FISH DOWNSTREAM PASSAGE AT THE TUM-HYDRO SHAFT POWER PLANT EXPERIMENTAL STUDY OF FISH BEHAVIOR

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Abstract

At the Technische Universität München an innovative hydro power concept has been developed. It is meant to achieve cost-effective fish protection and efficient downstream migration. A series of experiments with live fish was conducted at a micro hydro shaft power plant site (2 m³/s, 30 kW) under controlled laboratory conditions to investigate the fish protection at the employed horizontal screen and to optimize the efficiency of the provided downstream migration corridor. The behavior of several hundred fish of different species and sizes were investigated by underwater video and the collection of the migrated and the not migrated fish.

The results confirm the hydraulic dimensioning of the facility due to model test investigations, the functionality of the fish protection at the screen for all employed fish categories and the general workability and good acceptance of the fish downstream passage. Moreover they provide valuable species- and size-resolved details information about these points and the competitive analysis reveals that bottom near bypass system yields better efficiency than surface near ones under the given circumstances. The presented hydro power concept provides thus a verified and optimized fish protection and downstream migration.

Introduction

Hydraulic constructions may seriously interfere or completely obstruct the ecological continuity and particularly the fish migration in a water body. To maintain a sustainable fish population, a safe passage for migrating fish across stream barriers is essential. Fish passage facilities, as for example bypass rivers, fish-ways or fish passes were developed to minimize the environmental impact of dams. However, while there has been a significant progress in the design and implementation of fish-ways for upstream migration, downstream fish passages have not been sufficiently studied (Larinier, 2002). The downstream migrating fish mostly follow the main stream and thus pass through the turbine (Larinier, 2008). This results in fish injury and mortality depending mostly on the fish size, the turbine type and the operating conditions (Holzner, 2000). Therefore the principle of a fish downstream migration facility is to stop the fish before the turbine, to guide them to a bypass and finally to bring them downstream safely. The most common, reliable and promising approach to avoid fish turbine passage is a physical barrier, i.e. a fine enough trash rack/screen with adequate velocities. Whereas this can be achieved by space and constructional efforts, the guidance of the fish to the fish pass is more challenging. Some facilities show poor efficiency because fish cannot find the entrance of the bypass and swim towards the turbine or are pressed against the screen due to weakness after unsuccessful search. Thus concepts are required, which assure respectable attractiveness. The most direct and reliable method to investigate the efficiency of a bypass system is the observation of live fish.

In the Laboratory of Hydraulic and Water Resources Engineering (VAO) of the Technische Universität München (TUM) an innovative hydro power concept has been developed, the “TUM hydro shaft power plant”. Apart from other advantages it is meant to achieve cost-effective fish protection and efficient downstream migration. A horizontal river-bad flush quadrate intake plane provides a large screen surface with relatively low space requirement and constructional costs. Narrow bar distances (e.g. 20 mm) and limited maximum intake velocities (e.g. 0.5 m/s) prevent fish damage. In detail the bar clearance and the dimensioning of the maximum velocity at the screen can be adapted to the local fish population. Hydraulic model tests assure that maximum velocities do not exceed the design limits (Rutschmann et al., 2011). Downstream migration is provided by openings in the gate aside the screen and a free outflow to the downstream, where a water cushion prevents any fish damage. Number, size and positioning of these openings can be adapted to the local fish population to yield maximum efficiency. Figure 1 provides a schematic longitudinal section of a hydro shaft power plant.

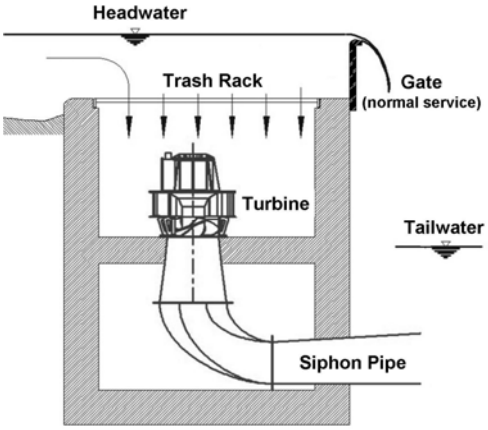

Figure 1: Schematic longitudinal section of a TUM hydro shaft power plant; river flow direction from the left to the right

Whereas the hydraulic model tests could assure, that all velocity limits are respected, the actual fish behavior could not be predicted. In particular there were no references concerning the fish comportment face to a horizontal intake plane and it remained doubtable if the protection standards which were developed for vertical screen planes hold valid for vertical orientation of the intake plane. Furthermore the efficiency of the openings and its dependency from the positioning in the gate were debatable. To investigate and optimize the ecological aspects of the hydro power concept tests with live fish were conducted at a large scale test facility at the VAO.

Methodology

Experimental Setup

The test series presented in here was conducted with a simplified setup, which reproduced the hydraulic conditions in the headwater of a hydro shaft power plant but did not include a locomotive gate or a trash rack cleaner. The turbine was replaced by a bottom outlet (dimensioned for 1.72 m³/s discharge at 1 m head). Shaft (2.5 m broad, 2.8 m long, 3.0 m deep) and weir were installed in an open air lab flume at the hydraulic laboratory in Obernach. The horizontal screen in the head water was 2.6 m long and 2.4 m wide with a rectangular screen bar profile and 15 mm bar clearance. It was installed flush with the head water river bed just in front of the weir.

Headwater (7.5 m long, 10.1 m wide, 0.7 m water surface elevation) and tail water (10 m long, 5.5 m wide, 2.7 m water surface elevation) of the test zone were separated from the surrounding canal system by grids, to prevent fish from escaping. A 55 m long and 9 m wide canal connected the test zone with an up-scaled Rehbock flume gauge which provided the system with water from the Isar river. Debris was held from the test area with a cleanable trash rack upstream the test facility.

The flow conditions in the head water were similar to the hydro power service situation, known from the physical model test including a turbine. Figure 2 shows the setup dry and in service.

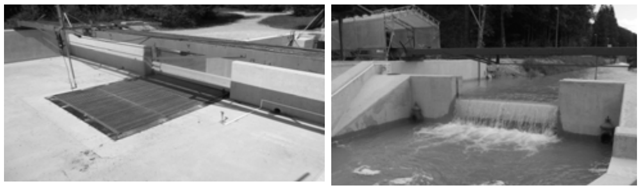

Figure 2: Test setup: dry trash rack from the head water right bank (left) and overflow of the gate from the downstream left bank (right)

The vertical gate alongside the trash was 2.8 m wide and 0.65 m high. It was equipped alternately with one of two opening variants for fish downstream migration (each 25 cm x 30 cm), one at the surface and one close to the screen (see figure 3). The top edge of the gate and the opening were rounded to avoid fish injury during the passage. For both variants the gate was 5 cm overflowed according to the hydraulic concept of the shaft hydro power plant.

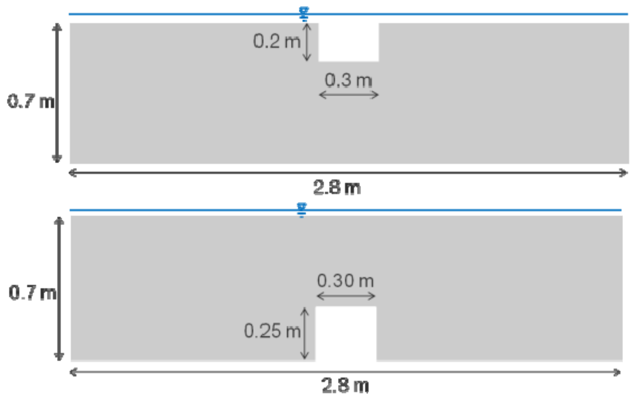

Figure 3: Vertical gate with position and dimension of the opening, variant 1/surface-near opening (top), variant 2/screen-near (bottom)

The discharge in the test facility was set in order to assure the required water surface elevation face to the respective opening variant. Details are provided in Table 1.

Table 1 Discharge distribution for each variant, variant 1: opening at the surface, variant 2: opening at the bottom

	Variant 1		Variant 2	
	[m³/s]	[%]	[m³/s]	[%]
Q_{weir}	0.053	3	0.059	3
$Q_{opening}$	0.071	4	0.153	8
$Q_{turbine}$	1.720	93	1.720	89
Q_{total}	1.843	100	1.932	100

One may note that a discharge proportion of 8 % for the downstream migration corridor in variant 2 seems uneconomically high. This is due to the minimum size of the opening and the relatively small turbine discharge. At real hydropower sites with larger turbine discharges the discharge proportion is correspondingly lower.

Fish collection and care

To get information with regard to different river sites and fish populations, three representative species were studied: Barbel (*Barbus barbus*), chub (*Squalius cephalus*) and brown trout (*Salmo trutta morpha fario*). For each species a variety of different sizes was given. They were categorized in three classes: Small, medium and big. The swimming behavior and habitat preferences of these species and sizes differ, so that they represent a main part of the ecological fish-spectrum of the rhitral, epi-potamal and meta-potamal region (ATV-DVWK, 2004).

Barbel and chub were caught in different rather small rivers in Bavaria, the brown trout originated from fish farms. 16 barbels with a mean total length (tl) of 52 ± SD 16 cm standard deviation (SD), 176 chubs, mean tl 26 ± 6 cm SD and 98 brown trout, mean tl 28 ± 8 cm SD were supplied. The fish were held in two circular flow tanks supplied with constant water from a spring (oxygen supply) and water from the Isar river (adaption to test conditions). The fish pool was veterinary investigated to assure good health conditions and all legal requirements and obligations concerning live animal experiments were respected.

Experimental procedure

Each test was started in the morning by establishing the hydraulic conditions and subsequently putting 59 fish with representative species and size distribution into the head water of the test setup, about 3 m upstream of the screen on the right side. In order to avoid learning effects most of the fish were employed only one time or maximal two times for the experiment. However, because of a too small number of barbel (n=16), they were used for each test. A possible learning effect for this specieS has to be considered.

Water turbidity was measured with a Secchi disk at the beginning and at the end of the test. The water temperature was recorded during the whole test duration (every 5 minutes). The fish behavior at screen and openings was recorded by underwater video camera and video from outside. To avoid a potential disturbance of the fish by artificial light, no such sources were employed and the observation was thus just possible during day light.

After 24 h the downstream passage was blocked, the discharge was shut down and all fish were caught. Number and type of fish (specie and size category) in head water and tail water were determined.

Both variants (surface near / bottom near) were repeated three times for statistical purpose. In order to allow a comparison without considering the seasonal change, the both variants were switched each time. Between each two tests there was a break of at least 22 h to provide some rest for those fish which were used repeatedly.

Results and Discussion

Experimental conditions

The weather situation during the test campaign was very favorable. Thanks to few precipitation during all of the test period the water turbidity was very low, which enabled fish behavior observation. The turbidity is furthermore an important factor concerning the downstream migration (Schwevers, 2000). The water temperature stayed also relatively constant, with a minimum temperature of 8.7°C and a maximum of 12.6°C. The constant conditions of the abiotic factors during all tests provide the comparability of the results.

Velocity at the screen

The three velocity components at the screen were measured in a 600 mm grid with a 3D-ADV probe in two heights (50 mm and 350 mm above the screen). Figure 4 shows exemplarily the visualized results for variant 2 in 50 mm above the trash rack. The main flow direction is from the left to the right, the fine black rectangle represents the inner shaft wall, the arrows show the horizontal velocity components and the grey scale and contour lines provide the vertical velocity component, where dark color means flow inside the shaft.

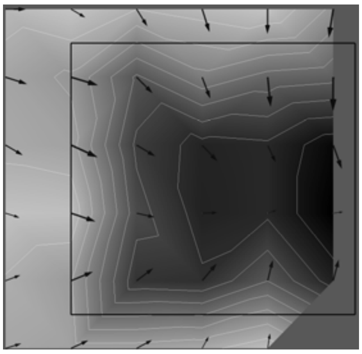

Figure 4: Velocity distribution at the screen for variant 2; main flow direction from the left to the right

The velocity distribution corresponds well to the flow fields measured at the physical model. This confirms that the experimental setup is suitable for the investigation of the fish behavior at similar hydro power plants. The flow conditions above the screen are identical although there is no turbine involved. The maximum velocity towards the shaft was found to be about 40 cm/s. This is exactly the design value und approves the correctness of the dimensioning guidelines deduced from the model tests.

Unlike the flow field measured at the physical model, figure 4 shows a maximum for the vertical velocity not just in the middle of the shaft, but also near the gate. This is due to the opening for fish downstream migration.

Complementary the velocities in the opening where measured with the ADV probe. 100 mm in front of the middle of the opening the velocity in the main flow direction was 97.7 cm/s for variant 1 and 120.9 cm/s for variant 2. The difference is due to the respective water head.

Fish protection at the screen

At the beginning of the tests only few or no fish could be observed at the screen. They required an adaptive phase before starting to be active and to explore the test zone. After a few hours, during the afternoon, it was possible to observe the fish at the screen. As already found in the fish experiments in summer 2010 (Cuchet et al., 2010) the fish activity depends on the water temperature and furthermore on the time of the day. The water temperature reaches a peak at the end of the day, which concords with the maximal activity of the fish at dusk. The juvenile chub and the barbel showed a gregarious intra-specific behavior, while the adult chub and the brown trout rested solitary.

During the test periods fish of all species and size categories could be observed above the screen. As soon as they were in the intake area and felt the velocity increases, they showed a rheoactiv behavior and oriented themselves according to the flow direction (see figure 5). They could swim against, with or lateral to the main flow and were free to move in all direction above the screen. The fish kept a certain distance (about 5-10 cm) above the screen surface and avoided any contact with it.

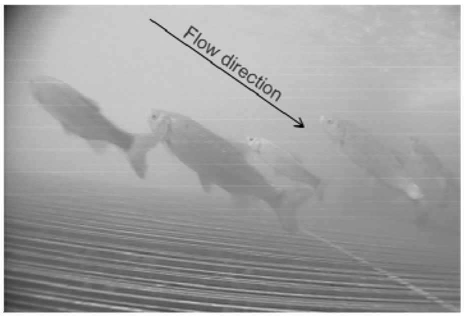

Figure 5: Fish above the screen, oriented with the flow direction

No fish was observed being pressed against or stuck at the screen. They were safe to stay at the screen without having any injury or being too exhausted to leave the intake area. All fish entered the intake area voluntarily as the flow conditions in the rest of the head water areal were much calmer and provided even rest rooms where velocities were almost null.

Fish passage to the downstream

The general functionality of the fish downstream migration corridor was confirmed. For both variants fish could be observed passing through the opening. Figure 6 shows an exemplary image sequence from a video.

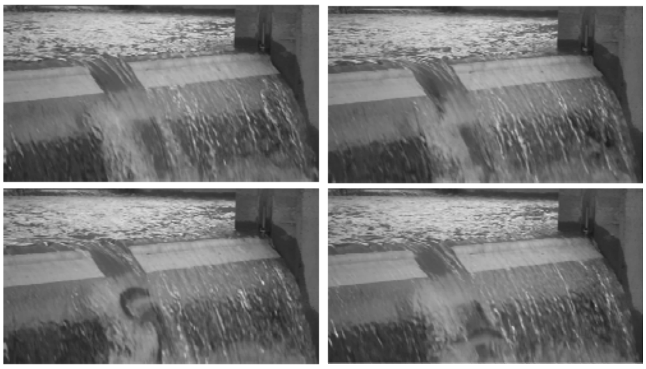

Figure 6: A big brown trout passing through the opening in variant 1; image sequence from the left to the right and from top to bottom

The collection of the migrated fish in the downstream showed that for both variants a respectable percentage of the fish used the passage possibility. Apart from the small barbel in variant 1 and the small brown trout in variant 2 fish of all species and size categories migrated to the downstream. Figure 7 shows the details averaged over the three repetitions per variant. The absolute values are influenced by a number of boundary conditions, e.g. the test duration and cannot be transferred to other hydro power sites. Nevertheless they confirm the general functionality, serve as hints for the respective efficiency and enable a comparison of the variants.

The second variant with the opening at the bottom shows apparently better results for all species and all sizes, except for the small brown trout where the opening at the surface (variant 1) seems to be better. This may possibly be explained by the lower velocity in the surface near opening which is more adequate for small fish with farm origin due to their limited swim capability. The general preference for the bottom near migration corridor is likely to be explainable by the tendency to avoid the surface with regard to exposure to potential predators from land and air. A detailed statistical analysis of the experimental data is under progress to assess the significance of the observations.

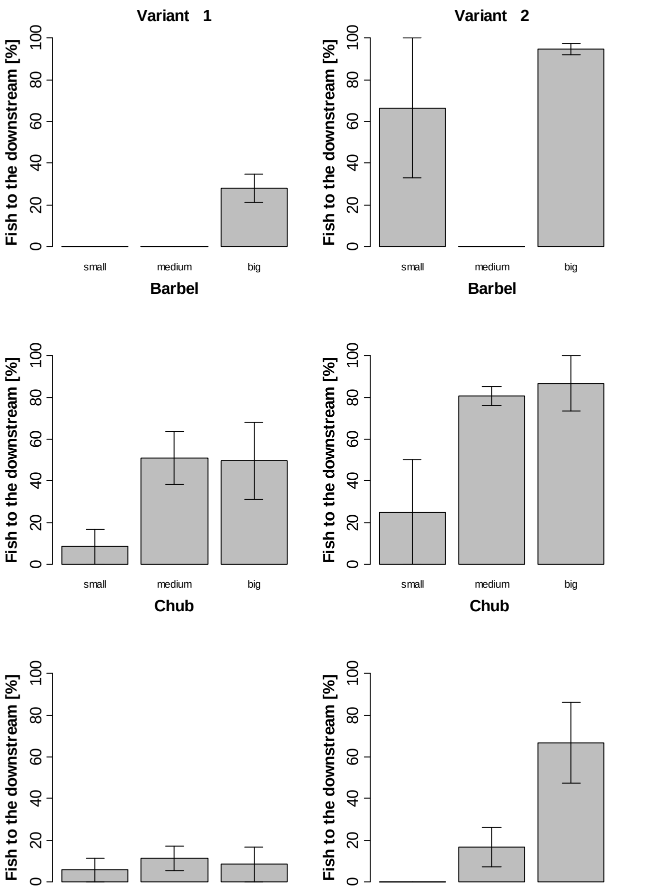

Figure 7: Results of the fish experiment for all fish species and sizes and both variants; average values +/- standard deviation; no medium size barbel were employed in the tests

Discussion of fish behavior

The analysis of the behavior documentation by video and of the collection of migrated fish with regard to species and sizes reveals a number of points.

Concerning the fish size, the relation between size and swim capacity (DWA, 2010) got obvious. In most of the cases (4/6) the bigger the fish were, the better they used the passage to the downstream. This was probably because of the higher swim capacity of larger fish and the relatively high flow velocities in the opening. The underwater video observation showed also that larger fish are more likely to enter the intake area and they stay for a longer time above the screen. Obviously small fish required more effort to swim above the screen and thus they rested shorter time in the intake area during each passage. Big fish stayed for hours above the screen with no difficulty. This also raises their probability to use the downstream migration corridor.

With regard to the different fish species a rather unexpected result was found. From literature references one could suppose the brown trout to be the best swimmer of the employed species. However, considering the fish which swim to the downstream, the most active specie was the chub, than the barbel and finally the brown trout. The underwater video observation showed similar results. Chub and barbel were often observed at the screen in contrary to the brown trout. Beside this, chub and barbel showed a clear tendency to swim in swarm whereas the brown trout stayed alone and competitive in their territory.

A possible explanation for the difference in activity between the chub and the barbel on the one and the brown trout on the other side is the water temperature conditions during the tests. Actually the water temperature was ranging from 8.8 to 12.6°C. For the barbel and the chub this is relatively cold for the relevant time of the year. Normally they live in habitats with a temperature of about 15°C at the relevant season as known from records at the origin rivers. With a colder water temperature than in their natural habitat, the chub and barbel may have shown a strong activity in order to find another, more comfortable habitat and therefore tried to swim to the downstream. On the other side, the brown trout were exactly in their habitat condition and thus had no reason to swim to the downstream.

Another explication for the difference in activity could be the origin of the fish. Chub and barbel were wild fish while the brown trout came from farm cultures. A difference in the swim behavior or swim capacity could be expected: a fish which stayed its whole life in a pool cannot have the same condition as a fish which lived in a natural river. It could be the reason why the brown trout stayed in the upstream where the condition was very comfortable and why they did not try the passage with high velocity and acceleration. This theory should be verified, for example by competitive tests with farm and wild fish of the same species and size under identical conditions.

Conclusion

The functionality of fish protection and of fish downstream migration at the TUM hydro shaft power plant concept have successfully been investigated by live fish behavior experiments. The tests confirmed that for the used representative variety of fish species and sizes from the rhithral and potamal river regime the flow condition at the screen do not cause problems. This evidences also, that the velocity limits for fish protection which have been developed for vertical intake planes hold valid for horizontal ones and that horizontal trash rack arrangements are in general suitable for fish protection. Furthermore the test series approved the efficiency of the fish downstream migration corridor and revealed a better effectiveness of the bottom near arrangement instead of the surface near downstream passage.

Beside these main issues of the research campaign, the tests showed also the correctness of the hydraulic dimensioning deduced from the model test and they demonstrated the feasibility of live fish experiments in large scale laboratory experiments.

The promising results for the ecological aspects of the hydro power concept have now furthermore to be tested for other fish species. Especially relatively weak swimmers like the bullhead have to be accounted for. Moreover the present tests only considered fish with more than 13 cm body length. Smaller fish may however cross the trash rack and get damaged in the turbine. For a complete ecological assessment of the hydro power concept and its potential impact on a river site's ecological state it is necessary to know the relevant damage rates. Of course these depend largely on the employed turbine type which is not predetermined as the hydro power concept is compatible with almost all underwater compact turbines. Nevertheless this type of investigation is desired for the most common type of suitable turbines. It also serves to evaluate the probability of small fish crossing the screen and to investigate the possibility of additional downstream migration corridors from inside the shaft.

Acknowledgments

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References

ATV-DVWK – Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. v. (2004), *Fischschutz- und Fischabstiegsanlagen – Bemessung, Gestaltung, Funktionskontrolle*. ATV-DVWK Themen, 256 S.

Cuchet, M., Hartlieb, A., Rutschmann, P. (2009), *Untersuchung des Fischverhaltens an einem geneigten Rechen*. Versuchsbericht des Lehrstuhls und der Versuchsanstalt für Wasserbau und Wasserwirtschaft, Nr.408, Technische Universität München

Cuchet, M., Mühlbauer, C., Ratschan, C., Hartlieb, A., Brinkmeier, B. (2011), *Behavioural experiments on the design of downstream fish passage facilities for potamodromous species*. 34th IAHR World Congress Brisbane

DWA – Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.v. (2010), *Fischaufstiegsanlagen und fischpassierbare Bauwerke – Gestaltung, Bemessung und Qualitätssicherung*. Merkblatt DWA-M 509 (Gelbdruck), 284 S.

Holzner, M. (2000), *Untersuchungen über die Schädigung von Fischen bei der Passage des Main-Kraftwerkes Dettelbach*. München, technische Universität, Fakultät für Landwirtschaft und Gartenbau, Dissertation 2000

Larinier, M. (2008), *Fish passage experience at small-scale hydro-electric power plants in France.* Hydrobiologia , 609 . pp. 97-108. ISSN 0018-8158

Larinier, M. and Travade, F. (2002), *Downstream migration: problems and facilities*. BFPP-Connaissance et Gestion du Patrimoine Aquatique, 364 supplément . ISSN 1297-6318

Rutschmann P., Sepp A., Geiger F., Barbier J. and Spiller S., „A new take on hydropower design“, Water Power & Dam Construction, Vol. 63, No. 3, pp. 22-25, 2011.

Schwevers, U. (2000), *Biologische Mechanismen der Fischabwanderung*, Wasser & Boden 52/4, 4 - 9.