Institute of Hydraulic and
Water Resources Engineering

TECHNISCHE
UNIVERSITÄT
MÜNCHEN

Oskar von Miller - Institut
82432 Obernach

Technische Universität München
Arcisstr. 21 • 80290 München

Monitoring of downstream passage of small fish at the TUM-Hydro Shaft Power Plant Prototype

Test report no. 429

Client: Bavarian Environment Agency (LfU)
86177 Augsburg

Obernach, June 2016

Franz Geiger

M.Sc. Stefan Schäfer
(Project Assistant)

Dipl.-Phys. F. Geiger
(Project Operator)

Univ. Prof. Dr. Rutschmann
(Director of the Institute)

Abstract

In a research project funded by the Bavarian State Ministry of the Environment and Consumer Protection the fish downstream passage at the innovative TUM Hydro Shaft Power Plant concept was investigated for fish which can physically pass through the screen. Behavior studies at a 35 kW prototype facility were conducted under nature-like but controlled laboratory conditions. Brown trout (*Salmo trutta fario*), grayling (*Thymallus thymallus*), barbel (*Barbus barbus*), minnow (*Phoxinus phoxinus*) and bullhead (*Cottus gobio*) with body lengths from 5 – 20 cm were employed. The passage distribution between the turbine and the fish downstream migration corridor as well as the injury and mortality rates during turbine passage were recorded for different flow velocities towards the screen and for different arrangements of the bypass. The results reveal that on the one hand portions of the downstream migrating or drifting fish did pass through the 20 mm horizontal screen and turbine and on the other hand portions of the fish traversed the provided downstream migration corridor. The injury and mortality rates of the fish with regard to facility passage were smaller than the turbine specific injury and mortality rates due to the passage distribution between turbine and bypass. Detailed statements depend on the respective fish species, fish sizes and facility configurations. The general influences of the parameters were assessed and the results were compared with literature references. The methodology offers prospect for a targeted adaption of hydro power plants to meet river site specific ecological requirements for fish protection.

Keywords: ecological connectivity, fish downstream migration, hydro power plant, fish experiment, fish behavior, horizontal intake plane, horizontal screen

Zusammenfassung

Im Rahmen eines vom Bayerischen Staatsministerium für Umwelt und Verbraucherschutz geförderten Forschungsprojektes wurde der Fischabstieg rechengängiger Fische am innovativen Wasserkraftkonzept Schachtkraftwerk untersucht. Hierzu wurden Fischverhaltensuntersuchungen an einer voll funktionsfähigen 35 kW Prototypanlage auf dem Gelände der Versuchsanstalt Obernach durchgeführt. Die Untersuchungen erfolgten unter naturnahen, aber kontrollierten Laborbedingungen mit Bachforellen (*Salmo trutta fario*), Äschen (*Thymallus thymallus*), Barben (*Barbus barbus*), Elritzen (*Phoxinus phoxinus*) und Koppen (*Cottus gobio*) mit Körperlängen von 5 – 20 cm. Für verschiedene Anströmgeschwindigkeiten des Rechens und Anordnungen des Abstiegskorridors wurden jeweils die Abstiegs- bzw. Abdriftverteilungen zwischen Rechen und Turbine einerseits und dem Fischabstiegskorridor andererseits, sowie die bei der Rechen- und Turbinenpassage auftretenden Verletzungs- bzw. Mortalitätsraten erfasst. Die Resultate zeigen, dass Anteile der rechengängigen Fische durch den 20 mm Rechen vor der Turbinenpassage abgehalten wurden und über den Fischabstieg ins Unterwasser gelangten. Die Verletzungs- und Mortalitätsraten hinsichtlich der Abwanderung bzw. Abdrift über die Gesamtanlage fielen aufgrund der Aufteilung der Passage zwischen Turbine und Fischabstiegskorridor entsprechend geringer aus, als die turbinenspezifischen Verletzungs- und Mortalitätsraten. Passageaufteilung sowie Verletzungs- und Mortalitätsraten hängen im Detail von der jeweiligen Fischart, Fischgröße und Anlagenkonfigurationen ab. Die Einflüsse der verschiedenen Parameter wurden untersucht und die Ergebnisse mit Literaturreferenzen abgeglichen. Das Studiendesign stellt potentiell eine gezielte Anlagendimensionierung zur Umsetzung standortspezifischer Fischschutzanforderungen in Aussicht.

Schlüsselwörter: Ökologische Durchgängigkeit, Fischabstieg, Wasserkraft, Fischverhaltensuntersuchungen, horizontale Rechenebene, Schachtkraftwerk

Table of content

List of figures

List of tables

1 Introduction

In 2011 a series of tests was conducted to assess and improve the fish protection and fish downstream migration at the TUM Hydro Shaft Power Plant. Details of the tests and the results as well as background information about the concept and the experimental approach are provided in the respective test report (Cuchet et al. 2012). The investigations were restricted to fish of rather large size and good swimming capacity. The body size disabled a passage through the screen. Furthermore, no turbine was included in the simplified test setup. The experiments revealed that the given fish species and sizes could move freely above the screen. Portions of the fish used the provided fish downstream migration corridor.

To investigate the efficiency of fish protection and fish downstream migration with regard to small fish and weak swimmers which can pass through the screen, a respective research campaign was conducted in 2013 and 2014 and partially funded by the Bavarian State Ministry of the Environment and Consumer Protection. The test series were supported and enabled by professional and material assistance of the Bavarian Environment Agency (LfU) – Unit Fish and Freshwater Ecology and the Bavarian State Research Center for Agriculture (LfL) – Institute for Fisheries, especially with regard to the fish supply. Furthermore, the fishery consultant of the district of Schwaben and the Bavarian Fishery Association (LFV) – Department for fishery, river and environment protection provided professional support. In the scope of the report these institutions are referred to as “consulting team”. Moreover, the project was surveyed by Udo Steinhörster, publicly appointed and sworn expert for fishery and fish ecology by the District Government of Upper Bavaria.

The 2011 test setup at the Hydraulic Laboratory in Obernach was complemented by a turbine and steel hydraulics constructions to provide a fully functional hydro power plant for the test procedure. Samples of small fish which could pass through the screen and the turbine were introduced to the test setup for different hydraulic situations and facility arrangements. The downstream migration routes and the resulting injury and mortality rates were recorded for each test variant and fish category. The results were analyzed in detail and evaluated statistically to assess the validity of the obtained data.

2 Methodology

The monitoring of fish downstream migration of small fish at the TUM Hydro Shaft Power Plant was conducted in the laboratory environment of the hydraulic laboratory in Obernach. For various geometric and hydraulic facility configurations fish ensembles were introduced in the head water of the hydro power facility. The fish behavior was observed for the 24 h test periods. Fish barriers in head and tail water enabled the recapture of almost all fish and the assessment of eventual fish injury or death.

2.1 Experimental Setup

The experimental setup for the fish behavior observation, i. e. the TUM hydro shaft power plant prototype, was installed in an open air lab flume. It was supplied with water from the Isar River via an up-scaled Rehbock flume gauge with about 2 m³/s capacity and 2 % nominal accuracy. The tail water surface elevation of the test section was set by gates in the downstream reach. Figure 1 shows a longitudinal section of the actual test setup. Detailed data is provided in Appendix A.

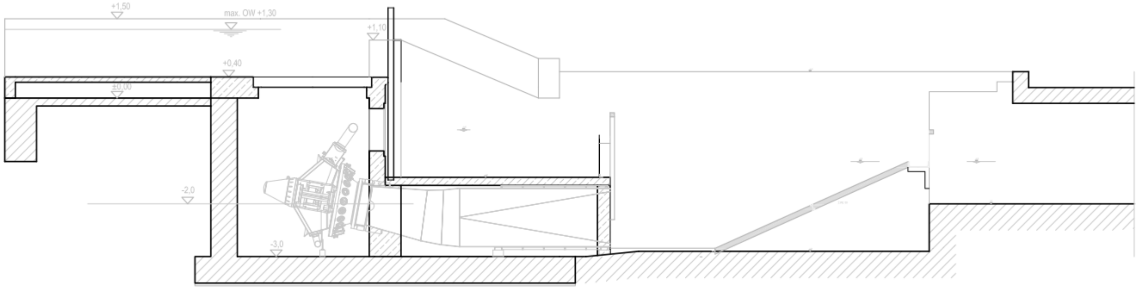

Figure 1: Longitudinal section of the test facility; Flow direction from the left to the right [m]

A double regulated Kaplan turbine with almost horizontal axis was installed in the shaft. Regulation was provided by positioning of the control device and the runner blades. The facility was not automated but controlled manually, which assured constant turbine conditions during the tests. Table 1 provides the primary turbine specifications.

Table 1: Turbine specifications of the KA75 Kaplan turbine from Geppert GmbH (A)

Head [m]	2.5
Discharge [m³/s]	1.5
Revolution [r/min.]	333
Runner diameter [mm]	750
Power [kW]	35

Figure 2 shows the turbine before being installed. The turbine was fixed to a concrete separating wall between the shaft and the tail water area. A closable opening in the wall provided access to the shaft. In the tail water section the area around the draft tube was filled and covered by concrete in order to gain smooth surfaces and simple geometry for fishing purpose.

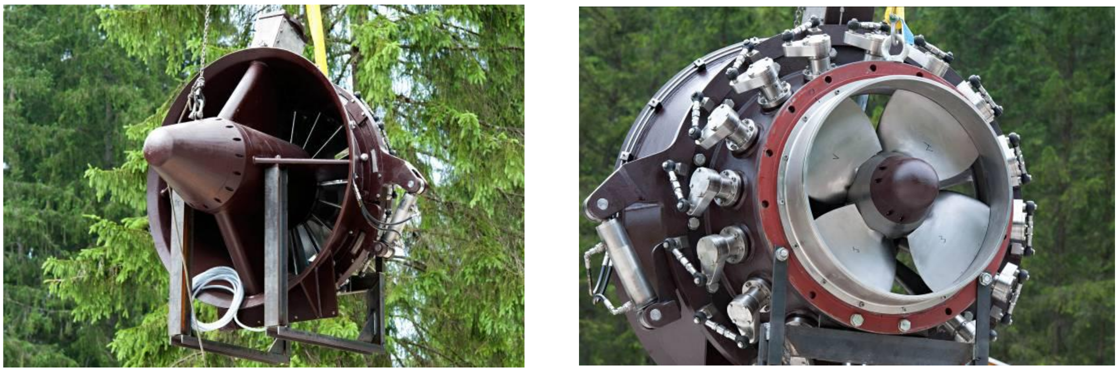

Figure 2: KA75 Kaplan turbine before being installed in the shaft

The steel hydraulics constructions were provided by Muhr GmbH (Brannenburg, Germany). The shaft was covered by a screen with 2 m x 2 m surface which featured a special bar profile and 20 mm bar clearance. It was divided in two partitions due to the trash rack cleaning installations. This circumstance was also used to implement two different cleaning techniques for simultaneous testing. A sluice gate completed the installation. It was equipped with a smoothly formed overflow profile in order to avoid fish damage. Figure 3 shows the steel hydraulic constructions and the employed bar profile. Several details of the steel hydraulics construction became of special interest during the research campaign as will be discussed later on (chapter 3.1.3).

Figure 3: Bar profile and sizes [mm] (left) and screen + sluice gate seen from the head water (right) - gate raised and without the overflow profile - see Figure 4 for the overflow profile

To provide a migration corridor from the intake area to the tail water, the sluice gate was equipped with a surface near and a bottom near opening which could be employed optionally. Each one resulted in a flow cross section of 30 cm width and 25 cm height. Details were formed to prevent fish damage during the passage. Figure 4 shows both arrangements.

Figure 4: Fish downstream migration opening variants: Surface near (left column) and bottom near (right column) positioning seen from the head water (top row) and from the tail water (bottom row)

A number of “fish barriers” were added to the hydro power setup in order to facilitate the fish passage experiments. To prevent fish from leaving the test section and also to avoid fish from the river system to enter the area, the test facility was sealed of the surrounding channel system. At the upstream end of the concrete head water floor a net with 6 mm mesh size was employed in 2013. It was replaced by a vertical plane of perforated metal plates in 2014. The resulting head water area was 7.5 m long and 10.1 m wide with 0.9 m water depth. Since floating debris from the river could block the flow cross section, all relevant material was extracted from the water in a station upstream of the flume gauge by cleanable screens and perforated metal plates.

Downstream the draft tube a sloped plane of perforated metal plates was installed. The upper end was slightly under the tail water surface and joined a small flume which served to retrieve the fish. A vertical plane of perforated metal plates joined the flume at the downstream direction to avoid any passage to the channel system. The sloped arrangement of the plates yielded a hazard-free guidance of the fish towards the flume near the surface. Both, vivid and dead fish could easily be extracted in the flume. Consequently, all observed injuries and death downstream the draft tube could be attributed to the screen and turbine passage.

To distinguish whether fish migrated through the screen and the turbine or via the bypass, an additional plane of perforated metal plates was installed in the cross section of the draft tube outlet. It was combined with metal plates which ensured a water cushion downstream of the migration corridor of at least 80 cm to prevent fish injury during bypass passage. It should be noted that any fish upstream migration via the opening in the gate or the turbine could be excluded as the flow velocities in these areas exceeded the swimming capacity of the fish. No upstream migration corridor was included in the test setup. Thus, the three installed fish barriers divided the test section in three areas and enabled the record of all fish downstream passages. Figure 5 illustrates the partitioning of the test setup.

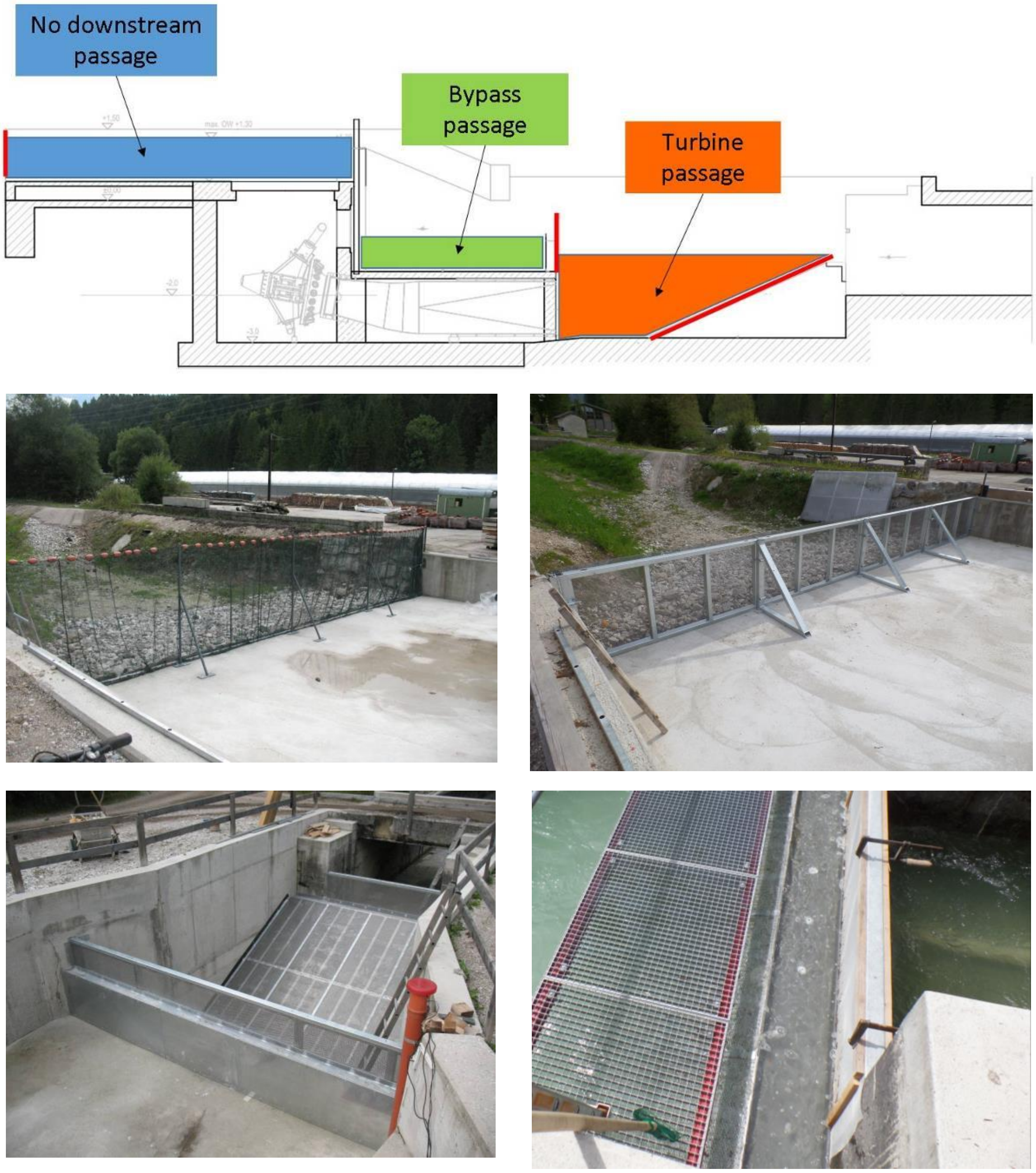

Figure 5: Fish barriers in the test setup: Schematic diagram (top – fish barriers represented as red lines), net installation upstream the test section in 2013 (middle – left) and the corresponding fish barrier in 2014 (middle – right), arrangement of metal plates in the tail water area (bottom – left) and the fish retrieval flume at its downstream end (bottom – right); Flow direction from the left to the right

The employed perforated metal plates featured stainless steel RV 10 – 14 specifications, i.e. 10 mm hole diameter. For tests with fish length smaller than 10 cm in 2014 the perforated metal plates were furthermore covered by synthetic mesh with 4 mm opening size. The construction of the fish barriers in head and tail water included a number of details to prevent any loop holes or hazard for the fish and to facilitate careful and effective fishing.

2.2 Hydraulic conditions

The fish behavior investigations were run under constant turbine service conditions. Gate and trash rack cleaner were not operated during the experiments. Floating debris were extracted from the water in a facility upstream the test setup. The head water elevation was adjusted by the turbine opening to achieve 0.9 m above the head water floor, which corresponded to the weir crest. The tail water elevation was regulated by sluice gates in the downstream channel system in order to obtain 2.5 m head. The gate position was set prior to the tests in a way that the upper edge was slightly below the weir crest. The exact position was calculated by Poleni hydraulics in order to create an overflow of 5 % of the turbine discharge. According to physical model tests and prior experiments a weir coefficient of 0.673 was employed. The actual height of the gate crest depended on the respective discharge. In order to evaluate the dependency of the fish behavior with regard to the approach flow velocity at the screen, this parameter and therefore the turbine discharge were varied. Three values were considered:

- According to common fish protection guidelines (at that time DWA 2004), a maximum velocity of 0.5 m/s at the screen was investigated. This corresponded to the turbine design discharge of 1.5 m³/s as the screen surface was dimensioned to meet these values.
- With regard to swimming capacity of weak swimmers (Dumont 2005, Ebel 2013) a maximum velocity of 0.3 m/s at the screen was considered.
- Additionally tests with a maximum velocity of 0.4 m/s at the screen were conducted to achieve a better understanding of the relation between fish behavior and flow velocity.

As the employed fish downstream migration arrangements requested an adjustment of the discharge, a set of six different hydraulic conditions was used. It is summarized in Table 2. The table also provides the theoretical average flow velocity towards the screen.

Table 2: Hydraulic parameters for the different test conditions

Bypass position	top	bottom	top	bottom	top	bottom
$v_{\text{max-screen-design}}$ [m/s]	0.3		0.4		0.5	
$v_{\text{average-screen}}$ [m/s]	0.24		0.32		0.38	
Q_{channel} [m³/s]	1.08	1.16	1.41	1.50	1.64	1.73
Q_{turbine} [m³/s]	0.96	0.96	1.28	1.28	1.50	1.50
Q_{bypass} [m³/s]	0.08	0.15	0.08	0.15	0.08	0.15
Q_{gate} [m³/s]	0.12	0.20	0.13	0.22	0.14	0.23
h_{overflow} [m]	0.054		0.066		0.073	

For all employed discharge settings the flow surface in the intake area was rather smooth with no serious vortex activity. Local vortices emerged irregularly in the corners were the sluice gate joined the weir. However, this unfavorable geometric detail did not alter the general intake hydraulics which corresponded to those from the physical model test and prior test series. Figure 6 shows the test facility in service for both downstream migration corridors and maximum discharge.

Figure 6: Tail water view of the test setup for the maximum turbine discharge and both migration corridors (surface near – left image and bottom near – right image)

It has to be noted, that the positioning of the gate was relatively imprecise with aberrations of about ± 2 mm. The turbine regulation depended on the water surface elevation and could not compensate that inaccuracy. In general the water surface elevations in head and tail water showed variations of about ± 1 cm due to slight discharge fluctuations. These were caused by the floating debris removal devices in the upstream channel system which gradually got blocked and were cleaned subsequently. The discharge fluctuations were regularly compensated by adjustments of the flume gauge. The actual discharge in the test setup altered during these adaption processes. The frequency and amplitude of the fluctuations depended on the amount of floating debris and the resulting cleaning intervals. Nevertheless, the discharge fluctuations and the resulting differences of the water surface elevations and flow velocities were restricted to small variations of the global parameters and it can be assumed that they did not considerably influence the fish behavior and the results of the investigations.

In addition to the actual fish behavioral studies a number of flow velocity measurements were conducted to verify the maximum velocities at the screen as well as the flow field distribution. The measurements were done with a 3D Nortek Field ADV probe. The measurement grid had a lateral resolution of 39 cm in both directions. It covered the whole intake plane and was positioned 4.6 cm above the screen surface. At each point the velocity for all three dimensions was recorded for at least 60 s and the time averaged velocities were calculated. The analysis of the results revealed a remarkable influence of the trash rack cleaning devices. The movable combs of the trash rack cleaner resulted in a local reduction of the flow cross section and an inhomogeneous flow field. Consequently the maximum approach flow velocities towards the screen were higher than scheduled. The trash rack cleaner combs on the orographic right field were dismounted for the fish experiments to reduce their influence as far as possible. Figure 7 provides an image of the employed screen with cleaner combs only installed in the orographic left field of the screen plane. These could not be removed due to statically reasons.

Figure 7: The employed screen as seen from the right bay

The measured flow velocity distributions are illustrated in Figure 8. The maximum velocities at the screen were remarkably above the design values as the division in two screen fields and the trash rack cleaning device in the orographic left field did deactivate about 20 % of the intended flow cross section. For convenience the documentation and discussion of the results refers to the design values for the approach flow velocity. This implies a conservative interpretation with regard to fish protection and fish downstream passage.

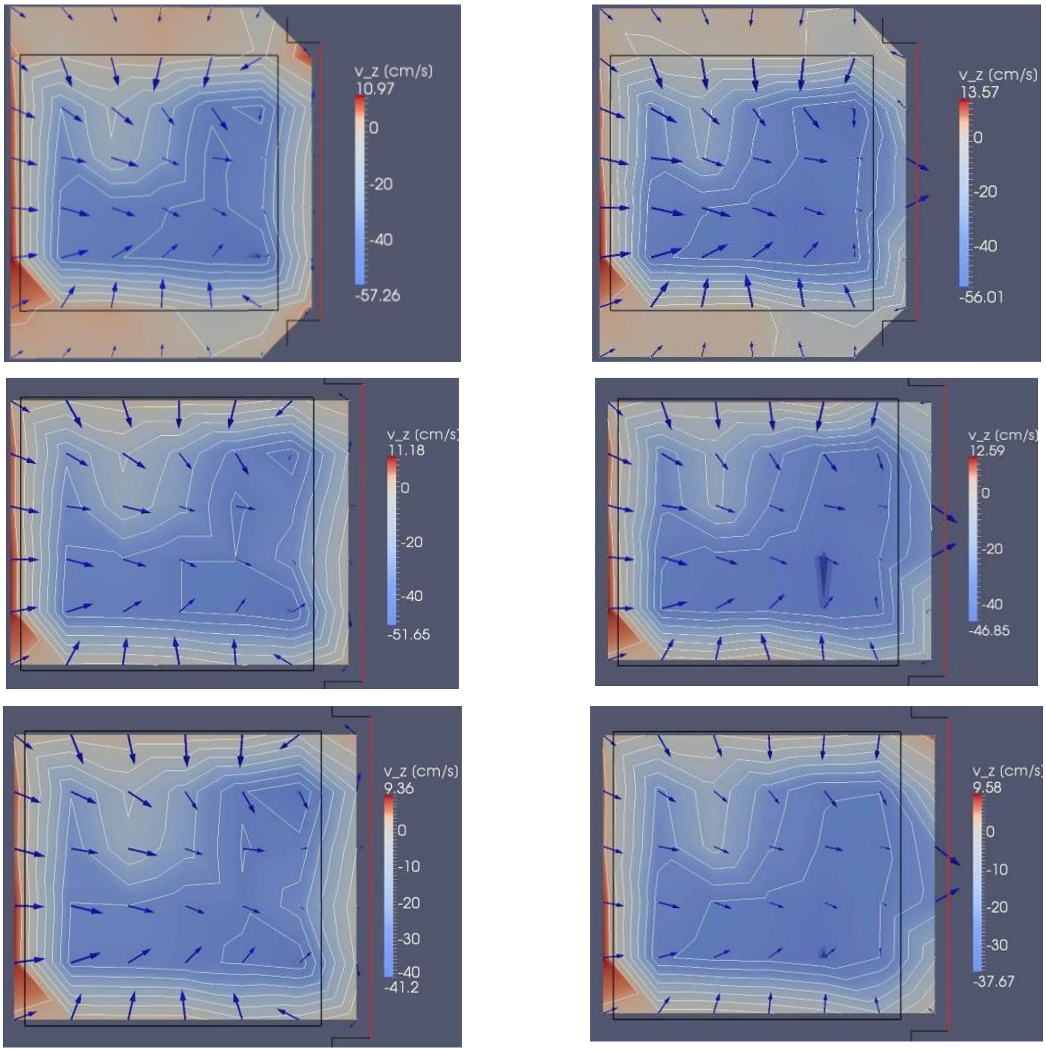

Figure 8: Visualization of the flow field measurement at the screen for the setup employed during the fish behavior experiments; Design velocities of 0.5 m/s (top line), 0.4 m/s (middle line) and 0.3 m/s (bottom line); Surface near opening (left column) and bottom near arrangement (right column); Main flow direction from the left to the right (equals the x-axis); The legends for the vertical velocity (z-axis) provide the maximum and minimum values measured; The black rectangle indicates the shaft and the red line represents the position of the gate

To assess the flow velocities in the bottom near downstream migration corridor an exemplary measurement was conducted for the hydraulic situation with a maximum velocity of 0.4 m/s towards the screen. Results are summarized in

Table 3. As Figure 8 illustrates the other discharge conditions did not entail relevant changes in this part of the flow field and one can assume similar velocities in the migration corridor. It can be noted that the velocity in the main flow direction is lower than the corresponding value during the test series with large fish (Cuchet et al. 2012). This can be explained by the geometry which was added

downstream of the opening as recommended by river ecologists (e.g. Udo Steinhörster) in order to improve downstream migration acceptance.

Table 3: Velocity measurement in the bottom near downstream migration corridor for a maximum velocity of 0.4 m/s towards the screen (time averaged values for 60 s at 10 Hz sample rate)

	v_x [cm/s]	v_y [cm/s]	v_z [cm/s]
Time Average	77.01	-4.85	-35.20
Standard deviation	3.31	6.11	3.17

2.3 Fish material

Laboratory investigations of fish behavior as well as the use of fish at hydro power plants for monitoring purpose are classified as bioassay. The present studies were approved by the District Government of Upper Bavaria. Whereas the investigation under laboratory conditions enabled in principle the targeted insertion of fish ensembles and a scientific test program, the test conduction with wild fish had to accommodate with the actual fish availability and the nature like environment involved seasonal influences.

According to the recommendations of the consulting team test with brown trout (*Salmo trutta fario*), grayling (*Thymallus thymallus*), barbel (*Barbus barbus*), bullhead (*Cottus gobio*) and minnow (*Phoxinus phoxinus*) were intended. The maximum fish length was scheduled with 20 cm since the bar clearance was 20 mm and all fish were meant to be able to pass through the screen (Ebel 2013). In order to keep the fish barriers clean and the hydraulic conditions constant, all floating debris from the river water had to be extracted upstream of the test section. With regard to this technical and practical challenge a minimum fish size of 5 cm was defined. This required mesh sizes of about 5 mm. The fish lengths range from 5 cm to 20 cm was divided in three equidistant groups (5 - 10 cm, 10 - 15 cm and 15 - 20 cm body length). The fish stocking in the tanks as well as the test conduction were done separated according to these size categories, in order to prevent predation among the fish. In some cases this could not be realized due to actual fish supply. The different fish species were mixed during the stocking and the tests for time effective test execution. As far as possible fish from natural rivers were employed to exclude behavioral differences to hatchery fish (Adam et al. 2011). For grayling and minnow only fish from hatcheries were used due to difficulties in obtaining wild fish of these species. In order to exclude learning effects and cumulative stress and injury, each fish was introduced just for one time into the experiment. According to statistical considerations a number of 32 fish of each species was originally intended for each test. With regard to the fish availability the actual fish numbers remained smaller in some cases. To achieve a larger statistical data bases the number of inserted fish per species and test was increased after test number 11 and up to 64 fish were inserted if available. In detail the actual input for each test is provided in Table 8.

Table 4 summarizes the employed fish charges. All fish from natural sites were caught by electro fishing. The fish were transported to the test facility several days before the tests started and stocked in circular flow tanks with water supply from the channel system in order to adapt them to the test conditions. The circular flow tanks were supplied with enrichment (e.g. shelter structures) for the fish in order to provide shelter and reduce stress. The fish were not fed during the stocking in the tanks or during the tests. Random samples of the natural fish assured good physical conditions concerning the health condition and possible infections (see Appendix D). No relevant physical problems aroused in the tanks. A number of fish “disappeared” in the tanks and during the experiments (see also chapter 3.1.2). At least for the fish tanks, this can only be explained by predation between the fish. The losses in the stock entailed further aberrations of the fish numbers which were introduced into the individual tests.

Table 4: Fish charges employed during the test series; the column for the fish length provides the targeted fish length range and the actual fish length range in brackets

Tests number	Origin	Supplier	Species	Length range [cm]
1 – 6	Murnauer Bach / Wielenbach	LfU – Ref. 54	Brown trout	15 – 20
1 – 6	Fish hatchery Wielenbach	LfU – Ref. 54	Grayling	15 – 20
7 – 10	Lech River and Wielenbach	LfU – Ref. 54	Brown trout	10 – 15 (8 – 15)
7 – 10	Fish hatchery Wielenbach	LfU – Ref. 54	Grayling	10 – 15 (9 – 12)
7 – 10	Ilz River	LfL – IFI	Brown trout	10 – 15 (9 – 12)
7 – 10	Ilz River	LfL – IFI	Bullhead	10 – 15 (5 – 12)
11	Hartbach and Kimsbach (Wielenbach)	LfU – Ref. 54	Brown trout	15 – 20
11	Fish hatchery Wielenbach	LfU – Ref. 54	Grayling	15 – 20
12	Wielenbach	LfU – Ref. 54	Brown trout	5 – 10 (8 – 10)
12	Fish hatchery Wielenbach	LfU – Ref. 54	Grayling	10 – 15 (10 – 15)
12	Wielenbach	LfU – Ref. 54	Bullhead	5 – 10 (6 – 10)
12	Fish hatchery Wielenbach	LfU – Ref. 54	Minnow	5 – 10 (5 – 8)
13 – 15	Wielenbach	LfU – Ref. 54	Brown trout	5 – 10 (7 – 13)
13 – 15	Fish hatchery Mauka	LFV Bayern	Grayling	5 – 10 (5 – 8)
13 – 16	Salgen	FFB Schwaben	Bullhead	5 – 15 (5 – 10)
15 – 16	Uffinger Ach	LfU – Ref. 54	Barbel	(4 – 20)
16 – 18	Wielenbach	LfU – Ref. 54	Brown trout	10 – 15 (10 – 15)
17 – 18	Fish hatchery Mauka	LFV Bayern	Brown trout	10 – 15 (10 – 16)
17 – 18	Fish hatchery Salgen	FFB Schwaben	Grayling	10 – 15 (10 – 18)
19 – 21	Fish hatchery Mauka	LFV Bayern	Brown trout	15 – 20 (16 – 25)
19 – 21	Fish hatchery Salgen	FFB Schwaben	Grayling	15 – 20 (14 – 22)

The size distribution of the provided fish ensembles differed from the scientific program. A number of fish were smaller or larger than the scheduled size categories. In order to retain a maximum data basis the fishing numbers for the respective individuals were kept in the data basis if consistent with the test concept. Results for fish with 4 - 5 cm body length were kept in the considerations since this threshold value was just scheduled with regard to the fish barriers and actualized fish barriers were sufficient to disable passage for these individuals. To assure that all fish could physically pass through the screen tests with the largest individuals were conducted. The fish were put on the screen or an equivalent gap of 20 mm width. Brown trout up to 22.5 cm body length could pass through the screen. Accordingly, the respective results were kept in the analysis. Three brown trout larger than 23 cm were not considered in the documentation or the data processing. However, the passage of large fish did include contact with the bars, especially with the pectoral fins when the fish passed with positive rheaotaxis. This might have influenced the passage probability through the screen. Furthermore, the largest individuals of the bullhead featured body width larger than 20 mm. As tests revealed these individuals could nevertheless pass through the screen as the height of the fish was smaller than 20 mm.

Whereas the fish length resolved analysis of the results was originally scheduled according to the three size categories the actual fish lengths were used for more precise considerations. Thus, the body lengths of all fish were measured after the observation period in the fish tanks. The choice of this instant of time avoided the influence of handling on the observation of damage rates. No individual fish lengths were available for tests number 1 - 6 and 11. These fish charges features rather homogeneous fish sizes and were approximated by typical values for exemplary records. For test number 7 only those fish which passed through the turbine were measured. Furthermore, for several tests single fish got missing during the observation period in the tanks due to predation. Missing data was completed by reconstructed fish lengths. Therefore the average value of the fish length of all remaining fish of similar species and passage comportment and the respective standard deviation were considered. Using the values for the specific test the lengths of the missing fish were calculated under the approximation of a normal distributed fish length. Figure 9 shows the size distribution for all covered fish. Table 5 provides the average body lengths and the respective standard deviations for each species.

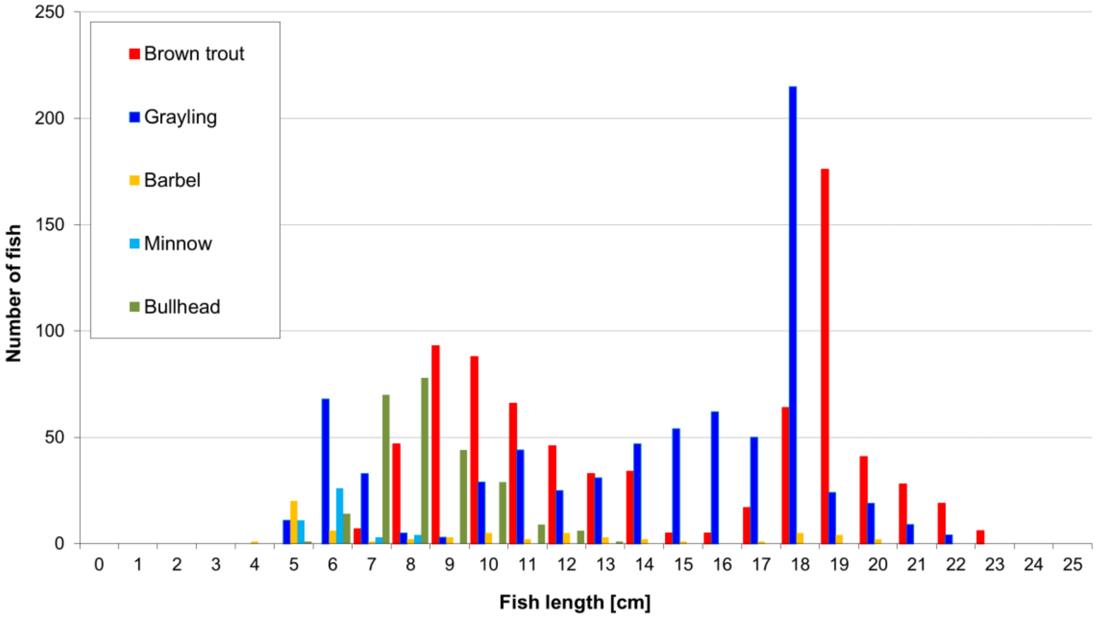

Figure 9: Size distribution of all covered fish

Table 5: Average body length and standard deviation of all registered fish

Fish species	Number of fish	Averaged body length [cm]	Standard deviation [cm]
Brown trout	775	14.3	4.5
Grayling	733	14.3	4.4
Barbel	63	9.9	5.1
Minnow	44	5.9	0.8
Bullhead	252	8.1	1.4

2.4 Experimental procedure

The experimental procedure followed a standardized protocol. After establishing the relevant geometric and hydraulic condition the sample of test fish was introduced into the headwater area. The introduction was done smoothly by flooding the transport container with all fish in the head water near the right bay and the upstream fish barrier. The container was subsequently slowly turned around and removed from the water.

Discharge, water surface elevations and turbine status were kept constant during the 24 h test duration. The water supply at the gauge flume was adjusted and recorded in adaption to the necessities with regard to floating debris load and the resulting affection of the discharge. The interval ranged from 10 minutes to one hour. The fish barriers were controlled at least every hour. Injured or dead fish were removed from the test site and treated in a prescribed manner (bioassay obligations). Four underwater video cameras (2 x Panasonic CCD 420TVL, 2 x Mangrove CM-DWL60CH), one at each corner of the screen, were employed for the documentation of the fish behavior at the screen and at the downstream passage opening. A motion detection software was employed to economize the recorded data (G01984 V3 and Fa. VC-12765). Two cameras were equipped with infrared illumination and image aquisition in order to get images during darkness without disturbing the fish behavior by artificial illumination. The complementary record of abiotic parameters was done by a WTW Multi 3430 with sensors for dissolved oxygen, pH-value, conductivity and temperature and a measurement interval of 10 minutes. A luxmeter was mounted near the head water fish barrier to assess the illumination with 1 minute measurement interval. The turbidity was analyzed with several hours interval by a WTW Turb 430. The position of the measurement devices for abiotic parameters and the insertion point of the fish are specified in Appendix A – Test Section.

After 24 h test duration the migration corridors were blocked by grids which disabled any further fish movement. Subsequently the discharge in the test facility was stopped and the water surface elevations were reduced. All fish were caught by hand nets, the respective location, the species and possible injuries were recorded and they were transferred to circular flow tanks. Several tanks were employed to stock the fish separated according to the location they were found. The fish were observed for at least 48 h in case of head water and fish downstream migration tail water. Those fish which had passed through the turbine were observed for 96 h. This enabled the identification of eventual long term damages, e.g. due to internal injuries. After the observation period the fish were investigated once again. Possible injury and the body length of the fish were recorded.

The injury was assessed by the physical appearance of the fish which included visible injuries as well as behavior aspects to account for internal injuries. Details were originally aligned to common monitoring approaches (Holzner 2000) and bioassay obligations. Since the number of injured and killed fish turned out to be manageable the documentation was not categorized but individual. Minor mechanical injury, i.e. the loss of single scales, could not be accounted for as this phenomenon was already present due to fishing and handling. An entire registration of all scale loss would require high handling effort and cause damage itself. Relevant cases of scale loss or skin damage would have been recorded and furthermore would have become evident during the observation period. Actually such cases did not occur.

If the cause of death was not obvious the fish were conserved and transferred to veterinary examinations (x-ray, autopsy, histology). Potential internal injury was not investigated if fish showed serious and lethal mechanical damage during the first test series. Since test number 13 all fish which were killed or seriously injured, were conserved and transferred for histological investigation of potential internal damage. Since the adequate conservation process for this investigation requires long exposure times, the actual histological analysis and its results were not available at the time of the elaboration of this documentation. The enhanced histological investigation was done in cooperation with the Ludwig-Maximilians-Universität München (LMU) and was beyond the scope of the actual project. Procedure and the results will be published subsequently.

Course of events

During the project runtime 21 single tests were started and 1974 fish were introduced into the experiment. Table 6 provides the boundary values of the abiotic parameters for all conducted tests. Two tests had to be stopped already after 12 h due to high floating debris load and resulting blocking of the fish barriers. Furthermore, test number 6 had to be aborted due to bad weather conditions and no migration or fishing results are available for this test (only video material). With regard to the relatively constant boundary conditions for all other experiments one can assume a good comparability of the results

Prior studies, with fish larger than the bar clearance, revealed ecological favorable conditions for the bottom near bypass configuration (Cuchet et al 2012) and first tests with small fish in 2013 confirmed this tendency. Therefore, the bottom near configuration was apparently ecologically favorable and consequently more relevant for future implementations of the hydro power concept. Thus the test series in 2014 focused exclusively on the bottom near arrangement in order to achieve better data basis for the results of this arrangement within the limited time schedule.

Table 6: Experimental boundary conditions during each 24 hours test period, minimum and maximum values recorded

Test No.	Start- Date & Time	Test duration [h]	Opening position	Velocity [m/s]	Temperature [°C]	Dissolved oxygen [mg/l]	pH-value	conductibility [mS/cm]	Light intensity [10^3 Lux]	Turbidity [NTU]
1	23.09.2013	24	surface	0.3	7	11	8.3	287	0	-
	10:48				10	11.9	8.3	291	65	-
2	25.09.2013	24	surface	0.4	7	11.4	8.2	289	0	20.7
	10:30				9.3	12	8.3	291	77	24
3	01.10.2013	24	surface	0.5	7.1	11.6	8.2	290	0	13.7
	11:00				8.2	12.2	8.3	292	18	16.9
4	03.10.2013	24	bottom	0.5	7.1	11.3	8.2	289	0	11.4
	10:13				9.6	12.2	8.3	293	40	16.5
5	08.10.2013	24	bottom	0.4	8	11.6	8.3	294	0	7.2
	11:00				9.2	12	8.3	297	30	8.2
6	10.10.2013	-	bottom	0.3	7.7	11.7	8.3	292	0	-
	10:30				7.8	11.9	8.4	296	15	-
7	14.10.2013	24	bottom	0.3	5.7	11.9	8.3	299	0	6.4
	10:50				7.8	12.6	8.4	305	63	8.8
8	17.10.2013	24	bottom	0.4	5.5	11.7	8.3	299	0	13.4
	10:45				8.2	12.7	8.3	303	65	22.3
9	21.10.2013	24	bottom	0.5	6.8	11.1	8.3	298	0	7.1
	10:45				8.9	11.8	8.4	301	57	9.9
10	24.10.2013	24	surface	0.5	6.9	11.1	8.3	290	0	5.7
	11:15				9	11.8	8.4	299	25	12.1
11	27.05.2014	24	bottom	0.5	6.9	10.3	8.3	290	0	9.9
	11:05				9.4	11.8	8.4	299	100	19
12	02.06.2014	12	bottom	0.5	7.8	10.5	8.3	285	0	3.71
	11:30				10.5	11.6	8.5	289	94	6.52
13	07.08.2014	24	bottom	0.3	8.7	10.4	8.5	296	0	42
	10:35				11.6	11.2	8.6	300	105	47.4
14	11.08.2014	12	bottom	0.4	10.7	10.5	8.4	277	0	38.7
	11:05				11.5	10.7	8.6	295	23	42.2
15	18.08.2014	24	bottom	0.5	8.3	10.3	8.5	300	0	25
	10:50				11.9	11.3	8.7	303	99	42.1
16	20.08.2014	24	bottom	0.5	8.2	10.9	8.5	298	0	12.8
	10:40				9.4	11.3	8.6	302	38	19.4
17	26.08.2014	24	bottom	0.4	8.5	8.9	8.6	300	0	4.65
	10:30				13	11.2	8.7	305	39	6.9
18	28.08.2014	24	bottom	0.3	8.3	10.3	8.6	283	0	3.8
	10:15				11.6	11.4	8.7	306	98	4.47
19	01.09.2014	24	bottom	0.4	8	11.1	8.5	292	0	36.1
	10:07				8.8	11.4	8.6	306	10	49.4
20	03.09.2014	24	bottom	0.5	8	10.6	8.6	300	0	17.9
	10:05				10.6	11.4	8.8	308	40	19.4
21	08.09.2014	24	bottom	0.3	8.6	10.5	8.6	297	0	4.9
	10:24				11.4	11.3	8.8	308	95	5.2

3 Results and discussion

The results of the laboratory investigations are summarized in chapter 3.1 with a differentiation between the visual observations of the fish behavior, the records of the downstream passage and the observed injury and mortality at the facility. The major issues “passage distribution between bypass and turbine” and “injury and mortality rates due to the turbine passage” are furthermore discussed in chapter 3.2 and chapter 3.3.

3.1 General results

3.1.1 Fish behaviour observations

The visual observation of the fish behaviour was hindered by the high water turbidity during almost all tests (c.f. Table 6). Only for some tests fish movement was visible from the outside or by the underwater video devices. The recorded material did not include sequences of fish in contact with the screen and can thus not clarify the screen passage process and potential damage due to the passage through the screen. Figure 10 shows examples of the video documentation.

Figure 10: Grayling with about 11 cm body length (left image) and brown trout with about 18 cm body length (right image) above the screen

As found during similar experiments (Cuchet et al. 2012) most fish rested near the insertion point for a certain period (30 min. - 1 h) before starting to explore the head water area. During periods of rather low turbidity swarms of grayling could be observed as they were traversing the headwater area, including the intake area. In one case one grayling of a swarm was drifted across the gate overflow to the tail water when the swarm passed near the gate. Brown trout, barbel, minnow and bullhead stayed mostly covered and were rarely observed.

3.1.2 Passage observations

Thanks to the fish barriers in the tail water area the downstream passage of all fish could be recorded. During the tests 670 fish moved or drifted to the tail water. 437 of them (65 %) passed through the bypass and 233 (35 %) got through the turbine. Individual fish of all employed species and size categories went unharmed through both passage options (bypass and turbine). In general the passage distribution i.e. the partitions of fish which passed through the turbine or the bypass depended on the respective fish and facility specifications, i.e. the fish species, the fish length, the bypass configuration and the approach flow velocity. The results are summarized in chapter 3.1.4. They are discussed in detail in chapter 3.2.

It remained unclear to which extend the passage was voluntary by active swimming or whether the fish were drifted to the tail water when their swimming capacity was exceeded in specific situations at screen or bypass. In general the fish were not forced into the intake area but could remain in the head water area where rest zones with low flow velocities were given. The theoretical average flow velocity in the head water area was < 0.12 m/s for the smallest and < 0.19 m/s for the largest discharge. The actual flow velocity in both junction areas of bank and weir tended towards zero. About 34 % of the inserted 1974 fish moved to the tail water. The proportion of migration itself was not an issue of this investigation. It was influenced by different environmental factors but also by the test conditions (Schwevers 2000). Related statements cannot be transferred to other river sites.

The regular inspection of the fish barriers in the tail water (at least once per hour) enabled some auxiliary time resolved observations of the downstream passage behaviour. During the tests with small grayling and minnow relatively large partitions of the inserted fish moved to the tail water and most of them could be extracted at the fish barriers within the first few hours of the test duration. This might be explained by the relatively low swimming capacity of these small fish (mostly 5 - 6 cm body length) of hatchery origin. Furthermore, some of the bullhead which passed through the turbine could be extracted at the fish barriers during the test period. This occurred mostly during the night/darkness, i.e. between 10:00 p.m. and 5:00 a.m.. Half of the injured brown trout (6 of 12) were found at the downstream fish barrier 30 minutes to 4 h after the test had started.

Despite the high efforts with regard to the fish barriers and the separation of fish size categories, a number of 28 fish could not be retrieved from the test section after the tests. This concerned mostly small fish. Predation was most likely to be responsible for the fish loss. Although there was regular activity around the test section one could not completely exclude the possibility of raptor attacks, e.g. by herons which were present in the surrounding area of the laboratory. Furthermore, a number of fish could not be retrieved in the fish tanks. As these were covered by grids, any transfer to the outside can be excluded. Thus loss of fish had to be caused by predation among the fish. Nevertheless, the overall recapture rate during the experiments was about 99 %. Those fish which could not be retrieved were not considered in the analysis of passage distributions or injury and mortality rates.

3.1.3 Injury and mortality observations

38 fish got killed during the turbine passage. This corresponds to 16 % of the fish which passed through the turbine (N = 233) and to 6 % of those which passed to the tail water (N = 670). 10 more fish showed injury which put in question whether the individual would have survived in a natural river. This corresponds to 4 % of the fish which passed through the turbine and to 1 % of those which passed to the tail water. To account for the uncertain survival chances for injured fish, the documentation and analysis was differentiated with regard to injured fish and dead fish. These values represent a bandwidth for the ecological interference on downstream passing fish. Furthermore, the analysis of injured or killed fish was conducted in relation to those fish which passed through the turbine on the one hand side and in relation to all fish which passed to the tail water on the other hand side. This enables the assessment of the turbine specific attributes as well as the hydro power facility.

All investigated species and all employed size categories were concerned by mortality due to turbine passage. The injury and mortality rates depended on the underlying fish and facility specifications. The obtained values are summarized in chapter 3.1.4. Details with regard to the fish lengths and a discussion of the results are provided in chapter 3.3. The majority of the injured or killed fish showed mechanical damage (29 individuals) and mostly severe mechanical injury (runner blade strikes with serious cutting wounds) with instant loss of life (19 individuals). Furthermore, a number of eye damage was observed (10 individuals). Figure 11 shows typical damage schemes.

Figure 11: Typical damage schemes: Grayling with transection (left), grayling with eye damage (middle) and bullhead with injured back (right)

During the test series in 2013 the reason of death for one brown trout with 10 cm body length was not obvious. Only eye damage was visible. The subsequent veterinary investigation could not clarify the cause of death. X-ray image and medical report are provided in Appendix C and Appendix D. Only in one case fish which had undergone the turbine passage died during the 96 h observation period: Two minnows (5 - 6 cm body length each) were found dead after 72 h observation time. It should be noted that several minnows which passed through the bypass or stayed in the head water also died in the respective observation tanks. Thus the cause of death remains unresolved. In order to achieve an upper limit for fish damage due to turbine passage, both individuals were counted as injured. Moreover, a number of injured fish survived the observation period but had bad prospects for recovery and survival in natural rivers. In detail three grayling with eye damage, one grayling with a wound on the back, three bullheads with wounds on the back area and one brown trout with a hematoma on the back were concerned. These individuals were also recorded as injured fish. A photo documentation of all injured fish is provided in Appendix C.

During the test series a number of fish were found dead at several locations of the test setup which were not connected to turbine damage. One grayling died in a gap (c.f. Figure 3) between the screen areas at the end of test number 1. Subsequently all gaps were closed by fill-ins. Furthermore, several fish died due to a cleft near the horizontal sealing of the sluice gate. Brown trout, grayling, bullhead and mostly fish of smaller sizes were affected. These fish were probably seeking cover in the corner between the gate and the floor and could not leave the position as a slight leakage created a suction effect. Any movement of the gate resulted in severe and lethal mechanical injury. Figure 12 shows details and examples.

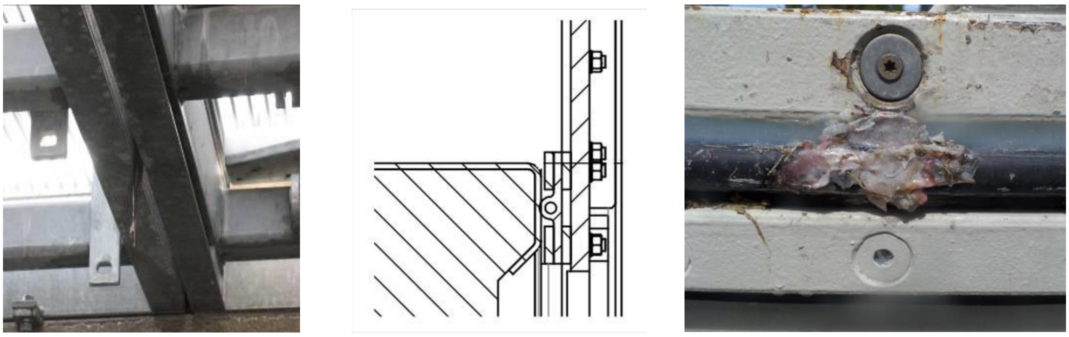

Figure 12: The gap between both screen areas (left), a longitudinal section of the horizontal sealing between the gate and the floor (middle) and a brown trout (~ 10 cm body length) killed at the sealing (right)

The observation of fish mortality at the steel hydraulics construction shows the importance of fish friendly design at all instances. To avoid such damage, the sealings have to be designed with regard to fish protection. However, it is independent of the shaft hydro power concept and the concerned fish were not considered in the analysis of passage or mortality rates. The critical construction details that led to the death of fish have to be accounted for further development of power plants.

3.1.4 Basic Data

The fishing records provided specified information for each fish species, fish size and facility configuration. The passage distribution and the injury and mortality rates with regard to turbine passage and facility passage were deduced from the respective fish numbers. Table 7 provides a summarized description of the employed terminology. In general the results depended on the particular facility and fish specifications. The deduced passage distributions, the injury and mortality rates include statistical spread according to the respective case numbers. The recorded data and the related results for each test are documented in Table 8. It should be noted that the results cannot be directly transferred to other hydro power designs or concepts, as details depended on various influences. An adequate transfer process is required.

Table 7: Definition of the employed terminology

Term	**Meaning / definition**
Bypass passage	Number of fish which passed through the bypass
Turbine passage unharmed	Number of fish which passed through the turbine with no indication of relevant injury, also after 96 h observation period
Turbine passage injured	Number of fish which passed through the turbine alive but with serious injury or which died during the observation period
Turbine passage dead	Number of fish which passed through the turbine and were killed or wounded with evident lethal consequence
Tail water	Total number of fish which passed to the tail water (bypass + turbine)
Passage distribution / Bypass passage partition	Number of fish which passed through the bypass divided by the total number of fish which passed to the tail water
Injury rate – facility	Number of fish which passed through the turbine with injury (lethal and non-lethal) divided by the total number of fish which passed to the tail water
Injury rate – turbine	Number of fish which passed through the turbine with injury (lethal and non-lethal) divided by the total number of fish which passed through the turbine
Mortality rate – facility	Number of fish which passed through the turbine and were killed divided by the total number of fish which passed to the tail water
Mortality rate – turbine	Number of fish which passed through the turbine and were killed divided by the total number of fish which passed through the turbine

Table 8: Test conditions and fishing records for all tests; see Table 7 for the terminology; “Input” refers to the amount of introduced fish

	Facility and fish specifications					Fishing observations				
Test number	Bypass config.	Approach flow velocity [m/s]	Fish species	Fish length category [cm] range	Input	Tail water	Bypass passage	Turbine passage unharmed	Turbine passage injured	Turbine passage dead
1	surface	0.3	Grayling	15--20	33	6	6	0	0	0
1	surface	0.3	Brown trout	15--20	27	3	3	0	0	0
2	surface	0.4	Grayling	15--20	32	2	1	1	0	0
2	surface	0.4	Brown trout	15--20	28	8	7	0	0	1
3	surface	0.5	Grayling	15--20	32	3	1	1	0	1
3	surface	0.5	Brown trout	15--20	28	6	5	1	0	0
4	bottom	0.5	Grayling	15--20	32	3	3	0	0	0
4	bottom	0.5	Brown trout	15--20	28	8	7	0	0	1
5	bottom	0.4	Grayling	15--20	32	3	3	0	0	0
5	bottom	0.4	Brown trout	15--20	28	1	1	0	0	0
6	bottom	0.3	Grayling	15--20	30	0	0	0	0	0
6	bottom	0.3	Brown trout	15--20	28	0	0	0	0	0
7	bottom	0.3	Grayling	10--15	25	7	7	0	0	0
7	bottom	0.3	Brown trout	10--15	25	10	9	0	0	1
7	bottom	0.3	Bullhead	10--15	25	8	2	6	0	0
8	bottom	0.4	Grayling	10--15	25	8	1	6	0	1
8	bottom	0.4	Brown trout	10--15	25	10	8	1	0	1
8	bottom	0.4	Bullhead	10--15	25	7	5	2	0	0
9	bottom	0.5	Grayling	10--15	25	0	0	0	0	0
9	bottom	0.5	Brown trout	10--15	25	10	3	5	0	2
9	bottom	0.5	Bullhead	10--15	25	6	1	5	0	0
10	surface	0.5	Grayling	10--15	16	7	4	3	0	0
10	surface	0.5	Brown trout	10--15	7	6	3	3	0	0
10	surface	0.5	Bullhead	10--15	23	6	1	5	0	0
11	surface	0.5	Brown trout	15--20	28	8	7	0	1	0
11	bottom	0.5	Grayling	15--20	32	7	5	2	0	0
12	bottom	0.5	Brown trout	5--15	64	12	4	6	0	2
12	bottom	0.5	Grayling	5--15	58	39	33	5	0	1
12	bottom	0.5	Bullhead	5--15	54	25	12	11	2	0
12	bottom	0.5	Minnow	5--15	49	37	24	9	2	2
13	bottom	0.3	Grayling	5--10	28	23	16	5	0	2
13	bottom	0.3	Brown trout	5--10	40	19	17	1	0	1
13	bottom	0.3	Bullhead	5--10	32	26	24	1	0	1
14	bottom	0.4	Grayling	5--10	27	23	11	8	2	2
14	bottom	0.4	Brown trout	5--10	40	14	8	6	0	0
14	bottom	0.4	Bullhead	5--10	32	30	25	5	0	0
15	bottom	0.5	Grayling	5--10	64	56	8	40	1	7
15	bottom	0.5	Brown trout	5--10	40	15	5	9	0	1
15	bottom	0.5	Bullhead	5--10	32	25	20	3	1	1
15	bottom	0.5	Barbel	5--10	35	23	7	16	0	0
16	bottom	0.5	Brown trout	10--15	45	6	2	3	0	1
16	bottom	0.5	Bullhead	10--15	19	15	9	6	0	0
16	bottom	0.5	Barbel	10--20	29	18	13	3	0	2
17	bottom	0.4	Grayling	10--15	60	7	5	2	0	0
17	bottom	0.4	Brown trout	10--15	60	10	8	2	0	0
18	bottom	0.3	Grayling	10--15	49	7	6	1	0	0
18	bottom	0.3	Brown trout	10--15	60	13	13	0	0	0
19	bottom	0.4	Grayling	15--20	60	44	39	0	0	5
19	bottom	0.4	Brown trout	15--20	64	5	5	0	0	0
20	bottom	0.5	Grayling	15--20	60	11	8	1	1	1
20	bottom	0.5	Brown trout	15--20	64	6	6	0	0	0
21	bottom	0.3	Grayling	15--20	56	9	7	1	0	1
21	bottom	0.3	Brown trout	15--20	64	9	9	0	0	0

The fish length range in Table 8 refers to the intended fish length for the particular test. The actual body lengths of the supplied fish slightly differed in several cases. This was accounted for by measuring the fish length. Furthermore, identical facility and fish specifications were employed in several tests to achieve higher case numbers and better statistical validity. Table 9 provides the regrouped data set with summarized results for each combination of facility and fish specifications. This table accounts for the actual fish lengths. The fish which did not fit in the design fish length categories were reported in two additional lines.

The 670 fish which got to the tail water were distributed over 50 categories of fish species, fish sizes, approach flow velocities and bypass corridor configurations. The resulting case numbers for the individual combinations were relatively small. The fish numbers in the column “tail water” should be accounted for, to assess the statistical data basis for the results concerning the passage distribution. The case numbers for the injury and mortality rates were respectively smaller. To evaluate the accuracy of the results, a statistical consideration of the confidence intervals for the passage distribution was conducted with Clopper-Pearson intervals. For a 95 % confidence level the actual passage distribution is located in an interval [CI-, CI+] around the observed value. A confidence interval consideration for the injury and mortality rates was not indicated with regard to the small case numbers of the individual parameter combinations.

Apart from the individual values for each combination of facility and fish specifications the recorded data also contains information about general dependencies of these results on the investigated parameters. These relations are discussed in chapter 3.2 and chapter 3.3. The discussion is facilitated by cm-resolved fish length data from the measurement of the actual fish lengths. To obtain a larger data basis for the consideration of single parameters the results for other parameters had to be pooled. Thus the results depend in detail on the species and size distributions of the underlying fish ensembles as well as on the test conditions during the test series. As the scientific program was subjected to numerous influences (availability of fish, downstream passage partitions, test feasibility, etc.), the pooled data was in general not balanced. Diagrams show the numbers and partitions of migrated or drifted fish in dependency of the fish length for each considered parameter. These diagrams feature the respective fish numbers and provide the cm-resolved data basis. With regard to the editorial design these graphics are summarized in Appendix B for most cases.

Confidence intervals (based on Clopper-Pearson intervals and 95% confidence level) are provided for a number of considerations to evaluate the statistical uncertainty of the respective results in the discussion. Furthermore, a statistical consideration of the (mm-resolved) data by linear regression and ancova analysis (R version 3.1.1) was conducted to assess the dependencies of the migration distribution and the injury and mortality rates on the bypass configuration, the approach flow velocity, the fish species and the fish length. The relations were considered to be statistical significant if the related p-value was smaller than 0.05. In the scope of the project a full model on the one hand side and models for single species on the other hand side were examined. The employed linear approach is not suitable to explain the actual fish behavior but to evaluate the reliability of the major trends. As shown in the following discussion the data contains complex relations which require an enhanced statistical modelling for a complete coverage. Such considerations were beyond the scope of the present project and might be conducted in subsequent research activities. However, the statistical considerations could already yield some basic statements.

It has to be stressed that the present results cannot be simply transferred from the specific Lab conditions to prototype conditions nor to other hydro power designs. The following is important:

- **The present tests and results were performed in a way to allow prediction of downstream passage distribution between bypass and turbine and probabilities for damage of fish during downstream migration at the shaft power plant only.**
- **The shaft power plant offers downstream migration possibilities which very much differ from other hydropower concepts. Therefore, the observed downstream migration probabilities differ from conventional designs.**
- **All tests were performed with fish that were not scaled to the dimensions of the test facility. The trash rack geometry as well as the velocity in the trash rack plane were correctly reproduced. The cross-sectional area of the inlet section must be regarded as a scaled size compared with most real hydropower plants. It could not be investigated how this effects the downstream migration probabilities.**
- **The same geometrical effect applies to the turbine. Comparing the size of the fish and the turbine diameter as well as their rotational speed it has to be stressed that the results measured in Obernach cannot be transferred to real hydropower plants "as measured".**
- **Only fish from 50mm up to about 200 mm length have been investigated in the present study. Depending on their body geometry most larger fish are protected from entering through the trash rack bars into the turbine. No indication can be given for smaller fish from the conducted tests. Therefore all results concern only the investigated fish species and the investigated length distribution and not entire population risks.**

Table 9: Fishing records, passage distribution and injury respective mortality rates for each facility and fish specification, [CI-; CI+] provides the 95 % confidence interval for the passage distribution

Bypass config.	Flow velocity [m/s]	Fish species	Fish length category [cm] range	Bypass passage	Turbine passage unharmed	Turbine passage injured	Turbine passage dead	Tail water	Passage distribution	CI-	CI+	Injury rate - facility	Injury rate - turbine	Mortality rate - facility	Mortality rate - turbine
surface	0.3	Grayling	5-10	0	0	0	0	0	-	-	-	-	-	-	-
surface	0.3	Grayling	10-15	0	0	0	0	0	-	-	-	-	-	-	-
surface	0.3	Grayling	15-20	6	0	0	0	6	1.00	0.61	1.00	0.00	-	0.00	-
surface	0.4	Grayling	5-10	0	0	0	0	0	-	-	-	-	-	-	-
surface	0.4	Grayling	10-15	0	0	0	0	0	-	-	-	-	-	-	-
surface	0.4	Grayling	15-20	1	1	0	0	2	0.50	0.01	0.99	0.00	0.00	0.00	0.00
surface	0.5	Grayling	5-10	0	0	0	0	0	-	-	-	-	-	-	-
surface	0.5	Grayling	10-15	4	3	0	0	7	0.57	0.18	0.90	0.00	0.00	0.00	0.00
surface	0.5	Grayling	15-20	1	1	0	1	3	0.33	0.01	0.91	0.33	0.50	0.33	0.50
bottom	0.3	Grayling	5-10	17	5	0	2	24	0.71	0.49	0.87	0.08	0.29	0.08	0.29
bottom	0.3	Grayling	10-15	10	1	0	0	11	0.91	0.59	1.00	0.00	0.00	0.00	0.00
bottom	0.3	Grayling	15-20	2	0	0	0	2	1.00	0.22	1.00	0.00	-	0.00	-
bottom	0.4	Grayling	5-10	11	8	2	2	23	0.48	0.27	0.69	0.17	0.33	0.09	0.17
bottom	0.4	Grayling	10-15	3	7	0	1	11	0.27	0.06	0.61	0.09	0.13	0.09	0.13
bottom	0.4	Grayling	15-20	40	1	0	4	45	0.89	0.76	0.96	0.09	0.80	0.09	0.80
bottom	0.5	Grayling	5-10	8	40	1	7	56	0.14	0.06	0.26	0.14	0.17	0.13	0.15
bottom	0.5	Grayling	10-15	32	5	0	1	38	0.84	0.69	0.94	0.03	0.17	0.03	0.17
bottom	0.5	Grayling	15-20	22	4	0	2	28	0.79	0.59	0.92	0.07	0.33	0.07	0.33
surface	0.3	Brown trout	5-10	0	0	0	0	0	-	-	-	-	-	-	-
surface	0.3	Brown trout	10-15	0	0	0	0	0	-	-	-	-	-	-	-
surface	0.3	Brown trout	15-20	3	0	0	0	3	1.00	0.37	1.00	0.00	-	0.00	-
surface	0.4	Brown trout	5-10	0	0	0	0	0	-	-	-	-	-	-	-
surface	0.4	Brown trout	10-15	0	0	0	0	0	-	-	-	-	-	-	-
surface	0.4	Brown trout	15-20	7	0	0	1	8	0.88	0.47	1.00	0.13	1.00	0.13	1.00
surface	0.5	Brown trout	5-10	1	1	0	0	2	0.50	0.01	0.99	0.00	0.00	0.00	0.00
surface	0.5	Brown trout	10-15	2	2	0	0	4	0.50	0.07	0.93	0.00	0.00	0.00	0.00
surface	0.5	Brown trout	15-20	5	1	0	0	6	0.83	0.36	1.00	0.00	0.00	0.00	0.00
bottom	0.3	Brown trout	5-10	16	1	0	0	17	0.94	0.71	1.00	0.00	0.00	0.00	0.00
bottom	0.3	Brown trout	10-15	23	0	0	2	25	0.92	0.74	0.99	0.08	1.00	0.08	1.00
bottom	0.3	Brown trout	15-20	0	0	0	0	0	-	-	-	-	-	-	-
bottom	0.4	Brown trout	5-10	9	6	0	0	15	0.60	0.32	0.84	0.00	0.00	0.00	0.00
bottom	0.4	Brown trout	10-15	14	3	0	1	18	0.78	0.52	0.94	0.06	0.25	0.06	0.25
bottom	0.4	Brown trout	15-20	4	0	0	0	4	1.00	0.47	1.00	0.00	-	0.00	-
bottom	0.5	Brown trout	5-10	7	17	0	3	27	0.26	0.11	0.46	0.11	0.15	0.11	0.15
bottom	0.5	Brown trout	10-15	6	6	0	3	15	0.40	0.16	0.68	0.20	0.33	0.20	0.33
bottom	0.5	Brown trout	15-20	20	0	1	1	22	0.91	0.71	0.99	0.09	1.00	0.05	0.50
bottom	0.5	Barbel	5-10	7	9	0	0	16	0.44	0.20	0.70	0.00	0.00	0.00	0.00
bottom	0.5	Barbel	10-15	5	1	0	0	6	0.83	0.36	1.00	0.00	0.00	0.00	0.00
bottom	0.5	Barbel	15-20	6	2	0	2	10	0.60	0.26	0.88	0.20	0.50	0.20	0.50
bottom	0.5	Minnow	5-10	24	9	2	2	37	0.65	0.47	0.80	0.11	0.31	0.05	0.15
surface	0.5	Bullhead	5-10	1	4	0	0	5	0.20	0.01	0.72	0.00	0.00	0.00	0.00
surface	0.5	Bullhead	10-15	0	1	0	0	1	0.00	0.00	0.95	0.00	0.00	0.00	0.00
bottom	0.3	Bullhead	5-10	26	6	0	1	33	0.79	0.61	0.91	0.03	0.14	0.03	0.14
bottom	0.3	Bullhead	10-15	0	1	0	0	1	0.00	0.00	0.95	0.00	0.00	0.00	0.00
bottom	0.4	Bullhead	5-10	28	6	0	0	34	0.82	0.65	0.93	0.00	0.00	0.00	0.00
bottom	0.4	Bullhead	10-15	2	1	0	0	3	0.67	0.09	0.99	0.00	0.00	0.00	0.00
bottom	0.5	Bullhead	5-10	33	19	3	1	56	0.59	0.45	0.72	0.07	0.17	0.02	0.04
bottom	0.5	Bullhead	10-15	9	6	0	0	15	0.60	0.32	0.84	0.00	0.00	0.00	0.00
All	All	All	< 5 cm	0	7	0	0	7	0.00	0.00	0.35	0.00	0.00	0.00	0.00
All	All	All	> 20 cm	22	0	1	1	24	0.92	0.73	0.99	0.08	1.00	0.04	0.50

3.2 Passage distribution between bypass and turbine

As presented in Table 9 partitions of the downstream migrating or drifting fish did pass through the provided downstream migration corridor for almost all combinations of the targeted facility and fish specifications. Only in two of 48 intended and realized combinations the partition of bypass passage was 0 %. It should be acknowledged that for both cases just one individual passed to the tail water, thus the inaccuracy of this result is very high (CI+ = 95 %). Furthermore, the additionally introduced fish category with body length smaller 5 cm showed a bypass partition of 0 % (7 individuals, CI+ = 35 %). In four cases the partition of bypass passage was 100 %. These results are also based on small case numbers of the underlying fish passage and feature high uncertainty (CI- from 22 % to 61 %). For all other combinations of fish and facility specifications the bypass passage partition varied over the whole range and was influenced by the respective parameter sets. A number of parameter considerations were conducted to extract relations between the passage distributions and the respective parameters.

3.2.1 Fish length considerations

The fish length was found to be of major influence for the passage distribution. Figure 13 shows the bypass passage partitions in function of the size categories. The data was pooled with regard to fish species, bypass configuration and approach flow velocity. The bypass passage partition was strictly monotonic increasing with increasing fish length. The confidence intervals for the three original size categories did not overlap. Results for the additional size categories suffered from low case numbers but confirmed the general trend. This trend is comprehensible, as the probability for physical contact between fish and screen bars in case of screen passage increases with the fish length.

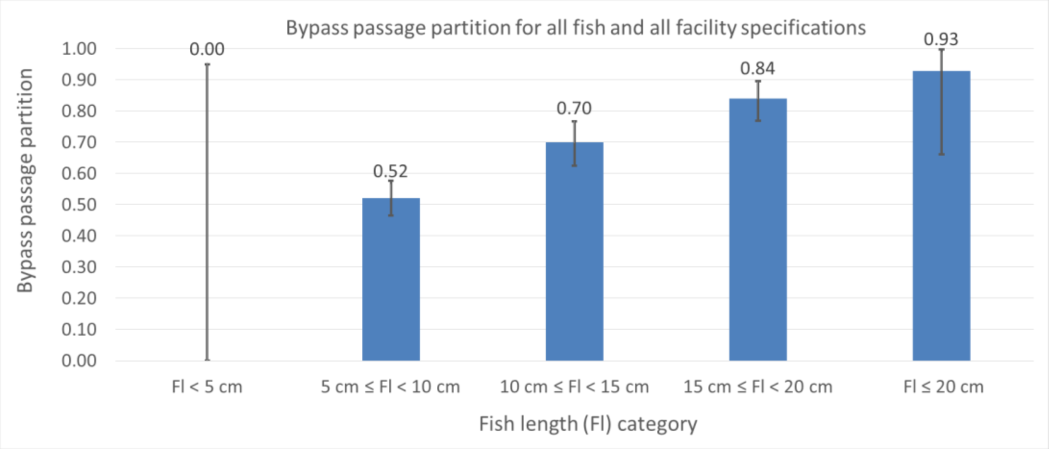

Figure 13: Bypass passage partitions and 95 % confidence intervals for all fish species, approach flow velocities and bypass configurations in dependency of the size categories

The relation between fish length and bypass passage partition is illustrated more detailed in Figure 14. This graphic is representative for a number of graphics which facilitate the parameter considerations and which are summarized in Appendix B. It shows the numbers of fish (upper chart) and partitions of fish (lower chart) which passed through the bypass and the turbine in dependency of the fish length with a cm-resolution for the fish length. Apart from the migration distribution between the bypass and the turbine the graphics include the differentiation of unharmed, injured and dead fish for turbine passage. The fish numbers concerning turbine passage refer to the right hand vertical axis in order to facilitate the comparison between bypass and turbine passage. The illustration of the fish partitions includes the actual fish numbers for each interval. For small case numbers the resulting uncertainty of the respective partition should be accounted for.

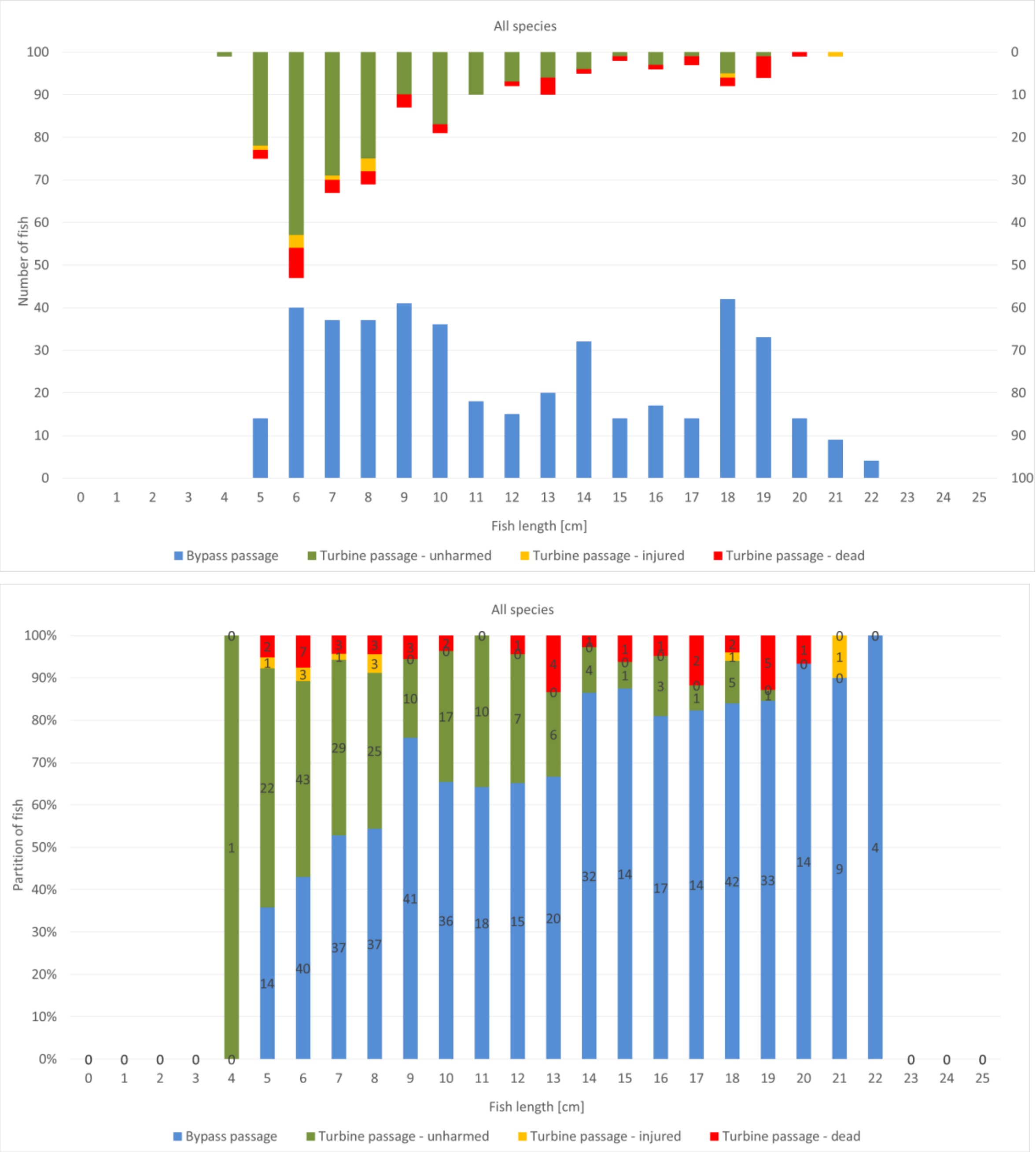

Figure 14: Fish numbers and fish partitions for bypass and turbine passage in dependency of the fish length for all fish species and all facility specifications

In Figure 14 the data for all fish species, approach flow velocities and bypass configurations was pooled. The chart confirms the increase of the bypass passage partition with increasing fish length. Furthermore, the statistical analysis by regression confirmed that the relation between the bypass passage partition and the fish length was statistical significant ($p < 0.05$). Consequently, the discussion of the remaining parameters was done with consideration of the fish length.

3.2.2 Approach flow velocity considerations

The approach flow velocity is likely to influence the fish behaviour at the screen and thus the bypass passage partitions for small fish. This aspect is also related to the dependency of the swimming capacity on the fish length. The possibilities of the laboratory setup were used for a targeted variation of the approach flow velocity. To assess the influence of this parameter on the observed passage distributions, Figure 15 presents the pooled data for all species and bypass configurations in resolution of the intended fish length categories. The chart provides the respective bypass passage partitions and the 95 % confidence intervals. The bypass passage partitions were decreasing with increasing approach flow velocity. Only the value for 0.4 m/s approach flow velocity and the medium fish length category did not fit directly into this trend. With regard to the confidence intervals it did not neglect it neither.

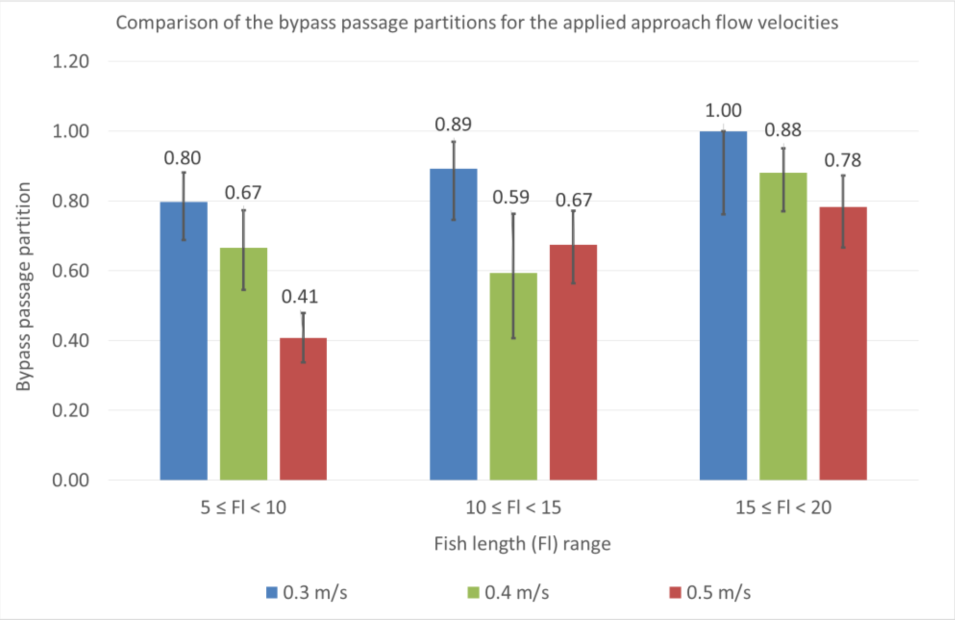

Figure 15: Comparison of the bypass passage partitions for the applied approach flow velocities in dependency of the intended fish size categories, including 95 % confidence intervals

The pooled fish numbers and partitions for each approach flow velocity with cm-resolved fish length are provided in diagrams B1 - B3 in Appendix B. For a direct comparison of the bypass passage partitions in dependency of the approach flow velocity and the cm-resolved fish length the respective values are summarized in Figure 16. Considering 0.3 m/s approach flow velocity only fish smaller than 13 cm body length passed through the turbine and for each cm-size class at least about 60 % of the fish passed through the bypass. For 0.4 m/s approach flow velocity fish up to 20 cm body length passed through the screen and the partitions of turbine passage for almost all fish sizes were higher than for 0.3 m/s and smaller than for 0.5 m/s approach flow velocity. Thus the bypass passage partition decreased with increasing approach flow velocity. The statistical analysis by regression confirmed a statistical significant relation ($p < 0.05$) between the bypass passage partition and the approach flow velocity.

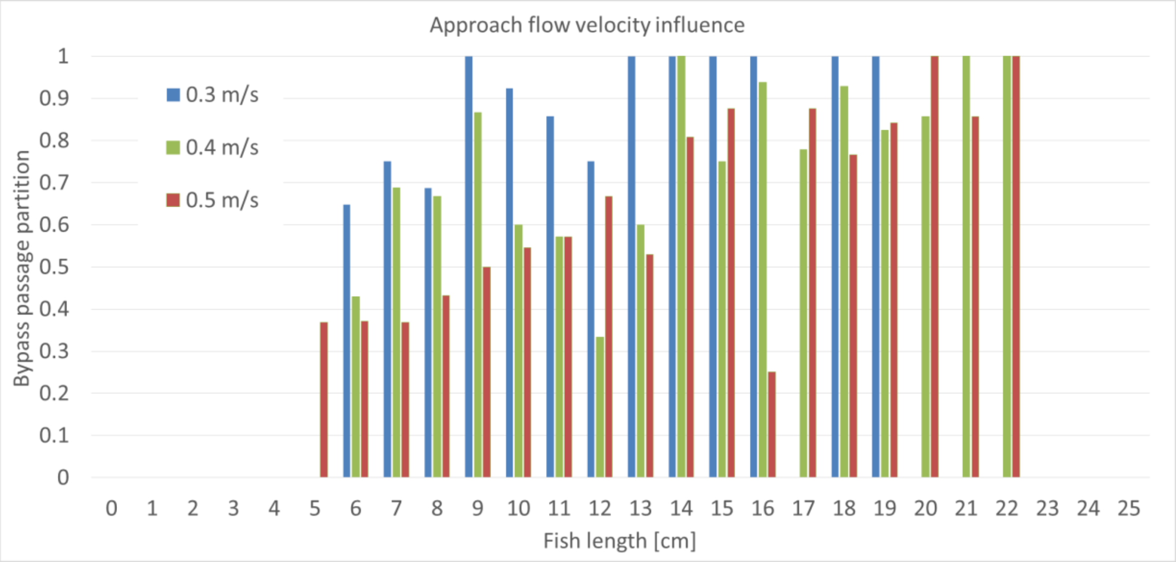

Figure 16: Comparison of bypass passage partitions of all fish and all bypass configurations in dependency of the fish length for the three employed approach flow velocities

Figure 16 and the respective diagrams in Appendix B show furthermore that the trend for increasing turbine passage partitions with decreasing fish length got more developed with increasing approach flow velocity. A possible interaction of these parameters will be discussed in chapter 3.2.4. It will also include a consideration of potential species dependencies.

The variation of the approach flow velocity was related to a change of discharge through the screen. As the discharge through the downstream migration corridor was independent of the approach flow velocity, the variation of the approach flow velocity altered the ratio of discharge between screen/turbine and bypass. Consequently, the passage distribution might have been influenced, as in general the passage distribution might have been a consequence of the discharge dispersal. Table 10 summarizes the discharge distributions and the passage distributions for the different approach flow velocities and bypass configurations. The discharge distribution is distinguished between bypass only or bypass plus gate overflow. Confidence intervals for the bypass passage partitions are provided.

Table 10: Discharge and passage distributions for different hydraulic conditions

Max. velocity towards screen	0.3 m/s	0.3 m/s	0.4 m/s	0.4 m/s	0.5 m/s	0.5 m/s
Bypass position	surface	bottom	surface	bottom	surface	bottom
Discharge portion bypass + gate	11 %	17 %	9 %	15 %	9 %	13 %
Discharge portion bypass	7 %	13 %	5 %	10 %	5 %	9 %
Bypass passage portion (fish numbers in brackets)	100 % (9/9)	83 % (94/113)	80 % (8/10)	73 % (119/162)	50 % (14/28)	55 % (193/348)
[CI-; CI+] confidence interval for 95 % confidence level	[0.72; 1.00]	[0.75; 0.90]	[0.44; 0.97]	[0.66; 0.80]	[0.31; 0.69]	[0.50; 0.61]

The portion of bypass passage of fish was 6 to 14 times higher than the discharge portion in the bypass. It was also 4 to 9 times higher than the discharge portion of bypass and gate. This was furthermore valid for most of the single fish species and fish length category combinations of Table 9. Thus the passage distribution was not just a consequence of the discharge dispersal. The flow cross section of the bypass was about 19 % of the flow cross section of the screen for all investigated parameter specifications. This is also factors smaller than the observed passage distributions. Thus the passage distribution was significantly influenced by the screen. The employed screen did serve as behavioral barrier for partitions of the fish ensemble and made partitions of the fish use the provided bypass.

3.2.3 Bypass configuration considerations

The possibility of controlled and flexible laboratory conditions at the test site was used for the competitive testing of surface near and bottom near bypass positions. A generalized comparison of both bypass variants is provided in Figure 17 which features pooled data with regard to fish species and approach flow velocities. The bypass passage partitions for the bottom near arrangement were higher for each of the intended fish length categories.

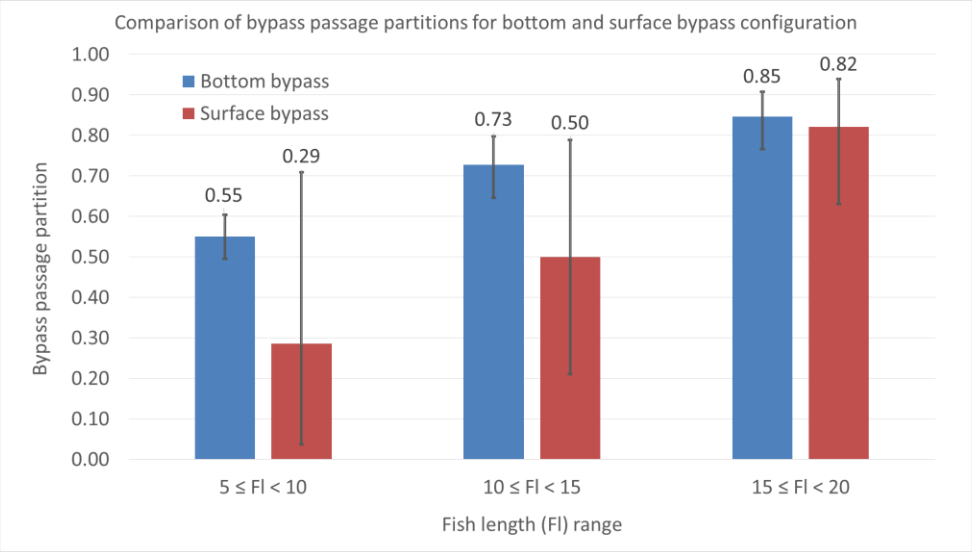

Figure 17: Comparison of the bypass passage partitions for bottom and surface bypass in dependency of the intended fish size categories, including 95 % confidence intervals

For a more detailed comparison of both variants the diagrams B4 and B5 in Appendix B provide the migration distributions, differentiated for the surface near and the bottom near bypass configurations. The graphics account only for brown trout and grayling as only these species featured data for both arrangements and a balanced data pool with regard to velocity influences. The seven comparable cm-size classes show a higher partition for bypass passage for the bottom near bypass arrangement in five cases. In this way the results suggest a higher probability for bypass passage compared to turbine passage for the bottom near bypass configuration and the given ensemble of brown trout, grayling and approach flow velocities. With regard to the bullhead only a comparison for 0.5 m/s approach flow velocity could be conducted. The data is provided in the diagrams B6 and B7 in Appendix B. The comparison of both bypass variants showed higher probability for bypass passage for the bottom near configuration. However, the surface bypass results were based on very small case numbers (6 individuals).

All comparisons of the bypass passage partitions for both bypass configurations showed higher bypass passage for the bottom near arrangement. This configuration would thus be ecological favourable. As the small case numbers for the surface bypass configuration entailed large uncertainty the statement could not be confirmed statistically. Actually 93 % (623 of 670 fish) of the fish passages to the tail water occurred during tests with the bottom near bypass configuration. Only 7 % (47 / 670) of the recorded passages took place during experiments with the surface near arrangement. This unbalance is mostly due to the focusing on the bottom bypass configuration in the test series in 2014. But as 13 % (254 / 1974) of the fish were introduced to the surface near arrangement, the unbalance is also influenced by an apparently higher attractiveness of the bottom near configuration. This would be coherent with findings for large fish (Cuchet et al. 2012).

It should be noted, that Table 10 indicates a higher bypass passage portion for the surface bypass configuration for two of three approach flow velocities. The contradiction to the statements above can be explained by statistical inaccuracy (c.f. confidence intervals in Table 10) and the underlying data ensemble which was not balanced with regard to the fish species and to the fish lengths. The majority of fish which passed to the tail water during tests with the bottom near bypass showed small body lengths. In contrast major parts of those fish which passed to the tail water during tests with the surface near bypass featured large sizes. Moreover, only relatively few fish passed during test with the surface near bypass. The lower limits of the confidence intervals were smaller for the surface near bypass configuration. It should furthermore be noted, that all lower limits of the confidence intervals for the bypass passage partitions in Table 10 were above the values of the discharge distribution. The effects of pooling and statistical inaccuracy have relatively limited magnitude face to the differences in bypass passage and discharge distributions and do not concern the statements in chapter 3.2.2.

3.2.4 Fish species considerations

With regard to individual abilities (e.g. swimming capacity) and preferences (e.g. bottom oriented comportment) the fish behaviour face to the screen and the resulting bypass passage partitions were likely to vary between the fish species. Figure 18 provides the bypass passage partitions for each of the intended and implemented fish species and size categories. This generalized comparison does not reveal systematic differences or relations between the species apart from a slight similarity in the results for brown trout and grayling.

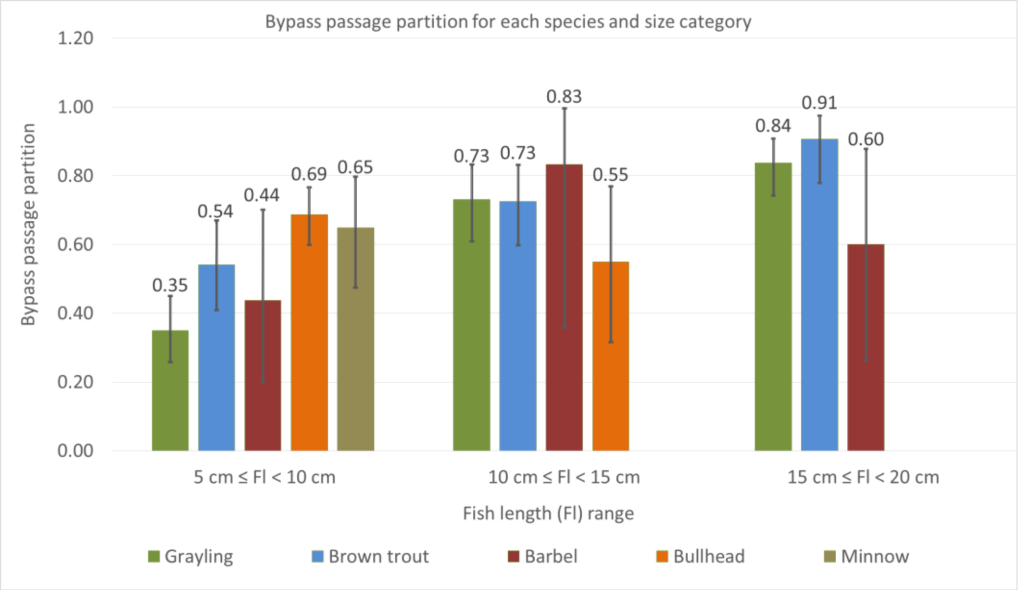

Figure 18: Bypass passage partitions for the species and size categories, including 95 % confidence intervals

To deduce species specific particularities the available data was analysed in more detail. The diagrams B8 - B12 in Appendix B show the numbers and partitions of migrated or drifted fish in dependency of the cm-resolved fish lengths for each fish species. The fish number ranges in the graphics for brown trout, grayling and bullhead and were therefore scaled to 70 fish for comparability. Those for barbel and minnow were scaled to 30 individuals in order to achieve better visibility face to the small case numbers for these species. Also the underlying data for barbel and minnow refer uniquely to the bottom bypass configuration and an approach flow velocity of 0.5 m/s as only data for this facility configuration was available. The graphics for brown trout, grayling and bullhead feature values which were pooled with regard to bypass configuration and approach flow velocity.

For brown trout and for grayling the diagrams of the bypass passage partitions in dependency of the fish length showed increasing bypass passage partitions with increasing fish lengths as already found for the whole fish ensemble. With regard to the pooled date both salmonids showed comparative behaviour. The bypass passage partitions for each facility specification and size category (c.f. Table 9) were higher for the brown trout than for the grayling in all except one case. The higher swimming capacity of the brown trout species or the wild origin of the brown trout could be possible explanations. A number of supplied brown trout and grayling turned out to be longer than 20 cm body length. Whereas tests with these individuals confirmed that they could physically pass through the 20 mm screen, this involved direct contact. Actually, only two of 24 individuals larger than 20 cm body length traversed the screen during the tests. In this context it should be acknowledged that fish length graphics feature rounded values, i.e. fish length charts of 20 cm include individuals from 19.5 cm to 20.4 cm body length. With regard to the comparison of brown trout and grayling to the whole fish ensemble it should be acknowledged that these species constituted the major parts of the fish ensemble, especially with regard to fish larger than 10 cm. Figure 19 shows the composition of the whole fish ensemble which passed to the tail water.

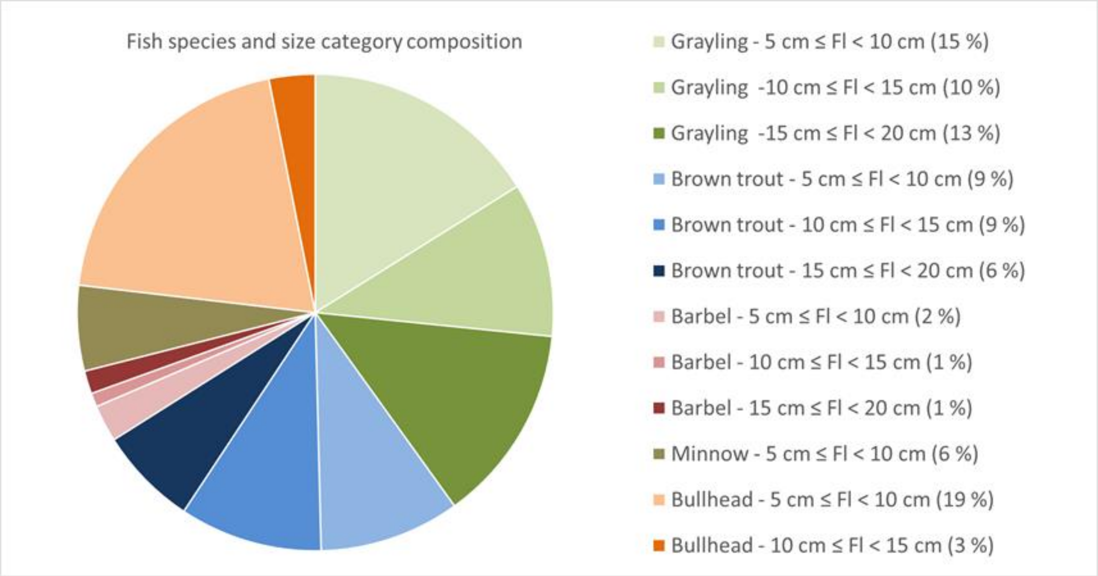

Figure 19: Composition of the fish ensemble which passed to the tail water with regard to species and fish length (Fl) categories, another 5 % of the fish featured Fl < 5 cm or Fl ≥ 20 cm

To further analyse the species specific behaviour of brown trout and grayling, the approach flow velocity was taken into account. Figure 20 and Figure 21 show the relations between the facility and fish specifications on the one hand side and the resulting bypass passage on the other hand side for both species. Only data for the bottom bypass configuration was considered in order to avoid an influence of data pooling. The bypass passage partitions for each approach flow velocity were differentiated with cm-resolution of the fish length. For the assessment of the parameter influence a first order approximation by fitted linear functions was included. It has to be acknowledged, that this approach serves merely to illustrate basic trends. The linear approach is not suitable for comprehensive modelling of the actual fish behavior. A respective statistical modelling of the obtained data was beyond the scope of the project. The uncertainty of the deduced functions is documented by the respective coefficients of determination.

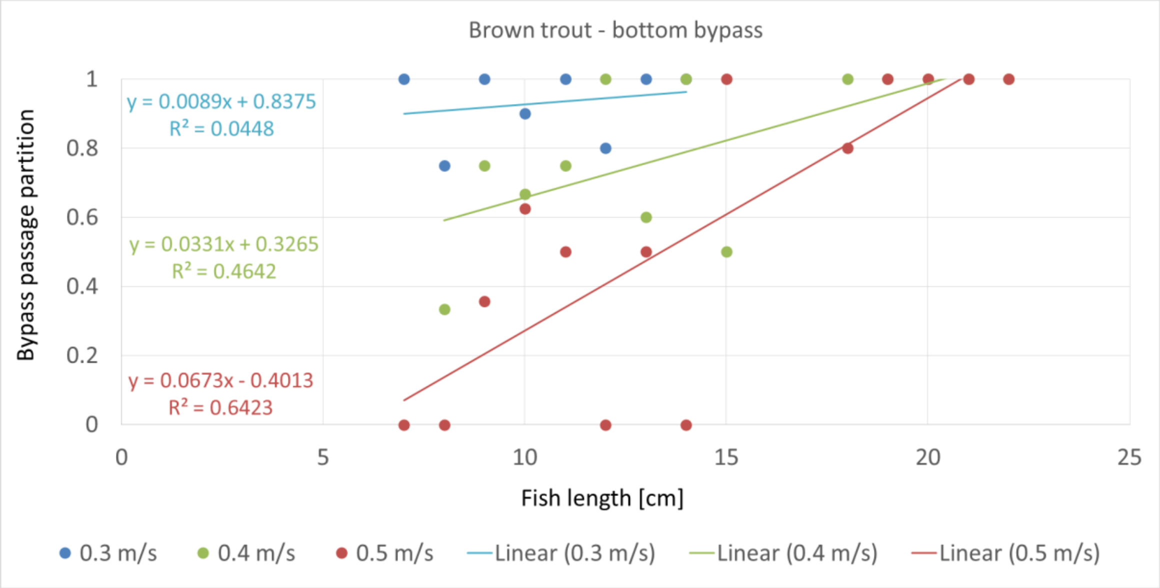

Figure 20: Bypass passage partitions in dependency of the fish length and the approach flow velocity for the brown trout and the bottom near bypass configuration

For the brown trout the offset of the linear functions is strictly monotonic decreasing and the inclination is strictly monotonic increasing with inclining approach flow velocity. The crossing point of the functions is above a fish length of 20 cm. Hence, the bypass passage incidence is increasing with increasing fish length and with decreasing approach flow velocity. The dependency of the bypass passage incidence on the fish length is more developed for higher approach flow velocities. These results show a well comprehensible systematic.

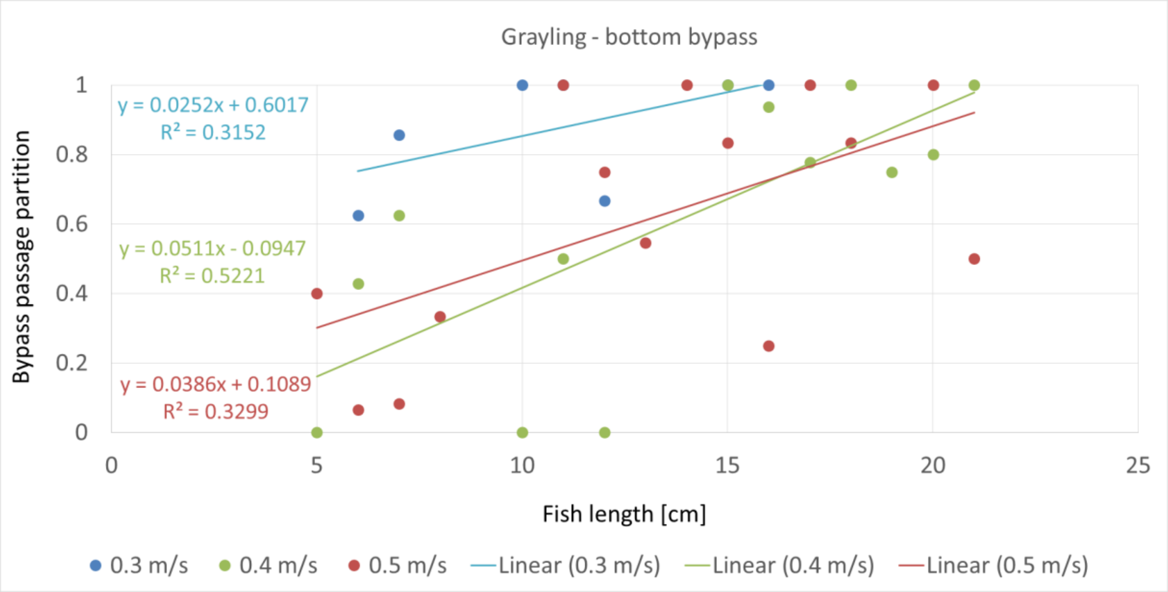

Figure 21: Bypass passage partitions in dependency of the fish length and the approach flow velocity for the grayling and the bottom near bypass configuration

For the grayling the offset of the linear functions as well as the inclination did not show monotonic relations with inclining approach flow velocity. The crossing point of the functions for 0.4 m/s and 0.5 m/s was in the fish body length range of 15 - 20 cm. Both functions covered similar regions and do not show systematic influence of the approach flow velocity on the bypass passage incidence for these conditions. This discrepancy to the brown trout findings might have been due to statistic spread but could also be systematic. As all grayling descended from fish farm the swimming capacity might have been less developed and consequently the results concerning the influence of the approach flow velocity might have been less distinct. For small approach flow velocities the bypass passage partition showed higher values.

The statistical analysis by regression confirmed statistical significant relations ($p < 0.05$) between the bypass passage partitions and the approach flow velocities as well as the fish length for both salmonids as already found for the whole fish ensemble. The bypass passage partition increased with decreasing approach flow velocity and with decreasing fish length. Details depend on the underlying assumptions with regard to possible interactions of the parameters.

Considering the bullhead Figure 18 indicates a trend for decreasing bypass passage partitions with increasing fish lengths, which would be contradictory to the findings for brown trout and grayling. The bypass passage partitions in dependency of the cm-resolved fish length (diagram 10 in Appendix B) actually do not show a distinct trend for increasing or decreasing bypass passage portions with increasing fish length. The available bullhead ensemble featured relatively small size variation and furthermore small fish numbers. The data basis was not sufficient to deduce a fish length dependency for this species. To compare the bullhead specific results with those of brown trout and grayling Table 11 summarizes the relevant passage distributions for brown trout, grayling and bullhead. Only fish with fish body lengths (Fl) of 6.5 cm ≤ Fl ≤ 12.4 cm were taken into account and only results for the bottom near bypass configuration, as only these parameters provided a sufficient and comparable data base. Whereas the bottom oriented behaviour of the bullhead would associate high turbine passage rates, the actual fishing numbers showed comparably higher passage rates for the bypass than for brown trout and grayling. However, it has to be taken into account that bullhead feature a wider body in relation to their length. Furthermore, geometric details of the screen construction might have influenced this finding. In detail the top edge of the screen surface was about 8 cm above the surrounding river bed (c.f. Figure 3 and Figure 7) whereas the bottom near bypass opening was flush with the floor.

Table 11: Bypass passage partitions for brown trout, grayling and bullhead of 7 – 12 cm fish length (Fl) and the bottom near bypass configuration

Bypass passage partitions (number of fish which passed to through the bypass / number of fish which passed to the tail water) for 6.5 cm ≤ Fl ≤ 12.4 cm, bottom bypass configuration and all approach flow velocities	Brown trout	Grayling	Bullhead
	61 % (51/84)	49 % (26/53)	70 % (96/137)

An additional consideration of the approach flow velocity similar to the procedure for brown trout and grayling was conducted for the bullhead. Figure 22 shows the corresponding graph. The available migration records were not sufficient to deduce a coherent systematic. The offset and the inclination of the linear functions did not feature monotonic relations with the fish body length or the approach flow velocity. The inclinations were negative, which indicated decreasing bypass passage incidence with increasing fish length. The crossing point of the linear functions was in the region of 10 cm fish body length which was close to the average fish body length for the given bullhead ensemble. Due to the small fish length range and case numbers of the bullhead data set no relevant trends could be deduced for this species.

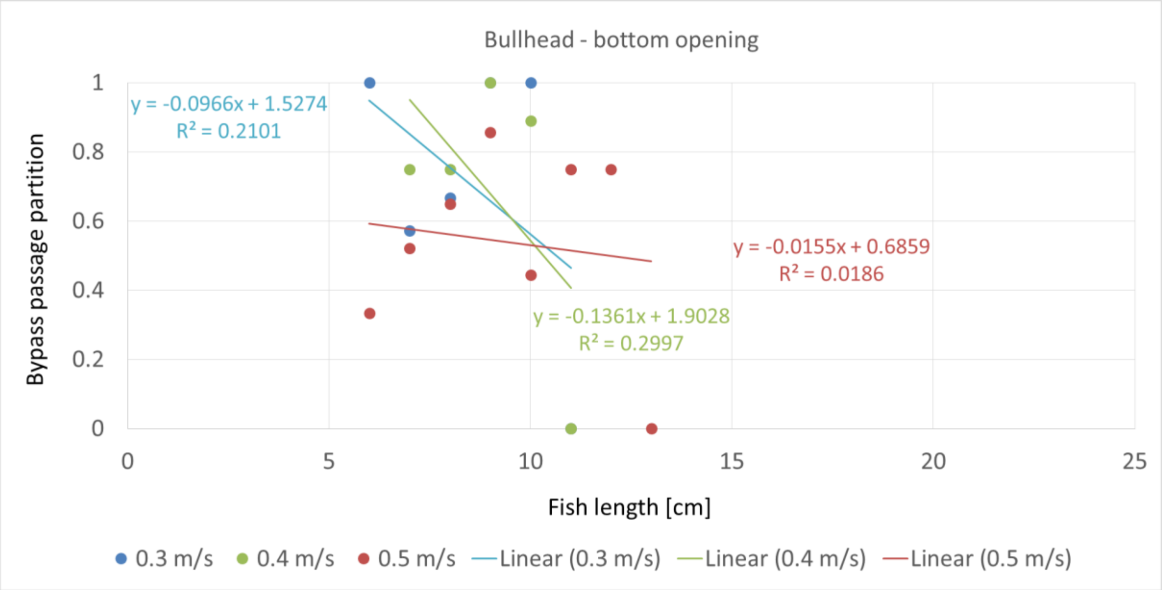

Figure 22: Bypass passage partitions in dependency of the fish length and the approach flow velocity for the bullhead and the bottom near bypass

With regard to barbel the small case numbers have to be acknowledged. The barbel contributed only 4 % of the fish which passed to the tail water. Furthermore, these fish were distributed over the whole size range. The comparison of the bypass passage partitions for barbel according to the size categories (c.f. Table 9 or Figure 18) shows no uniform trend for a dependency on the fish length or for systematic differences to the respective partitions of brown trout and grayling. Although, relatively many large barbel passed through the turbine (33 % or 4 individuals of 12 barbel with Fl > 15 cm which passed to the tail water), the bypass passage partitions for medium and small fish length categories were comparable to the results of brown trout and grayling. The graphical presentation of the bypass passage partitions for the barbel with a cm-resolved fish length (diagram B11 in Appendix B) shows a relatively high partition of turbine passage for fish with 5 cm body length. This accumulation is less visible in the fish size category considerations as a number of these fish featured body lengths 4.6 cm ≤ Fl < 5 cm. A modified fish length category of 4 cm ≤ FL < 10 cm results in a bypass passage partition of 30 % instead of 44 % for 5 cm ≤ FL < 10 cm. The results for the other species were not affected by the same modification of the fish length category. The result of the modified fish length category is relatively close to the respective value for brown trout (35 %). Due to the small case numbers and the resulting statistical uncertainty a general trend for more turbine passage of the typically bottom oriented barbel (Kottelat et al. 2007) could not be confirmed nor disproved.

Like for the bullhead the small fish length range and the limited case numbers of the provided fish ensemble did not allow the deduction of fish length dependencies for the minnow. The cm-resolved chart for the fish numbers and partitions in dependency of the fish length (diagram B12 in Appendix B) provides only data for four size classes and does not show a uniform trend. The percentage of bypass passage for all minnow was 65 %. This value is higher than the corresponding results for brown trout, grayling and barbel and close to the value for bullhead (c.f. Figure 18 or Table 9).

The species resolved considerations showed an influence of the species on the respective results for the bypass passage partitions. However, due to small fish length range for minnow and bullhead and because of small case numbers for barbel and minnow it was not possible to deduce distinct characteristics for these species. Thanks to the larger data basis for brown trout and grayling, systematic dependencies of the bypass passage partitions on fish length and approach flow velocity could be deduced. In general, the limited case numbers for various parameter combinations of fish and facility specifications and the potentially complex fish behaviour disabled a rapid modelling for statistical interpretation and require exhaustive analysis. This might be accomplished in ensuing projects.

3.3 Injury and mortality rates

Similar to the considerations for the migration distribution the potential dependencies of the injury and mortality rates on the relevant parameters were investigated. As mentioned in chapter 3.1.3 the analysis and documentation was diversified for mortality and injury rates in order to account for a bandwidth of the ecological impact. The mortality rate denotes the percentage of fish which got killed during turbine passage or which showed serious injury with inevitable lethal consequences (minimum bandwidth limit). Injury rate refers to those fish which showed furthermore injury with unclear prognosis for long term survival but also includes all individuals from the mortality rate (maximum bandwidth limit). Moreover, both rates can be related to the fish which passed through the turbine or to those which passed to the tail water (turbine plus bypass).

It should be noted, that the configuration of the bypass did not affect the conditions for the fish during the turbine passage. Thus the results for injury and mortality rates during turbine passage could be pooled with regard to this parameter without influencing the output. On the other hand the results for the injury and mortality rates with regard to the whole facility did in detail depend on the bypass position as these depended on the migration distribution. However, the data basis for the injury and mortality considerations was relatively small. For the tests with surface near bypass positioning only two individuals got killed during turbine passage. Thus no individual consideration for this parameter was conducted with regard to injury and mortality rates.

3.3.1 Fish length considerations

As the fish length influences the probability for runner strikes during turbine passage, this parameter is supposed to be of major impact for the mortality rates during turbine passage of low head hydro power plants. Numerous experimental studies already confirmed this aspect (Ebel 2013). Figure 23 shows the observed injury and mortality rates with regard to turbine and facility passage in dependency of the fish length categories pooled for all species, approach flow velocities and bypass configurations. The respective values are provided and the confidence intervals for a 95 % confidence level are included. The injury and mortality rates with regard to turbine passage increased with increasing fish length from about 14 % for the 5 - 10 cm fish length category to 53 % for the 15 - 20 cm category. The trend is coherent with literature references (Larinier et al. 2002). The additional categories feature high inaccuracy due to small case numbers. The injury and mortality rates with regard to facility passage were rather constant with values between 5 - 9 % for the originally intended size categories. The reduction is caused by the passage distribution as the injury/mortality rate with regard to facility passage is the product of the injury/mortality rate and the turbine passage partition.

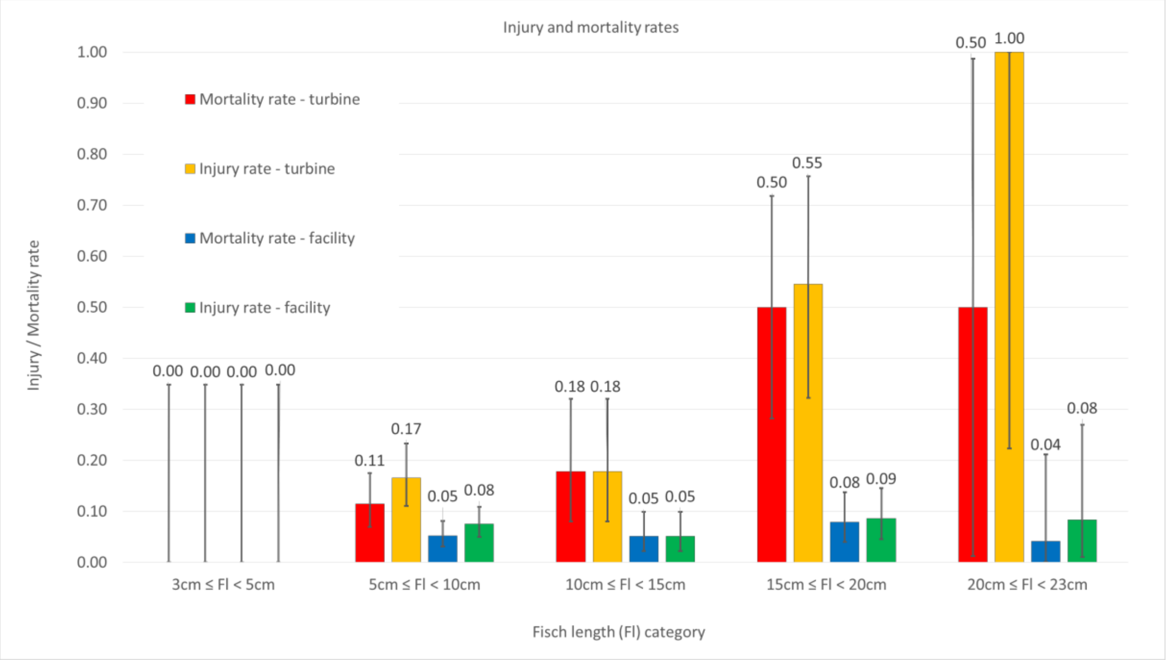

Figure 23: Injury and mortality rates with regard to the fish length categories, including 95 % confidence intervals

For further detailed presentation Figure 24 provides the respective fish numbers and the fish partitions concerning injury and mortality during turbine passage with a cm-size resolution. Similarly, the injury respective mortality rates showed an increasing trend with increasing fish length. The small case numbers, especially for larger fish, should be acknowledged. The injury and mortality rates of this fish data ensemble, with regard to facility passage, are included in Figure 14. Again they showed smaller and rather constant values due to the influence of the migration distribution. The statistical analysis by regression confirmed a statistical significant increase ($p < 0.05$) of the injury and the mortality rate with regard to turbine passage with increasing fish length. It should be noted that this statement refers mostly to mechanical injury.

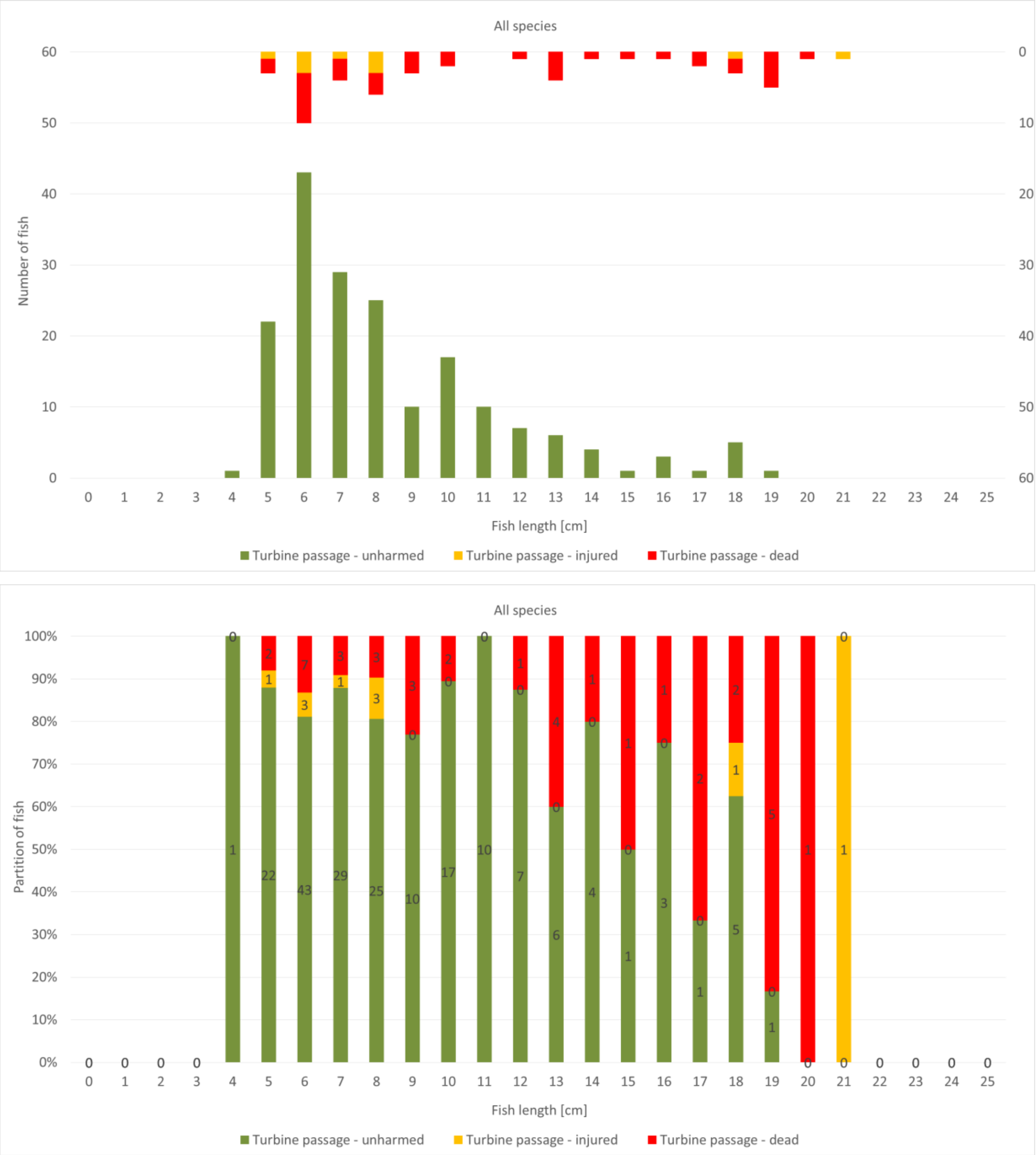

Figure 24: Fish numbers and fish partitions for unharmed, injured and lethal turbine passage in dependency of the fish length for all fish species and all facility specifications

Since the fish length showed a dominant influence on the injury and mortality, the discussion of the remaining parameters was again done with simultaneous consideration of the fish length. Consequently, the case numbers for each parameter value were too small to provide reasonable information in the cm-resolved diagrams of the dependency on the fish length.

3.3.2 Approach flow velocity considerations

The approach flow velocity directly influenced the discharge through the screen and therefore the discharge through the turbine. This entailed different flow velocities in the turbine and was achieved by specific conditions of the control device / wicket gate and the runner blades. Table 12 provides the respective values. The revolution speed of the runner was constant for all approach velocities (333 rpm). Figure 25 summarizes the injury and mortality rates of all fish in dependency of the approach flow velocity respectively the turbine discharge. As the fish length was already identified to be a major influence for the results, the data was separated for the fish length categories. The explicit rates and the confidence intervals for a 95 % confidence level are included for each combination of approach flow velocity and fish length category. The comparison of the results for the different approach flow velocities showed a trend for decreasing injury and mortality rates with regard to turbine passage with increasing turbine discharge. Such a trend would be coherent with literature references (Ebel 2013). However, the injury and mortality rates with regard to turbine passage showed high uncertainty due to small case numbers.

Table 12: Nominal angles of control device and runner blades for the investigated hydraulic conditions; an angle of 0° corresponds to complete closure of the respective installation

Approach flow velocity [m/s]	0.3	0.4	0.5
Turbine discharge [m³/s]	0.96	1.28	1.5
Control device angel [°]	41.6	48.0	53.3
Runner Blade angle [°]	11.3	18.2	22.8

The injury and mortality rates with regard to facility passage were again reduced because of the passage distribution. They ranged from 3 % - 10 % for the underlying data set. Thanks to the larger statistical data basis the confidence intervals were respectively smaller and locate the injury and mortality rates with regard to facility passage in a range from 0 % - 20 % for the respective fish and facility specifications. Although the injury and mortality rates with regard to facility passage were almost constant one might interpret a slight tendency for increasing injury and mortality rates with regard to facility passage with increasing approach flow velocity. Such trend could be valid if the decreasing effect due to the bypass passage partition was less developed than the increasing effect during turbine passage. Face to the statistical uncertainty such considerations remain theoretical and a clarification would require further test series to obtain better accuracy of the results.

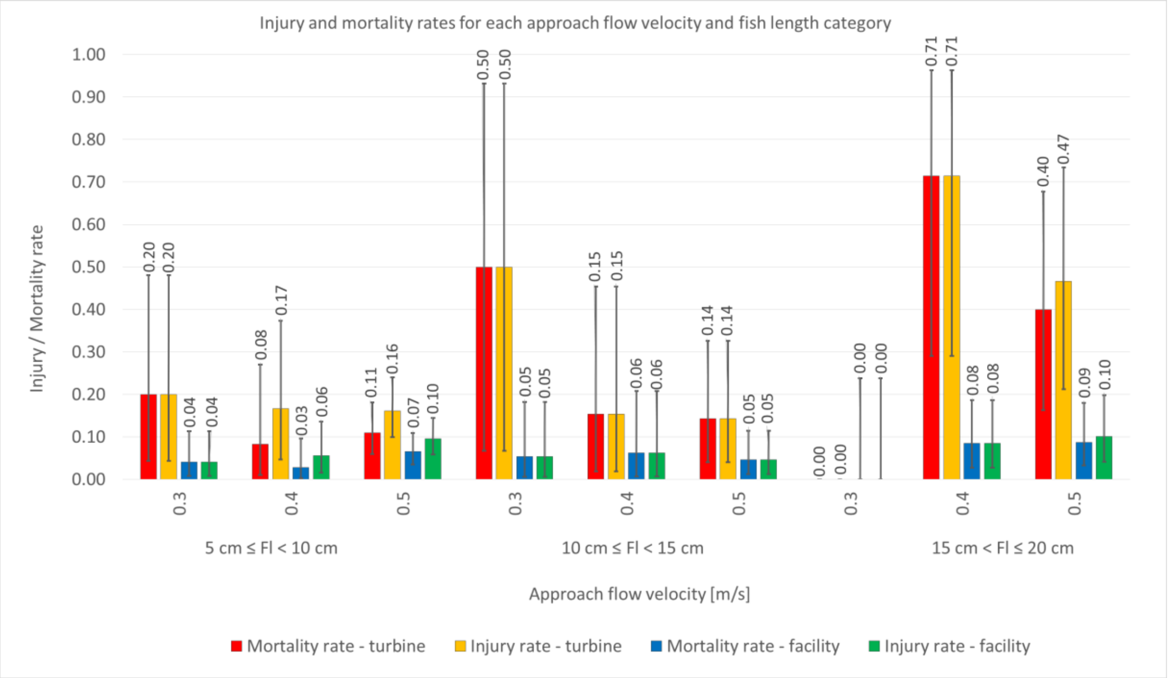

Figure 25: Injury and mortality rates with regard to turbine and facility passage for different approach flow velocities and fish length ranges, including 95 % confidence intervals

3.3.3 Fish species considerations

Considering the single fish species the number of fish which got injured or killed during turbine passage were relatively small. Consequently, no species specific reliable statements could be deduced. The mortality and injury rates with regard to turbine and facility passage for each combination of fish species and intended size category are provided in Figure 26. The included confidence intervals for a confidence level of 95 % demonstrate the uncertainty of the results for injury and mortality with regard to turbine passage. Especially large fish showed relatively high injury and mortality rates with regard to turbine passage. The corresponding confidence intervals range almost over the whole range of possible values as the case numbers were respectively small. Most of the injury and mortality rates with regard to turbine passage for small fish and also most of the injury and mortality rates with regard to facility passage were restricted to values around 10 % and the upper limit of the 95 % confidence interval was in the range of 20 % - 30 %.

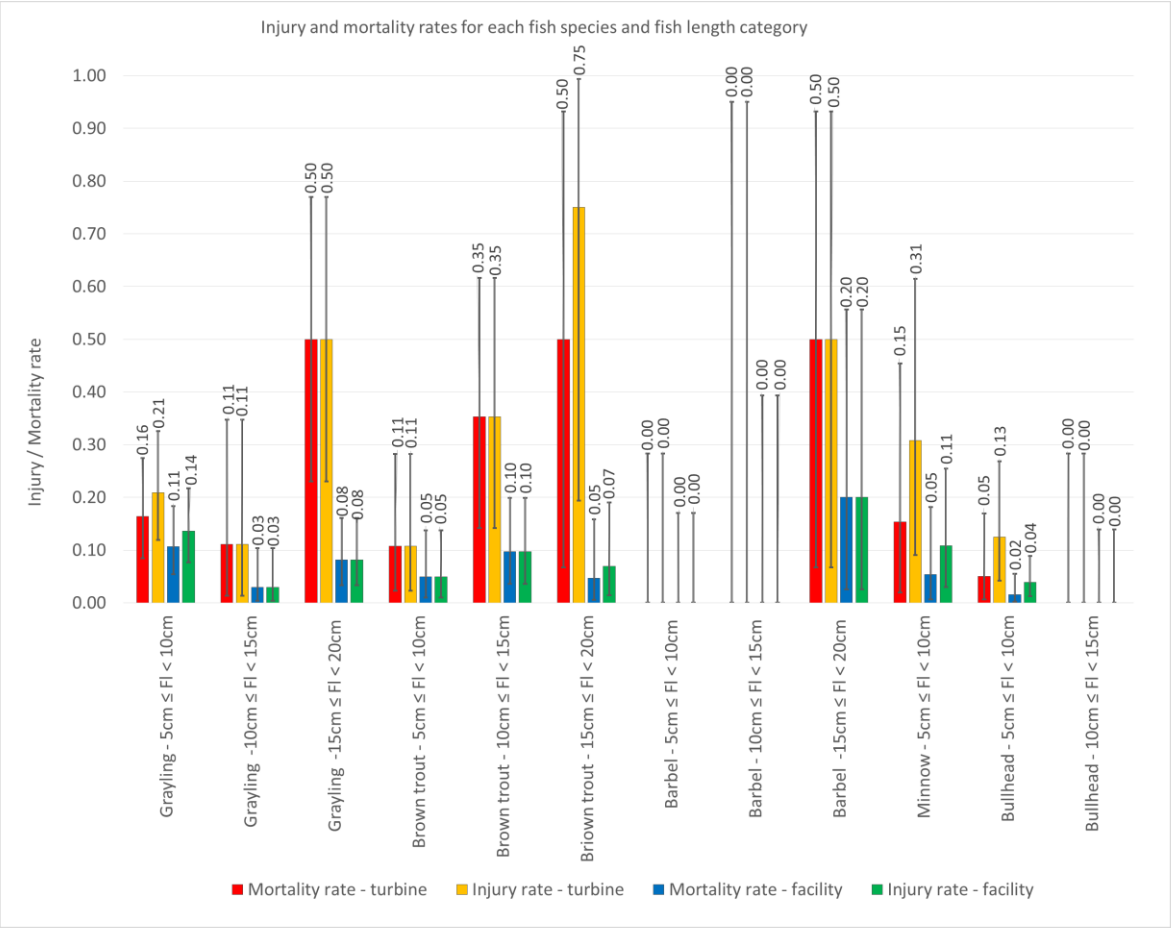

Figure 26: Injury and mortality rates with regard to turbine and facility passage for the fish species and size categories, including 95 % confidence intervals

In the discussion of the bypass passage partitions of the barbel the results depended on the exact definition of the fish length category. In case of the injury and mortality rates the altered fish length category for small fish (4 cm < Fl ≤ 5 cm) did not yield different results. Only the confidence interval was reduced. The values in Figure 26 are based on the original fish size category.

3.3.4 Comparison with literature references

Injury and mortality with regard to turbine passage

To further assess the validity of the obtained data, to identify eventual particularities of the test facility and to classify its characteristics with regard to mortality rates, a comparison with monitoring results of other hydro power facilities was intended. A number of such studies have been conducted to assess the mortality rates of fish during turbine passage throughout the last decades. No reference with directly comparable turbine specifications was available. Therefore, a mortality model was employed. Several models can be found in literature, which were either deduced from theoretical considerations or fitted to empirical data or a combination of both approaches. Ebel provided a summary of the available models and tested the respective validity (Ebel 2013). The advised physically deduced model for salmonids and Kaplan turbines (Monten 1985) was employed, since empirical models were out of the range of application for the specific conditions of the test facility.

The results of the model are illustrated in dependency of the fish length in Figure 27. The mortality rates were calculated for the three investigated turbine discharges. The model showed increasing mortality rates with decreasing turbine discharge, as found for the observed mortality rates with regard to turbine passage (c.f. chapter 3.3.2). Furthermore, the model showed an increasing mortality rate with increasing fish length, as also observed for the experimental data (c.f. chapter 3.3.1).

For the comparison of the experimental results and the model predictions, Figure 27 shows moreover the observed injury and mortality rates with regard to turbine passage for salmonids, i.e. the pooled data of brown trout and grayling. The observed values were averaged for the fish length categories in order to get a minimum statistical stability for the data points. The injury and mortality rate values of each size category were allocated at the arithmetic average of the respective fish length category to create a singular data point. Injury and mortality rates are provided for each approach flow velocity/turbine discharge. The data points for each approach flow velocity show fitted linear functions (offset = 0) for the injury respective mortality as a function of the fish length. To facilitate a quantitative comparison, the inclinations of the fitted linear functions and the inclination of the predicted mortality rates are summarized in Table 13.

Table 13: Inclinations of the predicted and observed mortality respective injury functions in dependency of the approach flow velocity respectively the turbine discharge

Approach flow velocity [m/s]	Turbine discharge [m³/s]	Model inclination	Mortality rate inclination	Injury rate inclination
0.3	0.96	0.038	0.048	0.048
0.4	1.28	0.029	0.027	0.028
0.5	1.5	0.025	0.019	0.022

Due to the small case numbers, the observed mortality rate values showed large variations. For 0.3 m/s approach flow velocity the fitted linear function for the observed mortality and injury showed remarkably higher inclination than the predicted mortality. It should be noted, that this was caused by the data point for the 10 - 15 cm fish length category. This data point is based on two killed fish out of a total of three fish. The 95 % confidence interval for this case is [0.09; 0.99]. Neglecting this data point resulted in an inclination of 0.033. The fitted linear functions for 0.4 m/s approach flow velocity were close to the predicted values. The single data points varied up to 20 %-mortality from the predictions. For 0.5 m/s approach flow velocity the fitted linear function showed smaller mortality values than the model predictions. The corresponding injury rate was closer but still underneath the model predictions.

It should be acknowledged that the presentation in Figure 27 does not account for the underlying case numbers of each data point. A comprehensive analysis (which would also include the actual fish length) was beyond the scope of the project but might be accomplished in ensuing research. The present analysis shows that the obtained data is coherent with literature references concerning the basic relations between mortality and fish length as well as between mortality and turbine discharge. The magnitude of the observed mortality (respective injury) rates with regard to turbine passage is in the range of the model predictions for the given facility specifications.

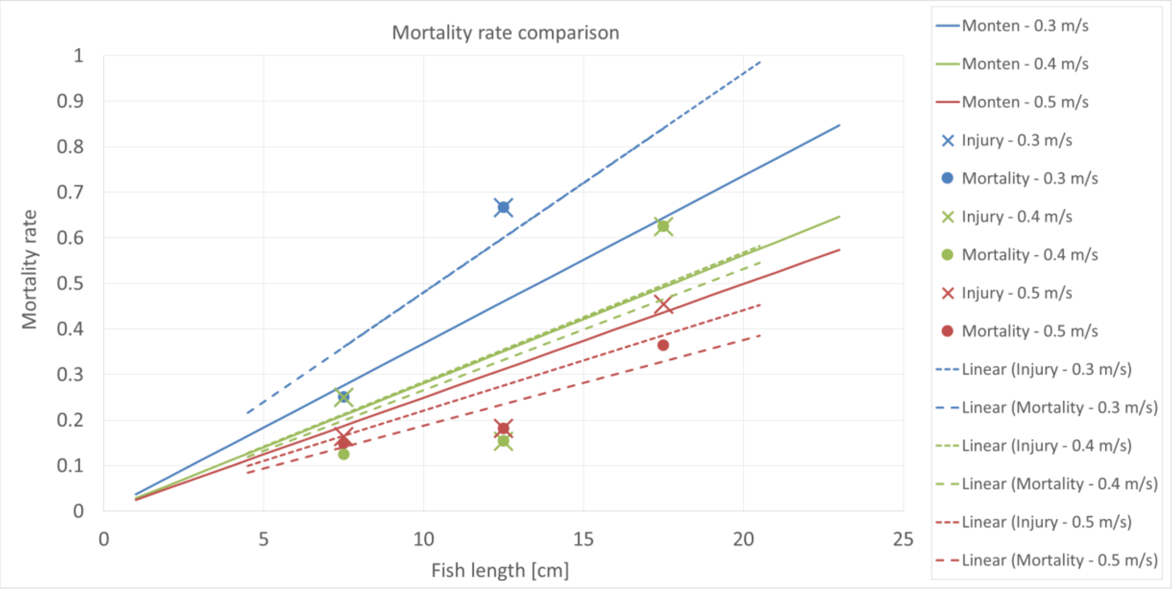

Figure 27: Calculated mortality rates and observed injury and mortality for brown trout and grayling – with velocity differentiation

Considering the observed injury schemes 40 % (19 of 48 fish) of the injured fish showed runner blade strikes with serious cuttings and instant loss of life. 60 % (29/48) of all injured fish showed obvious mechanical injury. The high rate of mechanical injury can be explained by the small ratio of fish length and runner blade (75 cm diameter) and by the high revolution of the turbine (333 rpm). Both parameters increase the probability for runner strikes (Ebel 2013). The high intensity of the mechanical injury could be due to the high revolution of the turbine runner and the resulting high impact velocity which is relevant for the damage grade (Monten 1985).

Internal injury due to pressure fluctuations and cavitation were less likely due to the small head of the test facility (Larinier et al. 1989). This is coherent with the dominance of mechanical injury. However, since internal injury was not investigated in case of lethal mechanical injury, the actual extend of internal injury remains unknown. The meanwhile adjoined histological investigation might clarify this point. Results will be published in the context of that research project. So far an accumulation of eye damage can be stated as 21 % (10/48) of the injured fish featured haemorrhage and/or swelling.

Injury and mortality with regard to facility passage

To assess the ecological impact of a hydro power site on descending fish, the mortality rates with regard to facility passage have to be considered. Due to the bypass passage distribution the mortality rates with regard to facility passage are respectively smaller than the mortality rates for turbine passage.

As presented in chapter 3.2.1 the percentage of fish which passed through the screen and the turbine increased statistical significantly with decreasing fish length. The mortality rates increased with the fish length (c.f. chapter 3.3.1). Both tendencies had a converging influence on the total damage rates for different fish sizes as these values are a product of the passage distributions and the mortality rates with regard to turbine passage. For example, small fish had higher probabilities to pass through the screen and the turbine but lower probabilities for injury during the turbine passage. Large fish had higher mortality rates during turbine passage but lower probability to pass through the screen.

These relations have a positive effect for the implementation of fish protection for a broad spectrum of different fish sizes. A similar effect was found for the influence of the approach flow velocity (c.f. chapter 3.2.2). The injury and mortality rates with regard to turbine passage increased with decreasing turbine discharge (c.f. chapter 3.3.2). Although this relation could not be stated with statistical significance for the given experimental results, literature references confirm such a relationship (Monten 1985). The incidence for screen and turbine passage decreased with decreasing flow velocities towards the screen (c.f. chapter 3.2.2). Consequently, a relatively constant level of fish protection for different service conditions of a hydro power plant face to seasonal discharge fluctuations is facilitated. Nevertheless, there might remain trends for the injury and mortality rates with regard to facility passage if the mutual compensation of the opposite influences is not complete, as already discussed in chapter 3.3.2.

A comparison of the injury and mortality rates with regard to facility passage is not promoted in the scope of this project. Only few relevant monitoring measures of downstream migration have already been conducted and the covered hydro power facilities and fish ensembles are not comparable without additional work. It should be noted that the specific hydro power plant of the test setup features rather exceptional parameters with regard to discharge and head. The setup was chosen large enough for live fish experiments under realistic conditions but small enough for the implementation in the laboratory channel system. The economic field of application for the hydro shaft power plant concept is prospectively above 100 kW. Such facilities will thus have turbine specifications comparable to literature references, i.e. larger runner diameters and lower revolutions than the test facility. The mortality rates during turbine passage will consequently correspond to the reference values.

The ecologically relevant mortality rates with regard to facility passage will be reduced by the bypass passage distribution. The magnitude of the bypass passage distribution might however also be affected by the facility size. Larger screen surfaces and smaller ratios of bypass to turbine discharge could reduce the bypass passage partition. For example, the distance between the screen outline and the bypass opening will supposable influence the passage distribution. Several bypass openings can be employed for large facilities to improve the bypass passage distributions. Moreover, the design approach flow velocity and the screen clearance might be adapted to meet the ecological requirements at specific sites. The resulting mortality rates for downstream migration with regard to the hydro power facility will be affected by all of these aspects. Global mortality rate statements include furthermore those fish bigger than the bar clearance which are protected by the screen (Cuchet et al. 2012).

4 Conclusion

Fish protection and fish downstream migration for fish which can physically traverse the screen were investigated at a fully functional prototype facility of the TUM shaft hydro power plant under nature like but controlled laboratory conditions. The employed methodology enabled to determine the passage distributions between bypass and turbine as well as the injury and mortality rates due to turbine passage for a set of brown trout, grayling, bullhead, barbel and minnow with 5 to 20 cm body length. Combinations of three different approach flow velocities at the screen and two geometric arrangements of the downstream migration bypass were tested.

For the investigated fish species and sizes the horizontal screen in combination with the employed bar clearance, flow velocities and the provided migration corridor achieved fish protection and safe downstream passage for partitions of the descending fish. An effect of the horizontal screen as behavioural barrier and not just as mechanical barrier was confirmed. Portions of the fish ensembles also passed through the screen and the turbine and were subjected to turbine specific injury and mortality rates. The determined passage distributions as well as the injury and mortality rates depended on the fish species, the fish sizes, the flow conditions and the facility configuration. For the given fish ensemble and the employed facility conditions a set of statements can be summarized:

- The portion of fish which passed through the screen and the turbine increased statistical significantly with decreasing fish length and with increasing flow velocity towards the screen.
- The bottom near bypass configuration yielded higher bypass passage portions for the investigated fish species and sizes.
- The injury and mortality rates during turbine passage increased statistical significantly with increasing fish length. With decreasing discharge the injury and mortality rates with regard to turbine passage increased by trend.
- The injury and mortality rates with regard to facility passage were reduced by the passage distribution between bypass and turbine. They showed relatively uniform values for the spectrum of employed fish species, fish sizes and flow conditions.
- The observed injury and mortality rates during turbine passage showed values in the range of literature references.

The coherence of the deduced relation with literature references confirms the general validity of the obtained data. Statements for particular fish and facility specifications have to be considered in view of the underlying statistical ensemble and the resulting confidence intervals. The values cannot be transferred directly to other facilities, as the specific facility details, service conditions and fish populations have to be accounted for. In general, more research in various fields is advisable to further clarify ecological aspects of hydro power usage.

Acknowledgement

The investigations were partially funded by the Bavarian State Ministry of the Environment and Consumer Protection (StMUV). They were supported and enabled by professional and material assistance of the Bavarian Environment Agency (LfU) – Unit Fish and Freshwater Ecology and the Bavarian State Research Center for Agriculture (LfL) – Institute for Fisheries, especially with regard to the fish supply. Furthermore the fishery consultant of the district of Schwaben and the Bavarian Fishery Association (LFV) – Department for fishery, river and environment protection provided professional support. Muhr GmbH company provided the steel hydraulics constructions.

References

Adam, B., Lehmann, B., (2011), *Ethohydraulik – Grundlagen, Mehtoden und Erkenntnisse*, Springer-Verlag Berlin Heidelberg, ISBN: 978-3-642-17209-0

Cuchet, M., Geiger, F., Sepp, A., Rutschmann, P., (2012), *Fish downstream passage at the TUM-Hydro Shaft Power Plant - Experimental study of fish behavior – Stage I*, Versuchsbericht des Lehrstuhls und der Versuchsanstalt für Wasserbau und Wasserwirtschaft, Nr.417, Technische Universität München

DWA, (2004), *Fischschutz- und Fischabstiegsanlagen – Bemessung, Gestaltung, Funktionskontrolle*. ATV-DVWK Themen

Dumont U., Anderer P., Schwevers U., (2005), *Handbuch Querbauwerke,* MUNLV – Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen, ISBN 3-9810063-2-1

Ebel G., (2013), *Fischschutz und Fischabstieg an Wasserkraftanlagen*, Mitteilungen aus dem Büro für Gewässerökologie und Fischereibiologie Dr. Ebel, Band 4, ISBN: 978-3-00-039686-1

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

Kottelat, M., Freyhof, J., (2007), Handbook of European freshwater fishes, Berlin, Germany, ISBN 978-8399-0298-4

Larinier, M., Dartiguelongue, J., (1989), *La Circulation Des Poisions Migrateurs: Le Transit A Travers Les Turbines Des Installations Hydroelectriques*, Bull. Fr. Pêche Piscic, 312 - 313

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

Monten E., (1985), *Fish and Turbine – Fish Injuries During Passage Through Power Station Turbines*, Vattenfall, Stockholm, ISBN 91-7186-247-1

Schwevers, U. (2000). “Biologische Mechanismen der Fischabwanderung”. In: Wasser und Boden 52.53, pp. 4–9.