impact on the flow behaviour. However, the Streamdiver might entice fish away from the fish way entrance.

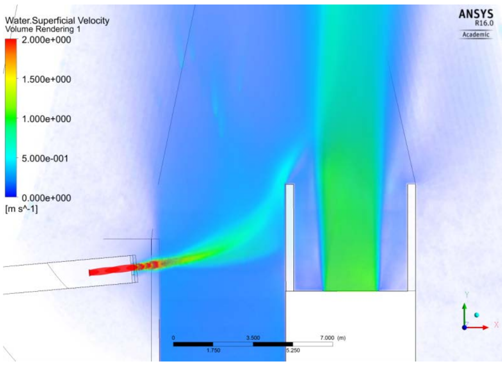
## 9.2. Reduced Mass Flow: $10 \times 10^3\,\mathrm{kg\,s^{-1}}$

Another common scenario is when the G3 is running at its lowest working point ($4 \times 10^3\,\mathrm{kg\,s^{-1}}$). The Streamdiver runs with $6 \times 10^3\,\mathrm{kg\,s^{-1}}$. The mass flow in the fish way is $181\,\mathrm{kg\,s^{-1}}$ and from the attraction water pipe $300\,\mathrm{kg\,s^{-1}}$ flow into the tail race channel. The water level is at 35.13 m.

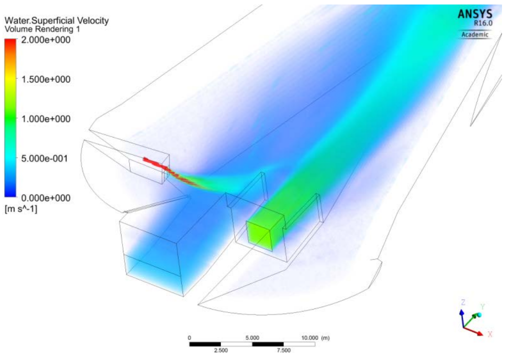
(a) Recorded flow behaviour.



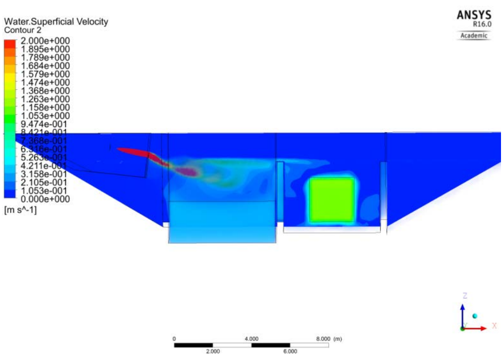
(b) Contour of superficial velocity at z = 35.05 m (slightly beneath the water surface).



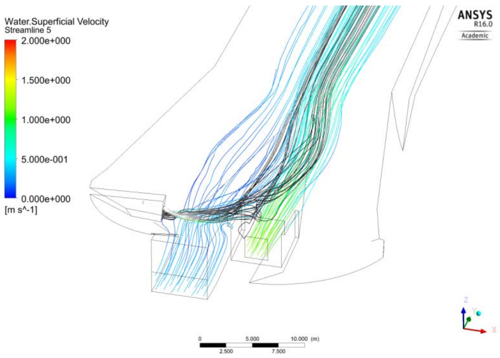
(c) Volume rendering of superficial flow velocity of water.



(d) Volume rendering of superficial flow velocity of water.



(e) Volume rendering of superficial flow velocity of water.



(f) Streamlines. Attraction water flow is coloured in greyscale.

Figure 9.2.: Superficial flow velocity of water from $0\,\mathrm{m\,s^{-1}}$ to $2\,\mathrm{m\,s^{-1}}$.

### 9.2.1. Comments to the simulation results

Figure 9.2(b) shows a similar flow behaviour to the one recorded (see figure 9.2(a)). The velocity of the inflowing water can be confirmed with the observations on site. It is only higher close to the surface as well as close to the turbines than the surrounding fluid. Further downstream, the attraction water doesn't have any influence any more with respect to flow velocity. That the flow observed is more straight as the one modelled can be explained with fluctuations on the one hand and changes of the water level on the other. When making the measurements on site, the water level was around 35.40 m although the typical level is 35.13 m when the water flow is low. This increases the possibility of the flow of crossing the wall instead of being blocked. A higher water level also leads to a smaller difference in height between the outlet of the attraction water pipe and the water surface. The smaller this difference is the more the flow can carry on straight without being forced to change its direction (due to gravity). However, due to the wall between the two turbine outlets, the attraction water is partly blocked before entering the tail race of Streamdiver. The flow is forced downstream. It remains in the centre of the channel, tending towards the side of the Streamdiver.

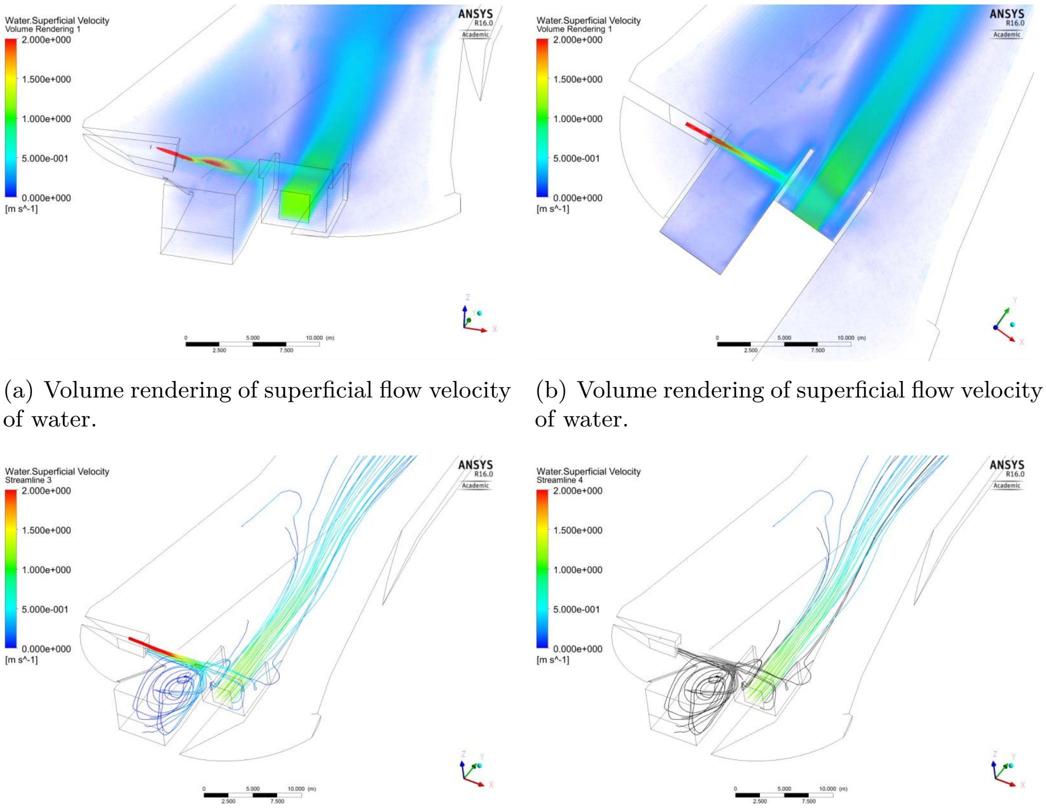
An interesting feature can be observed in the picture 9.2(e) which shows clearly how the flow splits and most of it dives down after entering the tail race channel. The rest remains in a comparably small surface flow. On site only this surface flow can be observed. This is an advantageous behaviour of the flow concerning the efficacy of the fish way. It manages to attract not only fish migrating close to the surface but all those in the upper half of the channel as well. Only in the bottom part the flow from the turbine is too strong for the fish way to have any influence.

### 9.2.2. Comparison to the previous situation

Like in the case of the high mass flow, the results from the models of the previous and the current situations with low mass flow are similar. Because of the wall between the two outlets the attraction water mass flow is almost completely blocked. Therefore the efficacy of the fish way is independent from the Streamdiver in this case as well.

## 9.3. Low Mass Flow: $6 \times 10^3\,\mathrm{kg\,s^{-1}}$

In this scenario only the Streamdiver is running while the G3 is shut down. It is a situation of which no recordings were done, so the results cannot be compared to observations on site. The water level is again at 35.5 m.




(a) Volume rendering of superficial flow velocity of water.

(b) Volume rendering of superficial flow velocity of water.

(c) Streamlines highlighting the flow from the attraction water pipe.

(d) Streamline highlighting the flows from the attraction water pipes, the fish way as well as the Streamdiver.

Figure 9.3.: Low mass flow: Streamdiver: $6 \times 10^3\,\mathrm{kg\,s^{-1}}$, G3: $0\,\mathrm{kg\,s^{-1}}$, attraction water: $300\,\mathrm{kg\,s^{-1}}$, fish way: $181\,\mathrm{kg\,s^{-1}}$. Superficial flow velocity of water from $0\,\mathrm{m\,s^{-1}}$ to $2\,\mathrm{m\,s^{-1}}$.

As can be expected the attraction water flows unhindered straight forward without being carried away. In figures 9.3(b) and 9.3(d) can be observed, however, that the wall between the two turbine outlets acts like a barrier and blocks the attraction water flow. Only a small amount of water remains to flow over the wall. This is also due to the lower water level which occurs when the water flow is low (see chapter 4). The wall is in that case only 13 cm below the water level. When the flow is high the distance between the water surface and the wall is 50 cm. The flow behaviour observed is close to the one with a low mass flow running through G3. After hitting the wall the flow velocity of the attraction water is reduced immensely and has hardly any influence on the flow in the main channel. It can be stated that only fish which don't swim in the main stream will find the entrance to the fish way. And this although the low water flow coming from the turbines increases the relevance of the water coming from the fish way and the attraction water pipe in regard of the total amount of the mass flows. The wall hinders the water to influence the water flow in the tail race of the Streamdiver and to entice fish away from there.

# 10. Variation of Angle

Possible improvements to the current situation could be reached by aligning the fish way and the corresponding attraction water pipe slightly to the main flow in the channel. If the attraction water does not flow into the main channel perpendicularly, it can be expected that it maintains its higher flow velocity longer. In order to examine the change in the efficacy of the fish way three different angles will be tested: 5° (current situation), 20° and 45°. An angle of zero degrees will only be examined for fish ways positioned further downstream (see chapter 11), as it is close enough to 5° to expect similar results. The results of the simulated model with an angle of 5° at the current place can be read in chapter 9, as it is the current case.

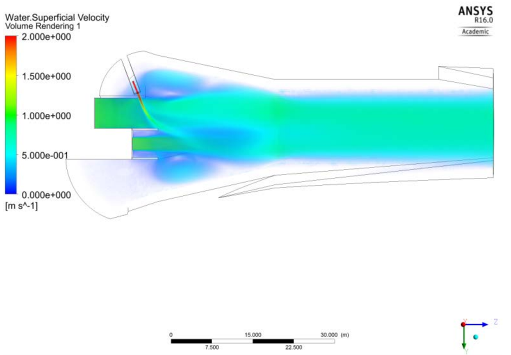
All simulations carried out for this chapter as well as those following will be with a maximum water flow through the turbines:

- Inlet G3: $13 \times 10^3\,\mathrm{kg\,s^{-1}}$
- Inlet Streamdiver: $6 \times 10^3\,\mathrm{kg\,s^{-1}}$
- Inlet fish way: $181\,\mathrm{kg\,s^{-1}}$
- Inlet attraction water pipe: $300\,\mathrm{kg\,s^{-1}}$

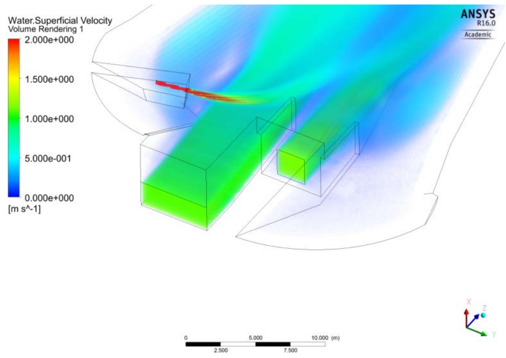
The situation with the highest water flow is supposed to be the one which leads to the lowest efficacy of the fish way. This is the reason for looking at this situation. If the fish way has a good efficacy at high mass flows, it can be assumed, that it is even better at lower mass flows. The water level is therefore at 35.5 m.

## 10.1. Angle of 20°

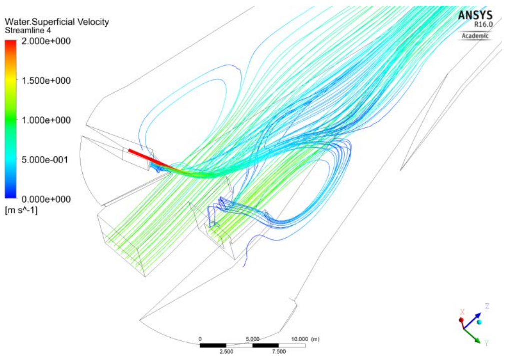
Running the simulation with the fish way and the attraction water pipe rotated by 20° around the vertical axis gives the following results:



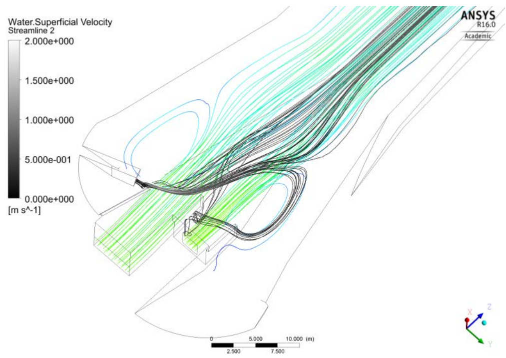

(a) Volume rendering of superficial flow velocity of water.




(b) Volume rendering of superficial flow velocity of water.




(c) Streamlines of the superficial flow velocity of water.



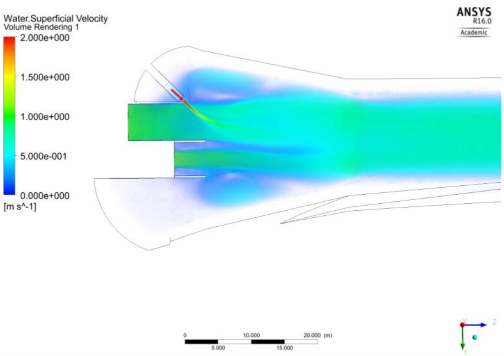

(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow are coloured in grey scale.

Figure 10.1.: Superficial flow velocity of water from $0\,\mathrm{m\,s^{-1}}$ to $2\,\mathrm{m\,s^{-1}}$. Mass flow: $6 \times 10^3\,\mathrm{kg\,s^{-1}}$ from Streamdiver, $13 \times 10^3\,\mathrm{kg\,s^{-1}}$ from G3, $300\,\mathrm{kg\,s^{-1}}$ from attraction water pipe, $181\,\mathrm{kg\,s^{-1}}$ from fish way.

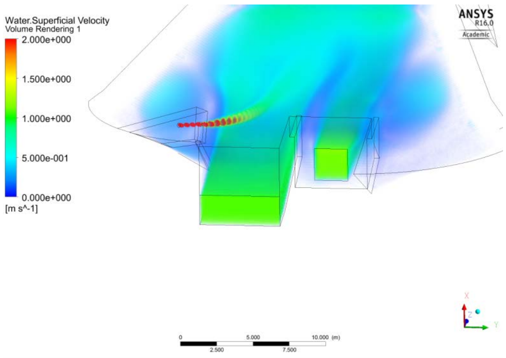
Comparing the above pictures to the results of the model of the current case (see chapter 9), it can be observed that with an angle of 20° the wall can be (more or less) avoided. This is especially important for the case of a low mass flow when the attraction water actually manages to cross the channel. A comparison to the case without an angle shows that the velocity of the attraction water remains longer at a higher level if the channel is aligned slightly to the flow. However, in figure 10.1(c) the velocity difference between the attraction water and the turbine flows is obvious. The two flows coming from the turbines are faster and will therefore entice the fish to the bottom of the channel. From observations on site it can be assumed for this case as well that, if the mass flow is high, the attraction water will be carried away before reaching the middle of the channel. The attraction water flow is therefore supposed to remain on the side on which it flows into the channel.

## 10.2. Angle of 45°

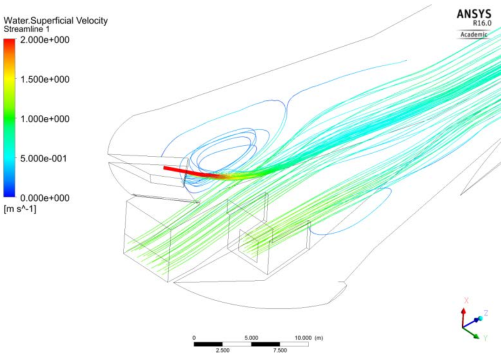
In order to examine the influence of the angle of the fish way it is rotated around the vertical axis keeping the outlet at the same place. Setting the angle to 45° leads to results as follows:



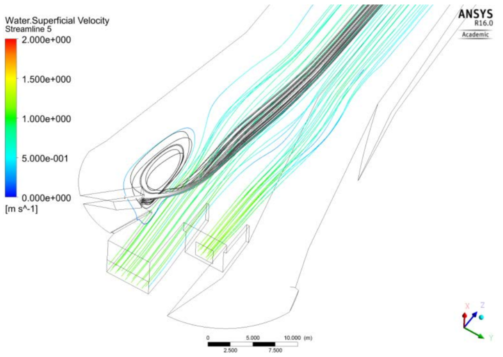

(a) Volume rendering of superficial flow velocity of water.




(b) Volume rendering of superficial flow velocity of water.




(c) Streamlines of the superficial flow velocity of water.




(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow are coloured in grey scale.

Figure 10.2.: Superficial flow velocity of water from $0\,\mathrm{m\,s^{-1}}$ to $2\,\mathrm{m\,s^{-1}}$. Mass flow: Streamdiver: $6 \times 10^3\,\mathrm{kg\,s^{-1}}$, G3: $13 \times 10^3\,\mathrm{kg\,s^{-1}}$, attraction water: $300\,\mathrm{kg\,s^{-1}}$, fish way: $181\,\mathrm{kg\,s^{-1}}$.

By changing the angle of the fish way the wall between the turbine outlets can be avoided. The attraction water forms a parallel flow to the one coming from G3 and it will flow in the middle of the channel further downstream. Keeping the observations on site in mind it can be stated that the attraction water will be carried away by the turbine flow faster than in the simulation results. However, as the attraction water enters the main channel almost in the same direction as the main flow, this will not have a huge influence. This kind of placement will attract fish travelling close to the surface in the middle of the channel or close to the bench on the same side as the fish way. Those which are deeper down or on the opposite side will not find the entrance. However, the advantage of a fish way that close to the turbine outlet is, that when the fish realise that the turbine outlet is not the right place for them, they will find the entrance of the fish way by only swimming up to the surface. The velocity of the attraction water flow in the channel is about the same as the main flow. It therefore does not attract fish away from the main stream but leads those close to the surface to the fish way entrance.

## 10.3. Conclusion: Influence of the Angle

Comparing the results of the situation with an angle of 45° to the ones obtained for the current case, it can be stated, that the angle increased the efficacy of the fish way. The main reason is the velocity. As during high mass flows the attraction water will be carried away by the main flow anyway, it makes more sense to position the pipe in a way that the higher velocity of the flow in the pipe can be maintained. For the same reason the angle of 45° is to be preferred over an angle of 20°.

# 11. Variation of Placement

The largest improvement is expected by moving the fish way five meters downstream in order to avoid the wall between the two outlets of the turbines. Furthermore it is only possible for the two turbine flows to mix after the wall and thereby break up the jet-like behaviour. At this place three different angles of the fish way compared to the flow direction are examined: 0°, 20° and 45°.

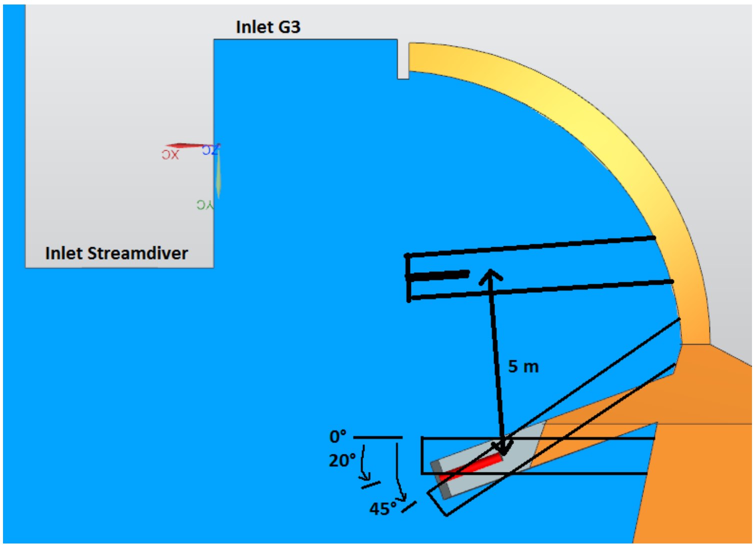



Figure 11.1.: Placement further downstream at three different angles

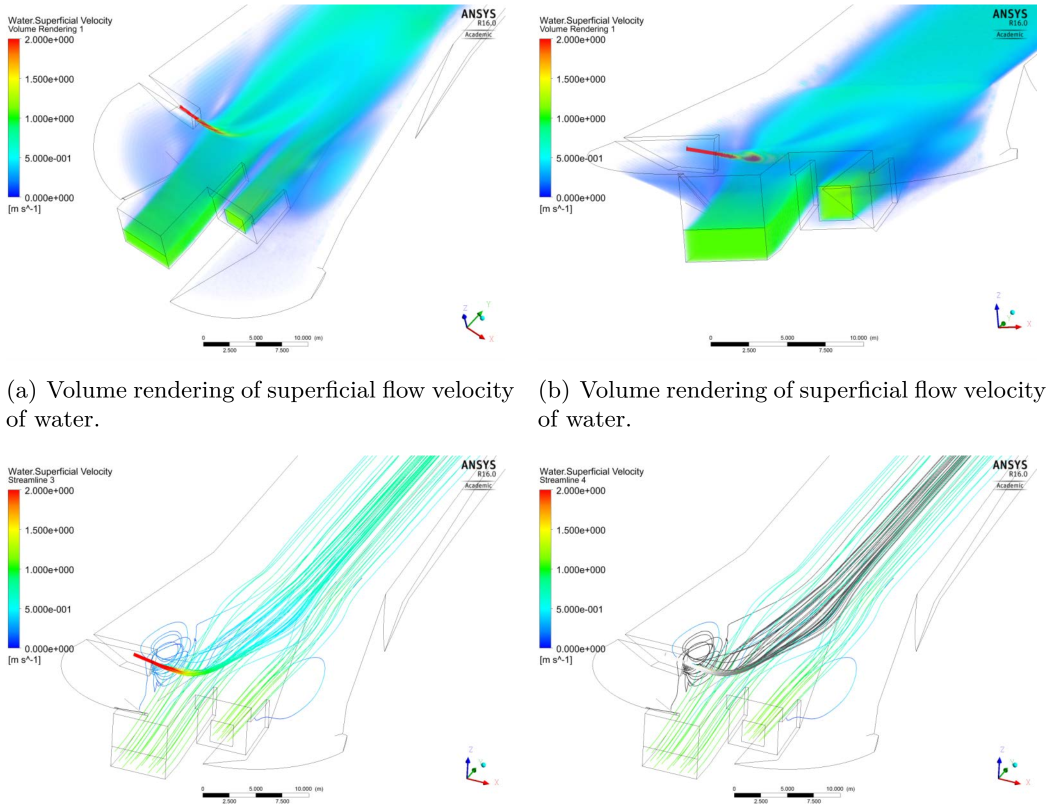
In the three following models the inlet conditions are the same as the ones in the previous simulation models:

- Inlet G3: $13 \times 10^3\,\mathrm{kg\,s^{-1}}$
- Inlet Streamdiver: $6 \times 10^3\,\mathrm{kg\,s^{-1}}$
- Inlet fish way: $181\,\mathrm{kg\,s^{-1}}$
- Inlet attraction water pipe: $300\,\mathrm{kg\,s^{-1}}$

Like before, the water level in the examined models is at 35.5 m.

## 11.1. Angle of 0°

A direct comparison of the improvement by a placing of the fish way further downstream can be best observed with a model in which the fish way is perpendicular to the flow direction in the tail race channel. The main improvement is expected from the fact that this way the wall between the turbine outlets can be avoided.




(a) Volume rendering of superficial flow velocity of water.

(b) Volume rendering of superficial flow velocity of water.

(c) Streamlines of the superficial flow velocity of water.

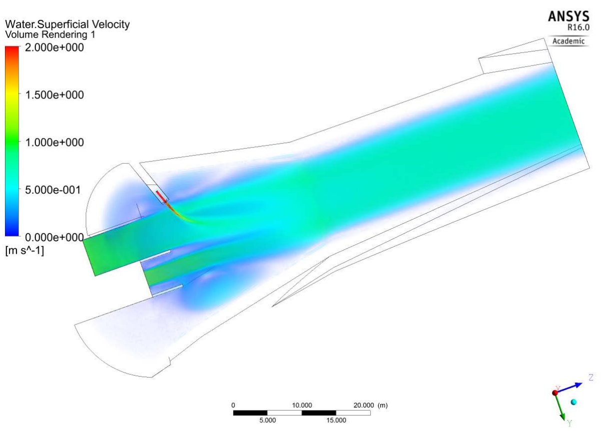
(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow are coloured in grey scale.

Figure 11.2.: Results of model with the fish way moved 5 m downstream and placed perpendicular to the main flow.

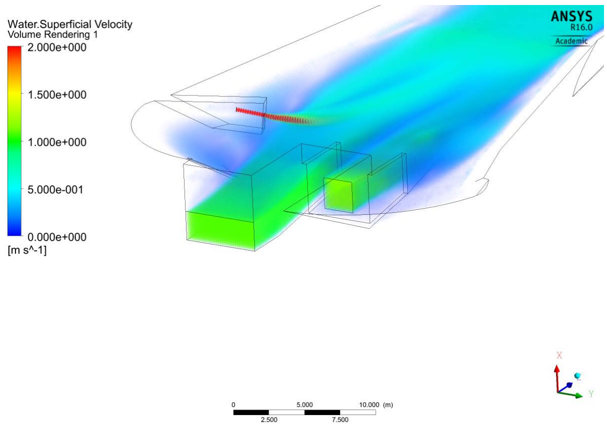
With the above pictures it can be stated that the flow from the attraction water pipe as well as the one from the fish way get carried away by the tail race of G3. This behaviour was observed on site for the current situation. The flow from G3 has come to the surface at this spot in the model. However, it seems that at least the outflow of the fish way and attraction water pipe manage to cover the uppermost layer of the stream in its whole width. So at least it attracts the fish migrating close to the surface to the fish way. An increase of the mass flow coming from the attraction water pipe might lead to draw fish into the wished direction better. Especially as the models underestimate the mixing behaviour of the flows due to the previous described jet-like behaviour and it therefore can be assumed, that in reality the attraction water flow gets carried away quicker than in the simulations. A big difference to the model of the current situation is the velocity of the attraction water flow in the main channel. It is as fast as the surrounding fluid and faster than the flow close to the channel boundaries.

## 11.2. Angle of 20°

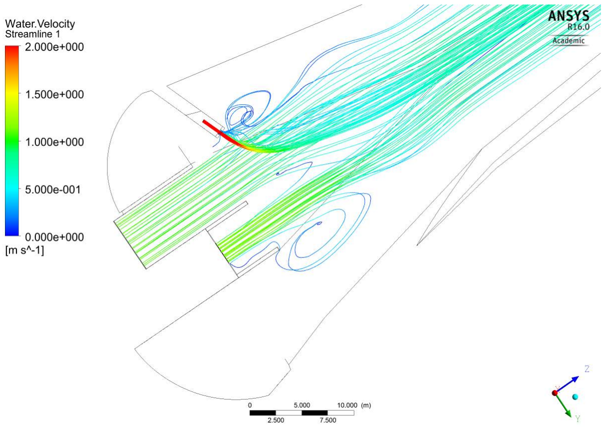
By rotating the fish way and the appendant attraction water pipe the water does not hit the surface as hard as it does if it crosses its flow way perpendicularly. This leads to a smaller influence close to the turbines.



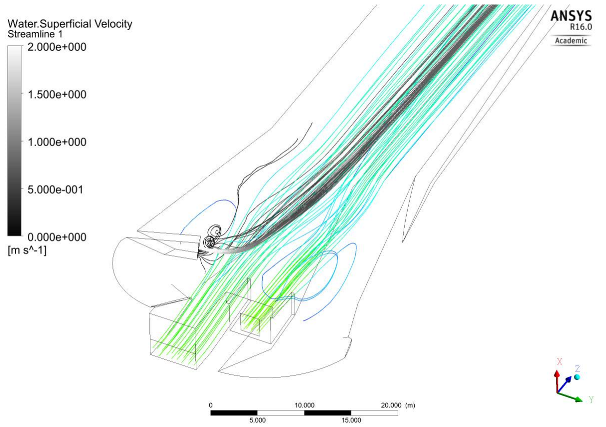

(a) Volume rendering of superficial flow velocity of water.




(b) Volume rendering of superficial flow velocity of water.




(c) Streamlines of the superficial flow velocity of water.



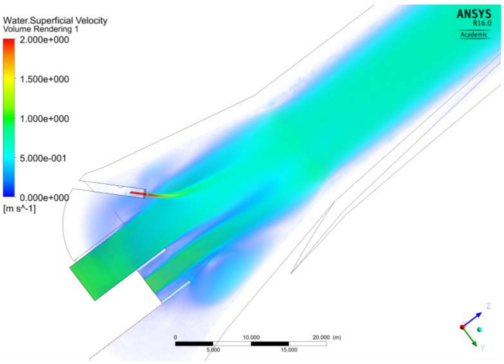

(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow are coloured in grey scale.

Figure 11.3.: Results of model with the fish way moved 5 m downstream and is placed with an angle of 20° to the main flow.

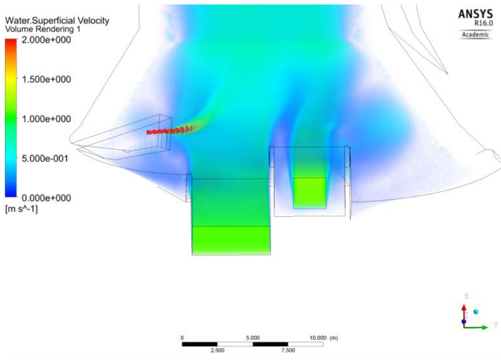
As can be seen in the above figures, through the angle the flow is less slowed down than if it flows into the tail race channel further upstream. Hence, it has a greater velocity further downstream and therefore a greater impact on the fish behaviour. In respect of the velocity, a change of angle at the same place doesn't seem to have a huge influence on the result (comparison with chapter 11.1). The water from the fish way is carried to the middle of the channel, close to the surface. Thus, fish swimming in the main stream close to the surface might be led to the entrance of the fish way, the rest will swim towards the turbines. As the attraction water is carried away soon after entering the main channel, it can be assumed, that this effect is increased in reality, but that the result is basically the same.

## 11.3. Angle of 45°

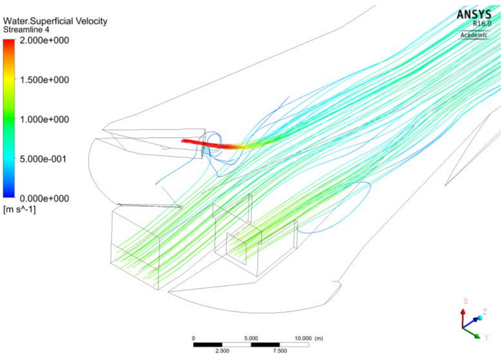
In chapter 10.3 it is suggested that an angle of 45° is to prefer to smaller ones. Therefore this angle is examined at the new place as well.



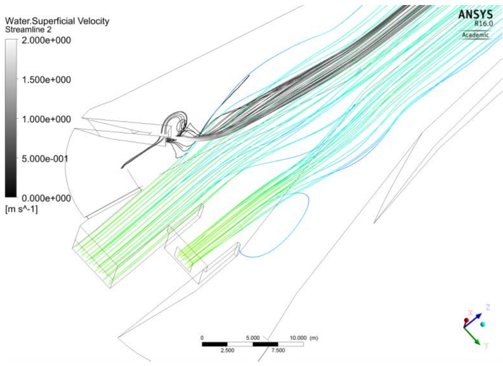

(a) Volume rendering of superficial flow velocity of water.




(b) Volume rendering of superficial flow velocity of water.




(c) Streamlines of the superficial flow velocity of water.




(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow are coloured in grey scale.

Figure 11.4.: Results of model with the fish way moved 5 m downstream and is placed perpendicular to the main flow.

The effects of the increased angle are similar as described in the previous section. However, as it is increased so much, the water sticks to one side and does not mix with the flow coming from the Streamdiver. Again, this effect is expected to be the same or even increased in reality. Therefore only fish swimming in this half of the channel will be attracted by the attraction water pipe. However, because of an angle this big the flow can almost continue its course without having to change direction much. Thus, it is not as much slowed down when hitting the water surface as it is in cases with smaller angles. It seems that at the new placement, an angle of 0° or 20° is to be preferred over the one with 45°. The results, however, depend as well on how much the fish way protrudes into the channel. Because of the shape of the channel the outlet of the fish way is closer to the main flow in the original place. The results of the model with an angle of 45° at the current position look more promising then the one moved further downstream, as the flow reaches the middle of the channel.

# 12. Increased Mass Flow

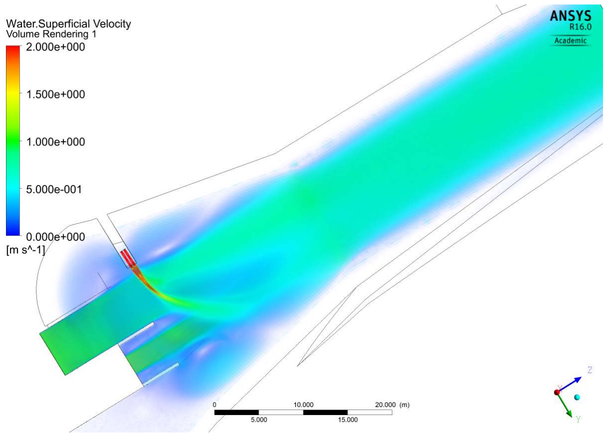
A change in the attraction water mass flow is a promising option. The easiest way of doing so is to install a second attraction water pipe next to the current one. It increases the impact of the attraction water. Furthermore, the installation of an additional attraction water pipe is relatively simple and therefore the effort is contained.

The effect of increased attraction water flow is examined at the downstream position. This way, the wall between the outlets does not have any impact on the fish way efficacy. As in the previous chapter, three different angles are looked at in order to find the best version and the water level is at 35.5 m.

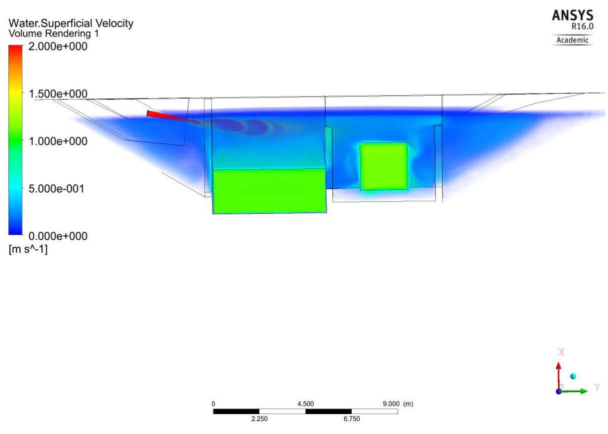
Like in the previous models, the inlet conditions are:

- Inlet G3: $13 \times 10^3\,\mathrm{kg\,s^{-1}}$
- Inlet Streamdiver: $6 \times 10^3\,\mathrm{kg\,s^{-1}}$
- Inlet fish way: $181\,\mathrm{kg\,s^{-1}}$
- Inlet attraction water pipes : $300\,\mathrm{kg\,s^{-1}}$ each

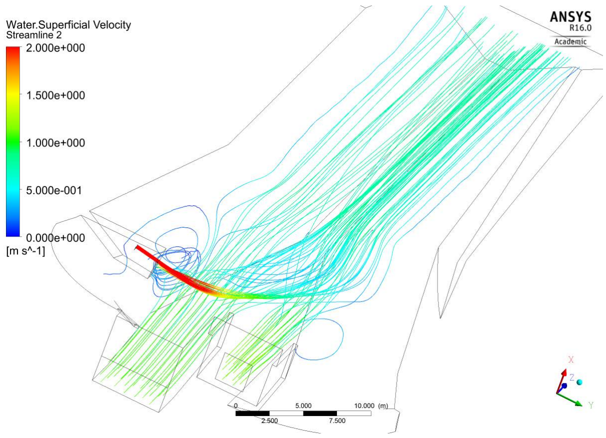
## 12.1. Angle of 0°, 2 pipes



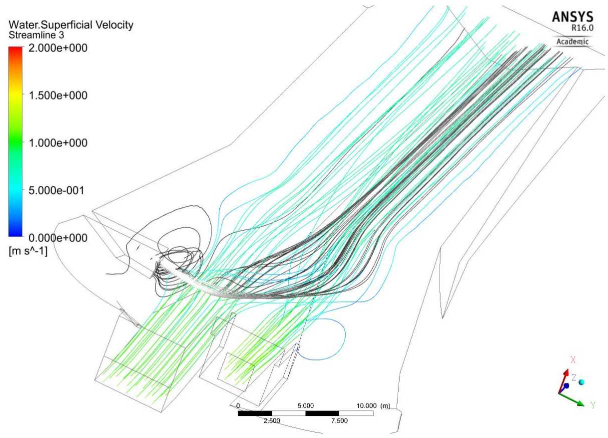

(a) Volume rendering of superficial flow velocity of water.




(b) Volume rendering of superficial flow velocity of water.




(c) Streamlines of the superficial flow velocity of water.

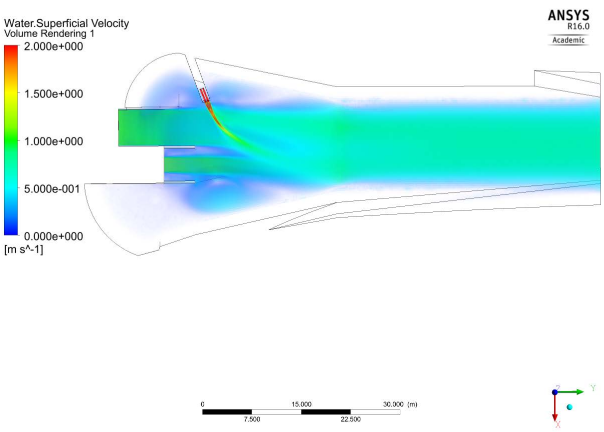



(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow are coloured in grey scale.

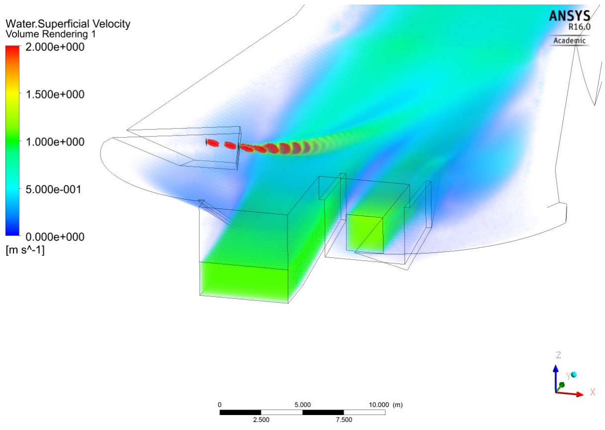
Figure 12.1.: Results of model with the fish way moved 5 m downstream and is placed perpendicular to the main flow. Two attraction water pipes with a flow of $300\,\mathrm{kg\,s^{-1}}$ each are installed.

If the fish way is reinforced with a second attraction water pipe of the same dimensions, its efficacy is enlarged as the flow is not carried away so quickly. The difference to only one attraction water pipe is clearly visible. As it hits the other side of the channel even though the flow coming from the turbines is at its maximum, a rotation of the fish way with more alignment to the general flow direction might bring some improvement. However, if it is taken into account that the attraction water is carried away faster in reality than in the model, this arrangement might be the optimum. Interesting to see is that the attraction water flow not only remains close to the surface but is as well deeper down closer to the bottom. Concerning the flow velocity the attraction water soon reaches the same as the surrounding fluid. In figure 12.1(c) it even seems as if the flow from the pipe is slightly faster than the main flow.

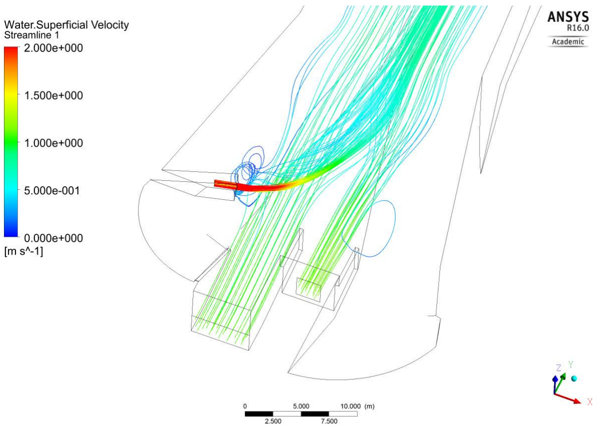
## 12.2. Angle of 20°, 2 pipes



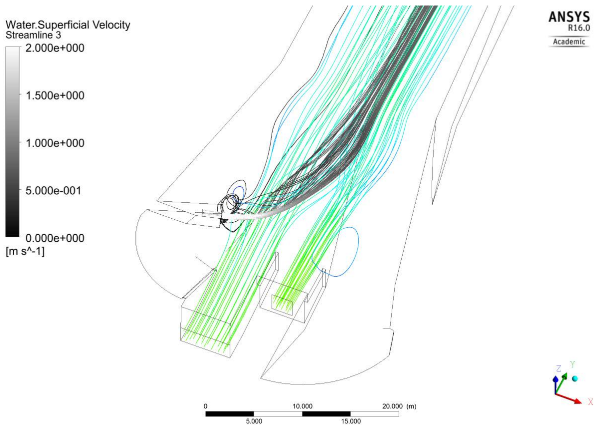

(a) Volume rendering of superficial flow velocity of water.




(b) Volume rendering of superficial flow velocity of water.




(c) Streamlines of the superficial flow velocity of water.

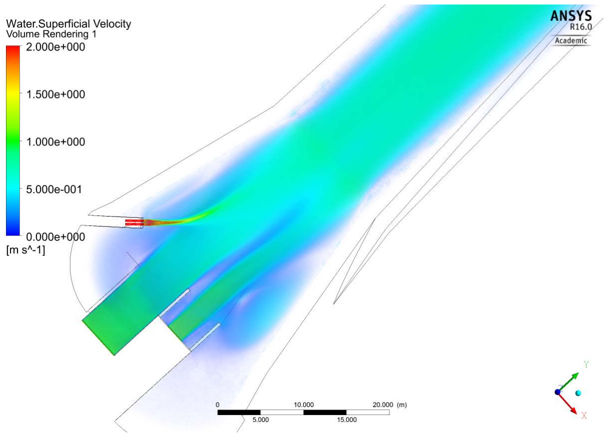



(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow are coloured in grey scale.

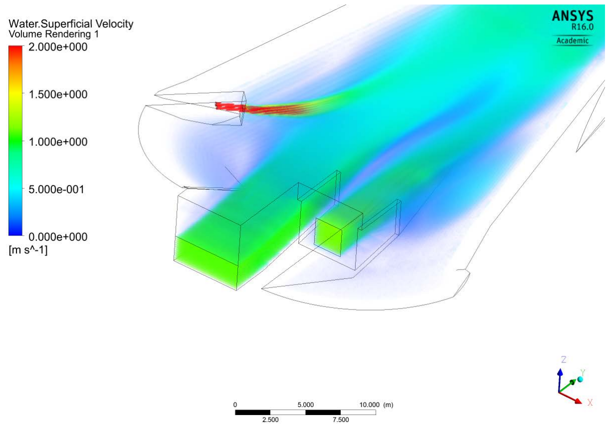
Figure 12.2.: Results of model with the fish way moved 5 m downstream and is placed perpendicular to the main flow. Two attraction water pipes with a flow of 300 $\mathrm{kg\,s^{-1}}$ each are installed.

Compared to the case with 0° the attraction mass flow seems to be more compact when the angle is increased to 20°. However, these two situations have in common that parts of the attraction water is closer to the bottom of the channel than in the cases with only one attraction water pipe. Results for the current model indicate a strong attraction water flow in the centre of the channel. As this is reached although the flow is carried away from the main flow soon after entering the channel, the results are assumed to be realistic. This kind of placement of the fish way promises a good efficacy. The only drawback is that the positioning of a fish way in such a distance to the turbine outlets will make it difficult for fish which follow the turbine flows to find the entrance.

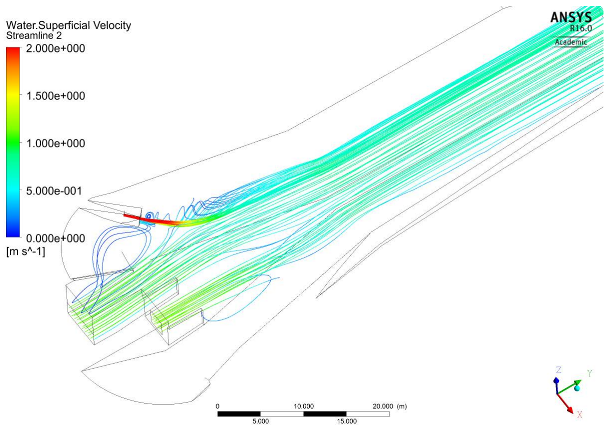
## 12.3. Angle of 45°, 2 pipes



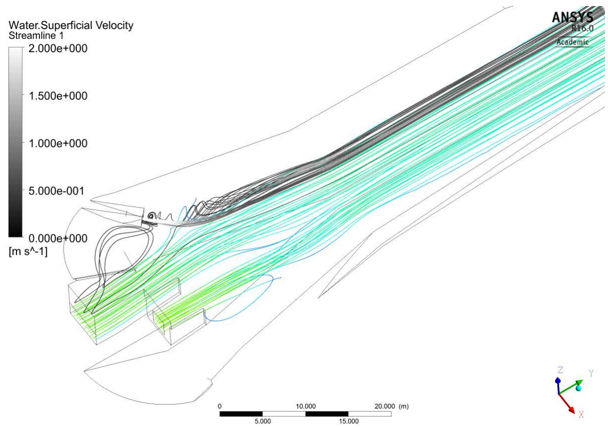

(a) Volume rendering of the superficial flow velocity of water.




(b) Volume rendering of the superficial flow velocity of water.




(c) Streamlines of the superficial flow velocity of water.



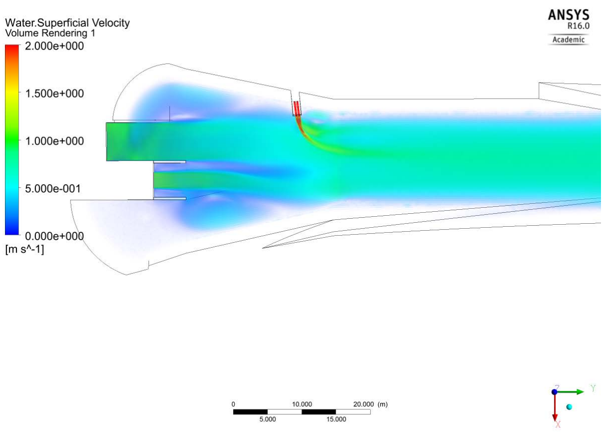

(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow are coloured in grey scale.

Figure 12.3.: Results of model with the fish way moved 5 m downstream and is placed with an angle of 45° to the main flow. Two attraction water pipes with a flow of 300 $\mathrm{kg\,s^{-1}}$ each are installed.

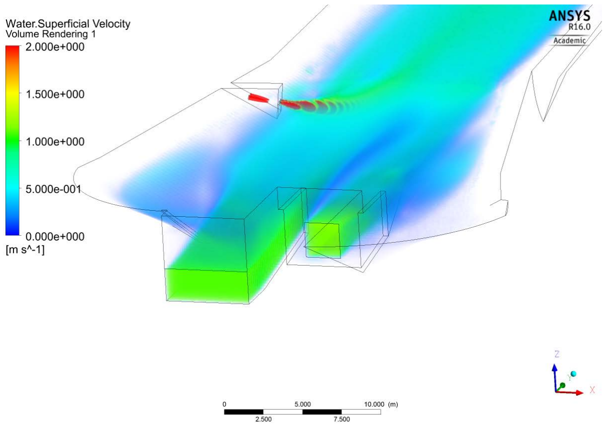
An angle of 45° seems to be too large for the flow to reach the middle of the channel. It remains on the side it flows into the tail race. This effect has already been observed in the case with only one attraction water pipe (see chapter 11.3), and is increased in this case. The desired improvement expected by adding an extra attraction water pipe is unmet. The velocity of the flow remains high close to the bench. However, this attracts only fish swimming there. Because of the closeness to the channel boundaries, the attraction water keeps close to the surface, as the channel is not as deep close to the bench as in the middle.

# 13. Further Downstream

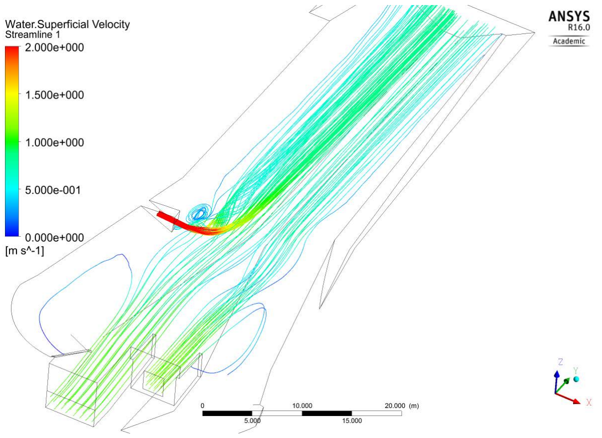
At last the fish way is moved further downstream and has now a distance to the original position of 20 m. The water from the fish way and the two attraction water pipes flows perpendicularly into the main channel. Like in the previous models, the mass flows are chosen as follows: G3: $13 \times 10^3\,\mathrm{kg\,s^{-1}}$, Streamdiver: $6 \times 10^3\,\mathrm{kg\,s^{-1}}$, fish way: $181\,\mathrm{kg\,s^{-1}}$ and attraction water: $300\,\mathrm{kg\,s^{-1}}$ each. The water level is at 35.5 m.



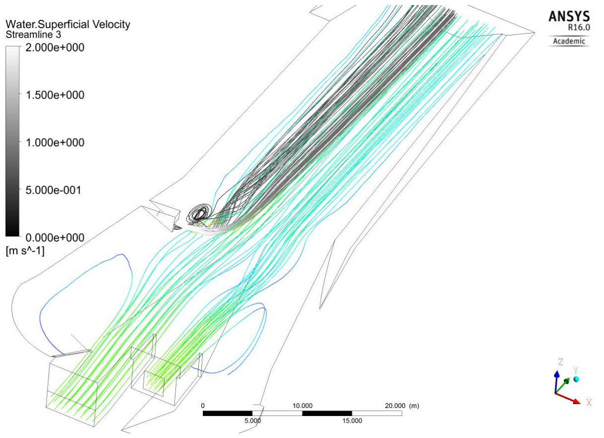

(a) Volume rendering of superficial flow velocity of water.




(b) Volume rendering of superficial flow velocity of water.




(c) Streamlines of the superficial flow velocity of water.




(d) Streamlines of the superficial flow velocity of water. Attraction water and fish way flow are coloured in grey scale.

Figure 13.1.: Results of model with the fish way moved 5 m downstream and is placed perpendicular to the main flow.

In contrast to all previous models the velocity of the attraction water is for the first time noticeably higher than than the water coming from the turbines. The results in chapter 12 also pointed in this direction, but the difference was less clear. However, the attraction water is carried away by the main flow instantly after hitting the surface and therefore remains on the same side from which it enters the tail race channel. Moving the fish way further into the tail race channel should lead to a situation in which the attraction water flow covers the upper part of the whole channel, not only on one side. According to the results received by the model, the attraction water flows into the main channel at the same location in which the two turbine flows become one flow.

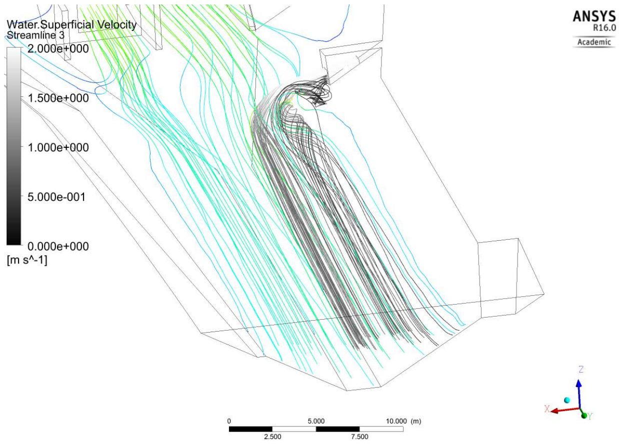



Figure 13.2.: View on the outlet. Streamlines of the superficial flow velocity of water. Attraction water and fish way flow are coloured in grey scale.

At the outlet the attraction water as well as the water from the fish way cover only the upper half of the channel (and, as mentioned above, only on one side). The main difference to the results received for the cases with a fish way further upstream is, that the flow is carried away as soon as it enters the tail race channel. And this despite the reinforcement with a second attraction water pipe. The main flow in the model seems to have reached the surface of the flow entirely at the location of the fish way.

One big disadvantage of positioning the fish way that far downstream of the turbines is that fish, which don't find the entrance at once when migrating upstream, will probably look close to the turbines for a way to move pass them. According to M. Larinier «fish tend to travel as far upstream as possible, until they are prevented from passing further by either a fall or water velocities which are so high that they are impossible to pass, or else by extreme turbulence. It is therefore advisable to install the entrance to the fishway as close as possible to the most upstream point or line reached by the migrating fish.» [6] As this thesis is held strictly technical, no conclusion can be drawn which is more important, to be close to the turbine outlets or to be able to have a better attraction of the fish to the fish way.

# 14. Weaknesses and Future Work

The present thesis, i.e. the underlying simulation model, is based on assumptions and simplifications made in order to achieve a computable model. To formulate suggestions for future work on the same model or for similar cases, the weaknesses of the current model need to be stated.

## 14.1. Model Weaknesses

- **Jet Stream:** The inlets are defined as mass flows perpendicular to the corresponding faces. Although a high turbulence intensity is chosen, the flows exhibit a jet-like behaviour and don't mix as fast as desired with the surrounding fluid.
- **Inlet Conditions:** Related to the first point mentioned is the weakness of the inlet conditions. The flow is assumed to have an even mass distribution over the inlets surface as well as only velocity components normal to the inlet.
- **Geometry:** Based on the drawings provided by Skellefteå Kraft the geometry has been set up and complemented by measurements. Still, it is simplified and replaces e.g. the stones in the river bed by a sand-grain roughness parameter which moves the wall virtually to half-roughness.
- **Turbulence Model:** Having chosen the Baseline Reynolds Stress turbulence model, improvements concerning changes in strain rate compared to two-equation models can be expected. However, it does not manage to model eddies and their detachment as accurate as the Detached Eddy Simulation turbulence model or models related to it. These might bring improvement to the results, as well as longer computing time.
- **Fish Behaviour:** In the present thesis it is assumed that all fish orient themselves only after the highest flow velocity. As wildlife usually is not as simple as that, the behaviour of the fish and how exactly they find the right path can be further investigated.
- **Verification:** Whether or not the improvements show the desired results can only be determined by observing the fish on site after changing the fish way.

## 14.2. Influence of Spill Water

A big part being left out in this thesis is the influence of the spill water in spring, which is needed for the fish migrating downstream. According to Rivinoja (see [10]) wild smolts are assumed to migrate downstream in May and June. Spill water is needed in that time period for them to be able to swim seawards. In the current case that water is spilled from above the turbine «Streamdiver» with $2\,\mathrm{m}^3\,\mathrm{s}^{-1}$.

A water fall of $2\,\mathrm{m}^3\,\mathrm{s}^{-1}$ right after the outlet of the turbine could lead to a breakup of the surface flow. How deep the influence of this vertical water flow is noticeable is difficult to say. However, as the flow from the turbine moves almost horizontally it can be expected that the spill water increases the turbulence intensity hugely as it hits it perpendicularly. This contributes to a breakup in the jet-like behaviour and part of the turbine flow is forced to spread to the side. It can therefore be assumed that the spill water, despite increasing the amount of water flowing downstream, will increase the efficacy of the fish way because it breaks up the flow coming from the Streamdiver.

## 14.3. Future Work

- As mentioned above, a change in the model settings can bring more accurate solutions (e.g. the use of another turbulence model).
- Examine the influence of having several fish ways. A possible combination is one fish way next to the turbine outlets and one further downstream. Another combination is to have one fish way on each side of the tail race channel.
- More knowledge of how fish orient themselves and their behaviour in general helps in finding an ideal way of constructing fish ways and attraction water pipes. This is of course dependent on the kind of fish concerned and therefore as well the location of the studies.
- Change the current construction of the fish way in order to improve its efficacy.

## 14.4. Recommendation

According to the literature, an entrance of the fish way should be as far upstream as possible. The results of the simulated models, however, show that a fish way further downstream increases the efficacy of the fish way. Therefore the best solution would be a fish way with two entrances: one close to the turbine outlets, and one further downstream. The one close to the turbines needs to have the entrance area in a tranquil zone and at a place which is accessible from the whole channel easily. Further downstream, the second fish way encloses an angle of 20° to the perpendicular position, and is reinforced with a second attraction water pipe.

# 15. Summary

**Literature:** The ideal fish way is positioned slightly upstream or level with the turbine outlets. It is close to the bench in a tranquil zone. The velocity of the attraction water in the channel is higher than the one of the surrounding fluid.

**Influence Streamdiver:** Because of the wall between the outlets of the two turbines, the installation of the «Streamdiver» has hardly any impact on the efficacy of the fish way and its attraction water. Especially as the Streamdiver is on the opposite side of the channel as well compared to the fish way. The attraction water is carried away by the main flow when the mass flow coming from G3 is high. And when it is low, the attraction water will be blocked by the wall. However, the flow coming from the «Streamdiver» might entice the fish away from the fish way.

**Influence Angle:** From the simulation results it can be concluded that the more the fish way is aligned to the main flow the more the velocity of the attraction water is maintained. However, the flow is better distributed over the channel if the fish way protrudes perpendicularly into it. Therefore an angle of 20° (to the current placement) is recommended. With an angle of 45° the fish way should protrude more into the channel which contradicts recommendations found in the literature study which state that the fish way should be as close to the bench as possible. If the fish way is placed perpendicularly to the flow the speed gained in the attraction water pipe is reduced too much after entering the channel.

**Influence Position:** It has to be taken into consideration that a displacement further downstream increases the probability that fish migrating upstream find the entrance of the fish way. However, if the fish have passed the fish way without entering it, it is less likely that the fish will move downstream in order to find the entrance. In such a case, a fish way closer to the turbines would have a higher chance of being found. The current position of the fish way, however, is not recommendable. On one hand the reason for that lies in the wall that blocks the attraction water flow. On the other hand the turbulences right by the fish way entrance contradicts recommendations from literature.

**Influence Mass Flow of Attraction Water:** When the mass flow of the attraction water is increased then so is its impact on the main flow in the channel. Therefore the installation of a second attraction water pipe can be recommended, especially because this can be realised without many difficulties.

**Recommendation:** In order to improve the efficacy of the fish way on site, it would be best to have two entrances: one close to the turbines in a tranquil zone (for example next to the outlet of «G3») and the second one further downstream to avoid the wall and attract fish from the whole channel. The second entrance ought to have a angle of around 20° to the perpendicular position. Increased attraction mass flow is recommendable (e.g. installation of a second pipe).

# 16. List of Figures

# 17. List of Tables

# 18. Bibliography

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# 19. Declaration of Authorship

### Declaration

I hereby certify that this thesis has been composed by me and is based on my own work, unless stated otherwise. No other persons work has been used without due acknowledgement in this thesis. All references and verbatim extracts have been quoted, and all sources of information, including graphs and data sets, have been specifically acknowledged. This thesis was not previously presented to another examination board and has not been published.

### Place, Date

Luleå, 05.02.2017

### Signature

Zoe Memphis Stadler

# A. Task Description

### Subject: Influence of a Hydro Power Plant on Upstream Fish Migration

| | |
|---|---|
| Student: | Zoe Stadler |
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### Short Description

In Robertsfors, Sweden, the water flow behaviour downstream of two turbines, owned by Skellefteå Kraft, is to be examined. Special focus lies on the water flow coming from the fish way and its influence on the flow field. It shall be determined whether the current situation is well enough for a working upstream fish migration or if the fish are more attracted to the outlet of the turbines. Additionally improvement possibilities, e.g. the placement of the fish way, are to be examined.

### Tasks

- Carry out measurements on site.
- Create a model of the current situation.
- Verification of the model using the measurements.
- Examination of different mass flows in the attraction water pipe.
- Examination of different angles of fish way and attraction water pipe.
- Examination of different placements of fish way and attraction water pipe.
- Suggest possible steps for improving the situation.

### Expected Results

- Analysis of the current situation.
- Weaknesses of the models.
- Suggestions of improvements.