DOWNSTREAM FISH MIGRATION AND INTAKE STRUCTURE OPTIMIZATION – A SYNERGY?

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Abstract

An important aspect of the process of water body restoration deals with the recreation of the flow continuum. This includes enabling the up- and downstream migration of fish, which can be hindered by run-of-river power plants. Currently especially the downstream migration that is vital to the preservation of quite a few European fish species is negatively affected. The revised Water Protection Act introduced in January 2011 in Switzerland demands that the major damages caused by men to the Swiss river ecosystems will have to be rectified within the next 20 years. This is a great challenge for the energy companies and cantons alike.

The Laboratory of Hydraulics, Hydrology and Glaciology (VAW) conducted hydraulic model tests on a future water power station at the Aare River planned to supply the natural river arm with an increased discharge of 40 m^3/s. To facilitate a safe downstream fish migration a horizontal guidance screen with a bypass system was tested. Simultaneously the intake structure was optimized for optimal turbine performance and it was found that both processes went hand in hand. The article gives an overview of the project and presents the hydraulic model test results.

Project overview

The Rüchlig hydropower plant (HPP) is a run-of-river power station at the Aare River operated by the Swiss utility Axpo AG. It consists of two main facilities: the power plant situated in an artificial channel and the weir for flood regulation in the old river course (Fig. 1).

Motivation

In connection with the upcoming renewal of the operating concession the overhaul and extension of the existing power plant, flood protection improvements and the increase of the residual amount of water from 10 to 40 m^3/s were planned. Since this increase of residual water was significant a feasibility study for an additional power plant at the weir in the Aare River was carried out. Several possible variants were suggested, which were then investigated in hydraulic model tests at VAW.

Scope of the investigation

This paper presents the model test results on a residual flow HPP on the left side of the Aare River which is equipped with a fish guidance and bypass system (Fig. 1).

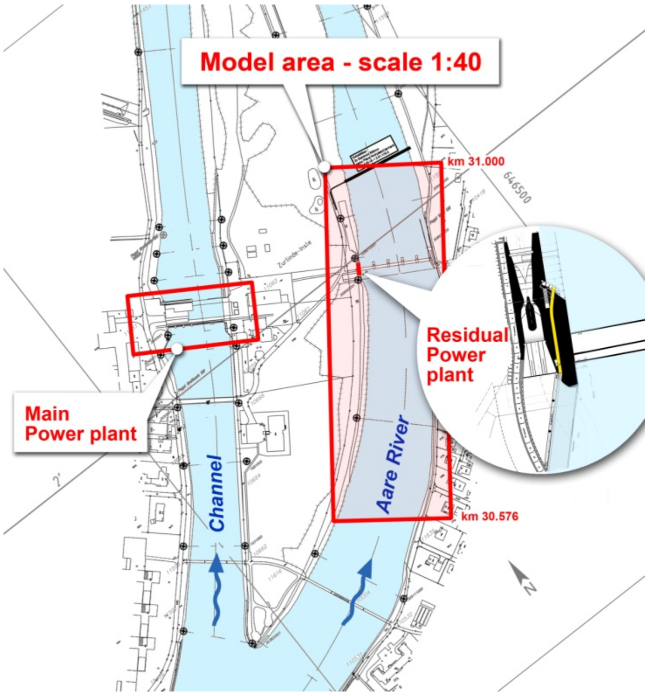

Figure 1: Plan view of the current HPP. The artificial Zurlinden Island in Aarau divides the Aare River into an artificial channel with the existing power plant (left) and the old river course with the Rüchlig Weir (right). The model area for the hydraulic investigation of the future residual flow HPP is marked in red.

Construction details

Figures 2 and 3 show the design details of the new HPP.

It is a typical bay run-of-river plant with the advantage of not constricting the width of the river bed and therefore not affecting the discharge capacity of the neighbouring weir. The plant has one turbine with adesign discharge of 40 m^3/s. The turbine intake is trumpet shaped with a width of 5.75 m and a height of 5.9 m. The power plant intake consists of a curved channel with a plain concrete invert.

To improve the ecological conditions the intake section is shielded by a fish guidance screen leading to a channel used for both downstream fish migration and flushing. This channel is located within the pier dividing the power plant and the weir.

The fish guidance screen is 28 m wide by 6 m high, with horizontal bars having an open spacing of 20 mm and covers the entire cross section of the intake structure.

The migration channel is 1 m wide and has a controlled discharge of 0.5 to 2 m^3/s depending on the upstream water level. The discharge is controlled by two notches in the vertical flap gate that closes the channel to the headwater. Those notches are situated on the ground and directly below the water surface to allow for the passage of fish with different migration preferences. To flush debris accumulated on the screen the flap gate can be fully opened.

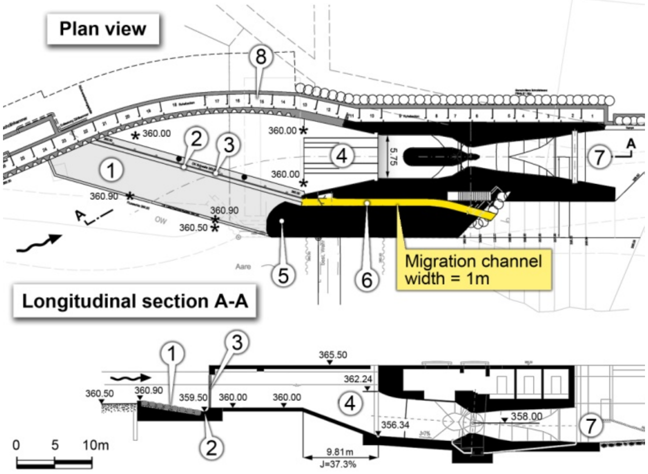

Figure 2: Plan view and cross section of the residual flow HPP: ① gravel barrier, ② blind drain, ③ fish guidance screen, ④ turbine intake, ⑤ intake pier, ⑥ fish downstream migration and flushing channel, ⑦ outlet structure, ⑧ fish upstream migration channel.

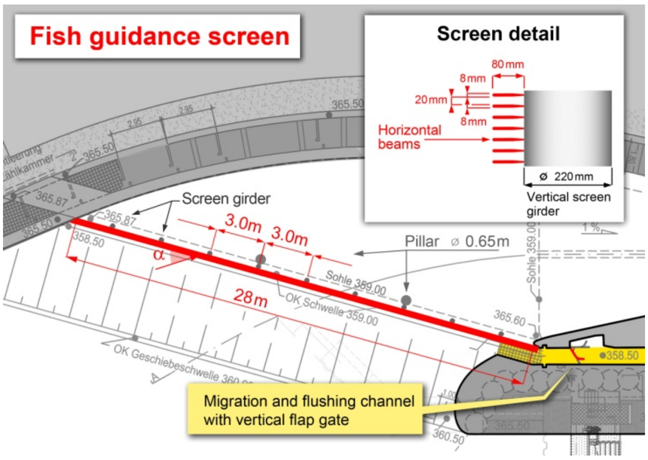

Figure 3: Plan view and cross section of the fish guidance screen with the approach flow angle α.

Project focus

The hydraulic model investigation had two major foci, namely the hydroelectric optimization and the realization of optimal ecological conditions. In detail the following goals had to be achieved:

• Minimizing intake losses and achieving favourable approach flow conditions in front of the turbine intake for the design discharge of 40 m^3/s.

• Adherence to the maximum allowed flow velocities at the fish guidance screen of 0.5 to 0.6 m/s vertical to the screen plane.

• Analysis of the approach flow angle to the screen.

• Analysis of the flow field at the intake area to the migration and flush channel.

• Optimization of the pier geometry to guarantee no flow separation.

• Documentation and prevention of air entraining vortices at the turbine intake.

• Monitoring of water levels, flow velocities and visualization of flow conditions.

• Qualitative analysis of the sediment transport processes in front of the power plant intake.

Hydraulic model

The existing Rüchlig Weir, the planed residual flow HPP with fish guidance screen and channel as well as the Aare river bed were modelled at VAW at a scale λ of 1:40 (see Fig. 1 for the model perimeter and Fig. 4 for an overview).

Experimental setup

The hydraulic model represented a 290 m long river section upstream of the power plant and the weir by taking into account the left turn of the Aare River which thereby allowed for the accurate reproduction of the approach flow conditions.

The river morphology was modelled with mortar with a surface roughness comparable to the natural roughness of the Aare River bed. The power plant, weir and guidance structures were built using PVC and brass (Fig. 5).

Measuring equipment and test setup

Hydraulic parameters were determined using the following measuring technics:

• Incoming and outgoing discharges were measured by magnetic flow meters and precision pumps, while the discharge in the migration and flush channel was determined via a gauging weir.

• Ultrasound probes and point gauges were used to collect data on the water levels at crucial locations in the reservoir.

• Flow velocity fields were recorded using ADV probes.

• Additionally the visual inspection of the flow conditions was enhanced by either colouring the water or adding confetti to illustrate large scale surface flow structures.

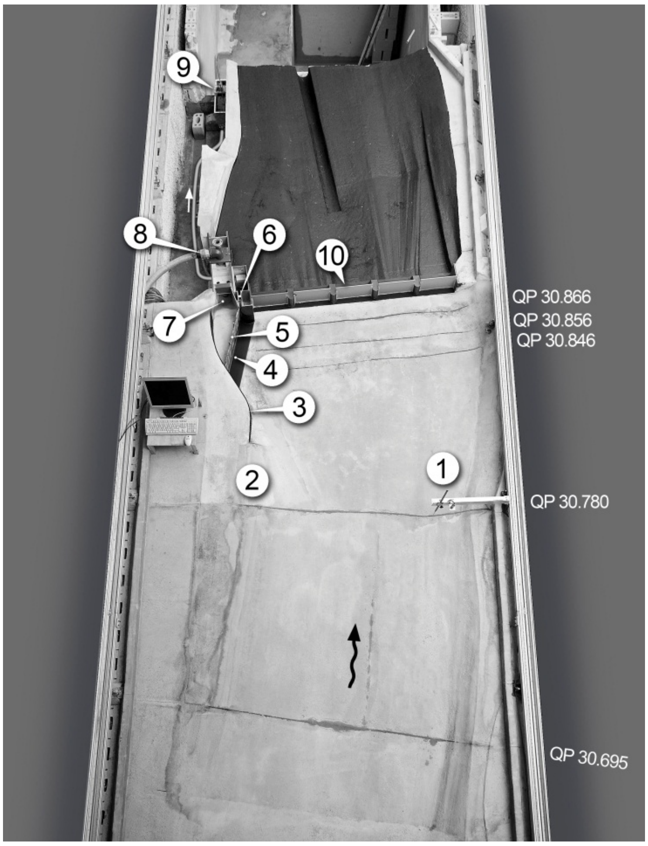

Figure 4: Plan view of the hydraulic model at a scale of 1:40: ① upstream ultrasound probe , ② left river bank, ③ left intake wall, ④ gravel barrier and blind drain, ⑤ fish guidance screen, ⑥ fish migration and flushing channel inside the intake pier, ⑦ residual flow HPP, ⑧ precision pump, ⑨ gauging weir for the fish migration and flushing channel, ⑩ Rüchlig Weir.

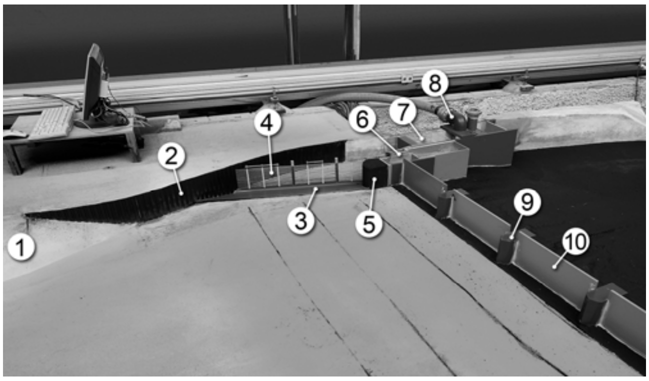

Figure 5: Detailed view of the scale model: ① river bank, ② intake wall, ③ gravel barrier and blind drain, ④ fish guidance screen, ⑤ intake pier, ⑥ fish migration and flushing channel, ⑦ turbine intake, ⑧ precision pump, ⑨ weir piers, ⑩ weir gates.

Model tests and results

Corresponding to the flow conditions in the prototype the following critical load cases were labelled and defined as:

• NB 9 - design discharge and water level with closed weir

• NB 7 - design discharge at low flow with closed weir

• NB 3 - design discharge at high flow with open weir

For the interpretation of the test results Froude similitude was applied because the predominant hydraulic process is free-surface flow which is governed by gravity.

Scope of results

This paper will focus on:

• The optimization of the turbine intake approach flow according to the criteria of the turbine manufacturer for a homogenous flow distribution.

• The adherence to the maximum flow velocity at the fish guidance screen as the determining factor for the ecological agreeability.

Figure 6 shows the control sections where the flow velocity measurements were carried out.

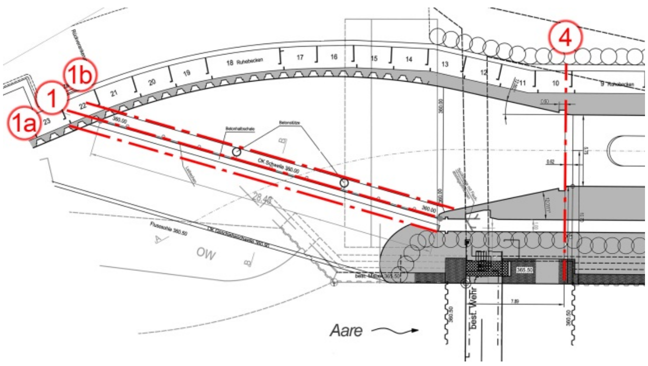

Figure 6: Plan view of the residual flow HPP with the control sections CS1, 1a and 1b to measure flow velocities at the fish guidance screen and CS4 to determine the turbine approach flow conditions.

Initial design

The measurements were conducted in the control section CS1 with the fish guidance screen being removed from the model. This was necessary because the densely packed screen bars prevented accurate measurements in this section with an ADV probe. Preliminary tests showed that the obtained velocity profiles at CS1 without fish guidance screen were in good agreement with the averaged velocity profiles between at CS1a and CS1b with fish guidance installed at high and low discharges. This was the case because the head loss at the fish guidance screen was minimal due to the very large intake section.

Figure 7 shows the velocity distribution in the control section CS1 at the fish guidance screen for the 3 critical load cases. Each one of them shows a distinctly asymmetrical pattern with velocities being the highest at the intake pier head and the lowest at the left intake wall due to the curvature effect at the entrance.

As expected high water levels lead to low flow velocities in the whole section, even resulting in negative velocities at the left intake wall for the load case NB3 where the total discharge exceeds the design discharge of the power plant and the weir is in operation as well.

Furthermore for every investigated water level the normal velocity at the screen close to the pier head section exceed the recommended maximum velocities of $v_x = 0.5\text{-}0.6$ m/s for safe fish guidance up to double the value. This may cause severe injury to migrating fish and has to be avoided.

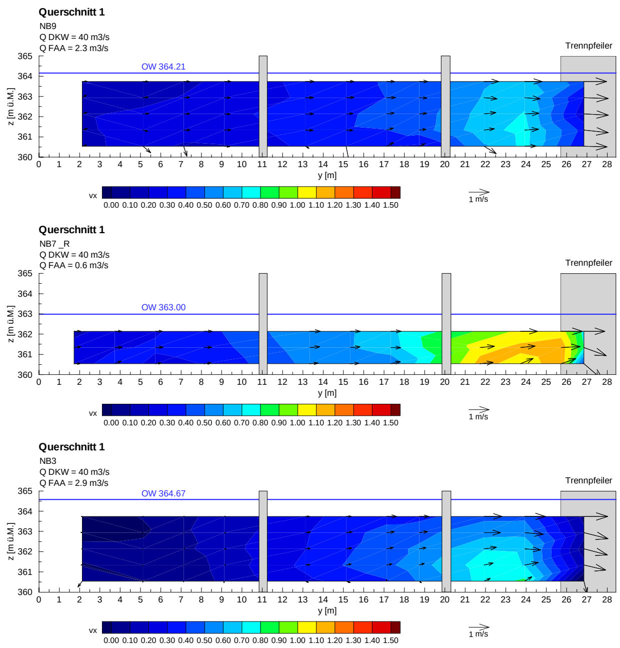

Figure 7: Contour lines of the velocity distribution normal to the fish guidance screen for the initial design for the load cases NB3, NB7 and NB9. The maximum admissible velocity for safe fish migration is exceeded in all load cases.

For optimal flow conditions at low head power plants, two prerequisites have to be met:

• Wing Load: The discharge load on the left and right half of intake section must not deviate more than 2.5% from the total discharge.

• Quadrant Load: The discharge deviation at each quadrant of the intake section must not exceed 10% of the total discharge.

The plots in Fig. 8 illustrate the velocity distributions with left and right wing loads relative to total discharge on the top (left) and the contour lines of the longitudinal velocities with the quadrant loads deviation from the total discharge on the top (right) at the turbine intake according to these demands.

For all load cases high flow discharges are observed on the left half of the intake sections in comparison to the right half. It is especially significant in load case NB7 where 59.4% of the total discharge agglomerates at the left half of the intake section exceeding the allowed margin of2.5%.

With high water levels the average flow velocities and the centrifugal force on the flow decrease due to the discharge being unchanged. As a result the discharge concentration diverges towards the centre of the intake and the extreme values decline.

It is clear that the discharge concentration on the left half of the intake and thus the asymmetric velocity distribution in the turbine intake section are negatively influenced by lower water levels.

A comparison of the load cases NB3 and NB9 points out the influence of the weir operation on the turbine intake flow. In both cases the flow distribution with regard to the left and right halves of the intake fulfills the criterion for optimal turbine efficiency. However the load case NB3 with the weir in operation violates the Quadrant Load condition and shows a rather distinct trend for a flow concentration in the upper half of the intake sections.

Therefore the initial design of the intake structure did neither meet the desired ecological nor the hydraulic requirements and an optimization was needed.

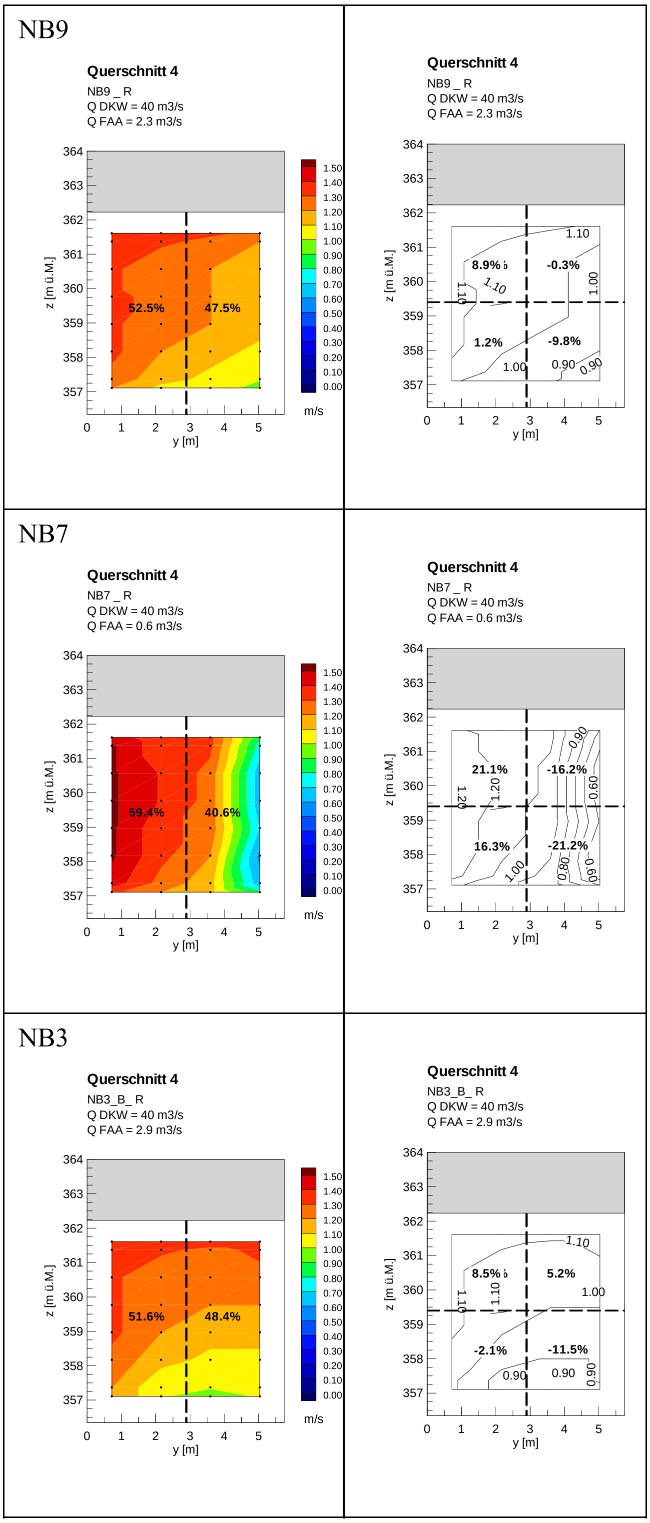

Figure 8: a) Velocity distributions with left and right wing loads relative to total discharge on the top and b) contour lines of the velocities with quadrant loads deviations from total discharge on the top at the turbine intake for the initial design for load cases NB3, NB7 and NB9. The criteria for optimal turbine performance are not fully met.

Optimized design

As a result of the investigation made on the initial design the following optimizations at the intake structure were executed (see Fig. 9):

• The bottom of the intake channel and the blind drain were lowered 1 m correspondingly increasing the height of the fish guidance screen to achieve lower flow velocities at the intake section of the power plant channel as well as in front of the turbine intake.

• A guidance wall was incorporated into the intake channel to improve the velocity distribution at the turbine intake.

• The gravel barrier received an aperture near the intake pier to improve the migration conditions for fish species living near the river bed.

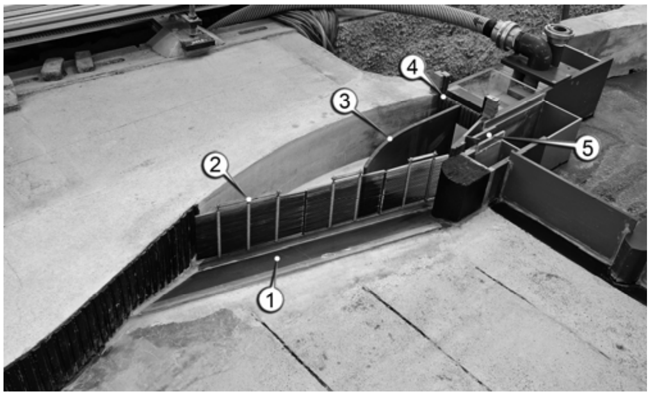

Figure 9: Detailed view of the power plant model after the optimization: ① lowered gravel barrier and blind drain, ② elevated fish guidance screen, ③ guidance wall in front of the turbine intake, ④ turbine intake, ⑤ fish migration and flushing channel.

The above listed design changes lead to an improvement of the ecologic as well as the hydraulic conditions of the power plant.

Figure 10 shows the velocity distribution in the control section CS1 at the fish guidance screen for the 3 critical load cases. They remain asymmetric but show significant improvements over the initial conditions. Velocities in the lower flow regions fully meet the conditions for safe fish migration and are slightly exceeded in higher layers of the flow near the intake pier. With respect to fish swimming performance and behaviour in the flow this is still a positive result, because only fish with excellent swimming capabilities normally migrate in these regions.

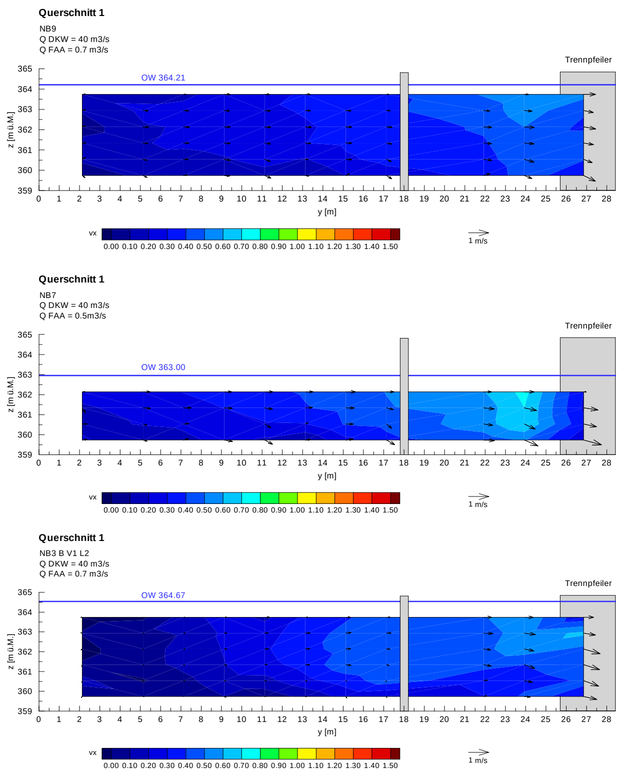

Figure 10: Cross-sectional velocity distribution in the control section CS 1 at the fish guidance screen for the optimized design for the load cases, NB3, NB7 and NB9.

Regarding the velocity distributions at the turbine intake the above listed modifications deliver positive results as well. Both flow distribution criteria for optimal turbine efficiency at the control section CS4 are now fully met for all load cases. As an example the load case NB7, which was most critical in the initial design, is documented in Fig. 11.

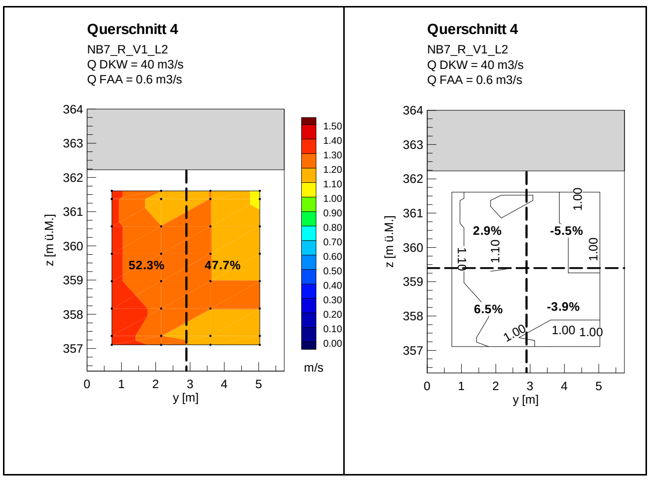

Figure 11: Velocity distributions with wing loads relative to total discharge on the top and contour lines of the velocities with quadrant loads deviations from total discharge at the turbine intake for the optimized design at load case NB7. The criteria for optimal turbine performance are fully met for all load cases.

Conclusions

The hydraulic model investigation of the residual flow HPP with a fish guidance system and its optimization showed the following results:

- The model investigation of the initial design showed the necessity for the optimization of the intake structure. On the one hand flow velocities at the fish guidance screen exceeded the biological design limits for safe fish migration and on the other hand the criteria for an efficient approach flow towards the turbines were not met.
- The load cases with low water levels were most critical having a negative impact on the velocity distribution at the fish guidance screen and at the turbine intake.
- Flow velocities normal to the fish guidance screen were asymmetrically distributed with high velocities close to the intake pier and very low velocities at the left intake wall.
- The optimization of the intake structure included the lowering of the intake channel invert and hence increased the fish guidance screen area allowing for the concurrent improvement of the performance of the fish guidance system and the hydraulic conditions of the facility.

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