

Restoration of Linear Passage for the Aquatic River Fauna – Physical Model Tests and Hydrodynamic 3D Flow Modeling Optimizing a Natural Shaped Fishway at the River Leine

Andreas Huesig¹, Tobias Linke²

The River Leine is segregated by several weirs for energy generation, which act as barriers for the migrating aquatic fauna. For one of these cases, a Natural shaped Fishway is planned to re-establish migration of fish and invertebrates. In order to facilitate the ascent for the aquatic fauna into the weir's backwater, the outlet of the Fishway was located downstream at the outside bend of River Leine. Due to water power generation of the weir, just a small donation flow for the Fishway in comparison to the flow of River Leine could be used to generate a discernible leading flow, which should lead the aquatic fauna, normally swimming at the undercut slope of a river, into the Fishway. In this outside bend, the River Ihme flows into River Leine generating an eddy, which urges fish not to swim at the undercut slope. Therefore, this eddy had to be suppressed or destroyed. Physical model tests helped finding a suitable solution in order to optimize the outlet of the Natural Shaped Fishway and to generate a distinct leading flow featuring the main frame conditions for the design of Fishways, but with a distinct smaller amount of flow inside the Fishway. Flow velocities were limited based upon swimming capabilities of the local migrating fauna. The junction between Fishway, downstream River Leine and River Ihme was designed with a vertical Current Deflection Wall (CDW) between Fishway and River Ihme. The cross-section of the Fishway was optimized varying several profiles ending up in a rectangular profile, which reduces friction and induces fauna-adequate current velocities in the Fishway despite the limited donation flow. Most important, a leading flow was generated distinguishable for migrating fish with a discernible current into the River Leine leading fish into the weir's backwater and ensuring restoration of linear passage. These results were confirmed in the 3D Numerical Model Star-CD using Mesher ICEM CFD after numerous adjustments showing the necessity of exact and narrow-meshed bathymetric data for the 3D Numerical Simulation. Based upon the results of the corresponding physical and numerical model tests it was possible to obtain a suitable solution both for this Fishway and future investigations on Natural Shaped Fishways.

1. Introduction

In the City of Hannover the River Leine is segregated by several weirs for energy generation. These weirs act as barriers for the migrating Aquatic Fauna. Therefore, Fishways are planned in order to re-establish the river continuum (VANNOTE ET AL., 1980) and fish migration in particular. One of these Fishways to be built is located in an ecological protected area, Fig. 1. Therefore, a Natural Shaped Fishway was selected for the most suitable solution in order not to

¹ Andreas Huesig, Dipl.-Ing., Research Associate, Franzius-Institute for Hydraulic, Waterway and Coastal Engineering, University of Hannover, Nienburger Strasse 4, 30167 Hannover, Germany

² Tobias Linke, Dipl.-Ing., Research Associate, Franzius-Institute for Hydraulic, Waterway and Coastal Engineering, University of Hannover, Nienburger Strasse 4, 30167 Hannover, Germany

disturb the environmental and ecological value of this area, although the course for the Natural Shaped Fishway with approx. 1.5 km in length has distinct higher area requirements than a technical Fishway.

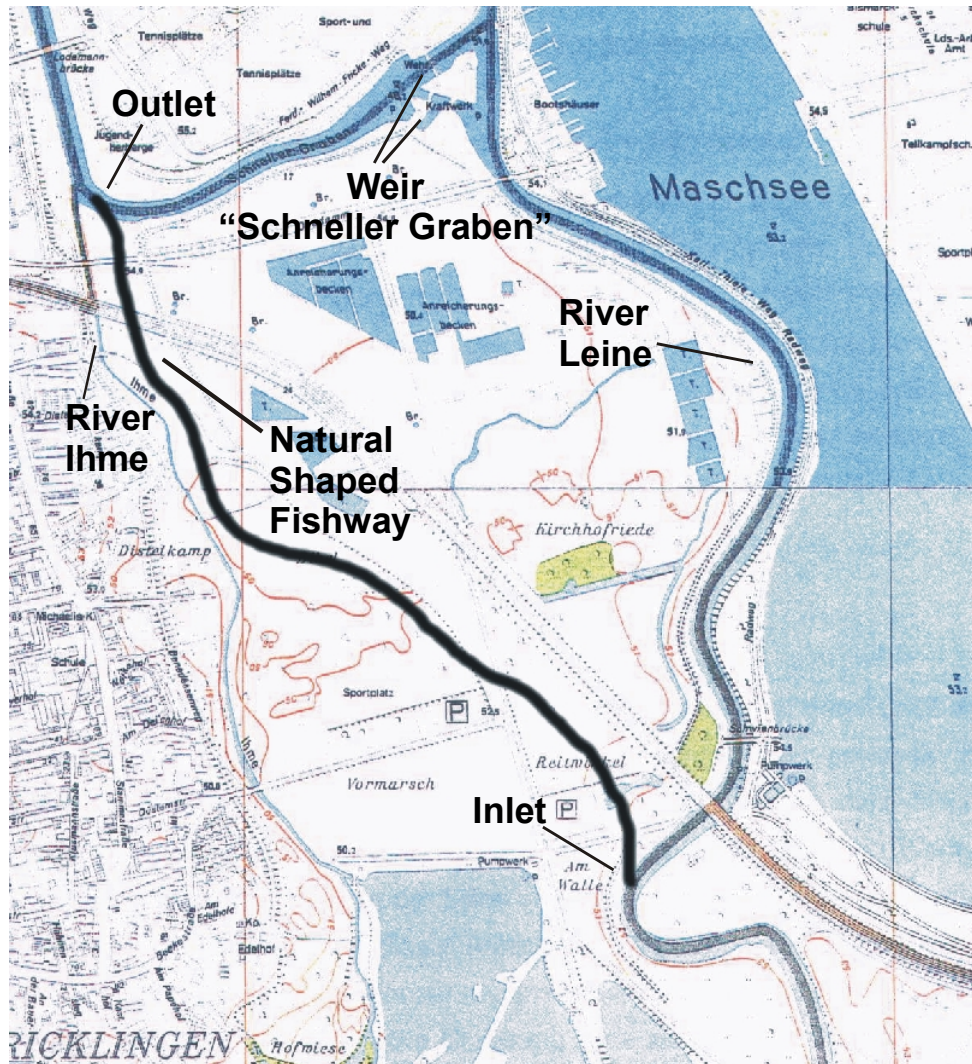


Figure 1: Map of River Leine, River Ihme, Weir and planned Natural Shaped Fishway

As the outlet of the Fishway is supposed to be located in the outside river bend due to fish' swimming conduct, the outlet is located 20 m upstream a junction of the River Leine with River Ihme. Investigations in prototype have shown, that the confluence of these two water courses induces a large eddy in front of the junction. For this reason, fish would not swim at the undercut slope but in the mid of the River Leine, which would enable them to find the outlet of the Fishway and to facilitate upstream migration.

Therefore, Physical Model Investigations were carried out in order to optimize the Fishway's outlet both aiming at generation of a distinct leading flow, destruction of the eddy at the junction of River Ihme and River Leine and guaranteeing that maximum flow velocities in the Fishway fall below swimming capabilities of the local aquatic fauna.

2. Boundary Conditions

The necessity of Physical Model Investigations became obvious as the relation between the main flow of River Leine $Q_{\text{Leine}} = 21.5 \text{ m}^3/\text{sec}$, the flow of River Ihme $Q_{\text{Ihme}} = 0.29 \text{ m}^3/\text{sec}$ and the donation flow of the Natural Shaped Fishway $Q_{\text{Fishway,max}} = 1.61 \text{ m}^3/\text{sec}$ were strongly unbalanced. Due to energy generation of the weir, the donation flow could not be increased. The local fish fauna was analyzed based upon fishing statistics in order to obtain maximum swimming capabilities as a major boundary condition for dimensioning the Fishway. The analysis made clear, that maximum flow velocities of $v_{\text{Fishway,max}} = 0.80 \text{ m/sec}$ must not be exceeded for a distance of approx. 50 m and flow velocities of $v_{\text{Fishway,max}} = 1.20 \text{ m/sec}$ must not be exceeded at all. For invertebrates moving on the river bed, these flow velocities ought to be reduced even more. Moreover, the water depth in the Natural Shaped Fishway should exceed $h = 0.70 \text{ m}$ with flat bed slopes, as respectively invertebrates are used to slopes of 1:15 or even less.

Considering the junction of the Fishway in the undercut slope of River Leine, the Fishway should be connected as close to the River bed due to bottom-near swimming aquatic inhabitants, although a bottom-near connection causes a larger cross-sectional discharge area at the Fishway's outlet with the effect of reduced current velocities for the Fishway and for the leading flow to be generated in the River Leine.

Investigations in prototype have shown, that the confluence of River Ihme and River Leine generates a large eddy. Due to usual swimming conducts of the aquatic fauna swimming against the streamthread of the main flow direction (Fig. 2), this eddy would enable fish and invertebrates to find the outlet of the Fishway unless the leading flow would suppress or destroy this eddy in the confluence area.

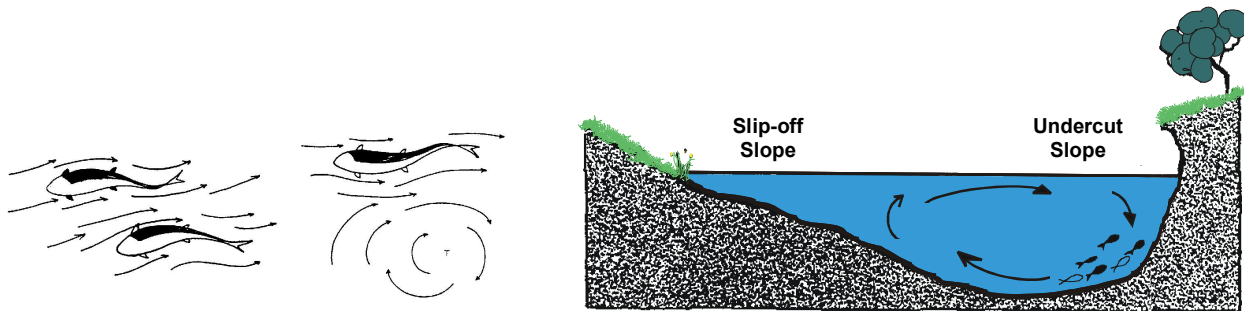


Figure 2: Fish' Swimming Conduct against the streamthread (left) and in River bends (right)

To find a compromise between the necessity of high current velocities for a distinct leading flow into River Leine and critical swimming velocities, the Fishway was segregated in several parts resulting in a steep slope with higher flow velocities in the outlet area, followed by flat sections with gentle slopes and pool areas, where fish and invertebrates could rest after the strenuous upstream ascent, as suggested for the design of Fishways (DEUTSCHER VERBAND FUER WASSER- UND KULTURBAU, 1996).

3. Experimental Set-up and Procedures

3.1 Physical Model Investigations

Boundaries for Physical Model Investigations and Numerical Simulations were determined as marked in Fig. 3.

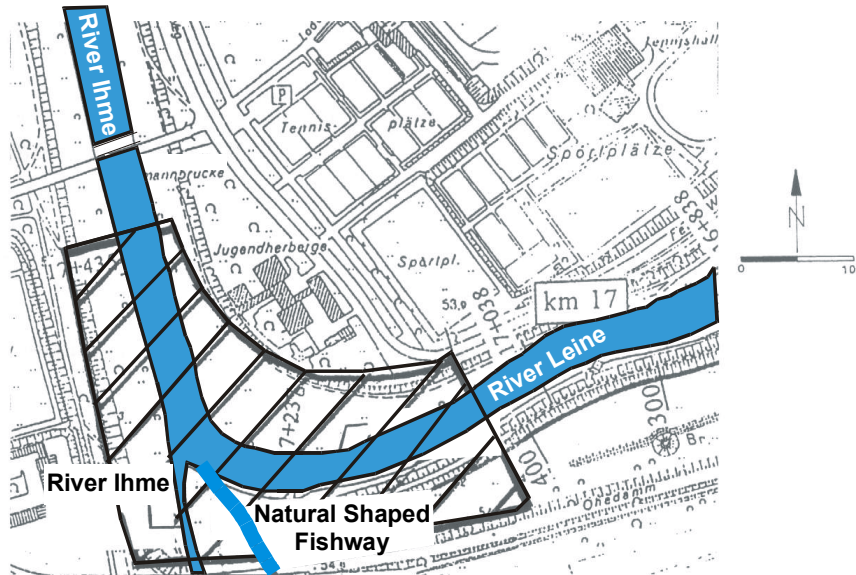


Figure 3: Map of confluence between River Leine, River Ihme and Natural Shaped Fishway and Boundaries for the Physical and Hybrid Model

Investigations were carried out in a fixed bed model with a scale of 1:20 applying FROUDE'S and REYNOLDS' laws for free surface flows. Model calibration was executed based upon measurements in prototype with surface and depth water floats as well as velocity profiles at the upper model boundary. Flow patterns were visualized and quantified by analysis of long-term photographs (exposure 4 seconds) of surface water floats. Corresponding current velocities in prototype and model were detected and the eddy between River Ihme and River Leine was located as known from prototype.

Several test sequences were carried out varying cross-sections and corresponding longitudinal sections, different donation flows, various Current Leading Structures like groynes or Current Deflection Walls (CDW) and Fishway's mouth angles resulting in two major test series (Modifications 1.x and Modifications 2.x), Table 1.

Modification 0.0 – 0.2	Calibration, blank tests
Modification 1.0 – 1.2	Natural shaped profile, bottom-near connection; CDW
Modification 2.0 – 2.3	Rectangular profile, stepwise increase of flow in the Fishway
Modification 2.4	Upstream Groyne
Modification 2.5	Upstream Groyne, CDW
Modification 2.6	CDW
Modification 3.0	Natural shaped profile, bottom-near connection, CDW

Table 1: Specifications and Modifications of the Test Series executed in the Physical Model

Modifications 1.x had the opportunity of a bottom-near junction with an outlet profile similar to a natural river with a wide entrance opening, whereas Modification 2.x was shaped in an rectangular profile and connected closer to the water surface with a water depth of 0.80 m, Fig. 4a and 4b.

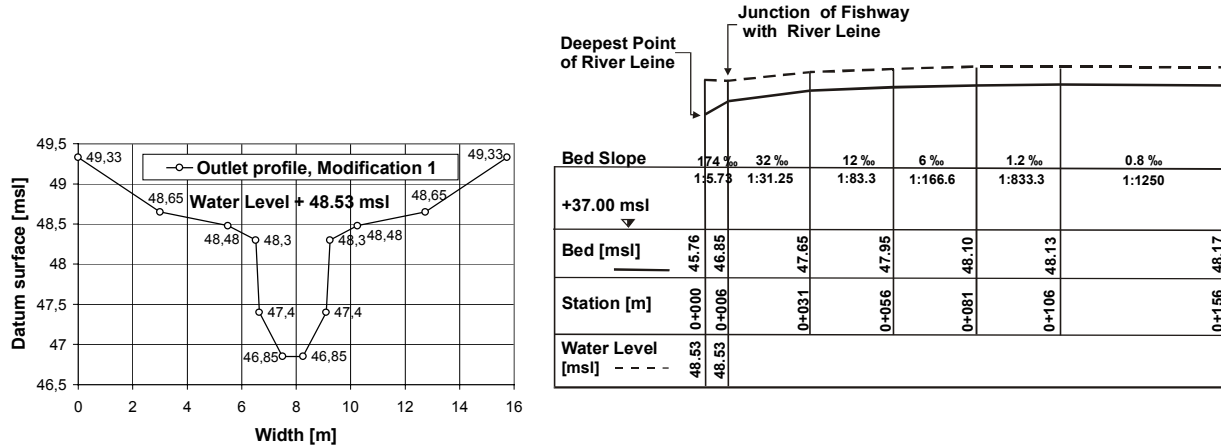


Figure 4a: Cross-section (left) and longitudinal section (right) for Modifications 1.x

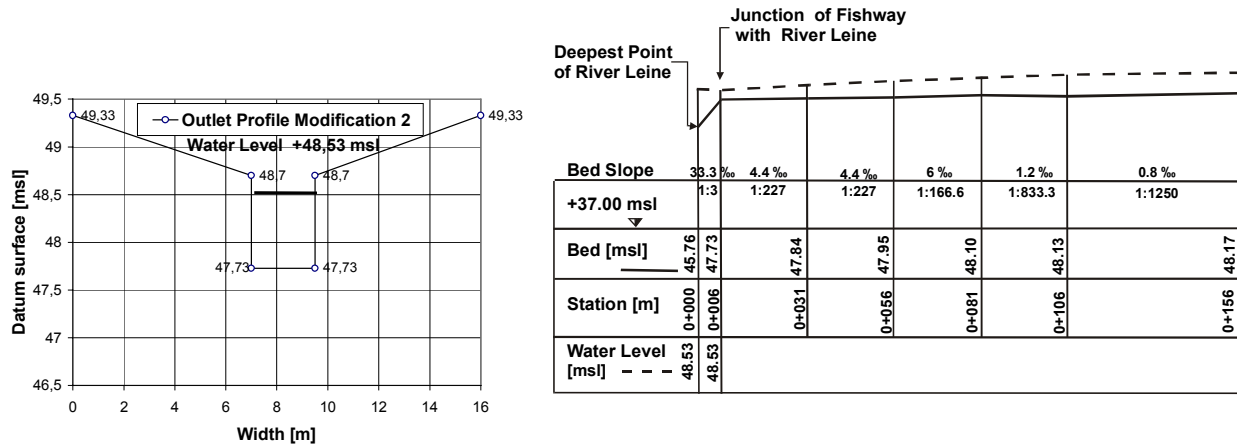


Figure 4b: Cross-section (left) and longitudinal section (right) for Modifications 2.x

3.2 Design of a Hybrid Mesh for Numerical Simulations

The geometric design for the Numerical Simulation was based upon the Tetra module of the mesher ICEM CFD for creation of unstructured tetrahedral meshes. The CAD geometry consisted of about 360 prescribed points in the cross-sections known from soundings as used for the design of the Physical Model. These points were transferred to B-Spline-curves and B-Spline-surfaces. The tetrahedral mesh was generated automatically applying the Octree approach, a spatial subdivision algorithm. Therefore an initial tetrahedron was created being large enough to enclose the hole model and was checked upon all of the size requests (predicate functions). If all predicate functions are satisfying, subdivision stops. Otherwise the tetrahedron is subdivided into eight smaller, congruent tetrahedra until all tetrahedra meet all predicate functions. After balancing the mesh in a way that elements sharing an edge or a face do not differ

in size by more than a factor of two, the unwanted parts of the mesh were cut. This cutter locates all tetrahedra belonging to a material point located anywhere in the part of the mesh to be retrieved and marks it as to be kept avoiding crossing any surface. This process results in a small mesh where required and a large mesh elsewhere. The mesh for this case study consists of 92000 cells with a maximum size of 3.6 m and a minimum size of 0.4 m representing all details. After that the mesh was smoothed up to an aspect ratio of 0.2 by moving and merging nodes, swapping edges to decrease mesh distortion. To increase numerical stability five prism layer with a height of 0.01 m to 0.10 m were located over the model (CFD & STRUCTURAL ENGINEERING GMBH, 1998).

For the analysis the Computational Fluid Dynamics solver Star-CD was used based upon the Finite-Volume method to discretize differential equations governing conservation of mass, momentum and energy. After import of the mesh into Star-CD, boundary conditions, consisting of the three inlets (Rivers Leine, River Ihme and Fishway), an outlet (downstream model boundary), a wall (River Bed and banks) and a free surface were specified. Each of the inlet flows was converted to an averaged inlet flow velocity at the upper model boundary of River Leine $v_{In_Leine} = 0.368$ m/sec, of River Ihme $v_{In_Ihme} = 0.047$ m/sec and of Natural Shaped Fishway $v_{In_Fishway} = 0.292$ m/sec. The outlet at the downstream model boundary was defined as grand total of the 3 inlet flows. The bed of the model was specified as a wall with a friction of $k_{ST}=32$ m^{1/3}/sec for the Rivers and 28 m^{1/3}/sec for the Fishway. As for the turbulence model, the standard k- ϵ -model was applied. The characteristic length was set to maximum water depth and the turbulence intensity to 10 %. The temporary discretisation was done fully implicit and the spatial discretisation with the monotone advection and reconstruction scheme (MARS), a multidimensional second-order scheme using default values. A transient solution algorithm working with implicit methods was used to solve the algebraic equations resulting from discretisation (STAR-CD, 1998).

4. Results of Physical Model Investigations and Numerical Simulations

4.1 Results of Physical Model Investigations

Results of the Physical Model Investigations showed, that it was not possible to generate a distinct leading flow in the Natural Shaped Fishway into the River Leine with the Parameters used in Modification 1.x as current velocities were too small due to large entrance opening. Therefore, Modification 2.x seemed more promising because of the smaller opening allowing higher current velocities in the Fishway.

Due to the unbalanced discharge in the River Leine of $Q_{Leine} = 21.5$ m³/sec and the Natural Shaped Fishway ($Q_{Fishway_max} = 1.61$ m³/sec), the expected leading flow could not be detected.

Although the donation flow was limited, test series Mod. 2.0 – Mod. 2.3 were carried out increasing the donation flow, but the intended significant leading flow could not be generated and flow velocities exceeded the upper limit of $v_{Fishway_max} = 1.20$ m/sec by far. For this reason, groynes and Current Deflection Walls (CDW) were installed upstream and downstream of the Fishway's junction in Mod. 2.4 – Mod. 2.6, Fig. 5, Fig. 6.

Aiming at deflection of the main flow of the River Leine, construction of a groyne upstream the Fishway resulted in a downstream eddy, but did not suppress generation of the eddy at the junction of River Ihme and River Leine, Fig. 5.

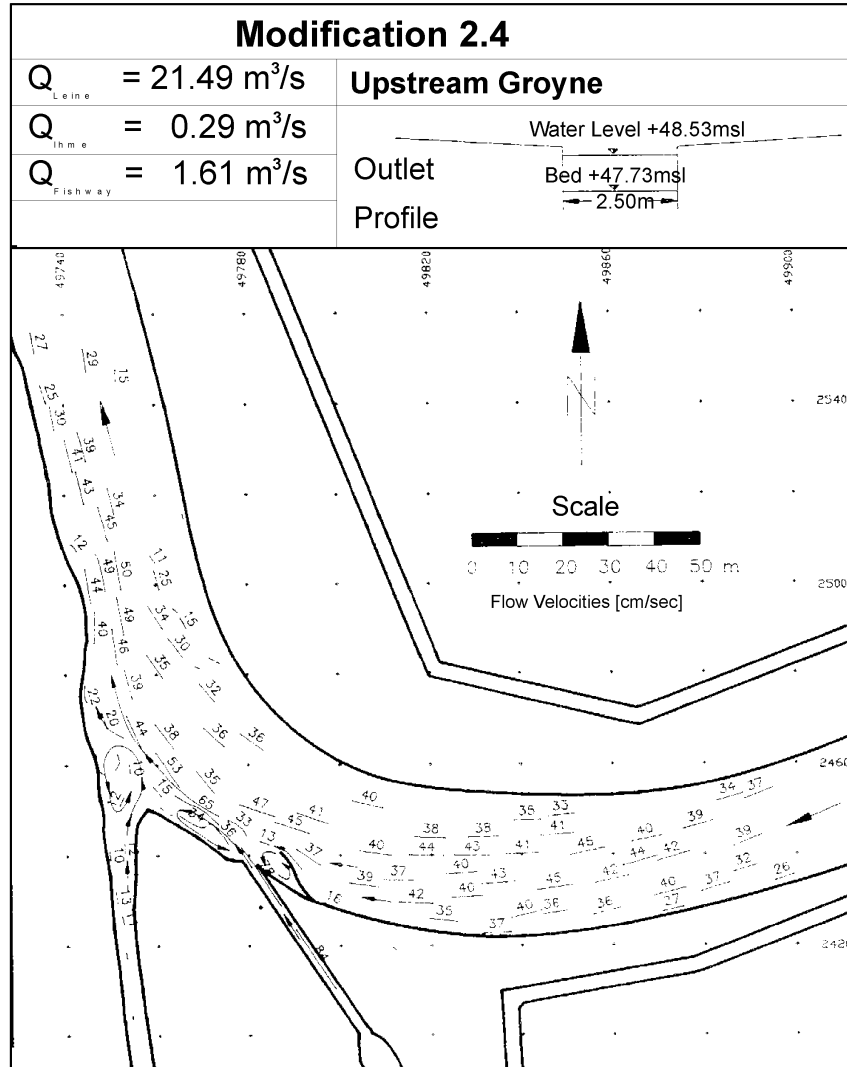


Figure 5: Modification 2.4 (Upstream Groyne)

As deflection of the main flow was not achieved, a vertical Current Deflection Wall as known as construction designed for reduction of sedimentation in harbors and harbor entrances (ZIMMERMANN ET AL., 1998) was installed at the downstream side of the Fishway's outlet intending at prevention of flow separation and at generation of a CDW-parallel, steady and distinguishable flow extending as wide as possible into River Leine, Fig. 6.

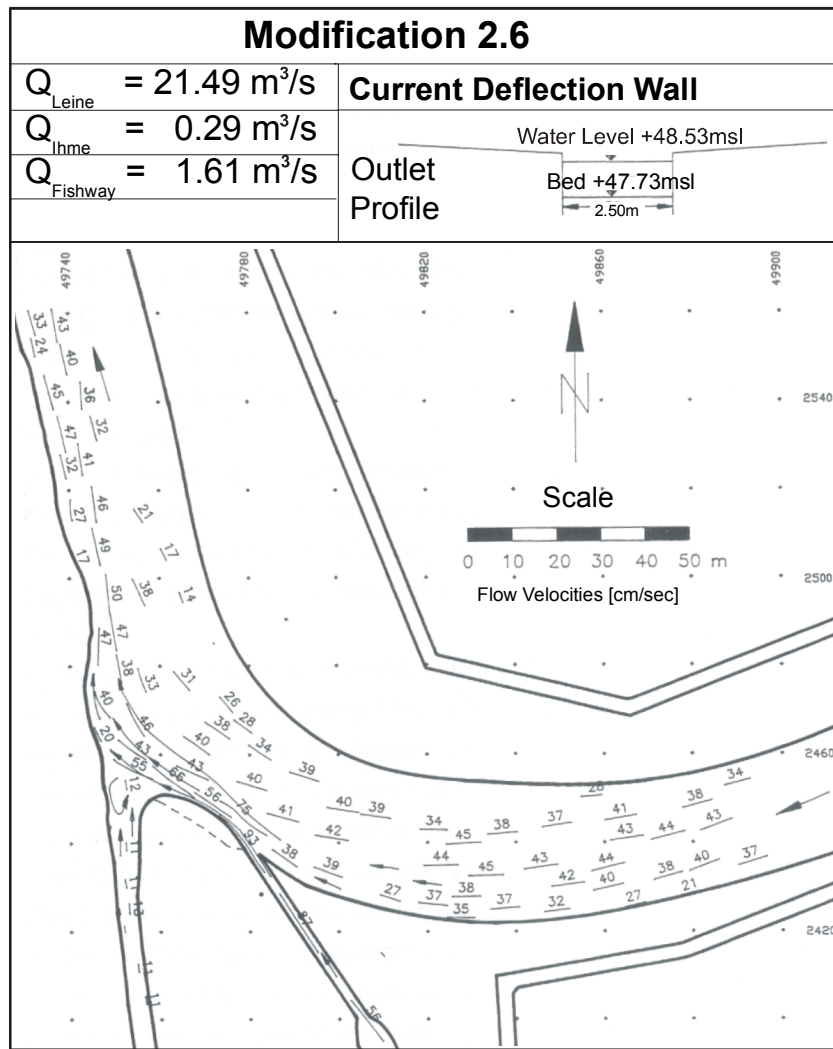


Figure 6: Modification 2.6 (Downstream Vertical Current Deflection Wall)

Fig. 6 shows the Natural Shaped Fishway's run-off parallel to the Current deflection Wall and the leading flow suppressing the eddy at the opening of the mouth of River Ihme and pushing the eddy into River Ihme and extending wide into River Leine with the expected maximum and fauna-adequate current velocities not exceeding the mentioned limitations.

Upstream the Fishway's section with high current velocities of 0.80 m/sec as seen in Fig. 6, a flat sections with gentle slopes were constructed, where ascending fish could rest. As the connection of the Fishway's bed with the River Leine was not bottom-near and with a steep slope, invertebrates would hardly recognize the Fishway, and if so, ascent would be difficult due to high current velocities, but the majority of the aquatic fauna would detect

4.2 Results of Numerical Simulations

The results of the Numerical Simulations are corresponding to those of the Physical Model Investigations (Fig. 7), although difficulties appeared due to the fact, that the mesh was set up

with just 15 cross-sections in longitudinal distances of approx. 50 m, whereas the soundings of each profile were measured in distances of less than 1.0 m. Problems occurred as the B-Splines for the prescribed points and curves had to be rounded due to the unbalanced distances in length and width. After manual correction and smoothing it was possible to calibrate the numerical model via comparison with measurements in prototype and in the Physical Model Tests.

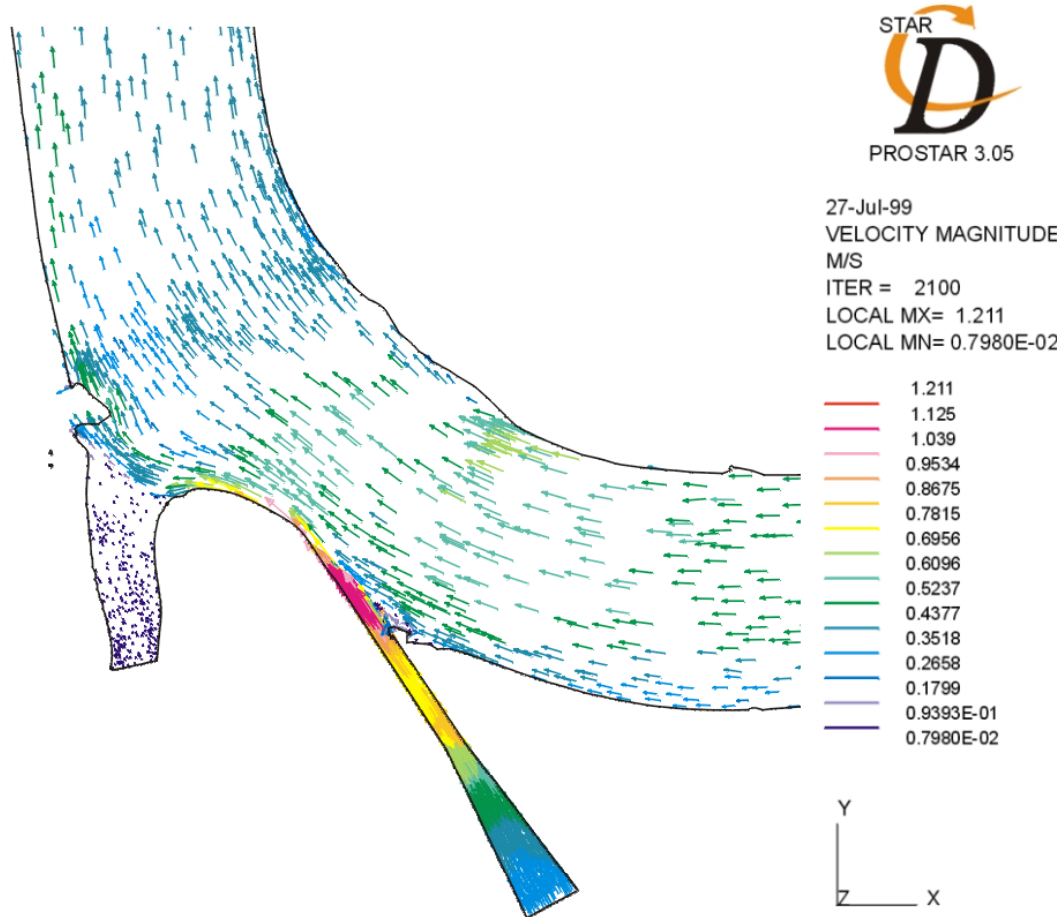


Figure 7: Results of the Numerical Simulation for Modification 2.6 (Current Deflection Wall)

5. Conclusion

The River Leine is segregated by a weir in the City of Hannover for Energy Generation. Therefore, linear passage for the Aquatic Fauna was to be restored by construction of a Natural Shaped Fishway, because the area for connection of Fishway and the River Leine is environmentally protected. In this area, the River Ihme discharges into River Leine in the outside River bend in a distance of approx. 10 m downstream the intended outlet of the Fishway inducing an eddy which would prevent fish usually swimming in outside river bends from detecting the mouth of the Fishway. Therefore, Hydraulic Model Investigations were executed aiming at optimization of the Fishway's mouth and connection to River Leine under consideration of the requirements of the local Aquatic Fauna.

The results of the Physical Model Investigations show, that despite the unbalanced flow-rates of River Leine, River Ihme and Natural Shaped Fishway it was possible to suppress the eddy and to generate a distinct leading flow discernible for the Aquatic Fauna.

Due to hydraulic boundary conditions, a bottom-near connection between River Leine and Fishway could not be realized, which might prevent some invertebrates and small fish from upstream migration. Bottom-near connection would result in lower flow velocities at the Fishway's outlet with the effect that the Fishway would not be detected at all.

The outlet structure of the Natural Shaped Fishway was designed in a rectangular profile with a width of 2.50 m and a water depth of 0.80 m and, most important, a vertical Current Deflection Wall at the downstream side of the Fishway with the effect of a streamlined, smooth and distinguishable leading flow into the River Leine.

These results were confirmed in the 3D Numerical Model Star-CD using Mesher ICEM CFD after numerous adjustments showing the necessity of exact and narrow-meshed bathymetric data for the 3D - Numerical Simulation.

Finally, the preferred Modification with a vertical Current Deflection Wall at the downstream side of the Fishway was selected for construction and was completed in Spring 1999. The efficiency of the Fishway will be investigated by fishing statistics in the upstream course of the River Leine and Fishway. The Natural Shaped Fishway is selected as an exhibition item and demonstration of the forthcoming EXPO 2000 in Hannover.

6. Literature

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