A numerical study of the location and function of the entrance of a fishway in a regulated river

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Abstract: Simulation driven design with Computational Fluid Dynamics has been used to evaluate the flow downstream a hydropower plant with regards to upstream migrating fish. Field measurements with an Acoustic Doppler Current Profiler were performed and the measurements were used to validate the simulations. The measurements indicate a more unstable flow than the simulations and the tailrace jet from the turbines is stronger in the simulations. The simulations are however considered to capture the important features of the flow in a way that makes them viable for attraction water simulations. A fishway entrance was included in the simulations and the subsequent attraction water was evaluated for two positions and two angles of the entrance at different turbine discharges. Results show that both positions are viable and that a position where the flow from the fishway does not have to compete with the flow from the power plant will generate superior attraction water. Simulations were also performed further downstream where the flow from the turbines meets the old river bed which is the current fish passage for upstream migrating fish. A modification of the old river bed was made in the model as one scenario to

generate better attraction water. This considerably increases the attraction water although it cannot compete with the flow from the tailrace tunnel.

Keywords: Fish migration, CFD, ADCP, validation, river flow

Introduction

Studies of tagged Atlantic salmon and sea trout in the river Vindelälven in northern Sweden during 1995-2005 have shown that only a third of the upstream migrating fish find their way to their natural spawning grounds (Lundqvist et al, 2008). The main reason for this is the Stornorrfors power plant. A major issue is that the fish are attracted into the tailrace channel rather than migrating up through the old river bed that offers a fishway around the turbines. The flow rate from the turbines is typically 20 times larger than the flow rate from the old river bed. The entrance from the old river bed into the confluence with the water from the turbines is very wide resulting in an overall low impact of the water from the old river bed. The fact that migrating fish are attracted to the tailrace of the turbines instead of the weaker current from the fishway is a common problem (Arnekleiv and Kraabøl, 1996; Webb, 1990). The problems upstream migrating fish come across in regulated rivers in northern Sweden has been examined by e g Lindmark (2008) and Rivinoja (2005).

There are two major measures that are being considered for improving the upstream migration of fish at the Stornorrfors power plant. One is to construct a new fishway from the tailrace channel since a majority of the fish resides there for a long period of time during the migration season (Rivinoja et al, 2001). The other alternative is to create better attraction water from the old river bed into the confluence area. The alternatives are here modeled with Computational Fluid Dynamics (CFD) and the attraction water created using given configurations is examined. The simulations are validated by measurement with an Acoustic Doppler Current Profiler (ADCP). This approach has previously been used by Rakowski et al. (2004) who used field-measured data to validate their CFD simulations downstream Bonneville powerhouse and spillway. The velocities were measured and averaged over a 10 minutes period to get adequate representation of the mean velocity. When comparing the CFD simulations (steady state, k-ε turbulence model) to ADCP data the modeled velocity was slightly lower than the measured, but within the standard deviation of the field velocity. Viscardi et al. (2006) also used ADCP measurements to validate CFD simulations (steady state, k-ε turbulence model, rigid lid, bed roughness Manning $n = 0.025$). In their case the velocities were averaged over 2 seconds in each vertical sample in order to minimize the effect of the tidal change and the velocities correspond reasonable accurate.

Materials and Methods

ADCP

To measure topology and water velocity downstream Stornorrfors power plant an ADCP was used. The ADCP has four transducers directed into the water. The transducers send out sound waves that reflect on small particles traveling with the water and the transducers detect the Doppler frequency of the returning sound wave, which is proportional to the velocity of the water (particle). ADCP is a relatively fast way of measuring velocities in field and to calculate river discharge. The ADCP used in this case is a RiverBoat RioGrande and the data processing was performed with the software Winriver II, both from RD Instruments.

The bathymetry in the area was measured using two set-ups. The ADCP was dragged besides a motorboat with a pole and rope, which enabled measurements close to the shoreline. By combining the bottom-tracking feature of the ADCP with GPS data, a point cloud consisting of ADCP provided depths at specific satellite coordinates was obtained. The ADCP however fails to find the bottom of the deepest area in the tailrace channel, hence a SIMRAD EY60, GPT 200 kHz, split beam echo sounder with the transducer mounted vertically on the boat was used near the tailrace tunnel outlet. The points of measurements are shown in Figure 1.

A steel wire was stretched across the tailrace channel and the ADCP was tethered to it. A manual winch enabled the ADCP to travel across the channel and capture the velocities in the entire cross-section. The transect, T2 in Figure 1, was measured on several occasions at different turbine discharges and a minimum of four times at each flow. To validate the accuracy of the ADCP, three vertical profiles in the T2 transect were measured during 1800-2000 s. The profiles were collected when the flow rate through the power plant was 570 m^3/s (according to the discharge calculation in WinRiver). Profiles were measured with a time difference of 0.95 s between ensembles. During measurements the distance to the shore was measured with a laser distance meter. The total width of the section was measured to 39.7 m and the profiles were located at 16, 23 and 32 m from the south shore.

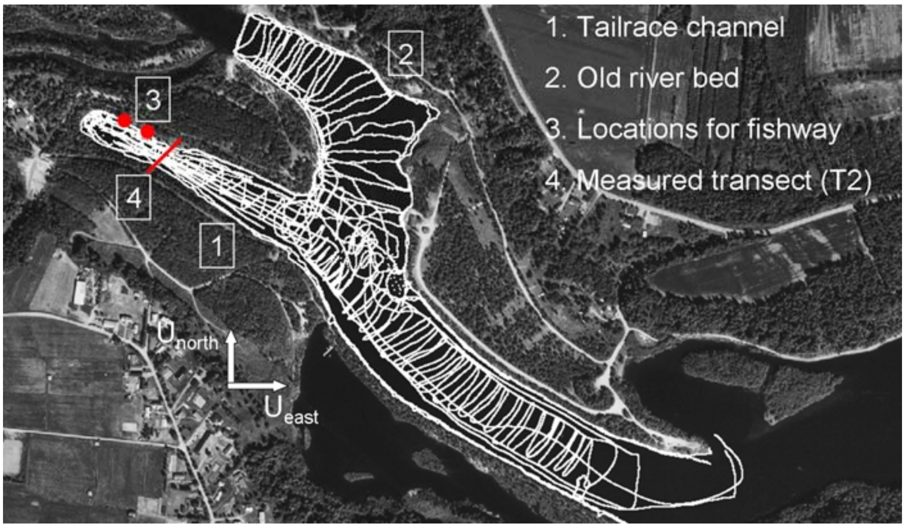

Figure 1: Aerial photograph of tailrace channel and confluence area downstream Stornorrfors power plant. White lines (points) represent data points used in geometry creation.

The accuracy of the ADCP depend on many factors, such as side-lobe interference, ringing, ADCP-flow interaction that exclude the ADCP from doing any measurements near the water surface or close to the bottom of the river (Simpson and Oltmann, 1993). Nystrom et al. (2007) compare ADCP accuracy with an Acoustic Doppler Velocimeter (ADV) in a lab flume with a turbulence intensity of 0.1. The ADCP measured during 15 min and the error was less than 3 % in the areas away from the boundaries not affected by ringing, side lobe interference and flow disturbance.

Numerical set-up

The point cloud collected with ADCP and SIMRAD seen in Figure 1 was converted to a bottom surface in the software Imageware 13. The surface was imported to Ansys Icem Cfd 11 where a solid model was created. The formed model was divided in two parts, the tailrace channel and the confluence area between the channel and the old river bed. The simulation volumes were discretized as tetrahedral elements in the CFD-model. Local refinements of the grid were carried out in areas of simulated attraction water to increase the resolution in the most interesting parts of the flow. The final grids for the tailrace channel consisted of ~500k nodes and the confluence area of ~600k nodes. Because of the time dependence of the flow the simulations had to be run on a transient solver which led to long calculation times, although a 150 node cluster was used. This is the main limitation for the mesh sizes. A full mesh study was not performed but the meshes are believed to capture the main features of the flow in a good manner.

In reality, the water from the power plant goes through an approximately 4 km long tunnel before entering the tailrace channel. To create a realistic inlet boundary condition for the simulations, this tunnel was modeled separately and the velocity profile at the end of the tunnel was used at the inlet of the tailrace channel simulations. The tunnel was given a sufficient length to give a fully developed velocity profile and the tunnel walls were given a wall roughness of a typical excavated rock. All simulations were run with the k-ε turbulence model with scalable wall functions and the high-resolution advection scheme. The high-resolution scheme uses a close to second order solution in areas with low variable gradients and in areas where the gradients change sharply it will be close to a first order solution (Ansys, 2007). The RMS residual target for all simulations was set to 10^{-6}. The effects of water temperature were not considered in the numerical investigation. The water surface was modeled as a rigid lid with zero friction. This approximation is viable when the surface level variation is smaller than 10% of the total channel depth (Rodriguez et al., 2004). Rigid lid simulations has been used to improve conditions for downstream migrating fish (Lundström et al, 2010), it has also been compared with free surface simulations and scale model attempts showing good results (Andersson et al, 2010). One important parameter in simulations of natural channels is the roughness of the bottom surface. Since this parameter is troublesome to measure in reality, a parameter study was performed in the numerical model.

Modifications to create attraction water

Two ways of improving the upstream fish migration around the power plant were studied: a new fishway in the tailrace channel and higher attraction to the old river bed. In the tailrace channel two positions and two angles of a new fishway entrance was studied. The positions were selected from previous observations of fish during the migration season. The dimensions of the entrance were 2 x 2.7 m^2 and the flow rate used was 10 m^3/s. The two inlet angles of the fishway entrance were; perpendicular and 45° to the main flow.

To modify the confluence area to improve the attraction to the old river bed a wall was added at a distance from the beach and all the flow in the old river bed is directed to the narrow open channel between the wall and the shoreline. The old river bed leads to a fishway at the power plant dam. The flow in the old river bed was set to 20 m^3/s and that from the tailrace tunnel to 350, 750 and 1000 m^3/s, representing a low flow, a normal flow and a flow close to the maximum flow, respectively.

Results and Discussion

With no surface roughness the jet leaving the tunnel barely leaves the bottom of the channel which does not seem likely with regards to the characteristics of free surface channel flow, see Figure 2. With a surface roughness of 0.3 m (Manning $n \approx 0.033$) which can be considered typical for a man made channel such as the tailrace channel (Arcement, jr and Schneider 1989), the velocity profile in the channel gives a more developed profile. Increasing the wall roughness length to 0.5 m (Manning $n \approx 0.037$) did not affect the solution in any major way and all following simulations on the tailrace channel were run with 0.3 m wall roughness.

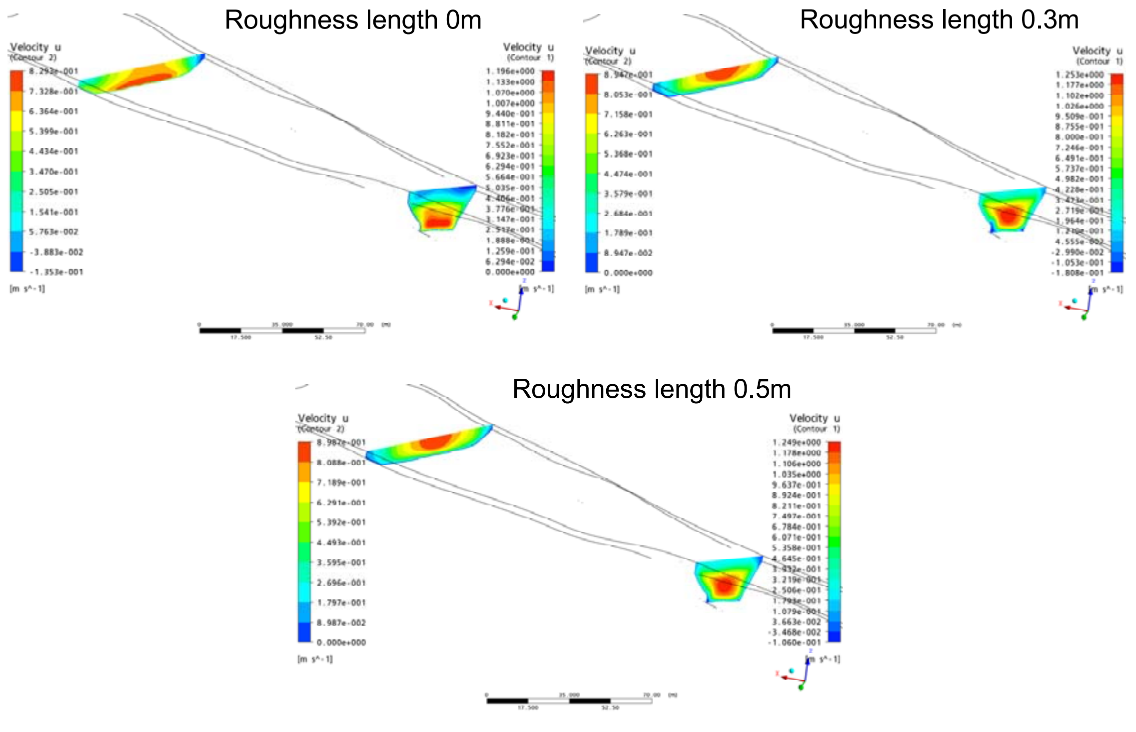

Figure 2: Parameter study of the wall roughness in the tailrace channel showing the development of the velocity profile at two different cross-sections for three different roughness values.

The results from ADCP measurements in the tailrace channel yields an unstable behavior of the flow, see Figure 3 showing a 12 x 12 m^2 section in the middle of the T2 transect where the raw data from the ADCP has been averaged to 1 x 1 m^2 cells. The measurements were taken in succession and the velocities have been normalized with transect average velocity to account for minor differences in total flow. The jet exiting the tunnel is apparently not well defined in these single transects. This time dependence of the flow is examined by keeping the ADCP in the same point and measuring the velocity during a longer time period. Three vertical profiles at 15.5, 22.7, 31.5 m from the south shore (the middle profile was measured twice) was measured. The standard deviation from the mean distance was 0.01 – 0.02 m. The results from the measurements show a highly fluctuating flow. Initial frequency analysis does not indicate any periodicity, however it cannot be excluded that fluctuations are influenced by large scale structures of the flow, originating from upstream instabilities. How the RMS velocity (east) stabilizes with time is shown for the profile at 23 m in Figure 4. From the results it is concluded that to measure representative velocities the profiles must be measured during at least 600 s. The measurements over a complete transect presented in Figure 3 took about 120 s which means that they by no means represent the mean velocity in that transect.

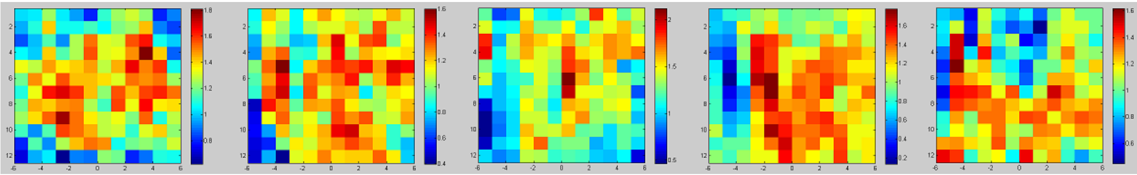

Figure 3: Five individual measurements in the same transect

To validate the simulations the time averaged velocities of the fixed-point measurements are used. In Figure 5 normalized velocity profiles are compared. The velocity is normalized with the bulk velocity $U_{bulk} = Q/A_{T2}$, where Q is the flow rate and A_{T2} is the area of the T2 transect (516 m^2 from the model). The jet that exits the tunnel appears closer to the water surface in measurements than in simulations. It is also much more diffuse in measurements. This is most apparent for the measurements at 32 m where measurements indicate a plug flow while the simulations yield a sinus-shaped profile. Hence there is a discrepancy at the surface and at the bottom. One reason for the differences might be the inlet boundary condition in the simulations, which is described as a stationary velocity profile where in reality effects of the turbines, larger discrete wall roughness elements or sudden changes in discharge may be occurring. Other contributing factors may be difference between model geometry and real geometry and oversimplified modeling of turbulence. It is also likely that the flow field is smeared out by the method to measure the velocity field. The discrepancy between simulations and measurements is a subject for future research as to turbulence intensity, for instance. The simulations are however considered to capture the main features of the flow well enough to function as a base for attraction water investigations.

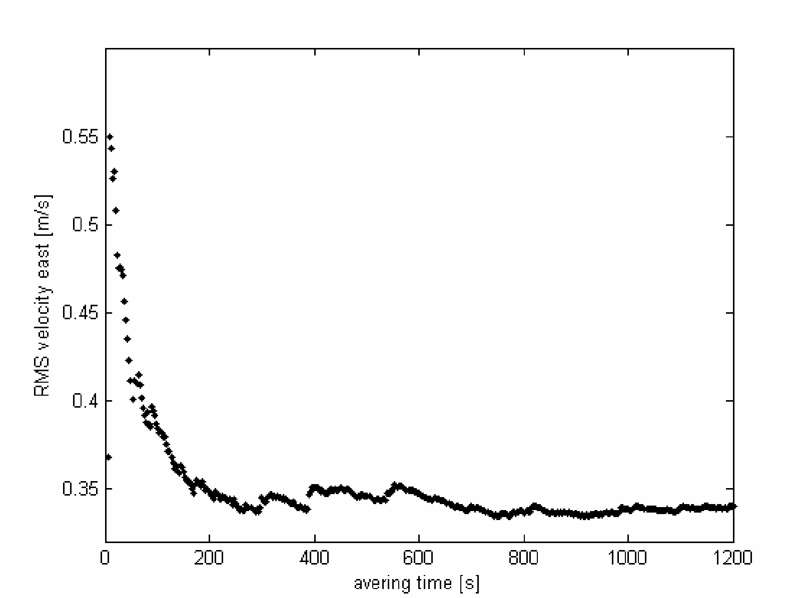

Figure 4: How the RMS of the east velocity component depends on the averaging time. Velocities from the profile 23 m from the south shore at 5 m depth.

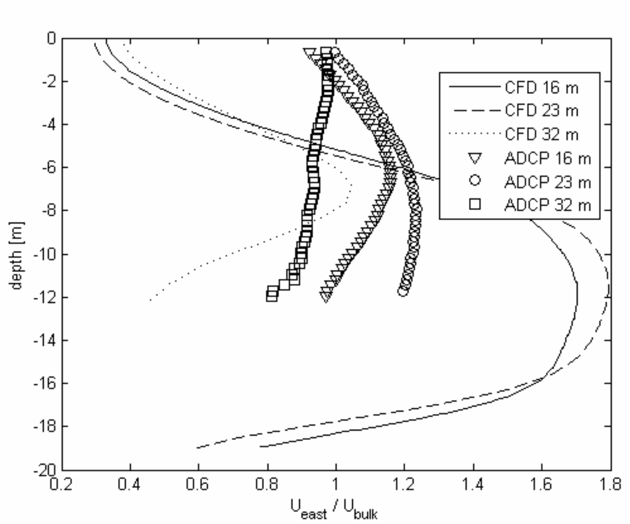

Figure 5: Comparison between vertical velocity profiles in experiments (ADCP) and simulation (CFD). U_{east} is the velocity in the east direction.

Attraction water generation

For position 1 the perpendicular entrance gives a noticeable jet that stretches to the centre of the channel while the angled inlet gives a jet that aligns with the flow from the tailrace tunnel and reaches further downstream, see Figure 6. In reality the attraction water created at this position may be less prominent because of the higher position of the jet seen in the results from the ADCP measurements. Even better attraction water is created at the second position as shown in Figure 7. Since the small jet from the fishway does not collide with the large jet from the tailrace tunnel, the generated attraction water stretches further out in the channel, see Figure 8. Noticeable attraction water was created even at the highest flow (1000 m^3/s) from the turbines, see Figure 9.

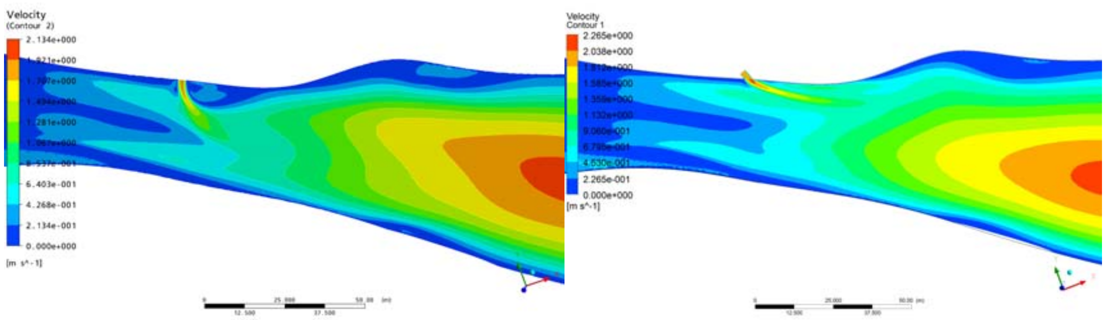

Figure 6: Fishway inlet at position 1 with 0° and 45° angle. The flow rate through the power plant is 750 m^3/s and the velocities are shown at 1 m depth.

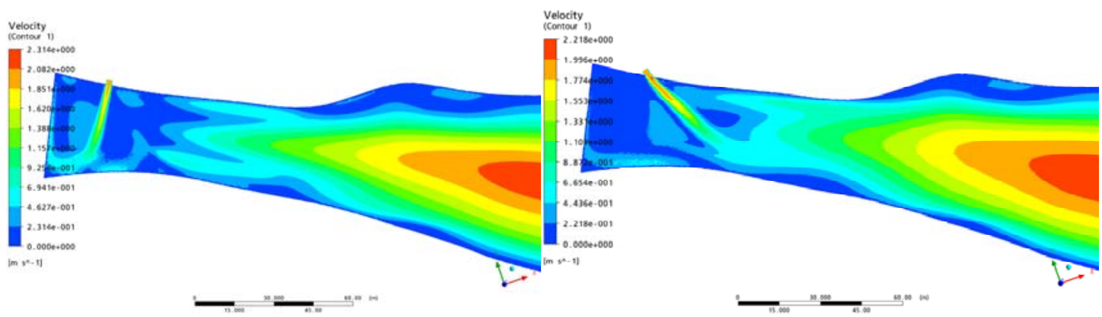

Figure 7: Fishway inlet at position 2 with 0° and 45° angle. The flow rate through the power plant is 750 m^3/s and the velocities are shown at 1 m depth.

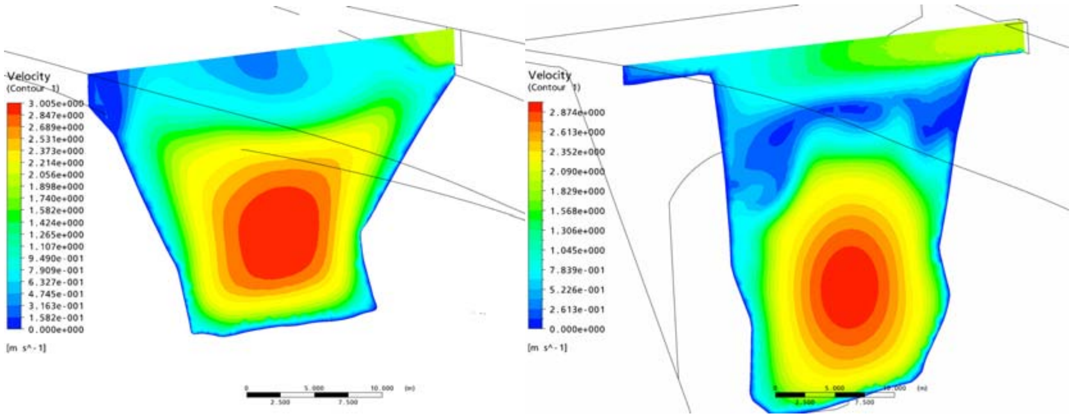

Figure 8: Fishway outlet (upper right corner) at position 1 and 2 with 0°angle. The flow rate through the power plant is 750 m^3/s.

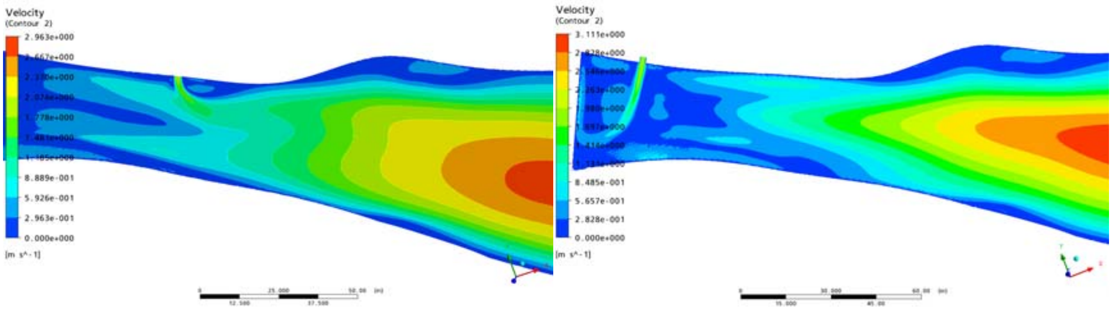

Figure 9: Fishway outlet at position 1 and 2 with 0° angle. The flow rate through the power plant is 1000 m^3/s.

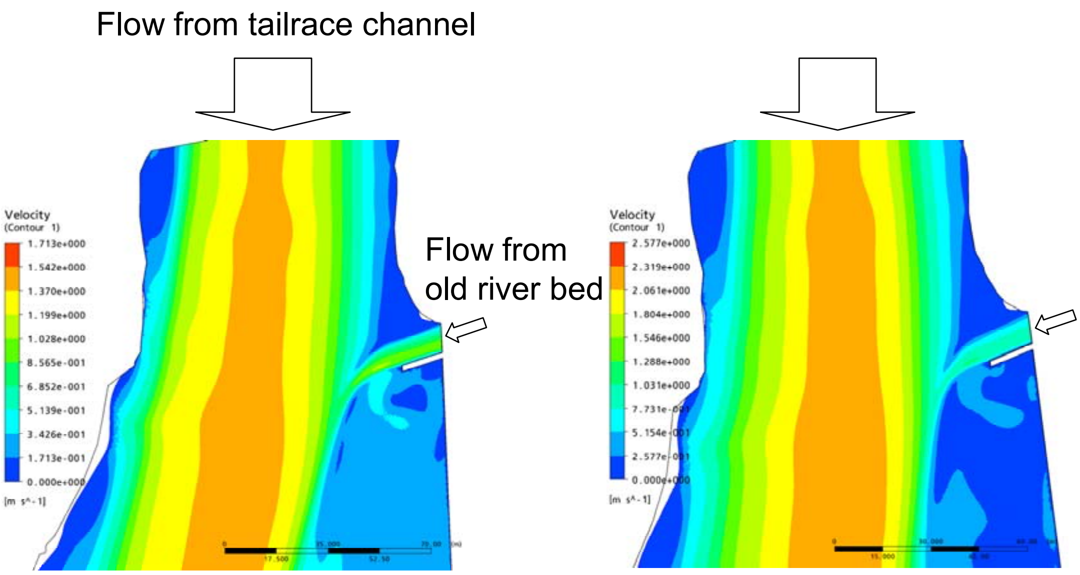

Figure 10: Confluence area with flow rate from the turbines of 500 m^3/s and 750 m3/s and flow rate in the old river bed is 20m^3/s. A wall is inserted 10m from the north shore.

Simulations of the confluence area where the attraction water from the old river bed was improved by adding a wall at a distance from the beach were performed. Figure 10 shows the generated attraction water at two flow rates from the turbines (500 and 750 m^3/s). This modification of the confluence would provide improved attraction water from the old river bed all the way to the main flow from the turbines. This should improve the probability that fish migrating upstream on the north side of the river (right-hand side in the figure) or fish exiting the tailrace tunnel on the north side would find the fish passage in the old river bed.

Conclusion

The measurements indicate a more unstable flow than the simulations and the tailrace jet from the turbines is stronger in the simulations. The simulations still capture the main characteristics of the flow well enough to base attraction water simulations on. A fishway in the tailrace channel can generate noticeable attraction water for all relevant flows from the turbines. Modifications of the confluence area can create better attraction water at certain locations however specific knowledge of the fish behavior in the area is most likely required to ascertain the effect on fish migration.

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